Low-Cost Science Mission Concepts for Mars Exploration

Program and Abstracts

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Low-Cost Science Mission Concepts for Mars Exploration

March 29–31, 2022
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NASA Mars Exploration Program

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LOW-COST SCIENCE MISSION CONCEPTS FOR MARS EXPLORATION

Agenda

Tuesday, March 29, 2022

8:30 a.m.	Fountain Ballroom	Welcome
8:45 a.m.	Fountain Ballroom	Mars Science Goals for Low-Cost Missions
10:15 a.m.	Fountain Ballroom	Programmatic Perspectives
1:00 p.m.	Fountain Ballroom	Lessons Learned in Low-Cost Mission Implementation
2:45 p.m.	Fountain Ballroom	Contributed Talks I
4:30 p.m.	Fountain Ballroom	Lightning Talks for Day 1 Poster Session
5:00 p.m.	Fountain Foyer	Poster Session Day 1

Wednesday, March 30, 2022

8:30 a.m.	Fountain Ballroom	Low-Cost Transportation to Mars
9:30 a.m.	Fountain Ballroom	Contributed Talks II
1:00 p.m.	Fountain Ballroom	Challenge of the Surface
1:45 p.m.	Fountain Ballroom	Contributed Talks III
3:30 p.m.	Fountain Ballroom	NASA Technology Investments
4:30 p.m.	Fountain Ballroom	Lightning Talks for Day 2 Poster Session
5:00 p.m.	Fountain Foyer	Poster Session Day 2

Thursday, March 31, 2022

8:30 a.m.	Fountain Ballroom	Commercial Innovation for Low-Cost Missions
9:30 a.m.	Fountain Ballroom	Cost Models for Low-Cost Missions
10:15 a.m.	Fountain Ballroom	Contributed Talks IV
11:15 a.m.	Fountain Ballroom	Closing Session

Low-Cost Science Mission Concepts for Mars Exploration

Program

Tuesday, March 29, 2022
WELCOME
8:30 a.m. Fountain Ballroom

Times	Panel Member	Moderators
8:30 a.m.	Eric Ianson	Chad Edwards Shannon Curry

Tuesday, March 29, 2022
MARS SCIENCE GOALS FOR LOW-COST MISSIONS
8:45 a.m. Fountain Ballroom
Perspectives on the potential role of low-cost missions in addressing Mars science objectives, including views from the Mars Exploration Program Analysis Group and the recent Mars Architecture Strategy Working Group.

Times	Panel Members	Moderators
8:45 a.m.	Don Banfield Aileen Yingst Bruce Jakosky Wendy Calvin Alfonso Davila Claire Newman	Rich Zurek
10:00 a.m.		BREAK

Tuesday, March 29, 2022
PROGRAMMATIC PERSPECTIVES
10:15 a.m. Fountain Ballroom
Programmatic views on the roles of low-cost missions in a future Mars exploration portfolio.

Chair: Chad Edwards

Times	Authors (*Presenter)	Abstract Title and Summary
10:15 a.m.	Parrish J. *	*Mars Exploration Program Office*
10:27 a.m.	Rucker M. A. *	*Role of Low-Cost Missions in Preparing for Human Mars Exploration* **[#5070]** Developing an enterprise-level architecture encompassing future human-robotic science and exploration at the Moon and Mars requires a visionary approach to ensure NASA is responsive to national priorities and global science and technology advancement objectives.

10:39 a.m.	Davis R. M. * Collom B. Viotti M. Kelley M.	*International Mars Ice Mapper Mission: A Reconnaissance Mission for the Human Exploration of Mars* **[#5071]** An overview of the International Mars Ice Mapper mission, which would detect the location, depth, spatial extent, and abundance of near-surface water ice, as well as the geotechnical characteristics of its overburden.
10:51 a.m.	Culbert C. J. *	*CLPS: Commercial Lunar Payload Services (CLPS)* **[#5073]** Discussion of the CLPS program using commercial services to deliver to the Moon.
11:03 a.m.		DISCUSSION
11:30 a.m.		LUNCH

Tuesday, March 29, 2022
LESSONS LEARNED IN LOW-COST MISSION IMPLEMENTATION
1:00 p.m. Fountain Ballroom
Interactive discussion on the challenges and success strategies for executing low-cost missions.

Times	Panel Members	Moderator
1:00 p.m.	Rob Lillis Bethany Ehlmann Craig Hardgrove Joel Krajewski Bob Balaram Bruce Jakosky	Shannon Curry
2:25 p.m.		BREAK

Tuesday, March 29, 2022
CONTRIBUTED TALKS I
2:45 p.m. Fountain Ballroom
Strategic Mars science questions; low-cost Mars mission concepts.

Times	Authors (*Presenter)	*Abstract Title and Summary*
2:45 p.m.	Fraeman A. A. * Rapin W. Bapst J. Matthies L. H. Ehlmann B. L. Golombek M. P. Langlais B. Lillis R. J. Mittelholz A. Weiss B. P. Chmielewski A. B. Delaune J. Izraelevitz J. S. Sklyanskyi E.	*Science Enabled by Aerial Explorers: Addressing Outstanding Questions in the Martian Geological Record* **[#5045]** A standalone Mars Science Helicopter could address questions about terrestrial planetary evolution. This asset could land using Mid-Air Helicopter Delivery, which would reduce EDL system complexity and cost.
3:00 p.m.	Montabone L. * Heavens N. G. Guzevich S. D. Cardesin-Moinelo A.	*Mars Weather Monitoring from Orbit: A Low-Cost Scenario* **[#5056]** We present a strategic Mars science objective well-suited to investigation via a low-cost, SmallSat constellation mission: weather monitoring.

3:15 p.m.	Sori M. M. * Ermakov A. I. Keane J. T. Bierson C. J. Bills B. G. Bramson A. M. D'Amico S. Evans A. J. Hemingway D. J. Izquierdo K. James P. B. Johnson B. C. Kahre M. A. Navarro T. O'Rourke J. G. Ojha L. Paik H. J. Park R. S. Simons M. Smith D. E. Smrekar S. E. Soderlund K. M. Steinbrügge G. Tikoo S. M. Vance S. D. Wagner N. L. Weber R. C. Zebker H. A.	*Compelling Science Enabled by Gravity Investigations at Mars* **[#5034]** We identify compelling questions in geodynamics and climate that could be realistically addressed by the acquisition of new gravity data at Mars. We will discuss which of these scientific questions could plausibly be addressed by low-cost missions.
3:30 p.m.	Guzewich S. D. * Heavens N. G. Montabone L. Lillis R. Barba N. Wooley R. Tamppari L. Abshire J. B. Smith M. D. Cremons D.	*PAWSS: Polar-Orbiting Atmospheric Wind Small Satellite* **[#5035]** Martian winds / Scientist's best friend / From small-sats.
3:45 p.m.	Heavens N. G. * Montabone L. Lillis R. Guzewich S. Barba N. Wooley R.	*AreostatioNary Exploration of Meteorology by Orbital Imaging (ANEMOI): A Low Cost Concept for Monitoring Martian Weather* **[#5013]** Our goal at Mars is to unite the circulation with accumulation, as my two eyes make one in sight.
4:00 p.m.	Hayne P. O. * Byrne S. Smith I. B. Banfield D. Barba N. Giersch L.	*Advancing Mars Polar Science with Micro-Landers* **[#5058]** Key questions in Mars polar science can be addressed using small payloads deployed to the surface of the polar layered deposits, which record climate variations over the last several million years.
4:15 p.m.		BREAK

Tuesday, March 29, 2022
LIGHTNING TALKS FOR DAY 1 POSTER SESSION
4:30 p.m. Fountain Ballroom

Presenters for the Day 1 Poster Session will present one-minute/one-slide previews of their posters.

Tuesday, March 29, 2022
POSTER SESSION: POSTER SESSION DAY 1
5:00 p.m. Fountain Foyer

Authors (*Denotes Presenter)	*Abstract Title and Summary*
Bramble M. S. Hand K. P.	*Consideration of the Martian Chloride Salt-Bearing Deposits as a Target for a Low-Cost Science Mission* **[#5064]** We consider science objectives and measurement requirements for a low-cost mission to the martian chloride salt-bearing deposits.
Battalio J. M.	*Opportunities for Constraining Mars's Atmospheric Dynamics with Both Surface Networks and a Martian Satellite Fleet* **[#5062]** Surface observation networks and satellite arrays can provide the next leap in our understanding of Mars's atmospheric dynamics. Given the age of current orbiters, we must push for new assets to ensure gaps in the atmospheric record are minimized.

Thiemann E. M. B. Eparvier F. G.	*Simple UV Photometers for Solar and Stellar Occultations of the Mars Upper Atmosphere* **[#5028]** Solar and stellar occultations provide direct measurements of atmospheric density. UV photometers significantly reduce instrument complexity and SWAP as compared to traditional spectrograph instruments.
Parfitt C. E. McSweeney A. G. Ball A. J. Orgel C. Khan M. Vijendran S.	*Low Cost Missions to Mars Studies at ESA* **[#5014]** There is interest at ESA to assess the possibility of implementing low cost missions to Mars in the late 2020s. Several studies to assess potential mission architectures that meet the criteria for a low cost Mars mission are presented.
Todd C. Espley J. Bowens R. Cacciottolo L. Chattrabhuti M. Cruz S. Festa A. Glait R. May R. McDougall J. Prober E. Schachter J. Wich J. Gruesbeck J. Guzewich S.	*Mars-BARS (Balloon for Aerial Regional-Scale Science): A Proposed Martian Aerial Platform Mission* **[#5038]** Mars-BARS is a proposed regional-scale study of Mars. A mission of this type and scale fills a gap between the local- and planetary-scale science. The aerial platform for this mission has been selected to be a balloon through a rigorous trade study.
Engler S. T. Idota T.	*Inexpensive Planetary Lava Tube Sky Light Lander and Exploration Drone* **[#5067]** We propose a primitive concept of a small low-cost lander and exploration drone for lava tubes which can be attached to any upcoming exploration probes to Mars and the Moon. We hope to connect with those with expertise to help move project forward.
Arruego I. Genzer M. Apéstigue V. Martínez-Oter J. Gonzalo A. Hieta M. Camañes C. Haukka H. González-Guerrero M. de Pedraza A. Kestila A. Sard I. Ortega C. Guerrero H. Domínguez-Pumar M. Espejo S. Ceballos J. Palin M. Kivekäs J. Koskimaa P. Rodriguez-Manfredi J. A. Talvioja M.	*Miniature Sensors Packages and Delivery System for Mars Exploration* **[#5029]** We describe a 25kg-penetrator carrying 5kg of scientific payload, aimed at deploying a network of environmental stations on Mars. EDL concept, structure, main system budgets and sensors will be presented. The project has been funded by an ESA TRP.
Putzig N. E. Bernardini F. Morgan G. A. Sizemore H. G. Clark R. N. Perry M. R. Sidney W. P. Abbud-Madrid A. Pelella A. V.	*Prospecting for Resources at Human Landing Sites on Mars* **[#5065]** We present a mission concept for rapidly implementing a Mars resource-prospecting orbiter to address uncertainties regarding buried ice and hydrated minerals using instruments and a spacecraft bus already at high technology readiness levels.
Stuurman C.	*COMPANION Smallsat RADAR Sounder for Mars Subsurface Imaging* **[#5018]** This abstract describes a low-cost mission concept for a high bandwidth, P-band, smallsat radar sounder intended as a piggyback or rideshare for low-cost delivery to Mars for the purpose of subsurface water ice detection.
Lee P. Riedel J. E. Jones-Wilson L. L. Bradford S. C. Gebara C. A. Jones-Wilson W.	*GlobeTrotter-Mars: All-Terrain Hopper for Mars Surface and Cave Exploration* **[#5059]** GlobeTrotter-Mars is a concept all-terrain hopper for Mars surface and cave exploration. Four GT-Mars mission concepts are presented: GTA to Aram Chaos, GTI to Ius Chasma in Valles Marineris, GTO to Oudemans Crater, and GTP to volcanic pits in Tharsis.

Lillis R. J. Curry S. M. Ma Y. J. Curtis D. W. Taylor E. R. Parker J. S. Hara T. Luhmann J. G. Barjatya A. Larson D. E. Livi R. Whittlesey P. Modolo R. Harada Y. Fowler C. M. Xu S. S. Brain D. A. Withers P. Thiemann E. M. B. Mosleh E. Mandy C.	*ESCAPADE: A Twin-Spacecraft SIMPLEX Mission to Unveil Mars' Unique Hybrid Magnetosphere* **[#5012]** ESCAPADE is a twin-spacecraft low-cost mission to explore the processes driving Mars' hybrid magnetosphere. Enabled by tailored approaches to risk management, vertical integration and contracting, ESCAPADE will launch on a TBD rideshare in 2024.
Bills B. G. Gorski K. M. Lysek M. J. Mischna M. A. Park R. S. Paik H. J. Moody M. V. Collins C. Norton R. S. Richardson M. I. Lee C.	*Gravitational Signatures of Seasonal Atmospheric Mass Transport on Mars* **[#5017]** We propose a mission which would accurately measure the gravitational signatures of seasonal atmospheric mass transport on Mars, using a gravity gradiometer instrument, similar to one currently under development within the NASA MatISSE program.
Kleinboehl A. Kass D. Piqueux S. Greybush S. J. Kenyon M. E.	*Mars Climate CubeSat Constellation (MC3) — A Low-Cost Orbital Constellation for Atmospheric Profiling, Polar Science and Surface Thermophysics* **[#5037]** The Mars Climate CubeSat Constellation (MC3) is a concept of a low-cost orbital constellation to investigate poorly characterized short-term atmospheric and surface processes by providing global measurement coverage at multiple local times.
Noell A. C. Boland J. S. Carpenter K. C. Karras J. T. McCormick R. Cooper M. Mandrake L. Castano R. Willis P. A. Mora M. F. Jaramillo E. A. Ferreira Santos M. S. Kaufman J. M. Lang J. A. Eby M. A. Davila A. F. Quinn R. C. Ricco A. J.	*Large Mars Surface Chemistry Science in a Small Budget* **[#5041]** The distribution of chlorine species and abiotic organics are some of the Mars surface investigations possible with a novel approach to low cost missions that make use of the MarsDrop microlanders, microrovers and miniature instrumentation.
Andersson L. Bering E. A.	*MARSCat: Imaging of the Martian Ionosphere using a CubeSat Constellation* **[#5068]** The MarsCAT (Mars Array of ionospheric Research Satellites forming the Constellation for Aeronomy and Tomography) Mission is a multi 6U CubeSat mission to study the ionosphere of Mars.
Hobbs S. W. Lambert A. Ryan M. J.	*Near-Space Testing of Low-Cost Remote Sensing Payload for Mars Applications* **[#5003]** Low-cost Raspberry Pi sensors were tested in near-space and were able to return scientifically useful results, indicating their utility for multispectral sensors for Mars.
Babu Mannam N. P. Kumar Duba P. Pachamuthu R.	*Bioinspired Dragonfly Concept for Mars Exploration: Analogous to Mars Ingenuity Helicopter* **[#5007]** The dragonfly-based unmanned aerial vehicle (UAV) is designed and developed which consists of a pair of forwarding and backward wings subjected to heave and pitch motions producing maximum lift and thrust forces.

Mayyasi M. Erickson P. Lind F. Semeter J. Mazumder M. Knapp M.	*An Energy-Efficient Incoherent Scatter Radar at Mars* **[#5010]** We describe a lander-based implementation for an energy-efficient incoherent scatter radar at Mars. This instrument concept allows unique measurements of thermal properties of the martian atmosphere in regions that orbiting spacecraft cannot explore.
Kereszturi A. Miyamoto H. Pal B.	*Flock of Low Cost Microlanders to Survey Liquid Water Potential on Mars Along the Receding Polar Cap* **[#5030]** Chain of micro-landers used only parachute driven deceleration could survey the temperature and humidity of the shallow subsurface zone on Mars along the receding springtime seasonal water ice cap edge.
Campbell C. L. Smith C. L. Innanen A. Kloos J. L. Stone H. Benedix G. Meka S. Marrable D. Moores J. E.	*MAPLE, a Simple Optical Meteorological Station for Mars* **[#5031]** The Mars Atmospheric Panoramic camera and Laser Experiment (MAPLE) is an optical meteorological station for studying aerosols. Based on techniques from martian surface missions it will have low power, data and cost to optimize the returnable science.

Wednesday, March 30, 2022
LOW-COST TRANSPORTATION TO MARS
8:30 a.m. Fountain Ballroom
Panelists will share industry and NASA perspectives on low-cost approaches to delivering science missions to Mars, including piggyback, rideshare, and small launch vehicle options.

Times	Panel Members	Moderator
8:30 a.m.	Julianna Scheiman Eric Salwan Shaun Daly Ryan Woolley	Nathan Barba

Wednesday, March 30, 2022
CONTRIBUTED TALKS II
9:30 a.m. Fountain Ballroom
Low-cost Mars mission concepts.

Times	Authors (*Presenter)	*Abstract Title and Summary*
9:30 a.m.	Diniega S. * Barba N. Giersch L. Jackson B. Soto A. Rafkin S. Swann C. Sullivan R. Banfield D. Fenton L.	*Optimally-Sized Mission Concepts for Focused In-Situ Studies of Planetary Surface-Atmosphere Interactions* **[#5044]** Small landers provide / Great surface process studies / Over different scales.
9:45 a.m.	Stähler S. C. * Panning M. P. Antonangeli D. Banerdt W. B. Banfield D. Banks M. Ceylan S. Charalambous C. Clinton J. Daubar I. Fernando B. Giardini D. Grott M. Horleston A. Hurst K. Kawamura T. Kim D. Knapmeyer M. Lorenz R. Margerin L. Marusiak A. Menina S. Mittelholz A. Murdoch N. Perrin C. Pike W. T. Schmelzbach C. Schmerr N. Schimmel M. Spiga A. Stott A. Taylor J. Weber R.	*A Cerberus Fossae Seismic Network* **[#5024]** Cerberus Fossae is the region of most significant tectonic activity in the InSight hemisphere, with a potential recent history of volcanism and water. We propose a geophysical and meteorological network of hard landers to unlock its secrets.

10:00 a.m.	Sapers H. M. * Moores J. E. Grandmont F. Maisonneuve M.	*The Martian Atmospheric Gas Evolution (MAGE) Experiment: High-Frequency Near-Surface Trace Gas Measurements on Mars* **[#5050]** MAGE: autonomous surface trace gas observatory capable of obtaining high-frequency sub-ppb measurements with low resource requirements compatible with three mission scenarios: (1) primary landed payload; (2) lander-integrated; (3) rover deployable.
10:15 a.m.	Smith I. B. * Calvin W. Becerra P. Landis M. Byrne S. Hayne P. Bapst J. Chmielewski A. B. Delaune J.	*Bifrost: Mars Polar Science Enabled by a Low-Cost Helicopter* **[#5066]** Mars Polar Science Helicopter with low-cost vehicle and payload.
10:30 a.m.		BREAK
10:45 a.m.	Calvin W. M. * Green R. O. Fraeman A. A. Ehlmann B. L. Horgan B. H. N. Seelos K. D. Murchie S. L.	*Oasis: Exploring Surface Water Reservoirs with Next Generation Imaging Spectrometers* **[#5025]** Water is key to understanding ancient and modern climate records. This mission concept explores and quantifies, at high spatial resolution, the near-surface reservoirs of water in hydrated minerals and volatile ices and their evolution through time.
11:00 a.m.	Malin M. * Yee T. Jordan K. Roman M. Svitek T. Troy D.	*Three Small Mars Missions Based on Common Spacecraft Systems: 1. Mars Stationary Orbiter (MSO)* **[#5048]** Mars Stationary Orbiter (MSO) makes sci obs of surf/atmos and provides UHF relay for landed assets. ESPA-sized S/C Rideshares to GTO, waits in cis-lunar space for TMI, uses its bi-prop for TMI and MOI (ΔV ~ 3200 m/s). 1 S/C = $16M, 4 and ops $75M.
11:15 a.m.	Colaprete A. * Cook A. Mauro D. Bookbinder J. Maryatt B.	*Aeolus: A Mars Climate Mission* **[#5061]** Aeolus is a small satellite mission to observe surface and atmospheric forcing and general circulation of Mars, by measuring surface energy balance, atmospheric temperatures, aerosols and clouds, and winds.
11:30 a.m.	Tamppari L. K. * Livesey N. J. Chattopadhyay G. Barba N. J. Guzewich S. Kleinböhl A.	*Scalable Mission Options for Measuring Winds and Water Vapor on Mars* **[#5020]** Wind and water vapor profiles in the martian atmosphere are needed, high-priority measurements identified in many Mars program reports. We provide instruments and several mission scenarios that would obtain one or both of these measurements.
11:45 a.m.		LUNCH

Wednesday, March 30, 2022
CHALLENGE OF THE SURFACE
1:00 p.m. Fountain Ballroom
Landing on Mars poses a particular challenge for low-cost missions; this panel examines strategies for affordable access to the martian surface.

Times	Authors (*Presenter)	Abstract Title and Summary
1:00 p.m.	R. Manning *	*Where's My Money Going? - What Makes Mars Landers Cost So Much and What Does It Take to Keep Costs Down?*
1:22 p.m.	A. Fraeman *	*An Outbrief from the 2021 KISS Workshop: "Revolutionizing Access to the Martian Surface"*

Wednesday, March 30, 2022
CONTRIBUTED TALKS III
1:45 p.m. Fountain Ballroom
Low-cost Mars mission concepts; capabilities of orbital and landed small spacecraft; mission design approaches.

Times	Authors (*Presenter)	*Abstract Title and Summary*
1:45 p.m.	Pagano T. S. * Mischna M. A. Liuzzi G.	*Hyperspectral Infrared Temperature Souding of Mars' Atmosphere in a CubeSat* **[#5019]** Advancements in detector and optics technology allow hyperspectral infrared measurements of Mars atmosphere to be made in a CubeSat. As done on Earth, these measurements can improve weather prediction on Mars and complement current observations.
2:00 p.m.	Giersch L. * Barba N. Cormarkovic V. Delapierre M. Golombek M. Williams N. Woolley R. Lobbia M. Sklyanskiy E. Burke R.	*SHIELD: A New Low-Cost Architecture for Delivering Science Payloads to the Surface of Mars* **[#5042]** The Small, High Impact Energy Landing Device (SHIELD) is being developed to demonstrate a new low-cost architecture for delivering science payloads to the surface of Mars.
2:15 p.m.	Austin A. * Lobbia M. Strauss B. Ravich J. Luthman L. Venkatapathy E. Wercinski P.	*Drag Modulation Aerocapture Technology to Enable SmallSat Mars Orbiters* **[#5021]** Aerocapture can enable science at Mars with SmallSats by using the drag of an atmospheric pass to reach orbit instead of large amounts of propellant. Drag modulation flight control allows for an orbit to be targeted in the presence of uncertainties.
2:30 p.m.	Benardini J. N. III * Seasly E. E. Spry J. A.	*Planetary Protection for Low-Cost Mars Missions* **[#5063]** This presentation will highlight planetary protection implementation strategies and issues for small robotic missions, based on mission case studies, and include a focus on NASA's recently revised requirements document for planetary protection .
2:45 p.m.	Parker J. S. * Ott C. Koehler A. Baskar S. Sullivan T. M.	*The ESCAPADE Mission Design* **[#5072]** The Escape, Plasma and Acceleration Dynamics Explorers (ESCAPADE) mission will send two spacecraft from a rideshare launch into a formation about Mars. This paper describes the astrodynamics challenges and ESCAPADE's robust solution.

3:00 p.m.	Wercinski P. * Venkatapathy E.	*Enabling New and Innovative Low Cost Mars Science Missions with the Adaptable, Deployable, Entry and Placement Technology (ADEPT)* **[#5022]** The Adaptable, Deployable, Entry and Placement Technology (ADEPT) is a low ballistic coefficient planetary entry system that employs an umbrella-like deployable structure to serve as a hypersonic decelerator.
3:15 p.m.		BREAK

Wednesday, March 30, 2022
NASA TECHNOLOGY INVESTMENTS
3:30 p.m. Fountain Ballroom
Panelists will discuss NASA technology investments that can contribute toward enabling low-cost Mars science missions.

Times	Panel Members	Moderator
3:30 p.m.	Carolyn Mercer Christopher Baker John Baker Michael Amato	Florence Tan

Wednesday, March 30, 2022
LIGHTNING TALKS FOR DAY 2 POSTER SESSION
4:30 p.m. Fountain Ballroom

Presenters for the Day 2 Poster Session will present one-minute/one-slide previews of their posters.

Wednesday, March 30, 2022
POSTER SESSION: POSTER SESSION DAY 2
5:00 p.m. Fountain Foyer

Authors (*Denotes Presenter)	*Abstract Title and Summary*
Putnam Z. R. Fawley D. M.	*Drag Modulation Trajectory Control for Delivery of Low-Cost Mars Orbiters and Landers* **[#5060]** Drag modulation is well-suited to low-cost missions because it provides good accuracy in a simple, mass-efficient package. We assess trajectory control options for aerocapture and entry drag modulation systems consistent with low-cost missions.
Deitrich N. Bayandor J.	*A Multifunctional Tensegrity Rover Concept for Exploration of Extreme Martian Terrains* **[#5033]** The proposed concept is a redesign of the Tension Adjustable Network for Deploying Entry Membrane (TANDEM) tensegrity rover for a low-cost mission to Mars. Focus is on the entry, descent, landing, and locomotion (EDLL).
Ramezani A. Sihite E. Devey S. Gharib M.	*Efficient and Endured Aerial Mobility on Mars Using Novel Morphing Micro Aerial Vehicle Designs* **[#5051]** This work presents our recent efforts to use aerial drones for Mars exploration.

Malin M. Yee T. Jordan K. Roman M. Svitek T. Troy D.	*Three Small Mars Missions Based on Common Spacecraft Systems: 3. Mars Microlander/Rover* **[#5055]** Mars Microlander/Rover is an ESPA-Grande-class S/C launched as a rideshare to GTO, uses a new, all-propulsive EDL system, a 1.6 m areoshell, a 40 kg rover with 12 kg of modular sci pld. Pallet lander w/ crushable nose. MER equivalent costs ≤ $300M.
Malin M. Yee T. Jordan K. Roman M. Svitek T. Troy D.	*Three Small Mars Missions based on Common Spacecraft Systems: 2. Mars High Resolution Imager (MHRI)* **[#5052]** Mars High Resolution Imager (MHRI) takes 11 cm/pxl pan and 64 cm/pxl 4 color 12 x 6 km swaths in stereo. It takes 10 m/pxl IR spectra between 1.2 µm and 6.3µm over 12 x 12 fields. Segmented 1 m mirror, is f/8,7. Total mission cost is $86M w reserves.
French R. T. Mosleh E.	*Affordable, High Impact Mission Concepts for Mars with Rocket Lab Space Systems* **[#5043]** Rocket Lab provides frequent and reliable access to space with electron and recently announced the neutron medium lift launch vehicle. The Space Systems Division is expanding with small spacecraft capable of delivering Decadal-class science.
Grasso C. A. Riedel R. E.	*Cost Savings with AutoNav Self-Navigating Spacecraft for Mars Missions* **[#5057]** AutoNav Mark 4 performs on-board guidance and navigation of spacecraft for small Mars missions. The flight software provides optical navigation services, using images to perform orbit determination, and deriving maneuvers onboard for TCMs and OTMs.
Mittelholz A. Heagy L. Johnson C. L. Langlais B. Lillis R. J. Rapin W.	*Helicopter Magnetic Field Surveys for Future Mars Missions* **[#5016]** We investigate data sets that a future helicopter-based magnetometer might be able to provide by constructing simple forward models that resemble a range of plausible subsurface geological structures that allow experimenting with survey design.
Wronkiewicz M. Anderson R. C. Bandyopadhyay S. Brandon E. J. Goel A. Vander Hook J. Mischna M. Villarreal M. Rossi F.	*Toward Economically Addressing Surface Science Questions on Mars with Distributed Instruments* **[#5049]** Investigation into the atmosphere and interior of Mars would benefit from global surface measurements. Distributed instruments (comprised of multiple sensor platforms) are suitable for such studies and amenable to many off-the-shelf technologies.
Albert S. W. Schaub H. Braun R. D.	*Efficient Delivery of a Network of Small Probes to the Martian Surface* **[#5011]** Networks of probes can uniquely enable science on Mars. Minimizing the number, size, and complexity of maneuvers is desirable for mission design. We adapt B-Plane targeting to design maneuvers to deliver a network of probes from one cruise stage.
Woolley R. C. Barba N.	*Mission Design Hurdles for Low-Cost Mars Missions* **[#5015]** In this poster, we identify five mission design challenges that any mission to Mars must address to successfully arrive. We then discuss strategies and solutions tailored to low-cost missions including ridesharing, propulsion, etc.
Choi S. H. Moses R. W.	*Low Cost Micro-Spectrometer for Resource Mapping on Mars* **[#5039]** A micro-spectrometer technology developed at NASA offers a low-cost sensor and measurement instrument that can be packaged to allow integration into exploration mission systems to enable measurements in extreme access and extreme environments.

Hardgrove C.	_Compact, Modular Neutron and Gamma-Ray Spectrometer for Small Spacecraft Missions_ **[#5076]** Mini-NS spectrometer has been developed as part of the first NASA SMD SIMPLEx mission LunaH-Map. Future Mars missions can use Mini-NS modules and signal processing electronics to detect and determine abundances of hydrogen and rock-forming elements.
Rapin W. Maurice S. Wiens R. C. Dubois B. Parot Y. Bernardi P. Nelson T. Clegg S.	_μLIBS: A Micro-Scale Elemental Analyser for Lightweight In Situ Exploration_ **[#5032]** Microanalysis is the next step forward in Mars exploration. We propose a new μ 1.5 kg instrument to perform precise elemental grid microanalyses at 20–50 cm standoff without the need of turret or arm deployment.
Rafkin S. C. R. Nowicki K. Silver J.	_A Low Cost Tunable Laser Spectrometer for Mars Water Vapor, Trace Gases, and Eddy Flux Measurements_ **[#5036]** We describe a TRL 6 instrument that is capable of high precision and high frequency (>40 Hz) measurements of water, CO_2, and various other trace gases, and which supports the acoustic determination of wind and eddy flux measurements at Mars.
Green R. O. Mouroulis P. Sullivan P. Bender H. Calvin W. Ehlmann B. Fraeman A. Thompson D. R. Vinckier Q. Keymeulen D. Klimesh M. Ardila D. Nadgauda S.	_Low-Cost, High Signal-to-Noise Ratio, and High Fidelity Imaging Spectrometers for Mars_ **[#5040]** Low-cost, high signal-to-noise ratio, and high fidelity imaging spectrometers for future Mars missions.
Baker J. D.	_Small Satellite Technologies for Low-Cost Mars Missions_ **[#5047]** New spacecraft and instrument capabilities exist today that can enable lower cost Mars exploration science missions. This abstract will describe at a high level several of the new capabilities available and the performance they offer.
Ramezani A. Sreenath K.	_Thruster-Assisted Legged Mobility for Explorations on Mars_ **[#5074]** In this abstract, we propose employing thruster-assisted legged locomotion in form of continuous hopping gait to achieve efficiency and robust mobility in partial gravity on Mars. We give a brief overview of ongoing research and produced results.
Profitiliotis G.	_Precompetitive Collaboration on Planetary Protection Technologies to Enable Low-Cost Mars Exploration_ **[#5027]** Planetary protection should be viewed as an avenue that accommodates the interests of space actors and of citizens, and should thus be maintained as a beneficial foundation for any upcoming Mars activities via a precompetitive collaboration scheme.
Ono M. Balaram B. J. Verma V. Atha D. J. Swan R. M. Didier A. K.	_New Rover CONOPS with High-Performance Onboard Computing: Give Up Raw Data to Reduce Ops Cost and Do More Science_ **[#5053]** Imagine every scientist/engineer can uplink and run analysis scripts on a rover like Jupyter Notebook. No need to downlink all the raw data anymore. This will remove the comm volume constraint, simplifying and saving the cost of tactical ops.

Brinckerhoff W. B. Davila A. F. Shkolyar S. Bebout L. E. Des Marais D. Getty S. Hoehler T. M. Jahnke L. Lau G. Lehmer O. Neveu M. Parenteau M. N. Pohorille A. Quinn R. C. Som S. Wilhelm M. B.	*The Life Detection Knowledge Base: Organizing Astrobiology Knowledge and Technology for Mission Concept Development* **[#5075]** We will summarize recent and planned efforts to develop the Life Detection Forum, a community-driven, living suite of online tools. LDF is intended to organize astrobiology knowledge and technology for use in life detection mission concept planning.

Thursday, March 31, 2022
COMMERCIAL INNOVATION FOR LOW-COST MISSIONS
8:30 a.m.   Fountain Ballroom
Panel members will discuss emerging commercial capabilities that can enable low-cost Mars mission concepts.

Times	Panel Members	Moderator
8:30 a.m.	Richard French Timothy Linn Johannes Loschnigg Steve Bailey	Nathan Barba

Thursday, March 31, 2022
COST MODELS FOR LOW-COST MISSIONS
9:30 a.m.   Fountain Ballroom
Cost estimating approaches applicable to low-cost Mars missions are presented, addressing science and mission scope as well as overall mission risk posture.

Times	Authors (*Presenter)	Abstract Title and Summary
9:30 a.m.	D. Bearden *	*Adapting Cost Estimation Models to New Approaches and Recommended Science Community Paths*
9:55 a.m.		BREAK

Thursday, March 31, 2022
CONTRIBUTED TALKS IV
10:15 a.m.   Fountain Ballroom
Low-COST Mars mission concepts; instruments, avionics, and subsystems.

Times	Authors (*Presenter)	*Abstract Title and Summary*
10:15 a.m.	Fleischer S. R. * Austin A. Barba N. J. Bjornstad P. Edwards C. D. Jr. Hihn J. M. Kolanjian A. Lock R. Saing M. Woolley R. C.	*Assessing Cost Drivers for Mars Small Spacecraft Missions* **[#5023]** Here we develop a cost model constrained by fundamental physics to predict formulation and implementation costs of small-medium missions to Mars as a function of a few, system-level inputs. Engineering and programmatic implications are discussed.
10:30 a.m.	Nunes D. C. * Grimm R. E. Barba N. Burgin M. Carpenter K. Krieger S. Manthena R. McGarey P.	*Transmissive H_2O Reconnaissance Sounder, TH_2OR — A Compact Time-Domain Electromagnetic Instrument for Groundwater Detection* **[#5054]** We are developing a planetary low-power, low-mass transient electromagnetic sounding instrument intended to test the hypothesis of an extant deep global aquifer at Mars.

10:45 a.m.	Wilhelm M. B. * Ricco A. J. Lee C. Lynch K. L. Beegle L. Cassell A. Barba N.	*Low-Cost Mars In-Situ Astrobiology Measurements and Strategy* **[#5069]** Low-cost Mars astrobiology missions should search for indicators of extant life, preserved remains of ancient life, and help improve understanding of modern habitability with a simple and complementary set of sensors in a small, ruggedized package.
11:00 a.m.	Espley J. R. * Sheppard D. A. Gruesbeck J. R. DiBraccio G. A.	*Magnetic Observations at Mars: Plasma, Crust, and Subsurface* **[#5046]** Magnetic observations at Mars are vital for several important areas, including its magnetosphere, atmosphere, crust, and subsurface. There are multiple low cost mission scenarios where magnetometers could make major advances in these areas.

Thursday, March 31, 2022
CLOSING SESSION
11:15 a.m. Fountain Ballroom
A summary discussion of conference highlights and take-aways.

Times	Panel Members	Moderators
11:15 a.m.	Eric Ianson Tiffany Morgan Joe Parrish Michael Meyer Scott Hubbard Aileen Yingst	Chad Edwards Shannon Curry
12:00 p.m.		*Adjourn*

Low-Cost Science Mission Concepts for Mars Exploration

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LOW-COST SCIENCE MISSION CONCEPTS FOR MARS EXPLORATION

Abstracts

EFFICIENT DELIVERY OF A NETWORK OF SMALL PROBES TO THE MARTIAN SURFACE. S. W. Albert[1], H. Schaub[1], and R. D. Braun[2], [1]University of Colorado Boulder, Aerospace Engineering Sciences, samuel.albert@colorado.edu, [2]California Institute of Technology, Graduate Aerospace Laboratories.

Introduction: Networks of small probes on the Martian surface can uniquely enable science. A variety of science investigations may benefit from simultaneous observations at different locations on the surface, and some relevant instruments such as microseismometers and meteorological suites can fit in a small package [1, 2]. An orbiter may be required to provide telecommunications relay to Earth, and such a spacecraft could also obtain complementary science measurements from orbit. The orbiter could additionally serve as a cruise stage, delivering the probes from Earth to Mars.

The lower the mass and volume of each probe, the more probes can be included for the same total mass, and keeping total launch and landing masses down is important for mission cost. The entry, descent, and landing (EDL) system is a significant contributor to mass, volume, and cost. One way to reduce this impact is to relax EDL requirements that drive system design, including landing accuracy and g-load [3]. The Small High Impact Energy Landing Device (SHIELD) would accomplish this by eliminating parachutes and retropropulsion, relying only on a low drag-to-mass-area ratio and crushable material for reduce to the landing decelerations to in the range of 1,000 Earth g's [4]. A multiprobe network mission may accommodate relaxed landing accuracy requirements because approximate relative landing locations and precise positioning post-landing are likely more important than accurate delivery to pre-determined sites, and the orbiter can be used for post-landing positioning. Design of science instruments tolerant to relatively high landing decelerations would further reduce constraints on the EDL system.

For a multiprobe mission as described so far, one orbiter and multiple probes travel together to Mars and must separate at some point to reach their respective desired final states. Maneuvers could be performed to align separate approach trajectories for the orbiter and probes but, assuming no propulsion subsystem for the probes, either the probes experience a long passive coast phase without the cruise stage or the orbiter performs a divert maneuver shortly before orbit insertion. One alternative co-delivery option is for the orbiter to achieve orbit insertion via aerocapture, and to design the orbiter and probes to target identical atmospheric entry conditions. Aerocapture is the technique of flying through a planet's atmosphere to reduce the spacecraft's energy and capture into orbit, reducing the ΔV requirement compared to propulsive orbit insertion [5]. For this co-delivery method, the orbiter and probes diverge in the atmosphere due to differences in their aerodynamic properties and control. By avoiding the need to set up two separate approach trajectories, this co-delivery technique reduces maneuver complexity during approach and eliminates a source of navigation error, while still gaining the benefits of a shared cruise stage between the orbiter and probe. Co-delivery of this kind is feasible at Mars for a range of entry conditions and vehicle types [6].

Study of Network Delivery: An example Mars multiprobe mission is defined, and the work investigates how probes could be delivered from a single cruise stage to form networks of various geometries and scales on the surface. The timing, magnitude, and direction of the ΔV produced by the separation events are varied and the resulting relative separation distances between landing sites is considered. If the separation occurs too late, the required ΔV magnitude becomes relatively large in order to achieve separation on the surface, and there may be insufficient time to measure and correct any error introduced to the orbiter trajectory. An early separation would reduce the required ΔV magnitude and leave time for potential reorientation and navigation updates for the orbiter. However, the relatively long coast phase amplifies the effect of any off-nominal separation ΔV on the probes' trajectories and requires longer battery life prior to landing.

To gain insight into these tradeoffs, a range of trajectories are simulated with varying separation magnitude and timing in four different directions. The landing locations are plotted, and the minimum and maximum distance between any two probes is reported for the probe network that results from each scenario. A Monte Carlo analysis is performed to quantify the impact of relevant uncertainties on the landing locations for one of these scenarios; the final study will include a more in-depth uncertainty quantification. The final study will investigate optimization of the separation event for a specific desired network geometry by adapting B-plane targeting to use relative probe distances as the objective function.

Preliminary Results: Figure 1 shows the landing locations of four probes due to a 10 cm/s separation impulse in the plus/minus along-track and plus/minus cross-track directions, where the separation timing ranges from 3 to ¼ days prior to entry. Figure 2 shows the same information, but against a to-scale Martian surface. The significantly greater sensitivity to ΔV in the along-track direction can be accommodated by earlier cross-track separations and later along-track separations. For the scenarios shown here, the minimum distance between probes on the surface ranged from 2.5 to 30 km, and the maximum distance ranged from 42 to 530 km. In general, separations of 10s to 100s of kilometers on the surface are achievable from a single approach trajectory by applying centimeters per second of ΔV roughly 1 day before entry.

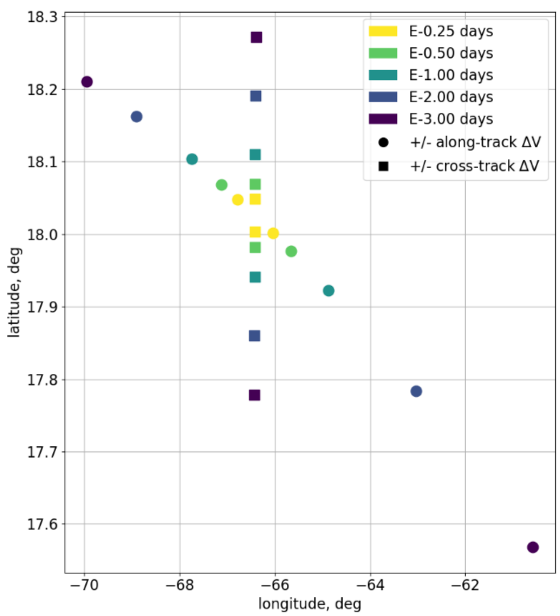

Figure 1: Landing locations on Mars for probes released with $\Delta V = 10\ cm/s$

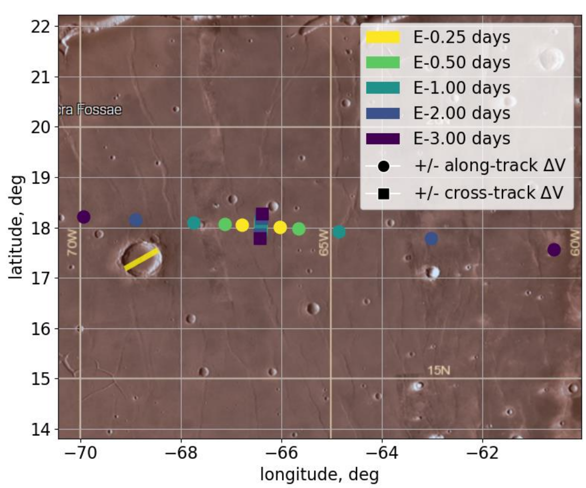

Figure 2: Fig. 2 data superimposed to-scale on the Martian surface.

The work so far captures sensitivity to separation ΔV and timing, as well as the effect of uncertainty, in an open-loop fashion. In order to target specific network geometries on the surface, the final study will demonstrate a closed-loop process that designs an efficient series of maneuvers. This will be accomplished by adapting B-plane targeting, commonly used for design of flyby or EDL trajectories, to target relative separation distances rather than the B-plane intersect point for a single trajectory. This would enable faster iterations during preliminary design of probe network missions, a relevant science mission concept for Mars exploration that is potentially low-cost.

Acknowledgments: This work was supported by a NASA Space Technology Research Fellowship. The first author acknowledges ideas, advice, and inspiration from other participants in the Revolutionizing Access to the Martian Surface workshop organized by the W. M. Keck Institute for Space Studies.

References: [1] Nunn, C., Pike, W. T., Standley, I. M., Calcutt, S. B., Kedar, S., and Panning, M. P. (2021) *The Planetary Science Journal*, *2*, *36-44*. [2] Rafkin, S. (2015) *IEEE Aerospace*. [3] Braun, R. D. and Manning, R. M. (2007) *JSR*, *44*, *310-323*. [4] Barba, N., Komarek, T., Woolley, R., Giersh, L., Stamenković, V., Gallagher, M., and Edwards, C. D. (2019) *IEEE Aerospace*. [5] Hall, J. L., Noca, A. N., and Bailey, R. W. (2005) *JSR*, *42*, *309-320*. [6] Albert, S. W., Braun, R. D., and Schaub, H. (2021) *JSR*, *in press*.

MARSCat: Imaging of the Martian Ionosphere using a CubeSat Constellation. L. Aandersson[1] and E. A. Bering[2], [1]University of Colorado, LASP, 3665 Discovery Drive Boulder, Colorado 80303 (laila.andersson@lasp.colorado.edu), [2]University of Houston, 3507 Cullen Blvd.,#617/PHYS 5005, Houston, TX, 77204, USA (ebering@Central.UH.EDU.

Introduction: The MarsCAT (Mars Array of ionospheric Research Satellites forming the Constellation for Aeronomy and Tomography) Mission is a multi 6U CubeSat mission to study the ionosphere of Mars. The mission will investigate the plasma and magnetic structure of the Martian ionosphere, including transient plasma structures. There is a growing need to understand the dynamics of the cold plasma at a planet resulting in two ongoing studies of missions using radio tomography at Earth to investigate the plasmasphere which expand and contract over hours to days. At Mars, the timescales are faster with no corotating plasma. The cold plasma is much more dynamic at Mars which statistical studies using in-situ observation alone cannot capture. The MARSCat mission has been developed to observe the cold plasma dynamics at Mars which influence the atmospheric escape and could impact communications at Mars. Ionospheric irregularities in the high density ionosphere has been observed with both the MEX and MAVEN missions presently orbiting Mars. The dedicated MARSC at mission using inter-spacecraft tomography is therefore needed for our understanding of the Martian ionosphere. This presentation will present MARSCat mission concept.

Reference:

Bering, E. A., Andersson, L., Moldwin, M., & Withers, P. (2021). MARSCat: Imaging of the Martian Ionosphere using a CubeSat Constellation. Bulletin of the AAS, 53(4). https://doi.org/10.3847/25c2cfeb.33ed0b33

Miniature sensors packages and delivery system for Mars exploration.

I.Arruego[1], M. Genzer[2], V. Apéstigue[3], J. Martínez-Oter[3], A. Gonzalo[1], M. Hieta[2], C. Camañes[4], H. Haukka[2], M. González-Guerrero[3], A. de Pedraza[1], A. Kestila[2], I. Sard[4], C. Ortega[4], H. Guerrero[6], M. Domínguez-Pumar[8], S. Espejo[7], J. Ceballos[7], M. Palin[2], J. Kivekäs[2], P. Koskimaa[2], J.A. Rodriguez-Manfredi[5] and M. Talvioja[9].
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Introduction: The use of networks of in-situ small scientific stations has been widely considered as a way to obtain an unpreceded improvement in our knowledge of the Martian atmosphere. Penetrators have been often considered for this [1]. They could be carried to the red planet in a large number by a single mission, providing simultaneous observations at different locations.

Amongst the ideas proposed through the last decades, the most relevant ones are Mars 96 [2] and the Deep Space probes (DS-2) launched with Mars Polar Lander in 1999 [3]. Both failed. In more recent times, the Mars MetNet Lander penetrator was about to be send to Mars on board the Russian mission Phobos Grunt, which also ended-up in a failure [4]. Other existing proposals such as the JPL's MarsDrop concept [5] or the Japanese Martian penetrator [6] are still in pre-liminary design phases.

By mid-2019 ESA launched an Announcement of Opportunity [7] for a Technology Research Program aimed at the development of 2 packages of miniature scientific sensors, for Mars and Moon exploration, together with a penetrator for the deployment of the first one. The selected proposal was the so-called "MiniPINS" (Miniature Planetary IN-situ Sensors), led by the Finnish Meteorological Institute (FMI) together with the Spanish National Institute of Aerospace Technology (INTA) and a consortium of other Spanish entities (AVS company, INTA/CSIC Astrobiology Center, Institute for Advanced Studies in Nanoscience of Madrid, Microelectronics institute of Seville and Polytechnic University of Catalonia).

The MiniPINS study: MiniPINS study aims at miniaturizing a set of scientific sensors that, in the case of Mars, would be deployed by a 25 kg penetrator with around 4-5 kg of payload. Several penetrators would be carried to the Martian orbit by an orbiter that would be oriented for the deployment of each one. Two inflatable elements are used during the EDL (Entry, Descent and Landing) sequence: an inflatable thermal protection shield, and a secondary braking and stabilizing inflatable device.

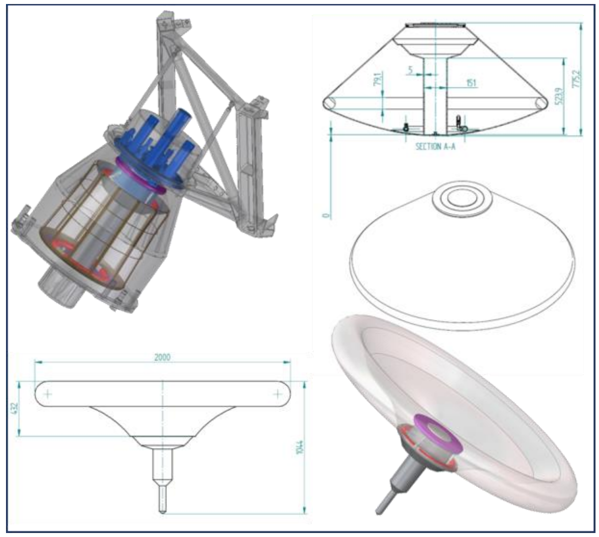


Fig. 1 Different views of the EDL elements.

The payload sensors include a camera, visual spectrometer, meteorological package, thermoprobes, an accelerometer, a chemistry package and a radiation monitor. The probe will also provide positioning signal and communications link to the Orbiter.

The expected impact speed is 60 to 80 m/s. The penetrator is a single-body structure with different sections: a first slender section to ensure a minimum penetration depth even in hard terrains, a second section wide enough to accommodate the main electronic subsystems (batteries, computer, radio, electronic power supply) and a third one called "stopper", wider than the previous, to guarantee that the probe stops and does not get buried even in soft terrains. It also accommodates a deployable boom, scientific sensors and antenna, and is covered by three deployable rigid solar panels.

The intended lifetime is one Martian year (extended mission, two years).

Critical technologies and environment: Amongst the key aspects of the design, the EDL system and the resistance to the impact are critical. Besides, the thermal conditioning together with the electrical power budget are also of paramount importance.

All the elements of the penetrator shall be light and robust, miniaturized but capable of surviving high G loads (with estimated peaks of a few thousand g's and durations up to around 10 ms, depending on soil hardness and impact speed). Most of the electronics and the scientific sensors will be designed with an operative thermal range reaching -120ºC, so that energy needs for heating are minimized (reduced to a small warm compartment for the battery pack).

The inflatable EDL concept would make intensive use of MetNet heritage with some modifications for the MiniPINS case and to increase stability. Trajectory calculations for reference landing sites have been computed and tolerances in atmospheric-entry speed and angle analyzed.

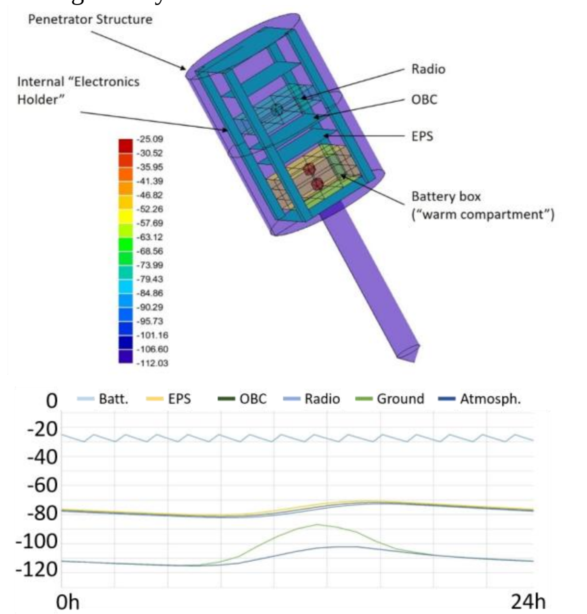


Fig. 2. Cold-case thermal analysis for one landing site.

Estimations of the available energy budget and thermal conditioning needs have been carried-out. Landing sites have been limited to latitudes under 40 degrees, above which a RHU – Radioactive Heating Unit – would be needed for battery-heating.

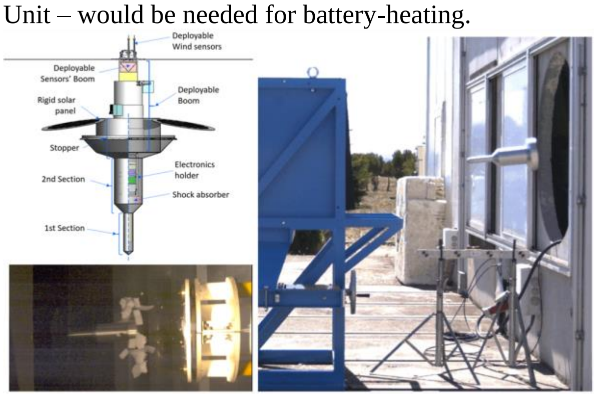


Fig. 3 Penetrator design and impact tests.

Regarding the resistance to impact, an impact test facility has been developed based on a compressed-air canyon and targets that allow different materials to be employed to simulate the terrain.

Finally, the consortium has a large experience in developing Radiation Hardened By Design (RHBD) and low temperature resistant mixed-signal ASICs for Mars [8]-[10] as well as other enabling technologies and particular miniature sensors [11]-[17] capable of surviving the extensive thermal cycling on Mars.

Fig. 4. Some miniature sensors developed by the consortium.

The output of this work will enable ESA to prepare and plan for technology development programs required to implement such ambitious planetary missions.

References: [1] R.D. Lorenz (2011) *Adv. Space Res.* 48(3):403-431. [2] Y.A. Surkov (1998) *Planet. Space Sci.* Vol. 46, 11/12, pp. 1689-1696. [3] S. Smrekar et al. (1999) *J. Geoph. Res.* 104, no. El 1, pp. 27,013-27,030. [4] Harri A-M et al. (2017), *Geosci. Instrum. Method. Data Syst.* 6, 103-124. [5] Staehle R. et al. (2015), *in Proc. AIAA/USU Small Sat. Conf.*, Utah, USA. [6] T. Kazama, K. Yamada and J. Koyanagi (2018) *in Proc. IPPW.* [7] ESA-TRP-TECMPA-SOW-013012, February 25th, 2019. [8] S. Espejo et al. (2018) *in Proc. AMICSA*, Leuven, Belgium. [9] Ramos-Martos J. (2012), *in Proc. AMICSA*, Noordwijk, Netherlands. [10] Sordo-Ibáñez S. et al. (2014) *in Proc. IEEE Me-troAeroSpace*, Benevento, Italy. [11] I. Arruego et al. (2018) *in Proc. IPPW*¸ Boulder, CO, USA. [12] F. Esposito et al. (2018) *Space Sci. Rev*. (2018) 214:103. [13] I. Arruego et al. (2017) *Adv. in Space Res*. 60 (2017) 103–120. [14] M.T. Atienza, et al, *Sens. and Act. A: Physical*, 267, 342-350, 2017. [15] J.A. Rodríguez-Manfredi et al. (2021) *Space Sci. Rev. 217:48.*[16] F. Cozzolino et al. (2021) *Meas.* 110075.[17] A. Russu et al. (2019*) in Proc. of SPIE*, Vol. 11129.

Drag Modulation Aerocapture Technology to Enable SmallSat Mars Orbiters. A. Austin[1], M. Lobbia[1], B. Strauss[1], J. Ravich[1], L. Luthman[1], E. Venkatapathy[2], P. Wercinski[2], [1]Jet Propulsion Laboratory, California Institute of Technology (alexander.austin@jpl.nasa.gov), [2]NASA Ames Research Center.

Introduction: With increasing interest in Mars science missions using small spacecraft, there are technical and programmatic challenges to address. While much focus has been on getting small satellites to the vicinity of Mars, the journey to get there is only half of the challenge; the spacecraft must also be able to slow down to enter orbit. Traditional methods of orbit insertion have utilized a chemical propulsion system, governed by the rocket equation, dictating that large amounts of propellant mass are needed to enact changes of velocity on a spacecraft. Electric propulsion architectures have vastly improved efficiency compared to chemical propulsion systems, but they come with other challenges, such as the requirement for a large power system and long interplanetary cruise times. For any system, but especially a SmallSat which is often volume and mass constrained, accommodating significant amounts of propellant, large power systems, or long cruise times can be prohibitive or impossible.

Aerocapture technology can enable increased science at Mars with small spacecraft and low cost. Aerocapture uses the drag of a single pass through the atmosphere to capture into orbit instead of relying on large quantities of rocket propellant. Using drag modulation flight control, an aerocapture vehicle adjusts its drag area during atmospheric flight, allowing it to target a particular orbit in the presence of navigation and atmospheric uncertainties [1].

Drag Modulation Aerocapture: The drag modulation aerocapture maneuver involves three main phases: interplanetary cruise and entry targeting, atmospheric deceleration, and post-aerocapture maneuvers. Figure 1 shows all of these maneuvers in the order that they occur.

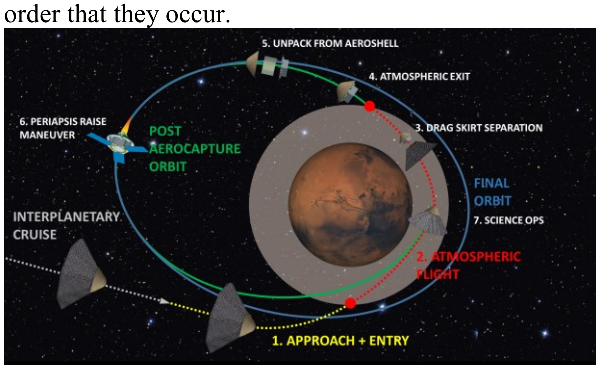


Figure 1: The drag modulation aerocapture maneuver, with all of the critical steps to enter orbit.

Because an aerocapture spacecraft uses atmospheric drag to slow down, it can tolerate very high required orbit insertion delta-v's. This leads to high flexibility in rideshare launch opportunities, with missions either going directly to Mars, or performing a gravity assist flyby on the way to another destination.

The spacecraft targets a direct entry into the Martian atmosphere, where it begins a period of deceleration due to the drag force imparted on it. In order to target a specific science orbit and account for day-of-flight uncertainties, a control system is needed. Drag modulation aerocapture uses in-flight transformations of an entry vehicle's drag area, by jettison of a drag skirt, to control the amount of deceleration produced during an atmospheric pass. The timing of the drag skirt jettison event is determined by a control algorithm with input from an onboard inertial measurement unit (IMU). The IMU estimates the deceleration of the vehicle and triggers the release of the drag skirt based on predicted atmospheric exit conditions that result in capture to the target orbit. This form of drag modulation flight control provides the control authority needed for a Mars science mission with a simple enough implementation to be integrated as part of a SmallSat.

After the vehicle has exited the atmosphere the spacecraft would now be in an elliptical orbit with the apoapsis at some altitude away from the planet and the periapsis at an altitude close to the lowest altitude seen during the atmospheric pass. The vehicle must therefore perform a small periapsis raise maneuver at apoapsis to bring periapsis out of the atmosphere. The delta-v required for this maneuver depends on the target apoapsis altitude, but is generally $\leq$ 50 m/s. The spacecraft can also perform an apoapsis adjustment maneuver or aerobraking, if necessary, to reach a final science orbit.

Aerocapture Reference Spacecraft Design: The aerocapture small spacecraft is made up of two main components: the spacecraft and the drag skirt, which can be seen in Figure 2. The spacecraft is the part of the system that remains in orbit after the aerocapture maneuver to perform the science mission. It contains all of the avionics, instruments, and other spacecraft components. The drag skirt is attached to the spacecraft during interplanetary cruise and is jettisoned during the aerocapture maneuver in the atmosphere to provide control over the amount of delta-v.

Control authority for the vehicle in the atmosphere is derived from the ratio of the ballistic coefficients of the pre-jettison and post-jettison configurations. For this reason, it is important that the drag skirt have a large diameter and thus drag area. Given the launch constraints of SmallSats as a rideshare (typically ESPA allocations), a deployable drag skirt is needed. The deployable drag skirt technology selected for this aerocapture system is the Adaptable, Deployable Entry and Placement Technology (ADEPT). ADEPT employs an umbrella-like deployable structure with a "skin" that is a 3-D woven carbon fabric serving as a TPS and as a structural surface that transfers aerodynamic deceleration forces to the underlying ribs [2].

In total, the notional aerocapture flight system is estimated to be 116 kg and the mass of the spacecraft by itself is 57 kg, giving a ballistic coefficient ratio of 4.27. The design includes approximately 6U of available volume for science payload. While this represents one potential aerocapture flight system, there exists a large trade space of opportunities to adjust the design for different science investigations and mission scales.

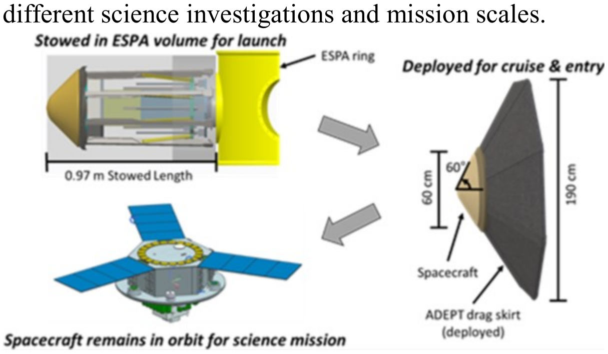


Figure 2: The aerocapture flight system is made up of two main components: the spacecraft and the drag skirt.

Mars Atmospheric Trajectory Modeling and Results: Critical to developing aerocapture technology and utilizing it in a Mars mission is performing detailed modeling and simulation of the atmospheric flight portion of the trajectory to understand driving requirements on the design of the spacecraft and expected orbit targeting accuracy in the presence of uncertainties. Comprehensive 6 degree-of-freedom simulations have been performed using JPL's DSENDS tool suite [3]. Figure 3 shows a nominal trajectory through the atmosphere for the spacecraft design shown in Figure 2 and a target elliptical orbit with a 2000 km apoapsis altitude. It can be seen that the atmospheric deceleration portion of the maneuver occurs over approximately 8 minutes with a peak g-load of 2.2, well within the capabilities of SmallSat flight hardware.

Not shown here are results from a full-set of Monte Carlo simulations which assess the aerocapture maneuver in the presence of a large number of sources of uncertainty including in the atmosphere, approach navigation, and the mass properties of the spacecraft. A more detailed discussion of these simulations and the results can be found in [4].

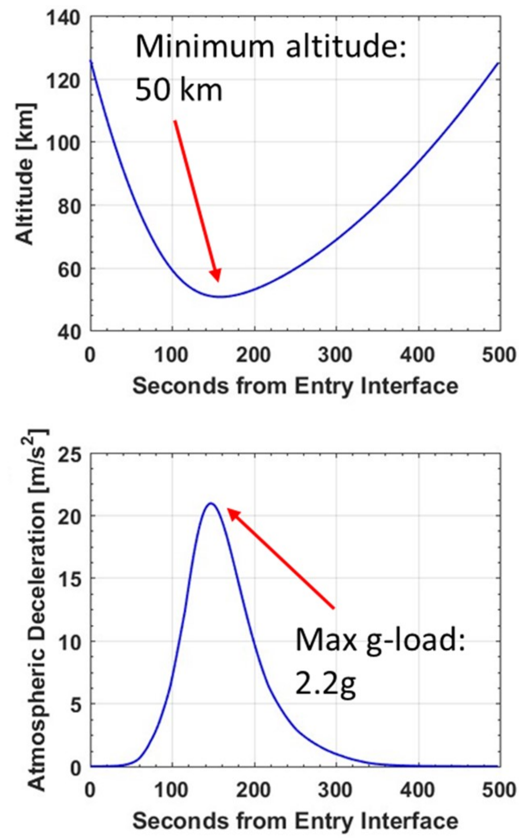


Figure 3: Nominal atmospheric trajectories for a Mars mission targeting a 2000 km elliptical orbit.

Conclusions: Drag modulation aerocapture technology can enable small Mars science orbiter missions at reduced cost because it decouples the largest driver of interplanetary missions, delta-V and its effect on required propellant, from the spacecraft design by using atmospheric drag to slow down. This will enable smaller spacecraft which are flexible to many launch opportunities and mission scales.

Acknowledgments: The research described in this paper was carried out at the Jet Propulsion Laboratory, California Institute of Technology, under a contract with the National Aeronautics and Space Administration.

References: [1] Z. Putnam and R. Braun (2014) *Drag-Modulation Flight-Control System Options for Planetary Aerocapture*. [2] Smith et al. (2015) *Nano-ADEPT: An Entry System for Secondary Payloads*. [3] J. Balaram at al. (2002) *DSENDS -A High-Fidelity Dynamics and Spacecraft Simulator for Entry, Descent and Surface Landing*. [4] B. Strauss et al. (2021) *Aerocapture Trajectories for Earth Orbit Technology Demonstration and Orbiter Science Missions at Venus, Mars, and Neptune*.

BIOINSPIRED DRAGONFLY CONCEPT FOR MARS EXPLORATION: ANALOGOUS TO MARS INGENUITY HELICOPTER. Naga Praveen Babu Mannam[1], Prashant Kumar Duba[2,] and P. Rajalakshmi[3], [1]NMICPS TiHAN IIT Hyderabad, Kandi – 502284, India, ee20pdf09@iith.ac.in. [2]NMICPS TiHAN IIT Hyderabad, Kandi – 502284, India, ee20resch11008@iith.ac.in. [3]NMICPS TiHAN IIT Hyderabad, Kandi – 502284, India, raji@ee.iith.ac.in.

Introduction: The MARS exploration research program has been carried out by various space organizations like ESA, NASA, ISRO, Blue Origin, SpaceX, and other academic institutions. Despite the ongoing research interest, flying on Mars remains challenging, owing to the Martian atmosphere's ultra-thin density. Because Mars' gravitational acceleration is 38 % of Earth's 9.8 m/s^2, its atmospheric density is just 1.3% that of Earth's. The aerodynamic forces are related to the density of the surrounding fluid. As a result, flying near the surface of Mars has been deemed nearly impossible. The suggested mission architecture (Fig. 1) includes a pre-existing Mars rover that acts as a mobile base for Mars bees, a deployable swarm of micro bioinspired flapping-wing vehicles (Dragonflies). Each Mars bee would include an inbuilt stereographic video camera in one ConOps scenario, allowing the swarm to create a 3D topographic model of the local terrain for rover path planning. The use of insect-inspired lift production to achieve flight on Mars has also been considered. The flapping-wing vehicle, Entomopter is designed with a blown-wing lift concept [1,2].

The first reference vehicle, the AeroVironment Nano Hummingbird [3], has a wingspread of 16 cm and a mass of 19 grams, including motors, batteries, controls, communication, and color video cameras. For a period of 10 minutes, the fully controllable vehicle was able to hover and fly ahead at 6.7 m/s. The Micro Aerial Vehicle (MAV) (Fig. 2) was developed and manufactured as the second reference vehicle. With motors, batteries, controllers, and communications, but no payloads, this vehicle weighs around 250 grams. This MAV can now fly for 10 to 15 minutes under control. We believe this vehicle is currently feasible after analyzing the current status of battery and sensor technologies. Miniaturization and energy storage advances and multi-functional designs will enable a future vehicle that weighs less than 100 grams.

The dragonfly based aerial vehicle consists of a pair of forward and backward wings consists of heave and pitch motions results in producing maximum lift and thrust forces [4]. In realistic, the horizontal figure-of-eight motion, the lift force of the wings contributes 35% of total force; the coefficient of lift for a 3D flapping wing is 20% less than that of a 2D airfoil [5]. Wingtip vortices can generate lift during a hover in an unstable flow rather than only drag on the wing. The thrust/propulsion efficiency of the dragonfly can be described as follows: when flapping with a 90°/180° phase lag, the hindwing sees a phase shift in thrust generation [4]. Due to wing deformations, the effective angle of attack and thrust forces are increased within a reasonable range of span wise flexibility. Compared to a single flapping wing design, the interaction effect of tandem wings reduces the force required by fore and hindwings are 14 % and 16 %. The drag force is required as the primary source of support for the dragonfly's weight when hovering with a big stroke plane angle [5].

Fig. 1: Marsbee mission architecture

Design Methodology: The bioinspired unmanned aerial vehicle (UAV) consists of quad wings arranged in the tandem mode in a staggered manner. The quad wing UAV at different stages of free flight condition forward flight was shown in Fig. 3. These four wings are subjected to heaving and pitching motion for generating the forward thrust. The phase angle between the two wings is 180º in tandem mode. The overall length is 540 mm, and each wingspan, 700 mm. Wings are made of flexible materials of polyethylene sheet of less than 1 mm and generate thrust two times greater than the rigid wings. The main structure of the UAV is made of carbon fiber and consists of two servo motors that actuate the wings synchronously for generating sufficient lift and thrust forces. The primary servo motor is connected to the gear train via crankshafts and flaps the quad wings in prescribed motion. The flapping amplitude of the wings is 41º. The wing's action consists of upstroke and down stroke. The down stroke of the wings produces maximum thrust, whereas the upstroke is the recovery stroke. The full flying speed of the vehicle is 2.5 m/s. In conventional fixed-wing unmanned aerial vehicles, stability will be achieved by the fixed wings. The rudder and propellers will control vehicle maneuvering for generating the forward thrust. In bioinspired UAVs, the flapping wings eliminate rudders, propeller devices. These wings serve the purpose of propulsion, maneuvering, and stability. The UAV is controlled remotely using a transmitter and receiver, which are located inside the body. The UAV wing forces are measured using a six-axis force transducer. The experimental setup consists of a UAV on a custom test stand that allows measuring unsteady forces produced by the UAV.

Results and Discussions: The quad wing UAV with two asymmetrically flapping wings in tandem, a systematic series of tests for thrust force measurement are carried out. A force transducer (iloadcell, USA) is used to measure the forces and torques on the flapping wings along orthogonal axes. The forces in this experiment have a range of 0.01 N. Each measurement has a mean error of 0.005N. The obtained force measurements were then transformed to lift and thrust in global coordinates using appropriate trigonometric conversions. In this study, lift force refers to the vertical component, whereas thrust in the global coordinate frame refers to the horizontal component. The force sensors detect a combination of wing aerodynamic force and wing inertial force. We subtract the gravity of the wing from the raw data to derive the aerodynamic information. The maximum thrust generated by two pairs of tandem wings is 0.5 N at 80% throttle and the minimum thrust force obtained is 0.114 N at 40 %. The velocity of quad wing UAV at 80% of maximum throttle is 2.5 to 3 m/s. The thrust forces versus as a function of throttle are observed in Fig. 4.

Fig. 2: Dragonfly based UAV (Mars bee)

Fig. 3: Dragonfly during forwarding flight

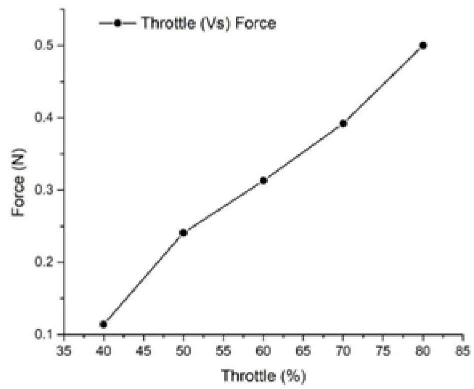


Fig. 4: Thrust force analysis of dragonfly.

Acknowledgments: This work is supported by DST National Mission – Interdisciplinary Cyber-Physical Systems (NM-ICPS), TiHAN, Indian Institute of Technology (IIT) Hyderabad.

References:

[1] Colozza, A. & Michelson, R. C. “Planetary Exploration Using Biomimetics – An Entomopter for Flight on Mars,” *NASA Institute for Advanced Concepts Phase II Project NAS5-98051 2002.*

[2] Bar-Cohen, Y., Colozza, A., Badescu, M., Sherrit, S. & Bao, X. “Biomimetic Flying Swarms of Entomopters for Mars Extreme Terrian Science Investigations”, *Concepts and Approaches for Mars Exploration, held June 12-14, 2012 in Houston, Texas. LPI Contribution No. 1679, id.4075, 2012.*

[3] Keennon, M., Klingebiel, K., Won, H. & Andriukov, A. “Development of Nano Hummingbrd: A tailess flapping wing Micro Air Vehicle,” *AIAA-2012-0588, 50th AIAA Aerospace Sciences Meeting, 09-12 January 2012, Nashville, Tennessee, 2012.*

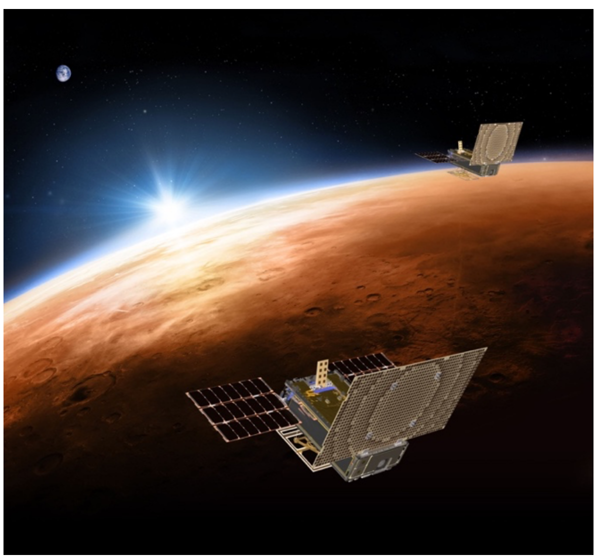
[4] Lian Y, Broering T, Hord K, Prater R. The characterization of tandem and corrugated wings. *Progress in Aerospace Sciences* 2013; 65(1): 41-69.

[5] Sun M, Lan SL. A computational study of the aerodynamic forces and power requirements of Dragonfly (Aeschna juncea) hovering. *J Exp Biol* 2004; 207(11): 1887-901.

Small Satellite Technologies for Low-cost Mars Missions. John D. Baker[1], [1]Jet Propulsion Laboratory, 4800 Oak Grove Dr, Pasadena CA 91109, MS 321-625, john.d.baker@jpl.nasa.gov

Introduction: New spacecraft and instrument capabilities exist today that can enable lower cost Mars exploration science missions. This abstract will describe at a high level several of the new capabilities available and the performance they offer. Over the past 9 years, NASA and the Jet Propulsion Lab have invested in numerous flight and instrument technologies to enable lower cost exploration of the solar system. Mars missions today use flight proven but often heavy and more expensive avionics to accomplish their missions. New spacecraft capabilities for lower cost, lower energy, missions are ready for flight including technologies for deep space communications, radiation tolerant flight computing, propulsion, attitude control, thermal control and light weight structures. Many of these technologies have been developed across multiple Projects, some have flown, some are now commercially available, most are now ready to fly on a mission.

The Mars Cube-One mission[1], as depicted in the image below, was the first to fly and operate a CubeSat in deep space, in fact all the way to Mars. A key

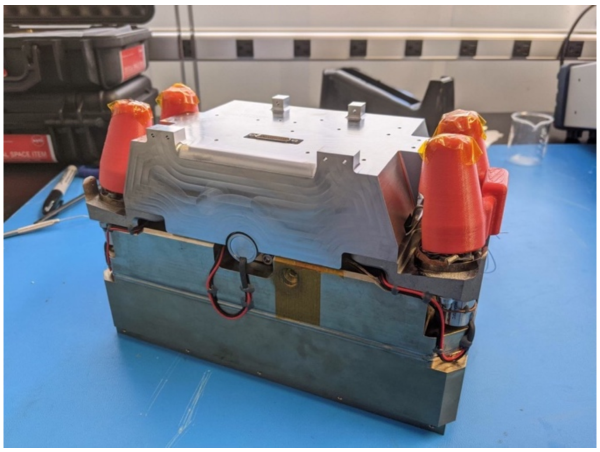


objective was demonstration of a miniaturized DSN compatible software defined radio and high gain reflectarray that also provided two-way coherent ranging. The radio used was the Iris[2] (V2.0), a 1 kg, CubeSat form factor/0.5U, rad-tolerant modular radio that was used during both cruise for X-band communication as well as to relay UHF data during the NASA Insight mission EDL. MarCO relayed 97% of the Insight mission EDL telemetry in real-time. This transponding 'smart' radio was designed for Class D / technology demonstration missions and is considerably less expensive than traditional deep space radios. Iris is capable of 12 MS/s using its Spacewire interface, advanced modulation and encoding, command link decryption, precision PN ranging and regenerative ranging. The radio also does the framing to meet CCSDS standards off-loading that process from the flight software. As demonstrated in deep space on the MarCO mission in 2018, the radio has been licensed to the Utah State University Space Dynamics Lab (SDL) for production. SDL continues to produce on average 3-5 radios per year to US government, commercial and International customers.

The second technology developed was the Sphinx flight computer in a CubeSat form factor that uses a fault tolerant rad hard dual core (GR712) Leon processor from Gaisler. The processor is capable of equivalent performance to current flight computers but uses 2.5W and weighs 132g. The Sphinx flight computer has been flight qualified and will be launched in 2022 on NEAScout[3] and Lunar Flashlight[4]. It is available commercially from Cobham Aeroflex at commercial, Class D and also Class B levels of mission reliability.

The third key technology is propulsion. See picture on next page. The NASA Lunar Flashlight Project with support from the Air Force Research Lab (AFRL) succeeded in developing a pump-fed green monopropellant (AF-M315E) propulsion system[5] that is scalable from 6U / 14 kg CubeSats to 100 kg microsatellites. This propulsion system[6] was developed by the Marshall Space Flight Center (MSFC) and Georgia Tech (GT) with oversight by JPL. Capable of more than 1000 m/s of delta-v, this system is promising for orbit insertion maneuvers and planetary missions.

Looking to the future, JPL has and continues to develop a number of other technologies for Mars and solar system exploration including a variety of thermal management technologies suited to small spacecraft such as a 2-phase thermal management system, additively manufactured radiators, accumulators, battery packs, and thermosyphons. Other technologies include a quad-core Leon processor with significant computing power called Sabertooth, a magnetically shielded electric Xe hall-thruster propulsion system for long duration missions, a multi-functional additively manufactured primary structure-tank for a blow down bi-propulsion system capable of >2000 m/s delta-v.



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References:

[1] Klesh, A., Krajewski, J., MarCO: CubeSats to Mars in 2016. AIAA/USU Small Satellite Conference, 2015.

[2] Kobayashi, M., Shihabi, M., Taylor, J., Mars Cube One Telecommunications Subsystem Design, https://descanso.jpl.nasa.gov/DPSummary/Summary.html, Article 18, September 2021.

[3] McNutt, L., Johnson, L., Kahn, P., Castillo-Rogez, J., Frick, A. Near-Earth Asteroid Scout, Proceedings of the AIAA Aerospace Conference, AIAA 2014-4435.

[4] Baker, J.D., Seybold, C., Cohen, B., Lunar Flashlight Mission Information, http://www.jpl.nasa.gov/cubesat/missions/lunar_flashlight.php

[5] Huggins, G.M., Talaksi, A., Andrews, D., Lightsey, E.G., Cavender, D., McQueen, D., Williams, H., Diaz, C., Baker, J., Kowalkowski, M.; “Development of a CubeSat-Scale Green Monopropellant Propulsion System for NASA’s Lunar Flashlight Mission,” AIAA 2021-1976, AIAA SciTech 2021 Forum, January 2021.

[6] Cheek, N., Daniel, N., Lightsey, E.G., Peet, S., Smith, C., Cavender, D.; “Development of a COTS-Based Propulsion System Controller for NASA’s Lunar Flashlight CubeSat Mission”, SSC21-IX-06, AIAA 35th Annual Small Satellite Conference, August 2021.

OPPORTUNITIES FOR CONSTRAINING MARS'S ATMOSPHERIC DYNAMICS WITH BOTH A SURFACE NETWORK AND MARTIAN SATELLITE FLEET.

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Introduction: The past decades have provided accelerating understanding of Mars's weather and dust storms [1] thanks to continual monitoring of the atmosphere. To continue this trend, maintain existing capabilities, and support future crewed missions, the community must build upon previous successes by the development and coordination of new surface and orbital weather monitoring. Reanalysis datasets [2,3] enable comparison of Mars's atmospheric dynamics and rely on soundings—from Thermal Emission Spectrometer (TES) and Mars Climate Sounder (MCS)—to constrain simulations, enabling many advances [4,5,6,7,8]. Yet each instrument best observes the atmosphere only twice per sol at specific heights.

Demonstration of problem: For all of the advancements in observations, gaps in coverage remain, presenting challenges to understanding Mars's atmospheric dynamics. Three examples are described.

Transient wave discrepancies. Two Hovmöllers for the same period and MY in northern fall are depicted in Fig. 1 from OpenMARS [2] and an EMARS member [3]. Discrepancies between the nominally observation-constrained datasets are clear. At L_s=190°, OpenMARS shows a zonal wavenumber 3 structure, but the EMARS member exhibits wavenumber 2. The v5 MCS soundings do not sufficiently constrain reanalyses [7], so confidence on the atmospheric state depends on agreement across reanalyses or with other observable features, like dust storms [1]. These discrepancies are important for weather forecasting and diagnosis and in understanding the climate state [8].

Limited areal mesoscale coverage. Long-term observation by the Thermal Emission Imaging System (THEMIS) on Odyssey has enabled studies of gravity waves [9] and other atmospheric features but is still limited to twice-daily observations and in observing only 32 km in the cross-track direction, which misses vast swathes of coverage, even over 30° of L_s (Fig. 2).

Dust storm observations. Finally, long-term dust storm datasets have been enabled by near-continuous orbital monitoring. The Mars Dust Activity Database [1] stretches 8 Mars Years with ~15,000 individual dust storm instances cataloged. However, a drawback with this dataset is the lack of diurnal coverage, with each of the 12 Mars Color Imager (MARCI) swaths taken at the same local time. Limited diurnal coverage means the development of dust storms is not captured. An example of the enormous growth across sols is shown in Fig. 3, juxtaposing two consecutive sols. The distance between the southern edges of dust activity is $\mathcal{O}$(1000) km, averaging to a speed of $\mathcal{O}$(10) m s^{-1}.

Observation strategies/solutions: Two sets of complimentary observations would help overcome the identified issues in the current observation platforms, while maintaining current capabilities and increasing the potential for new science.

Surface networks. Concepts for surface networks date back decades. The Pascal Mission [10] consisted of 18 stations to measure winds, pressure, temperature, and humidity. To an extent, Curiosity, Perseverance, and InSight comprise a Martian "mesonet," capable of describing waves in the eastern hemisphere, but to fully realize surface dynamics and better connect the middle atmosphere to the surface, a Pascal-like approach is need, like the in-development MetNet [11]. Even greater advances would result from combining surface observations with low-atmosphere detection capabilities, like the Phoenix Lander's Lidar or Mars Exploration Rover's MiniTES [12].

The question of coverage is critical, requiring Observing System Simulation Experiments (OSSEs) [13] to test the impact of observation strategies. For

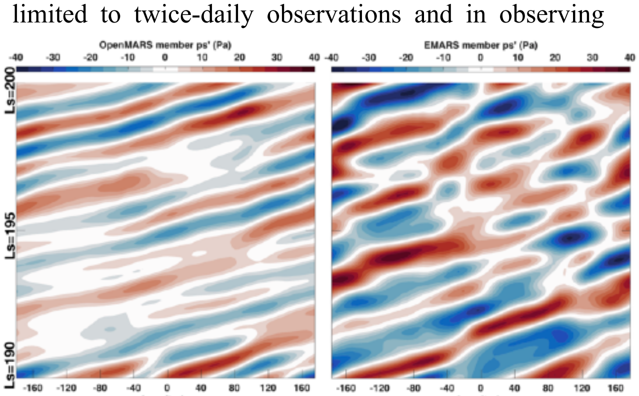

Fig. 1: Hovmöllers of eddy surface pressure from MY 31 [7].

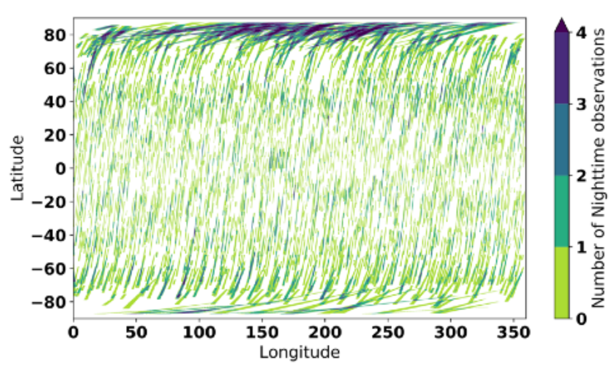

Fig. 2: THEMIS obs. (L_s=120°–150° MY 32) [11].

example, the longitudinal coverage required to fully diagnose planetary waves is ~2m+1, where m=zonal wavenumber [10]. Waves in the SH can be m=4 [6,7], so up to 9 stations at a given latitude might be needed. This estimate does not account for topographic effects, which will modulate waves through channels [14], so testing station impact on errors is crucial.

Satellite constellations. Geostationary satellites revolutionized weather forecasting for Earth, and the need for satellite networks or areostationary platforms for Martian weather analysis is recognized [15,16]. Many mission concepts have been proposed (MACO, [17]) or are in development (MOSAIC [18]). Three instrument classes would provide the most benefit to observing Martian weather.

<u>Best of both (profiler) worlds:</u> The fidelity of TES and MCS varies with height. TES seems to perform better than MCS near the surface, and the opposite occurs aloft [6,7,8]. Combining the benefits of each will help constrain atmospheric eddies. Better, orbital Lidar may enable observations of winds [20], important for constraining dust and volatile cycles. Multiple orbits with similar instrumentation would enable continuous monitoring of the atmosphere and close a fundamental gap in observations. Specifically, non-sun-synchronous observations are needed to remove periodicities caused by precessing orbits [19].

<u>All the MARCIs:</u> The transition from MOC to MARCI observations represented a leap in the ability to diagnose dust storms and clouds [1, 19]. Similar improvements should come with multiple observation platforms. Visible cameras should exist on all new orbiters, with areostationary satellites even more insightful. Though this might cause a data return problem [1,15], strategies can be implemented to reduce redundant data: saving data only above a certain change detection threshold or only transmitting global images every hour. Nevertheless, these types of observations will enable robust analyses via tracking the initial growth and full lifetime of dust storms.

<u>Wide-angle THEMIS:</u> Finally, inclusion of high-resolution, horizontal observations presents an additional opportunity. Low horizontal coverage by THEMIS (Fig. 2) reduces the return of wave activity searches. One solution is inclusion of IR channels on new cameras, particularly around the 15 μm CO_2 band, like THEMIS channel 10. This would permit wide-ranging spatial studies of multiple atmospheric levels to constrain vertical momentum and dust transport.

Outlook: Given the age of MRO and ODY and the lack of firm plans for new orbiters, the community must push for new assets on the surface and in orbit to ensure that gaps in the atmospheric record are minimized. These sorts of measurement platforms are critical for forecasting dust storms [16].

Acknowledgments: MDGMs are on PDS Annex. MDAD is at Harvard Datavserse.

References: [1] Battalio, M. & Wang, H. (2021) *Icar., 354* 114059. [2] Holmes, J., et al., (2020) *PSS*, *188* 104962. [3] Greybush, S., et al., (2019) *Geo. Data J.*, *6*(2). [4] Battalio, M., et al., (2016) *Icar.*, *276*. [5] Battalio, M. (In press) *JAS.* [6] Battalio, M. & Wang H. (2020) *Icar., 338* 113507. [7] Greybush, S., et al., (2019) *Icar., 317* 158–181. [8] Battalio, M. & Lora, J. (2021) *Nat. Astr*. [9] Battalio, M., et al., (in prep JGR:E). [10] Haberle, R., et al., (2003) *MAMO*. [11] Harri, A.M., et al., (2019). *EPSC-DPS 2019* #13:405–1. [12] Mason, E. & Smith, M. (2021) *Icar., 360* 114350. [13] Reale, O., et al., (2021) *BAAS 53*(4). [14] Battalio, M. & Wang, H. (2018) *Icar., 321* 367. [15] Montabone, L., et al., (2021) *BAAS 53*(4). [16] Newman, C., et al., (2021) *BAAS 53*(4). [17] Kursinski, E., et al. (2004) ed. Kirchengast et al., 393–405. [18] Lillis, R., et al., *PSJ 2*(5). [19] Wang, H. & González, A. (2021) *Geos., 11*(8). [20] Guzewich, S., et al., (2021) *BAAS 53*(4).

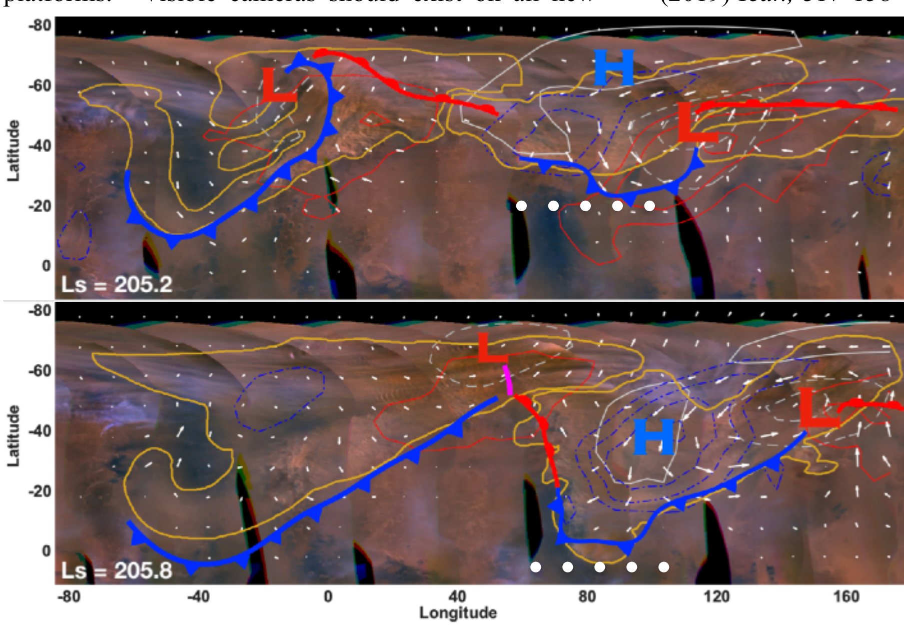

Fig. 3: MY 31 MDGM and MDAD (gold contours) [1] with eddy winds (vectors), pressure (white contours & "H/L"), temperature (red/blue contours) [2], with fronts. Southern edge of the dust in Utopia (thick dotted line), moves >1000 km.

PLANETARY PROTECTION FOR LOW COST MARS MISSIONS.
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Introduction: Planetary protection is the discipline of avoiding causing harmful contamination of the celestial bodies we visit, as well as protecting the "home planet" from the uncontrolled introduction of extraterrestrial contamination.

The Committee on Space Research manages the consensus policy on planetary protection [1], which is the internationally recognized approach to complying with Article IX of the 1967 UN Outer Space Treaty [2] that requires nations to commit to "pursue studies of outer space, including the Moon and other celestial bodies, and conduct exploration of them so as to avoid their harmful contamination and also adverse changes in the environment of the Earth resulting from the introduction of extraterrestrial matter and, where necessary, shall adopt appropriate measures for this purpose."

Context: NASA, together with as agencies from other spacefaring nations, have established requirements for missions beyond the Earth's biosphere to limit the potential for such harmful contamination. These historic approaches (see e.g., [3]) have often involved significant level of resource commitment for both robotic and crewed missions. These approaches may well be out of reach for the smaller, cost-constrained missions of the type being discussed at this workshop. However, the contamination potential for Mars is independent of mission size or cost, and more related to the cleanliness environments and processing heritage of the mission hardware.

Discussion: This presentation will highlight planetary protection implementation strategies and issues for small robotic missions, based on mission case studies, and include a focus on NASA's recently revised requirements document for planetary protection [4], as well as the recent National Academies report on bioburden requirements for Mars missions [5].

Additionally, the role of low-cost missions in collecting key data ahead of the crewed exploration of Mars will be discussed.

Acknowledgments: Work by Spry is supported through the SETI Institute by NASA contract 80HQTR20F0153 for support of all phases of current and future planetary protection missions to ensure compliance with planetary protection standards.

References:

[1] COSPAR Policy on Planetary Protection (2021) at: https://cosparhq.cnes.fr/assets/uploads/2021/07/PPPolicy_2021_3-June.pdf

[2]Treaty on Principles Governing the Activities of States in the Exploration and Use of Outer Space, including the Moon and Other Celestial Bodies (Outer Space Treaty) United Nations (1967) accessible at: https://www.unoosa.org/oosa/en/ourwork/spacelaw/treaties/introouterspacetreaty.html

[3]Meltzer, M (2012) When Biospheres Collide, NASA SP 2011-4234, NASA Washington DC.

[4]NASA (2021) NPR8715.24 Planetary Protection Provisions for Robotic Extraterrestrial Missions accessible at: https://nodis3.gsfc.nasa.gov/displayDir.cfm?t=NPR&c=8715&s=24

[5]NASEM (2021) Evaluation of Bioburden Requirements for Mars Missions at: https://doi.org/10.17226/26336

GRAVITATIONAL SIGNATURES OF SEASONAL ATMOSPHERIC MASS TRANSPORT ON MARS.

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Introduction: A dedicated time-variable gravity mission could do for Mars what the GRACE and GRACE-Follow-On missions have done for Earth. Prior to these missions, time-variable gravity on Earth was seen as only a minor sub-set of planetary geodesy. Sufficiently accurate measurements have transformed that view, and have now become a key component of monitoring global climate change on Earth [1, 2]. On Mars, a similar mission could serve as an initial step towards the goal of more definitively characterizing Mars surface and subsurface geophysical properties, which is seen as an early step in the assessment of subsurface habitability investigations.

As a low-cost element of a MASWG-defined mission 'arc,' a dedicated time-variable gravity mission could provide early insight into sources, sinks and transport of both CO_2 and H_2O on the martian surface and subsurface, and serve as a link between present-day investigations and future steps along such a multi-mission 'arc'.

We thus propose a mission concept that would deploy a superconducting gravity gradiometer (SGG) instrument [3, 4] into a circular, near-polar orbit. It would monitor the seasonal cycle of volatile mass transport, for at least 2 Mars years, and do so much more accurately than can be done at present.

As has been seen on Earth, these new and more accurate measurements of time-variable gravity on Mars will provide improved insight into key dynamical parameters and processes of the atmospheric mass transport cycle.

Mission conops: A relatively small spacecraft could carry a 15 kg SGG to Mars. Additional required equipment would include a cryocooler and accelerometer, both consistent, in mass and volume, with a spacecraft of modest payload. Chemical and solar electric propulsion approaches could be used to get the SGG to Mars. An orbital altitude as low as 200 km would be possible—low enough to experience drag from Mars' tenuous atmosphere—and countered by an SEP system, analogous to the operational architecture of the terrestrial GOCE mission. A polar orbit would ensure global gravity coverage.

Expected signal: Using the atmospheric general circulation model MarsWRF [5], we have simulated the spatio-temporal pattern of atmospheric mass transport, over an annual cycle, using nominal values of emissivity and albedo for the polar caps, and total mass of transportable CO_2, from [6].

Each grid cell contains CO_2 in the atmospheric column, and many cells also have condensed CO_2 on the surface. The gravitational signature of the mass transport is expressed as a spherical harmonic series expansion of the external gravitational potential, using the sum of surface and atmospheric contributions. The temporal pattern is represented by a Fourier series, with up to 12 cycles per year, for each spherical harmonic coefficient.

Much of the latter part of our analysis is identical to that described for atmospheric transport on Venus [7]. Figure 1 shows the RMS amplitude spectrum for the simulated gravitational signal, up to harmonic degee 40, and at temporal frequencies up to 12 cycles per year.

Expected error: We can easily compute the expected error in the time-variable gravity field estimates which would be obtained via a range of measurement approaches. The analysis follows that given in [7,8].

In particular, we consider 3 measurement configurations. One is Earth-based Doppler tracking of a single spacecraft, which is the only source of current knowledge of the Mars gravity field [9,10]. Time variable signals are currently resolved, but not well enough to constrain the atmospheric dynamics. Another approach uses Doppler measurements of range-rate variations between a pair of co-orbiting spacecraft, as was used in GRAIL [11]. The third approach uses a gradiometer [3,4].

Figure 2 shows the static field RMS amplitude spectrum [12], as a solid line, and the dashed lines show error spectra for measurements taken in a circular polar orbit, for 30 days, at either 250 or 350 km altitude. The accuracy obtained, even in that short a sampling session, is sufficient that the 20 or so views of the gravity field obtained each year would provide clear signatures of temporal change.

Summary: While any of the 3 measurement approaches could be usefully deployed, we see that the gradiometer does a much better job in resolving the higher spatial frequency signals. It also has the advantage of only requiring a single spacecraft, whereas the GRAIL-type co-orbital pair requires two separate spacecraft.

References: [1] Tapley,B.D. et al.(2004) Sci., 305, 503-505. [2] Tapley, B.D. et al. (2019), Nat. Clim. Change, 9, 359-369. [3] Shirron, P.J. et al. (1996), Cryogenics, 36, 805-813. [4] Griggs, C.E. et al. (2017), Phys. Rev. Appl. 8, 064024 [5] Richardson, M.I et al. (2007), JGR, 112, E09001. [6] Guo et al. (2009), JGR 114 E07006 [7] Bills, B.G. et al. (2020), Icarus, 304, 113568. [8] Bills, B.G. and A.I. Ermakov (2019), Plan. Space Sci., 179, 104744. [9] Konopliv, A.S. et al. (2016), JGR, 118, 1415-1434. [10] Genova, A. et al. (2016), Icarus, 272, 228-245. [11] Zuber, M.T. et al. (2013), Sci., 339, 668-671 [12] Kaula, W.M. (2013) Theory of satellite geodesy,

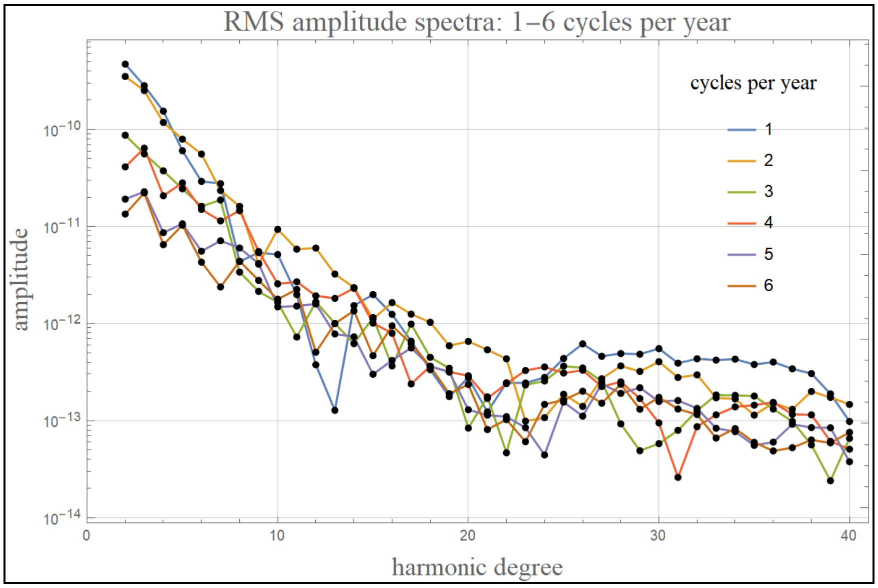

Figure 1. RMS amplitude spectra of Mars time variable gravity.

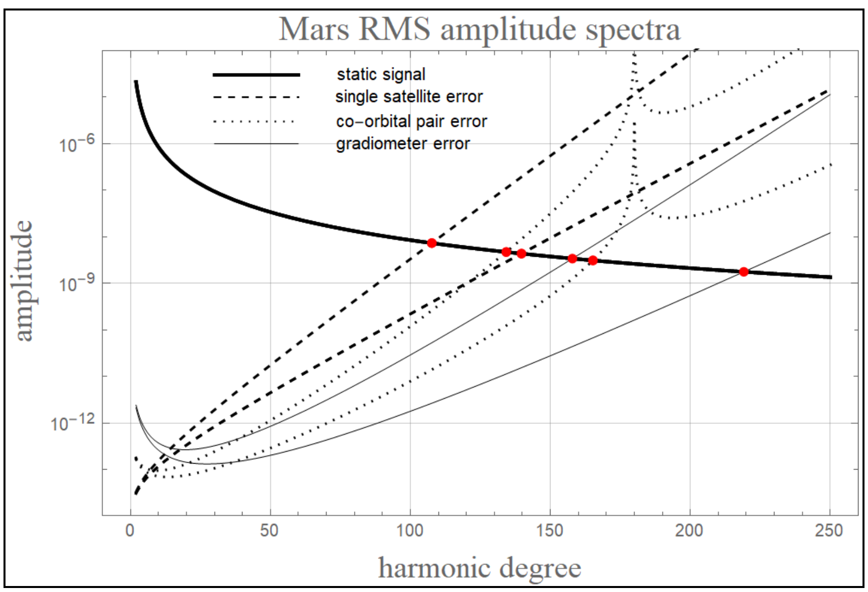

Figure 2. RMS error spectra for various measurement configurations.

CONSIDERATION OF THE MARTIAN CHLORIDE SALT-BEARING DEPOSITS AS A TARGET FOR A LOW-COST SCIENCE MISSION. M. S. Bramble[1] and K. P. Hand[1], [1]Jet Propulsion Laboratory, California Institute of Technology, 4800 Oak Grove Drive, Pasadena, CA 91109, USA (michael.s.bramble@jpl.nasa.gov).

Introduction: Putative chloride salt-bearing deposits are perhaps one of the most compositionally-enigmatic surface features on Mars. Since their initial identification, the exact composition and provenance of these deposits have remained elusive despite over a decade of orbital and laboratory analyses. The geomorphology of these surface deposits, along with their interpreted halite-bearing composition, suggests a past of surface water activity. A landed scientific mission to explore the composition and geological history of the putative chloride salt-bearing deposits would be well-suited in scope for a low-cost mission. This mission would yield insights into the past history of surface water activity on Mars, confirm the composition of an enigmatic landform, as well as visit a landform of possible significant interest for astrobiology.

Background: Landforms with a suggestive chloride salt-bearing composition have been identified via a set of unique spectral characteristics that pair with an intriguing set of geomorphic properties. Initially, thermal infrared images from the Thermal Emission Imaging System (THEMIS) exhibited landforms with distinct spectral properties, and orbital imagery revealed light-toned, polygonally fractured materials that blanket underlying topography [1]. The chloride composition is derived by an absence of spectral absorption features for other mineral phases and distinct spectral slopes at thermal [2] and near-infrared wavelengths [3,4] that can be attributed to halides [2,5]. Mid-infrared analyses constrain the halite abundance at ~10–25% via laboratory and model studies of two component mixtures with the remainder consisting of regional martian regolith [6]. Near-infrared spectra can be explained by mixtures of anhydrous chloride salts and silicates [3,5], while other evaporites and weathering products can only be present at the level of 1–5 wt% abundance [7]. Of all the chlorides, halite is the best match to explain all the spectral and geological characteristics [6]. Despite the rigor of the cited work, the chlorides remain somewhat controversial as they remain distinguished via an absence of spectral features as opposed to the presence of diagnostic spectral absorptions.

The orbital imagery of chloride salt-bearing deposits exhibits a range of morphologies. These include occurrences in paleolake basins and in the vicinity of valley network terrains [2], as well as correlation with inverted channels and terminations at fan deposits [8]. The deposits commonly appear in local topographic lows [2,9] and their morphological characteristics suggest that they drape the local topography. They are often observed in association with underlying, darker, phyllosilicate-bearing units, in possibly stratified lacustrine deposits. Polygonal fracturing is observed at the deposits and has been interpreted as desiccation fractures or salt-related polygons [1,4]. The spectroscopic signatures suggest the deposits are well indurated but friable [6]. The majority of observations remain consistent with one of the original formation hypotheses: that these features formed via the ponding and evaporation of surface runoff or discharged groundwater [2]. Other formation hypotheses include volcanic sources, playa environments, lacustrine environments [10], hydrothermal brines, or an icy top-down melting process paired with concentration via seasonal sublimation and dehydration [11].

Science objectives: Science objectives geared towards a low-cost mission to the chloride salt-bearing deposits could include: (1) Determine the composition of one the most compositionally-enigmatic landforms. (2) Determine the geological history of these deposits and how it relates to proposed formation mechanisms. (3) Interpret the early climate history and habitability conditions during the formation of these deposits from their geological history. (4) Investigate for possible biosignatures for indicators of life.

Measurement requirements: A low-cost mission would likely be well-suited in scope to address these science objectives. Below are example measurement requirements that could address the above objectives.

A key requirement would be to distinguish the geochemistry and mineralogy of the surface materials. We know from orbital analyses that the standard VNIR and mid-infrared spectrometers commonly deployed on planetary spacecraft at Mars would not be sufficient for deciphering these surface features. Therefore, other methods would be required; these could include X-ray fluorescence or alpha particle X-ray spectroscopy. Furthermore, these could provide bulk chemistry of the sample from which the mineralogy could be derived.

To support the geochemical analyses, the lander would need to distinguish grain sizes, grain textures, and petrographic-scale mineralogy. This would be best achieved with a form of microscopic imager. Mid-infrared laboratory data when paired with THEMIS data suggests that 63 to 180 μm particle sizes are consistent with regions of coarse particulate surfaces in orbital data, and particle sizes of <10 μm in cases with regions of fine-particulate surfaces [6]. Near-infrared laboratory data tell a similar story with labradorite-halite mixtures >10 µm in particle size matching observed spectral characteristics, and halite-basalt mixtures matched observed characteristics for grain sizes of 63–90 and 125–180 µm with ≤25% halite abundance [5]. Therefore, we may expect salt particles in the 50–200 µm range with the possible addition of smaller coatings from friable particles.

Lastly, context measurements observing the vicinity of the other measurements would address a suite of questions related to the science objectives. For example, multiple hypotheses exist for the formation mechanism of the polygonal fracturing observed from orbit. When paired with the above geochemical, mineralogical, and microscopic imagery data, the requisite data to distinguish these hypotheses could be met with context imagery provided by cameras that observe the workspace and the vicinity of the lander. The surface around the lander would need to be imaged likely within a radius of a few tens of meters at a scale that provides context of the spot size of the microscopic imager. This data would also be imperative to pair the *in situ* measurements with the orbital data sets.

Landing site selection: The chloride salt-bearing deposits as a mission target provides several possible candidate landing sites even with engineering constraints of other missions. Of the ~640 distinct sites reported in the data base of Osterloo et al. [2], ~125 remain after the Mars 2020 landing site selection engineering constraints are applied (**Figure 1**). This may likely serve as a useful proxy for site exclusion based on factors such as latitude and altitude that would apply to a future low-cost mission. Of all the chloride salt-bearing deposits, two are larger than, and ~7 more would fill about half of the area of the final landing ellipses for Mars Exploration Rovers [12].

These sites can scale from flagship class mission science (as was argued for MSL and Mars2020) to focused, targeted science questions in a low-cost mission. While these sites are likely not equal in all aspects, the distribution of these sites across the surface may help facilitate the possibility of a chloride salt-bearing deposit mission being part of a multi-small-payload mission in a ride-along form [13]. Additionally, having a suite of sites would allow for the selection of one that may perhaps facilitate science of another small spacecraft mission.

Conclusion: A landed mission to the chloride salt-bearing deposits would address several outstanding questions of martian geological history and provide constraints on the past habitability and climate history. If a halite composition is confirmed and the abundances match the orbital analysis, this terrain would be unlike any other explored on the surface to date. Additionally, ancient salt deposits on the Earth have demonstrated the capability of entombing and preserving microbial fossils and other biomarkers, which leads to the intriguing possibility of preserved biosignatures from early Mars in the chloride salt-bearing deposits. The lander would likely be exploring the last stages of a wetter Mars as the planet dried out, and understanding this drying out phase is critical to understanding the evolution of the early martian climate.

References: [1] Osterloo M. M. et al. (2008) Science, 319, 1651–1654. [2] Osterloo M. M. et al. (2010) JGR, 115, E10. [3] Ruesch O. et al. (2012) JGR, 117, E11. [4] El-Maarry M. R. et al. (2013) JGR, 118, 2263-2278. [5] Jensen H. B. and Glotch T. D. (2011) JGR, 116, E12. [6] Glotch T. D. et al. (2016) JGR, 121, 454–471. [7] Ye C. and Glotch T. D. (2019) JGR, 124, 209–222. [8] Osterloo M. M. and Hynek B. M. (2015) LPSC XLVI, Abstract #1054. [9] Wray J. J. et al. (2009) Geology, 37, 1043–1046. [10] Hynek B. M. et al. (2015) Geology, 43, 787–790. [11] Deutsch A. N. and Head J. W. (2017) LPSC XLVIII, Abstract #2214. [12] Golombek M. P. et al. (2003) JGR, 108, E12. [13] Barba N. et al. (2021) IEEE Aerospace Conference, 50100. [14] Smith D. E. et al. (2001) JGR 106, 23689–23722.

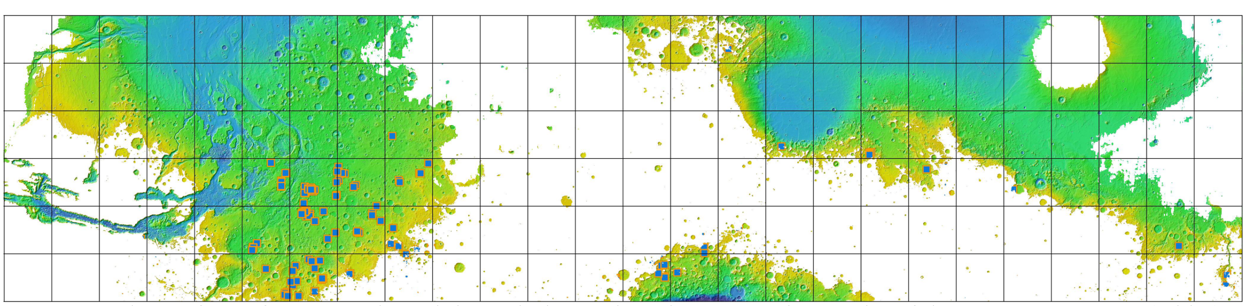

Figure 1: The surface of Mars as viewed through the engineering constraint masks of the Mars 2020 rover (white). The blue squares represent chloride salt-bearing deposits [2] that are not masked out. The basemap is the colorized MOLA elevation map [14].

THE LIFE DETECTION KNOWLEDGE BASE: ORGANIZING ASTROBIOLOGY KNOWLEDGE AND TECHNOLOGY FOR MISSION CONCEPT DEVELOPMENT. W. B. Brinckerhoff[1], A. F. Davila[2], S. Shkolyar[1,3,4], L. E. Bebout[2], D. Des Marais[2], S. Getty[1], T. M. Hoehler[2], L. Jahnke[2], G. Lau[3], O. Lehmer[2], M. Neveu[1,4], M. N. Parenteau[2], A. Pohorille[2], R. C. Quinn[2], S. Som[2,3], M. B. Wilhelm[2]. [1]Solar System Exploration Division, NASA Goddard Space Flight Center, Mail Code 690, Greenbelt, MD 20771, [2]NASA Ames Research Center, Moffett Field, CA 94035, [3]Blue Marble Space Institute of Science, 600 1st Avenue, 1st Floor, Seattle, Washington 98104, [4]Department of Astronomy, University of Maryland, College Park, MD.

Introduction: Recent planetary exploration has revealed a multiplicity of habitable worlds within and beyond our solar system. Future spaceflight missions to seek possible evidence of life on these worlds are currently being conceptualized and developed for the next decade and beyond. In motivating this broad and ambitious endeavor, a National Academies consensus study report in 2019 recommended that NASA "…should support the community in developing a comprehensive framework for assessment—including the potential for abiosignatures, false positives, and false negatives—to guide testing and evaluation of in situ and remote biosignatures" [1].

The problem of organizing life detection strategies into a coherent, functional framework has multiple possible solutions (e.g., [2]). All share common challenges, stemming from the fact that astrobiology knowledge is *diverse*, often taking forms not directly amenable to mission analysis; *diffuse*, in that it is spread across many disciplines and a wide-ranging literature; and, in some key areas, *incomplete*. Similarly, the full range of relevant expertise lies distributed across science and technology communities that, in many cases, have had little previous experience with the design and/or implementation of robotic spaceflight missions, or have not perceived the relevance of their science to the search for evidence of life beyond Earth.

The Life Detection Forum (LDF) is a community-owned suite of online tools (see https://www.nfold.org/ldf) to help organize and evaluate astrobiology knowledge and technology in a way that facilitates their infusion into life detection studies and missions. It is coordinated by the Center for Life Detection (CLD) supported by a diverse group of researchers at NASA's Ames Research Center and Goddard Space Flight Center to tackle the next set of challenges science must overcome to be able to one day detect life beyond Earth. A core tool of the the LDF is the Life Detection Knowledge Base (LDKB), which serves as a user-contributed repository of relevant knowledge.

LDKB Structure: In the LDKB, knowledge is structured in the form of arguments supporting or contradicting the value of a given measurement as evidence for life. Arguments are grouped according to common criteria (which have themselves been developed by the community through a workshop held by CLD in 2020), and each argument is supported by evidence drawn from diverse scientific literature. LDKB thus mirrors normal scientific discourse and maps content into essential measurement assessment concepts, such as false positives, false negatives, and signal-to-noise ratio (e.g., see [3]).

Community involvement: The LDKB is intended to be continuously updated with user-contributed knowledge. LDKB was rolled out to the community in 2021 at a second workshop that involved 180+ participants. Those participants later formed five CLD-facilitated "Content Development Groups" to create LDKB entries for at least fifteen life detection measurement types, to both engage and train users toward building a base of community-sourced content.

Future content development activities, emphasizing different areas of expertise relevant to astrobiology, will be focused on LDKB knowledge gaps. The objective of upcoming community activities is to reach the "critical mass" of content needed for widespread adoption of the tool and to transition toward the long-term model of content provision by individual researchers.

Relevance for Mars mission concept development: The LDKB serves the purpose of streamlining life detection knowledge organization and structured discussion and consensus development to benefit design and implementation of robotic planetary missions, including to Mars. One of the main challenges in this regard is the need to synchronize LDKB-derived science requirements with the fundamental principles and practices that apply to robotic mission projects, especially those under severe resource constraints. Missions must establish a clear and direct relationship between the types of measurements needed to achieve the mission goal, the instrumentation required for the measurements, and the type and quantity of data that must be obtained. Science traceability from goals to measurements to data must be practical and self-contained for mission feasibility within scope. The LDKB has been designed to provide an entry point for focused life-detection investigations called for by science traceability, as well as to identify technology gaps in life detection science. The LDKB, which is a "before-the-fact" mission planning tool, is complementary to the *Standards of Evidence for Life Detection Community Workshop* findings [4], which provide "after-the-fact" guidance on potential biosignature detection, identification, assessment, and discrimination.

Acknowledgements: The CLD is supported within the Network for Life Detection (NfoLD) under NASA's Science Mission Directorate.

References: [1] NASEM (2019) *The National Academies Press,* Washington, D.C. doi: 10.17226/25252. [2] Neveu M. et al. (2018) *Astrobiology, 18,* doi: 10.1089/ast.2017.1773. [3] Hoehler T. et al. (2021) Planetary Science and Astrobiology Decadal Survey 2023-2032 white paper e-id. 202, doi: 10.3847/25c2cfeb.bd9172f9. [4] Graham H., Meadows V., et al. (2021) https://www.nfold.org/soe-endorsements (White Paper draft)

OASIS: EXPLORING SURFACE WATER RESERVOIRS WITH NEXT GENERATION IMAGING SPECTROMETERS. W. M. Calvin[1], R. O. Green[2], A. A. Fraeman[2], B. L. Ehlmann[3], Briony H. N. Horgan[4], K. D. Seelos[5] and S. L. Murchie[5], [1]Geological Sci & Eng, University of Nevada, Reno, wcalvin@unr.edu, [2]Jet Propulsion Laboratory, [3]Caltech, [4]Purdue University, [5]Johns Hopkins University Applied Physics Lab.

Summary: Water is the key to the past habitability of Mars and it is the link between current and recent climate and the record of climate changes that is stored in the polar layered deposits (PLD). This low-cost mission concept builds on the major discoveries from MRO to explore and quantify, at high spatial resolution, the near-surface reservoirs of water in hydrated minerals and volatile ices (seasonal and perennial deposits) and their evolution through time. The mission concept takes advantage of developments in orbital imaging spectroscopy to achieve 3x better spatial resolution than the best CRISM imagery and acquire THEMIS resolution data with TES spectral fidelity. The combined short-wave and long-wave infrared (SWIR and LWIR) capabilities at significantly enhanced spatial scales is expected to unlock geologic and climate changes through time.

Introduction: Since the last decadal survey, numerous reports have cited the need to better understand both the vertical structure of the polar deposits [1-6] as well as the nature and timing of major environmental transitions recorded in the myriad sites where alteration minerals have been identified [1-3, 7-9]. A small, low-cost mission focused on the details and abundance of the surface water inventory can have significant impact and help answer major questions with regard to the nature and history of water-rock interactions and the quantity and nature of both ice and non-ice constituents of the PLD. This type of small spacecraft mission was identified in the recent Mars Architecture Strategy Working Group (MASWG) report linked to two mission Arcs (#1 Diverse Ancient Environments and Habitability, and #3 Ice and Geologically Recent Climate Change) [10].

Major Science Questions: The Oasis small mission concept can address several major open questions. How are the current surface ice deposits linked to current and recent climate? How are dust and volatiles cycled between the surface and atmosphere and how does dust contribute to the formation of layers? How do known deposits of aqueous alteration minerals relate to and record ancient environmental transitions? Which environments are conducive to the origin and possible evolution of life? Fundamental to these questions is the need to characterize the compositional diversity linked to water at spatial scales significantly better than current orbital data.

Measurement Approach: Both NEX-SAG and ICE-SAG strawman payloads [1, 4] included a CRISM-like instrument and a THEMIS-like thermal mapper at improved spatial resolution over current measurements. Advances from CRISM imaging spectroscopy have demonstrated that high resolution compositional information is required to resolve the details of transitions in mineral assemblages that signal changes in environmental conditions. For example, Fig. 1 illustrates the detail available at 5m/pix with the CaSSIS camera on TGO. The current best SWIR data are from CRISM at 18 m/pix, which has illuminated thousands of sites where alteration minerals are exposed [8, 9].

THEMIS, a multi-channel LWIR imager at 100 m/pixel, has provided global maps, but cannot provide detailed mineralogy and is usually supplemented with data from TES. However, TES had a very coarse spatial resolution (>3km) that was insufficient for detecting outcrop scale mineralogy. As part of the MORIE mission concept study [11, 12], we proposed a dual-range spectral system with a single shared telescope. The SWIR and LWIR spectrometers have similar telescope requirements in terms of diffraction and signal-to-noise ratio. Using a beam splitter allows the instruments to share a telescope and reduce overall mass while still achieving the desired spatial resolution in both SWIR and LWIR.

The Mars Aqueous Environment Spectral Imager (MAESI). Taking advantage of significant instrument development at JPL [13], including systems created for both earth and planetary applications (EMIT, MISE, M3, UCIS-Moon, HVM3 on Lunar Trailblazer) a compact, high TRL instrument (Fig. 2) can be created that covers wavelengths from 600 to 3600 nm at SNR values similar or better than CRISM with 10nm spectral sampling, a spatial footprint of ~6m and a swath of 5km. Higher spatial resolution compositional data will identify both primary minerals and their alteration products across environments and ages and provide a comprehensive record for many sites beyond the 4 surface locations visited by rovers. Additionally, this wavelength range can provide detailed compositional measurements of ice and non-ice components of the PLD [e.g., 14, 15].

Mars Far Infrared Emission imager (Mars-FIRE). The MORIE mission included a LWIR imager that has heritage from PREFIRE using a grating for dispersion and uncooled micro-thermopile arrays. The design achieved a spectral range from 6–25 µm, in at least 20 channels with < 1 µm bandpass, and < 100 m spatial resolution. This instrument can provide quantitative mineral abundance estimates with spectral fidelity and mineral discrimination similar to TES, but with a significantly improved footprint (equivalent to THEMIS), revolutionizing our understanding of both primary and alteration mineralogy. This wavelength range is also important for mapping polar ices and atmospheric conditions [16, 17].

The Mars Atmosphere and Volatile Resource Investigation Camera (MAVRIC). Also included in MORIE was a small, lightweight wide-angle camera to continue the decades long record of weather and seasonal frost monitoring from MOC and MARCI at better spatial resolution. This updated camera images limb-to-limb on the dayside in one dozen visible and SWIR bands acquiring daily global coverage to characterize seasonal frost, clouds and dust-storm evolution. SWIR channels can discriminate volatile ices and the visible separates ice vs dust clouds.

Implementation: Detailed study needs to explore whether this tandem spectroscopic system is achievable within the cost and mass bounds envisioned for low-cost missions. Imaging goals are to revisit high priority sites that record polar and environmental stratigraphy to determine the nature of transitions and unconformities. MAESI alone could be a compelling SIMPLEx concept (similar to Lunar Trailblazer) focused solely on alteration environments and minerals. However, the addition of LWIR and concurrent observation of locations in both wavelength ranges provides an unprecedented and unique view under similar atmospheric conditions. By also including ice reservoirs Oasis can quantify all visible surface reservoirs of water of interest both for the evolution of the Martian ancient and present climate, but also possibly useful as a resource for future explorers on the surface.

Acknowledgments: This mission concept has benefitted from conversations and analysis that occurred in support of various mission proposals in the past several years, including Discovery, SIMPLEx, and the PMCS MORIE. Our thanks to the broader team of colleagues that have helped refine these ideas.

References: [1] MEPAG NEX-SAG Report 2015, [2] NASEM CAPS “Getting Ready for the Next Planetary Science Decadal Survey” 2017. [3] NASEM Planetary Decadal Midterm Review 2018. [4] MEPAG ICE-SAG Report 2019. [5] Smith et al 2020 PSS 184. [6]Becerra et al 2021 *Planet. Sci. J.* **2** 209. [7] NASEM Astrobiology Strategy 2019. [8] Ehlmann et al 2011, Nature 479, 7371, 53-60. [9] Ehlmann and Edwards, 2014, Ann Rev Earth Planet Sci, 42, 291. [10] MASWG Report, Jakosky et al 2020. [11] Calvin et al 2021 *Planet. Sci. J.* **2** 76. [12] Calvin et al 2020 Mars Orbiter for Resources, Ices, and Environments (MORIE) (Washington, DC: NASA). [13] Green et al "Low-Cost ... Imaging Spectrometers for Mars" this conference. [14] Calvin et al 2009, JGR, 114, doi:10.1029/2009JE 003348. [15] Doute et al 2007, PSS 55, 113-133. [16] Kieffer and Titus 2001, Icarus, 154, 162-180. [17] Piqueux et al 2015, Icarus 251, 164-180.

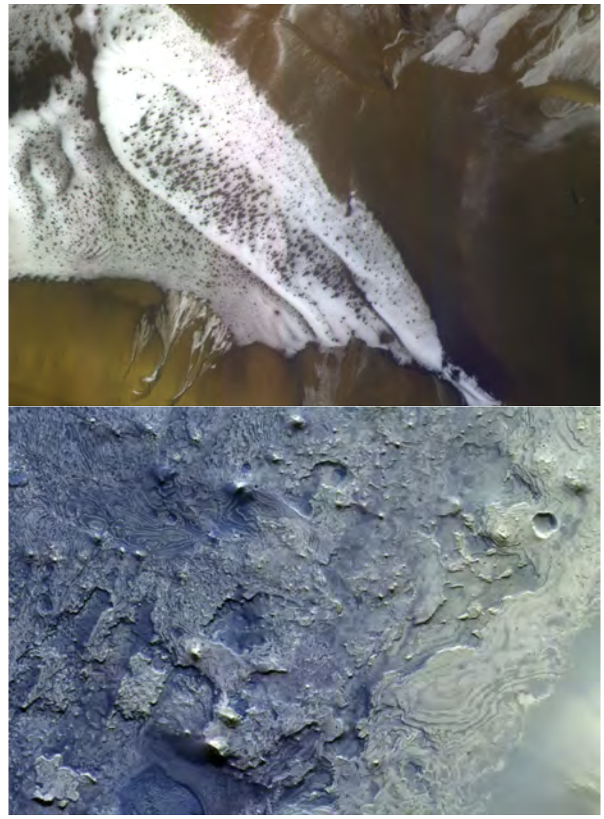

Figure 1: Next generation imaging spectrometers can capture compositional information at 5m/pixel spatial scales, equivalent to CaSSIS. The upper image shows seasonal ice covering a crater wall at 68°S, near Sisyphi Planum. The lower image illustrates layered erosional morphology at the SE rim of Izamal crater in Meridiani Planum. Image credit ESA/ROSCOSMOS/CASSIS.

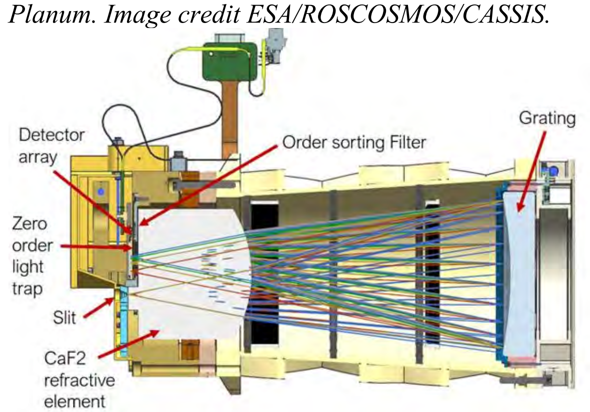

Figure 2: JPL prototype for the MAESI instrument based on a Dyson spectrometer operating in a push-broom mode. See also [13].

MAPLE, a Simple Optical Meteorological Station for Mars. C. L. Campbell[1*], C. L. Smith[2], A. Innanen[1], J. L. Kloos[3] , H. Stone[1] , G. Benedix[4,5] , S. Meka[6], D. Marrable[6], and J. E. Moores[1] [1]Centre for Research in Earth and Space Science, York University, Toronto, ON M3H 1P3, CA, [2]Oberlin College, 173 W Lorain St, Oberlin, OH 44074, USA. [3]University of Maryland, College Park, Maryland, USA, [4]Space Science and Technology Centre, School of Earth and Planetary Sciences, Curtin University, Perth, WA, 6845, Australia. [5]Planetary Science Institute, 1700 E. Fort Lowell, Suite 106, Tucson, AZ 85719, [6]Curtin Institute for Computation, Curtin University, Kent Street, Bentley, Perth, WA, 6845, Australia, *ccamp93@yorku.ca

Introduction: Martian atmospheric studies must use both orbital and surface data to piece together how the atmosphere acts as a whole. To fill in the gaps, Global Climate Models (GCMs) are used, but must still rely on Martian data to help increase the accuracy of the model. Orbiters have an advantage of observing multiple locations over a large range of altitudes, however, there is increased error closer to the surface [1]. Surface spacecraft can solve this problem but can study local atmospheric conditions and have plenty of constraints, such as data volume, maneuverability and power. To study the atmosphere as a whole, it was suggested that a minimum of 15 dedicated meteorological stations are needed to validate GCMs [2]. To accomplish this the Mars Atmospheric Panoramic camera and Laser Experiment (MAPLE) will combine everything we've learned from current and past Mars missions to maximize the returnable science in a small and low powered spacecraft.

Methods: It has been proven through several Mars missions that an onboard camera can produce useful meteorological data. The Phoenix mission was successful in studying the properties of atmospheric aerosols by imaging the onboard lidar. Only four experiments were carried out over the course of the mission due to the complexity of managing two separate instruments simultaneously and the small field of view of the camera [3]. Taking this into account, MAPLE will utilize a panoramic camera to capture the full sky, minimizing operational complexity. An example of the panoramic camera used on MAPLE is shown in Figure 1. Multiple low powered lasers will also be added to study the shape and size of the aerosols. Further, atmospheric movies taken by the Mars Science Laboratory (MSL, Curiosity) demonstrates a way to investigate a variety of aerosol parameters using simple imaging [4,5,6,7,8,9] and will be applied to MAPLE.

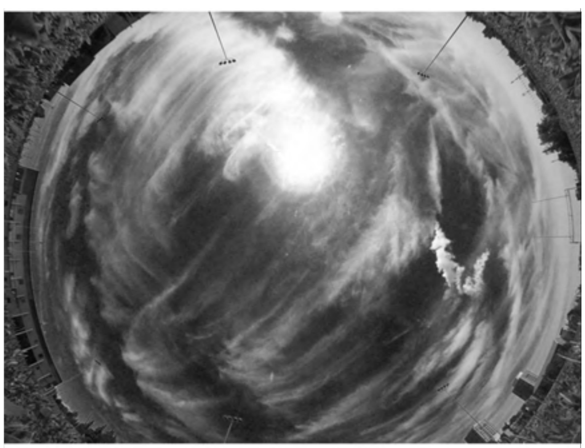

Fig. 1: An image taken by a panoramic camera similar to the one that will be used on MAPLE. It was done on a cloudy day to determine the aerosol's visibility through the camera

Another issue with Martian data acquisition is the data volume of each individual observation. Currently, images taken from Martian surface spacecraft must be downlinked first and then analyzed by a human operator. This limits the number of observations to only a few per week. To tackle this, an algorithm has been tested on previously analyzed MSL atmospheric movies and proved to be viable to measure wind direction and angular wind velocity [10]. Only the values of the parameter calculated would be returned instead of each individual image in the observation, significantly reducing data volume. Figure 2 shows an example of an atmospheric movie taken by MSL with a red arrow representing the meteorological wind direction calculated by the algorithm. If MAPLE could directly calculate these parameters onboard, it would remove the

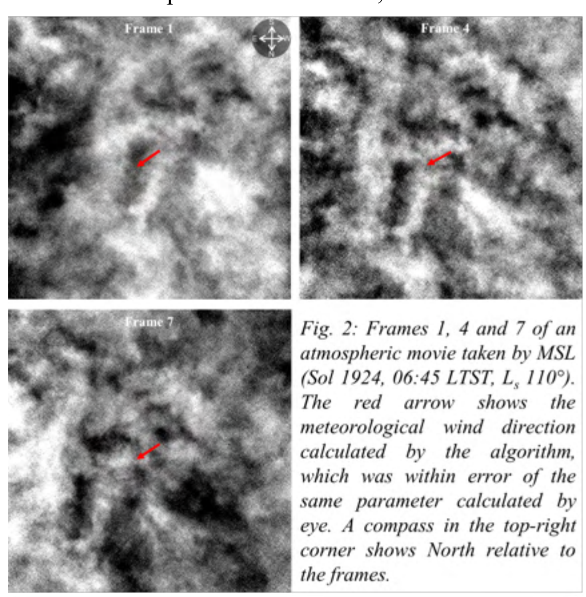

Fig. 2: Frames 1, 4 and 7 of an atmospheric movie taken by MSL (Sol 1924, 06:45 LTST, L_s 110°). The red arrow shows the meteorological wind direction calculated by the algorithm, which was within error of the same parameter calculated by eye. A compass in the top-right corner shows North relative to the frames.

need to downlink every image, allowing more observations to be taken for the same data volume.

Lab and Field Testing: To fully characterize and set-up MAPLE for Martian use, it will first be tested in lab conditions. Different lasers will be used to determine which wavelength range and positioning is ideal. Once initial testing is complete, MAPLE will be taken to two locations (aerosol-rich and Martian-like Arctic), observations collected, and data analyzed from those field sites to evaluate its viability for Martian use. If a success, MAPLE could be revolutionary for Martian meteorology data and increasing the accuracy of GCMs.

References: [1] Kleinbohl A., et al. (2009) *JGR-Planets*, *114*, E10006. [2] Haberle, R. M. and Catling, D. C. (1996) *Planet Space Sci*., *Vol. 44, No. 11*, 1361-1383. [3] Moores, J. E., et al. (2011) *Geophys. Res. Lett.*, *38*, L04203. [4] Campbell C. L. et al., (2020) *P&SS, 182,* 104785. [5] Cooper B. A. et al. (2019) *P&SS. 168,* 62-72.[6] Francis R. et al. (2014) *Acta Astronautica, 94*, 776-783. [7] Kloos et al. (2016) *Adv Sp Res.*, *58,* 1223-1240. [8] Kloos et al. (2018) *JGR-Planets, 123,* 233–245. [9] Moores et al. (2015) *Adv Sp Res*., *55*, 2217–2238. [10] Campbell C. L. et al., (2021) *Acta Astronautica*, *181*, 1-13.

Low Cost Micro-Spectrometer for Resource Mapping on Mars. S. H. Choi[1] and R. W. Moses[2]; [1]Advanced Materials and Processing Branch, Research Directorate, NASA Langley Research Center, MS 188A, Hampton, VA 23681-2199; PH (757) 864-1408; email: sang.h.choi@nasa.gov; [2]Atmospheric Flight and Entry Systems Branch, Engineering Directorate, NASA Langley Research Center, MS 489, Hampton, VA 23681-2199, email: robert.w.moses@nasa.gov

Abstract: Scientific measurements within craters and along steep embankments on Mars pose extreme challenges since astronauts and rovers cannot access them. However, these areas offer the potential for the greatest science return. NASA Langley Research Center (LaRC) has invented a deployable wireless micro-spectrometer [1-13] capable of accessing those challenging areas and using telemetry send measurements to a receiver safely outside those extreme environments. A prototype of the micro-spectrometer concept was fabricated and successfully tested for measurement of dopamine as a neural probe [14]. The bullet-sized micro-spectrometer concept can be designed for deployment by an astronaut, a rover, an aerial drone, or a lander, and the measurements broadcasted back to a receiver [13,15,16]. This device can also be installed on rover tires, under the astronaut's boots, or a cane stick. The bullet-like consumable micro-spectrometer can penetrate soil to spectrally identify the components of the soil, such as water or minerals. The signals of the soil assay data are transmitted to a mother station through a telemetry system. The LaRC developed micro-spectrometer bullet consists of micro-spectrometer optics with an all imbedded burst-mode LED UV light source, a super-capacitor with control electronics, and telemetry electronics. Prototypes have been fabricated to demonstrate spectral assay of soil components. Further maturation of this technology would be necessary for demonstration on Mars. Future work includes a potential R&D program that includes other NASA Centers and industry partners interested in developing a business case that requires knowledge of the locations of extraterrestrial ice, for instance.

REFERENCES:

1. Park, Y. and Choi, S.H. (2010), "Linear Fresnel Spectrometer Chip With Gradient Line Grating", NASA Case No. LAR 17947-1, August 17, 2010.
2. U.S. Patent 9,046,418 B1, June 2, 2015.
3. Park, Y., Wright, J.D., Jensen, J.D.L., King, G.C., Choi, S.H. (2005), "Diffraction Analysis for Periodic Nano-scale Apertures, Scatterers and Absorbers", IOP Journal, Measurement Science and Technology, 16, pp2208-2212.
4. Park, Y., Koch, L., Park, S.J., King, G.C., Song, K.D., Choi, S.H. (2008), "Miniaturization of a Fresnel Spectrometer", Journal of Optics A: Pure and Applied Optics, Vol. 10, 095301, doi: 10.1088/1464-4258/10/9/095301.
5. Park, Y. and Choi, S.H. (2013), "Miniaturization of Optical Spectroscopes into Fresnel Micro Spectrometer", Commemorative Paper, Journal of Nanophotonics, Vol. 7, 077599.
6. U.S. Patent 8,089,677, January 3, 2012.
7. U.S. Patent 7,379,231 B2, May 27, 2008.
8. U.S. Patent 8,294,989, October 23, 2012.
9. U.S. Patent 8,015,815 B2, September 13, 2011.
10. U.S. Patent 8,174,695, May 8, 2012.
11. U.S. Patent 8,059,273 B2, November 15, 2011.
12. U.S. Patent 8,094,306, January 10, 2012.
13. Sang H. Choi and Robert W. Moses (2019), NASA Invention Disclosure, "Deployable Micro-spectrometer Bullets", NASA Case No. LAR 19610-1, e-NTR #: 1552997528, March 19, 2019.
14. Min Hyuck Kim, Hargsoon Yoon, Sang H. Choi, Fei Zhao, Jongsung Kim, Kyo D. Song, and Uhn Lee, "Miniaturized and Wireless Optical Neurotransmitter Sensor for Real-time Monitoring of Dopamine in the Brain", Sensors, Vol. 16, Issue 11, (ISSN 1424-8220; CODEN: SENSC9), Nov. 2016.
15. Sang H. Choi and Robert W. Moses, "Micro-Spectrometer for Resource Mapping in Extreme Environments", IAC-19-D1.3.9x52141, Proceedings of 70th International Astronautical Congress (IAC), Washington D.C., 21-25 October 2019.
16. Sang H. Choi and Robert W. Moses, "Development of Resource Mapping Device for Extreme Environments", Proceedings of ASCE Earth & Space Conference, Seattle WA, April 19-23, 2021.

Aeolus: A Mars Climate Mission. A. Colaprete[1], A. Cook[1], D. Mauro[1], J. Bookbinder[1], B. Maryatt[1], [1]NASA Ames Research Center, Moffett Field, Mountain View, CA, anthony.colaprete-1@nasa.gov

Introduction: Aeolus is a small satellite mission to observe surface and atmospheric forcing and general circulation of Mars, by measuring surface energy balance, atmospheric temperatures, aerosols and clouds, and winds. Critically, Aeolus will make these measurements at all local times of day, providing information on both seasonal and diurnal variability. To date, direct measurements of Martian wind speeds have only been possible at the surface, only during daylight hours, and over small areas limited by rover traverse capabilities. From orbit, thermal measurements (e.g., estimates from assumed geostrophic balance) as well as images of dust storms and dune migration have provided inputs to derive current data sets on Martian winds. However, Mars General Circulation models demonstrate that wind speeds derived from these indirect measurements may be in error by 50 to 100%. For this reason, direct wind velocity measurements have been deemed “High Priority” by MEPAG (Mars Exploration Program Analysis Group); measuring wind speeds and corresponding thermal data is vital to understanding the climate of Mars.

The Aeolus Payload: Aeolus will carry three instruments: (1) Mars Doppler Wind and Temperature Souder (MDWTS), (2) Thermal Limb Sounder (TLS) and (3) the Surface Radiometric Sensor Package (SuRSeP). MDWTS utilizes gas cell radiometers to measure winds with an accuracy of better than 5 m/s day and night from the near surface (<5 km) to altitudes as high as 120 km with < 5 km vertical resolution. The TLS will measure atmospheric temperatures, water ice clouds, and dust abundances across all altitudes where winds are measured. SuRSeP is a nadir viewing radiometer, will measure the total reflected solar and emitted thermal radiance, surface temperature, and water cloud and dust total column abundances. The combined spectral and thermal measurements will provide a new understanding of the global energy balance, dust transport processes, and climate cycles in the Martian atmosphere. Aeolus will consist of a single satellite in a near-polar orbit, allowing it to pass over all local times, with the baseline mission observing all seasons of an entire Martian year (two Earth years). The lowest cost approach has Aeolus as a ride-along that used the prime spacecraft for orbit insertion and relay communication through other existing orbiting assets.

Aeolus was one of two Martian smallsat concepts selected for study through the Planetary Science Deep Space SmallSat Studies program. This talk will provide an overview of the mission, including science rationale, instruments, spacecraft, and mission operations concept.

CLPS: Commercial Lunar Payload Services. Chris Culbert, NASA/Johnson Space Center, Mail Code XA, Houston, TX 77058 Christopher.J.Culbert@nasa.gov

The Commercial Lunar Payload Services (CLPS) project is opening the door to lunar exploration on a cadence not seen since the mid-1960s. Following a model similar to that of major national delivery services (e.g. USPS), NASA has contracted with 14 commercial companies that may propose to deliver payloads to the lunar surface in order to support scientific investigations, technology demonstrations, and reduce risk associated with the human return to the Moon. NASA intends to solicit for at least two deliveries to the lunar surface per year for the foreseeable future with the first two deliveries to Lacus Mortis and Oceanus Procellarum in 2022 followed by 6 other deliveries through 2024 spread around to scientific regions of interest including the lunar poles, lunar magnetic anomalies, as well as volcanic and impact terrains. Future deliveries beyond 2024 will focus on answering major scientific questions outlined in community documents and may begin delivering infrastructure associated with the Artemis humans to the surface campaign. This talk will outline the philosophy behind the CLPS model, discuss lessons learned so far, describe upcoming lunar deliveries, and discuss the various opportunities open to the greater community for contributing/proposing a payload for lunar surface operation.

International Mars Ice Mapper Mission: A Reconnaissance Mission for the Human Exploration of Mars

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[3]NASA Goddard Spaceflight Center, 8800 Greenbelt Rd., Greenbelt, MD 20771

This talk will provide an overview of ongoing planning for the International Mars Ice Mapper (I-MIM) mission, which would detect the location, depth, spatial extent, and abundance of near-surface (top 5-10 meters) water ice, as well as the geotechnical characteristics of its overburden. NASA is collaborating with the Canadian, Italian, Dutch, and Japanese space agencies to develop this concept. This international collaboration along with potential commercial contributors, makes this mission both affordable and achievable. An Agency-level initiative, Mars Ice Mapper would be the first dedicated reconnaissance mission to Mars designed to focus on “what we need to know before humans go.”

Finding places on Mars with abundant, accessible, near-surface water ice will drive the future selection and characterization of candidate sites for the first human mission(s) to the surface. Access to water ice will be central to scientific investigations led by future human explorers on the surface, who may one day core, sample, and analyze the ice to understand the record of climate and geologic change on Mars. Water ice is also a critical Martian natural resource that would supply local "ingredients" for propellant (hydrogen as a component of methane and oxygen) to launch astronauts from the Martian surface for their return trip to Earth, as well provide resources for back-up life support, civil engineering, mining, manufacturing, and eventually, agriculture.

The mission concept includes a sun-synchronous, polar orbiter carrying a multimode, L-band synthetic aperture radar (SAR) / SAR Sounder and the possibility of additional high-altitude communications orbiters. This next-generation communications capability would support the high data volume from the SAR, enable continuous connectivity between Earth and Mars, and provide high-bandwidth, high-data-rate communications orders of magnitude greater than current capabilities for all future Mars missions.

Multilateral mission planners are exploring the potential for high-volume, high-data-rate communications relay and supplemental, synergistic payloads and rideshares (within mission boundary conditions). This potential for a high-data-rate communications capability would support the SAR’s anticipated high data volume. If implemented (likely with international and/or commercial partners), this optional capability would significantly lower costs for future Mars missions that would no longer need their own high-performance antennas. All science data from the mission would be made available to the international science community for both planetary science and reconnaissance.

This talk will focus on the status and benefits of the current multilateral concept study for I-MIM and potential opportunities to enable small missions to Mars.

A Multifunctional Tensegrity Rover Concept for Exploration of Extreme Martian Terrains

N. Deitrich and J. Bayandor, ***CR***ashworthiness for ***A***erospace ***S***tructures and ***H***ybrids (***CRASH***) Lab, Deptartment of Mechanical and Aerospace Engineering, University at Buffalo - The State University of New York.

Introduction: The proposed concept is a redesign of the Tension Adjustable Network for Deploying Entry Membrane (TANDEM) tensegrity rover[1] for a low-cost mission to Mars. Focus is on the entry, descent, landing, and locomotion (EDLL).

Tensegrity Rover: The TANDEM concept combines a tensegrity rover with an Adaptable Deployable Entry and Placement Technology[2] (ADEPT) semi-rigid heatshield to create a multifunctional EDLL vehicle. The original TANDEM serves as a lightweight landing solution, providing the required scientific capabilities on the surface of Venus as recommended by the Decadal Survey with a combined entry aeroshell and navigation drag plate[1]. Additionally, TANDEM tensegrity rover can traverse rough terrains and offer reduced risk associated with its landing. The tension network distributes loads during landing and protects the payload at omni-directional impact. Surface locomotion is achieved by actuating the tensile members, causing a rolling motion that enables traverse on a variety of terrains[3]. The payload interacts with the environment via the actuated tensegrity frame and remains protected even if multiple compression and tension members fail. TANDEM is a compact, lightweight, and multifunctional system readily adaptable for a low-cost mission to Mars.

Concept of Operation: TANDEM uses its actively controlled tensegrity frame throughout the EDLL sequence. Figure 1 shows the EDLL profile of TANDEM for a Mars mission. The vehicle reaches Mars in its stowed configuration. Before entry, the tensegrity frame deploys the heatshield for atmospheric entry. Following peak heating and deceleration, the tensegrity frame adjusts the shape of its aeroshell for lifting/guided entry. Like previous Mars missions, a supersonic parachute slows the vehicle, after which the heatshield is separated. At this point, the backshell rocket is ignited before the tensegrity bridle cord is cut, detaching the tensegrity lander from the entry module. As the vehicle gets closer to the ground, it reconfigures to prepare for an omni-directional landing. TANDEM's free fall to the surface leads to an impact landing within the allowable velocity range consistent with the constraints considered for the design of the tensegrity frame. The proposed EDL architecture is similar to that of the Mars Pathfinder lander, replacing the inflatable airbag system with a multifunctional tensegrity rover. Once on the ground, the actuated tensegrity frame utilized throughout the EDL process is reused as a mobility platform to explore the Martian surface. The central payload module can support a variety of science instruments and sensors, which can benefit from TANDEM's unique access and locomotion capabilities across rough terrains.

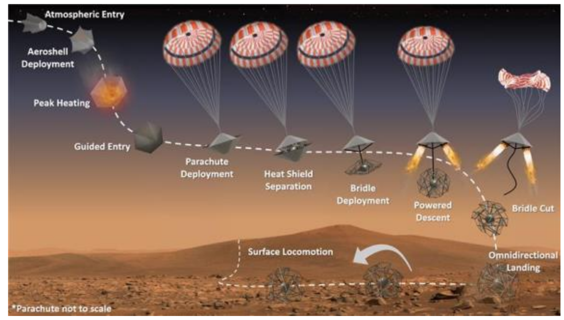

Figure 1: CONOPS for a Mars Mission.

Extreme Terrain Mobility: The traditional rover designs limit access to several Martian terrain features such as glaciers and volcanos. The TANDEM concept can explore a broader range of terrains with its omni-directional payload protection and versatile locomotive capabilities. TANDEM actively controls the tension network to produce different gaits such as rolling and hopping. It will be trained in simulated Martian environments for a variety of efficient locomotion strategies.

Prototype Development: An articulated tensegrity rover is currently under development for a Venus mission, funded by the NASA Innovative Advance Concepts (NIAC) Program[4]. The prototype will perform the EDL configuration changes as well as rolling locomotion. Additionally, scaled EDL prototypes are under construction for wind tunnel experiments.

References: **[1]** Schroeder, K., Samareh, J., and Bayandor, J. (2018) "TANDEM: Tension Adjustable Network for Deploying Entry Membrane," *Journal of Spacecraft and Rockets*, Vol. 55, No. 6, pp 1379-1392. **[2]** Wercinski, P. F., Smith, B., Yount, B., Kruger, C., Brivkalns, C., Makino, A., Cassell, A., Dutta, S., Ghassemieh, S., and Wu, S. (2017) "ADEPT Sounding Rocket (SR-1) flight experiment overview," Aerospace Conference, 2017 IEEE, IEEE, pp. 1–7. **[3]** SunSpiral, V., Agogino, A., and Atkinson, D. (2015) "Super Ball Bot - Structures for Planetary Landing and Exploration, NIAC Phase II Final Report." **[4]** Bayandor. J., Samareh, J., Vespignani, M., Bruce, J. (2020) "TANDEM NIAC Phase II."

Optimally-sized Mission Concepts for Focused In-situ Studies of Planetary Surface-atmosphere Interactions.

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Introduction: Recent technology advances in science, engineering, and computing now enable detailed, near real-time data collection and analysis of planetary atmosphere-surface interactions. These developments present novel opportunities for impactful research into environments and geomorphic activity on planetary bodies, in the next decade, particularly for studies of present-day martian surface activity, such as aeolian sand/dust transport and volatile cycles. We will describe critical science gaps that require in-situ studies of martian surface-atmosphere interactions and key enabling factors for mission concepts to close those gaps. This presentation follows from a community-generated white paper for the ongoing Planetary Science/Astrobiology Decadal Survey [1], an IEEE paper [2], small spacecraft concept development at JPL [3], and numerous community discussions.

High-priority Science Investigations: Surface-atmosphere interactions are key active processes on rocky planetary bodies. In particular, the exchange of volatiles and transport of sediment (sand/dust) and volatiles actively shape planetary surfaces, even on bodies hosting only a transient and/or thin atmosphere [1,4,5]. These interactions alter planetary landscapes, drive loss/growth of crucial atmospheric constituents, and influence climate and weather. All of these connections affect interpretation of observed or modeled geology, geomorphology, climate, and related hazards. These interpretations influence predictions used in mission design, including EDL and surface operations of robotic and human missions, and recognition of potentially habitable environments.

Analogous terrestrial processes are often studied intensively via numerical modeling that integrates empirical results from laboratory and/or field studies of process-response interactions between the atmosphere and relevant surface landforms. Incorporating such in-situ measurements into models has advanced understanding of atmosphere-surface interactions and related geomorphic processes on Earth and, given the aforementioned advancements, is poised to do so on other planets. However, model testing and refinement have, so far, not been possible in other planetary environments, and such investigations require different technologies, mission architectures, and operations designs than have been used by e.g., large rovers focused on geochemical investigations, to fully address the key gaps in our understanding while keeping cost and risk low.

Recent Technology Advances: Recent advances in four areas make low-cost/-risk mission concepts feasible:

1) Small, landed spacecraft concepts that enable low-cost delivery of small, highly integrated payload suites, especially to Mars [e.g., 2,3];
2) Advances in miniaturization, data quality, and acquisition capabilities have improved terrestrial field instrumentation, and analogous instruments focused on planetary application are now approaching TRL 6, via NASA support such as PICASSO and MatISSE [1,2];
3) The maturation of models and wealth of environmental context information for Mars that enables optimal use of ground truth observations towards advancing our understanding of natural systems, from small-scale to global [2]; and
4) Advances in onboard science data analysis and decision-making enable strategic use of spacecraft resources while characterizing environmental background cycles as well as transient events [2].

Combining ongoing developments in all of these areas, and ensuring compatibility, opens new ways to explore, measure, and understand Mars and our Solar System.

Notional Mission Concepts:

Different high-priority science questions can be addressed with data collected by a single lander, or with correlated observations from a few landers. Thus, within different cost envelopes, compelling mission concepts can be developed. This ability to size the science aims of a mission concept—while remaining focused on high-priority science—is characteristic of small lander architecture modularity along with the science focus on natural systems and processes that are inherently multi-scale. Here, we describe three low-cost mission concepts that appear feasible in the next decade. Payload elements of these different concepts could be mostly similar (as many of the same measurements are needed; e.g., Figure 1), but the landing site criteria and concept of operations design (i.e., frequency and timing of observation collection) would likely differ.

Additionally, while we focus here on concepts involving one or more landers, pairing lander(s) with a small orbiter would significantly extend the concurrent contextual information available for model validation and testing [6] and potentially provide more direct linkages between surface conditions and higher atmosphere and/or global systems. Additionally, such an orbiter may provide a relay link.

Groundtruthing with a single lander. Observations of the full near-surface meteorological environment within at least one "representative" and "simple" site on Mars, acquired through at least two Mars seasons and ideally one Mars year, would provide novel ground truth data for validating, calibrating, and refining many near-surface atmospheric dynamics models. Observations should include surface pressure, the net energy flux balance at the atmosphere-surface interface, and vertical profiles of wind velocities, volatile mixing ratios, dust concentration, and temperature [6]. Correlating these observations with measurements of volatile and/or sediment flux would test those flux models under martian conditions and enable characterization of the dynamic, climate-driven exchange of volatiles, dust, and energy between the surface and the atmosphere.

Additionally, individual datasets would aid many other process models. For example, high-resolution tracking of wind velocities would test models of wind gust distributions and calibrate comparisons between the wind environment implied by aeolian bedform orientations and numerical predictions of global and mesoscale circulation models.

While some in situ measurements have been obtained by a few landed missions [e.g., 7], such measurements are typically sparse, collected under environments that change in both time and space as the rover moves, and suffer from orientation-/location-dependent interference of the spacecraft body as well as a lack of correlation with other relevant environmental measurements. Measurements correlated in time and space across an integrated meteorological instrumentation suite, collected at high-frequency from a stationary lander with minimized spacecraft-caused environmental perturbations, would significantly enhance both confidence in models of these natural systems.

Regional study with 3+ landers. Sending more than one lander to Mars (with the type of payload described above) would yield all the ground truth benefits of one lander, enhancing robustness for both landing/operations risk (i.e., if one doesn't operate as planned) and science interpretation (i.e., if one lands in a "less representative" or dynamically complex location, as well as providing multiple ground truth datasets).

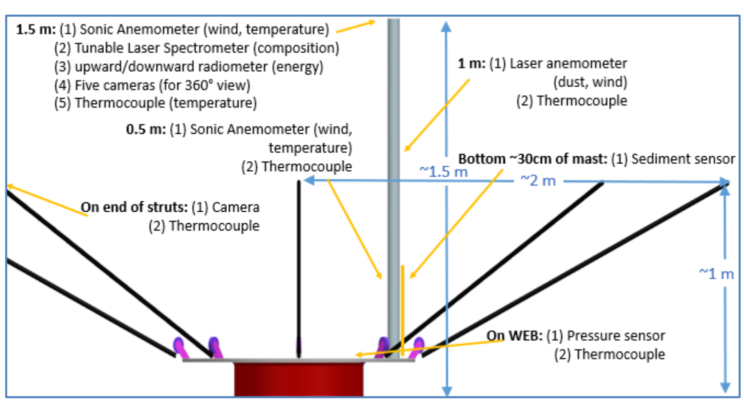
Additionally, comparing observations between the landers elucidates regional-scale atmospheric dynamics and sediment/volatile transport. For example, if the landers are distributed through a large crater, then the wind flow through the crater can be traced and compared with model predictions, which are important for EDL design as well as constraining aeolian-driven erosion processes and rates (e.g., the formation of Aeolis Mons [8,9] or estimates for exposure ages [10]). A dust storm could be tracked as it sweeps through the area. If a trace gas (like methane) is detected, its source location and transport over time could be constrained via triangulation.

Global study with 3+ landers. Sending more than one lander to Mars, but distributing them across latitudes (e.g., equatorial and ~40°N/S) would provide a look at a diversity of environments on Mars, under varying wintertime frost conditions. This architecture would provide the same risk reduction benefits as the regional study, but the broader science questions addressed through comparison of different landers' observations would focus on the global meteorological patterns of Mars, rather than regional.

Acknowledgments: A portion of this work was carried out at the Jet Propulsion Laboratory, California Institute of Technology, under a contract with the National Aeronautics and Space Administration (80NM0018D0004).

References: [1] Diniega et al. (2021) *BAAS*, **53**(4), PS&A DS 2023-2032 white paper e-id. 044. [2] Diniega et al. (2021) *BAAS*, **53**(4), PS&A DS 2023-2032 white paper e-id. 044. [3] Barba et al., (2021) *2021 IEEE Aerospace Conference* (50100), 1-7. [4] Diniega et al. (2021) *Geomorphology*, **380**, 107627. [5] Diniega et al. (2017) *Aeolian Res.*, **26**, 5–27. [6] Report from the Ice and Climate Evolution Science Analysis group (ICE-SAG) (2019) http://mepag.nasa.gov/reports.cfm. [7] Martinez et al. (2017) *SSR*, **212**, 295–338. [8] Day & Kocurek (2016) *Icarus*, **280**, 37-71. [9] Martin et al. (2021) *EPSL*, **554**, 116667. [10] Chojnacki et al. (2018) *JGR Planets*, **123**, 468–488.

Figure 1: Rough schematic for one concept for a lander, addressing meteorological and aeolian investigations. Deployed configuration is based on the SHIELD lander concept, bringing ~6 kg of payload to the Mars surface [3] and using a retractable drag skirt (here only the struts are shown) to slow descent.



INEXPENSIVE PLANETARY LAVA TUBE SKY LIGHT LANDER AND EXPLORATION DRONE.

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Introduction: Planetary Pyroducts (lava tubes) are large structures formed by lava flowing from a volcanic vent. Once the eruption is completed the tube will empty leaving a large tubular cave under the crust. These underground Pyroducts on Earth have been observed to be extend over 30km on with a diameter of 15 meters and a depth up to 15 meters below the surface. [1]

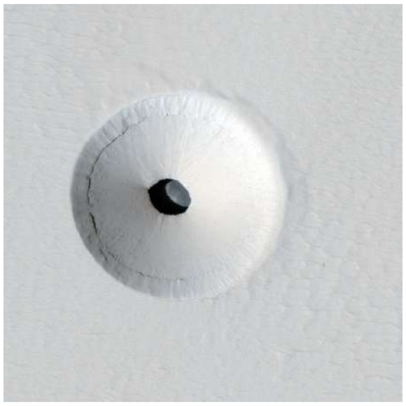


Figure 2: HiRise satellite image of skylight opening that is 35 meters across on the Mars Pavonis Mons volcano.

Pyroducts can be accessed through sections of tube collapse which produce a circular hole in the surface of the planetary body spanning the diameter of the tube which are known as sky lights. Sky lights have been observed on Mars and the Moon through orbital satellites. On Mars the sky lights have a diameter up to On the Moon skylights have been observed to be up to 500 m. [2] Extensive studies looking at colonization of Pyroducts on Mars and the Moon have been proposed as locations building colony settlements with their large size and natural radiation protection. [3] Additional studies examining Pyroduct exploration rovers and drones have been researched to show a variety of options in rover platform type and sizes. [4]

This meeting presentation proposes a primitive concept of a low-cost lander and exploration drone mission which can be attached to any upcoming explorations to Mars and the Moon. The lander and drone are expected to be about the size of two CubeSat [5] satellites. The proposed lander would use existing proven technology for communication, power, and articulation. It will also have a relatively high landing velocity with significantly less deceleration requirements. A multiple robotic exploration drone is proposed which would map out the interior of the Pyroducts as much as possible. It is hoped the low cost and simplistic approach should provide an avenue for an actual mission within a short time frame.

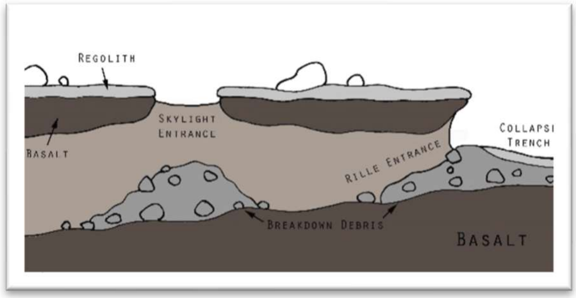


Figure 1: Cross section of a lava tube with sky light. Image shows the collapsed opening with rubble directly under. A Rille Entrance is also shown where a collapsed trench encounters the tube.

The authors are looking for those with expertise to help to take the next steps with this concept. Ideally to create a more detailed feasibility study which will hopefully lead to a real-life exploration mission. Additionally, we seek expertise and advice regarding potential communication and engineering avenues to explore.

Skylight lander: The lander proposed here is a sky light lander which is designed to straddle over the top of the sky light opening using long cable fitted with anchors. The concept is that the lander will detach from a probe approaching the planetary body and will line itself up with the center of the sky light. The lander will be launched with high rotational velocity and will decelerate slightly using propellent as it drops towards the target.

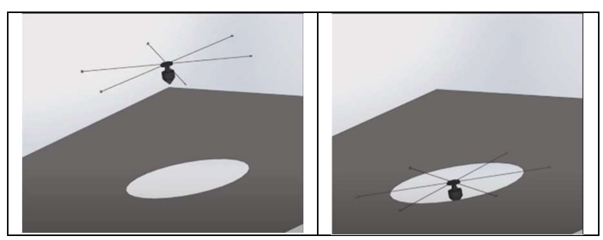


Figure 3: Left side shows the lander falling towards the skylight with the anchor cables fully extended. The right image shows the lander after the anchors have impacted the surface suspending the lander over the center of the sky light entrance to the lava tube.

As the lander approaches the surface it will cast out four cables fitted with hook anchors on the ends. As the cables are let out, the high rotation of the lander will extend the cables outward the distance required for the anchors to impact on the planetary surface. As the cables are let out the rotation of the lander will slow as it transfers energy to the cables. The lander reaches the sky light with the four cables with attached anchors impacting the surface creating a suspension system for the lander to straddle across the skylight.

With low mass, proper shock absorption design, and high tensile strength cables, the lander could stop from a potentially high velocity with little to no need to slow down after its detachment from the primary space probe.

Placing itself across the top of the sky light, the lander is in a primary position for collecting solar energy and maintaining communication with orbiting satellites. It is also in an excellent position to map and image the initial cavern of the sky light cave. It also will serve as the communication relay and power source for the exploration drone which will detach itself from the lander and drop into the Pyroduct below.

Multi-Robot Exploration: Once the lander is positioned at the entrance of the cave, aerial robots are deployed one by one. The robots maintain the distances to their neighbors by taking a measurement on their relative pose. When a robot is too close to the other robots behind it, it moves further away from them. Meanwhile, if it is going to be too far away to communicate with its neighbors, it tries to stay so that others can catch up with it to avoid disconnection. Based on these rules, they gradually move into deeper areas of the environment while maintaining connectivity. By communicating with their neighbors, the robots establish an ad hoc network so that they can pass their data between them and finally to the lander.

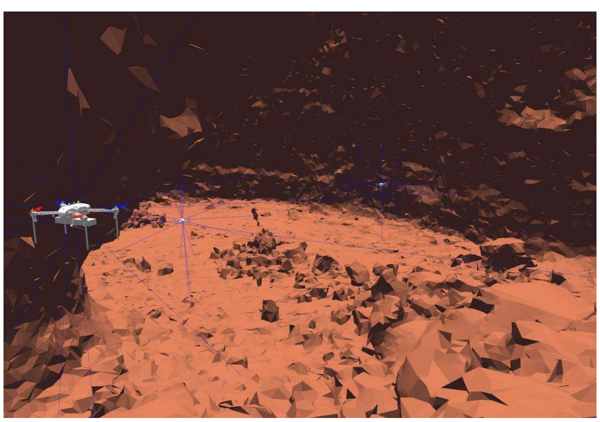


Figure 4: Drone shown exploring lava tube cavern marking and mapping points which are shared with the other drones.

This communication approach allows the robots to perform decentralized cooperative localization. Each robot exchanges the estimated global location with that of its neighbor. Based on the data from the other and the relative pose, the robot updates its own estimation. When these interactions form a loop, they effectively reduce uncertainty in their localization.

The robots also individually build maps based on locally gained information. The maps are built based on their estimated locations which are updated by the cooperative localization, leading to more accurate mapping results. Instead of building a single map, each robot builds submaps, each of which represent a specific local area. After repeating this process, the robot will hold a series of submaps along its trajectory.

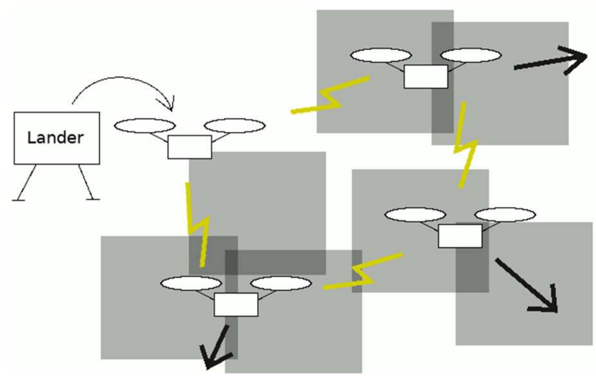


Figure 5: Multiple drones being coordinated from the lander to collectively share and send back to the lander for transmission to orbiting satellite.

Through the frequent interactions with the neighbors, the robot will know the recent locations of the neighboring drones. Passing submaps between drones can reduce the amount of mapping data and can also utilize the mapping data from the others.

This technique will hopefully allow the drones to extend deep into the lava tube while maintaining communication which will be passed back to the lander. The lander will then upload this data to orbiting satellites to be communicated to back Earth.

References:

[1] S. J. Mackie, *The Geology of the Sea*, vol. 3, no. 07. 1860.

[2] T. H. E. Future and O. F. Astronaut, "Pla mo," pp. 20–29.

[3] F. O. F. The, "Technologies Enabling Exploration of Skylights , Lava Tubes and Caves," 2012.

[4] W. Whittaker, "Technologies enabling exploration of skylights, lava tubes and caves," *NASA, US, Report, no. NNX11AR42G*, 2012.

[5] Y. J. Song, H. Jin, and I. Garick-Bethell, "Lunar CubeSat impact trajectory characteristics as a function of its release conditions," *Math. Probl. Eng.*, vol. 2015, 2015, doi: 10.1155/2015/681901.

MAGNETIC OBSERVATIONS AT MARS: PLASMA, CRUST, AND SUBSURFACE. Jared Espley[1], Dave Sheppard[1] , Jacob Gruesbeck[1], Gina DiBraccio[1]. [1]NASA's Goddard Space Flight Center (Jared.R.Espley@nasa.gov)

Summary: Magnetic observations at Mars are vital for several important areas, including its magnetosphere, ionosphere, atmosphere, crust, and subsurface. There are multiple low cost mission scenarios where magnetometers could make major advances in these science areas. Some examples include multi-point measurements of the plasma environment, regional scale magnetic surveying of crustal magnetism, and subsurface sounding. There are several types of magnetometers that could be used depending the exact goals and mission scenario, but all magnetometers are relatively low resource instruments.

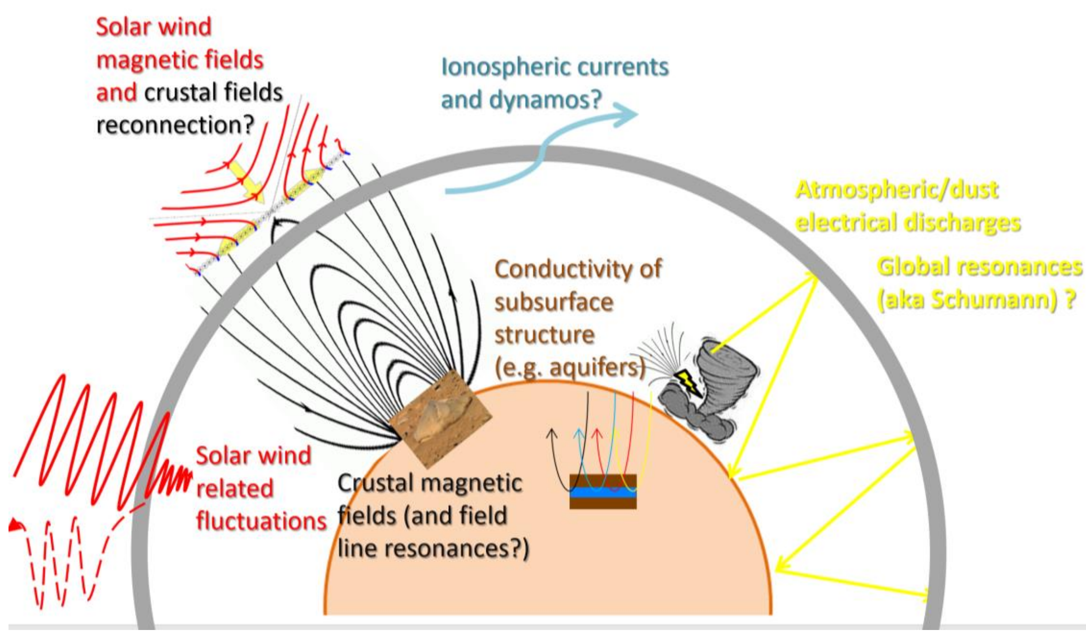
Science Areas: Magnetic observations are relevant to all areas of Mars (**Figure 1**), including:

- Near-Mars solar wind monitoring (e.g. at Mars' L1 point)
- Understanding Mars' hybrid magnetosphere and ionosphere and their role in atmospheric loss
- Searching for signs of atmospheric electricity (dust-driven?)
- Mapping crustal magnetism and using that to interpret Martian geologic history
- Probing the subsurface and its structure, including layering, aquifers, and caves.

Example Mission scenarios: A wide variety of mission scenarios exist to make such observations; nearly all of these could be part of low cost missions. Specific examples include:

Subsurface sounding: A variety of science targets lie in the subsurface including the global/regional/local stratigraphy, mineral concentrations, potential aquifers, and potential void spaces (e.g. caves). E&M sounding is a technique used on Earth for such work; doing this at Mars is an obvious step as we increasingly send more assets to the surface. Low resource mission scenarios include 1) small, deployable packages that could make the necessary multi-point measurements or 2) instruments on mobile assets (robotic rovers/flyers, driven vehicles, or even astronauts) that could conduct surveys. In all cases, some techniques would use only low-frequency magnetometers (i.e. fluxgates) alone. Other techniques would combine active source elements or other instruments (e.g. electrometers).

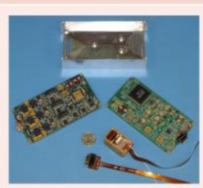
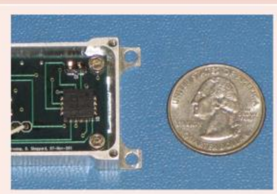
Regional scale magnetic surveying: The crustal magnetic fields were created when the magnetic field from a planet-scale dynamo was imprinted on magnetically susceptible rocks prior to dynamo cessation. Because of this, the crustal magnetic fields are important observations for understanding martian planetary evolution as tectonic, volcanic, and/or cratering events altered/erased the magnetic signature in the processed crust. Maps from orbital altitudes have yielded very important first steps but are limited in spatial resolution which limits their interpretative capability. A magnetic mapping survey done near the surface across a regional scale would dramatically increase our understanding of tectonics, volcanism, and water alteration in the region. Such a survey would be best accomplished by an aerial platform such as a plane, balloon, or rotor-craft [see Todd et al. at this conference]. Some of these mission scenarios would be



achievable under a low cost architecture especially if the platform could launch directly from the surface after having been delivered there as part of a larger payload.

Multi-point measurements of the magnetosphere and ionosphere: The hybrid magnetosphere and its co-mingled ionosphere are dynamic plasma laboratories. While much progress has been made (e.g. by MAVEN) in understanding their overall structure and their impact on atmospheric escape, many questions remain. Disentangling spatial vs. temporal variability is especially challenging with single spacecraft because of the planetary rotation of strong crustal magnetic fields. Missions with two or more spacecraft will be key to making progress here. Several mission scenarios have been proposed, including the ESCAPADE mission in development now. Different scenarios would emphasize various aspects (e.g. ionospheric, magnetospheric, space weather) depending on their configurations. Low cost, SmallSat style orbiters would likely meet most mission requirements.

Magnetometer instrumentation: A variety of measurements techniques have been used to measure magnetic fields in space. However, to-date, the most successful type of instrument has been the fluxgate magnetometer, especially the standard sized ones (e.g. MAVEN). As part of their success, fluxgate magnetometers have always had modest system requirements. However, for possible mission opportunities that are resource-constrained such as SmallSats, small landers, or aerial platforms, we have recently modernized our small fluxgates which offer mass savings (total instrument mass of < 1 kg) for slightly diminished capability ($\delta B \sim 0.1$ nT). For truly speculative missions with extremely modest science goals ($\delta B > 10$ nT), chip-scale instruments are available similar to commercially available magnetometers in smartphones. **Figure 2** shows the basic instrument specifications for the currently available Goddard magnetometers.

	Standard Fluxgate	Small Fluxgate	Magneto-resistive/inductive
Example Heritage	MAVEN, Parker	CLPS, GTOSat	None/Limited
Capability	**~< 0.01 nT**	**~ 0.1 nT**	**~>10 nT**
Sensor Mass	400 g	30 g	<1g
Total Mass	~ 1 kg	< 1 kg	<< 1 kg
Power	~1 W	<0.5 W	<0.1 W
Radiation Sensor	5+ Mrad TID	5+ Mrad TID	?
Radiation Electronics	100 krad TID	100 krad TID	?
Hardware Examples			

Assessing Cost Drivers for Mars Small Spacecraft Missions. Samuel R. Fleischer[1,*], Alex Austin[1], Nathan J. Barba[1], Patrick Bjornstad[1], Charles D. Edwards, Jr., Jairus M. Hihn[1], Anto Kolanjian[1], Robert Lock[1], Michael Saing[1], Ryan C. Woolley[1]. [1]Jet Propulsion Laboratory, California Institute of Technology, 4800 Oak Grove Dr. Pasadena, CA 91109, 818-354-4408. [*]Corresponding author contact: Samuel.R.Fleischer@jpl.nasa.gov.

Introduction and Programmatic Motivation: Considering the plans for implementation of the high-priority, flagship-class Mars Sample Return campaign, any additional near-term Mars science missions will likely be highly cost-constrained to fit within the overall NASA funding environment. According to the recent Mars Architecture Strategy Working Group report, "*Mars, the Nearest Habitable World—A Comprehensive Program for Future Mars Exploration*" [1], a new class of Mars missions in the \$100M - \$300M cost range could play a critical role in a possible future Mars Exploration Program mission portfolio. This would fill the gap in the Mars mission portfolio between the SIMPLEx missions, cost-capped at \$55M, and the Discovery missions, cost-capped at \$500M. Multiple studies in support of NASA's current Planetary Science and Astrobiology Decadal Survey [2] also explore how low-cost missions, well below the Discovery cost cap, could support a future Mars program [3,4].

These low-cost missions will be enabled by the confluence of several factors, including focused science-driven investigations, instrument and avionic miniaturization, and new low-cost commercial capabilities and processes. Here we report on a recent study to identify significant cost drivers for low-cost Mars small spacecraft orbiter missions. In particular, based on regression analysis of relevant as-flown missions and recent mission concept studies, we assess the parametric dependence of mission cost on key mission characteristics, including science payload mass, science payload power, spacecraft ΔV ("Delta-V") budget (which depends on the mode of transfer from Earth to Mars as well as on the final targeted science orbit and the means to achieve that orbit), and mission risk classification.

Ultimately, by establishing a better understanding of small spacecraft mission costs as a function of these key mission parameters, we hope to inform programmatic considerations of the role of small spacecraft missions in a future Mars Exploration Program mission portfolio and help to establish an appropriate Mars small spacecraft mission target cost range that best enables compelling science via a series of frequent low-cost Mars missions.

Mission Design Considerations: At a high level, there are three main categories of delivery methods of small spacecraft to Martian orbit: (1) piggyback or ride-along with a Mars-bound primary mission, (2) rideshare to an Earth orbit followed by independent propulsion to Mars orbit, and (3) a dedicated launch vehicle. The amount of ΔV required for a Mars orbiter depends primarily on the following factors (in roughly descending order of importance): (a) starting (or drop-off) point at which the s/c is responsible for its own

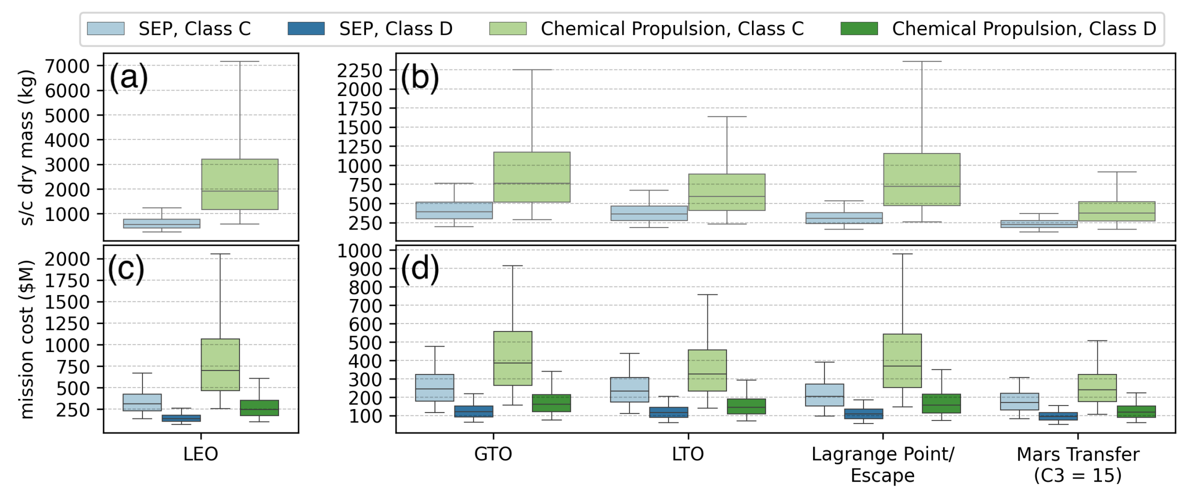


Figure 1. Spacecraft dry mass (a, b) and Phase A-D mission cost (including 30% reserves, not including launch) (c, d) of a mission to low Mars orbit (LMO) as a function of mission class, initial orbit, and propulsion type. The top panels represent mass for both Class C and D missions. We assume a 20kg, 20W optical payload with a 24-month design life. Whiskers represent the 5th and 95th percentiles of the predictions (90% credible interval). Our database contains flown Class D missions that fall below the cost and mass trade space expressed in the figure. All Class D mission predictions shown must be considered an extrapolation.

propulsion, (b) final destination orbit at Mars, (c) propulsion system – high-thrust (chemical) vs. low-thrust (solar-electric propulsion (SEP)), (d) total time-of-flight (TOF), and (e) launch date or opportunity.

As an input to the cost models in this study, the ΔV requirements contain minimum, maximum, and most-likely values for each starting/ending point pair. Starting points include LEO, GTO, LTO, and Escape, Mars Transfer (C3=15), 2-sol, Areostationary, Phobos, and LMO. In this presentation we consider only LMO as a final orbit, where the starting/ending pair LMO/LMO contains enough ΔV for orbit maintenance.

Models and Methods: A fundamental issue with current cost estimation and modeling practices, especially when conducting trades in the early lifecycle, is that they are not fully integrated with engineering models and the constraints imposed by physics. Additionally, most trade studies do not consider how uncertainty propagates through a model (including uncertainty of fitted model parameters and inputs). In this paper we propose a means to estimate the key design parameters that drive cost and their associated uncertainties in early formulation.

Here we address these issues in the following ways: first, we infuse the Tsiolkovsky rocket equation with a linear regression to estimate propellant and dry spacecraft mass. If payload mass, ΔV, and propulsion type (and thus I_{SP}) are known, then there are two unknowns in the Tsiolkovsky rocket equation:

$$\Delta V = I_{\mathrm{SP}} g_0 \log\left(\frac{m_{\mathrm{SC}} + m_{\mathrm{PL}} + m_{\mathrm{prop}}}{m_{\mathrm{SC}} + m_{\mathrm{PL}}}\right),$$

in particular the dry spacecraft mass m_{SC} and the propellant mass m_{prop}. Next, we use data from previously flown missions and Team X studies to generate a regression of the following form:

$$\log(m_{\mathrm{sc}}) = \beta_0 + \beta_1 \log(m_{prop}) + (\beta_2 + \beta_3 \times \mathrm{SEP}) \log(m_{\mathrm{PL}}) + \epsilon,$$

where ϵ is a normally distributed error term with mean 0 and variance σ^2. We use a Bayesian statistics framework, which allows us to incorporate all sources of uncertainty and variation, to estimate the multivariate posterior distribution for β_0, β_1, β_2, β_3, and σ^2. We propagate full mass and cost distributions through all models to maintain the effects of all sources of variation.

The regression equation contains the same unknowns as the rocket equation (m_{SC} and m_{prop}). We can thus solve for the intersection of these two curves in m_{SC}-m_{prop} space to calculate a physically-constrained estimate of spacecraft mass as a function of payload mass, ΔV, and propulsion type.

The spacecraft mass distribution is then passed into another Bayesian regression model (details omitted) to generate a distribution of spacecraft cost. We then use the NASA Instrument Cost Model (NICM, [5]) to generate a distribution of payload costs and a cost Rule of Thumb model to wrap spacecraft and payload cost up into total Phase A-D mission cost.

Results and Discussion: Spacecraft mass is extremely sensitive to initial and final orbit, which impact the required ΔV (Figure 1). S/C Mass is also a predictor of S/C cost, which is a predictor of Phase A-D mission cost; thus, increases in required ΔV result in large increases in mission cost. This effect is proportionally greater for missions with a less massive payload and is is more pronounced for spacecraft utilizing chemical propulsion (due to their low I_{SP}) in comparison to spacecraft utilizing SEP. For a fixed initial and final orbit (fixed ΔV distribution) and a fixed payload mass, SEP missions generally require significantly less propellant mass (and thus less spacecraft mass) than chemical propulsion missions, which results in lower total Phase A-D mission cost.

Our results show that there is a potential cost-performance design space for small Mars missions in the \$100M-\$300M cost range that merits further exploration. We find that while LEO is an infeasible initial orbit, other Earth orbits may act as reasonable drop-off points for Mars-bound small missions.

Acknowledgment: The research described in this paper was carried out at the Jet Propulsion laboratory, California Institute of Technology, under a contract with the National Aeronautics and Space Administration.

References: [1] Jakosky, B., et al. "Mars, The Nearest Habitable World – A Comprehensive Program for Future Mars Exploration." *Bulletin of the American Astronomical Society* 53.4 (2021): 029.

[2] National Academies of Sciences, Engineering, & Medicine (NASEM). (2018). Visions into Voyages for Planetary Science in the Decade 2013-2022: A Midterm Review. The National Academies Press.

[3] Barba, N., et al. "High Science Value Return of Small Spacecraft at Mars." *Planetary Decadal Whitepaper: 2023-2032*, (2020).

[4] Kaufman, J., et al. "Expanding Mars Science Return in the MSR Era: The Need for, Capabilities of, and Challenges Associated with Small Mars Science Missions." *Planetary Decadal Whitepaper: 2023-2032*, (2020).

[5] Mrozinski, J. "NASA Instrument Cost Model (NICM) Version 9." JPL Report 982-0000 Rev 9, November 2020.

SCIENCE ENABLED BY AERIAL EXPLORERS: ADDRESSING OUTSTANDING QUESTIONS IN THE MARTIAN GEOLOGICAL RECORD.
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Introduction: Mars is the only place in our solar system with a rock record that preserves the first billion years of evolution of an Earth-like world. Studying this period will enable us to better understand the factors that drive the divergent evolutionary paths of small rocky planets [1]. Exploring this well-preserved record of major geological evolution can solve key questions in planetary science today [2]:

(i) How do core dynamos form and evolve?

(ii) What processes form early planetary crusts?

(iii) What are early drivers of climate evolution?

Despite their importance, Mars' most ancient terrains have never been explored in situ. This is due in part to the fact that many are found in the Martian highlands, which have elevations that are inaccessible by traditional entry, descent, and landing systems (EDL). Others are too steep or rough to be explored with existing rovers (e.g., walls of Valles Marineris).

The success of the Ingenuity Mars helicopter sets the stage for a potential future standalone Mars Science Helicopter (MSH) that could explore ancient outcrops at high elevations or in steep terrains. Current MSH concept designs allow up to ~5 kg of science payload and traverses of several kilometers per flight [3].

An EDL strategy called Mid-Air Helicopter Delivery (MAHD) is used to deliver MSH to the Martian surface. In MAHD, the rotorcraft transitions from the stowed configuration inside the aeroshell during atmospheric descent to stable controlled flight before landing. This eliminates the need to carry a large dedicated lander and provides volume for larger rotors in the aeroshell, hence more scientific payload. The lower entry mass enables landing at higher elevation than other EDL approaches [4]. An additional major advantage is the ability to have large landing ellipses with dangerous terrain as the helicopter can autonomously navigate a safe airfield to land on within the ellipse. Finally MAHD reduces EDL system complexity, mass and importantly cost. Details of MAHD are discussed in [4].

Goals and associated measurements: A MSH could perform landed and in-flight observations on geological units in tandem (Fig. 1) using four instruments capable of fitting within the payload mass limit: a magnetometer, a context camera, a chemistry instrument such as a micro-laser induced breakdown spectroscopy (LIBS) or X-ray fluorescence (XRF), and an imaging spectrometer for mineralogy. Combined, data from these instruments could collect key measurements required to address all three goals:

Goal 1: Paleomagnetism. Establishing the time history of the strength and direction of Mars' now-extinct global magnetic field is critical to understanding the thermal evolution of Mars to the escape of Mars' atmosphere and its long-term habitability. In coarse-scale orbital data, strong crustal fields are mostly found in highland terrains, e.g., Cimmera-Sirenum block [5] (Fig. 2). There are currently limited data on the remanent magnetic field that would help constrain the evolution of the dynamo and correlate it with processes of crustal formation and climatic evolution recorded in sedimentary sequences. Acquiring the first in situ stratigraphic analysis of the remanent magnetic field on temporally-constrained Noachian outcrops would constrain the lifetime of the early dynamo. Furthermore, in situ measurements of bedrock could yield the first constraints on the field's paleodirection, which in turn could constrain the history of reversals and possibly even tectonic events. Required measurements include crustal field strength and direction coordinated with imagery and mineralogy [15].

Goal 2: Magmatism/tectonism. The degree of crustal differentiation and the question of early crustal recycling on Mars has not been settled, yet this topic is

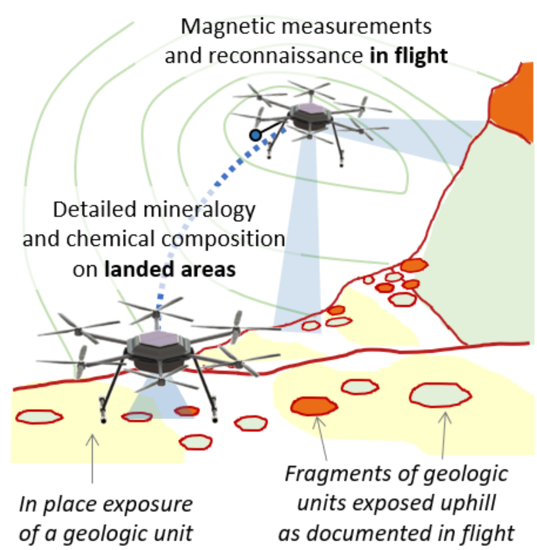

Figure 1: Geological investigation using coupled landed and in-flight observations.

fundamental for understanding the early Mars system. Magmas drive the flux of volatiles from the interior, and are therefore a major contributor to climatic evolution. *In situ* data on the lithology of key Noachian crustal components (Fig. 2) are now needed to test models for the origin of the global crustal dichotomy and processes that formed the early crust. With evidence for feldspathic and silica-rich magmatic rocks in the southern hemisphere [6–8], it is possible that a significant fraction of the crust forming the southern highlands has a more evolved composition resembling the magmatic series of the Archean proto-continental crust. Such models add to the collective lines of evidence towards major shifts in our understanding of early Mars history and need to be tested *in situ*. Required measurements include high resolution images of rock textures, chemistry and mineralogy.

Goal 3: Paleoenvironment. Sedimentary outcrops [11] and sequences of secondary minerals [16] found in Noachian and Hesperian terrains record changing aqueous conditions, atmospheric redox state, and climates on throughout Mars' history. Exploring these outcrops *in situ* will advance our knowledge on early paleoenvironments. Integrating these results with goals 1 and 2 will help understand how evolutionary processes, such as volcanic degassing and loss of Mars' atmosphere to space, drove the nature and persistence of habitable environment on Mars. Required measurements include high resolution compositional, textural, and stratigraphic mapping of key areas.

Conclusions: The key advantage of helicopters is that they can cover 100+ km over a mission lifetime and to traverse steep and rough terrains. MSH coupled with MAHD will be transformative over current flagship rover designs because it will enable *in situ* access at regional scales, at reduced cost, and will bridge the gap between orbital maps and detailed *in situ* analyses.

Acknowledgments: This work is for planning and discussion purposes only. This research was carried out at the Jet Propulsion Laboratory, California Institute of Technology, under a contract with the National Aeronautics and Space Administration © 2021.

References: [1] Ehlmann B. L. et al. (2016) *J. Geophys. Res. Planets* **121**, 1927–1961. [2] Rapin W. et al. (2021) *Bull. AAS* **53**. [3] Bapst J. et al. (2021) *Bull. AAS* **53.** [4] Delaune J. et al. (2022) *IEEE Aero. Conf.*. [5] Bouley S. et al. (2020) *Nat. Geosci.* **13**, 105–109. [6] Carter J. and Poulet F. (2013) *Nat. Geosci.* **6**, 1008–1012. [7] Wray J. J. et al. (2013) *Nat. Geosci.* **6**, 1013–1017. [8] Sautter V. et al. (2015) *Nat. Geosci.* **8**, 605–609. [11] Grotzinger J. P. and Milliken R. E. (Eds.) (2012) *Sedimentary Geology of Mars*. [12] Langlais B. et al. (2019) *J. Geophys. Res. Planets* **124**, 1542–1569. [13] Tanaka K. L. et al. (2014) *Geologic Map of Mars*. [14] Sautter V. and Payre V. (2021) *Comptes Rendus Géoscience* **353**, 1–30. [15] Mittelholz et al. (2021) *Bllt. of the American Astr. Soc*. [16] Ehlmann & Edwards, (2014) *Annual Reviews of Earth & Planet sci.,* 42.

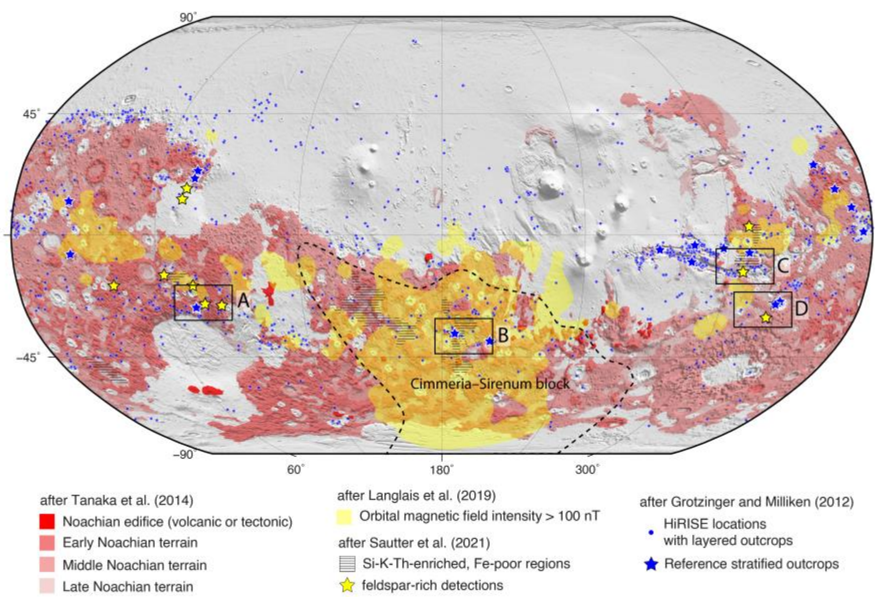

Figure 2: MSH provides decisive advantages to investigate the record of : paleomagnetism (in yellow area of crustal magnetic field >100 nT based on orbital measurements by MGS and MAVEN [12]), crust formation (Noachian aged-terrains [13], evolved igneous compositions [14], outline of Cimmeria-Sirenum block [5]) and paleoenvironments (stratified deposits observed in HiRISE data [11]). Regions of interest combining all objectives include northern Hellas (A), Eridania basin (B), Valles Marineris (C) and Holden crater (D).

AFFORDABLE, HIGH IMPACT MISSION CONCEPTS FOR MARS WITH ROCKET LAB SPACE SYSTEMS. R. T. French[1] and E. Mosleh[1], [1]Rocket Lab USA, Inc. 3881 McGowen Street, Long Beach, CA 90808, r.french@rocketlabusa.com

Introduction: Since 2017, Rocket Lab has been providing frequent and reliable access to space with the Electron launch vehicle with deployments of 105 satellites to orbit across 21 launches to date. Recently, the Neutron medium lift vehicle was also announced. The Space Systems Division is expanding with small spacecraft capable of delivering Decadal-class science [1].

Rocket Lab's Space Systems Division is moving up the value chain with end-to-end mission services with the Photon small spacecraft and down the value chain with spacecraft components, built around the acquisition of Sinclair Interplanetary in 2020 and the acquisition of Advanced Solutions, Inc. (ASI) in 2021. Sinclair Interplanetary by Rocket Lab provides best in class small spacecraft attitude control sensors and actuators including reaction wheel assemblies and star trackers. ASI by Rocket Lab provides flight software, ground software, and mission simulation tools.

Photon is an end-to-end mission capability that includes launch, satellite, ground, and mission operations as a bundled service. When launched on Electron, Photon eliminates the parasitic mass of deployed spacecraft and duplicative subsystems by operating as Electron's Kick Stage and allowing full use of the fairing by the payload. Photon is not bound to the Electron launch vehicle, however. Photon can fly on Electron, Neutron, or as a secondary payload on other launch vehicles.

Photon is evolved from Electron's Kick Stage, building on significant flight history including primary propulsion, reaction control system, flight computer, and sensors. With the addition of high-power generation, high-accuracy attitude determination and control, more radiation-tolerant avionics, and high-speed downlink, Photon can be configured for LEO, MEO, GEO, lunar, or interplanetary applications.

The first Photon, called "First Light" and shown in Figure 1, was launched in August 2020 on Flight 14. It first deployed Capella's Sequoia satellite and then 'reset' into satellite mode, successfully demonstrating solar arrays, power management, thermal management, and torque rods. First Light is now operating as an on-orbit testbed for flight and ground software validation, demonstrating lights out operations at Rocket Lab's Mission Operations Center in Long Beach, CA.

The second Photon, called "Pathstone," launched in March 2021 on Flight 19 and deployed BlackSky Globals's BlackSky 7 satellite. Pathstone is a risk reduction mission for the NASA CAPSTONE lunar mission. It also demonstrated rapid integration of Photon core systems with the Kick Stage production flow, required for hosted payload missions and low-cost tech demonstrations.

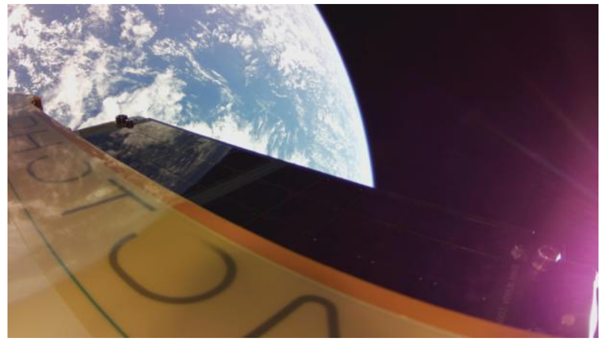

Figure 1: Photon "First Light" launched in August 2020 and is now operated as an on-orbit testbed.

A high-energy variant of Photon will fly in 2022 to propel the NASA Cislunar Autonomous Positioning System Technology Operations and Navigation Experiment (CAPSTONE) mission to the moon. While NASA performs the primary mission, Rocket Lab plans to execute a secondary mission to demonstrate the high-energy Photon's deep space operations capabilities with a lunar flyby.

In late 2020, UC Berkeley's Space Sciences Laboratory selected Rocket Lab to provide the spacecraft buses for the NASA Escape and Plasma Acceleration and Dynamics Explorers (ESCAPADE) mission to Mars, shown in Figure 2. The mission Principal Investigator is Rob Lillis and includes two spacecraft in Mars orbit to understand the structure, composition, variability, and dynamics of Mars' unique hybrid magnetosphere, demonstrating Decadal-class small spacecraft capabilities for Mars [2]. The mission passed PDR in June 2021, was confirmed for implementation in August 2021, and the mission will launch as a rideshare on a NASA-provided launch vehicle in 2024.

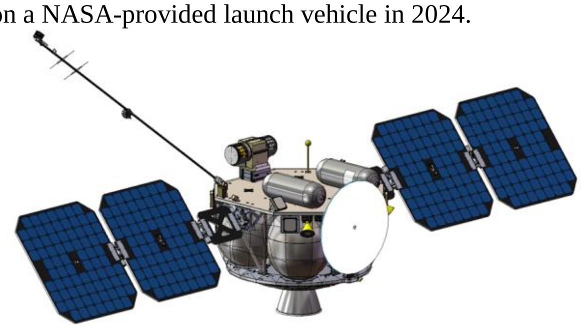

Figure 2: A pair of Photon spacecraft will fly on the ESCAPADE mission launching in 2024 to explore Mars' unique hybrid magnetosphere.

Rocket Lab has also made the engineering and financial commitment to fly a private mission to Venus in 2023 to help answer the question, "Are we alone in the universe?" The mission, shown in Figure 3, will deploy a small probe into the atmosphere in a search for biomarkers to advance habitability studies of the cloud layer. The mission is planned for launch in May 2023 on Electron from Rocket Lab's Launch Complex-1. The mission will follow a hyperbolic trajectory with the high-energy Photon performing as the cruise stage followed by deployment of a small probe in a direct entry into the Venusian atmosphere for the science phase of the mission. The mission leverages CAPSTONE investments in the high-energy Photon and Electron to deliver low-cost, Decadal-class science. The mission also serves as a model for affordable science investigations of Mars [3].

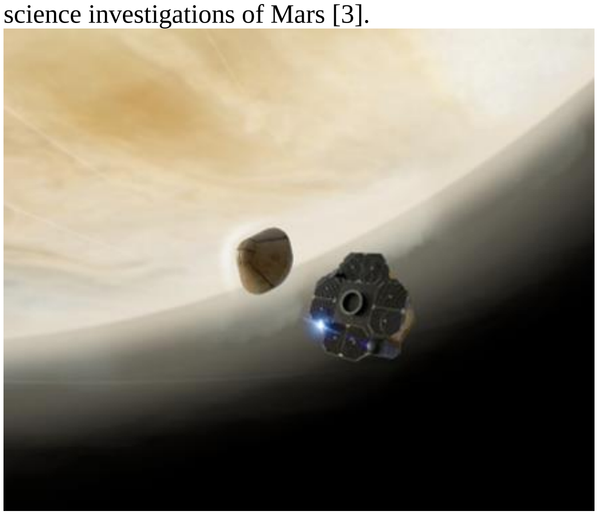

Figure 3: Rocket Lab's Venus 2023 mission serves as a model for affordable, high impact missions to Mars.

Rocket Lab will also fly a Photon in 2024 to demonstrate cryogenic fluid management technologies to support future on-orbit propellant depots for NASA on the LOXSAT 1 mission. The LOXSAT 1 mission, led by Eta Space, also demonstrates the value of dedicated small launch bundled with small spacecraft for affordable end-to-end mission implementation.

Varda Space Industries, a venture-backed startup developing factories for in-space manufacturing, recently selected Rocket Lab for a trio of missions in low Earth orbit. After launch as a secondary payload on Photon, the Varda space factory payload will manufacture optical glass fiber and then transfer the finished product to an entry capsule. Photon will then target an atmospheric entry with Rocket Lab's in-house Curie engine, a storable bi-propellant in-space propulsion system, above the Utah Test and Training Range. After targeting the entry interface, the entry capsule separates and follows a ballistic trajectory into the atmosphere. The mission design matures precision guidance, navigation, and control capabilities at Rocket Lab that are required for Venus 2023 and other entry probe missions, including to Mars.

This paper will present mission concepts for Mars that leverage Rocket Lab's Space Systems growing capabilities including orbiters, concepts for Phobos and Deimos exploration, probes, landers, the use of new technologies like aerobraking to increase payload mass, concepts for replacing aging telecommunications infrastructure, and technology demonstrations to advance capabilities for future higher value missions.

Acknowledgments: The NASA CAPSTONE mission is supported under NASA contract 80KSC020C0002. The NASA ESCAPADE mission is supported under UC Berkeley subcontract 00010676 under NASA contract 80MSFC19C0041. The NASA LOXSAT 1 mission is supported under an Eta Space subcontract under NASA contract 80MSFC21C0008. The Venus 2023 mission is supported by a non-reimbursable Space Act agreement with NASA ARC.

References:

[1] French, R., et al. (2020) *White Paper Submission to the Planetary Science and Astrobiology Decadal Survey (2023-2032)*, 413. [2] Barba, N., et al. (2020) *White Paper Submission to the Planetary Science and Astrobiology Decadal Survey (2023-2032)*, 368. [3] French, R., et al. (2021) *35th Annual Small Satellite Conference,* SSC21-IV-03.

SHIELD: a new low-cost architecture for delivering science payloads to the surface of Mars. Lou Giersch[1,*,♣], Nathan J. Barba[1], Velibor Cormarkovic[1], Melanie Delapierre[1], Matt Golombek[1], Nathan Williams[1], Ryan C. Woolley[1], Marcus Lobbia[1], Evgeniy Sklyanskiy[1], Robert Burke[1]. [1]Jet Propulsion Laboratory, California Institute of Technology, 4800 Oak Grove Dr. Pasadena, CA 91109, 818-354-4408. [*]Corresponding author contact: giersch@jpl.nasa.gov. ♣Presenting author contact: giersch@jpl.nasa.gov.

Introduction: The Small, High Impact Energy Landing Device (SHIELD) is being developed to demonstrate a new low-cost architecture for delivering science payloads to the surface of Mars. The Mars science community has a need for low cost landers capable of providing access to the surface of Mars, and satisfying this need would enable a broad suite of potential missions that can complement substantially higher cost “flagship class” missions such as Mars Sample Return. The missions thus enabled could range from missions that use a single lander to conduct a highly focused investigation, and missions using large numbers of landers distributed over Mars, and supplemental “piggyback” landers initially hosted by and used in tandem with Mars orbiters. This paper will discuss the current status of SHIELD development and the anticipated capabilities of this lander.

The overall architectural goal of SHIELD is to reduce the cost of delivering science payloads to the surface of Mars. This goal was selected under the assumption that minimizing cost would increase the quantity and frequency of Mars surface science missions, which would in turn accelerate the rate of scientific discovery. One result of this goal has been an effort to reduce the complexity of subsystems needed to deliver science payloads to the surface of Mars, or to eliminate some subsystems completely. The current state of the art for Mars landers is to use a heatshield during entry, parachutes during descent, and either a propulsion system or propulsion and airbag systems during landing. These technologies have worked successfully for Mars landers with entry masses ranging from 600 kg to 3300 kg, and typically result in peak decelerations limited to < 15 g (147 m/sec^2) during entry, but can be as high as 50 g (490 m/sec^2) during landing if airbags are used. In order to reduce cost, SHIELD has no parachute system and no airbag or propulsive landing systems. Instead, SHIELD uses a low ballistic coefficient and an impact attenuator to limit landing decelerations to ≤ 2000 g.

Mission Design Considerations: Current assumptions regarding resources (mass, geometric size, power per sol, data volume per sol) that will be available to SHIELD-hosted science payloads will be discussed. Preliminary analysis of the entry and descent trajectory of the SHIELD lander has also been conducted, as has a preliminary assessment of SHIELD landing sites with regards to potentially hazardous rock sizes and abundances. Landing site latitude and elevation considerations have also been considered and the implications will be discussed.

Results and Discussion: The SHIELD impact attenuator was successfully tested in September of 2021. This test was conducted at the full impact speed anticipated at Mars (50 m/sec). An accelerometer package was included in the test article to directly measure the deceleration profile of the payload. High speed video footage of the test was also collected and used to measure impact speed and observe the impact attenuator. This test was preceded by finite element modeling of the impact attenuator, which included predictions for the deceleration profile.

Acknowledgment: The research described in this paper was carried out at the Jet Propulsion laboratory, California Institute of Technology, under a contract with the National Aeronautics and Space Administration.

Cost Savings with AutoNav Self-navigating Spacecraft for Mars Missions. Dr. Christopher Grasso[1] and James Edward Riedel[2], [1]Blue Sun Enterprises, Inc. (1942 Broadway Street Suite 314, Boulder, CO, 80302, cgrasso@bluesunenterprises.com), [2]Jet Propulsion Laboratory (4800 Oak Grove Drive, Pasadena, CA 91109 joseph.e.riedel@jpl.nasa.gov).

Introduction: The growing number of missions in deep space, from Discovery class missions like Psyche[20] down to very small spacecraft like INSPIRE [1], Mars Cube One [2], and Lunar Flashlight [3] is driving the need for standardized, flexible, full-featured flight software for spacecraft guidance, navigation, and control (GNC). Small Mars missions could similarly reduce navigation-related expenses.

Autonomous GNC allows a spacecraft to perform most of its own navigation activities without the need for as many ground-based personnel and as much Deep Space Network contact time. These autonomous activities include: 1) absolute spacecraft position determination within heliocentric, planet-centric, and small-body-centric systems; 2) determining spacecraft position relative to small bodies and other spacecraft for rendezvous and contact purposes; 3) orbit determination; 4) target tracking of asteroids, comets, ground apertures, spacecraft, and ground-based assets; 5) interplanetary trajectory derivation; 6) low-thrust maneuvering (e.g. solar electric propulsion); 7) ephemeris calculation of solar system bodies and spacecraft; 8) pointing.

AutoNav Mark 3[7][16] from the Jet Propulsion Laboratory existed for some time in prototype form and implemented many of the above functions. Older AutoNav components have been successfully hosted onboard three separate deep space missions, including Deep Impact [17], Stardust [18], and Deep Space 1 [19]. Under NASA SBIR contract 80NSSC18C0043, AutoNav Mark 4 has been completed, based on Mark 3, and made available as a commercialized product meeting NASA Class B software standards, thereby enabling its inclusion on a wide variety of NASA and non-NASA missions.

Commercialization reduces risk and cost for missions to Mars by allowing those missions to perform autonomous on-board navigation with only a minimal need for navigation specialists. This in turn could allow organizations including Goddard's Navigation and Mission Design Branch and JPL's Mission Design and Navigation Section to support a wider array of deep-space missions, leveraging on-board autonomy to reduce the time required for experts to perform needed activities like orbit determination, maneuver determination, and derivation of trajectories. Missions internal to NASA (center-driven and contracted) and external (international, university, and commercial) could then contract with organizations like JPL's Navigation Section for partial expert time, reducing mission costs and sharing high-quality navigation expertise across multiple missions in a market-like way.

AutoNav Mark 4 source code is designed and tested to be compatible with a variety of different CPUs (e.g. SPARC, PPC, Intel), real-time operating systems (VxWorks, RTEMS), and flight software cores (NASA Core Flight System / Core Flight Executive, Blue Sun BRIDGE). This approach allows the software to be deployed in the widest-possible set of environments: 1) included in the flight software load of the spacecraft hosted aboard the command and data handling avionics; 2) within a space radio built to be compatible with the NASA Space Telecommunications Radio System (STRS) Architecture Standard (NASA-STD-4009) [5][6] like an extended Iris[4] radio with larger memory space; and 3) in a dedicated stand-alone computing platform which interfaces to the flight computer via serial connection.

This paper will outline historical use of AutoNav on deep space missions, and explore applications of its capabilities specifically to Mars mission scenarios and phases, including cruise, Mars Orbit Insertion (MOI), and both ballistic and electric propulsion orbit maintenance. Methodology behind optical navigation using Mars satellites and planetary terrain will be explored. Sequence and autonomy strategies to run AutoNav Mark 4 using Virtual Machine Language 3 [5][6][8][9][10][11][12][13][14][15] will be detailed. Deployment methodologies and cost savings to missions using AutoNav Mark 4 will then be projected.

References: Use the brief numbered style common in many abstracts, e.g., [1], [2], etc. References should then appear in numerical order in the reference list, and should use the following abbreviated style:

[1] Klesh, A., et al. "INSPIRE: Interplanetary NanoSpacecraft Pathfinder In Relevant Environment," Proceeding of the 27th Annual AIAA/USU Conference on Small Satellites, 2013.

[2] Foust, J., "CubeSats to Mars and beyond," The Space Review, http://www.thespacereview.com/article/2814/1, August 24, 2015.

[3] Cohen, B. A, et al., "Lunar Flashlight: Mapping Lunar Surface Volatiles Using a Cubesat," Annual

Meeting of the Lunar Exploration Analysis Group, 2014.

[4] Duncan, C., et al. “Iris Transponder – Communications and Navigation for Deep Space,” Proceeding of the 28th Annual AIAA/USU Conference on Small Satellites, 2014.

[5] Grasso, C. A., “VML 3.0 Reactive Rendezvous and Docking Sequencer for Mars Sample Return”, AIAA Space Operations Conference Proceedings, May 2014.

[6] “Virtual Machine Language Controls Remote Devices,” Spinoff, p.122, NASA Office of the Chief Technologist, 2013.

[7] Guinn, J. R., Riedel, J. E., Bhaskaran, S, et al., “The Deep-space Positioning System Concept: Automating Complex Navigation Operations Beyond the Earth”, AIAA SPACE 2016, AIAA SPACE Forum, (AIAA 2016-5409) .

[8] Grasso, C. A., Riedel, J. E., “VML 3.0 Reactive Sequencing Objects and Matrix Math Operations for Attitude Profiling”, AIAA Space Operations Conference Proceedings, May 2012.

[9] Grasso, C. A. and Lock, P. D., “Flight-Ground Integration: the Future of Operability”, Space Operations: Innovations, Inventions, and Discoveries, edited by Cruzen, Schmidhuber, and Dubon, AIAA, Progress in Astronautics and Aeronautics vol. 249, 2015.

[10] Grasso, C. A. and Lock, P. D., “VML Sequencing: Growing Capabilities over Multiple Missions”, 2008 AIAA Space Operations Conference Proceedings, document 092407 May 2008.

[11] Grasso, C. A., “Virtual Machine Language (VML)”, NPO 40365, JPL Commercial Programs Office, Innovative Technology Asset Management Group, Docket Date: 12-May-2003.

[12] Grasso, C. A., “Virtual Machine Language (VML) NASA Board Award”, NASA Inventions and Contributions Board, NASA Technical Report 40365, Award Date: September 7, 2006.

[13] Grasso, C. A., “The Fully Programmable Spacecraft: Procedural Sequencing for JPL Deep Space Missions Using VML (Virtual Machine Language)", IEEE Aerospace Applications Conference, March 2002.

[14] Peer, S. and Grasso, C. A., “Spitzer Space Telescope Use of Virtual Machine Language”, 2003 IEEE Aerospace Conference Proceedings, December 2004.

[15] Grasso, C. A., “Techniques for Simplifying Operations Using VML (Virtual Machine Language) Sequencing on Mars Odyssey and SIRTF”, 2003 IEEE Aerospace Applications Conference, March 2003.

[16] Riedel, J. A., Grasso, C. A., et al., “AutoNav Mark 3: Engineering the Next Generation of Autonomous Onboard Navigation and Guidance”, AIAA Guidance, Navigation and Control Conference, August 2006.

[17] Riedel, J. A., Grasso, C. A., et al., “Configuring the Deep Impact AutoNav System for Lunar, Comet and Mars Landing”, AIAA Astrodynamics Specialist Conference, August 2008.

[18] Bhaskaran, S., Mastrodemos, N., Riedel, J., Synnott, S., “Optical Navigation for the Stardust Wild 2 Encounter”, 18th International Symposium of Space Flight Dynamics, 11-15 October, 2004, Munich.

[19] Rayman, M. D., Chadbourne, P. A., et al., “Mission Design for Deep Space 1: a Low-thrust Technology Validation Mission,” whitepaper, Jet Propulsion Laboratory, California Institute of Technology.

[20] “Psyche: Journey to a Metal World,” Arizona State University, https://sese.asu.edu/research/psyche (2017).

LOW-COST, HIGH SIGNAL-TO-NOISE RATIO, AND HIGH FIDELITY IMAGING SPECTROMETERS FOR MARS. R. O. Green (Robert.O.Green@jpl.nasa.gov)[1], P. Mouroulis[1], P. Sullivan[1], H. Bender[1], W. Calvin[2], B. Ehlmann[3], A. Fraeman[1], D. R.Thompson[1], Q. Vinckier[1], D. Keymeulen[1], M. Klimesh[1], D. Ardila[1], and S. Nadgauda[1] [1]Jet Propulsion Laboratory, California Institute of Technology, University of Nevada, Reno[2], California Institute of Technology[3]

Introduction: The first imaging spectrometer, AIS[1], was proposed at $75K in 1979 and made discoveries at Cuprite, NV in 1982. Since that time, there has been a sustained focus on improved Signal-to-Noise Ratio (SNR) and improved measurement fidelity for science and discovery on Earth and through the solar system. In conjunction with the lessons over the last three decades, the arrival of new compact/uniform imaging spectrometer designs[2] along with the latest detectors, optical components, thermals systems, and electronics now enable a new generation of small, low-cost imaging spectrometers with a high signal-to-noise ratio (SNR) and excellent measurement uniformity/fidelity[3] (e.g. low smile and low keystone). We describe examples of a current telescope prototype as well as Offner and Dyson imaging spectrometers and new spectral data compression solutions that are available today to support high SNR imaging spectroscopy measurements (Figure 1) for low-cost Mars missions.

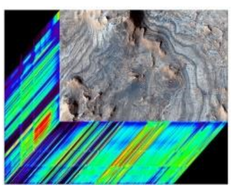

Figure 1. Depiction of a notional imaging spectroscopy measurement with a spectrum acquired for every point in the image from 600 to 3600 nm with 10 nm sampling and a GSD of ≤6 m.

Telescope: JPL has developed and tested a low-cost telescope (Figure 2). This telescope is directly compatible with an Offner imaging spectrometer covering the spectral range from 600 to 3600 nm with 10 nm sampling and supports ≤6 m ground sample distance (GSD) from Mars orbit. The telescope is all aluminum and includes a focus mechanism on the secondary. This prototype could be updated to support an optically fast Dyson imaging spectrometer option.

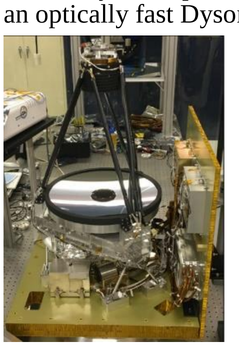

Figure 2. Low-cost telescope prototype that has been developed and qualified. This telescope is compatible with ≤6 m GSD imaging spectroscopy from Mars orbit.

Offner Design: Offner imaging spectrometers have been used very successfully at Mars and elsewhere in the solar system[4,5,6]. Low-cost implementations of this design have continued to advance as exemplified by the NASA UCIS-Moon[7,8] (Figure 3) DALI project for landed opportunities and the HVM[3] instrument on the Lunar Trailblazer[9] SIMPLEx project for orbital observations. These current implementations take advantage of updated detector arrays, e-beam grating fabrication, optical design refinements, thermal control advances, and modern electronics to deliver improved performance with reduced size, mass, and power. The UCIS-Moon Offner imaging spectrometer (Figure 3) can be directly adapted to the prototype telescope (Figure 2). In conjunction with the high SNR performance of the instrument, spacecraft ground motion compensation (GMC) can be used to increase the integration time to meet the specific required SNR performance for the targeted science observations.

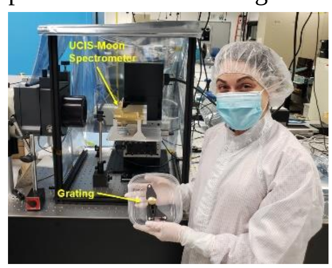

Figure 3. 2021 state-of-the-art UCIS-Moon Offner imaging spectrometer (600 to 3600 nm @ 10 nm) with modern CHROMA detector array, e-beam grating, and advanced electronics.

Dyson Design: Over the last decade and currently there has been increased use of the Dyson imaging spectrometer design form[2]. The Dyson has the advantage of allowing an optically faster imaging spectrometer with reduced size and mass compared to an equivalent Offner instrument. Challenges of the Dyson are the need for a refractive element and a comparatively large concave grating. Solutions to these challenges have been found over the past decade. The Mapping Imaging Spectrometer for Europa (MISE) uses an F/1.4 throughput Dyson[10,11].over the spectral range from 800 to 5000 nm. The Earth Surface Mineral Dust Source Investigation (EMIT)[12] uses an F/1.8 Dyson over the range 380 to 2500 nm.

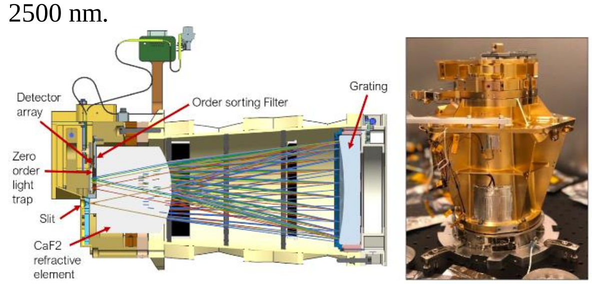

Figure 4. 2021 EMIT F/1.8 Dyson imaging spectrometer.

Based on the low volume and mass potential of the Dyson, there has been a just completed investment to develop a CubeSat sized VSWIR+MWIR (600 to 3600 nm) Dyson Imaging Spectrometer (VMDIS)[13]. This instrument is designed for the latest digital out CHROMA detector array to further reduce electronics mass. VMDIS has been developed and aligned in 2021 (Figure 5). This imaging spectrometer is available to support low-cost mars orbital missions and other missions through the solar system. The spectral range can be extended to shorter and longer wavelengths if required. The high throughput and low F-number of VMDIS would require specialized adaptation of the prototype telescope (Figure 2) for use in Mars orbit.

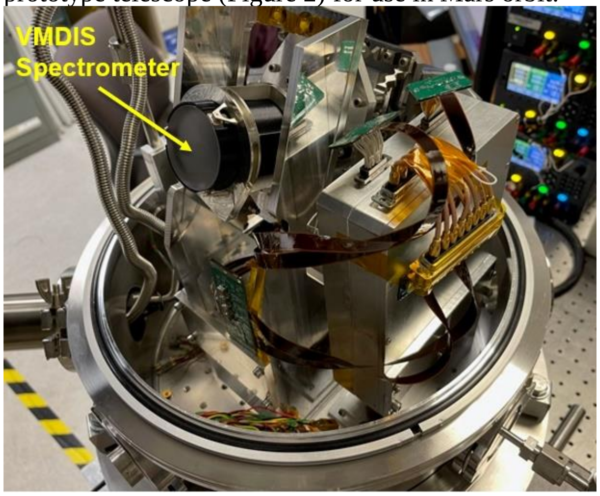

Figure 5. 2021 VMDIS in the thermal vacuum chamber used for alignment and testing of this CubeSat sized imaging spectrometer that is designed for 600 to 3600 nm at 10 nm sampling with the latest digital out detector array.

Spectral Data Compression: In parallel with advances in hardware a new spectral data compression algorithm has been developed the delivers 4X lossless compression and >10 high fidelity lossy compression for imaging spectroscopy measurements. This algorithm has been tested in real-time with Earth airborne imaging spectrometers and is encoded in the EMIT FPGA and is enabling for low-cost Mars missions

Surface Missions: Analysis of the completed VMDIS has shown promise for an even small/lighter imaging spectrometer that could be used in future surface missions when interfaced with an appropriately small telescope. This configuration is termed microVMDIS. Work is ongoing to develop the electronics and thermal configuration to support this new complete solution for future low-cost Mars missions including a science helicopter.

Summary and Conclusion: These latest imaging spectrometers, telescope, and spectral data compression developments and prototypes take advantage of lessons learned over the last three decades as well as the availability of new detectors, optical designs, optical components, thermal systems, and electronics. These modern instruments deliver high SNR and excellent measurement uniformity (low smile and low keystone) with reduced volume, mass, and power. The imaging spectrometer developments presented here are available to support low-cost and high fidelity instruments for science and discovery on Mars and throughout the solar system.

Acknowledgments: The authors gratefully acknowledge NASA and all those who have contributed to advancing imaging spectrometer design and development knowledge for science and discovery. A portion of this work was carried out at the Jet Propulsion Laboratory / California Institute of Technology, Pasadena, California, under contract with the National Aeronautics and Space Administration.

References: [1]Vane, G., AFH Goetz, and J. B. Wellman. "Airborne imaging spectrometer: A new tool for remote sensing." IEEE Transactions on Geoscience and Remote Sensing 6 (1984): 546-549. [2]Mouroulis, P.; Green, R. O.; Chrien, T. G. Design of pushbroom imaging spectrometers for optimum recovery of spectroscopic and spatial information. Applied Optics, 2000, 39.13: 2210-2220. [3]Mouroulis, P., and R. O. Green. "Review of high fidelity imaging spectrometer design for remote sensing." Optical Engineering 57, no. 4 (2018): 040901. [4]Murchie, S., et al. "Compact reconnaissance imaging spectrometer for Mars (CRISM) on Mars reconnaissance orbiter (MRO)." Journal of Geophysical Research: Planets 112.E5 (2007). [5] Ungar, S. G., J. S. Pearlman, J. A. Mendenhall, and Dennis Reuter. "Overview of the earth observing one (EO-1) mission." IEEE Transactions on Geoscience and Remote Sensing 41, no. 6 (2003): 1149-1159. [6] Green, R. O., et al. "The Moon Mineralogy Mapper (M3) imaging spectrometer for lunar science: Instrument description, calibration, on-orbit measurements, science data calibration, and on-orbit validation." Journal of Geophysical Research: Planets 116.E10 (2011). [7] Fraeman, A. A., J. M. Haag, M. L. Eastwood, W. Chen, I. M. McKinley, M. Sandford, D. L. Blaney, et al. "An Ultra-Compact Imaging Spectrometer for the lunar surface: UCIS-Moon." In Lunar and Planetary Science Conference, no. 2326, p. 1610. 2020. [8] Haag, J. M., M. S. Gibson, W. Chen, I. M. McKinley, Abigail A. Fraeman, and Pantazis Mouroulis. "Ultra-Compact Imaging Spectrometer Moon (UCIS-Moon) for lunar surface missions: Optical, optomechanical, and thermal design." In Imaging Spectrometry XXIV: Applications, Sensors, and Processing, vol. 11504, p. 1150403. International Society for Optics and Photonics, 2020.[9] Ehlmann, B. L., R. L. Klima, C. L. Bennett, D. L. Blaney, N. E. Bowles, S. B. Calcutt, J. L. Dickson et al. "Lunar Trailblazer: A Pioneering Small Satellite for Lunar Water and Lunar Geology." In AGU Fall Meeting Abstracts, vol. 2020, pp. P060-02. 2020. [10] Blaney, D. L., C. A. Hibbitts, R. O. Green, R. N. Clark, J. B. Dalton, A. G. Davies, Y. Langevin, et al. "The Mapping Imaging Spectrometer for Europa (MISE): Science and Instrument Development Status." In Lunar and Planetary Science Conference, no. 2326, p. 1582. 2020. [11] Bender, H. A., D. L. Blaney, P. Mouroulis, L. A. Moore, and B. E. Van Gorp. "Optical design of the Mapping Imaging Spectrometer for Europa (MISE)." In Imaging Spectrometry XXIII: Applications, Sensors, and Processing, vol. 11130, p. 111300C. International Society for Optics and Photonics, 2019. [12]Green, R. O., N. Mahowald, C. Ung, D. R. Thompson, L. Bator, M. Bennet, M. Bernas et al. "The Earth surface mineral dust source investigation: An Earth science imaging spectroscopy mission." In 2020 IEEE Aerospace Conference, pp. 1-15. IEEE, 2020. [13]Mouroulis, P., R. O. Green, D. W. Wilson, C. S. Smith, and M. F. Lin. "Compact imaging spectrometer for planetary missions." In Imaging Spectrometry XXIV: Applications, Sensors, and Processing, vol. 11504, p. 1150406. International Society for Optics and Photonics, 2020. [14]Klimesh, M. (2006). Low-Complexity Adaptive Lossless Compression of Hyperspectral Imagery, Proc. SPIE Optics & Photonics Conference, 6300, 9. doi:10.1117/12.682624. [15]Keymeulen, D., N. Aranki, A. Bakhshi, H. Luong, C. Sarture, D. Dolman (2014). Airborne Demonstration of FPGA implementation of Fast Lossless Hyperspectral Data Compression System, Adap. Hard. Sys. Conf., 278-284. doi:10.1109/AHS.2014.6880188.

PAWSS: POLAR-ORBITING ATMOSPHERIC WIND SMALL SATELLITE. S. D. Guzewich[1], N.G. Heavens[2,3], L. Montabone[2,4], R. Lillis[5], N. Barba[6], R. Wooley[6], L. Tamppari[6], J.B. Abshire[1,7], M.D. Smith[1], and D. Cremons[1]; [1]NASA Goddard Space Flight Center, 8800 Greenbelt Rd, Greenbelt, MD, 20771 (scott.d.guzewich@nasa.gov), [2]Space Science Institute, 4765 Walnut St, Suite B, Boulder, CO 80301; [3]Earth Science and Engineering, Imperial College, London, Royal School of Mines, Prince Consort Rd, South Kensington, London, UK SW7 2BP; [4]Laboratoire de Météorologie Dynamique, Sorbonne Université, Campus Pierre-et-Marie-Curie, 4 Place Jussieu, 75005 Paris, France; [5]Space Sciences Laboratory, UC Berkeley, 7 Gauss Way, Berkeley, CA, 94720; [6]NASA JPL, Caltech, 4800 Oak Grove Dr, Pasadena, CA 91109; [7]University of Maryland, College Park, MD 20742.

Introduction: The fleet of Mars orbiters in the 21st century have provided two decades of unbroken observations of atmospheric temperature and dust and water ice abundances. This has led to myriad discoveries about the climatology and processes in the martian atmosphere. However, despite the high priority of global measurements of wind velocity in Mars Exploration Program Analysis Group (MEPAG) Science Goals [1] and a variety of mission concept analysis groups focusing on science [2,3] and preparation for human exploration [4], we lack systematic measurements of atmospheric winds.

Recent developments have led to several candidate instruments to measure global vertically-resolved winds that are ready for flight using lidar backscatter [5] and sub-millimeter sounding [6,7] techniques. The differing techniques both capture middle atmospheric winds (10-40 km altitude) at vertical resolutions comparable to or better than existing temperature measurements (e.g., [8]). The lidar instrument would also retrieve lower atmospheric (surface-10 km) winds and a sub-millimeter would retrieve winds at higher altitudes (40-100 km).

We propose a small Sun-synchronous polar-orbiting spacecraft to carry one of these flight-ready instruments, building off the Mars Orbiters for Surface, Atmosphere, and Ionosphere Connections (MOSAIC) mission concept study for the 2020 Planetary Science and Astrobiology Decadal Survey [9].

Mission and Spacecraft: Our spacecraft is derived from descope options presented for the MOSAIC mission concept [9], specifically a smaller version of the “mini-mothership.” The MOSAIC mini-mothership concept included four instruments: P-band synthetic aperture radar, wind lidar, thermal infrared radiometer, and wide-angle camera resulting in a ~1200 kg dry mass spacecraft (including margin). By focusing on either a wind lidar or sub-millimeter sounder we aim for under 40 kg of instrument payload and thus <400 kg dry mass for the entire spacecraft.

Local-time resolved atmospheric measurements are highly valued by the scientific community [1] but are beyond the capabilities of a single polar-orbiting spacecraft due to the significant Δv required for plane-change orbit maneuvers [9]. For congruency with existing observations (largely at 2-3 am/pm), we would target a Mars Reconnaissance Orbiter-like 87° inclined ~300 km altitude Sun-synchronous orbit with 3am/3pm equator crossings.

All instruments would optimally operate constantly with a 90% duty cycle or higher resulting in 1-4 Gb/day of science data [9].

Instruments: The Mars lidar for global climate measurements from orbit (MARLI) is a Doppler near-infrared lidar designed to measure the frequency shift of laser backscatter from atmospheric aerosols [5]. MARLI is under development at NASA Goddard Space Flight Center through NASA Maturation of Instruments for Solar System Exploration (MatISSE) program funding to reach TRL 6. In a fixed configuration, MARLI would measure the line-of-sight wind vector pointed cross-track to the spacecraft motion. Fully vector-resolved winds are possible if a tip-tilt table is used to pivot the laser and receiver telescope. In addition to wind measurements, MARLI would retrieve dust and water ice aerosol abundances from the surface – 40 km.

The Jet Propulsion Laboratory has developed a sub-millimeter sounder for the martian atmosphere to TRL 5 with limited additional testing needed to reach TRL 6 [6,7]. It retrieves line-of-sight winds, temperature, and trace gas (e.g., H_2O, HDO, etc.) mixing ratios, and with two antennas would retrieve vector-resolved winds, from ~10 km - 100 km altitude.

If additional payload can be accommodated, a miniature thermal infrared radiometer (e.g., mini-Mars Climate Sounder) would be an optimal pairing with a wind measurement instrument. A thermal infrared radiometer would be able to retrieve temperature, dust, water vapor and water ice aerosols in the middle atmosphere to provide highly complementary measurements to wind velocity.

Science Objectives: Wind connects a climate system as the agent of transport of heat, momentum, aerosols, and trace gas species. Wind is also the primary agent of geologic change on Mars over the last ~3 Gy.

The PAWSS mission would be designed to operate for at least one Mars year to understand the full seasonal cycle of the atmospheric circulation and how it responds to significant events such as dust storms. A longer mission would be optimal to capture infrequent events such as global dust storms.

The primary science objective of the mission is to measure lower and middle atmospheric horizontal wind velocities (at least 10-40 km altitude range) with vertical resolutions ≤5 km, horizontal resolutions ≤300 km, and precisions ≤5 m/s at 2 local times of day (notionally 3am/3pm). This would meet high priority MEPAG science goals [1], reduce risk for future human surface operations and entry/descent/landing, and provide an invaluable resource for the improvement of Mars atmospheric models.

A second science objective would be simultaneous measurements of temperature, dust, and water ice aerosols. This would allow for direct concurrent calculation of transport and fluxes of energy and material horizontally through the martian climate system.

Conclusions and Summary: Direct and global measurements of wind velocity are the highest priority Mars atmospheric science objective that must be accomplished from orbit [2]. Instruments that can make these measurements are ready for flight development.

We believe that PAWSS, a small spacecraft bus in a low polar orbit, offers a low cost and low risk opportunity to achieve these science objectives at sub-Discovery mission cost.

Acknowledgments: This work is supported in part by NASA's MatISSE program and NASA's Planetary Mission Concept Study program (80NSSC20K0578).

References: [1] Mars Exploration Program Analysis Group (2018), MEPAG Science Goals, https://mepag.jpl.nasa.gov. [2] MEPAG NEX-SAG Report (2015), B. Campbell and R. Zurek, https://mepag.nasa.gov/reports.cfm. [3] MEPAG ICE-SAG Report (2019), S. Diniega and N.E. Putzig, https://mepag.nasa.gov/reports.cfm. [4] MEPAG P-SAG (2012), D.W. Beaty and M.H. Carr, https://mepag.nasa.gov/reports.cfm. [5] Cremons, D.R., Abshire, J.B., Sun, X. *et al.* Design of a direct-detection wind and aerosol lidar for mars orbit. *CEAS Space J* **12,** 149–162 (2020). [6] Read et al., (2018), *Plan. and Sp. Sci.,* 161. [7] Tamppari et al., (2022), *Plan. and Sp. Sci., submitted.* [8] McCleese, D.G. et al. (2010), JGR-Planets, 115, E12016. [9] Lillis, R. et al. (2021), PSJ, 2, 211.

COMPACT, MODULAR NEUTRON AND GAMMA-RAY SPECTROMETER FOR SMALL SPACECRAFT MISSIONS. C. Hardgrove[1] [1]Arizona State University (781 E Terrace Rd, Tempe, AZ chardgro@asu.edu)

Introduction: The first NASA Small Innovative Missions for Planetary eXploration (SIMPLEX) program selection in 2015 was the Lunar Polar Hydrogen Mapper (LunaH-Map) mission. The LunaH-Map spacecraft is currently one of ten 6U cubesats that are integrated into the Orion Stage Adapter (OSA) and are awaiting launch on the Space Launch System (SLS) Artemis-1 mission, currently scheduled for early 2022. LunaH-Map will deploy from the OSA and use a small propulsion system to maneuver into a highly elliptical polar science orbit around the Moon, with perilune altitudes at the South Pole dipping to ~10-12 km elevation above the terrain. Once in the science orbit, LunaH-Map will use a newly developed neutron and gamma-ray spectrometer to measure epithermal neutron counts above the lunar South Pole over a period of 2 months (>280 orbits) [1].

The maps produced by the LunaH-Map mission will be used to place constraints on the bulk abundance of water-ice (at ~200 ppm H or more) at spatial scales of ~20 km. These maps can be used to determine if water-ice is only enriched within regions of permanent shadow, or if there may be illuminated regions that may contain buried water-ice enrichments [2]. For future landed or airborne Mars missions, a similar sensor could be used to characterize the H abundance to 1 meter depth to within 0.5 wt.% with measurement times on the order of 30 minutes or less.

The neutron sensor on the LunaH-Map mission, called the Miniature Neutron Spectrometer (Mini-NS) was designed, fabricated and qualified for flight as part of the LunaH-Map SIMPLEX program (Figure 1 left). The Mini-NS development also leveraged technologies matured in the NASA Planetary Instrument Concepts for Advancement of Solar System Observations (PICASSO) instrument incubator program [3]. As the LunaH-Map science mission (~2-4 months) is significantly shorter than previous lunar science missions, the Mini-NS was designed to achieve count rates approximately double that of the Lunar Prospector Neutron Spectrometer (Figure 2). In order to achieve this, a modular design was required as individual sensors could not be grown of sufficient size to meet the mission requirements. Future versions of the Mini-NS can use a different numbers of sensor heads or thicknesses to meet different mission requirements for hydrogen and characteristic gamma-ray detection.

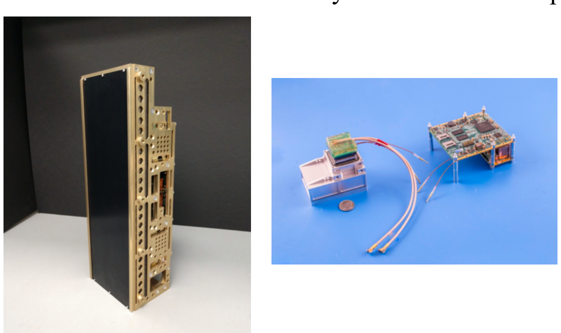

Figure X: left – flight model of the LunaH-Map Mini-NS. Total volume is approximately 2U. right – a single sensor module and electronics assembly boards. The Mini-NS is comprised of eight total sensor modules and two electronics assembly boards.

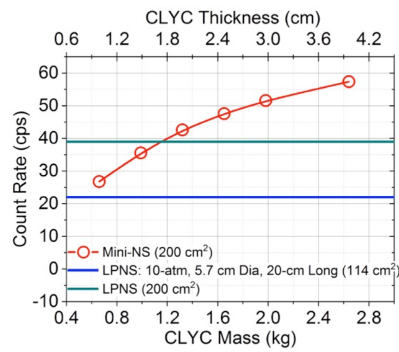

Figure 2: Modeled epithermal neutron count rates for CLYC sensors heads of varying thickness (red line). Also shown are the count rates for the Lunar Prospector He-3 tubes (blue line) and the Lunar Prospector He-3 tubes extended to encompass the equivalent area of the Mini-NS (green line). For a 2cm thick CLYC sensor, the Mini-NS exceeds twice the epithermal neutron count rates of the Lunar Prospector He-3 tubes.

Compact, Modular, Cubesat Design: The Mini-NS is the first planetary instrument to use CLYC (Cs_2LiYCl_6:Ce), an inorganic scintillator with elpasolite crystal structure for neutron detection [4]. The high thermal and epithermal neutron detection efficiency of CLYC make it comparable to more commonly used gas proportional counter detectors like He-3 (Figure 2). CLYC can also be used across a wide temperature range, typically -25C to +50C [5]. During data acquisition, temperature stability to within +/- 1 degree C is required for gamma-ray detection and is preferred (but not required) for neutron detection.

The LunaH-Map Mini-NS uses two detectors that are comprised of four CLYC modules each. Each detector electronics assembly can power and readout data from up to four individual modules simultaneously. A single module is shown in Figure 1 *right*. Each module consists of a hermetically sealed CLYC scintillator in an aluminum housing. The sensors are encased with a 0.5 mm layer of gadolinium to provide sensitivity to primarily epithermal neutrons. The module has been designed to provide space for the crystal to thermally expand and contract while maintaining a good optical connection to the quartz window. A photomultiplier tube (PMT) is placed into the module and is sealed at the window. The PMT is not centered on the module, which is an atypical design. The configuration accommodates the spatial constraints of the cubesat form-factor to provide the maximum surface area exposed to a planetary surface. The single module, as well as the full LunaH-Map Mini-NS instrument configuration, have passed the thermal vacuum and vibration testing requirements for launch on the Space Launch System Artemis-1 mission.

The readout electronics are separated into two sections, an analog board that primarily provides high voltage and pulse shaping circuitry, and a digital board that serves as the signal processing and command and data handling board (Xilinx Zynq XQ7Z020). The signals from the PMTs are summed to a single analog to digital converter (ADC) operated at 250 mega-samples per second. The FPGA signal processing enables pulse-shape-discrimination (PSD), which allows the module to separate neutron from gamma-ray interactions by analysis of the shape and duration of triggered waveforms. Example neutron and gamma-ray spectra are shown in Figure 3. The digital readout electronics are mounted to the exterior support frame of the instrument, where the heat generated in these electronics is directly dissipated to the spacecraft chassis. The instrument interfaces with the spacecraft via RS422, providing a once per second heartbeat to monitor the instrument health. Data products are stored locally on the instrument and are time-tagged for correlation to spacecraft ephemeris. The mass of an individual module is approximately 400 grams, and the total mass of the LunaH-Map Mini-NS is 3.4 kg with an estimated power draw of 9.6 W (4.8W per 4 module detector). In stand-by mode, the spacecraft will interface with the instrument to transfer data or to initiate data acquisition, where the power draw in this state is estimated to be 3.6 W (1.8W per 4 module detector). Data are stored on two redundant 16GB SD cards on each detector electronics board assembly.

Conclusions: The Mini-NS has been developed, qualified and flown on the LunaH-Map mission to meet specific science requirements using a low-cost design and implementation approach. The Mini-NS development provides a foundation for future compact, module-based neutron and gamma-ray spectrometers on low-cost Mars missions.

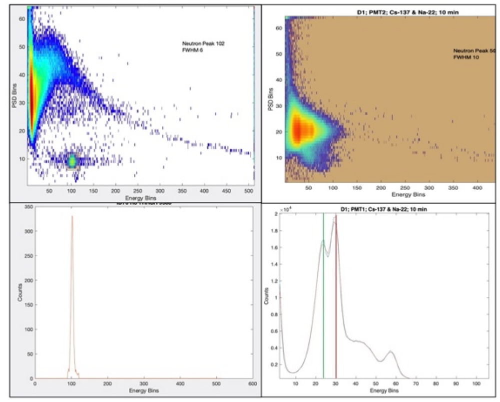

Figure 3: *Top left* – Energy spectrum from one module exposed to a Cf-252 neutron source. *Bottom left* – Neutrons are isolated using PSD and the neutron-only spectrum can be extracted. *Top right* – energy spectrum from one module exposed to Na-22 and Ce-137. *Bottom right* – Gamma-ray spectrum is shown with Na-22 line (green) at 511 keV and Ce-137 line (red) at 662 keV.

A small neutron and gamma-ray sensor would be ideal on a Mars rover or aerial platform, and could be used to provide quantification of the hydration to within 0.5 wt.% (water-equivalent-hydrogen) and the burial depth to hydrogen enrichments (to within +/- 10cm). Required gamma-ray sensitivities and elemental detection limits set by mission science requirements will drive sensor head configurations on future Mars missions.

Instrument Specifications			
	1 Sensor	4 Sensors	8 Sensors (LMAP Mini-NS)
Mass	400 grams	1.6 kg	3.2 kg
Power	4.8 W	4.8 W	9.6 W
Volume	0.25 U	1 U	2 U

Data Volumes			
Name	**Type**	**Size**	**Event Rate**
Energy Spectrum	2D Histogram	66 kB/module	Invariant
Event-by-Event Data	4 PSD parameters per event. PSD Filtered.	7.5 kB/sec compressed 15.2 kB/sec uncompressed	3 kHz

References: [1] Hardgrove et al., (2020) IEEE [2] Prettyman et al (2019) *AGU* [3] Heffern et al., (2021) NIMA *in press* [4] Glodo I. J. (2008) IEEE [5] Johnson et al., (2017) SPIE.

ADVANCING MARS POLAR SCIENCE WITH MICRO-LANDERS. P. O. Hayne[1], S. Byrne[2], I.B. Smith[3,4], D. Banfield[5], N. Barba[6], and L. Giersch[6] [1]University of Colorado Boulder (Paul.Hayne@Colorado.edu), [2]Lunar and Planetary Laboratory, University of Arizona, [3]York University, [4]Planetary Science Institute, [5]Cornell University, [6]NASA – Jet Propulsion Laboratory, California Institute of Technology.

Motivation: Understanding the recent climate history of Mars requires models that can accurately reproduce observations of the present-day atmosphere. To extrapolate backward in time, these models must also account for volatile exchange between the atmosphere and the polar deposits [1,2]. The polar layered deposits (PLD) record climate variations spanning the last several million years, due to obliquity-driven insolation cycles [3]. However, to interpret this climate record, observational data are lacking in several key areas: 1) surface winds are largely unknown, especially in the polar regions [4,5], 2) quantities of water and CO_2 exchanged with the polar caps are poorly constrained [6], and 3) the spatial scales of fine layers in the PLD may be unresolved from orbit [7]. Therefore, new measurements are needed to validate models and confidently extend them to past climate regimes.

A 2017 Keck Institute for Space Studies (KISS) study on Mars polar exploration brought together >30 experts to determine required measurements to investigate the climate record contained in the PLD [8]. This study also developed mission concepts to accomplish these measurements. Here, we report on a mission concept using micro-landers to accomplish a critical subset of these measurements.

Science Objectives: Major science questions to be addressed in order to extract and interpret the climate record stored in Mars' PLD include:

a) What are the present and past fluxes of volatiles, dust, and energy into and out of the polar regions?
b) How do orbital forcings and exchange with other reservoirs affect those fluxes?
c) What chemical and physical processes form and modify layers?
d) What is the timespan, completeness, and temporal resolution of the PLD climate record?

The micro lander concept addresses Questions (a), (c), and (d), through the following science Objectives:

1) Constrain and validate mesoscale models of polar atmospheric circulation, boundary layer turbulence, and volatile exchange
2) Resolve the thinnest layers in the PLD to constrain rates of accumulation/ablation and link to orbital observations
3) Determine isotopic fractionation recording volatile exchange in the PLD

Implementation: The micro-landers are based on the Mars Drop and SHIELD concepts [9,11], using small probes to deliver ~1 kg or more of science payload to the surface. Each probe carries meteorological instruments to measure wind velocity, temperature, pressure, and humidity. Possible additional measurements include: 1) ground-penetrating radar to resolve thin layers in the PLD, and 2) tunable laser spectroscopy to determine isotopic abundances in the icy layers. The probes can be dispersed across the NPLD, which is a low-hazard landing site. Any number of probes could be utilized to address the science objectives with varying degrees of completeness.

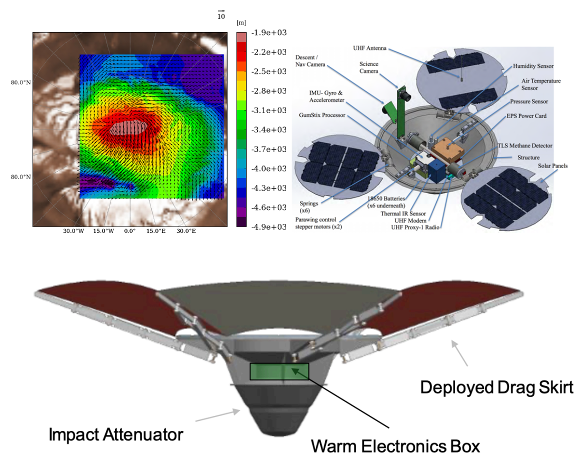

Figure 1: (upper left) Modeled near-surface winds over the north polar residual cap [10], which could be directly measured with the micro lander concept. (upper-right) MarsDROP [9] micro-lander with one possible payload configuration. (lower panel) SHIELD lander for delivering several kg of payload using a "rough landing" approach [11].

References: [1] Jakosky, B. M. and R. M. Haberle, in *Mars*, U. Arizona Press, 1992. [2] Hayne, P. O. et al., *Icarus*, *231*, 2014. [3] Phillips, R. et al., *Science*, 2008. [4] Leovy, C., *Nature*, *412*, 2001. [5] Smith, I. B., and A. Spiga, *Icarus*, 2017. [6] Jakosky, B. and R. Phillips, *Nature*, *412*, 2001. [7] Putzig, N., et al., *Icarus*, 2017. [8] http://kiss.caltech.edu/workshops/polar/polar.html [9] Staehle, R. et al., *Small Satellite Conf.*, 2015. [10] Spiga, A. and I. B. Smith, *Icarus*, 308, 2018. [11] Barba, N. et al., *IEEE Aerospace Conference* (50100), pp. 1-7, 2021.

AREOSTATIONARY EXPLORATION OF METEOROLOGY BY ORBITAL IMAGING (ANEMOI): A LOW COST CONCEPT FOR MONITORING MARTIAN WEATHER N.G. Heavens[1,2], L. Montabone[1,3], R. Lillis[4], S. Guzewich[5], N. Barba[6], R. Woolley[6]; [1]Space Science Institute, 4765 Walnut St, Suite B, Boulder, CO 80301 (nheavens@spacescience.org); [2]Earth Science and Engineering, Imperial College, London, Royal School of Mines, Prince Consort Rd, South Kensington, London, UK SW7 2BP; [3]Laboratoire de Météorologie Dynamique, Sorbonne Université, Campus Pierre-et-Marie-Curie, 4 Place Jussieu, 75005 Paris, France; [4]Space Sciences Laboratory, UC Berkeley, 7 Gauss Way, Berkeley, CA, 94720; [5]NASA Goddard Spaceflight Center, 8800 Greenbelt Rd, Greenbelt, MD, 20771; [6]NASA JPL, Caltech, 4800 Oak Grove Dr, Pasadena, CA 91109.

Introduction: The Precursor Strategy Analysis Group (P-SAG) identified lower atmospheric wind observations as a top priority to enable human exploration of Mars's surface because of the usefulness of wind measurements for model validation [1]. P-SAG also emphasized that, "Long-lived orbiters with global diurnal coverage will provide the largest volume of atmospheric data to support model development and validation" [1]. A decade later, lower atmospheric wind observations and global diurnal coverage of atmospheric observations remain major gaps [2], though intentional local time drift in the MAVEN and ExoMars TGO orbits, cross-track observations by MRO-MCS, and full disk imaging by EMM have expanded diurnal coverage somewhat [3–6].

Systematic wind observations nevertheless remain as tenuous as ever. There are maturing instrument/spacecraft concepts for wind observations that use lidar or passive sub-mm remote sensing [7,8], but the high mass and expense of these instruments forces platforms carrying them toward large, low-risk spacecraft buses in polar, low Mars orbits [7,9], making satellite wind measurements at Mars expensive and incongruous with global diurnal coverage.

Here, we study AreostatioNary Exploration of Meteorology by Orbital Imaging (ANEMOI), an alternate mission concept that focuses on using visible imaging to make lower atmospheric wind measurements with global diurnal coverage at low cost; that as a bonus enables gains in understanding the structure, evolution, and climatology of Martian weather systems, including dust storms. ANEMOI also will make complementary measurements in the thermal and near-infrared that will continue and enhance important climatologies from MGS and MRO, help trace the movement of dust and volatiles, and map pressure variations in large-scale weather systems.

ANEMOI's acronym is the Greek name for the winds of the four cardinal directions, emphasizing the centrality of wind measurements, cooperation between multiple spacecraft, and global coverage to the concept.

Overview: ANEMOI consists of four satellites, each in areostationary (equatorial at an altitude of 17031.5 km) orbits of Mars that are spaced 90° apart. This arrangement allows continuous imaging of the planet from roughly 80° S to 80° N [10]. Assuming stereoscopy from areostationary platforms is possible ±65° from disk center [11], the overlap between the coverage of each satellite makes it possible to perform stereoscopy over 160° of longitude at the Equator (in 4x40° bands separated by 50° and over a smaller range at higher latitude (Fig. 1)

Each spacecraft carries a payload consisting of visible imager for full disk imaging every < 60 minutes, an infrared radiometer that images the full disk every < 60 minutes, and a NIR point spectrometer that takes measurements on a line as the visible imager scans. This payload is nearly identical to the Areo B carrier described in the recent MOSAIC Planetary Mission Concept Study or the MACAWS areostationary constellation concept's three orbiters [9,13].

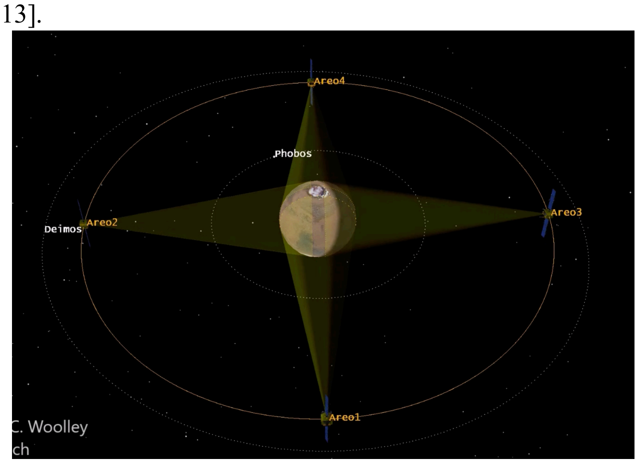

Fig. 1: A still from an animation [12] showing an ANEMOI-like constellation observing Mars.

Measurement Objectives:

Visible Imaging: High cadence imaging of Mars's dayside by areostationary satellites will enable cloud top wind measurements by tracking the motion of features across images. This approach was demonstrated using MGS-MOC imagery by [14], which was able to obtain 500–800 wind vectors/week using overlapping imagery near the poles taken ~ 2 hours apart. By imaging most of the planet more frequently, we expect that wind vector diagnosis rates at least two orders of magnitude greater might be possible.

However, the altitude of the cloud top/wind vector will be unknown. This limitation may be partly overcome by using stereoscopy, which uses the differing vantage points of the areostationary satellites in their mutual overlap regions to measure cloud height. A feature above the surface will appear farther from the center of the disk observed by each spacecraft than its map position. Thus, the difference in the apparent map position between images by the two spacecraft is proportional to the height of the feature above the surface. The precision of this method will depend on geometry and feature sharpness but is typically ~50% of the horizontal resolution of the visible image [11], i.e., ~2 km for ANEMOI. (Note that stereoscopy will impose a concept of operations requirement to minimize time between images of the same area within mutual overlap regions.)

Stereoscopic effects for mesospheric clouds at 70 km altitude have been identified in visible images of Mars from low orbits when color filters observe at slightly different angles [15]. Shadows allowed diagnosis of dust storm heights ranging from 11–29 km during the MY 25 planet-encircling dust event [16]. Under less extreme conditions, water ice or dust cloud tops often cap the planetary boundary layer at 3–10 km [14,17], where wind measurements are highest priority for human exploration needs [2]. Data assimilation would be a possible alternative to stereoscopy.

Thermal Infrared Imaging: ANEMOI will extend the TIR-based product capabilities of MGS-TES and EMM-EMIRS to all times of day continuously, including low vertical resolution lower atmospheric temperature measurements and dust, water ice, and water vapor column opacities. The lower resolution of TIR observations and the higher transparency of aerosols vs. the visible should preclude stereoscopy, but dust storm structural and climatological information as well as limited cloud-tracked winds should be possible. The surface temperature record from TIR imaging may allow the detection of shallow ice deposits, [18] though super-resolution techniques will be necessary to resolve them.

Near-Infrared Spectroscopy: Winds near the surface of Mars will be driven by surface pressure gradients balanced by friction. Mars's reflectivity near 2000 nm can be used to measure surface pressure [19]. ANEMOI would make point NIR measurements along the scan path of the visible imager to obtain surface pressure at ~50 km resolution: a good candidate for data assimilation.

Instruments:

Table 1*:* Notional Payload

Type	Visible Imager (ECAM-C50)	TIR Imaging (mini-MCS) Radiometer	NIR Spectrometer (Argus 2000)
Provider	MSSS	JPL	Thoth Technology, Inc.
TRL	9	6	6
Heritage	OSIRIS-REX: classified Earth observer	MRO-MCS	Argus 1000 (CanX-1)
Mass	0.5 kg	3.5 kg	0.3 kg

Spacecraft, Launcher, and Insertion into Areostationary Orbit: Options for spacecraft, launcher, and insertion into orbit were still under study at the time of abstract submission. One key tradespace to be examined is solar electric propulsion vs. chemical propulsion.

Acknowledgments: This work is supported in part by NASA's Planetary Mission Concept Study program (80NSSC20K0578).

References:

[1] Beaty, D.W. and M.H. Carr (2012), https://mepag.jpl.nasa.gov/reports/P-SAG_final_report_06-30-12_main_v26.pdf; [2] MEPAG (2020) https://mepag.jpl.nasa.gov/reports.cfm; [3] Jakosky, B.M. et al. (2015), *Space Sci. Rev.*, 195, 3–48; [4] Vago, J. et al. (2015), *Solar Syst. Res.*, 49, 518528; [5] Kleinböhl, A. et al. (2013), *GRL*, 40, 1952–1959; [6] AIA Wadhi, M. (2021), *IEEE Conference on Aerospace*, doi: 10.1109/AERO50100.2021.9438178; [7] Cremons, D.R. et al. (2020), *CEAS Space Journal*, 12, 149–162; [8] Read, W.G. et al. (2018), *PSS*, 161, 26–40; [9] Lillis, R. et al. (2021), *PSJ*, xxx; [10] Montabone, L. and Heavens, N.G. et al. (2021), *BAAS*, 53 (4), 281; [11] Carr, J.L. et al. (2020), *Remote Sensing*, 12, 3779; [12] Woolley, R. (2020), https://mepag.jpl.nasa.gov/reports/decadal2023-2032/AreoAnimation.mp4; [13] Montabone, L. et al. (2021), *EPSC 2021*, 625; [14] Wang, H. and Ingersoll, A.P. (2003), *JGR*, 108 (E9), 5110; [15] Clancy, R.T. (2019), *Icarus*, 328, 246–273; [16] Cantor, B.M. (2007), *Icarus*, 186, 60–96; [17] Hinson, D.P. et al. (2008), *Icarus*, 198, 57–66; [18] Piqueux, S. (2019), *GRL*, 46, 14290–14298; [19] Toigo, A.D. (2013), *JGR Plan.*, 118, 89–104.

NEAR-SPACE TESTING OF LOW-COST REMOTE SENSING PAYLOAD FOR MARS APPLICATIONS.
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Introduction: This work presents a method for testing low-cost remote sensors in a Mars-like environment. Low-cost sensors have driven a revolution in citizen science and shown utility in multispectral imaging of the natural and built environment [1]. In this research, the utility of Raspberry Pi (RPi)-based remote sensing is analysed for near-space applications. Of particular interest is whether open-source remote sensors, such as the RPi and associated cameras, can survive and return useful data in the stratospheric environment. where temperatures and pressures approximate those found on the Martian surface (-40 °C and 0.01 bar, [2]). Additionally, Raspberry Pi cameras are sensitive to wavelengths useful for discrimination of Martian geological features [3]. In this work the Mk 1 and Mk 2 Raspberry Pi cameras were flown to near-space near West Wyalong, New South Wales, Australia, and normalized difference vegetation index (NDVI) was used as a metric to determine their utility as a deep space multispectral sensor. A red filter was applied to each camera to ensure visible light to be recorded on the red channel and near infra-red (NIR) wavelengths on the blue channel by virtue of the filter response allowing NIR throughput. Mk 1 (12 mm diameter 3.6 mm focal length F-2.9 lens) and Mk 2 (6 mm diameter, 3.04 mm focal length F-2 lens) RPi camera images captured at maximum altitude were georeferenced and polygons representing bare fields and vegetation (minimum 50 polygons per class for 100 total polygons) were extracted from each image. Each polygon represented a discrete unit of soil or vegetation. NDVI generated from these polygons were then compared with those generated from LANDSAT 7 imagery acquired within 1 month of the flight (LE07_L2SP_092083_20200529_20200820_02, LE07_L2SP_092084_20201020_20201116_02). Regression analysis was used to compare fitted relationships between the RPi and LANDSAT results.

Results: The filtered cameras returned imagery throughout the flight to altitudes of 32 km and 34 km respectively (Fig. 1A). The cameras also returned single-filtered images within 1 km of launch (Mk 1 image, Fig. 1b) and at maximum altitude (Mk 1 Fig. 1c). Soil regions (red polygons Figs. 1b and 1c) exhibited red tones in the images, while vegetated regions (blue polygons Figs. 1b and 1c) were cyan/blue in colour.

Temperature and pressure profiles for the balloon flight (Mk 2 flight shown, Fig. 2a) show decrease to minimum pressure of 0.01 atmosphere (ATM) just prior to balloon burst, while minimum temperature (-47ºC, Fig. 2a) occurred part way through descent.

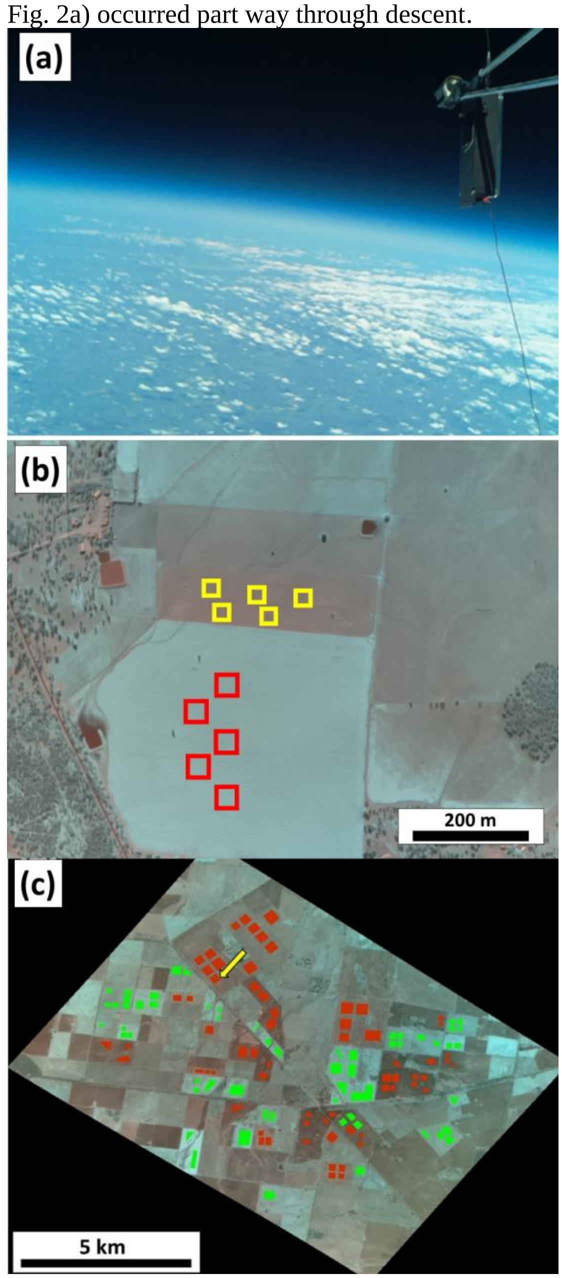

Fig. 1(a). Horizon view of Mk 2 balloon flight at 34 km altitude. (b) Mk 1 mid-altitude (~5.1 km) red-filter image showing locations of sampled vegetation and soil pixels. (c) Mk 1 red-filtered image of the May 2020 balloon flight showing sampled vegetation (green) and soil (red) polygons.

Regression analysis between the Mk 1 camera and LANDSAT 7 NDVI revealed an exponential relationship and an R^2 fit of 0.73 (Fig. 2b). The Mk 2 camera also exhibited an exponential regression with a higher R^2 fit of 0.87 (Fig. 2c).

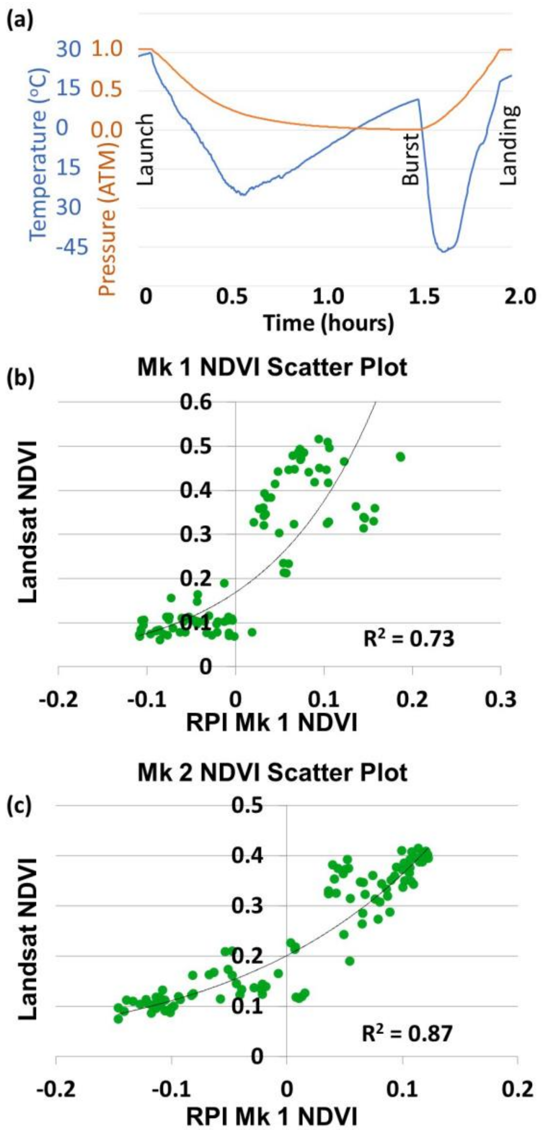

Fig. 2(a). Temperature and pressure data returned from the Mk 2 HAB flight with launch, balloon burst and landing events shown. (b) Regression analysis between RPi Mk 1 camera and LANDSAT 7 image at high altitude. (c) Regression analysis between RPi Mk 2 camera and LANDSAT 7 at high altitude.

Discussion: Single-filter NDVI calibration and high-altitude balloon flights of the popular RPi Mk 1 and Mk 2 cameras revealed useful information on the behaviour of these sensors for VIS/NIR remote sensing in the near-space environment, particularly their utility for vegetation analysis. While Raspberry Pi cameras have been used in land and drone-based applications [4]; the use of balloons enabled characterization of the camera performance that was nearer to the space remote sensing environment. The balloon flights were timed to ensure maximum altitude was attained within two hours of local noon. These time periods have proved popular with some Earth mapping orbital spacecraft [6], by ensuring a minimum of shadowing, and enhancing the fidelity of returned NDVI results.

NDVI values for the Mk 1 and Mk 2 cameras were consistently lower than for the LANDSAT 7 image results. This was most likely due to potential mixing between red and NIR in the red channel of the RPi camera response where RPi sensitivity overlaps in the 600–700nm range. The red filter blocks the blue component of the spectrum in the blue channel, allowing this to approximate NIR. Despite this limitation, NDVI values of the RPi cameras were consistent; regression analysis revealed that the results from the Mk 2 camera in particular were able to be corrected for JPEG image gamma provided radiometrically-corrected imagery was collected during similar time periods, with LANDSAT 7 data being the example used in this work.

On-board image processing was considered for either compensating for the spectral mixing between bands, or generating NDVI in flight. Ground-based testing and an additional payload flown on a high-altitude balloon flight were conducted to trial the utility of these methods. It was found that the processing speed of the RPi Model A+ payload hardware was insufficient to generate consistent results throughout the flight, causing critical imaging opportunities to be lost. Further data losses occurred from in-flight processing anomalies, precluding useful analysis in this work.

Conclusion: The RPi Mk 1 and Mk 2 Raspberry Pi cameras successfully operated in near-space and captured VIS/NIR imagery useful for scientific remote sensing applications through a single filter. JPEG compressed imagery suffered distortions from gamma correction and pre-image processing, although these were able to be corrected provided access to radiometrically-calibrated data was available.

Acknowledgments: We gratefully acknowledge Mars Society Australia, for assistance with this project. We would also like to thank Geoscience Australia for grant funding to facilitate this work.

References:

[1] Pagnutti M.A. et al. (2017) *J. Elec. Eng. 26*, 013014. [2] Barlow N. (2008) *Cambridge Univ. Press*, UK. [3] Bell III et al. (2008) *Cambridge Univ. Press*, NY. [4] Belcore E. et al. (2019) *IRPRSSIS*. [5] Wertz et al. (2011) *Microcosm Press*, CA.

FLOCK OF LOW COST MICROLANDERS TO SURVEY LIQUID WATER POTENTIAL ON MARS ALONG THE RECEDING POLAR CAP. A. Kereszturi[1], H. Miyamoto[2], B. Pal[1,3] B. [1]Research Centre for Astronomy and Earth Sciences, Konkoly Thege Miklos Astronomical Institute, Hungary. [2]Dept. Systems Innovation, University of Tokyo, Tokyo, Bunkyo, Japan. [3]Eötvös Lorand University, Budapest, Hungary (kereszturi.akos@csfk.org)

Introduction: The aim of this work is to overview a possible near future mission, composed of several small, identical landers/ electromagnetic property measurement devices, which would survey the specific humidity values at the surface and shallow subsurface on Mars. The already available in-situ humidity detectors on Mars provided some information like TECP [1], REMS [2] as well as useful constrains. However these data do not give results on the area of seasonal water ice surface cover and on the ice content change in the shallow subsurface regolith layer by in-situ methods at high temporal resolution from multiple sites simultaneously. The proposed mission could survey several locations on Mars around the receding edge of the northern or southern seasonal cap, which are otherwise difficult to explore for larger rovers. It would able to analyze both the water ice coverage, defrosted surface with shallow ice [3], hydrated and later dehydrated shallow regolith. The pioneering aspects of this mission are the first in-situ measurements of humidity and temperature daily cycles (at the most relevant springtime period) at different depths in the shallow subsurface, definitely with and without water ice and hydrated OH content at a fast changing location regarding volatile occurrence.

Methods: The small landers would be constructed by using already existing and tested technology. We call these probes microlanders, because although they are designed as strong and robust like a penetrator and could penetrate a few cms below the surface, their main aim is to realize electromagnetic property measurements. The almost purely heritage based payload would help to assure mission success and shorten the amount of time needed for design planning. Main focus of the lander construction should be on ensuring their sturdiness while keeping costs low. After landing, the probes could use the orbiters to relay data back to the Earth. This could be done by non-oriented radio broadcasting, thus their orientation after landing would be no issue.

Results: Below we outline the elements of the concept, grouped according to the main topics.

Getting to Mars: As the mass scale of the probes is in the order of 1-3 kg, similar to the mas of Deep Space-2 penetrators [4], a piggyback mission is proposed to arrive to Mars. The atmospheric entry could happen directly from interplanetary orbit. The best case scenario should be such an atmospheric entry point, that the microlanders could land during spring at the edge of the seasonal ice cap. The number of such penetrators can be tailored to the available funding, thus the full cost of the mission is flexible.

Timing of landing: The focus should be the local springs, when the seasonal polar caps recede. Although seasonal parameters influence the mission much as the landing should ideally happen during the given L_S interval (approximately between LS 0^o–90^o in the northern, and LS 180^o–270^o in the southern hemisphere), the landing and the surface survival is almost independent on meteorological conditions, like temperature and atmospheric humidity.

Landing process: Landing accuracy is expected to be in the order of some 100 kms, thus in general only the atmospheric entry sites matter. Several probes could enter behind the same heat shield as one unit, and then they could separate during the atmospheric descend. Timing of the separation and parachute deployment could help to adjust the distance of the final surface landing points. These could be even further apart by using parachutes in different sizes.

Surface activity: The main mission of the probes is to gain accurate in-situ measurements from various parts of the Martian surface simultaneously. Acquired data would provide a better understanding of the climate and smaller scale variations. Useful data to measure would be for example surface temperature, relative humidity, pressure, wind speed and direction. By dropping the probes in a chain-like formation, the acquired data could be used to extrapolate to other areas, where nothing has landed yet, and also might witness the sublimation of water ice cap, shallow subsurface ice sublimation and final dehydration subsequently at different locations, under somewhat different conditions.

Required lifetime: It should cover the period from the exposure of seasonal water ice cover till the substantial decrease of regolith H_2O content and even dehydration. This would mean roughly 80 L_S in the northern hemisphere. Due to the limited sunlight available it is challenging to survive using batteries, however it could be achieved with the low energy consumption of the microlanders.

Technical requirements: For the probes: two different options could be considered; the simpler one is powered by batteries and is able to survive only some daily cycles, while a more complex and expensive one could be equipped with a deployable solar panel, ejected to the surface after landing. The latter could support survival for the suggested 80 L_S duration covering the recession of the polar cap and dehydration of the soil.

Proposed scientific payload: Similar temperature and humidity sensor at two or three locations from the lowest possible to the highest possible point on the probe. Very simple light detection sensor is linked to the temperature/humidity detector pair, to identify if the given sensor is covered by regolith (penetrated below the surface or exposed).

Data transfer: By small UHF non-oriented radio broadcast for orbiter missions' passages using around 6-8 kbit/s rate. This requires most of the energy besides possible heating (this later might be minimal by available design of specific humidity and temperature detectors).

Number of probes: Although only one probe could provide good results in itself, in an ideal case multiple probes would result in an even better outcome. Especially since their production would not inflate the cost much (as these are small, inexpensive, low mass probes), and the launch mass increase with raising the number of probes is only moderate as well. In the case of "poor targeting" (with 3 probes for example), even if they enter the atmosphere at the same location and direction, during deceleration and parachute descent phase, the landing distance between them is expected to be around 100 km. If small differences in the parachute size is designed, this distance could be expanded to around 1000 km. The main issue to consider here is more useful results are gained if the distance between these probes increases in meridional direction, they witness the transit of the receding cap edge at different seasonal times and conditions. Although such meridional spatial arrangement between the probes do not emerge by chance, especially as the entry direction used to be in the ecliptic plane – but there is a chance to arrive to the atmosphere at 4-6 degrees [5] relatively to the local horizontal plane at high geographic latitude with proper adjustment of launch time to Martian seasons.

Discussion: The main benefit would be to gain daily and seasonal temporal resolution data on humidity, and better outline the possibility of deliquescence based liquid water potential and related brine formation possibility. While future landers (mainly roves) might carry humidity detectors, no one is planned to gain direct in-situ data from the mm-cm-dm deep shallow subsurface. The receding edges of the seasonal polar caps are also hard to reach by larger rovers. If the small probes prove to be useful, the mission could be expanded in the future to other hard to reach areas as well. According to recent modeling results [6] the receding edges of the polar caps could provide a brief window for possible brine formation through deliquescence. By employing small landers we could get in-situ confirmation of this suggested phenomenon. If brine formation is confirmed, this could be used as a potential resource for future crewed missions as well.

Possible mission scenarios: Because of the simplicity of this mission, there are several possible outcomes and related mission scenarios. Depending on the regolith hardness and design of probes, penetrators could be deeply buried or loosely covered by debris, or even parts of them could stay exposed to the free atmosphere. All of these situations would provide useful information on the volatile cycle, subsurface H_2O migration and exchange processes with the atmosphere. The joint evaluation of the measured daily cycles, including light intensity changes at the detectors allow the rough depth estimation of the given detector at the deepest part of the penetrator needle.

Possibility to accompany other missions: It is proposed and being favorable that this mission could be accompanied with other hard lander style mission or instrument proposals like OPRA [7], or the MetNet isson proposal [8], WetSen detector [9]. New instrumental technology [10] would also provide ideal conditions for such miniaturized sensor sets.

Conclusions: Expected outcome from the mission are the followings: 1. determination of humidity and temperature value of the sublimation of the seasonal ice cap (improving current models where only the temperature is well known), 2. determination of the very near surface humidity, clarifying daily volatile cycle, 3. understanding the vapor migration inside the regolith, 4. understanding the possibility of deliquescence, 5. provide in-situ data to validate regolith desiccation models.

Acknowledgments: This work was aided with the TKA Campus Mundi grant number 303538.

References: [1] Fischer E. et al. 2019. *JGR* 124, 2780-2792. [2] Martin-Toorres J. et al. 2015. *Nature Geosci.* 8, 357-361. [3] Kuzmkin R.O. et al. 2007. *Sol. Sys. Res.* 41, 89-102. [4] Smrekar S.E. & Gavit S.A. 1998. *1st Int. Conf. on Mars Polar Sci*. 3039. [5] Albert S.W. & Braun R.D. 2020. *AIAA 2020-1737.* [6] Pal, Kereszturi 2021 – *Icarus* in press. [7] El Shafie et al. 2008. *LPSC XXXIX*, #2125. [8] Haukka H. et al. 2012. *EGU* p.8073. [9] Tomkinson T. et al. 2008. LPSC XXXIX, #2040. [10] Parthana D. et al. 2021. *Plan. Space Sci.* 195, id. 105132.

MARS CLIMATE CUBESAT CONSTELLATION (MC³) – A LOW-COST ORBITAL CONSTELLATION FOR ATMOSPHERIC PROFILING, POLAR SCIENCE AND SURFACE THERMOPHYSICS.
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Introduction: Over the last decade considerable progress has been made in understanding the structure of the martian atmosphere. Current work focuses on identifying dynamical processes, radiative effects, and surface-atmosphere interactions that are responsible for shaping the dynamic atmosphere and weather of Mars.

A key issue that limits progress in this area is the lack of global coverage at many simultaneous local times. Numerous short-term atmospheric and surface processes are poorly characterized. Atmospheric dynamics on Mars is largely determined by atmospheric tides but the identification and characterization of tides, especially higher order modes, is limited by local time coverage [1,2]. Tidal forcing is strongly controlled by aerosol distributions, in particular clouds, which predominantly form in temperature minima created by tides, hence establishing a feedback loop [1,3]. The inhomogeneous vertical distribution of atmospheric dust that suggests convective activity triggered by solar heating of dust may play a crucial role in dust and water transport [4,5]. Concerning surface effects, diurnal H_2O and CO_2 frosts may have a significant impact on the regolith structure [6]. The vertical temperature structure and heterogeneity of the Martian near-subsurface is largely unknown and could be addressed with such observations, supporting the evaluation of Planetary Protection requirements [7]. In addition, the energy balance of the Martian surface could be evaluated with much higher accuracy.

The assimilation of atmospheric data into Mars Global Climate Models promises further progress. It provides re-analyses of meteorological data similar to meteorological re-analyses on Earth, which are used for a multitude of applications and provide an accurate picture of the atmospheric state and dynamics [7,8]. However, global thermal tides in the atmosphere, as well as the radiative forcing by dust and water ice, which are locally variable but influence the atmosphere on a global scale, result in the Mars atmosphere exhibiting more globally connected features than Earth, making data assimilation more difficult [9].

The need for measurements that "significantly improve spatial and temporal coverage and resolution beyond the existing data has been identified in the MEPAG Goals document (Goal II, Sub-objective A1) with higher priority. The orbital constellation outlined here would provide "diurnal coverage [that] is needed in order to capture ephemeral phenomena, as well as systems (such as dust storms) that evolve over timescales of less than a day" (MEPAG Goal II, Investigation A1.1). The proposed constellation is a subset of the larger-scale constellation of Mars Orbiters for Surface, Atmosphere, and Ionosphere Connections (MOSAIC) [10], which was studied as a Planetary Mission Concept Study to provide input to the upcoming Planetary Science Decadal Survey. Assimilating near real-time data at multiple local times could pave the way towards forecasting martian weather in support of landing, aerocapture and surface operations of future robotic and crewed missions.

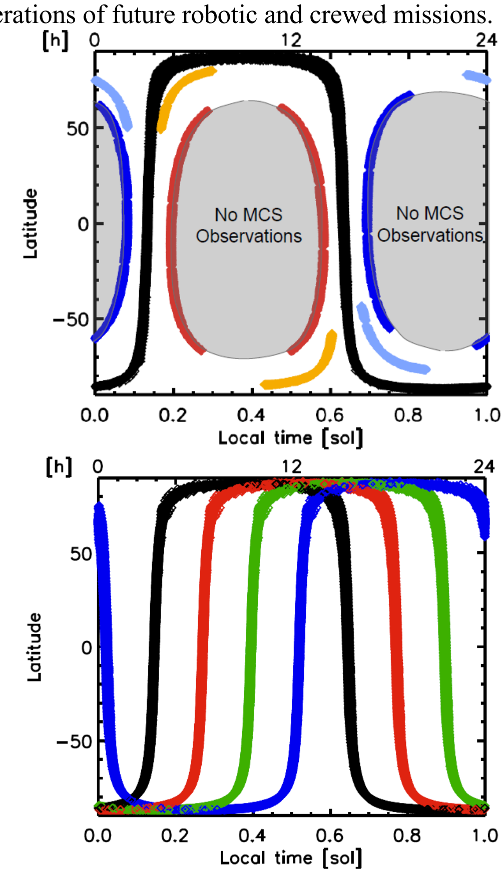

Figure 1: (Top) Positions of MCS atmospheric limb observations vs. latitude and local time. Black symbols indicate measurements along the orbit track, while colored symbols indicate measurements not along the orbit track. Gray shaded areas are inaccessible to MCS. (Bottom) Simulated measurement coverage that would be achieved by along-track measurements from four sun-synchronous platforms with nodal spacings of 45°, corresponding to ~3 hours in local time.

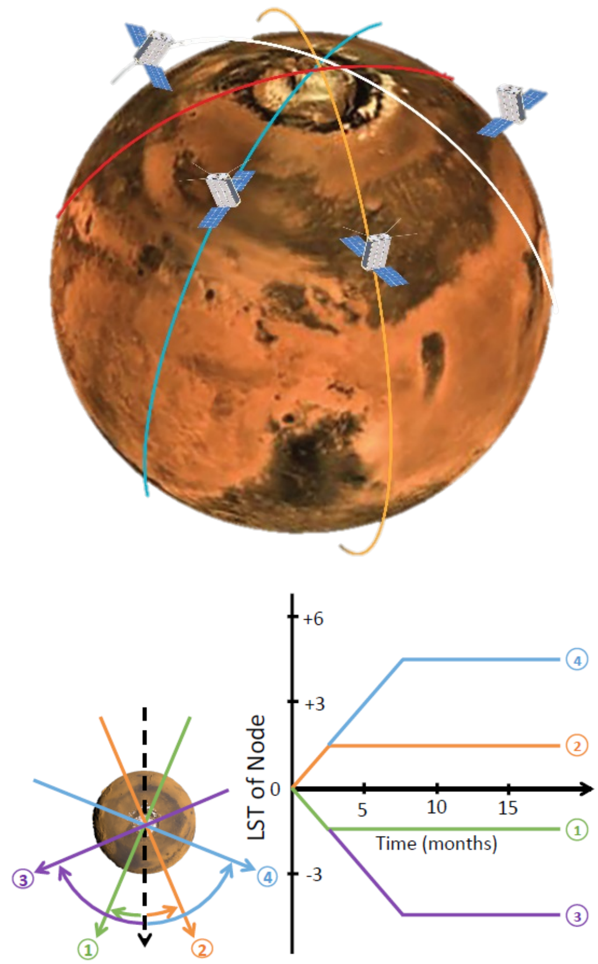

Figure 2: (Top) Graphical representation of a constellation of four CubeSats or SmallSats in low Mars polar orbits with 45° nodal spacing. (Bottom) After deployment from a carrier orbiter, the CubeSats drift to their desired nodes within a few months.

Approach: Figure 1 (top) shows the local time coverage obtained by the Mars Climate Sounder (MCS) [12] from its host platform, the Mars Reconnaissance Orbiter. Through its ability of slewing in azimuth, MCS has access to local times up to ±1.5 h from the nominal local time of the sun-synchronous orbit at low latitudes and to a somewhat larger local time range at high latitudes. However, large ranges in local time remain inaccessible.

Figure 1 (bottom) shows the local time coverage that would be achievable with along-track only measurements from four sun-synchronous spacecraft in low Mars orbit. A node spacing of 45° would provide pole-to-pole global coverage every 3 hours in local time. Measurements at different local times would occur simultaneously, providing much tighter constraints on atmospheric models than, e.g., measurements from a single orbiter at moderate inclination, which drifts through local times on time-scales of months.

A constellation of SmallSats or CubeSats in Mars orbit could be used to perform such measurements (Figure 2). Limb- and nadir radiometry measurements would require a low altitude orbit of moderate to high inclination around Mars. Four satellites with a constant node spacing of 45° between orbits would ensure that atmospheric and surface observations over the same areas would be performed in regular local time intervals of 3 hours.

Satellites in a CubeSat form factor could reach their desired nodes under their own propulsion with-in a few months if deployed from Mars orbit. If the satellites were to perform their own orbit insertion a larger form factor would likely be required.

Measurements would be based on passive infrared radiometry in limb and nadir geometry as demonstrated by MCS [12,13], in a derivative optimized for SmallSats [11]. They would provide profiles of temperature, dust, water ice and water vapor with 2.5 km vertical resolution, together with atmospherically corrected surface temperatures [6]. In analogy to MCS, the instrument would have 8 spectral channels in the IR from 12-45 µm and a visible/near-IR channel. MCS capabilities would be enhanced by adding a functional water vapor channel at far-infrared wavelengths. Each channel would consist of a linear array of uncooled thermopile detectors, providing instantaneous profile measurements when vertically pointed at the limb. This approach would yield high vertical resolution measurements of surface and atmospheric temperature, aerosols opacities and water vapor mixing ratios with dense global coverage at multiple local times.

Acknowledgments: Work at the Jet Propulsion Laboratory, California Institute of Technology, is performed under contract with NASA. © 2021, California Institute of Technology. Government sponsorship acknowledged.

References: [1] Kleinböhl, A., et al. (2013) *GRL 40,* 1952-1959. [2] Forbes, J., et al. (2020) *JGR 125,* e2020JA028140. [3] Lee, C., et al. (2009) *JGR 114,* E03005. [4] Spiga, A., et al. (2013) *JGR 118,* 746-767. [5] Heavens, N. G., et al. (2018) *Nat. Astron., 2,* 126-132. [6] Piqueux, S., et al. (2016) *JGR 121,* 1174–1189. [7] NASEM (2021), doi:10.17226/26336. [8] Montabone, L., et al. (2014) *Geosci. Data J. 1,* 129-139. [9] Greybush, S. J., et al. (2019) *Geosci. Data J., 6,* 137-150. [10] Navarro, T., et al. (2017) *ESS 4,* 690–722. [11] Lillis, R. J., et al. (2021) *PSJ 2,* 211. [12] McCleese, D. J., et al., (2007) *JGR 112,* E05S06. [13] Kleinböhl, A., et al. (2009) *JGR 114,* E10006.

GLOBETROTTER-MARS: ALL-TERRAIN HOPPER FOR MARS SURFACE & CAVE EXPLORATION.

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Introduction. GlobeTrotter (GT) is a concept all-terrain hopper for Moon, Mars and small body surface and subsurface (pit/cave) exploration under development at JPL and SETI Institute [1-6]. At the core of the system lies a small thrustered spacecraft with an up to 5 kg payload suite shielded by a multiple airbag-like shell of tensegrity structures, giving GT the ability to launch, make ballistic hops, and bounce elastically across even extremely rough terrain. GT-Mars would enable low-cost, robust access to, and exploration of, extreme terrain on Mars, including high priority science but heretofore too challenging and costly to access targets such as canyons, chaotic terrain, rock glaciers, Martian highlands, polar caps, giant volcanoes, and volcanic lava pits and caves **(Fig. 1).** GT-Mars would be propelled by planetary-protection-friendly cold-gas thrusters. GT-Mars would be solar-powered.

Missions and Payloads. We present four notional GT-Mars science mission concepts: GTA to Aram Chaos; GTI to Ius Chasma; GTO to Oudemans Crater; and GTP to volcanic pits in Tharsis. Their payload suites share common elements such as omnidirectional color cameras (e.g., OCCAM) and the spacecraft's accelerometers, and mission-specific instruments such as a neutron spectrometer (e.g., NSS) and UV-Raman spectrometer (e.g., SHERLOC) for GTA and GTP, and a near-IR spectrometer (e.g., NIRVSS) for GTI and GTO **(Table 1).**

Table 1: GT-Mars Missions, Payload Suites & Masses.

GT-Mars Mission		Payload & Mass: Color Camera Ex: OCCAM	Neutron Spectrom. Ex: NSS	Near-IR Spectrom. Ex: NIRVSS	UV,Raman Spectr. Ex: SHERLOC	Tot Payl Mass -kg
GTA	Aram Chaos	1.0	1.9		1.8	4.7
GTI	Ius Chasma	1.0		3.5		4.5
GTO	Oudemans	1.0		3.5		4.5
GTP	Volcanic Pits	1.0	1.9		1.8	4.7

GTA: Mission To Aram Chaos. A GT mission to Aram Chaos would investigate impact cratering on Early Mars, Aram's Noachian aqueous and eolian sedimentary record, the major ground ice melting event that gave rise to the chaotic terrain, whether or not the larger mesas on Aram's floor still contain ground ice, the "wet" environments implied by the younger hematite and hydrated sulfate bearing sedimentary units, and the source region of the Aram Valley canyon **(Fig. 2).**

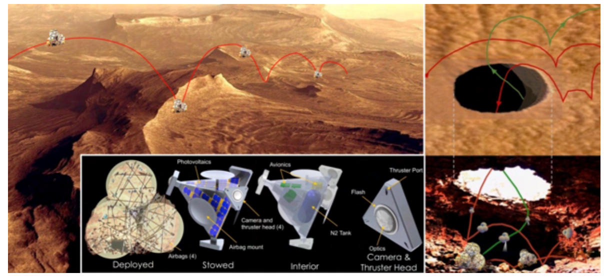

Figure 1: *GT-Mars is an all-terrain tensegrity-shielded hopper for Mars surface and subsurface (cave) exploration.*

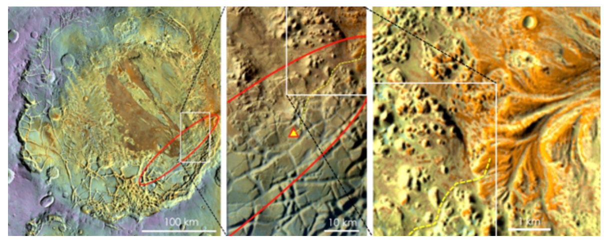

Figure 2: GTA: Mission to Aram Chaos. Left: *Notional 130 km × 30 km 3-sigma landing error ellipse (red) on THEMIS mosaic of Aram Chaos' floor. Landing anywhere within this ellipse and traversing 30 km would give access to a rich variety of terrain types, including chaotic terrain with potentially ice-rich mesas towards the SE, S, and SW, hematite and sulfate deposits towards the NW, chaotic terrain w/ small knobby hills towards the N, and/or H_2O outflow channels or deposits toward the E and NE.* ***Center:*** *Enlargement of boxed area in left figure. An example 30 km traverse along Aram Chaos' floor (yellow dotted path). The traverse runs from mesa top landing site (triangle) to the outflow channels and deposits to the E and NE, via knobby terrain to the N.* ***Right:*** *Detail of area boxed in the figure at center. Warmer tones of higher grounds in the outflow channels or deposits indicate greater amounts of hard sediments compared to the lower grounds or knobby terrain to the W. Ridges of harder sediments alternating with grooves gouged into more erodible layers suggest complex, repeated deposition cycles (NASA MGS THEMIS+ESA MEX HRSC).*

GTI: Mission To Ius Chasma, Valles Marineris (VM). A GT mission to Ius Chasma would first traverse Sinai Planum to study Mars' ancient highlands crust, then descend into a tributary valley to Ius Chasma to test the glacial hypothesis for the valley's origin, and study progressively older Valles Marineris materials **(Fig. 3)**.

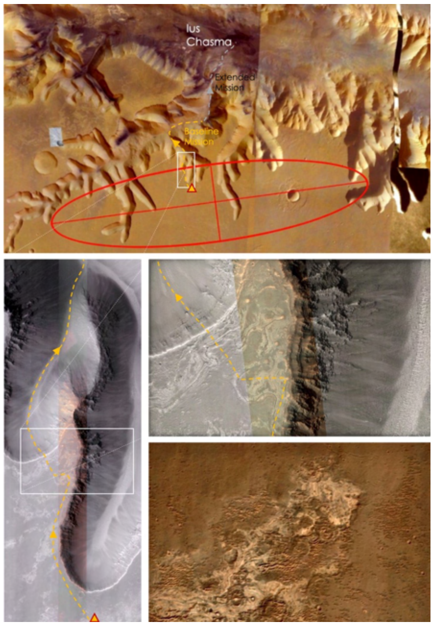

Figure 3: GTI: Mission to Ius Chasma. Top: *3-sigma landing error ellipse on Sinai Planum of 130 km × 30 km. Baseline mission traverse from landing site (red triangle) is 30 km (yellow dashed line). Extended mission (30 km) shown as gray dashed line.* ***Bottom Left:*** *Detail of boxed area in top figure.* ***Bottom Right****: GTI would also examine light-tone deposits. (NASA MRO HiRISE/Google Mars).*

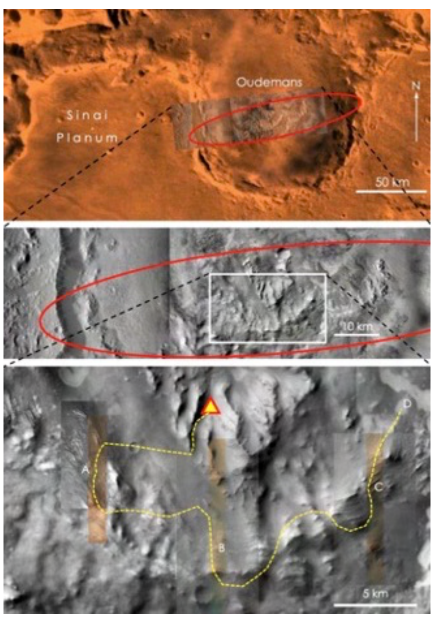

Figure 4: GTO: Mission to Oudemans. Top: *Notional 130 km × 30 km 3-sigma landing error ellipse. Oudemans Crater breaches VM's S rim.* ***Middle:*** *Central portion of Oudemans.* ***Bottom:*** *Detail of boxed area in middle figure showing central peak area. 30 km traverse along the floor (yellow dotted path) meanders from landing site (triangle) through exposures of once horizontal layered deposits now presenting near-vertical dip (A, B, C), to the light-toned deposits (D). (NASA MRO CTX + HiRISE / Google Mars).*

GTO: Mission To Oudemans. A GT mission to Oudemans would investigate impact cratering on Mars and large sections of VM-associated volcanic and sedimentary layered deposits **(Fig. 4).**

GTP: Mission To Volcanic Pits, Tharsis Montes. A GT mission to Tharsis would explore Martian volcanoes and potentially ice-rich caves (e.g., lava tubes) **(Fig. 5).**

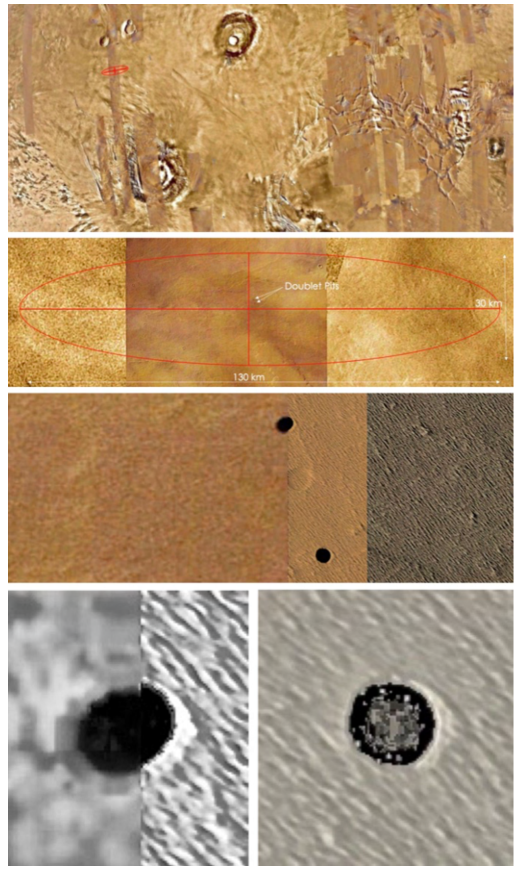

Figure 5. GTP: Mission to Volcanic Pits. Top: *Two pits located 160 km SSE of Biblis Tholus and 540 km NNW of Arsia Mons. Elevation: +4.4 km.* ***Second row****: 3-sigma landing error ellipse 130 km × 30 km.* ***Bottom two rows:*** *Pits are 110-120 m in diameter, and 810 m apart. Their floor is too dark to image from orbit in reflected light. Do they give access to ice-rich caves in adjacent subsurface? (NASA MRO HiRISE).*

Acknowledgments: Support for this study was provided in part by JPL's Mars Program Office and the SETI Institute.

References: [1] Lee, P. et al. (2019). *NASA ESF*, NASA ARC, #013; [2] Lee, P. et al. (2019). *9th Int'l Conf. on Mars*, Pasadena, CA, Jul, 2019, #6448. [3] Lee, P. (2020). *3rd Int'l. Planet. Caves Conf.*, Feb 2020, San Antonio, TX, #1066. [4] Lee, P. et al. (2020). *LPSC-2020*. #2917. [5] Lee, P. (2020). NASA LSSW 2020, Virtual Sess. 5, Oct, 2020, #6015. [6] Riedel, J. E. et al. (2021). NASA *ESF - European Lunar Symp.*, Abstract.

ESCAPADE: A TWIN-SPACECRAFT SIMPLEX MISSION TO UNVEIL MARS' UNIQUE HYBRID MAGNETOSPHERE

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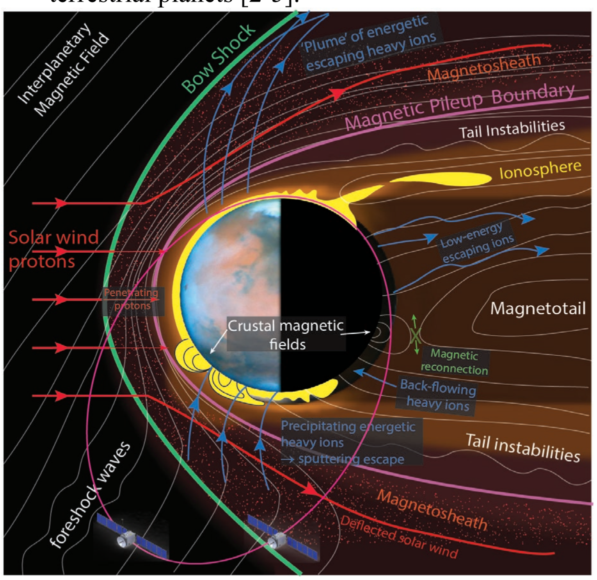
Plasma Measurements at Mars: why do we care? Plasma measurements of the Mars environment are required to understand:

1. The structure, composition, variability and dynamics of Mars' unique hybrid magnetosphere (i.e. sharing properties of both intrinsic and induced magnetospheres) [e.g. 1].
2. Atmospheric Escape Processes: ion escape and sputtering escape help drive climate evolution of terrestrial planets [2-5].



A single platform leaves major questions unanswered. The MAVEN and Mars Express missions have revolutionized our understanding of the Mars near-space environment and atmospheric escape [1]. However, their orbits are not coordinated, nor are there instrument complements similar (crucially Mars express lacks a magnetometer). Thus they are effectively single measurement platforms, suffering from the following drawbacks:

1) spatial and temporal variations in escape fluxes cannot be distinguished
2) responses of escape fluxes and other magnetospheric dynamics to changing solar wind conditions (~1 minute) can only be measured with a time-lag of an hour or (much) more

A Multi-spacecraft revolution. In the last 20 years, multi-spacecraft missions like Cluster II, THEMIS, Van Allen Probes, and MMS have revolutionized our understanding of the causes, patterns, and variability of a wide array of space plasma phenomena in the Earth's magnetospheric environment. ESCAPADE is a twin-spacecraft Mars mission that will similarly revolutionize our understanding of how solar wind momentum and energy flows throughout Mars' magnetosphere to drive ion and sputtering escape, two processes which have helped shape Mars' climate evolution over solar system history.

ESCAPADE Goals & Objectives:

Goal A: *Understand the processes controlling the structure of Mars' hybrid magnetosphere and how it guides ion flows.*

Goal B. *Understand how energy and momentum is transported from the solar wind through Mars' magnetosphere.*

Goal C. *Understand the processes controlling the flow of energy and matter into and out of the collisional atmosphere.*

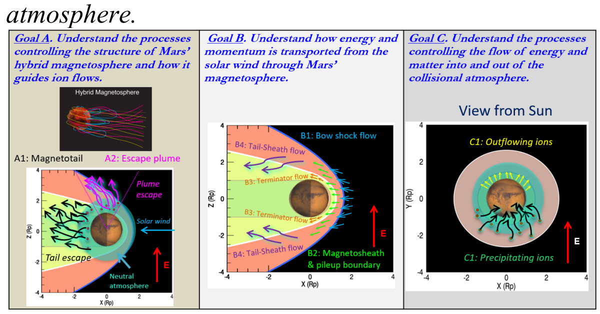


Figure 2: ESCAPADE's 3 goals & 7 objectives covering important aspects of magnetic structure and plasma flows in Mars's unique hybrid magnetosphere.

ESCAPADE will measure magnetic field strength and topology, ion plasma distributions (separated into light and heavy masses), as well as suprathermal electron flows and thermal electron and ion densities from elliptical, 200 km x ~7000 km orbits. These will be measured using four in situ instruments, shown in the figure below with their locations on the ESCAPADE spacecraft.

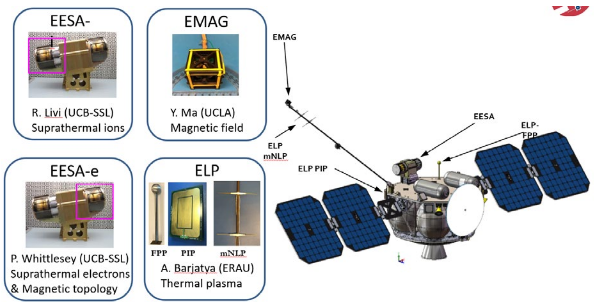


Figure 3: ESCAPADE in situ instrumentation & accommodation on the ESCAPADE spacecraft.

ESCAPADE Spacecraft. The twin ESCAPADE spacecraft will be provided under a firm fixed-price (FFP) contract between UC Berkeley and Rocket Lab USA (Long Beach, California). At ~120 kg (dry mass) they fall approximately between cubesats and typical interplanetary spacecraft (on a logarithmic scale). Powered by deployed solar arrays, propulsion is provided by HyperCurie engines and sufficient fuel to enable >2500 m/s of Delta-V.

ESCAPADE Mission Design involves a ballistic 11-month Hohmann Type II transfer following a trans Mars injection in October 2024. Following a Mars orbit insertion in September 2025, the spacecraft will spend 7 months adjusting orbits before the 11-month science mission begins in April 2026.

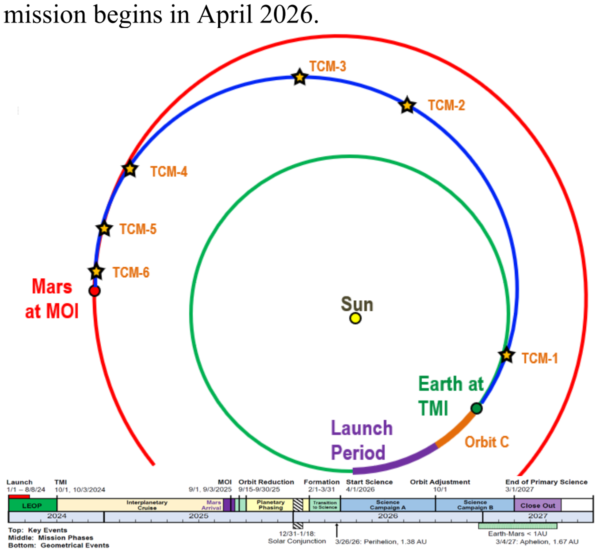


Figure 4: ESCAPADE Mission design and timeline

ESCAPADE's strategically-designed, 1-year, 2-part scientific campaign of temporally and spatially-separated multipoint measurements in different parts of Mars' diverse plasma environment will for the first time unravel the cause-and-effect of solar wind control of ion and sputtering escape. The figures below illustrate ESCAPADE's science operations concept.

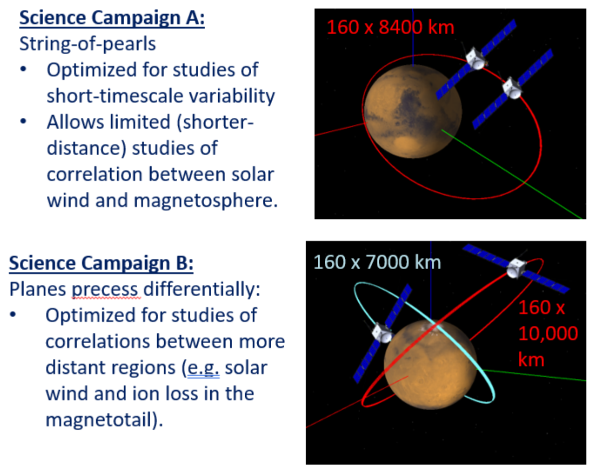


Figure 5: ESCAPADE's science campaigns A and B.

ESCAPADE project status. In August 2021, ESCAPADE passed KDP-C and is currently in Phase C. ESCAPADE is funded by NASA's Heliophysics Division and is managed by the Planetary Mission Program Office (MSFC). Total mission budget is $78.5 million including launch vehicle and all reserves.

References: [1] Brain, D. A. et al. (2015), Mars Book II, [2] Jakosky et al., *SSR*, 2015, [3] Lillis et al., *SSR*, 2015, [4] Luhmann et al., *JGR*, 1992, [5] Brain et al., *GRL*, 2015

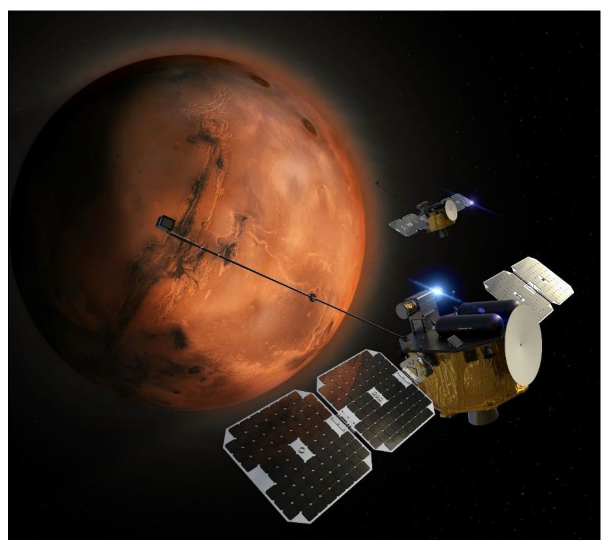


Figure 6: artist's impression of the two ESCAPADE spacecraft ("Blue" and "Gold") in Mars orbit.

Three Small Mars Missions based on Common Spacecraft Systems: 1. Mars Stationary Orbiter (MSO)).

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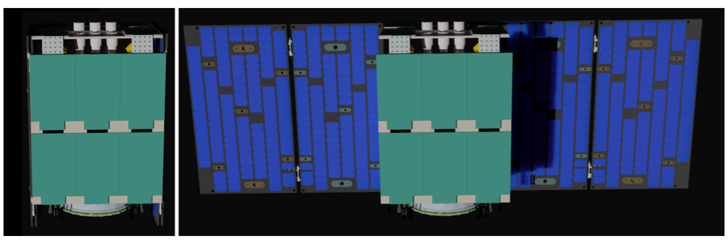
Introduction: We are presenting three different Mars mission concepts based on common spacecraft subsystems. We followed a component approach, similar to 20th century audio entertainment systems, as opposed to pre-packaged systems. The focus is on finding the highest quality subsystems for deep space environments to mix and match for planetary application; as opposed to choosing from fully integrated systems designed for Earth orbit. Deep space missions are primarily distinguished from terrestrial missions by the need for high delta velocities (ΔV), deep space telecommunications compatibility, large data volumes, variable power requirements and availability, and broad operating temperature ranges.



MSO in Launch Configuration (left) and Deployed (right)
Ka-band antennae are green, payload of cameras at top
Vehicle is Standard ESPA dimensions ~ 100 cm x 67 cm x 60 cm

Our mission objectives are to send vehicles to Mars, diversify the launch opportunities beyond dedicated Mars trajectories, and address both scientific and technical goals. This abstract first describes the subsystems we have developed for a self-funded Mars spacecraft, with the intention of addressing the primary major weakness of our previous NASA proposals, *i.e.,* that we had not previously built a spacecraft. The abstract concludes by describing the simple orbiter mission, science objectives, science payload, and costs.

Spacecraft Subsystems:

Flight Computer and Telecommunications (Radio): We selected the Rincon AstroSDR, a combined flight computer and software defined radio with flight heritage. The main ASDR device is executing Linux on a dual core ARM Cortex A9 processor, supported by a large FPGA 1GB ECC RAM, and 8GB radiation tolerant NAND flash memory. A 2TB flash memory allows storing all science data onboard for long portions of the mission for downlink flexibility as datarates vary significantly. Onboard *Python* support enables flexible scripting and fast development.

GNU Radio running on the ASDR supports features of a functional DSN compatible transceiver, including, BPSK/QPSK modulation with residual and suppressed carrier downlink, turbo codes, DDOR, and PN and sequential ranging. A Prox-1 compatible UHF radio is under development. The radio is capable of generating arbitrary waveforms and is easily software upgradeable in Mars orbit. Possible future uses include generating a GPS-like navigation signal (using the onboard atomic clock) and upgraded encoding/modulation schemes for inter-asset links. Maximum radio bandwidth is ~50MHz operating nominally at a UHF intermediate frequency. UHF is upconverted to X- and Ka-Band and converted down from X-Band to UHF for DSN uplink. The downlink system performance is 85.6 dBm EIRP at Ka-Band. An additive manufacturing process produced Ka-Band slotted waveguide antennas to form a 2x3 array for the primary downlink. X-Band patch array medium gain antennae support the primary uplink and contingency downlink. Expected peak downlink from Mars is 815kb/s (Ka-Band January 2025), X-band uplink 30kb/s. UHF Prox-1 Forward link 39kb/s, UHF Prox-1 Return link 88kb/s from areostationary orbit.

Flight Software: We chose Advanced Solutions, Inc. for the flight and attitude control subsystem software. ASI's modular, reconfigurable MAX flight software allows mission specific solutions to be created using standard interfaces, configuration files and tools to minimize development time. MAX includes the On-board Dynamic Software Simulator (ODySSy) which allows "test like you fly" operations at all stages of integration. ASI also provides their Ground Data System (GDS) for a complete software solution that allows commanding, telemetry display and logging and ground operations to be included from the start of I&T.

Attitude Control: ASI also supports MSSS with attitude control design and analysis, applying the experience they gained on numerous missions including Osiris-Rex, Juno, MRO, and Mars Insight. Our team surveyed available ACS components and selected a set of robust, flight proven hardware from vendors who are leaders in their fields. The Sinclair Interplanetary Star Tracker ST-16-RT2 delivers 5” (arcsec) cross-boresight accuracy and 55” about the boresight, featuring a 15 x 20° FOV in a radiation tolerant design. Sinclair will also supply the GEO rated 1.0 Nms reaction wheels. These units are rated for over

60 krad total dose and LET immunity to 50 MeV-cm2/mg and deliver up to 100 mNm of torque. The Sensonor STIM377H IMU provides precise stable gyro and accelerometer data with better than 0.3 °/hr bias instability and 0.15 $°/hr^{1/2}$angular random walk. New Space Systems Sun Sensors provide sun reference for rapid safe mode recovery. Sixteen Stellar Exploration 0.25N hydrazine thrusters provide roll control during main engine burns and precise orbit adjustments and desaturation of the reaction wheels. The system provides 0.10° control with 0.05° knowledge for staring during data collection and transmission to earth and 0.5 deg control during slews at up to 1.4 °/sec.

Mission-specific Sub-systems:

Propulsion: MSSS has teamed with Stellar Exploration Inc, to provide propulsion and power subsystems as well as mission support. The propulsion system utilizes hydrazine and nitrogen tetroxide as the propellants for the eight 5-N axial thrusters which are used for the major maneuvers. 152 kg of propellant is stored in the common-bulkhead titanium tank that is the largest single component of the spacecraft and used as the primary structure to which the rest of the components are attached. This large propellant mass fraction gives MSO a 3200 m/s ΔV capability, enabling it to reach Mars Synchronous Orbit from a GTO starting point. The pump-fed thrusters can be throttled to control pitch and yaw during main engine burns. The low pressure tanks simplify launch integration even for rideshare payloads, and is preferable from launch safety risk perspective.

Power: Six Stellar Exploration flight proven battery modules have extensive heritage from the Iceye radar satellites and others missions. This 400 Wh battery supports continuous science and communication activities even for the longest 79 minute Mars eclipse period. The power distribution and regulation electronics is similarly based on heritage designs. DHV is providing the MSO solar array producing at least 172 Watts at the maximum distance from the sun while the spacecraft is Earth-pointed.

Payload: MSO features seven cameras from MSSS to image the entire disk of Mars including ≥ 100 km above the limb. The visible light C50 camera will provide RGB color images of Mars with a Bayer pattern filter on its 1944x2592 pixel CMOS detector at 3.2 km Nadir scale and 7.7 km scale at the edge of the FOV. Six mid- to long-wave infrared IR3C cameras employ the uncooled SCD 640x480 microbolometer with custom optics and filters to provide between 26.7 and 32.1 km Airy Disk scale at the edge of the FOV. The mid-wave IR channels are centered around 7.9 µm, 9.3 µm, and 11.8 µm to observe surface temperature, atmospheric dust opacity, and water ice opacity respectively. The long wave IR channels are designed to observe between 14.1 and 15.0 µm to recover atmospheric temperature over three altitude bands. Observations will be made of the entire visible Mars disk every 15 minutes for an entire Mars year in the baseline mission.

MSO Objectives*:* The primary objective is to get into Mars orbit. We selected a Mars synchronous orbit at 0°N, 254° W, that views the Curiosity, InSight, and Perseverance landers at about 11° emission angle. MSO can communicate at maximum data rates with all three landers simultaneously, and at any time of day (on Earth or Mars), enabling 24/7 operations. MSO is a tech demo for legacy surface comm systems. A network of ≥ 3 would provide global coverage.

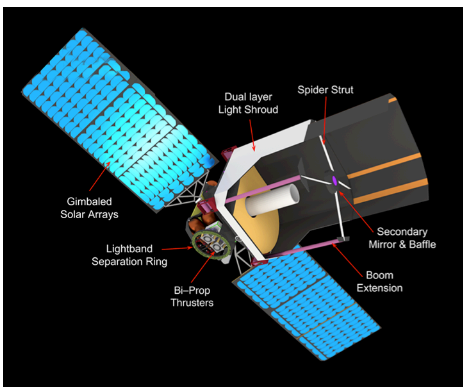
The primary science objectives are to continue 27 years of orbital monitoring of the surface and atmosphere of Mars at visible and thermal IR, at scales amenable to analysis by GCMs and other models. A constellation would provide global coverage.

To meet the objective of increasing the number of Mars launch opportunities, we recognized that GTOs provide a perigee velocity of 90% of escape velocity. GTO rideshare launches are much less expensive and greatly outnumber launches to Mars. We designed our ESPA-class S/C and propulsion system (220 kg wet mass) to launch before the nominal Mars launch date during a given opportunity, providing flexibility for finding a ride. Early launches then raise their apogees to cis-lunar storage orbits, and phase the perigee to occur on the date of the requisite TMI.

Costs: Prior to starting development of MSO, we spent ~$6M performing concept and design studies. Our total Phase A-D costs, of which ~38% has already been spent, is ~$16M. Phase E costs, including pre-launch DSN testing, launch, DSN tracking and data collection during Cruise and in-orbit, and mission operations in orbit, are estimated to be ~$6M. Duplicate S/C would cost $16M, and ~$3M for operating each. A four S/C network costs ~$75M, or $100M with 33% reserve.

Three Small Mars Missions based on Common Spacecraft Systems: 2. Mars High Resolution Imager (MHRI). M. Malin[1], T. Yee[1], K. Jordan[1], M. Roman[1] and T. Svitek[2], D. Troy[2], [1]Malin Space Science Systems, P.O. Box 91048, San Diego, CA 92191-0148, malin@mssss.com, [2]Stellar Exploration Inc, 835 Airport Dr, San Luis Obispo CA 93401, tomas@stellar-exploration.com.

Introduction: We discuss here a second mission based on a common subsystem design, but differing in substantive ways from the first mission, MSO. The primary objectives are still to get into the required orbit of Mars, to increase the launch opportunities, and to return large volumes of science data. MSO is intended to take low resolution images from areostationary orbit, while MHRI is intended to acquire high resolution images from a low altitude sun-synchronous polar orbit -- specifically, thousands of targeted images at high resolution (2-3x better than HiRISE), in stereo and in multiple colors (at reduced resolution). The required payload (large aperture, long focal length camera and sophisticated image processing capabilities) is a more massive payload than MSO.



Primary Differences between the two Orbiters: This payload size and mass requires an ESPA-Grande launch slot, to maintain the GTO launch capability. Available launch mass of 450 kg consists of 110 kg for the S/C system and payload, 50 kg for inert propulsion and 290 kg for propellant. The 2900 m/s ΔV capability is sufficient (with margins) to depart from GTO, insert into a Trans Mars Trajectory, cruise to Mars, insert into a loose, elliptical Mars orbit, aerobrake to reduce periapsis to 300 km, then maintain a 200 by 300 km altitude for at least 2 Mars years.

Payload: The MHRI payload consists of the primary high-resolution imager (new development and much larger than MSO cameras) and the context imagers (similar to MSO and based on existing MSSS hardware). The C50 visible context camera has 3.5° FOV (~12 km) and 4.6 m/pixel IFOV. Two IR3C infrared cameras provide compositional information mostly for hydrated minerals. Each IR3C has 1.8° FOV (6.4 km resulting in combined ~12 km swath) and 10 m/pixel IFOV, with a spectral range of 1.2 µm to 6.25 µm (8000 cm^{-1} to 1600 cm^{-1}) at 13.33^{-1} cm spectral sampling.

High Resolution Imager Focal Plane consists of three Teledyne-DALSA I-49-122888-00-R backside illuminated CMOS detector packages, each with two 12,288 7-µm panchromatic channels and four 3072 28-µm color channels, packaged on the same focal plane assembly providing 36K 0.8 µrad panchromatic and 4 9K 3.22 µrad color IFOVs covering ~6 km swaths, sampling 16 cm/pixel (pan) and 64 cm/pixel (color). Additionally, the two panchromatic sensors are offset by ½ pixel along the array (cross-track), that allows for computationally synthesizing between 1.3 and 1.5 times higher spatial samples [1]. Appropriate clocking of ≤198 TDI lines can yield square panchromatic pixels at 10-12 cm/pixel.

High Resolution Imager Optics uses a segmented deployable 1 m aperture primary mirror, with 8.7 m focal length (F/8.7) and 0.8 µrad IFOV.

We baseline a Ritchey–Chrétien telescope design, based on our experience (MGS MOC, LROC NAC) because it is optically and mechanically simple, less sensitive to environment and straightforward to fabricate, as compared to alternatives (e.g., a three-mirror anastigmat). The deployable primary mirror has two optical segments plus the deployable secondary mirror support structure permitting the 1 m aperture and the long focal length to be accommodated in the limited ESPA-Grande volume. Precision alignment of the telescope optical elements uses a combination of mechanical registration (within 20 µm) and piezo-actuators (sub-nanometer steps with 35 µm range). The alignment is established by star imaging and maintained by capacitive sensors during surface imaging. The cross-track field of view is 1.66° covering 5.8 km from 200 km (8.7 km from 300 km).

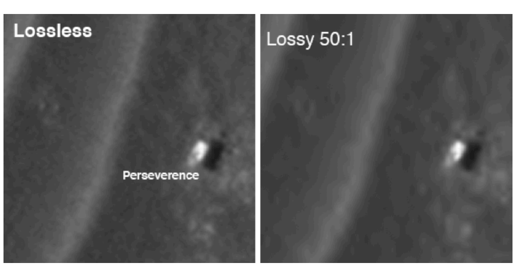
Two primary half-mirror segments are supported on individual substructures, braced against launch loads while stowed and providing the joining interface once deployed. The substructures are connected together through a motor driven hinge. During deployment, each half-mirror substructure is rotated 45° outward, away from its stowed support location. As the substructures come together to form the assembled primary mirror, they are driven into mechanical alignment through an array of registry interfaces. The assembly is held in place with a series of latches that prevent separation between the substructures during operation. As the primary mirror halves come together the secondary mirror and associated support are pushed away from their launch position by the spider strut assembly. Each of the four struts are connected to the end of a lenticular boom that further extends the secondary mirror assembly to yield a 1 m separation (f/1 primary) distance between the mirrors, with a magnification of 8.7X on the aspherical secondary mirror, to achieve the requisite f/8.7 optical system and 8.7 m focal length. For reference, our Mars Observer Camera had a 7.77X magnification on its secondary.

An optical bench containing the field flattening lenses in a tube, a tubular light shielding baffle, and the image detector FPA are deployed last. From the stowed position the three assemblies are driven forward on a motorized slide mechanism, projecting the optical bench and baffle tube through the center of the primary mirror to the focus position. The detector housing remains behind the primary mirror segments and includes a registration interface that aligns the optics appropriately with the detectors.

The optical bench assembly consists of three lenses for image correction and expansion over the detector area. The elements are fix-mounted with respect to each other within the bench, and the focal plane housing. The light shield tube structure extends beyond the optical bench. The detector assembly includes the electro-optical sensing device(s) and a board stack with readout and processing electronics. The electronics are mounted to the backside of the FPA to reduce harness length for high-speed data transfer between boards. This design allows the optical elements in the tube to be collimated with the sensing devices during assembly on the ground, and held in place to optical tolerances during launch loads.

The secondary mirror is attached to a 6-degree of freedom piezo actuated hexapod stage. The hexapod alignment stage is capable of displacements of ±6.5mm laterally and ±5.0mm inline from center at 2.0nm increments and rotations of ±7.0º (122 mrad) in pitch and roll at 0.2µrad increments.

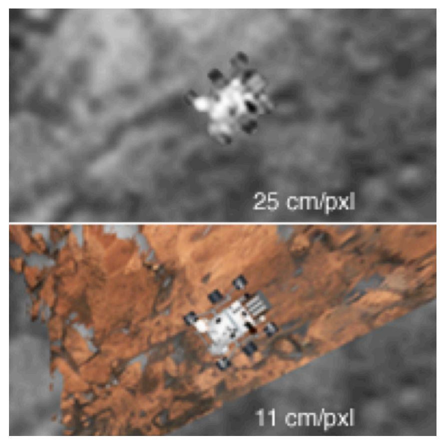
Several techniques will be used to achieve alignment within tolerance and co-phasing of segments



JPEG2000 Compression comparison: Left lossless, right 50:1 lossy. Image is HiRISE view of Perseverence rover at Jezzero Crater.

to a small fraction of 450 nm (the shortest wavelength of the pan-bandpass mode), including direct metrology and area array detectors that view the different segments of the primary mirror and measure the focus and phase retrieval techniques, using images of stars.

Results: As with many planetary missions, this one is severely limited by downlink rate. A typical (6 km cross track by 12 km along track) high res stereo data set is 1.8E11 bits (16-bit pixels), and the color data for that typical pass is 1.1E10 bits. The context imager provides geometrically constrained stereo observations over a 12 x 12 km area at 1.1E8 bits, and the IR spectrometer would need 1.11E12 bits to cover the same area. Thus a single site from all cameras is 1.3E12 bits. Not all of these bits can be sent to the Earth, but JP2000 compression of 50:1 preserves much of the high spatial resolution data, and 200:1 preserves much of the lower frequency data, and at high downlink rates (800kpbs) about 7 sites could be returned per day, although at low downlink rates this is only 0.5 sites per day. Mission total downlink would permit about 700 sites in a Mars year of observations. Additional downlink capability is being explored.



Top: HiRISE background with model of Curiosity Rover at 25 cm/pxl. Bot: Masstcam mosaic over Top view at 11 cm/pxl

Cost Estimate: The recurring cost for the components in common with the MSO spacecraft being built is $13M. The MHRI propulsion system adds $6M while the MHRI payload is $28M and additional mission development costs are $3M. Total Phase A-D costs are $50M. Phase E costs are $6M/yr for 2 years. Adding a 40% reserve to development costs and 33% reserve to operations yields a total mission cost of $86M.

Reference

[1] R. Reulkea, U. Tempelmannb, D. Stallmannc, M. Cramera, N. Haalaa (2006) Improvement of Spatial Resolution with Staggered Arrays as used in the Airborne Optical Sensor ADS40, ISPRS Journal of Photogrammetry and Remote Sensing **60**, *2*, 81-90.

Three Small Mars Missions based on Common Spacecraft Systems: 3. Mars Microlander/Rover.

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Introduction: This abstract discusses new innovative capabilities for Mars surface exploration, achieved by combining proven Mars exploration techniques with several innovative commercial space technologies including those described in our earlier abstracts. This concept is intended to maximize surface science within a constrained but credible mission scope.

flight system:

Cruise stage delivers the Entry Descent and Landing system (EDL) and the rover) from the launch deployment (GTO to maximize rideshare launch opportunities), through cis-lunar phasing orbits and trans Mars trajectory injection towards direct entry into the Mars atmosphere. The cruise stage components are based on the MSO spacecraft bus, under development for a nominal 2024 launch and described in our first abstract. The common cruise requirements of this mission and MSO enable hardware commonality (without some features like Ka-band downlink). Propellant sizing between the two missions is comparable (the lander mission is heavier but does not require the MOI maneuver) so is sized for heavier ESPA.

The EDL system consists of heatshield, backshell, propulsion, rover egress platform (integrated with the crushable palette) and avionics and our focus here.

Science rover for this mission is estimated at 40 kg and ~70 cm x 50 cm footprint, roughly between the Sojourner and MER rovers. Technology advances (plus UHF-only, no DTE) results in science capability of this rover that exceeds MER.

Science Instrumentation: accommodation will be modular. For a Geology mission, space adapted COTS XRF and LIBS devices (e.g., SciAps ruggedized hand-held field spectrometers), multi-spectral imaging and IR3C IR spectrometry (1.2µm to 6.2 µm), all of which are ≤ 2 kg each, can be flown within the available 12 kg of payload mass.

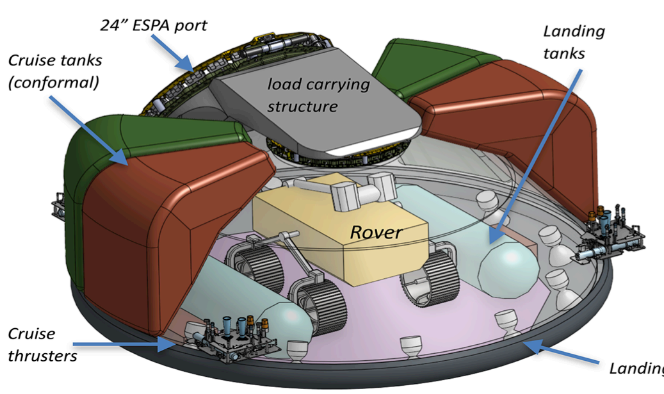
EDL design is focused on risk mitigation, not performance, essential to developing a new Mars landing system at an affordable cost. It relies on a proven 70° blunt-cone aeroshell to slow from the entry velocity of ~6 km/sec to subsonic ~250 m/s. High-thrust propulsion enables soft landing without parachute (simplifying the EDL sequence, reducing cost and improving reliability). Eliminating the parachute mitigates the Mars landing challenges of variable atmosphere and the difficulty of EDL qualification on Earth. The no-parachute ballistic descent reduces critical dependencies by eliminating narrow constraints on speed and pressure for the parachute deployment. The crushable palette lander enables soft landing on rough unpredictable terrain.

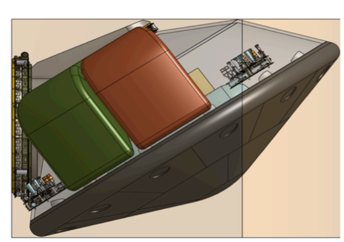
This EDL design also allows an increased Mars entry angle (-35°), significantly reducing the landing error ellipse for ballistic entry to ~20 km even without guided entry. This landing error is within the nominal rover drive capability (~25 km), thus enabling the "Go-To" science. The ballistic/ propulsive EDL enables access to higher altitudes (~4 km above MOLA datum) than existing systems.

This blend of heritage aeroshell/TPS and proven chemical propulsion results in high-reliability low-risk system capable of controlled soft landing with the minimal number of discrete steps and separation events during the EDL sequence.

Aeroshell: The 1.6 m diameter aeroshell has the ballistic coefficient of ~50 kg/m^2 (MER was 70 kg/ m^2). Even with the steeper entry, the 220 W/m2 peak heating rate is less than MER. Steep entry angles are more suitable for the proven ablative low-density TPS materials like SLA-561 or PICA.

The steeper entry results in higher quasi-static g- loads, ultimately limiting the entry angle (-35° entry results in ~30 g's, depending on the approach velocity). Our baseline is a compromise between landing error and rover design impact





The 1.6 m diameter aeroshell fits the maximum envelope that matches both ULA and SpaceX rideshare constraints

from deceleration loads. The entry angle does not impact the blunt body configuration because aerodynamic coefficients are functions of local conditions (Mach number and angle of attack) not entry angle, preserving the 70° blunt body heritage for Mars entry.

The lower ballistic coefficient is essential to achieve the stable aeroshell center of mass during the transonic regime. The preliminary aeroshell CG value of cone-apex-to-cg-distance/diameter (Xcg/D) ~ 0.19 (at transonic) is dynamically stable even without parachute (based on wind tunnels tests). Two factors contribute to this low stable CG location: 1) low-pressure conformal propellant tanks (positioned low inside the aeroshell) and 2) absence of the parachute deployment canister and its support.

Lander propulsion uses conventional hydrazine propellant and catalyst. This design leverages our team experience with propulsion hardware development (flight heritage on the Transporter-2/EG3 mission and several ongoing flight hardware projects). The EDL propulsion requires scaling up the existing thruster but that <1 minute, compared to the current 4+ hours operational lifetime mitigates the risk.

The propulsion systems rely on small electric pumps to pressurize propellants, thus eliminating high-pressure tanks having advantages: absence of high pressures simplifies range safety for rideshare launch, and propellant tanks can be conveniently shaped for optimal packaging within the aeroshell to match CG constraints. Pumps enable differential thrust throttling capability, eliminating need for off-pulsing. The proposed thruster expansion ratio of 1:60 maintains the exit pressure even against the atmospheric dynamic pressure at the initiation of the powered descent (~12 kPa).

Rover egress platform supports the rover during the entry and landing. The lander impacts at velocity of 8±0.5 m/s, aligned along the local gravity vector within ±6°. Residual horizontal velocity under 0.5 m/s ensures that the impact energy is channeled along the rover vertical axis. Low lander Xcg/D design tolerates landing on slopes of up to 35°.

The crushable palette is designed to tolerate landing on rough terrain, by conforming to landing site surface contour (rocks and local slopes) without damaging the rover. The interior space between heatshield and the rover egress platform is structured to absorb impact energy with layered stack of pre-crushed low-density honeycomb and variable density open-cell foam (progressively increasing strength from the heatshield apex to the rigid rover deck).

Parameter	Value
Mission design	GTO to direct mass entry
Launch vehicle interface	24” port (secondary PL)
Launch mass (ESPA Grande)	318 kg
Cruise phase dv capability	1800 m/sec
Cruise propellant (biprop)	151 kg
Entry mass (after cruise jettison)	107 kg
Entry ballistic coefficient	~50 kg/m2
Lander dv capability	450 m/sec
Lander propellant (monoprop)	20 kg
Landing prop thrust	960 N (total)
Number of landing thrusters	12 (80 N each)
Aeroshell + crushable pallet	19 kg
Rover egress platform	3 kg
Rover mass	40 kg

Lander avionics is based on subset of the MSO avionics supplemented by EDL-unique sensors (vertical range detector and residual horizontal velocity sensor). The ongoing CLPS programs are producing miniaturized and affordable landing altitude/velocity sensors.

Mission operations would rely on typical DSN support during the cruise phase, supplemented by additional near-earth networks during the cis-lunar phasing orbits. Critical event telemetry during the Mars entry and the rover operations are both supported by the existing and future UHF Proximity-1 relays. If an aerosynchronous relay platform is available, operations would not need to be fully synchronized with Mars time.

Costs: This mission is a concept based on existing small spacecraft technology. Some feasibility studies would need to be undertaken, including some prototyping to be able to develop a reasonable and plausible cost estimate. We note that JPL’s study of Mars Rovers in the early 2000’s, that led to the Mars Exploration Rover mission, designed a new EDL approach and rover, estimated a cost of about $300M. That was proposed to NASA HQ, and the Administrator asked, “How much for two?” JPL’s response was $600M - $700M. NASA funded the MER mission, which eventually cost $744M for the hardware. We are suggesting this type of development fits within the Mars Small Mission cost guidelines at ≤ $300M.

AN ENERGY-EFFICIENT INCOHERENT SCATTER RADAR AT MARS. M. Mayyasi[1], P. Erickson[2], F. Lind[2], J. Semeter[1], M. Mazumder[1], M. Knapp[2], [1]Boston University (majdm@bu.edu, Center for Space Physics, 725 Commonwealth Avenue, Boston, MA 02215), [2]Haystack Observatory, Massachusetts Institute of Technology.

Introduction: Planetary bodies with atmospheres have layers of charged particles (ions and electrons) referred to as ionospheres [1]. The chemical composition of the ionosphere depends on the neutral atmosphere it derives from, while the thermal and dynamical properties of an ionosphere are driven by processes intrinsic to the planet (e.g., magnetic fields), as well as extrinsic to its atmosphere (e.g., solar forcing). Results from recent missions to Mars have emphasized the important role that atmospheric and ionospheric properties play in the loss and evolution of the planet's primordially rich atmosphere [2]. The temperatures of the neutral atmosphere and the charged particles (also referred to as plasma) are different in ways that are presently poorly understood [e.g., 3, 4]. These temperatures, their differences, and their small-to-large scale variability in time and space can greatly impact the regional, global, and evolutionary properties of atmospheres.

To date, in situ measurements of the plasma properties at Mars have been limited spatially to altitudes of orbiting spacecraft, or limited regionally to the location, time, and observational conditions of the Viking Lander probes. A popular technique to obtain routine observations of the plasma properties at Earth uses incoherent scatter radar (IS Radar). In this work, an IS Radar concept for Mars is presented that utilizes novel developments to miniaturize terrestrial IS Radar design and to improve its efficiency in order to provide an instrument concept that would be deployable to Mars. The measurement capabilities of such an instrument would identify lower-atmospheric properties such as composition, dynamics, and escape rates; allow for identification of heating sources and sinks of Mars' atmospheric energy budget; and facilitate an understanding of surface-to-space communications, particularly during entry, descent, and landing.

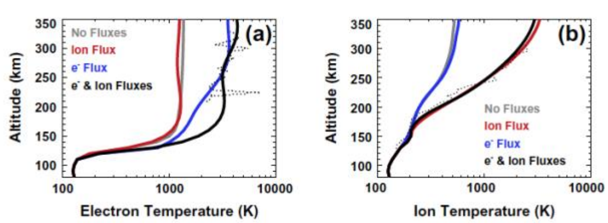


Figure 1. Discrepancy between measured and expected plasma temperatures at Mars. From Fig 8 in [3].

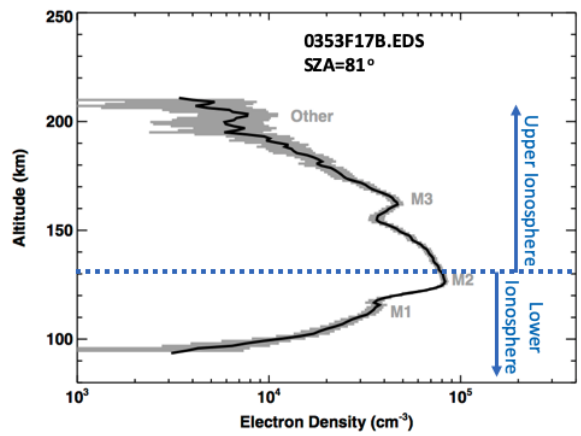


Figure 2. A 'typical' ionospheric profile (black) with measurement uncertainties (grey), obtained by MGS [5]. The lower ionosphere is poorly sampled at Mars compared with the upper atmosphere, due to spacecraft limitations.

Figure 3. Left: Phased-array IS Radar at Resolute Bay, Canada. Right: A rendition of an IS Radar concept for Mars.

References:

[1] Schunk, R. W., and A. F. Nagy (2009), Ionospheres, 2nded. Cambridge University Press, New York.

[2] Jakosky, B. et al (2018), Loss of the Martian atmosphere to space: Present-day loss rated determined from *MAVEN* observations and integrated loss through time, Icarus, 315, 146-157, doi:10.1016/j.icarus.2018.05.030

[3] Matta, M. et al. (2014), Numerical simulations of ion and electron temperatures in the ionosphere of Mars: Multiple ions and diurnal variations, Icarus, 227, 78-88, doi:10.1016/j.icarus.2013.09.006

[4] Hanley, G., et al. (2020), O_2^+ Temperature Profiles Measured in the Martian Ionosphere, EPSC, v.14, EPSC2020-349.

[5] Mayyasi, M., Withers, P., Fallows, K., (2018). A sporadic topside layer in the ionosphere of Mars from analysis of MGS radio occultation data, JGR, 123, 883–900. https://doi.org/10.1002/2017JA024938

HELICOPTER MAGNETIC FIELD SURVEYS FOR FUTURE MARS MISSIONS. A. Mittelholz[1], L. Heagy[2], C. L. Johnson[2,3], B. Langlais[4], R. J. Lillis[5], W. Rapin[6], [1]ETH Zurich, Switzerland (amittelholz@erdw.ethz.ch). [2]Dept. of Earth, Ocean and Atmospheric Sciences, UBC, Vancouver, BC, V6T 1Z4, Canada. [3]PSI, Tucson, AZ 85719, USA. [4]Laboratoire de Planétologie et Géodynamique, UMR 6112, Université de Nantes, Université d'Angers, CNRS, Nantes, France. [5]SSL, University of California, Berkeley, California, USA. [6]IRAP, CNRS, Toulouse, France.

Introduction: The recent successful flight demonstration of Mars2020's helicopter Ingenuity has opened doors for future Mars mission concepts that exploit modern technology and proposed missions as well as white papers for the NASA decadal survey 2021 suggested adding a magnetometer as payload to explore the martian crustal magnetic field [1]–[3].

Planetary magnetic fields are linked to processes within and outside a planet; they provide constraints on the interior thermal evolution through the characteristics and timing of a dynamo field, and on surficial processes including water interaction, impacts and tectonics through crustal remanent magnetization. The presence or absence of a global dynamo field can influence atmospheric escape through time and thus the current state of a planet. These far-ranging aspects lead to planetary magnetism being a fundamental area of study.

The martian crustal magnetic field has been studied extensively using orbital data sets from Mars Atmosphere and Volatile EvolutioN (MAVEN) and Mars Global Surveyor (MGS). These complementary data sets have allowed global studies of the magnetic field and resulted in variable models of the crustal magnetic field (e.g., [4]–[6]). While those models allow predictions for the field at any altitude including the surface, they lack short wavelength information which is not resolvable from orbital altitude. The minimum resolvable wavelengths are approximated by the lowest altitude coverage, in this case ~130 km. The InSight lander [7], [8] and the Chinese Tianwen [9] missions have recently acquired magnetic measurements of the local field at each landing site. However, to-date no measurements at scales between those of local surface data and global orbital data have been collected (Fig. 1).

On Mars, strong crustal magnetic fields concentrated mostly in the Southern hemisphere indicate that a global dynamo field was once active. The timing and mechanism of this dynamo field has been widely discussed (e.g., [10]–[12]). Further questions are related to the heterogenous distribution of crustal fields, magnetic carriers that could give rise to them and mechanisms that would result in the inferred remanence [1]. Correlation of crustal magnetic fields with geological structures or data sets such as gravity or mineralogy can provide information on such questions. For example, the correlation of a volcanic structure or crater magnetic field signature with a unit of known age can provide information on dynamo timing. However, correlations can only be assessed for spatially resolved structures (i.e., $\lambda > \sim 130$ km). On Earth, detection of marine magnetic anomalies, key supporting evidence for plate tectonics, was only possible with near-surface magnetic field measurements [13].

In this study, we investigate data sets that a future helicopter-based magnetometer might be able to provide. We construct simple forward models that resemble a range of plausible subsurface geological structures that allow us to experiment with survey design, e.g., the value of multiple measurements horizontally and/or vertically and their trade-offs with regional data coverage. We investigate the extent to which different survey geometries could resolve structures of potential interest, such as buried intrusions, crater materials etc. We use these results to assess the capabilities of helicopter-based studies in addressing some of the open questions in the field. These kinds of considerations can optimize science return for possible future missions and demonstrate their scientific value.

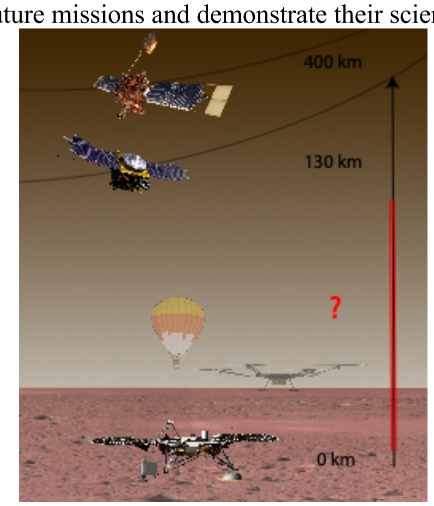


Fig. 1 The lack of magnetometer data between 0 and 130 km.

Methods: We adapt the approach presented in [14] and perform magnetic vector inversions using a spherical formulation that allows sparsity assumptions to be imposed for magnetization direction and amplitude separately. This allows recovery of subsurface structure without extensive smoothing. Depending on the geological setting, we use octree (e.g., for local anomalies) or tensor (e.g., for large scale layering) meshes. All results are produced using the open-source SimPEG software [15] . Here, we construct simple case studies such as that shown in Fig. 2. In this example, we define a magnetization structure that mimics a dike intrusion in the subsurface, and predict the field along three helicopter tracks.

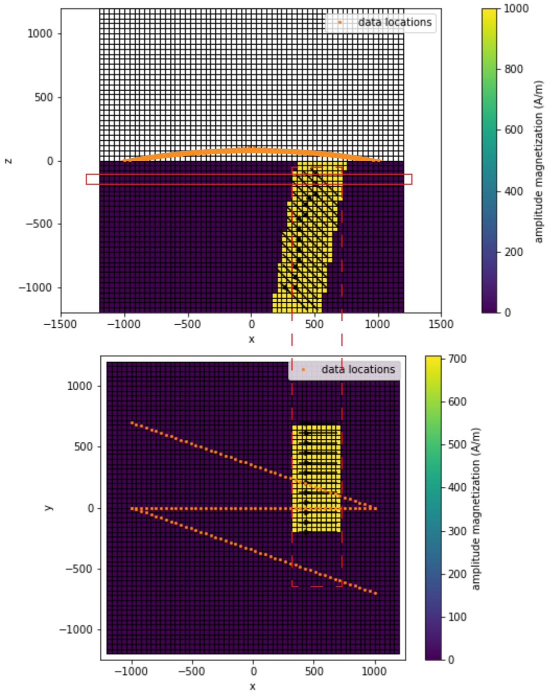


Fig. 2: Model setup showing a magnetized structure in an unmagnetized medium and three helicopter tracks (orange). Each track ascends to 50 m above the surface and lands again. Red dashed lines highlight the slice shown in the other panel
.

Results: In our inversion results (Fig. 3) we can identify the dike feature most clearly down to 500 m, but are insensitive to deep (>1 km) structure. The dip of the dike is not resolved, but the inversion favors a vertical, slightly broader structure at shallow depths. This is typical for non-unique problems in which the case of a deep, diagonal vs a broader, more shallow structure cannot easily be distinguished. However, the edges of the dike are recovered and the basic dike structure can be identified with only 3 tracks. This example demonstrates the ability to recover subsurface structure with only few tracks. If information on age of the structure is available, we can place constraints on timing based on identified magnetized structure. Further more complex scenarios will be implemented to test capabilities of helicopter mission.

Outlook: Mission planning requires clearly defined open science questions and the ability to address them with given data sets. Here we showcase some of the tools available that could be used to construct models for specific geological scenarios and assess the extent to which such structures could be recovered with helicopter-borne magnetometer measurements. These can motivate the community to think about important aspects for a future mission:

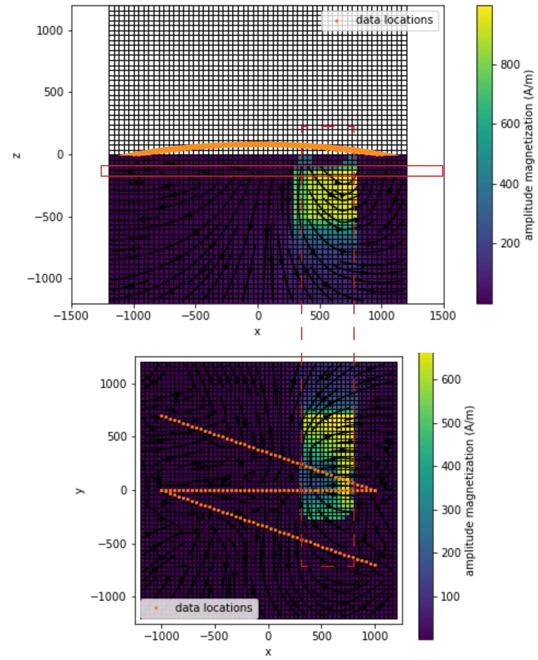


Fig. 3: Inversion results corresponding to Figure 2.

Technical Aspects: (1) What is the ideal survey design given the distance vs dense coverage tradeoff? What is the value of vertical vs horizontal coverage? (2) What are complementary instruments that could benefit the science return? For example, a gravimeter could provide a link between subsurface structure that might be magnetized and help unravel magnetization acquisition mechanisms.

Science: (1) Which questions can be addressed with a low altitude magnetometer? While questions regarding the nature and characteristics of the crustal magnetic field are discussed elsewhere [1], other communities (i.e., volcanologists, geologists) might want to exploit information gained from this experiment.

References: [1] Mittelholz et al. (2021) *Bllt. of the American Astr. Soc*. [2] Bapst et al. (2021) *Bllt. of the American Astr. Soc*. [3] Rapin et al. (2021) *Bllt. of the American Astr. Soc*. [4] Langlais et al., (2019) *JGR Planets.* [5] Mittelholz et al., (2018) *JGR Planets*. [6] Morschhauser et al., (2014) *JGR Planets*. [7] Johnson et al., (2020) *Nature Geoscience*. [8] Banfield et al., (2019) *Space Science Reviews*. [9] Du et al., (2020) *Space Science Reviews*. [10] Mittelholz et al., (2020) Science Advances [11] Lillis et al, (2013) *JGR Planets*. [12] Hemingway et al., (2021) *JGR Planets*. [13] Ravat et al., (2011) *Icarus.* [14] Fournier et al., (2019) *Geophysics.* [15] Cockett et et al., (2015) *Exploration Geophysics.*

MARS WEATHER MONITORING FROM ORBIT: A LOW-COST SCENARIO. L. Montabone[1,2,3], N. G. Heavens[1,4], S. D. Guzewich[5], A. Cardesin-Moinelo[6], [1]Space Science Institute, 4765 Walnut St, Suite B, Boulder, CO 80301 (lmontabone@spacescience.org), [2]Laboratoire de Météorologie Dynamique, Sorbonne Université, Campus Pierre-et-Marie-Curie, 4 Place Jussieu, 75005 Paris, France; [3]Paneureka, Savoie-Technolac Science/Technology Park, 17 Rue du Lac Saint-André, 73370 Le Bourget-du-Lac, France; [4]Earth Science and Engineering, Imperial College, London, Royal School of Mines, Prince Consort Rd, South Kensington, London, UK SW7 2BP; [5]NASA Goddard Space Flight Center, 8800 Greenbelt Rd, Greenbelt, MD, 20771; [6]European Space Astronomy Center, Camino bajo del Castillo, s/n, Urbanización Villafranca del Castillo, Villanueva de la Cañada, E-28692 Madrid, Spain; [7]Instituto de AstroFisica e Ciencias do Spaço, Rua das Estrelas, 4150-762 Porto, Portugal.

Introduction: Past and present orbiters have been able to provide a great picture of Mars's global climate, and good insights into its meteorology. As a result, the significance of diurnal meteorological variability argues for orbital observations that span the diurnal cycle. Additionally, the rapid dynamics of meteorological phenomena such as dust storms and water/CO_2 ice clouds, together with their spatial extension and duration/repeatability, argue for continuous and simultaneous observations across the planet. As it happened for the study of meteorology on Earth in the 1970s, now is the right time to introduce monitoring to the observation paradigm for the Martian atmosphere, so far almost exclusively focused on mapping. The Emirates Mars Mission (EMM) is the spacecraft that has started such a transition.

Science from weather monitoring: A long-standing question in the study of Martian meteorology is: How do dust storms evolve into extreme, planet-encircling events? This is the kind of questions for which global, continuous, simultaneous weather monitoring from orbit is required. Scientific understanding of the onset and evolution of dust storms is then likely to enable forecasting, a key requirement for future human exploration missions.

Dust storms are not the only possible focus of weather monitoring from orbit. The meteorological significance of Mars's water and CO_2 ice clouds is still underexplored, particularly in relation to their diurnal variability. Monitoring winds in the lower and middle atmosphere is a key priority to understand circulation regimes and confirm numerical model hypotheses. For instance, the study of the connection between the formation of CO_2 ice clouds in the polar region and the change in dynamical regime both in baroclinic wave activity [1] and in polar vortex dynamics [2] requires an improvement in the spatial and temporal data coverage as well as in the type of observed variables (e.g. atmospheric wind and surface pressure).

Why using SmallSats for weather? Except for EMM, past and present orbital missions at Mars do not have the study of climate, let alone weather, as main objective. The type of objectives, payloads, ConOps and risks of these single-spacecraft missions are quite different from what could be specifically designed today for a weather-monitoring mission.

Weather monitoring requires global or quasi-global observations. Observing at high cadence all locations simultaneously are other two key requirements. In term of observed variables, atmospheric and surface temperatures, three-dimensional aerosol (as well as water vapor) distributions, atmospheric wind, and surface pressure are desirable.

Today, these requirements could be satisfied by using a constellation of small, low-mass, low-cost, possibly higher risk satellites (i.e. SmallSats) with focused payloads in a combination of standard (e.g. Sun-synchronous polar) and/or novel orbits (e.g. areosynchronous or areostationary, see e.g. [3]).

The use of SmallSats for space science in general has been advocated by COSPAR [4] and, specifically for Mars science, by the Mars Architecture Strategy Working Group (MASWG) [5]. Although weather monitoring is not explicitly mentioned in either documents, it is a science objective particularly well suited for a SmallSat mission. This is even more so when looking at possible science objectives for missions to Mars in the current decade, in parallel to Mars Sample Return (MSR), International-Mars Ice Mapper (I-MIM), and as a precursor to future missions in support of human exploration.

Current mission concepts: To our knowledge, several mission concepts or parts of mission concepts using SmallSats with some weather monitoring capabilities have been developed worldwide, and made publicly available in the past five years:

- Mars Aerosol Tracker –MAT [6]. This is a single-spacecraft mission concept in areostationary orbit, with the objective of monitoring regional weather.
- Mars Orbiter for Surface-Atmosphere-Ionosphere-Connections –MOSAIC [7]. Although the full MOSAIC mission concept is far from being a low-cost, weather-focused concept, some specific platforms (Polar small orbiters, Areo smallsat B) and descope options (the "Threshold" options, only

including a constellation of three areostationary orbiters and a mini-mothership, with limited payload) have these characteristics.

- Small Mars Mission Architecture Study – SMARTieS [8]. This study by ESA involves three concepts, one of which (a three-spacecraft trans-areostationary constellation) has a weather monitoring capability, although its main objective is communication relay.
- Monitoring Areostationary Constellation for Atmosphere and Weather in Space –MACAWS [9]. This mission concept is derived from MOSAIC by retaining a constellation of three areostationary satellites with the objective of monitoring both atmospheric and space weather.
- Areostationary Exploration of Meteorology by Orbital Imaging –ANEMOI [10]. This concept is also derived from MOSAIC by retaining a constellation of four areostationary satellites with a focus on wind measurements using cloud tracking, together with general weather monitoring.
- Polar-Orbiting Atmospheric Wind Small Satellite – PAWSS [11]. This is another concept derived from MOSAIC by retaining a mini-mothership in Sun-synchronous polar orbit with a focus on wind measurements using a Doppler near-IR lidar, together with other atmospheric measurements.

International collaboration scenario: In their fifth recommendation, [4] described very well the benefits of international collaboration in SmallSat missions: “The results of an international effort to build small satellite constellations would be valuable for all of the participants, and would be more valuable than the individual parts. Such a large-scale effort would enable the pursuit of visionary goals, and ultimately lead to both technological and scientific breakthroughs. Small satellites enable new models of international collaboration, with involvement by many more nations, in worldwide, ambitious projects”.

A constellation of several SmallSats with the objective of monitoring the Martian weather could be a mission shared by two or more space agencies, including participation from commercial entities. Both MSR and I-MIM missions are currently managed as international collaborations. A weather-monitoring mission to Mars in the current decade, based on an orbital constellation, would necessarily need to be smaller in scale, although part of the reduction in scale could simply be equivalent to accept higher risks. Nevertheless, if one wants to satisfactorily fulfill the weather-monitoring objective, it is hard to think that a single entity alone could launch such a mission in the current decade. Conversely, an international collaboration scenario could be financially and strategically well suited.

NASA and ESA are obvious possible partners, also taking into account their respective efforts in looking into low-cost mission concept studies having Mars’s weather as an objective. However, other space agencies or commercial entities could potentially be interested and contribute, provided two key requirements for a successful constellation mission are fulfilled: 1) the payload on similar platforms is the same (e.g. the same visible camera is used aboard all areostationary orbiters), and 2) a single entity is charged with ConOps responsibility.

Next step, OSSEs: While waiting for the first available opportunity to send a satellite constellation to monitor the Martian weather, something can and should be preliminarily done to verify and/or optimize the configuration and payload of such a constellation: Observing System Simulation Experiments (OSSEs). This framework has been used for more than 30 years as a tool to evaluate the benefits of future instruments for the Earth, so it is now the right time to simulate the impact of atmospheric observations that do not yet exist for Mars (see also [12]).

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References: [1] Mulholland D. P. et al. (2016), *Icarus*, 264, 465–477. [2] Toigo A. D. et al. (2017), *GRL*, 44, (1), 71-78 [3] Montabone, L. and Heavens, N. G. et al. (2021), BAAS, 53 (4), 281. [4] Millan R. M. et al. (2019), *Adv. Space Res.*, 64 (8), 1466-1517. [5] Jakosky B. M. et al. (2020), MASWG report [6] Montabone L. et al. (2018) *LPSC XLIX*, Abstract #2083 [7] Lillis R. J. et al. (2021), *PSJ* 2 :211. [8] Parfitt C. E. et al. (2021), *Adv. Astron.* 2021. [9] Montabone, L. et al. (2021), *EPSC 2021*, 625. [10] Heavens N. G. et al. (2021), this issue [11] Guzewich S. D. et al. (2021), this issue [12] Reale O. et al. (2021), *BAAS*, 53 (4), 110.

Large Mars Surface Chemistry Science in a Small Budget.

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Introduction: The success of the Mars exploration program has provided a wealth of information on the mineralogy and chemistry of Mars, but as with any good line of investigation it has generated even more questions to answer. While some of these questions will have to wait for samples to be returned from Mars, a number of questions about Mars surface chemistry can be addressed with more targeted missions. Two specific examples are: 1) What is the distribution of chlorine species in the regolith [1, 2], and are their salts important in features like the Recurring Slope Lineae (RSL) [3, 4]? 2) What is the extent and speciation of abiotic organic acids such as benzoic and oxalic acids potentially identified by the Curiosity mission [5, 6]. These types of surface chemistry science missions are enabled by developments in micro-landers, micro-rovers, surgical-class robotic manipulation, miniaturized instrumentation, and advanced autonomy software.

Our present Mars mission architecture affords a look at ≤ 2 new sites on Mars every 26 months. These sites must be “safe,” both for landing and because of planetary protection requirements that keep missions away from possible liquid water or brines of high interest such as RSLs. We propose a mission architecture that, for a modest incremental cost above that of planned Mars missions, can add focused investigations at up to ~10 new sites each Mars launch period, targeted to the most promising sites with the ability to assure sterilization of landed hardware.

Mission System Elements Include:

1. MarsDrop microlanders[7-9], 30 – 45 cm in diameter, with <~3-10 kg entry mass, based on The Aerospace Corporation’s thrice flown Reentry Breakup Recorder (REBR) [10-12], plus a Rogallo-style steerable parawing and JPL’s Terrain Relative Navigation (TRN) navigate-to-target image processing system [13, 14]. These microlanders can be placed in a biocontainment bag (post ground sterilization) that burns up upon entry to allow safe access to sites.

2. Pop Up Flat Folding Exploration Rovers (PUFFER), 100 – 200 g, already tested to negotiate slopes up to ~45 deg on terrestrial desert terrain [15].

3. Robotic arm <300 g based on Miniature *In-vivo* Surgical Robot [16, 17], to collect and deliver damp or icy soil samples to analytical instruments.

5. Electrochemical instrumentation (derived from Phoenix mission heritage) [18], <500 g to detect and speciate soluble chlorine species like chloride, chlorate, and perchlorate.

6. Capillary electrophoresis instrumentation using conductivity detection for analysis of abiotic organic acids and inorganic oxyanions [19, 20].

7. Semi-autonomous navigation and investigation operations software [21], to enable mission operations with modest ground teams across simultaneous investigations at multiple sites.

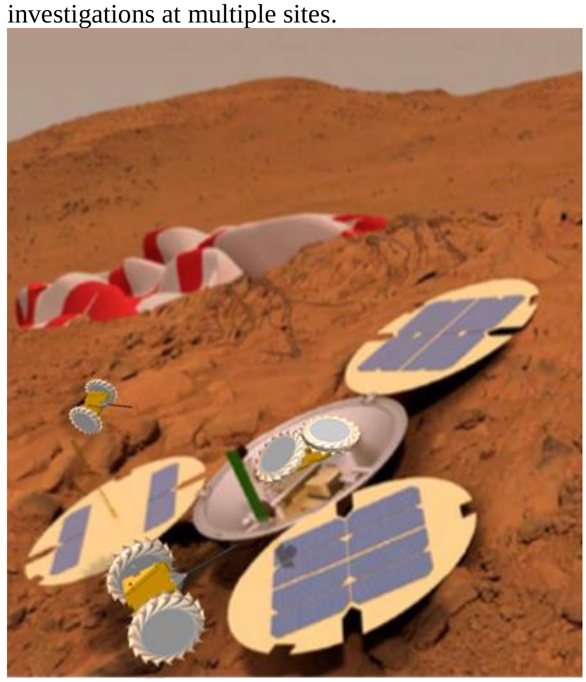

Figure 1. Artist concept of MarsDrop with PUFFERs deploying. Image courtesy of the The Aerospace Corporation.

An example mission could follow this sequence: MarsDrop microlanders take one or more PUFFER microrovers to within the rover’s range (~100 – 500 m out-and-back) of one or more RSL over sufficiently navigable terrain. Each microrover, deployed by spring and burnwire (or robot arm), can go with a conductivity probe style electrochemical sensor to measure water activity at the RSL or a nearby control location. After that they will collect a small sample of regolith from their location using a tail scoop, and brings it back to its MarsDrop lander. A small robotic arm reaches over the side of the lander [16], grabs the sample from the PUFFER, and places it into the sample opening for a small array of ion selective electrodes to assess the inorganic ions including chloride, chlorate, and perchlorate. Alternatively, a capillary electrophoresis system could be used to look for the presence of small organic acids, including oxalate from potential oxalate minerals. Navigation can be provided by a combination of stored high-res orbital imagery, pre-landing frames taken from the MarsDrop descent camera used to steer to target, and very small cameras on PUFFER itself, correlating terrain in a semi-automated manner after an approximate path is uplinked from the ground based on tracking information.

While every element of the mission architecture is critical, the development of the MarsDrop microlanders has been a truly enabling capability. MarsDrop's outer mold line is based on that of REBR, which, in turn, is based on that of the Deep Space 2 Mars surface penetrator entry vehicles (whose success remains unknown) [22]. However, REBRs have been used successfully thrice to carry instrument payloads from Earth orbit through atmospheric reentry. While not specifically designed to survive an Earth landing, two of the three REBR flights did survive ocean landings for up to 17 hours [10, 11]. Using current atmospheric models, simulations show that after entering Mars' atmosphere from a direct entry trajectory or orbit, that this aeroshell shape and a mass loading of required subsystems plus instrument payload, will decelerate to subsonic speeds several kilometers above much of Mars' surface. Once subsonic, a parawing will be deployed to glide and reduce vertical landing velocity to ~7 m/s. Terrestrial MarsDrop technology demonstration vehicles have been lifted to 30 km altitude on weather balloons and dropped to reach Mars-like dynamic pressure at Mars atmospheric density, successfully deploying a parawing and gliding down [7, 8, 9]. Such a parawing may be steered using imagery from a forward/down-looking camera to implement terrain-relative navigation and guidance. Targeting entry toward richly-populated RSL areas on Mars leads to a certain dispersion when the parawing deploys at 7 km--then onboard reachability algorithms dynamically chose a target landing site based on stored and preprocessed MRO imagery. With a correct atmospheric entry injection point, landing accuracy has been estimated to be within ~100 from the desired landing point. The microlander could survive a roll-and-tumble landing scenario through the use of modern cellphone shock packaging and a slightly crushable carbon-carbon heat shield structure. Self-righting petals then unfold exposing solar panels and an antenna linking to existing or future orbiting relay assets. All subsystems required to support surface operations fit in the available volume, with room for an instrument payload up to ~1 kg, which can be increased with a somewhat larger diameter entry vehicle, up to a sufficiently low ballistic coefficient to enable subsonic parawing deployment [8].

Only recently has providing so much hardware and software capability in small, low-power, sterilizable systems become credible. But with Mars Helicopter, smartphones, CubeSats, FPGAs, robotic surgery, self-driving cars, and the like, an affordable path to making high impact surface science measurements on Mars may be emerging. Some Mars mission cruise stages have enough mass margin that up to ten MarsDrop microlanders could be accommodated (with <20 kg per lander including attach-and-deploy hardware) and deployed to destinations separate from the primary spacecraft. This MarsDrop architecture could enable not only the proposed mission to be implemented as a modest-cost, secondary payload on a "classical" Mars mission, but also many other missions with equally compelling science objectives.

References:

[1] Hecht, M.H., et al. (2009) *Science*, *325*, 64-67.
[2] Sutter, B., et al. (2016) *International Journal of Astrobiology*, 1-15.
[3] McEwen, A.S., et al. (2014) *Nature Geosci*, *7*, 53-58.
[4] Ojha, L., et al. (2015) *Nature Geosci*, *advance online publication*.
[5] Franz, H.B., et al. (2020) *Nature Astronomy*, *4*, 526-532.
[6] Freissinet, C., et al. (2015) *Journal of Geophysical Research: Planets*, *120*, 495-514.
[7] Staehle, R.L., et al. (2014) *International Astronautical Congress* Abs# IAC-14-B4.8.11x22457
[8] Staehle, R.L., et al. (2015) *AIAA/USU Small Satellite Conference* Abs# SSC15-XI-3
[9] Eby, M. (2013) *2nd Interplanetary Cubesat Conference*. Ithaca, New York
[10] Ailor, W.H., et al. (2013) *6th European Conference on Space Debris*. Darmstadt, Germany
[11] Feistel, A.S., et al. (2013) *6th IAASS Conference*. Montreal, Canada
[12] Weaver, M.A. and W.H. Ailor. (2012) *AIAA Space 2012 Conference*. Pasadena, CA
[13] Mohan, S., et al. (2016) *13th International Planetary Probe Worksop*. Laurel, MD
[14] Setterfield, T.P., et al. (2021) *Journal of Guidance, Control, and Dynamics*, *44*, 1239-1252.
[15] Davydychev, I.A., et al. (2019) *Journal of Mechanisms and Robotics*, *11*.
[16] McCormick, R., et al. (2017) *2017 IEEE Aerospace Conference*.
[17] McCormick, R.L., 2011. Mechanical Engineering, University of Nebraska, Lincoln
[18] Kounaves, S.P., et al. (2009) *J. Geophys. Res. [Planets]*, *114*.
[19] Jaramillo, E.A., et al. (2021) *ELECTROPHORESIS*, *42*, 1956-1964.
[20] Zamuruyev, K., et al. (2021) *Analytical Chemistry*, *93*, 9647-9655.
[21] Estlin, T.A., et al. (2012) *ACM Trans. Intell. Syst. Technol.*, *3*, Article 50.
[22] Braun, R.D., et al. (1999) *Journal of Spacecraft and Rockets*, *36*, 412-420.

Transmissive H_2O Reconnaissance Sounder, TH2OR – A Compact Time-Domain Electromagnetic Instrument for Groundwater Detection.
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Introduction: A decades-long, systematic program of exploration has permitted us to vastly rewrite our understanding of Mars via a series of remote sensing and in situ investigations. Many of these investigations are still ongoing, with the latest effort encapsulated by the rover Perseverance in its search for evidence of past martian life and its role as the point of the sample return spear.

Despite the scientifically invaluable samples that are beginning to be collected for a potential return and a possible answer for whether life once existed there, Mars still withholds some first order questions about its history and evolution. One such question is the inventory, distribution, and destiny of its water. Water not only plays a crucial role in biology, but it also influences a variety of key geologic/geophysical processes, such as mineralogy, rheology, and magma generation, style of volcanism, and tectonics.

A lot of attention has been paid to the presence of water at the surface in shallow depths. We now know that the bulk of the polar layered deposits [1, 2] and of the mid-latitude lobate debris apron [3] deposits consist of nearly pure water ice. We also know that shallow ground ice is likely to be present at the Vastitas Borealis [4, 5]. Briny water has been invoked to explain gullies and recurring slope lineae (RSLs), along with other anhydrous mechanisms [6-8].

The presence of deep groundwater has been long hypothesized to exist at Mars in the form of a global aquifer that could be retained to present day [9-11], but this has been difficult to test due to the limitations of data available. The MARSIS and SHARAD radar sounders did not provide a positive detection of a water table at depth (the tentative identification of subglacial lakes [12] is controversial). Results from the SEIS instrument suggest that seismic propagation velocities in the upper martian crust are a little slower than expected, which could be due to the presence of volatiles [13]. Other geophysical data either do not have lateral resolution or sufficient reach in depth to allow a proper interrogation of the subsurface for groundwater.

Transient Electromagnetic (TEM) Sounding: One of the most common geophysical methods utilized in searching and mapping groundwater on Earth is TEM sounding. This method involves the generation of a primary magnetic field via an electric current flowing in a loop antenna and, upon the interruption of this primary field, the induction of eddy currents in the subsurface. These loop-shaped eddy currents, proportional to the electrical conductivity of the subsurface material, diffuse downward and create a secondary magnetic field, which is then detected at the surface with either coils or loop antennas. Changes in electric conductivity at depth, such as those caused by the presence of groundwater, alter the decay of these currents and the associated secondary magnetic field, which is detected at the surface and inverted for the electric conductivity structure of the subsurface.

There are various implementations to TEM currently being used in the field: stationary vs. moving, time- vs. frequency-domain, surface-deployed vs. airborne. These typically involve equipment that is relatively heavy (>10’s kg) and power-hungry (>>10’s W). Further, sounding to multi-km depths require loop antennas that are larger in diameter.

An advantage of Mars over the Earth for the application of TEM is that its shallow subsurface is colder and potentially devoid of water/brines, as suggested by the majority of models. As a result, the geoelectric structure of the martian subsurface is likely to be consistent with a resistive layer [14]. If groundwater is present, then this uppermost resistive layer should overlie a conductive layer. The depth and the degree of conductivity, invertible to water content and its salinity, is what TEM would allow investigators to obtain for Mars. Thermal modeling indicates that the depth to water may vary from 2 to 7 km [**Fig. 1**].

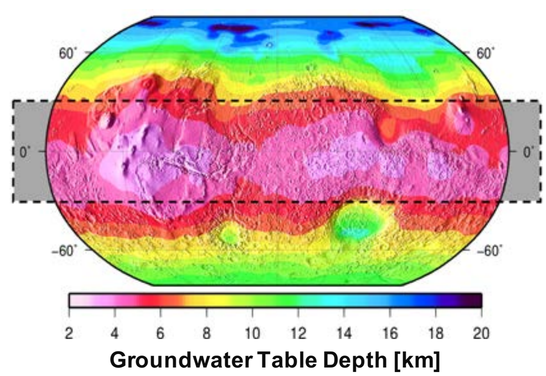

Fig. 1 – Groundwater table depth for pure water using the heat flow model of [15] and longitudinally averaged surface temperature. Shallowest plausible depths (2-7 km) lie in an equatorial band, denoted by the shaded box.

TH2OR: We have implemented and tested (TRL-4) a planetary TEM prototype for Mars. It strives to be modest in mass (<10 kg) and in power consumption (≤ 30 W) and compatible with a variety of mission concepts. TH2OR hardware is divided into three key subsystems: (1) the electronics, (2) loop antenna and its deployment system [**Fig. 2**].

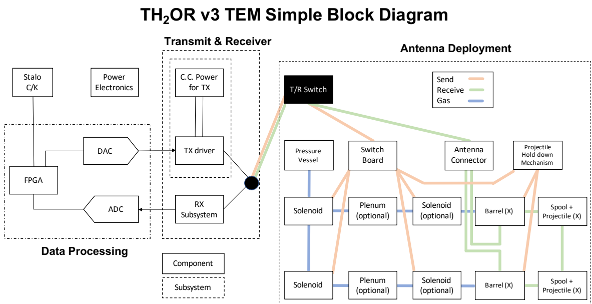

Fig. 2: Block diagram of the TH2OR prototype.

The electronics contains a Transmitter (TX), a receiver (RX), power management, and a control and data handling (C&DH) module. Our modeling indicates that our TX antenna will have to consist of a loop size on the order of 100 meters wide to detect groundwater that is several kilometers deep. We have studied a variety of deployment methods and rated them according to technical feasibility and ease of implementation [*McGarey et al.*, *in prep*], and elected a cold-gas ballistic deployer for prototyping and testing. This deployment approach has heritage in the work of [16].

Fig. 3 – Still-frame from a launch of the COTS implementation of the TH2OR launcher, showing the two projectiles exiting their launch tubes.

It consists of two projectiles, each containing two wire spools that are interconnected, that are launched simultaneously [**Fig. 3**]. During ballistic flight, the spools unwind. Upon landing, the projectiles will have deployed a triangular wire loop connected to the TH2OR electronics.

Future Missions: TH2OR's relatively low mass and power allow it to be a viable instrument in future low-cost missions while addressing a first order science question. Several enticing future mission scenarios are pairing TH2OR with (1) a Phoenix/InSight derivative soft lander, or (2) the JPL SHIELD rough lander. A mission profile of 90 sols would allow our team to acquire and stack soundings to improve signal-to-noise ratio of the measurements. A key advantage of pairing TH2OR with the SHIELD concept is that multiple rough landers could be used in deploying more than TH2OR units to the martian surface at key locations that would permit the robust testing of the global aquifer hypothesis.

References: **[1]** Zuber M.T., et al., Science, 2007. 317: p. 1718-1719. **[2]** Phillips R.J, et al. Science, 2008. 320(5880): p. 1182-1185. **[3]** Holt J.W., et al., Science, 2008. 322: p. 1235-1238. **[4]** Feldman W.C., et al., JGR 2004. 109(E9). **[5]** Byrne, S., et al., Science, 2009. 325(5948): p. 1674-1676. **[6]** Malin, M.C. and K.S. Edgett, Science, 2000. 288: p. 2330-2335. **[7]** Diniega, S., et al., Geology, 2010. 38(11): p. 1047-1050. **[8]** Dundas, C.M., et al., Nature Geosci., 2017. 10(12): p. 903-907. **[9]** Clifford, S.M. and T.J. Parker, Icarus, 2001. 154(1): p. 40-79. **[10]** Clifford, S. M., et al., JGR, 2010. 115, E07001. **[11]** Grimm, R. E., et al., JGR, 2017. 122, p.94-109. **[12]** Orosei, R., et al., Radar evidence of subglacial liquid water on Mars. Science, 2018. 361(6401): p. 490-493. **[13]** Lognonné, P., et al., Nature Geosci., 2020. 13(3): p. 213-220. **[14]** Grimm, R.E., JGR, 2002. 107(E2). **[15]** Plesa, A.C., et al., GRL, 2018. 45(22): p. 12,198-12,209. **[16]** Grimm, R.E., et al., PSS, 2009. 57(11): p. 1268-1281.

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NEW ROVER CONOPS WITH HIGH-PERFORMANCE ONBOARD COMPUTING: GIVE UP RAW DATA TO REDUCE OPS COST AND DO MORE SCIENCE. M., Ono[1], J (Bob) Balaram[1], V. Verma[1], D. Atha[1], M. Swan[1], A. Didier[1], [1]Jet Propulsion Laboratory, California Institute of Technology, Pasadena, CA 91109. ono@jpl.nasa.gov.

Introduction: A major portion of time during the tactical operation of Mars rovers is spent for selecting, prioritizing, and coordinating science and engineering activities such that they fit within resource constraints, including the downlink data volume, energy, and time. In particular, the downlink data volume constraint is getting particularly tighter in recent missions because modern instruments produce increasingly high data volume while the communication bandwidth is essentially bounded by the law of physics. The tactical operation would be substantially simplified, hence the operation cost could be reduced, if the data volume constraint is relaxed or even removed.

We propose a new operation paradigm for achieving this goal. The key observation is that, both in science and engineering applications, the bit size of raw data is typically much greater than the volume of *processed* information that is needed for scientific or engineering analysis. For example, a full-resolution image from Mastcam-Z, the main science camera on Perseverance, is about 700 kB in volume and we downlinked 29,685 images up to Sol 243, totaling ~20 GB of data. But of course, scientists do not use every pixel of these images; what they really look for in the images are geological features, typically represented by specific geometric configurations or textures. An end product after processing hundreds of Mascam-Z images could be a single geological map summarizing the spatial distribution of the features. For another example, a 100-meter drive of Perseverance produces 7-12 MB of drive telemetry, which records every detail of the rover's motion at 8 Hz, including position, attitude, steering angles, encoder readings, motor currents and many other information. But what the ground engineers eventually pay attention to is the signs of anomaly, such as excessive motor currents or high slip; if a drive is nominal, the vast majority of this data is unused. What if, then, we process the raw data *onboard* and only downlink the processed data that is relevant to scientific or engineering analyses, such as a list of detected science features (with cropped images) or a list of potential signs of anomaly while driving?

A major roadblock for such onboard, high-level information processing has been the onboard computational resource. RAD750, the main onboard computer of Perseverance, is obviously not sufficient for performing complex image or signal processing such as object detection, semantic segmentation, or anomaly detection. Interestingly, RAD750 is *not* the best processor that Perseverance has; Qualcomm's Snapdragon 801, a modern mobile processor, is on her Heli Base Station, a device for communicating with Mars Helicopter Ingenuity; also, Intel's Atom E3845 processors are on engineering cameras. In the reminder of this paper, we will introduce two particular uses cases of these high-performance co-processors (meaning auxiliary CPU, GPU, or other types of processors that are separate from the main processor that runs the main flight software) for lowering operation cost and accommodating more science activities for a given communication constraint.

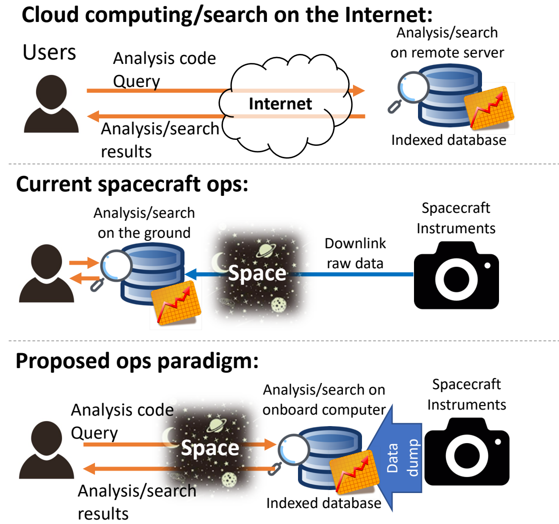

Figure 1. Concept of Interplanetary Cloud Computing and Search

Use Case 1 – Interplanetary Cloud Computing: Cloud computing has been a major trend over the last few years, even for spacecraft operations. For example, Mars 2020 uses a cloud-based Jupyter Notebook for the downlink analysis. It allows users to run any python scripts on a remote server where the data resides. Users do not need to download the data to their local computer for running analysis. Moreover, since the Jupiter environment is compartmentalized for each user, a bug or crash produced by an undisciplined user does not propagate to the system.

We can set up such a compartmentalized and insulated environment on a high-performance co-processor. As illustrated in Figure 1, scientists and engineers would upload analysis codes and downlink *processed* information, rather than raw data. Using an ARM-based mobile processor is particularly beneficial because of low power consumption (e.g., Snapdragon 801 on Ingenuity only consumes ~3.5W during flight), hence the analysis can be run during the idle time of the rover. Since it is a co-processor, even if the user's code crashes, it does not affect the flight software on the main CPU that is vital to the spacecraft.

Example: Recently, convolutional neural networks (CNNs) have been successfully used for scientific image processing, ranging from object detection/tracking/classification and mapping (semantic segmentation). Modern mobile processors, such as Snapdragon, usually comes with GPU or AI processors specialized for running deep neural networks efficiently (your smart phone runs neural networks routinely on the images you take). There are CNN architectures specialized for mobile devices, such as MobineNet [1], designed for low-power processor and low memory footprint.

For example, Soil Property and Object Classification (SPOC) has demonstrated the capability of classifying terrain types on rover's Navcam images (Figure 2) [2]. It employs MobileNetV2 backbone, which runs tens of msec on Snapdragon; it achieved 96.7% classification accuracy compared to the classification by a group of human experts consisting of Rover Planners and Project Scientists of MSL. While SPOC focuses on terrain classification for traversability assessment, the same approach is applicable for geological terrain classification, which in turn enables automated geological mapping. Instead of downlinking a Mascam-Z mosaic consisting of hundreds to thousands of images, a user can perform terrain classification and mapping onboard and download the resulting geological map. Of course, the user can selectively request the raw images at the areas of interest, identified by the geological map.

Use Case 2 – Interplanetary Google Search: When you search for information on the Internet, you don't need to download all the data to your local computer; instead, you send a query to a remote search server where the data is stored and indexed, and you only download the information you are seeking for, based on the result of a search.

The same paradigm is applicable to spacecraft operation; as shown in Figure 1, an onboard high-performance processor can index the data stored onboard; a user sends a query to the spacecraft, such as "cross-bedding layers on Mascam-Z images" or "high-slip event while driving," and selectively downlinks the relevant data.

Example: If you have an iPhone, you can search your photos by keywords (and it is usually very accurate). This is because your iPhone runs CNN on all the photos you took and indexes them. Recently, we

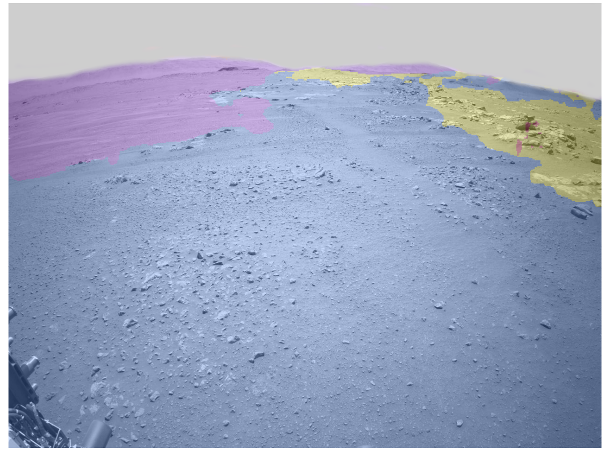

Figure 2. Terrain classification by SPOC on a Sol 200 image of Perseverance. Blue – soil, purple – sand, yellow – rock.

developed the Science Captioning of Terrain Images (SCOTI) model, which produces natural language captions of Mars images [3]. Although SCOTI is at an early stage of software maturity, such capability would allow rovers to preprocess all the images and index them onboard so that the users can search by keywords. This allows a rover to gather a substantially greater volume of scientific and engineering data than it can downlink without missing interests of science of signs of important events.

Conclusions: Onboard, high-performance computation would enable a new operation paradigm where raw data is processed onboard and only the processed data, which typically has a substantially smaller data footprint, is downlinked. This would not only enable to collect more scientific data but also help reduce the cost of future rover missions because coordinating activities to fit within a data downlink budget is a substantial effort in the current tactical rover operation paradigm.

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References: [1] M. Sandler et al. (2018) "Inverted residuals and linear bottlenecks: Mobile networks for classification, detection and segmentation," arXiv:1801.04381 [2] D. Atha et al. (2021) Multi-mission Terrain Classifier for Safe RoverNavigation and Automated Science. To appear in IEEE Aerospace Conference. [3] D. Qiu et al. (2020) "SCOTI: Science Captioning of Terrain Images for data prioritization and local image search." *Planetary and Space Science* vol 188.

HYPERSPECTRAL INFRARED TEMPERATURE SOUNDING OF MARS' ATMOSPHERE IN A CUBESAT. T. Pagano[1], M.A. Mischna[1] and G. Liuzzi[2], [1]Jet Propulsion Laboratory, California Institute of Technology, 4800 Oak Grove Dr. Pasadena, CA 91109, thomas.s.pagano@jpl.nasa.gov [2]NASA Goddard Space Flight Center, 8800 Greenbelt Rd. Greenbelt, MD, 20771.

Introduction: We have determined that a nadir-viewing, cross-track scanning, hyperspectral infrared sounder (HSIR) can provide information about the martian boundary layer—the lowest ~10 km of the atmosphere—a region that has heretofore been poorly observed due to the limitations of prior orbital instruments. Hyperspectral IR sounders are widely used today for measuring temperature and water vapor profiles on Earth's atmosphere with high impact to the operational forecast [1]. State-of-the-art infrared detector technology now allows megapixel formats that enable a larger collecting area for the detector, allowing the optical system to be smaller. These advancements have led to the ability to achieve HSIR capabilities at Mars, similar to those provided in today's Earth observing sensors, in the size of a CubeSat. Such a small, comparatively low-cost, payload enables multiple spacecraft to be flown concurrently, in different orbits, providing full time-of-day coverage of the martian atmosphere. Such an approach has been an objective of the Mars community for some time, and was most recently illustrated in the MOSAIC satellite constellation design responding to the Planetary Science and Astrobiology Decadal Survey [2].

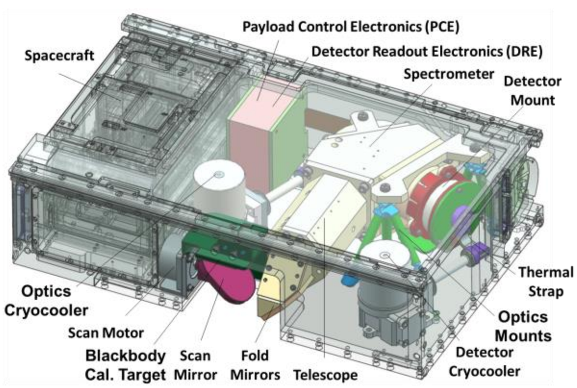

Figure 1: Potential layout of HSIR in a 6U CubeSat form factor, based on CIRAS.

The Value of HSIR: HSIR can markedly increase the vertical and horizontal resolution of retrieved temperature profiles in the near-surface boundary layer of the martian atmosphere. A cross-track scanning HSIR accomplishes this by operating along the 4.3 μm CO_2 absorption band and adjacent CO spectral features, with spectral resolution ($\lambda/\Delta\lambda$>1000) at ~10-km-scale horizontal resolution. Due to its hyperspectral approach, HSIR can obtain up to 2-3 km vertical resolution—a factor of two greater than the current state-of-the-art. By scanning the surface in the cross-track direction, HSIR is capable of retrieving radiance information at a scale more consistent with today's numerical models, providing assimilation data to the models over broader swaths than before. For example, a single HSIR instrument can provide over 180 soundings in a single 23 s scan vs. 1 sounding in a 34 s scan for MCS. Additional instruments comprising a spacecraft constellation can improve time coverage and provide additional information on winds through data assimilation, or through atmospheric motion vector (AMV) tracking [3]. Of additional benefit to Mars science is the ability to observe more deeply into dusty atmospheric conditions from orbit, filling in gaps in the long-term observational record.

HSIR Instrumentation: New technologies exist today that greatly reduce the size, weight and power (SWaP) of an HSIR instrument. For example, JPL's CubeSat Infrared Atmospheric Sounder (CIRAS) [4], for Earth-based applications, achieves spectral coverage from 4.08-5.13 μm, with spectral resolution of 3.3 nm. This instrument provides over 625 spectral channels and fits in a 4U volume. CIRAS uses a 512 x 640 pixel format High Operating Temperature Barrier Infrared Detector (HOT-BIRD) array developed at JPL to allow higher operating temperature, improve uniformity and operability and reduce cost compared to HgCdTe arrays. CIRAS also employs a JPL-developed immersion grating that reduces the size of the spectrometer, enabling it to fit in a CubeSat. The wide field and slow scan of CIRAS allow the aperture to be small, also contributing to its compact design. JPL has completed both ambient and thermal-vacuum testing of a high-fidelity prototype of CIRAS, bringing it to TRL 5. We can leverage this development towards applications to shortwave IR profiling of planetary atmospheres.

Radiative Transfer Simulations and Retrievals: Simulations of sample HSIR spectra and a characterization of its sensitivity to the martian atmospheric state have been performed. The simulations were made with the Planetary Spectrum Generator (PSG, [5]) which includes a retrieval module capable of computing the sensitivity of simulated data to specified parameters in the form of averaging kernels and Degrees of Freedom of Signal (DOFS) for the instruments being considered. Instrument characteristics (noise and spectral response) for an HSIR grating sounder similar to CIRAS operating in the shortwave CO_2 band were assumed, and sample retrievals were obtained for a range of atmospheric conditions. Results show that the CIRAS-like instrument has good sensitivity in daytime conditions with low to average dust and water ice loading, having maximum sensitivity between 10 and 25 km of altitude, and a maximum vertical resolution of about 3 km in the lowest layers (Figure 2). Even under high dust loading (τ=2.75), successful retrievals are obtained in the lower atmosphere (Figure 3). Performance at night, and in the polar regions, is much less satisfactory, since the temperatures are much colder and reflected sunlight is lower, reducing retrieval sensitivity.

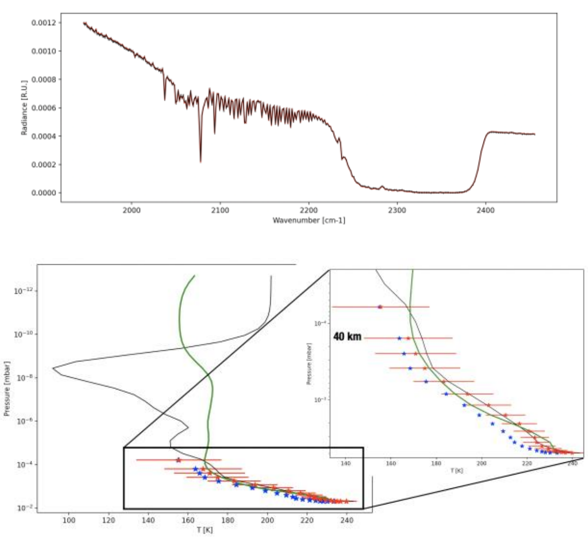

Figure 2: (top) True daytime spectrum (black) and MWIR retrieval (red) showing CO_2 absorption band between 2200-2400 cm^{-1} and CO spectral features between 2050-2200 cm^{-1} with low dust and water ice abundance. **(bottom)** retrieved temperature profile (green), initial guess (blue stars) final solution (red stars, with uncertainties), and true profile (black). Temperature precision is <5 K below 25 km.

Advantages over LWIR Approaches: HSIR provides several advantages in profiling that are designed to complement existing profiling methods (Table 1). These include the ability to peer deeper into the atmosphere, with maximum sensitivity as low as 3 km above the surface, yielding excellent coverage of the martian boundary layer. Vertical resolution in the lower atmosphere is also high, as much as 3 km, providing an unprecedented peek in the vertical dimension. The nadir viewing angle, with a wide scan swath provides comparable horizontal resolution to existing approaches, but with as much as two orders of magnitude more spatial coverage, providing greater mapping capabilities than before. Lastly, its small form factor (6U) enables the deployment of multiple spacecraft in different orbits with full time-of-day coverage, providing new information about the diurnal temperature cycle in the martian atmosphere.

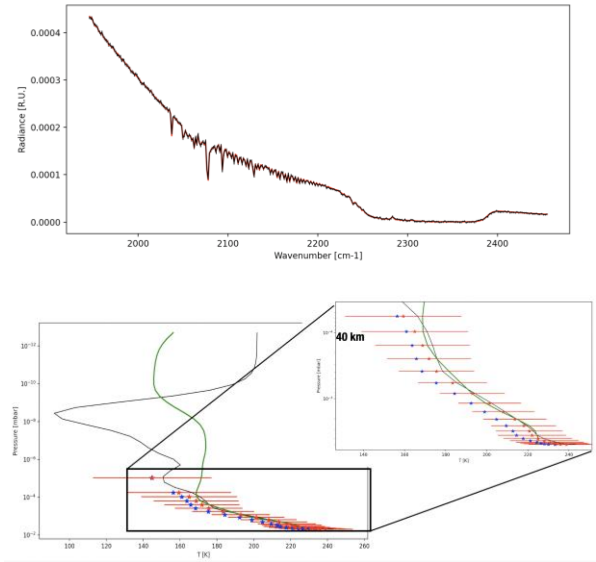

Figure 3: Same as Figure 2, but for a high dust, high water ice scenario. Temperature precision falls to ~12 K, but retrievals are still obtained close to the surface.

Table 1: Comparison of HSIR instrument parameters to existing profiling approaches. Advantages of HSIR are highlighted in bold, red font.

	PFS	MCS	HSIR
Spacecraft	MEX	MRO	Future
Vert. Range [km]	1-40	10-90	1-30
Vert. Res. [km]	<5	4-6	**3-5**
Horiz. Range [km]	12x20	105x105	**716**
Horiz. Res. [km]	12x20	4.4x8.2 nadir; 200 limb	13.5
Soundings/Day	429	2,541	**676,174**
Retrieval Acc.[K]	2-6	0.5-2	<2-6
IR Spectral Range [cm^{-1}]	270-1800	220-870	1950-2450
Mass [kg]	31.2	9	**4**
Power [W]	35	11	23

Acknowledgments: A portion of this work was performed at the Jet Propulsion Laboratory, California Institute of Technology, under a contract with the National Aeronautics and Space Administration (80NM0018D0004).

References: [1] Chahine, M.T. et al. (2006) Bull. AMS 87, 911-926. [2] Lillis, R.J. et al. (2021) Planet Sci J., 2 :211. [3] Santek, D. et al. (2019) Rem. Sens. 11, 2597. [4] Pagano, T.S. et al. (2019) J. App. Rem. Sens. 13(3), 032512. [5] Villanueva, G. L. et al. (2018), JQSRT 217, 86-104.

Low Cost Missions to Mars Studies at ESA

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Introduction: While the vast majority of ESA's funding for Mars exploration in the 2020s is planned to be invested in ExoMars and Mars Sample Return, there is interest to assess the possibility of implementing a low cost mission to Mars in parallel with, or soon after, the completion of the MSR programme.

Missions to Mars at the small scale have not been greatly studied within ESA since Mars Express two decades ago and preliminary concepts for a Mars Micro Mission as an 'Arrow' mission of the Aurora programme. Since then, the landscape of technologies (in particular those relevant for small, Earth orbit platforms and instrumentation) and launch capabilities (e.g. rideshares) have matured significantly, offering promising new opportunities for low-cost implementations of interplanetary missions. The ESA programmatic framework with the advent of the Aurora programme, now European Exploration Envelope Programme (E3P), and approach to low-cost planetary missions has thus evolved over the years.

In 2020, a study was undertaken in the Concurrent Design Facility at ESA ESTEC to assess low-cost mission architectures for small satellite missions to Mars. Given strict programmatic constraints, the focus of the study was on a low cost, short mission development schedule, and with a cost-driven spacecraft design and mission architecture. This study was followed up by a pre-Phase A industrial study with European primes to investigate current European technology heritage and how it could be adapted to a variety of low-cost Mars missions. Initially, small satellites (<500kg) were considered, however it became clear that satellites with masses of 650-900kg at Mars were at the "sweet spot" of the trade between the cost driven programmatic constraints and performance outcomes of mission. The outcome of both the CDF study and the industrial study indicated technical and programmatic feasibility for a 2028 launch, therefore there is an opportunity to fill a critical data gap for the European science and exploration community at the end of the decade with a small, low cost mission to Mars. A longer term series of low cost Mars missions could then be envisaged on a regular cadence in the 2030's.

Several additional relevant concepts are also under study, including an adaptation of European kick stage technology as interplanetary carriers to enable small satellite Mars missions without the cost and complexity of custom-designed large propulsion modules, and a demonstration of aerocapture technologies at Mars. Aerocapture is the use of aerodynamic drag from a single pass through the atmosphere to decelerate enough to achieve orbit insertion, rather than doing so by propulsive means. This concept, if successfully implemented, could then be available to trade vs. propulsive orbit insertion in the design of larger missions (whether to Mars in the frame of human-scale exploration scenarios, or to other worlds with atmospheres). A small science mission could offer an ideal opportunity to 'piggyback' a flight demonstration of this technique at Mars.

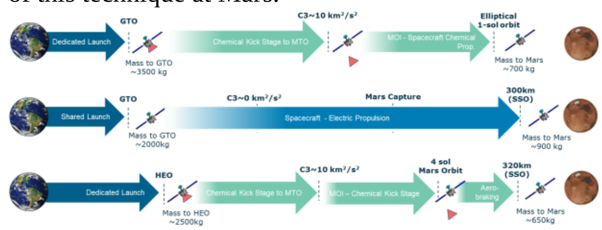

Figure 1: Potential low cost Mars transfer scenarios

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References:[1] Parfitt C.E. et. al. Small Mars Mission Architecture Study (SMARTieS) CDF Study Report, CDF-205(A), 2020

THE ESCAPADE MISSION DESIGN. J. S. Parker,[1] C. Ott[2], A. Koehler[2], S. Baskar[2], and T. M. Sullivan[2], [1]Chief Technology Officer, Advanced Space, parker@advancedspace.com, [2]Astrodynamicist, Advanced Space.

Introduction: The Escape, Plasma and Acceleration Dynamics Explorers (ESCAPADE) mission is supported by NASA's Science Mission Directorate (SMD) within an opportunity under the Small Innovative Missions for Planetary Exploration (SIMPLEx) program. The ESCAPADE mission includes two identical 374-kg spacecraft that will enter the same elliptical orbit about Mars, collecting in situ atmospheric data in formation over six months. The spacecraft will then transition to different science orbits and collect spatially different, simultaneous observations of the atmosphere over the next five months, with opportunities for extensions. This paper describes the mission design that enables two spacecraft to launch via one or two low-cost rideshare launches, transfer to Mars, and establish the Martian formation.

Launch: ESCAPADE has been designed to be capable of launching aboard a wide variety of rideshare launches. Each of the spacecraft may be launched on different launches or together on the same vehicle. ESCAPADE can certainly launch aboard a direct-to-Mars rideshare, if the launch is scheduled during late September or early October, 2024. ESCAPADE has sufficient propellant to boost itself from a 1.6-day orbit if the rideshare deposits one or both of the spacecraft in such a large Earth orbit. This paper describes the range of rideshare orbits that do satisfy ESCAPADE's mission, and how ESCAPADE can harness carefully designed maneuvers to shift from, say, a 98-degree orbit (rideshare with a Sun Synchronous orbiter) to the interplanetary cruise. ESCAPADE's baseline design implements a rideshare with a single Sun Synchronous primary host.

Interplanetary Cruise: ESCAPADE's interplanetary cruise is designed to transfer the two spacecraft from their nominal Trans-Mars Injection (TMI) states to their nominal Mars Orbit Insertion (MOI) states. The two TMI maneuvers are scheduled for October 1 and 3, 2024; the two MOI maneuvers are scheduled for September 1 and 3, 2025. The interplanetary cruise is designed to minimize fuel use while satisfying planetary protection and the ability to communicate to both spacecraft simultaneously via the DSN's Multiple Spacecraft per Aperture (MSPA) capabilities. This requires that the two spacecraft fly within only 0.06 degrees or less of each other, as viewed by a DSN antenna. The preliminary design of the maneuvers to achieve this cruise will be presented.

Orbit Reduction and Transition to Science Formation at Mars: When the two ESCAPADE vehicles arrive at Mars, they each enter capture orbits about Mars. The orbit reduction phase then transitions the two vehicles from being in two distinctly different orbits about Mars, which do not cross, into a single elliptical orbit about Mars. This process uses 7 maneuvers on each spacecraft, designed to carefully reduce each spacecraft's orbit and transition them into the same orbit within tolerance, all in the presence of maneuver execution errors and several other navigation errors. This is the first time two spacecraft will enter the same orbit simultaneously and establish a string of pearls formation about another planet.

Science Phase: The ESCAPADE science phase includes Science Campaign A and B. Campaign A involves the two spacecraft orbiting Mars in nearly identical orbits, with one spacecraft leading the other by 5 to 30 minutes, such that they adjust their spacing in an oscillation and sample all separations between 5 and 30 minutes several times. Their periapse altitude is in the upper atmosphere, apoapse altitude is at 8400 km, orbital inclination is 65 degrees, and periapse is situated largely over the Southern hemisphere to maximize the science value of the observations. Science Campaign A extends for six months. Each spacecraft then adjusts its apoapse, with one spacecraft raising it to 10,000 km and the other lowering it to 7000 km. In this way the orbits precess differently and the two spacecraft sample different regions of the Martian environments. This campaign extends five months beyond Campaign A.

The science orbits involve the spacecraft dipping into the upper atmosphere to collect in situ measurements of particles and ions. The orbital periapses are adjusted weekly to track the peak density of the atmospheric passage, maximizing the science return.

Solutions: The ESCAPADE mission is the first mission to place two spacecraft into the same elliptical orbit about another planet in a formation, through a very low budget opportunity. The mission design described here enables the mission to collect high value science with minimal risk within the constraints of this opportunity. This paper focuses on the GNC challenges and solutions developed to meet these objectives.

PRECOMPETITIVE COLLABORATION ON PLANETARY PROTECTION TECHNOLOGIES TO ENABLE LOW-COST MARS EXPLORATION. G. Profitiliotis[1], [1]Department of Humanities, Social Sciences, and Law, National Technical University of Athens, 9, Iroon Polytechneiou St., Zographou Campus, 15773, Athens, Greece, gprofitil@mail.ntua.gr.

Planetary Protection has been defined as a set of guidelines concerning the avoidance of bidirectional biological material exchange between the Earth and other celestial bodies; the protection of the terrestrial biosphere from extraterrestrial biological material is called "backward contamination" mitigation, while the protection of extraterrestrial environments from terrestrial biological material is called "forward contamination" mitigation. The goals of planetary protection are, on the one hand, the protection of astrobiology science from false results, and, on the other hand, the protection of the terrestrial biosphere from the hazards of the introduction of putative non-terrestrial life [1].

As the barriers to entry in the field of Mars exploration gradually become lower, thanks to technological innovations and organizational changes that are taking place, the number of players interested in entering the field is expected to increase. Indeed, a number of private space actors are already pioneering such endeavors, heralding a potential paradigm shift in how Mars exploration might be conducted in the future. However, this increased interest, along with the regulatory gaps and ambiguities that permeate this field, may drive the emergence of "tragedy of the commons" or "free-riders" types of problems [2].

As it has been previously demonstrated [3], the prevention of forward and backward contamination between Earth and Mars is perceived as highly valuable by citizens, in an economic sense, who seem to be willing to pay significant amounts to maintain the economic benefits that they believe they derive from the avoidance of biological cross-contamination between Earth and Mars. This finding suggests that there is an imminent need to consider planetary protection from an extended perspective that does not focus solely on the economics of the private costs and private benefits which influence the internal decision-making of public and private organizations, but also includes the external costs and external benefits that extend to other actors as well.

Consequently, planetary protection should not be viewed as a nonsensical legal obstacle to be overcome by the space actors that will undertake Mars exploration in the future; rather, it should be viewed as an avenue that accommodates the interests of both the multitude of space actors and of society at large, and should thus be maintained as a beneficial foundation for any upcoming activities. Nevertheless, it can be expected that, in an effort to decrease overall mission costs, space actors may set a firm goal to minimize planetary protection costs that are internal to their core business [2]. To prevent any irresponsible oversights and actions for reducing costs that may prove detrimental to the overall interests of space actors and of society at large, planetary protection technologies should not be seen as an area for active competition but should be reframed as a critical field for precompetitive collaboration.

Precompetitive collaboration refers to cooperative early-stage research and development which, instead of focusing on the creation of marketable goods, produces data or tools, not for the sake of a single organization but for the benefit of a whole industrial sector. This model of collaboration allows competitors to share and better utilize their financial and knowledge resources, in order to overcome common problems, support enabling technologies, and set standards [4].

Under such a precompetitive collaboration scheme for planetary protection technologies, perhaps promulgated on the United Nations level [5], international and commercial actors may form crucial partnerships by pooling their resources to finance programs that will pursue the anticipated desirable goal of cost reduction. This collaborative funding effort may be accelerated by a flagship project that might take the form of an international planetary protection analogue program and its respective testbed facility [6].

References: [1] Frick A. et al. (2014) *Advances in Space Research, 54(2)*, 221-240. [2] Profitiliotis G. and Loizidou M. (2019) *Advances in Space Research 63(1)*, 598-605. [3] Profitiliotis G. (2021) *Advances in Space Research, 67(12)*, 4158-4176. [4] Contreras J. L. and Vertinsky L. S. (2016) *North Carolina Law Review, 95(1)*, 67-132. [5] Profitiliotis G. (2020) *Journal of Science Policy & Governance, 16(2)*, 1-7. [6] Conley C. A. and Rummel, J. D. (2008) *Acta Astronautica, 63*, 1025-1030.

DRAG MODULATION TRAJECTORY CONTROL FOR DELIVERY OF LOW-COST MARS ORBITERS AND LANDERS. Z. R. Putnam[1] and D. M. Fawley[2], [1]University of Illinois at Urbana-Champaign, zputnam@illinois.edu, [2]University of Illinois at Urbana-Champaign, dfawley2@illinois.edu.

Introduction: Future low-cost science missions to Mars will benefit from independent delivery systems: for orbiters, orbit insertion capability; for surface missions, entry, descent, and landing capability. Drag modulation is a simple, potentially low-cost trajectory control method that can be used to reduce terminal state error during entry, descent and landing and orbit insertion via aerocapture. Drag modulation is uniquely suited to small, low-cost vehicles because it does not require a reaction control system, ballast mass, or flight at non-zero angles of attack, yet still provides good accuracy. [1][2] In this work we assess multiple guidance, navigation, and control options for aerocapture and entry drag modulation systems. We further identify likely control authority boundaries to inform approach navigation accuracy requirements and drag area size requirements.

Advances in deployable decelerators and associated thermal protection systems, such as ADEPT [3], enable sufficiently large drag areas for drag modulation while maintaining compatibility with rideshare launch volume requirements (e.g. ESPA). Development of a drag modulation capability for low-cost missions to Mars would expand rideshare opportunities for targeted science investigations: with an independent entry or aerocapture system onboard, a small mission could rideshare with any spacecraft on a Mars-bound trajectory, e.g. a small satellite orbiter could rideshare with a host lander or share a launch with a host but cruise to Mars as a free flyer.

Drag modulation is not a new concept but is receiving renewed attention due to its potential application to low-cost missions. Fundamentally, drag modulation trajectory control utilizes changes in drag area to modify the vehicle ballistic coefficient in flight. The ratio of maximum to minimum ballistic coefficient is a measure of the control authority of a drag-modulation system. Larger ballistic coefficient ratios imply wider flight-path angle corridors to accommodate approach navigation and targeting error, improved capability to fly out day-of-flight uncertainty, and a larger range of available ground/orbit targets from a given initial state.

The disadvantages of drag modulation trajectory control are the lack of out-of-plane control authority and the need for a high-dynamic pressure jettison event. However, recent studies have shown that the absence of out-of-plane control authority may not be an issue with current approach navigation accuracy and the favorable ballistic coefficient ratio between the vehicle and the jettisoned drag area make far-field recontact improbably and studies have shown that near-field recontact is also unlikely [4][5].

Recent studies have shown drag modulation can provide good accuracy for entry [2] and aerocapture [1] at Mars. Titan and Venus aerocapture and an Earth-based aerocapture demonstration mission using drag modulation have also been studied. [6][7] Results indicate that single-stage discrete-event drag modulation likely provides sufficient performance to support a variety of science missions. For aerocapture, drag modulation systems significantly reduce required propellant mass; this feature of drag modulation systems may be particularly attractive for rideshare missions where perceived volatility of a relatively-large small satellite propulsion system may complicate host accommodation. For entry missions, drag modulation may provide landed accuracy in the same class as the Mars Science Laboratory with sufficiently accurate approach navigation and targeting at a lower system complexity than existing bank-to-steer systems.

System Concept: We assume the simplest possible drag-modulation system for aerocapture and entry: discrete, single-event jettison. A drag skirt is deployed prior to atmospheric interface (possibly prior to launch). The vehicle begins to decelerate after passing atmospheric interface. During atmospheric flight, the onboard guidance, navigation, and control system determines when to jettison the drag skirt to achieve desired terminal conditions (landed accuracy for entry, apoapsis altitude for aerocapture). After the drag skirt is jettisoned, the vehicle continues to decelerate until the terminal condition is reached. The onboard navigation system is assumed to consist of an inertial measurement unit only.

Real-time guidance algorithm options are assessed, including numeric predictor-correctors (NPC) and velocity-based triggers. The NPC algorithms integrate the equations of motion each guidance cycle to predict terminal states; the drag skirt jettison time is then adjusted to null predicted terminal state error. Velocity triggers are developed using pre-flight simulation data to determine a nominal jettison velocity. This velocity may be used directly, or state-based correction terms may be added to improve accuracy.

Application to Entry: For Mars entry, the NPC performed the same for a range of relevant ballistic coefficient ratios, but velocity-trigger performance generally worsened with increasing ratio (Fig. 1). The NPC algorithm can accurately target a significantly larger proportion of the nominal range capability relative to the velocity trigger. Overall, while velocity trigger performance is not as consistent as the NPC, the trigger shows comparable performance for steep initial flight-path angles, high initial velocities, low ballistic coefficient ratios, and short-range targets.

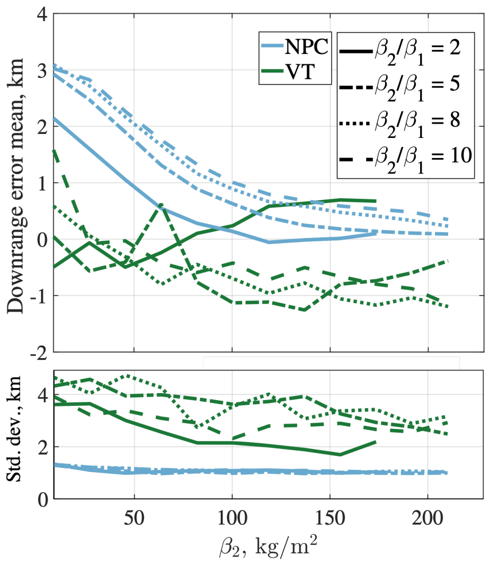

Figure 1. Entry accuracy across a range of parameters [8].

The feasible entry space was investigated for both algorithm types by varying the entry flight-path angle and entry velocity. The robustness of the NPC results in a feasible space limited by vehicle system parameters rather than guidance performance. The velocity trigger feasible space is limited by guidance performance for shallow entries, but vehicle system parameters are limiting factors for steep entries. The NPC is capable of accuracies better than 5 km across a wide range of initial conditions and vehicle parameters; the velocity trigger can provide accuracies better than approximately 10 km across the same parameters. The velocity trigger may be a desirable option when cost is more important than accuracy and onboard computational resources are limited.

Application to Aerocapture: The NPC and velocity trigger algorithms perform similarly for aerocapture applications. Similar to entry, the NPC provides consistent good performance across a range of target orbits and initial conditions. Using a simple velocity trigger without correction terms results in unacceptable performance for low-altitude target orbits (Fig. 2). For higher altitude orbits, successful orbit insertion is possible, but the propellant mass required to eliminate insertion errors is higher for the velocity trigger. Overall, aerocapture significantly reduces required propellant mass and overall orbit insertion system mass relative to fully-propulsive orbit insertion options. Further, the low ballistic coefficient of the aerocapture vehicle results in a relatively benign aerothermal environment, and peak acceleration is well within limits for robotic spacecraft.

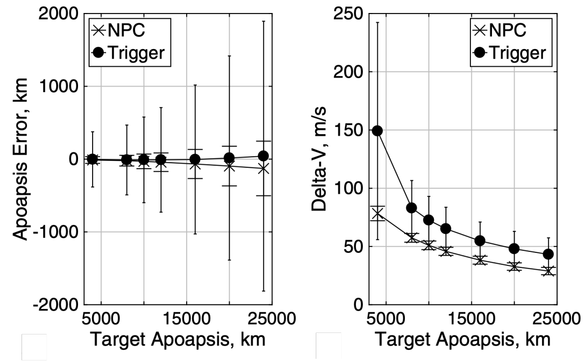

Figure 2. Aerocapture accuracy across target orbits [9].

Conclusions: Results indicate that modest ballistic coefficient ratios, coupled with capable real-time guidance algorithms, may provide sufficient flight performance over a wide range of approach states for both aerocapture and entry drag modulation systems in support of low-cost targeted science investigations at Mars. Drag modulation systems can accommodate the range of likely ballistic coefficients (and associated vehicle and payload masses) for small, low-cost missions and accommodate landing at a range of surface altitudes. Modern commercial and flight processor throughput likely mitigates most of the disadvantages of the better-performing numeric predictor-corrector guidance algorithms, but simpler guidance algorithms may provide adequate performance for some missions. Further, nearly identical drag modulation systems may be used for both aerocapture and entry, reducing development cost and providing more flight experience with a common system, which may enable incremental system improvements and additional per-unit cost reduction.

References: [1] Putnam Z. R. and Braun R. D. (2014) *J Spacecr Rockets*, 51, 139-150. [2] Putnam Z. R. and Braun R. D. (2014) *J Spacecr Rockets*, 51, 128-138. [3] Smith et al. (2015) *IEEE Aerospace Conf.* [4] Rollock A. E. and Braun R. D. (2020) *AIAA SciTech Conf.* [5] McClary M. and Putnam Z. R. (2021) *AIAA SciTech Conf.* [6] Roelke E. and Braun R. D. (2021) *J Spacer Rockets*, 58, 190-199. [7] Werner M. S. and Braun R. D. (2019) *J Spacer Rockets*, 56, 1704-1713. [8] Fawley D. and Putnam Z. R. (2021) *J Spacer Rockets*, 58, 1071-1083. [9] Falcone G. et al. (2019) *J Spacecr Rockets*, 56, 1689-1703.

Prospecting for Resources at Human Landing Sites on Mars. N.E. Putzig[1], F. Bernardini[1], G.A. Morgan[1], H.G. Sizemore[1], R.N. Clark[1], M.R. Perry[1], W.P. Sidney[2], A. Abbud-Madrid[3], Alessio V. Pelella. [1]Planetary Science Institute, [2]University of Colorado, [3]Colorado School of Mines. Contact: nathaniel@putzig.com.

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Introduction: With growing interest in sending humans to Mars, the identification and assessment of in-situ resources at intended landing sites is of paramount importance not only for establishing a permanent presence but also for enabling return-propellant production on early missions.

Remote-sensing orbital Mars missions up to this point have been focused primarily on science return, and the evaluation of resources has been limited to the use of data from instruments designed for other purposes [1-8]. Thus, there remain a number of critical uncertainties, notably in the location, depth, and purity of buried ice and in the characteristics of the ice overburden as well as other resources such as hydrated minerals. While discussions are underway to implement a complex International-Mars Ice Mapper mission, it remains to be seen whether this effort will be carried through to launch and whether it will provide all the requisite capabilities for resource assessment.

Here, we present a mission concept for rapidly implementing a resource-prospecting orbiter to address these uncertainties using instruments and a spacecraft bus already at high technology readiness levels. Leveraging previous and current assets, the concept will also implement an optimal orbit strategy to build on previous global ice-mapping efforts (Fig. 1).

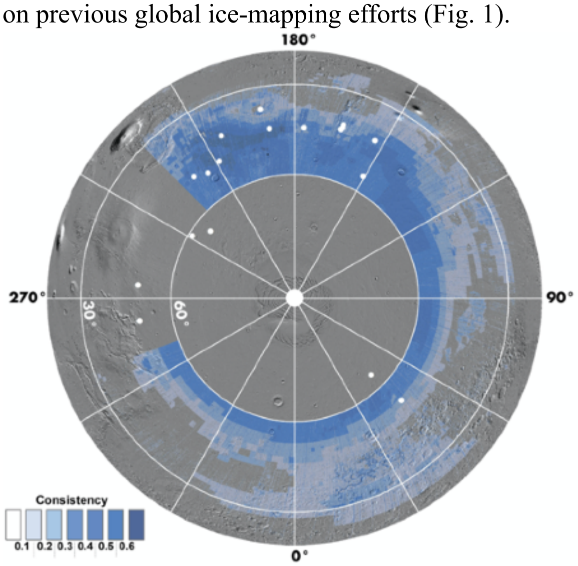

Fig 1. Mars Northern Hemisphere Ice Consistency [8]. White dots are locations of ice-exposing impacts [1].

Instruments: The science and exploration payload is composed of a multi-band radar sounder operating in the VHF frequency spectrum, an imaging spectrometer, and a high-resolution context camera.

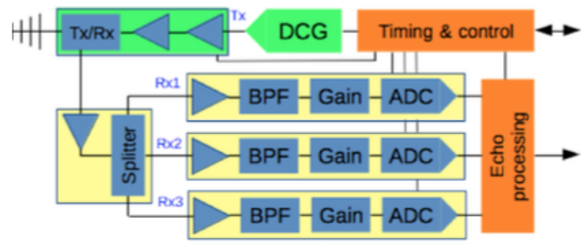

Fig. 2. Radar sounder architecture.

To enable characterization of buried ices and their overburden, the radar sounder (Fig. 2) will provide 1-m or finer vertical resolution, a penetration depth of 20 m through regolith, and an along-track footprint of less than 100 m (with synthetic aperture processing).

The imaging spectrometer design will be focused primarily on identifying and mapping hydrated minerals, but it will also allow thermal measurements for assessing physical properties of surface materials. A spectral range of 0.4 to 5 microns with a resolution of <10 nm FWHM and a sampling interval of 5 nm will enable such measurements, and a spatial resolution of 20 m per pixel will allow characterization at landing-site scales.

For the imaging camera, a novel approach will be used to achieve high resolution at lower cost, specifically using commercial off-the-shelf technologies while also taking a focused observing approach of a few images per orbit concentrated on relatively small targets.

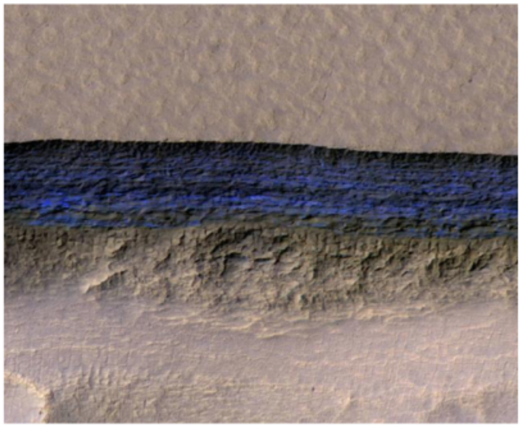

Fig. 3. Exposed ice deposit at 56°S imaged by HiRISE.

Mission Design: In general, an overall engineering simplification is achieved by using proven technologies and constraining the primary mission to resource prospecting within focused areas. This will lead to important reductions in risk and overall costs for the spacecraft itself and for operations. Because of this increased efficiency and lower coverage area for the nominal mission, it is also possible to use a smaller mass onboard memory, an important aspect when radars are involved. A proportional reduction in the download data volume reduces the performances required for the onboard downlink equipment.

The mission concept is patterned after, but not constrained to, a flight-proven, low-cost, medium-size mission bus (one cubic meter in volume) (Fig. 4). The mission plan is simplified by limiting targeting in the primary mission to areas of highest resource interest that are scattered across the northern and southern mid-latitudes. By adopting a focused approach, it is possible to reduce the delta-V needs of a typical science mission, concentrating the consumables and operations to the prospecting activities. Once the primary mission is over, it will be possible to target additional areas, to satisfy other needs.

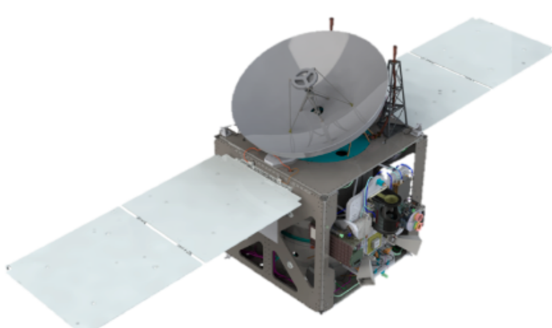

Fig. 4. CU LASP Astrolabe spacecraft bus.

Fig. 4. CU LASP Astrolabe spacecraft bus.

From a flight-dynamics point of view, in contrast to science-driven missions that require circular, sun-synchronous polar orbits to facilitate consistent observational conditions while achieving global mapping (e.g., Mars Reconnaissance Orbiter), a mission focused on local resources is instead concerned with a more targeted approach. Low- and mid-latitude regions with previous detections of potential shallow ice deposits are of the highest value for resource prospecting. We therefore propose a mission architecture with a highly eccentric, high-inclination polar orbit, positioning the periapsis over the mid-latitudes, alternating northern and southern ones, perhaps with a seasonal rotation of the apsides line.

Summary: Future steps in the human exploration and colonization of Mars require enabling technologies and enabling knowledge. Efficient, dedicated, and resources-focused missions are the key to building up the required knowledge.

The workshop presentation will highlight how a different approach in defining mission constraints enables substantial cost efficiencies while reducing the technological risk through the use of less exotic components and solutions.

References: [1] Byrne S. et al. (2009) Science 325, 1674–1676. [2] Levy J.S. et al. (2014) JGR 119, 2188–2196. [3] Holt J.W. et al. (2008) Science 322, 1235–1238. [4] Plaut J.J. et al. (2009) GRL 36, L02203. [5] Karlsson N.B. et al. (2015) GRL 42, 2627–2633. [6] Bramson A.M. et al. (2015) GRL 42, 6566–6574. [7] Stuurman C.M. et al. (2016) GRL 43, 9484–9491. [8] Morgan G.A. et al. (2021) Nat. Astro. 5, 230–236.

A LOW COST TUNABLE LASER SPECTROMETER FOR MARS WATER VAPOR, TRACE GASES, AND EDDY FLUX MEASUREMENTS.

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Introduction: The Mars science community has specifically recognized the importance of measurements of water vapor, trace gases, and turbulent eddy fluxes within the atmosphere of Mars. The MEPAG Science Goals Document identifies understanding the structure and processes operating in boundary layer as its highest priority Climate Science Goals [1]. We have developed an instrument that is capable of high precision and high frequency (>40 Hz) measurements of water, CO_2, and various other trace gases, and which supports the acoustic determination of wind [2] and eddy flux measurements (Fig. 1).

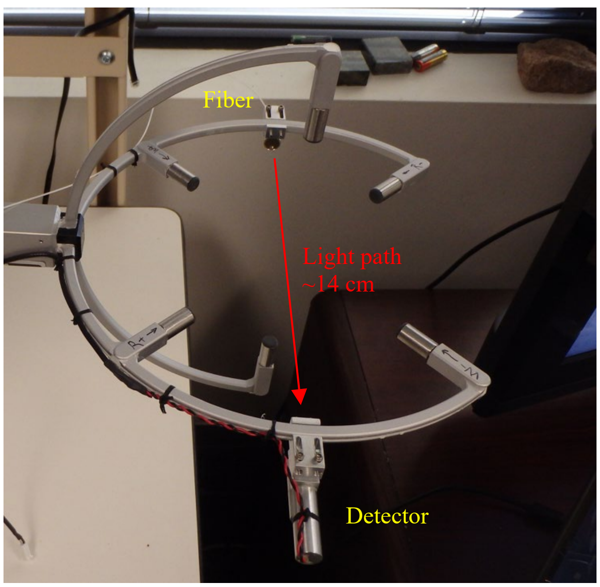


Figure 1. The TLS sensor consists of a laser diode, connected through fiber, and a detector. The TLS sensor above is mounted on an acoustic anemometer structure. Any structure that provides a mechanically stable path of 10-20 cm is suitable for the TLS.

Science Traceability and Measurement Requirements: Prior and ongoing meteorological measurements are insufficient to determine the physical processes associated with the exchange of water between the surface and atmosphere and the transport of water vapor by eddies. The same is true for other trace gases. Additionally, there is a lack of high quality and high frequency wind and temperature data. These parameters are measured best through acoustic techniques, but measurement of CO_2 is needed to produce the highest fidelity measurements [2].

Water vapor: If the Martian air were saturated with water, the water vapor pressure associated with the warmest air temperatures would be in excess of 600 Pa. While this value exceeds the total atmospheric pressure on Mars, it nonetheless provides a hard physical upper limit of dynamic range for a Mars water vapor sensor. At the other extreme, we might imagine just 10% relative humidity at 150 K. (Observations indicate that air in the polar hood regions is very cloudy, suggesting a value closer to 100%.) A relative humidity of 10% at 150 K corresponds to a vapor pressure of order 10^{-5} Pa. Thus, the total dynamic range for a water vapor sensor is no greater than 7 decades (600 Pa to 10-5 Pa). This corresponds to a vapor mixing ratio of 10^{-8} to 10^{-1}. A resolution of ~1% water concentration or mixing ratio is adequate to address science objectives.

Carbon dioxide: The dominant gas in the Martian atmosphere, CO_2, is of variable concentration due to its volatility at Mars temperatures and pressures and the exchange with the surface at high latitudes (i.e., the seasonal polar caps). Consequently, the gas can serve as a good indicator of the CO_2 deposition/sublimation cycle and as an indicator of atmospheric mixing. Additionally, if acoustic methods are used to determine temperature or winds, CO_2 abundance measurements can be used to accurately determine the thermodynamic properties that relate the adiabatic speed of sound to temperature [2]. For minimal error, CO_2 accuracies of better than 0.1% are ideal.

Methane: The accurate measurement of methane remains a hot topic due to the apparent discrepancy between surface and orbital measurements. Accuracy to >0.1 ppbv are required, based on the surface measurements of MSL. Additionally, the measurements should be able to be done frequently and with low power in order to better characterize the diurnal and seasonal cycle [3].

Eddy Fluxes: Turbulent eddies in the planetary boundary layer of the terrestrial planet atmospheres are the primary mechanism by which energy, momentum, gasses, and aerosols are exchanged between the surface and the atmosphere. The importance of eddies has long been recognized by the Earth atmospheric science community. Every climate and weather forecasting model in existence relies extensively on turbulent eddy theory supported through observational validation. The importance of eddies in atmospheric dynamics, chemistry, and climate science cannot be overstated.

The atmospheres of the other terrestrial planets are no different than Earth. An understanding of the climate and weather of these other planets rests up-on the work and transport of turbulent eddies.

Turbulent eddy fluxes have never been measured on Mars, because doing so requires high precision, high frequency, cross-correlated measurements of wind with temperature and gas abundance. Model estimates of eddy fluxes vary by factors of two or more [4][5], and these differences can result in different predictions about the safety of landing sites, as well as general scientific results. Measurement frequency of wind and gas must be >40 Hz. Wind accuracy of >1 cm/s and gas accuracy of > 0.1% is required.

Instrument Description:

Heritage. All of the needed measurements for Mars identified previously are routinely done for Earth with a tunable laser spectrometer coupled to an acoustic anemometer. Therefore, we used as a starting point for our Mars instrument, a compact and low-power field-quality TLS hygrometer developed and manufactured by Southwest Sciences, Inc. (SWS). Versions of this instrument function in the laboratory and field environment on Earth [6][7], and have been flown on high-altitude balloons, sounding rockets and on aircraft. The instrument consists of a vertical cavity emitting laser (VCSEL) source a photodetector, and laser driving and digital signal processing electronics. For most gases, wavelength modulated spectroscopy (WMS) is used to increase sensitivity and reduce 1/f noise in particular. Fractional absorption accuracies to better than 10^{-5} are now routinely made in the lab and with commercial TLS systems using WMS. The WMS signal is analyzed with multi-linear least squares fitting to find the concentration. These techniques easily achieve the needed accuracies for water and CO_2.

The Mars TLS. Over the last decade, we have matured the commercial system to TRL 6. Further, we have added the capability to add up four channels as part of the standard design. These channels can be used to measure four different gases, or they can be used for redundancy. An optional multipass optical cell can be included for low abundance gases like CH_4, although the addition of that element lowers the full instrument to TRL 5. The Mars TLS is intended to be flown as a stand-alone sensor, or, ideally, directly incorporated onto the structure of an acoustic anemometer.

Current best estimates for resources are <500 mW, <750 g (sensor plus 1U electronics), and volume (≤125 cm^3 plus electronics). Cost is estimated at $5M-$10M depending on mission class and mission requirements.

Relevant Environment Demonstration: Since the TLS is ideally accommodated on an acoustic anemometer structure, a great deal of field testing used this configuration. Additionally, key components, especially the laser diodes, where subjected to temperature cycling between liquid N_2 and the laboratory environment. The diodes are not susceptible to Mars radiation based on testing results from the vendor and other users. Recently, the diodes were drop tested to 2000g by JPL and found to survive and function without issue. This last test indicates that the instrument could likely be accommodated on a small, Mars drop lander [8].

In the field, the TLS was found to perform flawlessly under harsh conditions of wind, rain, snow, hail, freeze/thaw cycle, animals, and insects (Figure 2). Not all of these are (obviously) relevant to Mars, but it did demonstrate the robustness of the entire instrument under extreme conditions. For all practical purposes, the Earth environment is far harsher than Mars, except for the cold temperatures. Cold temperatures were validated at the component level, as previously indicated. Low pressure is inconsequential (i.e., not relevant) for operation, function or performance.

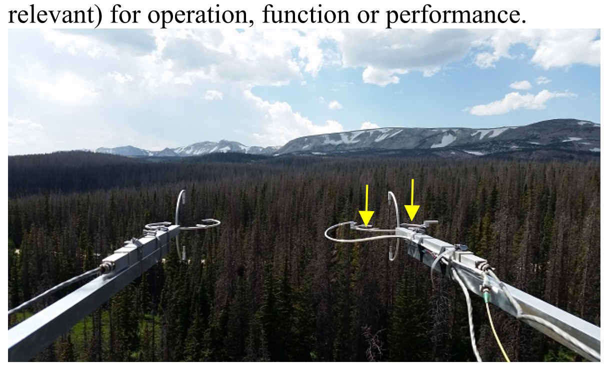


Figure 2. The TLS was deployed in many harsh terrestrial environments, such as shown above near tree line (~10,000 ft) in the Snowy Range of Wyoming. The yellow arrows show the location of the very small laser and detector comprising the TLS sensor accommodate on an anemometer. It was also deployed at the base of the Colorado foothills and subjected to >80 mph winds, hail, rain, snow, and freeze/thaw.

Acknowledgments: Initial instrument development was funded by the NASA PIDD Program with further development and maturation supported by SwRI IR&D.

References: [1] MEPAG, 2020. [2] Rafkin S., and Banfield, D. (2020), *Plan. & Space Sci.*, 193. [3] Pla-Garcia et al. (2019), *J. Geophys. Res. Planets*, 124(8). [4] Michaels, T. I., and S. C. R. Rafkin (2004), *QJRMS*, 130(599). [5] Toigo, A. D., et al. (2003), J. Geophys. Res., 108(E6). [6] Paige, M. E. (2005), *J. Atmos. & Ocean. Tech.*[7] Zondlo, M. A., et al. (2010), J. Geophys. Res., 115(D20). [8] Diniega et al., (2021), Low Cost Mission to Mars Workshop.

Thruster-Assisted Legged Mobility for Explorations on Mars. A. Ramezani[1] and K. Sreenath [2], [1]Electrical and Computer Engineering Dept., Northeastern University, Boston, MA (a.ramezani@northeastern.edu), [2]Mechanical Engineering Dept., University of California Berkeley (koushil@ucberkeley.edu).

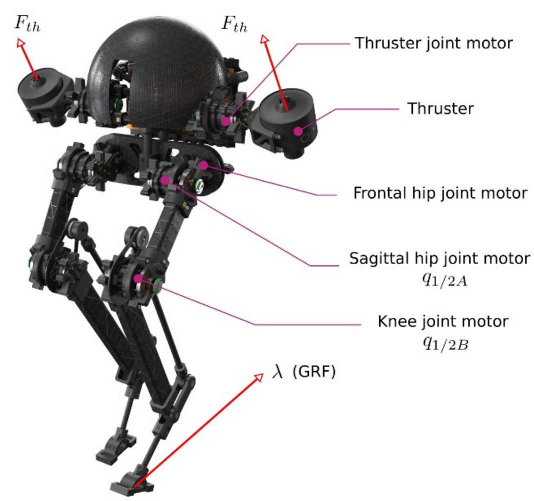
Introduction: Past missions to Mars revealed surface characteristics of the Martian regolith that were not apparent from distant observation. Specifically, in NASA's mission, where twin Mars Exploration Rovers named Spirit (MER-A) and Opportunity (MER-B) landed on the Martian surface, the rovers reported extremely rough terrain posing severe mobility challenges to any ground robot developed by that date. The uncertainty of regolith porosity and density in different regions creates an obstacle for machinery to move through without being stopped. In an adversarial environment such as Mars, multi-modal mobility can significantly increase the chance of success. While the most useful configurations of future Mars rover explorers are still under development, it is already clear that future rovers must operate quite differently from NASA's previous, successful family of ground rovers. JPL's current Perseverance design with its aerial hitchhiker emanates the message that the importance of multi-modal mobility is getting endorsed by the designers.

Thruster-Assisted Legged Mobility on Mars: Motivated by the recent success of Perseverance and Ingenuity, in this project, we want to explore the feasibility of achieving hopping-based legged mobility on the Moon using an existing TRL-4 platform at Northeastern University (NU) called Harpy (see *Figure 1*).

In brevity, Harpy comprises two legs and two coaxial thrusters attached to its torso. Its inverted-pendulum-style design, where the total mass is located on the torso by designing extremely lightweight legs, facilitates the platform's closed-loop feedback design. The thrusters permit hopping-style locomotion on rough terrain while the legs support landing at each hopping motion. The idea is to use the legs to achieve intermittent interactions with the Martian surface and use the thruster to control Harpy's posture during the flight time.

State of The Art. State-of-the-art bipedal legged robots have no thrusters. Therefore, their ability to regulate ground contact forces is limited to upper body posture control. This limitation particularly becomes important in rough terrain locomotion problem because the robot can violate ground force feasibility conditions by virtue of ground topology irregularities. Partial gravity over Martian surface and the leg-thruster combination can offer novel mobility means for space explorations and support new research opportunities for unexplored dynamics and control problems.

Figure 1: Shows NU's Harpy platform.



Challenges and Research Gap. The major challenges remain at the hardware and control design levels. Our current prototype at NU is under development and grand challenges associated with the design and fabrication have been resolved. A major challenge so far solved by the NU team constitutes the design and development of lightweight hardware that can accommodate actuators used in legged locomotion. These actuators are often bulky and the integration of several actuators can result in high payloads which are not desirable in a hopping system.

Control is another important challenge resolved addressed in multiple publications so far [1]. While legged robot control have immensely advanced in recent years, thruster-assisted robots have largely remained unexplored. Control design in these systems involves the synchronous actuation of the legs and the thrusters.

Future Steps and Concluding Remarks: Our future steps includes 1) expanding our understanding of how Martian partial gravity can be copied in our system to realistically simulate our controllers; 2) exploring motion planning algorithms that permit switching between different forms of mobility modes to minimize/maximize desired costs, e.g., efficiency or operation time; 3) ground effects

Acknowledgments: We like to thank students at NU who helped us develop the preliminary version of Harpy.

References:

[1] K. Liang, E. Sihite, and A. Ramezani, ”Rough-Terrain Locomotion and Unilateral Contact Force Regulations With a Multi-Modal Legged Robot,” *American Control Conference (ACC)*, New Orleans, Louisiana, May 26-28, 2021.

Efficient and Endured Aerial Mobility on Mars Using Novel Morphing Micro Aerial Vehicle Designs. A. Ramezani, [1] E. Sihite[2], S. Devey[2] and M. Gharib[2] [1] Electrical and Computer Engineering Dept., Northeastern University, Boston, MA (a.ramezani@northeastern.edu), [2]Aerospace Engineering Dept., California Institute of Technology (ericsihite@gmail.com, sdevey@caltech.edu, mgharib@caltech.edu).

Introduction: NASA's Mars Perseverance rover carried the Ingenuity Mars Helicopter for the first demonstration of aerial mobility on another planet. Weighing only about 4 pounds (1.8 kilograms), Ingenuity's propulsion systems are based on a standard coaxial configuration consisting of four specially made carbon-fiber blades, arranged into two rotors that spin in opposite directions at around 2,400 rpm – many times faster than a drone on Earth, which is mainly due to Mars' thin atmosphere makes it difficult to achieve enough lift.

The application of rotary-wing systems, which operate based on producing powerful and continuous air jets, can be very costly from an energy consumption standpoint. While the magnitude of dissipative and drag forces acting on the Ingenuity robot passing through Mars atmosphere can be negligible, the large and fast-rotating blades used to maximize lift in a low-density atmosphere require powerful actuators because of their massive mass inertia. These energy-hungry actuators can significantly reduce the operation time of the Ingenuity robot. We have developed a flapping Micro Aerial Vehicle (MAV), shown in *Figure 1*, that can offer efficient aerial mobility for future Mars explorations. Here, we briefly describe the technology.

State of The Art: Many flapping robot designs have been introduced, including small and medium to larger robots, which all share a common design theme: no active wing planform articulations. In all of these systems, the wings are widely made of a single segment. They can translate relative to the body to a flapping motion. Hence, these systems are mono-modal because they only possess one kinematic mode. Wing kinematic adjustments occur in the form of quasi-static joint movements at the wing base (e.g., lagging or feathering) for flight control purposes.

Here, we consider wing planform dynamic conformations because of the underlying energy efficiency mechanisms involved in fast wing expansion and contractions [1]. Below we briefly describe the idea.

Efficiency Mechanism for Endured Flights in Mars Thin Atmosphere: One wingbeat cycle in our robot (shown in *Figure 1*) flight consists of two movements: a downstroke phase, which is initiated by both wings expanding and an upstroke phase, which brings the wings upward followed by collapsing the elbows. This motion pattern improves the efficiency of the animal through a two-fold mechanism.

First, during upstrokes, the negative lift force, which depends on the wing surface area is reduced compared to downstrokes yielding a larger net positive force through a single wingbeat. Second, a wing with reduced moment of inertia travels faster in space resulting in shorter upstrokes. This means that the duration within which the center of mass accelerates downwards due to the negative lift force is reduced. Despite being challenging, copying this dynamic morphing feat can significantly improve flight efficiency of future Mars flying robots.

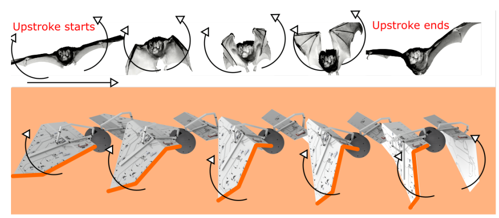


Figure 1: Mars Morphing Micro Aerial Vehicle

Challenges. Here, the main challenges, including hardware and control design, have been partially addressed. In tail-less flapping flight, the main issue is instability since the passively stabilizing components such as tail, rudder, etc., are missing. In our design, the stability properties are even weaker due to dynamic wing planform conformations (we have noticed large pitching instability modes). Therefore, active stabilization through closed-loop feedback must be considered. For active stabilization and control, other than predicting complex fluid-structure interactions, we require small actuators with large energy density for fast response and corrections from a hardware standpoint. Because these morphing drones possess many active coordinates, the state-of-the-art actuators, which are often very bulky, is impossible. Therefore, as part of the ongoing research, we are addressing some of the challenges.

Ongoing Research. Currently, we are studying indicial models of fluid-structure interactions. These models, whose state-space forms can be hard-coded in the system and without significant computation overhead, can accurately predict the resulting aerodynamic forces. While finding these models can be challenging by itself, the gains are enormous for real-time closed-loop feedback.

Concluding Remarks: Mars's unusual environment can pose major challenges for future aerial vehicles. Rotorcraft have shown proven capabilities on Earth; however, they can suffer from their high-rate energy consumptions. We have explored novel bioinspired propulsion designs based on dynamic wing planform conformations that have not been studied before. These designs can promise endured operation times in future Mars explorations.

Acknowledgments: We like to thank students at X in helping us develop the preliminary version of our bio-inspired Mars MAV.

References:

[1] A. Ramezani, S.-J. Chung, and S. Hutchinson, ”A biomimetic robotic platform to study flight specializations of bats,” *Science* (Robotics-AAAS), volume 2, issue 3, pages: eaal2505, February 2017 (cover article; [also featured in *Nature* 542,140 (09 February 2017) doi:10.1038/542140a]).

µLIBS: A MICRO-SCALE ELEMENTAL ANALYSER FOR LIGHTWEIGHT *IN SITU* EXPLORATION.

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Need for microanalyses: Analysis at submillimeter scale, or microanalysis, is the next step forward in Mars exploration. A diversity of rock micro-textures have now been observed *in situ*, sedimentary, igneous or of uncertain origin [1]. Yet the lack of associated chemical micro-analysis prevents further understanding of geologic units. Indeed, microanalyses associates chemical composition with submillimeter scale fractures or void fills, as well as matrices, crystals, mesostasis and alteration phases in igneous rocks or individual grains, concretions and cements in fine-grained sedimentary rocks, all crucial to reconstruct the processes that generated these features and the corresponding environmental history.

Laser Induced Breakdown Spectroscopy (LIBS) is a technique that uniquely provides elemental abundance at submillimeter scale on naturally exposed rocks while removing surface coatings or dust. It can quantify the abundance of major elements (Si, Fe, Mg, Al, Ca, K, Na, Ti) in addition to volatiles relevant to the detection of organics (C, H, N, O, P, S) as well as other light and/or minor elements (Li, Sr, Cr, Rb, Mn...). As it documents elemental composition down to mineral grain size it is also able to detect mineral end-members and infer mineral assemblages in addition to bulk chemistry.

Technology and heritage: LIBS is now widely used in the laboratory for microanalyses, and on Mars nearly a decade of experience with the ChemCam instrument [2], and now SuperCam [3,4], has proven the technique's reliability and capability to analyze rocks at a submillimeter scale for geological investigations. Miniaturization has recently matured and now a set of handheld commercial devices ≤ 2 kg (battery and gas purge included) are available for geochemical analyses [5]. Based on ChemCam and SuperCam subsystems heritage, we propose a new ≤ 1.5 kg instrument to perform LIBS analyses on Mars' surface with architecture closer to handheld devices.

Foreseen capabilities: µLIBS will operate at a distance of 20-50 cm allowing for significant mass reduction compared to ChemCam and SuperCam designs. Importantly, it will include a 2-axis actuated folding mirror allowing for the analysis of multiple targets within an area below the platform (Figure 1). This mechanism will enable precise pointing of the 50 µm laser spot to perform closely-spaced grid observations. It also includes a remote micro-imager to provide dust-free micro-textures with elemental grid overlaid. µLIBS laser can operate at 10 Hz and lower energy, making a typical 10x10 grid observation under an estimated 20 min duration for ~2.3 Wh.

Conclusions: µLIBS can provide micro-scale elemental analyses with science return similar to contact instruments, for lower cost as it can operate remotely with high-precision from a mobile platform undercarriage with no need of arm deployment nor platform turret. It is overall low risk (heritage-based), low mass, and low cost with significant improvements in terms of pointing and rapidity.

References: [1] Mangold N. et al. (2017) *Icarus* **284**, 1–17. [2] Maurice S. et al. (2016) *J. Anal. At. Spectrom.* **31**, 863–889. [3] Maurice S. et al. (2021) *Space Sci. Rev.* **217**, 47. [4] Wiens R. C. et al. (2020) *Space Sci. Rev.* **217**, 4. [5] Senesi G. S. et al. (2021) *Spectrochim. Acta Part B At. Spectrosc.* **175**, 106013.

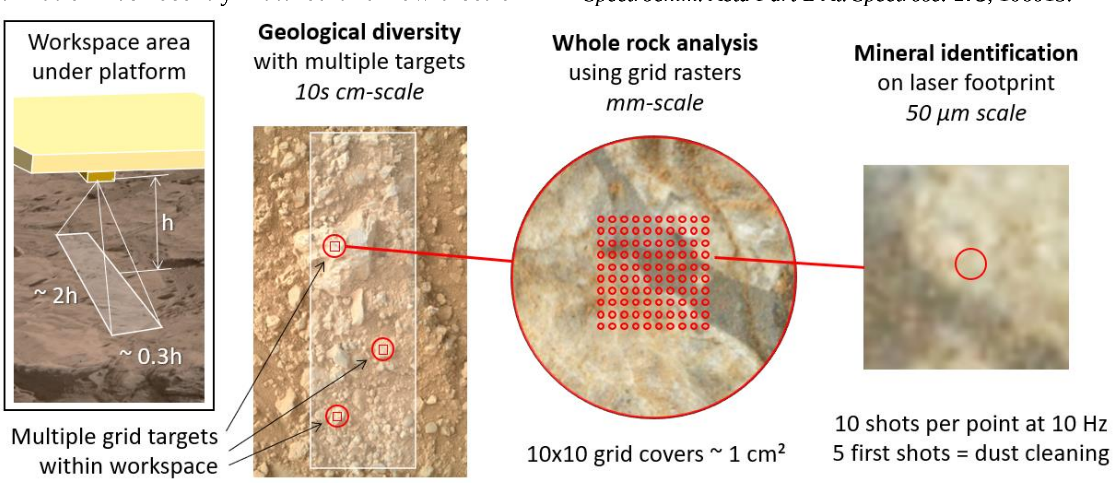

Figure 1: µLIBS provides a nested multi-scale analysis, from the selection of several targets in a decimeter scale workspace to the 50 µm footprint of laser spots following grid rasters. Example workspace: Curiosity rover, sol 387, MAHLI standoff distance at 25 cm on target Ruker.

Role of low-cost missions in preparing for human Mars exploration

Developing an enterprise-level architecture encompassing future human-robotic science and exploration at the Moon and Mars requires a visionary approach to ensure NASA is responsive to national priorities and global science and technology advancement objectives. While the initial capabilities needed to return humans to the Moon may be well understood, NASA is still formulating a long-term infrastructure at the Moon and working to narrow the trade space for the first human missions to Mars. This talk will focus on the formulation and current status of engineering and design applications for a long-term and robust exploration architecture.

THE MARTIAN ATMOSPHERIC GAS EVOLUTION (MAGE) EXPERIMENT: HIGH-GREQUENCY NEAR-SURFACE TRACE GAS MEASUREMENTS ON MARS. H. M. Sapers[1], J. E. Moores[1], F. Grandmont[2], M. Maisonneuve[2]. [1]Department of Earth and Space Science and Engineering, Lassonde School of Engineering, York University, Toronto, ON (hsapers@yorku.ca), Canada, [2]ABB Inc – Space and Defense, Québec, QC, Canada

Introduction: Two decades of observing methane on Mars[1-7] have generated data indicative of a dynamic, geochemical system characterized by a profile similar to the release of methane from seeps on Earth[8, 9] producing distinct enigmatic pulses known as plumes separated by slow background seepage. These observations demonstrate a lack of understanding of fundamental aspects of the Martian methane cycle and have raised significant questions into the geochemical, and potentially biological, processes that could account for the observations, underscoring a pressing need for additional data in the form of near-surface, high-frequency (hourly to sub-diurnal) observations. Our current understanding of the Martian methane cycle is limited by the relative paucity of measurements: the lack of coordinating measurements is a product of mission specific and technological constraints. Here we propose a small, autonomous, surface trace gas observatory capable of obtaining high-frequency trace gas measurements (table 1) at the sub-ppb level with low resource requirements and a form-factor approximating a 6U cubesat that would be compatible with three mission scenarios: (1) Primary payload of a dedicated landed mission (stationary) or an instrument contribution that can be (2) Integrated into a lander, or (3) Rover deployable (stationary or rover-mounted).

Current spectroscopic limitations: Current spectrometers have limited capacity for high frequency, high sensitivity measurements needed to understand the processes driving methane in the Martian atmosphere. With the exception of a large plume observed in 2013 by both SAM-TLS[3] onboard the MSL rover and PFS[6] onboard Mars Express, no two measurements have overlapped in space, time, and sensitivity. A background seasonal methane cycle is observed at the sub-ppb level averaging 0.41 ppbv at Gale Crater[4] likely resulting from a small, constant process of a few kg/sol[10] over the 18,400 km^2 area of the crater is below the detection limits by the ESA TGP, ACS, and NOMAD instruments[7]. To adequately describe any episodic process, observations of that process must be obtained at a cadence sufficient to profile flux variations. Observational campaigns limited to orbital limb measurements (e.g. TGO) or sub-synchronous mapping orbits (e.g. MRO, MGS) will miss diurnal effects. An instrument capable of methane measurements with a high temporal resolution will fill temporal gaps, addressing large uncertainties in current models[11].

Proposed measurements: There are three main measurement goals required to understand the key processes that contribute to the observed levels of methane in the atmosphere[12]: 1) continuous monitoring to capture the ramp-up and decay of a methane plume event; 2) observations capturing the entire diurnal cycle of the background seepage; 3) measurement of the $^{13}C/^{12}C$ isotopic ratio of the methane released during a plume event. Several complementary measurements will provide additional context for the interpretation of the primary data: additional atmospheric components (table 1), and meteorological data including wind speed and direction, temperature, pressure, and relative humidity.

Table 1: proposed MAGE measurements[12]

species	cadence	Conc.	objective
CH_4	hourly	0.2-20+ ppbv	Seek new chemistry, understand abiotic/biotic sources and sinks
O_3	hourly	<300 ppbv	Correct CH_4
CO_2	hourly	95%	Calibration and total pressure
CO	hourly	0.07 ppbv	Carbon-oxygen cycling and atm disequilibrium
O_2	hourly	0.2%	Understand oxidation potential of atm
C_2H_6	plume	unknown	Distinguish between biogenic and abiotic CH_4 and assess broader hydrocarbon cycles
$^{12}CH_4$/ $^{13}CH_4$	plume	unknown	

MAGE: The Martian Atmospheric Gas Evolution (MAGE) Off-Axis Integrated Cavity-enhanced Output Spectrometer (OA-ICOS) is a small gas-analyzer designed to conduct hourly, sub-ppb measurements of methane on Mars from a landed platform with low resource requirements. The proposed sensor is based on OA-ICOS technology developed by ABB Inc and supported with over $1.2M in funding from the Canadian Space Agency. The instrument is robust and has been deployed terrestrially on aircraft, automobiles, and drones. The sensor is currently being developed to TRL-5 through dedicated power and mass reduction and will be deployed at a Mars analog site in the high Canadian Arctic as well as on a planned stratospheric balloon flight. OA-ICOS is comparable to Cavity-Ringdown Spectroscopy with specific mission-relevant advantages: lack of precisely aligned optics (rendering the OA-ICOS resistant to vibration (launch and EDL) as well as pressure and temperature changes Δ100 K between day and night on Mars), and a simple electronic backend compared to most CRDS setups (facilitation of better and quicker calibrations and fewer potential points of failure). OA-ICOS also permits a wider dynamic range for the gasses being analyzed: up to 100% of the inlet gas, allowing CO_2 to be investigated at the same time as gasses of more than a billion times lower concentration, such as methane and ozone. The instrument works best at low pressures mitigating the need to run the cavity below ambient pressure. OA-ICOS can be compared to existing *in situ* spectroscopic techniques used to sample the near-surface Martian atmosphere. Whereas the SAM-TLS spectrometer employs a Herriott cell with an effective 0.0168 km path length, the OA-ICOS (fig. 1) could be configured with an effective path length of up to 100 km, improving sensitivity by 10, 000x. Notably, OC-ICOS further removes the resource-intensive step employed by the SAM-TLS that requires several hours of pumping over a CO_2 scrubber. As currently designed for commercial use, the drone-mounted OA-ICOS has a mass of 3 kg and could be accommodated within a 6U-sized deployable surface package.

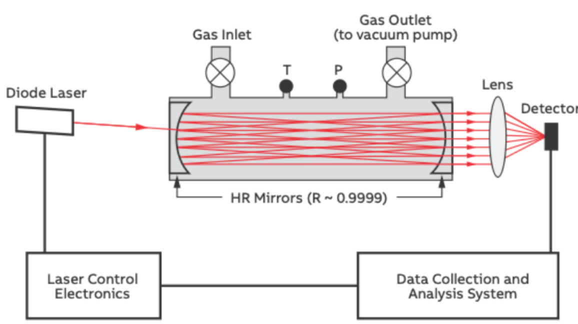

Figure 1: OA-ICOS schematic[12]

Mission concepts: The MAGE system could be deployed in several configurations allowing for different potential mission scenarios and architectures including a stand-alone station/network or integrated lander/rover instrument. To characterize both methane plumes and background seepage, it is necessary to acquire high frequency measurements for at least one Mars year. Notably, a regular measurement campaign at even a monthly timescale has never been attempted. Geographically, even a single location would establish a baseline of diurnal and seasonal variations of trace gas concentrations that are necessary for the recognition of ephemeral events, such as plumes. However, being able to compare multiple ground stations would allow for differences in subsurface seepage to be quantified and would facilitate the construction of a global picture of methane emission. A rover-mounted (or distributed rover-network) configuration would allow seepage to be measured at multiple locations using the same instrument permitting cross-calibration while a high sample rate would mitigate the confounding effect of variable terrain. Alternatively, the OA-ICOS could be deployed as part of a stand-alone weather station at one or more locations with complementary meteorological sensors, power generation, communications, and thermal controls (collectively the MAGE stations). Even a single MAGE instrument, either stationary or rover-deployed would revolutionize our understanding of the evolution of near surface trace gas concentrations.

Acknowledgments: We gratefully acknowledge the contributions of the co-authors and signatories on the MAGE science[11] and mission-concept[12] white papers submitted to the Planetary Sciences and Astrobiology Decadal Survey 2023-2032.

References: [1] Mumma, M.J. et al. Science 323, 1041–1045 (2009). [2] Formisano, V., Atreya, S., Encrenaz, T., Ignatiev, N. & Giuranna, M. Science 306, 1758–1761 (2004). [3] Webster, C.R. et al. Science 347, 415–417 (2015). [4] Webster, C.R. et al. Science 360, 1093–1096 (2018). [5] Geminale, A., Formisano, V. & Sindoni, G. Planet. Space Sci. 59, 137–148 (2011). [6] Giuranna, M. et al. Nat. Geosci. 12, 326–332 (2019). [7] Korablev, O. et al. Nature 568, 517–520 (2019). [8] Oehler, D.Z. & Etiope, G. Astrobiology 17, 1233–1264 (2017). [9] Etiope, G. & Oehler, D.Z. Planet. Space Sci. 168, 52–61 (2019). [10] Moores, J.E. et al. Geophys. Res. Lett. [11] Moores, J.E. et al. Bull. Am. Astron. Soc. 53, e-id 125 (2021). [12] Sapers, H.M. et al. Bull. Am. Astron. Soc. 53, e-id 382 (2021).

BIFROST: MARS POLAR SCIENCE ENABLED BY LOW-COST HELICOPTER. I. B. Smith[1,2] (ibsmith@yorku.ca); W. Calvin[3]; P Becerra[4]; M. Landis[5]; S. Byrne[6]; P. Hayne[5]; J. Bapst[7], A. B. Chmielewski[7], J. Delaune[7], L. Matthies[7], [1]York University, Toronto, Ontario, [2]Planetary Science Institute, Lakewood, Co; [3]University of Nevada, Reno; [4]Universitët Bern; [5]University of Colorado; [6]University of Arizona; [7]Jet Propulsion Laboratory, California Institute of Technology

Introduction: Recent topical meetings and workshops have solidified the aims of the Mars Polar Science Community in the form of conference reports, summarizing the polar science community's goals [1-3] and white papers aimed at guiding the discussion for planetary science in the coming decades [4-8], with [4] titled "Solar-system-wide significance of Mars polar science," having 180 co-authors and signatories.

Based on those massive, community led efforts, the Mars Exploration Program Analysis Group has updated their Goals Document twice, once in 2018 in order to match the fast-moving knowledge of Mars Polar Science (MPS) [9] and again in 2020 [10]. MEPAG also commissioned the Ice and Climate Evolution Science Analysis Group (ICE-SAG), who again reiterated the importance of MPS and the technologies that would enable this science [11]. Finally, a Keck Institute for Space Science workshop laid out a plan entitled "The Holy Grail: A road map for unlocking the climate record stored within Mars' polar layered deposits" with the intent of enumerating science objectives and the technologies to address them from large to low-cost missions [12].

Those reports had anticipated a suite of potential missions ranging from orbiters to static and roving landers, to low-cost missions. The low-cost missions included cubesats and lightweight platforms that could enter Mars' atmosphere unguided, saving significant cost for entry, descent, and landing (EDL), such as the Mars Polar Drop concept [13].

The lightweight landed platforms would have an extremely light payload but remain fixed in position, able to sample atmospheric constituents with a tunable laser spectrometer (TLS), wind speeds with a sonic anemometer, temperature, pressure, and humidity (TPH) with a meteorologic package, or even include a ground penetrating radar (GPR) to gain subsurface information.

New Observation Platforms: Since the writing of those summaries, a new technology has been demonstrated that could enable small payloads with enhanced surface mobility, namely airborne observations made by the Ingenuity Helicopter.

Ingenuity, with a cost estimation of $80M USD [14], has demonstrated that airborne reconnaissance is possible on Mars within the definition of "low-cost". The payload for an Ingenuity-class helicopter is small; the entire rotorcraft has a mass of 1.8 kg, but it included inertial sensors, a laser altimeter, and two cameras.

Mid-air Delivery: Ingenuity was deployed from beneath the Perseverance rover, and this platform will not be available for a low-cost polar helicopter. Traditional EDL architecture using a lander restricts the space available to accommodate large rotors, hence large scientific payload, in the aeroshell. Their cost can also be prohibitive. Mid-air delivery avoids the need for a lander by letting the helicopter take off from a small jetpack platform, after the aeroshell and parachute have completed their tasks [15]. Further, with its own landing gear and avionics, the helicopter itself is equipped for a safe soft landing.

Science Investigations Enabled by a Helicopter: The existing payload of Ingenuity, if sent to the north polar layered deposits (NPLD), would address several of the science goals of the Mars Polar Science Community [1-13]. Next-generation vehicles would have greater capabilities including increased payload capacity up to ~5 kg, accommodating a range of science instruments [16].

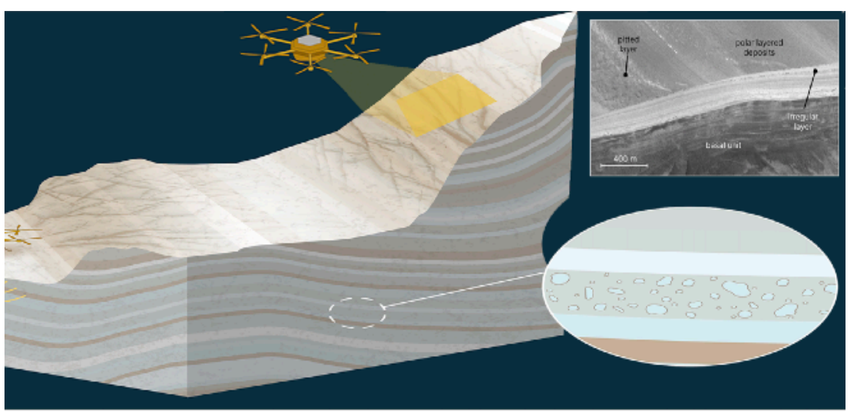

Figure 1: North polar science opportunities with Mars Science Helicopters. Cameras would investigate outcropping layers, surface texture, impact craters, and more. Radar would investigate subsurface layering down to ~30 m, giving a very high resolution climate record down to cm scale.

Layer spacing: Modest cameras could investigate ice layers at spiral trough outcrops for their spatial frequency and albedo down to the centimeter scale, providing important constraints that cannot be obtained even from the highest resolution orbital cameras.

Wind speeds: Rotors can interact with local winds, and an internal inertia measurement unit measuring induced forces of winds could also serve as an anemometer, both while landed and during flight.

Surface-atmosphere processes: In-situ investigations with cameras could observe the fine-scale sublimation and condensation activities at various sites along a traverse in order to constrain the energy balance of the NPLD during a summer mission.

Layer continuity: With the inclusion of modest payload enhancements, made possible with a next-generation vehicle [16], we could include a low-power GPR that has a mass under 1 kg, making possible the detection of subsurface layers, down to about 30 m depth, across the entirety of an airborne traverse - thus connecting radar observations to optical observations, an important technique that would answer several science questions.

A new technology GPR instrument is under development at JPL that will meet the requirements of the helicopter designed for operation in the NPLD regions. This miniature GPR is expected to have mass of approximately 0.9 kg and radar power of 2.5 W. With 900 MHz of bandwidth, the instrument will provide resolution of better than 20 cm to the depths of 25 m and lower resolution deeper. This is a substantial improvement in performance over the recent WISDOM (1.5 kg, 15 W) instrument on ESA's ExoMars rover and RIMFAX (2.5 kg, 10 W) on NASA's Perseverance.

Climate Record: Using the GPR and layer spacing observed from navigation cameras, we could have a contiguous climate record across the traverse that spans >60 kyr (with the published accumulation rate of 0.5 mm/yr [1,12]). That depth would enable detailed characterization of a precession cycle and half of an obliquity cycle.

Investigations at outcrops using the navigation cameras would provide a secondary measurement to the top 30 m provided by the GPR and add up to 500 more meters of cm-scale layer observations.

Polar Advantages: The NPLD is sometimes called "the safest place to land on Mars". This is because it is possible to land in a 100 km landing ellipse that contains no boulders. Further, surface slopes on the plateaus between spiral troughs are extremely low, with ~1 m topographic perturbations over tens of meter baselines [17].

If a solar-powered mission were to land in the northern summer, then the mission would have several advantages related to power generation (24-hour sunlight) and the thermal environment (minimum thermal swings compared to lower latitudes). Thus, an airborne mission could recharge faster than anywhere else on the planet, flying more often, and using less energy to warm the electronics. Finally, a polar helicopter mission could accomplish all of its goals during summer months for a nominal 90 days.

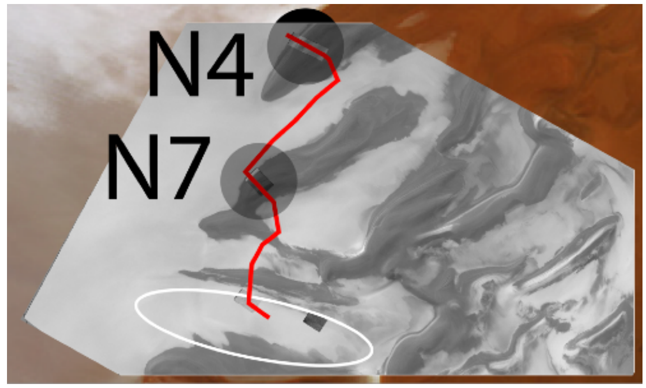

Figure 2: Notional traverse starting near 81.5° N, 31° E. Traverse includes multiple, young impact craters and several NPLD outcrops, including N4 and N6 from [18].

Acknowledgments: The cost information contained in this document is of a budgetary and planning nature and is intended for informational purposes only. It does not constitute a commitment on the part of JPL and/or Caltech. This work is for planning and discussion purposes only. Portions of this research were carried out at the Jet Propulsion Laboratory, California Institute of Technology, under a contract with the National Aeronautics and Space Administration © 2021.

References: [1] Smith, I.B. *et al.* (2018), *Icarus*, 308, 2–14. [2] Diniega, S., Smith, I.B., (2020). *PSS* 182, 104813. [3] Becerra, P., et al. (2021). *Planet. Sci. J.* 2, 209. [4] Smith, I. B. et al (2021). Solar-system-wide significance of Mars polar science. *Bulletin of the AAS* 53. [5] Thomas, N., et al. (2021) Exp Astron. [6] Smith, I., et al. (2021). Unlocking the Climate Record Stored within Mars' Polar Layered Deposits. Bulletin of the AAS 53 (4). [7] Diniega, S., et al. (2021). Bulletin of *the AAS* 53 (044). [8] Becerra, et al. *Bulletin of the AAS* 53 (144). [9] Banfield, D., et al. (2018) MEPAG Goals. [10] Banfield, D., et al. (2020) MEPAG Goals. [11] Report from the Ice and Climate Evolution Science Analysis group (ICE-SAG). [12] Smith, I.B., et al., (2020). *PSS* 184, 104841. [13] Hayne, P.B. (2022) L-CSMCME. [14] https://www.planetary.org/space-policy/cost-of-perseverance. [15] Delaune J. et al. (2022) *IEEE Aero. Conf.* [16] Bapst, J. et al. (2021). *Bulletin of the AAS* 53, 361. [17] Wilcoski, A.X. and Hayne, P.O. (2020). *JGRP* 125, e2020JE006570. [18] Becerra, P. et al (2017). *GRL*. 2016GL071197.

COMPELLING SCIENCE ENABLED BY GRAVITY INVESTIGATIONS AT MARS.

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Introduction: Geodesy is a powerful way to investigate a planet's formation, evolution, interior structure, and active processes. The power of geodesy is best demonstrated in the Earth-Moon system, where spacecraft missions like GRACE, LRO, and GRAIL have transformed geodesy from a purely geophysical tool into one that unlocks advances in geology, hydrology, climate change, and more. However, while geodetic measurements have flourished at the Earth and Moon, planetary geodesy has lagged behind (Fig. 1).

To address this issue, we are conducting a Keck Institute for Space Studies (KISS) study program [1] that identifies the transformative science that would be enabled by next-generation geodesy at other planetary bodies and the mission architectures needed to achieve that science. At the time of this writing, we have held one workshop focused on developing the most important scientific questions that could be addressed with geodesy beyond the Earth-Moon system. A second technology-focused workshop will be held in November 2021. Our study program discusses Mars, Venus, and Ocean Worlds and considers a variety of potential orbital, aerial, and landed assets.

Here, we focus on a subset of our study program that is relevant for this workshop: gravity science at Mars. Our group has identified a wealth of scientific questions that can be realistically addressed with this method if new geodetic data is acquired. In particular, we identified compelling science under two broad themes: climate and geodynamics. Below, we summarize the current state of gravity science from Mars, describe the compelling science under both themes that could be achieved with new gravity data at Mars, and discuss plausible mission architectures to obtain such data.

Current data: Our present knowledge of the Martian gravity field comes from Doppler tracking of individual orbital spacecraft, including the Mars Reconnaissance Orbiter, Mars Odyssey, and Mars Global Surveyor [2, 3]. The currently known gravity field has laterally variable uncertainty. It is accurate up to spherical harmonic degree ≈80 in the northern mid-latitudes and up to degree ≈100 at the south pole [2]. This field has proven valuable in, for example, inferring broad crustal thickness maps under assumptions of uniform density [4] or constraining the density of large polar deposits [5, 6]. However, the resolution and precision of the current field does not allow for many valuable analyses that could be done at Mars with realistically attainable gravity data. Below, we describe examples of such scientific investigations that address two broad questions: (1) What is the geodynamical history of Mars, and how and why does it differ from Earth's? (2) How do planetary climates respond to orbital forcing? This list is not exhaustive.

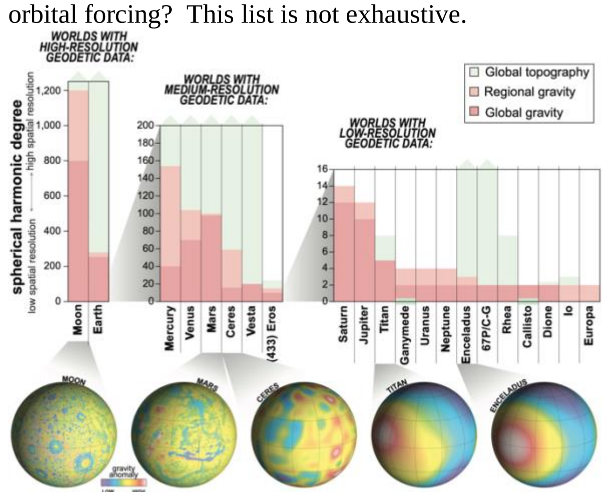

Figure 1: Current knowledge of gravity and topography across the Solar System from remote sensing spacecraft. Resolution in terms of the maximum spherical harmonic degree derived where signal is greater than uncertainty. Note change in vertical axis scale between the three plots.

Geodynamics: The global north-south dichotomy in topography, geology, and other datasets is the largest and most fundamental geophysical feature of Mars. Despite its profound importance in controlling planetary evolution, there is no consensus in how the dichotomy was formed [7]. Hypotheses for dichotomy formation include endogenic [e.g., 8, 9] and exogenic [e.g., 10, 11] processes, and combinations thereof [12]. A crustal thickness map derived under an assumption of uniform density shows global asymmetry [4]; a critical factor in testing dichotomy origin hypotheses is determining whether an asymmetry in crustal density instead is viable [13, 14]. A confident distinction between these possibilities is not currently possible, but would be if global gravity data were sufficiently precise to map Mars' crustal density independent of complicating effects from relief along the crust-mantle interface, as was done at the Moon with GRAIL data [15].

The Martian lithosphere records the history of the geodynamics of the planet. The history of the tectonic regime is debated [e.g., 16], and is inferred indirectly from, e.g., magmatic history [17]. Sufficiently precise gravity data would directly address this topic allowing for constraint of Mars' effective elastic thickness [e.g., 18]. New gravity data would be especially useful in determining elastic thickness at the time of loading of small-wavelength features and thus allow for reconstruction of the planet's thermal history.

A better understanding of Mars' thermal evolution and north-south dichotomy origin will also provide insights into the planet's magnetic field history and mechanisms of core dynamics [19]. Geodetic observations may additionally produce independent estimates of core size and composition that would complement those derived by the InSight mission [20].

Climate: On Earth, gravity has proved to be one of the most valuable datasets in study of climate. On Mars, this theme can only be touched on with current data, such as constraining density of polar deposits [5] or detecting seasonal volatile cycles [2]. A higher resolution static gravity field would allow for testing of the total water volumes present in the mid-latitudes, especially in areas where ice content is currently debated like Arcadia Planitia [21, 22] or the Medusa Fossae Formation [22, 23]. This investigation would have critical implications for human exploration [24].

A powerful dataset in studying Martian climate would be time-variable gravity. Time-variable gravity has allowed observation of ice sheet mass balance, hydrological cycles, and sea level change on Earth [25]. On Mars, data with sufficient precision and time baseline could be used analogously. Gravitational monitoring over multiple years could study sources and sinks of H_2O and CO_2, including quantifying interannual changes in polar cap mass balance and volatile loss from the planet. The dust cycle can also be studied; hypotheses on the initiation, evolution, and decay of dust storms can be tested, likely by observing the gravitational signature of related atmospheric effects rather than the direct mass of lofted dust.

Paths Forward: In November 2021, we are holding a KISS workshop with focus on identifying the mission architectures that could enable the gravity science described above. We are studying concepts that include spacecraft-to-spacecraft tracking, orbital gradiometry, small single spacecraft equipped with geodetic quality accelerometers (SmallSats), and regional gravimetry from aerial vehicles. At the Low-Cost Science Mission Concepts for Mars Exploration workshop, we will report the results of our November workshop. We will focus our report on identifying which of these architectures hold promise for compelling science return on the themes of geodynamics and/or climate at a cost of ~$300 million or less.

Next-generation geodesy at Mars may be accomplishable at low costs. While not all geodetic measurements or investigations are feasible at low costs, a certain subset is. For example, gravity science could be accomplished by Doppler measurements between small (potentially CubeSat class) radio beacons. These spacecraft could be placed on low-altitude orbits to fill in key data gaps that address some of the motivating science questions outlined above.

Low-cost geodesy is demonstrated by NASA's past missions, like GRAIL and LRO. GRAIL, a two-spacecraft geodesy mission to the Moon [26], has been the lowest-cost Discovery mission of the past 15 years (Phase A–E cost: ~$300M; with launch vehicle: $450M, for the primary phase)—far less than the cost of modern Discovery missions (e.g., Lucy, Psyche) [27].

Conclusion: Elevating gravity science at Mars to a level similar to that achieved in the Earth-Moon system will enable compelling research to address outstanding questions in Martian geodynamics and climate. Some subset of this science may be possible with relatively low-cost missions.

Acknowledgments: This work is supported in part by the W.M. Keck Institute for Space Studies.

References: [1] Next-Generation Planetary Geodesy (2021), KISS Study Program. [2] Genova et al. (2016) *Icarus* 272. [3] Konopliv et al. (2016), *Icarus* 274. [4] Zuber et al. (2000), *Science* 287. [5] Zuber et al. (2007), *Science* 317. [6] Ojha et al. (2019), *Geophys. Res. Lett.* 46. [7] Mars Geological Enigmas (2021), pg. 474. [8] Zhong and Zuber (2001), *Earth Planet. Sci. Lett.* 189. [9] Roberts (2021), *Mars Geological Enigmas* Ch. 17. [10] Andrews-Hanna et al. (2008), *Nature* 453. [11] Citron (2021), *Mars Geological Enigmas* Ch. 16. [12] Citron et al. (2018), *Earth Planet. Sci. Lett.* 491. [13] Ojha et al. (2020), LPSC 51st, 2386. [14] Wieczorek et al. (2021), LPSC 52nd, 1412. [15] Wieczorek et al. (2013), *Science* 339. [16] Sleep (1994), *J. Geophys. Res. Planets* 99. [17] Horgan (2013), *Nature Geosci.* 6. [18] McGovern et al. (2002), *J. Geophys. Res. Planets* 107. [19] Breuer and Spohn (2003), *J. Geophys. Res. Planets* 108. [20] Stähler et al. (2021), *Science* 373. [21] Bramson et al. (2015), *Geophys. Res. Lett.* 42. [22] Campbell and Morgan (2018), *Geophys. Res. Lett.* 45. [23] Ojha and Lewis (2018), *J. Geophys. Res. Planets* 123. [24] Heldmann et al. (2014), *Astrobiology* 14. [25] Tapley et al. (2019), *Nature Climate Change* 9. [26] Zuber et al. (2013), *Science* 339. [27] Glaze, L (2020) presentation to the Committee on Astrobio. and Planet. Sci.

A CERBERUS FOSSAE SEISMIC NETWORK S. C. Stähler[1], M. P. Panning[2], D. Antonangeli[3], W. B. Banerdt[2], D. Banfield[4], M. Banks[5], S. Ceylan[1], C. Charalambous[6], J. Clinton[1], I. Daubar[7], B. Fernando[8], D. Giardini[1], M. Grott[9], A. Horleston[10], K. Hurst[2], T. Kawamura[11], A. Khan[1], D. Kim[1], M. Knapmeyer[9], B. Knapmeyer-Endrun[12], R. Lorenz[13], L. Margerin[14], A. Marusiak[2], S. Menina[14], A. Mittelholz[1], N. Murdoch[15], Y. Nishikawa[16], C. Perrin[17], W. T. Pike[6], C. Schmelzbach[1], N. Schmerr[18], M. Schimmel[18], A. Spiga[3], A. Stott[15], J. Taylor[9], and R. Weber[19]. [1]ETH Zürich, Switzerland (simon.staehler@erdw.ethz), [2]JPL, Pasadena CA, USA [3]Sorbonne U, Paris, France [4]Cornell, Ithaka NY, USA [5]NASA GSFC, Greenbelt MD, USA, [6]Imperial College, London, UK, [7]Brown U, Providence RI, USA [8]U Oxford, UK [9]DLR, Berlin, Germany, [10]U Bristol, UK [11]IPGP, Paris, France [12]U Cologne, Germany, [13]APL, JHU, USA, [14]U Toulouse, France, [15]ISAE-Supaero, Toulouse, France, [16]KUT, Kochi, Japan, [17]LPG, Nantes, France [18]U Maryland, College Park MD, USA and [19]NASA MSFC, Huntsville AL, USA

Scientific Rationale: For hundreds of years, planet Mars has been the subject of heated controversy amongst scientists. Specifically the question whether the planet might have been less arid and cold and more habitable in the past has been discussed over and over again. It is by now widely accepted that the planet had a wet and periodically warm past in the Noachian [1], but it is still open whether liquid water has played any role geologically in recent times or is even present in significant amounts near the surface today [2]. One key area are the Cerberus Fossae, a system of $<$ 10 Ma old, 1200 km long grabens in Eastern Elysium Planitia. They connect to sediments in Athabasca Valles that have been interpreted as being created by volcanic activity that melted a significant cryospheric layer leading to catastrophic flooding 8-10 Ma ago [3], but could alternatively be explained by very low viscosity lava as well [4, 5].

The InSight mission [6] deployed the first successful seismometer to the surface of Mars and could detect a significant number of marsquakes over three years. The most significant quakes of the first year on Mars have been located specifically in the Cerberus Fossae system [7, 8], with focal mechanisms of an extensional tectonic setting [9]. Of the remaining 40 deep (LF) quakes, a significant number is located in a distance compatible with a source in or near Cerberus Fossae as well [10]. This means that at least on the hemisphere of InSight, tectonic activity is not primarily driven by cooling and contraction of the planet (as proposed by [11, 12], among others), but by highly localized stress, potentially related to ongoing volcanic activity [13]. A second type of shallow marsquakes shows an upper crust that combines strong heterogeneities and low seismic attenuation, reminiscent of lunar quakes [14, 15], at least in the upper kilometers. These observations seem incompatible with large amounts of water in the crust, either as a frozen groundwater layer or as water saved within minerals (which has been proposed as the sink of the water lost since the Noachian [16]). In combination, InSight has therefore shown that even the first analysis of seismic data challenges the concept of dominant tectonics on single plate planets, as well as fluid content in the accessible part of the crust. Cerberus Fossae is an ideal focal point to explore these questions further, answering the question whether habitable pockets might survive over long periods in an otherwise barren world. This results in the following **mission goals**:

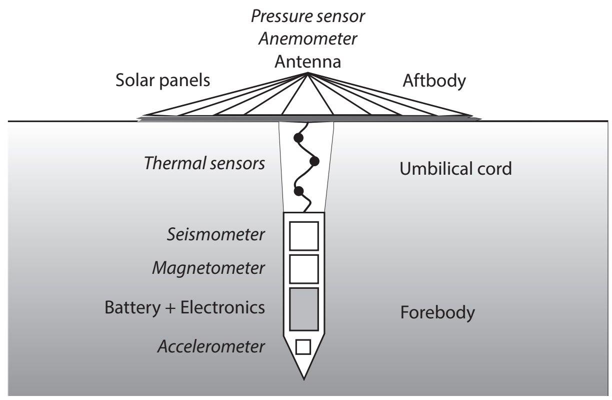

Figure 1: Cross section of one penetrator. The forebody contains a seismometer, a magnetometer, an accelerometer, as well as electronics. The aftbody disconnects during impact and stays above the surface. It is connected to the forebody by an umbilical cord with thermal sensors and contains solar panels and a basic meteorological suite. The seismometer is the main instrument of the mission and well-coupled to the ground. The accelerometer is used to measure ground rigidity during impact.

G1: Locate shallow and deep marsquakes with an uncertainly of less than 20 km. Determine the regional stress field and the driving mechanism behind the opening of C.F.

G2: Determine a velocity and attenuation model of the crust and uppermost mantle in the Cerberus Fossae region. Constrain the temperature gradient in the uppermost 20 km and find the bottom of the fractured, low attenuation layer. Confirm or exclude the existence of a frozen water layer below C.F..

G3: Constrain the ground rigidity and thermal diffusivity of the top meter at the landing site. Distinguish between fluvial sediments and basalt as a top layer.

G4: Observe wind and air pressure continuously on a regional scale. Refine regional climate models to understand aeolian deposition as seen from orbit.

Instruments

Short period seismometer The seismometer is located in the forebody and well-connected to the ground. The burial and the distance to the aftbody reduce ambient noise (G1, G2).

Accelerometer By measuring the deceleration during impact, the accelerometer determines the rigidity of the upper subsurface (G3).

Pressure and anemometer Build a first regional meteorological network on Mars and distinguish marsquake signals from noise. The Solar panels allow to monitor cloud coverage continuously [17] or constrain times of Phobos eclipses [18] (G4).

EM Sounder or magnetometer Installation of a magnetometer network or concurrent measurement of the electric field would allow for direct inversion for conductivity and therefore mineralogy [19] (G2, G3).

Thermal sensors Determine the thermal diffusivity and from it constrain the material properties at landing site (G2, G3).

Mission trade space: The InSight mission has proven the value of a carefully deployed very broadband seismometer (VBB) [20] to determine the deepest structure [21] and infer the composition of the planet as a whole, whereas local seismicity cannot be reliably located from a single instrument, given the strong scattering and therefore lack of polarization [14]. A seismic network could use arrival times to locate quakes, but the deployment effort of the VBB, including the usage of a robot arm for 90 Sols is prohibitive. The InSight seismic data has shown however that local and shallow marsquakes can be observed well with a short period seismometer with significantly lower installation effort [8]. If the lander has a low wind cross section and good ground coupling, operation from inside the lander is possible.

A soft lander has a significant cost penalty due to the EDL system, which can be avoided by a penetrator [22, 23]. A seismic network can operate successfully with 4 instruments. Reliability requirements can be reduced from the typical '3 σ' values, if loss of one or two landers during EDL is acceptable, which significantly reduces the design and qualification cost of each single lander.

Mission concept: We propose a network of 6 initial penetrators or hard landers spread over the center of Cerberus Fossae, each equipped with a 3 component InSight-SP short period seismometer and a meteorological instrument suite (see above). The penetrators would be separated from the cruise spacecraft during approach of Mars and steer independently towards preprogrammed locations within Cerberus Fossae. Typical landing ellipse sizes of 200x50 km would ensure distribution over the target area, with the goal of having at least 4 successful landings and deployments.

Impact velocities of Martian penetrators can be reduced with moderate parachutes to values of 50-80 m/s, resulting in decelerations below 500g, as shown in the Mars96 concept [24, 22]. Power generation has been Achilles' heel of planetary penetrators, with solar panels being heavy and fragile and radio-thermal-generators being generally unavailable. However, the progress on solar panels has significantly reduced weight and increased stability, which makes it possible to include them in an aft body. We propose to disconnect the forebody mechanically from the surface aftbody, to reduce wind-induced seismic noise and improve ground coupling, similar to the Mars96 concept. We propose a mission duration of one Martian year, which should result in observation of several deeper and > 80 shallow marsquakes. Communication is possible via an omnidirectional UHF antenna and the existing fleet of relay orbiters.

References: **[1]** R. D. Wordsworth. In: (2016). DOI: 10.1146/annurev-earth-060115-012355. **[2]** J. Tarnas et al. In: (2021). DOI: 10.1089/ast.2020.2386. **[3]** D. M. Burr. In: (2002). DOI: 10.1029/2001GL013345. **[4]** J. P. Cassanelli and J. W. Head. In: (2018). DOI: 10.1016/j.pss.2018.04.024. **[5]** W. L. Jaeger et al. In: (2007). DOI: 10.1126/science.1143315. **[6]** W. B. Banerdt et al. In: (2020). DOI: 10.1038/s41561-020-0544-y. **[7]** D. Giardini et al. In: (2020). DOI: 10.1038/s41561-020-0539-8. **[8]** J. F. Clinton et al. In: (2021). DOI: 10.1016/j.pepi.2020.106595. **[9]** N. Brinkman et al. In: (2021). DOI: 10.1029/2020je006546. **[10]** I. M. Service. 2021. DOI: 10.12686/A11. **[11]** R. J. Phillips. Tech. rep. 1991. **[12]** M. Knapmeyer et al. In: (2006). DOI: 10.1029/2006JE002708. **[13]** S. Kedar et al. In: (2021). DOI: 10.1029/2020JE006518. **[14]** M. van Driel et al. In: (2021). DOI: 10.1029/2020JE006670. **[15]** P. Lognonné et al. In: (2020). DOI: 10.1038/s41561-020-0536-y. **[16]** E. L. Scheller et al. In: (2021). DOI: 10.1126/science.abc7717. **[17]** R. D. Lorenz et al. In: (2020). DOI: 10.1029/2019EA000992. **[18]** S. C. Stähler et al. In: (2020). DOI: 10.1002/essoar.10503257.1. **[19]** R. E. Grimm and G. T. Delory. In: (2012). DOI: https://doi.org/10.1016/j.asr.2011.12.014. **[20]** P. Lognonné et al. In: (2019). DOI: 10.1007/s11214-018-0574-6. **[21]** S. C. Stähler et al. In: (2021). DOI: 10.1126/science.abi7730. **[22]** R. D. Lorenz. In: (2011). DOI: 10.1016/j.asr.2011.03.033. **[23]** N. Barba et al. In: (2019). **[24]** Y. A. Surkov and R. S. Kremnev. In: (1998). DOI: 10.1016/S0032-0633(98)00071-3.

COMPANION SMALLSAT RADAR SOUNDER FOR MARS SUBSURFACE IMAGING. C. Stuurman[1], [1]Jet Propulsion Laboratory, California Institute of Technology (cassie.stuurman@jpl.nasa.gov)

Introduction: Over 40 years of investigations from Mars orbit have produced science results ranging from its surface to its interior. Throughout Mars exploration, however, a gap in our measurement of its geologic column has persisted in the 1-15 m range, bounded by instruments such as GRS [1] probing up to 1 m maximum depth and SHARAD resolving subsurface radar stratigraphy as shallow as 15 m [2].

The near (~1-15 m) subsurface of Mars is an increasingly high-priority science target as an understanding of its composition, formation, and evolution would address multiple open questions related to the recent climate and geologic history of Mars, such as the distribution, depth, and composition of buried water ice in the midlatitudes; the age and evolution of the youngest sections of the polar layered deposits; and the relationship between putative subsurface volatiles and surface morphologies too small or too shallow to be resolved by previous radar missions to Mars. Additionally, accessible volatiles such as water ice or water-bearing minerals are of interest as ISRU candidates for future human exploration and also rover-based astrobiological investigations [3]. Previous radar sounder missions have enabled the detection of abundant buried water ice in the Mars midlatitudes, but the current vertical resolution of ~10-15 m is insufficient for ISRU mission planning.

This abstract describes a low-cost mission concept for a high bandwidth, P-band, smallsat radar sounder intended as a piggyback or rideshare for low-cost delivery to Mars. Radar sounding profiles offer insight into the electrical properties and structure of the planetary subsurface, especially where sharp contrasts in the dielectric permittivity due to transitions between rock, water ice, carbon dioxide ice, and dust are expected. Arguably, a Yagi sounder on a smallsat is the minimum mission required to answer our questions surrounding shallow volatiles on Mars with applications in geologic science, climate science, and future exploration.

Concept: A compact spacecraft bus with dedicated P-band radar science payload designed to piggyback or rideshare with a larger planetary mission. Table 1 describes the technical specifications of the payload. The main science objectives are to (1) characterize the distribution and composition of near-subsurface (1-15 m) volatiles on Mars; (2) measure the depth to the water ice table from 30° poleward; (3) determine the formation and evolution of the polar layered deposits throughout its most shallow, recent sections and (4) retrieve the first radar sounding profiles from the polar observation gap on Mars.

Table 1: Concept Specifications

Parameter	Value
Orbit altitude	300 km
Center frequency	450 MHz
Transmit peak RF power	100 W
Pulse length	20 μs
Antenna type	Deployable Yagi
Antenna length + boom	1.1 m
Antenna gain	11 dB
Payload mass	13 kg
Bandwidth	85 MHz
Data rate (raw)	73 Mb/s
Azimuth resolution (FZ)	317 m
Range resolution	1.88 m (free space), 0.99 m (water ice)
Swath width	25 km
Heritage	SHARAD [2], OASIS [4], Juventas [5], NORSAT-2 [6]

Heritage: In recent years, several spaceborne radar sounders and cubesat-deployable Yagi concepts have been proposed and developed. The OASIS project is a spaceborne VHF radar sounder concept with a deployable cross-Yagi antenna designed to image terrestrial ice sheets and detect shallow desert aquifers [4]. Juventas is a VHF radar sounder designed for ESA's Hera mission and will be the first radar to image the interior of an asteroid. Juventas has a wet mass of 12 kg and 6U total size, demonstrating the capability of cubesat sounding radars for planetary exploration [5]. NORSAT-2 is a 15 kg cubesat that is currently operating in Earth orbit and is a relevant example of a compact, spaceborne, and deployable cross-Yagi antenna [6].

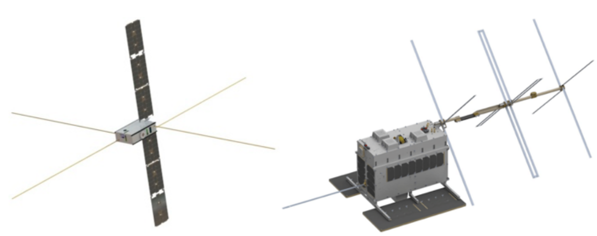

Figure 1: (left) The Juventas VHF cubesat radar on ESA's Hera mission. (right) NSC's NORSAT-2 with deployable VHF cross-Yagi antenna.

Cost: Monte Carlo costing simulations estimate the median payload cost as $29.9M. The total A-D mission cost (including 30% reserves) is estimated at $67.7M-$204.7M. This was determined using a MEP spacecraft study model [7] that considers a number of input factors such as estimated payload mass and power, final mission class, propulsion type (if needed), expected Delta-v, etc. The most influential cost variable for this mission concept is whether the mission arrives by piggyback or rideshare (as this drives the propulsion requirement).

Challenges and Trades: This section reviews some of the important options for the concept and their impact on mission complexity, science, and cost.

Piggyback vs. Rideshare: The biggest driver of mass and cost is whether or not propulsion is required, which in turn depends on the orbiter's method of arrival in orbit. If it is possible to "piggyback" the smallsat into its orbit by a separate mothership then propulsion will not be required. The median expected spacecraft mass in the piggyback case is 36 kg, and the simulated A-D mission cost has an interquartile range of $67.7M-$118.8M. This is an attractive option given the low cost of the mission, but comes at a trade for control of the satellite's orbit. If instead the spacecraft operates as a rideshare with a mission that is not going to Mars, SEP propulsion will be required. Simulations using a lunar transfer orbit and 10 km/s expected Delta-v result in a median wet mass of 498 kg and total A-D mission cost of $131.6M-$204.7M.

Resolution and penetration depth: Horizontal resolutions 100 m or finer are of interest for ISRU science goals [4]. For this concept, azimuth resolution finer than ~317 m is possible at a trade for higher center frequency and reduced penetration depth. Little is known about the scattering properties of the Mars subsurface at P-band, complicating estimations of maximum detectable interface depths. Models of radar penetration through simulated martian media estimate maximum penetration depths up to 15 m in icy soil for center frequencies of 450 MHz, but these estimations can vary depending on radar performance, the scattering behaviour of the subsurface, and the assumed volume fraction of inclusions [8]. To confidently address the science objective of imaging buried water ice in the martian midlatitudes, a higher frequency sounder is not recommend. Combining a low-cost, P-band sounder with a higher resolution/shallow-penetrating partner mission would be ideally suited to address the question of shallow subsurface ice at useful penetration depths and sufficient resolution for ISRU.

Number of orbiters: Given that the expected cost of this mission concept is relatively low, it may be possible to build multiple orbiters and release them in a swarm configuration. This would reduce overall mission risk while amplifying potential science return. It also opens the possibility of coordinated radar swarm sounding for reduced clutter, improved across-track resolution, and increased SNR [9].

Summary: Planetary exploration by cubesat is an increasingly established form of generating high science return at drastically reduced costs. A smallsat P-band radar sounder as a COMPANION (*COMpact P-bANd Investigator Of the Near-subsurface*) mission for a larger Mars orbiter could be done at a low budget, with potential to answer critical science and exploration questions involving the shallow subsurface of Mars.

Acknowledgments: Nathan Barba for his support and enthusiasm in the development of this concept; Tony Freeman for his mentorship on the radar systems engineering; Jeff Plaut and Eric Petersen for their thoughts on scientific impact and credibility; Ying Lin for her radar sounding and lightweight payload expertise; Bryan Stuurman for the helpful conversations on feasibility; and the JPL MEP study team for their costing simulations.

References: [1] Saunders, R. S. et al. (2004) *Space Science Reviews, 110.1,* 1–36. [2] Seu R. et al. (2007) *Journal of Geophysical Research: Planets,* 112.E5. [3] Banfield, D. et al. (2020) *white paper posted by the Mars Exploration Program Analysis Group (MEPAG).* [4] Freeman, A. et al. (2017) *IEEE Transactions on Geoscience and Remote Sensing, 55.10,* 5833-5842. [5] Henrique, A. et al. (2020) *EGU General Assembly Conference Abstracts.* [6] Bradbury, L.M. (2019) *Acta Astronautica, 156,* 44-50. [7] Edwards, C.D. (2022) *Submitted to IEEE Aerospace Conference*. [8] Pettinelli, E. et al. (2007) *IEEE Transactions on Geoscience and Remote Sensing, 45.5*, 1271 – 1281. [9] Carrer, L. et al. (2019) *IEEE Transactions on Geoscience and Remote Sensing, 57.12,* 9791-9809.

Scalable mission options for measuring winds and water vapor on Mars. L. K. Tamppari[1], N. J. Livesey[1], G. Chattopadhyay[1], and N. J. Barba[1], S. Guzewich[2], A. Kleinböhl[1]. [1]Jet Propulsion Laboratory/California Institute of Technology (4800 Oak Grove Dr., Pasadena, CA 91109; leslie.tamppari@jpl.nasa.gov), [2] NASA Goddard Space Flight Center, 8800 Greenbelt Rd, Greenbelt, MD, 20771.

Introduction: The Planetary Decadal Survey [1], the Mars Exploration Program Analysis Group (MEPAG [2]) and other NASA committees (e.g., the Next Orbiter Science Analysis Group [NEX-SAG; 3]) have cited high-priority science knowledge gaps related to understanding the current Martian climate and weather, specifically, the need for new measurements of global wind and water vapor profiles in the lowest 100 km of the atmosphere are essential to filling these gaps and resolving outstanding questions. Measuring these quantities and their variation with time would revolutionize our understanding of the general behavior, stability and history of Mars' weather and climate. Such measurements could be made by high-TRL instruments, flown individually, together on a focused mission, or as part of a larger mission architecture. The information gained would provide insight into past climate and be useful for future robotic and human exploration needs as well.

Thus far, Mars research has benefitted from several orbiting spacecraft that have characterized the Martian atmosphere fairly well in terms of temperature, pressure, dust and ice aerosols, and column water vapor amount. The ExoMars Trace Gas Orbiter also measures profiles of the abundance of many key trace gases, and MAVEN is studying the upper atmosphere.

Despite this important observational record, systematic and global, vertical profiles of water vapor and wind are very limited, and existing temperature retrievals can be hindered by large amounts of aerosols [4]. Water vapor vertical distributions are important for understanding water cycling between ice and sub-surface reservoirs. Further, water vapor profiles along with simultaneous temperature profiles, including in the presence of dust and ice, are critical to understand cloud formation which has a surprisingly large radiative impact on the atmosphere [5]. Winds are almost completely unmeasured, yet are critical for understanding fundamental Martian processes driving the dust and water cycles. In addition, winds are desired for safe landing of robotic and human spacecraft. In lieu of actual measurements, global circulation model output is often used to aid in spacecraft and mission design, but the models are largely unvalidated against winds. The NEX-SAG [3] found: *"Observation of wind velocity is the single most valuable new measurement that can be made to advance knowledge of atmospheric dynamic processes. Near-simultaneous observations of atmospheric wind velocities, temperatures, aerosols, and water vapor with global coverage are required to properly understand the complex interactions that define the current climate."*

Wind and Water Vapor Measurement Concept: A passive sub-mm limb sounding instrument is ideally suited to provide the needed wind, water vapor, and temperature profile measurements. The technique has high heritage in Earth-science, and dramatic advances in associated technology in the past decade+ (driven in part by the communications industry) enable significant reductions in needed power, mass and complexity. Such an instrument can make measurements both day and night, and in the presence of atmospheric dust loading, measuring between 0–100+ km altitude [6]. A sub-mm for Mars has been under development and is TRL 5 with many TRL 6 components (Fig. 1).

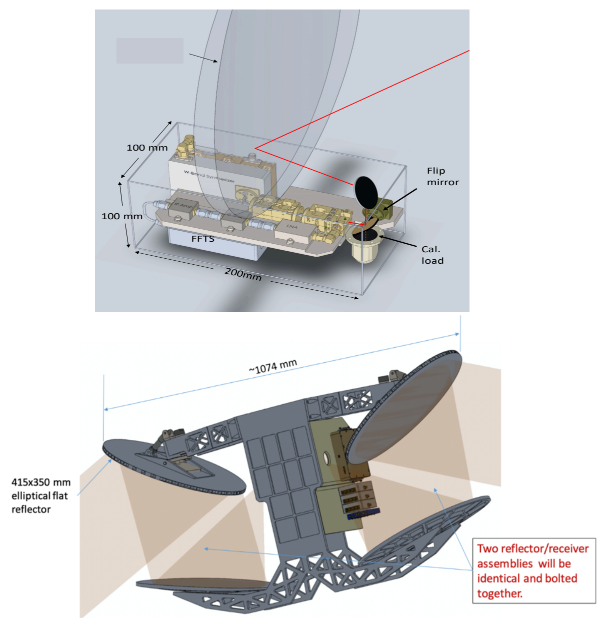

Fig. 1. (Top) Concept for single-antenna sub-mm instrument. (Bottom) Concept for dual-antenna, scanning sub-mm instrument.

Aerosol measurement instrument: To measure the vertical distribution of dust and water-ice aerosols in the atmosphere, a thermal IR profiler similar to the MCS aboard MRO [7] would be ideal and would also provide additional temperature and water vapor measurements to those from the sub-mm instrument, measured over a similar altitude range with comparable vertical resolution, both day and night. A wide-angle camera similar to MARCI [8] would facilitate placement of the other measurements into the big picture of weather patterns seen via global maps.

Enhancement Instrumentation: A Doppler lidar [e.g., 9] would be an enhancement and would provide higher vertical resolution line-of-sight winds in the bottom 40 km of the atmosphere.

Mission Concepts:

SIMPLEX+: A highly-focused mission to observe key locations and seasons in the Martian atmosphere could be done in the $70M range and provide the first line-of-sight atmospheric wind profiles for Mars, allowing outstanding questions [1-3] to be answered and global circulations models to be constrained. Science objectives: (1) Determine the location, speed, and direction (east vs. west) of the **northern polar jet** during northern winter and the **putative equatorial jet**; (2) Determine the **vapor amount in the middle atmosphere** in the southern mid-latitudes during southern spring and summer; (3) Determine the **water vapor vertical profile (non-uniformity thereof) in the boundary layer** and aloft in the northern polar region during northern spring and summer; (4) Determine when **saturation conditions** occur and if and when **supersaturation** exists.

The mission concept is a cubesat or smallsat in a near-polar or inclined orbit for at least one Mars year. The spacecraft could perform the azimuthal pointing and limb-sounding "nodding" required. It would carry a single-antenna (one direction), body-mounted, sub-mm sounder to provide line-of-sight wind (from which vector winds could be inferred given sufficient coverage/revisits along complementary lines of sight), temperature, and water vapor measurements. The spacecraft could use solar-electric propulsion (SEP) or chemical propulsion (trade) to achieve Mars orbit. All needed technologies are available immediately.

This concept includes a simplified version of the ideal sub-mm sounder (the ideal instrument, see Fig. 1, would be able to scan 360 deg azimuth and take data in two, ~orthogonal directions near-simultaneously for vector wind determination, discussed below). However, a few, concise, and highly-valuable objectives can be accomplished at this reduced price point. As such, this concept could be a pre-cursor to a more sophisticated instrument and mission concept.

Low-Cost class: A mission to observe the first systematic and global vertical profiles of temperature, water vapor, and vector wind could be done in the ~$100-300M range and would provide a wealth of information on Mars global atmospheric circulation and to constrain models. Science Objectives: (1) Constrain global circulation and transport by measuring, for the first time, the global horizontal and vertical wind vectors and vertical water vapor profiles; (2) Provide data for validation of global circulation models and to ensure safety of landed robotic (and future) human missions, and (3) Determine when **saturation conditions** occur and if and when **supersaturation** exists.

The mission concept is a smallsat in a near-polar or inclined orbit for at least one Mars year. It would carry a dual-antenna, articulated sub-mm sounder (Fig. 1) to provide vertical profiles of vector winds, temperature, and water vapor. To obtain information on the forcing of the atmosphere, a low-cost, low-mass thermal IR profiler or weather camera could be added. The spacecraft could use SEP or chemical propulsion (trade) to achieve Mars orbit. All needed technologies are available immediately.

Discovery class: A climate-focused mission with 3-4 instruments would provide the first systematic and global atmospheric wind and water vapor profiles for Mars, along with profiles of temperature and aerosols, allowing the *forcing and response* of the atmosphere to be constrained for the first time. Science Objectives: (1) Constrain global circulation and transport by measuring, for the first time, the global horizontal and vertical wind vectors and water vapor profiles; (2) constrain atmospheric forcing via temperature and aerosol measurements, (3) Provide data for validation of global circulation models and to ensure safety of landed robotic (and future) human missions, and (4) Determine when **saturation conditions** occur and if and when **supersaturation** exists.

This mission concept is a single orbiter, in quasi-polar orbit, using SEP and observing Mars for at least one Mars year. Instruments would include a sub-mm sounder (vertical profiles of temperature and water vapor (0-80 km) and wind from 10-80 km), a wind LIDAR (vertical profiles of wind from 0-~40 km), a thermal-infrared sounder (Temperature and aerosol profiles from 5-80 km), and a wide-angle camera. SEP allows for ample power for the LIDAR, and also allows for changing from near-polar to inclined orbit to provide time-of-day sampling. All technologies needed are available immediately.

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References: [1] Vision and Voyages (2011); [2] MEPAG (2020) http://mepag.jpl.nasa.gov; [3] NEX-SAG (2015) http://mepag.jpl.nasa.gov; [4] D. Kass, pers. comm., 2017; [5] Madeleine et al. (2011), *JGR* 116 (E11010). [6] Read et al., (2018), *Plan. and Sp. Sci.,* 161; [7] McCleese et al. (2007), *JGR* 112 (E05S06); [8] Bell et al. (2009), *JGR* 114 (E08S92), [9] Cremons et al. (2020), *CEAS Sp. J.*, 12 2.

SIMPLE UV PHOTOMETERS FOR SOLAR AND STELLAR OCCULTATIONS OF THE MARS UPPER ATMOSPHERE. E. M. B. Thiemann[1] and F. G. Eparvier[1], [1]Laboratory for Atmospheric and Space Physics, University of Colorado, 3665 Discovery Drive, Boulder, 80303; thiemann@lasp.colorado.edu

Introduction: Solar and stellar occultations provide direct measurements of atmospheric density, and are a major contributor to the current understanding of the thermal structure, composition and variability of the Mars atmosphere from the surface boundary layer to the exobase. Although recent occultations have been made by relatively large and complex instruments such as SPICAM (Spectroscopy for the Investigation of the Characteristics of the Atmosphere of Mars) onboard Mars Express, IUVS (Imaging Ultraviolet Spectrograph) onboard MAVEN (Mars Atmosphere and Volatile EvolutioN) and NOMAD (Nadir Occultation for Mars Discovery) onboard TGO (Trace Gas Orbiter), high quality occultation measurements of major species can be made by much simpler UV photometers as has been recently demonstrated [1] with MAVEN EUVM (Extreme Ultraviolet Monitor).

Concept Background and Overview: The solar occultation measurement principle is simple. The measured intensity (I) normalized by its value at the top of the atmosphere (I_0) is related to the line-of-sight (LOS) column density by $\mathrm{Ln}(I/I_0)=-\Sigma N_i\sigma_i$. If most (>90%) of the absorption is due to a single species, as is generally the case in the Mars atmosphere below the exobase, measurements at only a single wavelength band are required. Each additional species can be resolved with a single, appropriately selected, band (i.e. 2 bands for 2 species, 3 bands for 3 species, ...). Additionally, occultation measurements are highly accurate and insensitive to degradation if the instrument relative bandpass is well known. This is a result of the dependence on relative (i.e I/I_0) rather than absolute intensity.

UV photometers significantly reduce instrument complexity and SWAP (size, weight and power) as compared to the aforementioned occultation instruments while providing necessary spectral resolution for measuring major species composition and temperature. Rather than using a grating spectrograph and 2-d detectors, as is the case with SPICAM, IUVS and NOMAD, transmission filters and ambient-temperature single-pixel detectors are used. As a rough comparison, the optics required to isolate the appropriate bandpass are reduced from being the size of 1-2 shoe boxes to that of 1-2 D-size batteries. Additionally, the simplification of the detector system, simplifies the electronics and data rate. For solar occultations, no additional front-end optics are required, although their inclusion will improve vertical resolution, while for stellar occultations, a primary mirror comparable to those on IUVS and SPICAM would be required.

In this presentation, we show examples of past UV photometer measurements of atmospheric density at Earth and Mars, review the capabilities and limitations of high-TRL transmission filter and detector technology, discuss retrieval methods and associated uncertainties, and provide example solar and stellar occultation instrument configurations for probing the Mars atmosphere.

References:

[1] Thiemann et al. (2008) *JGR: Planets, 90,* 123.9, 2248-2269.

Mars-BARS (Balloon for Aerial Regional-Scale Science): a Proposed Martian Aerial Platform Mission. C. Todd[1], J. Espley[2], R. Bowens[1], L. Cacciottolo[1], M. Chattrabhuti[1], S. Cruz[1], A. Festa[1], R. Glait[1], R. May[1], J. McDougall[1], E. Prober[1], J. Schachter[1], J. Wich[1], J. Gruesbeck[2], and S. Guzewich[2], [1]University of Michigan (cwtodd@umich.edu, rpbowens@umich.edu, lucaccio@umich.edu, mchattra@umich.edu, juanse@umich.edu, afesta@umich.edu, glait@umich.edu, remay@umich.edu, jackmcd@umich.edu, etprober@umich.edu, jschach@umich.edu, jameswic@umich.edu), [2]Goddard Space Flight Center (jared.r.espley@nasa.gov, jacob.r.gruesbeck@nasa.gov, scott.d.guzewich@nasa.gov).

Introduction: Mars-BARS is a proposed regional-scale environmental study of Mars that leverages an aerial platform capable of covering hundreds of kilometers (500+ km) at low-altitude (1-8 km) while carrying a suite of scientific instruments that collect data to address several fundamental questions regarding the Martian environment. A mission of this type and scale fills a gap between the local- and planetary-scale whereby certain regional phenomena could not be adequately measured.

Through a rigorous down-select process, the aerial platform for this mission has been selected to be a balloon, which was preferred to both fixed-wing and rotary-craft options. The proposed design consists of a balloon capable of lifting a 100 kg strawman payload with an average power consumption of 140 W. The balloon does not carry an onboard propulsion but features an altitude control system and it can determine its location with an accuracy better than 100m.

Top-Level Science Objectives: The strawman science payload for the evaluated mission concept was derived from the regional-scale science proposal produced by the science team at Goddard Spaceflight Center (GSFC) and supplied to the student engineering team at the University of Michigan's Department of Climate and Space Sciences and Engineering (UM CLaSP). The mission design was conducted as part of a graduate-level course on spacecraft design.

The four primary science objectives of this mission are as follows: 1) to show how regional crustal magnetic fields demonstrate the history of Martian tectonics, volcanism, and cratering; 2) to determine the astrobiological significance of regional surface radiation; 3) to resolve contradictory understandings of methane distribution around sources and sinks at a regional and planetary scale; 4) to identify landscape geomorphology as well as capture video for mineralogy analysis.

Top-Level Mission Requirements: The mission requirements for the platform were either directly dictated by the science team at GSFC or derived from the needs of the science objectives, and are as follows: 1) the mission shall conduct science observations for 500 km in linear distance traveled. The mission shall cover at least three approx. linear segments each at least 30 km long and separated by a mean distance of at least 10 km; 2) the mission shall sample the Martian atmosphere to a spatial resolution of better than 1 km; 3) the mission shall report its location at all times to better than 1 km accuracy in all three dimensions; 4) the platform shall have a mean altitude during observations of between 1 and 8 km; 5) the mission shall be conducted in the region 30 to 60 S, 150 to 210 E at Mars; 6) the mission shall return at least 1.5 Gbits of data to Earth using the DSN via orbiting relay to downlink science and housekeeping data per Martian sol; 7) during science observations, all instruments shall be collecting data; 8) the mission shall conduct observations for at least two Martian sols.

Platform Trade Study: Several vehicle platforms were evaluated to satisfy the top-level mission requirements. A trade study was performed to analyze which platform could best meet these requirements.

Fixed-Wing Platform. The first platform considered was a fixed wing vehicle. Fixed wings are capable of performing forward motion with respect to a moving medium to generate lift. The scientific payload is kept inside the body of the aircraft. Three different fixed wing technologies were considered to determine the most appropriate application to Mars-BARS. The glider concept would be released upon entry into the Martian atmosphere and would collect data while gliding to the ground. The propellor-driven fixed-wing craft would generate lift through a rotary propellor mechanism. The rocket-propelled glider would use chemical rockets to increase its velocity (and therefore altitude) by generating thrust in bursts and then gliding back down following a thrusting maneuver.

Rotorcraft Platform. The next platform considered was a rotorcraft. Rotorcraft generate lift through rotary propellors mounted at the top of the platform, which rotate parallel to the ground and are controlled via remote input. The rotorcraft stands out from other platforms by having the capability of making precise directional changes even on Martian atmospheric flight, where the flow easily separates from a wing surface, allowing for precise acquisition of image data in various places on the Martian surface. Control is attainable without increasing flight speed, as flight speed directly affects measurement resolution. These requirements were mission-essential restrictions through which prospective aircraft were evaluated.

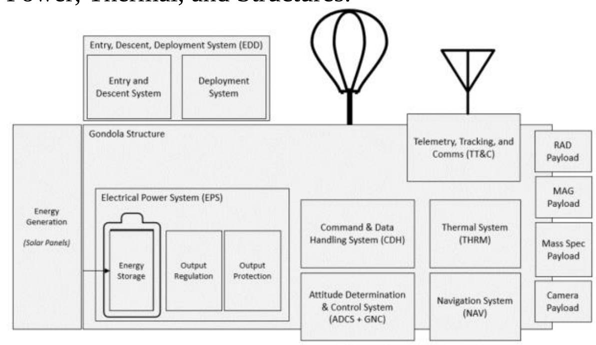
Balloon Platform. The final platform considered in this trade study was the balloon, defined to be any platform that achieved altitude through the passive containment of a lifting gas in an envelope. This method operates at a lower power cost to the fixed-wing and rotorcraft platforms, though it lacks control over the direction of the platform, which would drift passively in accordance with the wind at a given altitude of operation. For this trade study, three platform types were considered: a Montgolfiere-style balloon with an open-to-atmosphere envelope that uses heated gas for lift, a high-altitude-balloon (HAB)-style balloon such as those used for weather monitoring in the upper Earth atmosphere, and a zeppelin-style airship with rudder control and an elongated envelope.

Platform Selection. The criteria for platform selection were defined as all aspects of the vehicle essential to carrying out the top-level requirements. Criteria were further subdivided into high weight (valued at 3) and low weight (valued at 1) scores based on the impact of the criteria on the overall mission. A Pugh chart was used to categorically rate each platform in each of the criteria. The balloon craft was used as a baseline for comparison, meaning it received a score of zero for each. For the other two platforms, a positive rating indicates that the craft will accomplish the criteria in a simpler or more robust manner than the balloon, and a negative rating indicates that the craft will have more difficulty accomplishing the criteria.

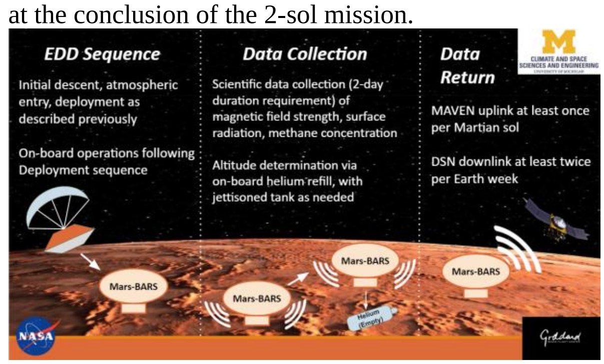
Criteria	Weight	Balloon	Fixed-Wing	Rotorcraft
Mass	3	0	0	0
Ease of Deployment	3	0	0	-1
Flight Distance	3	0	0	-1
Power Requirements	3	0	0	-1
Spatial Awareness	3	0	0	0
Packing	3	0	0	1
Max. Altitude	3	0	0	-1
Ease of take off	1	0	0	-1
Lifetime	1	0	-1	-1
Flight Time	1	0	-1	-1
Speed	1	0	1	0
Robustness	1	0	0	0
Level of Autonomy	1	0	-1	-1
Controllability	1	0	1	0
+1		--	2	3
0		28	23	9
-1		--	3	16
TOTAL		0	-1	-13

As neither the fixed-wing nor the rotorcraft platform succeeded in outperforming the balloon platform, the latter was selected as the platform for the mission to be carried out on.

Subsystems: After selecting the balloon platform, the next step was to consider all relevant subsystems. The eight subsystems needed are as follows: Entry, Descent, and Deployment (EDD), Attitude Determination and Control (ADCS), Guidance and Navigation (GNC), Command and Data Handling (CDH), Telemetry, Tracking, and Command (TTC), Power, Thermal, and Structures.



Concept of Operations: The full operation of the platform over the 2-day mission duration is broadly divided into three modes of operation – EDD Sequence, Data Collection, and Data Return – with provisions to continue operation between the Data Collection and Data Return modes indefinitely should the mission duration be extended beyond this. There is opportunity for multiple passes over the course of the 2-sol mission duration, meaning that the current operational mode of the balloon will vary between Data Collection and Data Return multiple times before the data is finally transmitted across the DSN to Earth at the conclusion of the 2-sol mission.



Conclusion: The Mars-BARS regional-scale aerial platform will address fundamental questions about the Martian environment with low-cost methodology. A balloon platform was chosen to accomplish this task, with detailed subsystem analysis performed to ensure the proper function and fulfillment of critical mission requirements while operating in the Martian environment.

Enabling New and Innovative Low Cost Mars Science Missions with the Adaptable, Deployable, Entry and Placement Technology (ADEPT). P. F. Wercinski[1] and E. Venkatapathy[2]

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Summary: The Adaptive Deployable Entry and Placement Technology (ADEPT) offers a delivery capability for Small Sat or CubeSat orbiter(s), in-situ elements, or landers. ADEPT can deliver the same science payload to a destination with a stowed diameter a factor of 2-4 times smaller than an equivalent rigid aeroshell, alleviating volumetric constraints on the secondary payload accommodation or primary carrier spacecraft bus. The ADEPT system can support payload over a range of mass and geometries to offer a delivery capability for a single or constellation of spacecraft supporting the goals and objectives of "Low Cost Mars Science Missions."

Introduction: Development and demonstration for utilizing Small Satellites beyond low earth orbit for a wide range of planetary science missions is making steady progress. Several secondary CubeSat payload missions are under study at Mars, cis-Lunar Space, near Earth objects, Venus, and destination beyond. In some cases, these smaller systems may enable utilization of otherwise unused capacity of larger "host" missions. Development of entry systems that leverage and accommodate Small Satellite technology will substantially expand the range of mission applications by offering the capability for high-speed entry or aerocapture at destinations with atmospheres.[1] Recent development progress in Adaptive Deployable Entry and Placement Technology (ADEPT) offers unique benefits over traditional rigid aeroshells including volume, mass and payload form factor, with a delivery capability for a single or constellation of spacecraft supporting the goals and objectives of Low Cost Mars Science missions.

Technology Description for Small Spacecraft and Small EDL Missions: ADEPT is a low ballistic coefficient planetary entry system that employs an umbrella-like deployable structure to serve as a hypersonic decelerator. The ADEPT aeroshell drag surface is a 3-D woven carbon fabric that serves as a thermal protection system (TPS) and as a structural surface that transfers aerodynamic deceleration forces to the underlying ribs. The ADEPT structural skeleton is made up of four primary structural elements: main body, nose cap, ribs, and struts. An image of ADEPT is shown in Figure 1. The central nose cap is constructed much like a conventional rigid aeroshell. Its shape is a sphere-cone that provides the transition to the faceted pyramid shape of the deployed carbon fabric aeroshell. The nose cap is typically covered with an ablative TPS. The ribs provide the framework that supports the tensioned carbon fabric. The ribs are hinged at their attachment to the nose cap and are supported via struts at a point along their span that is compatible with structural and deployment mechanism requirements. The struts that support the ribs are installed in pairs to carry the aerodynamic loads transmitted from the carbon fabric and ribs back to the main body lower ring. The pairing of struts also provides lateral stability, torsional stability, and improved folding of the ADEPT structure. The aerodynamic surface is formed by tensioning 3D-woven carbon fabric over the ribs of the structural skeleton. High-purity intermediate modulus carbon fiber yarn is used to create a membrane that serves as the structural surface and the thermal barrier. The high temperature capability of the carbon cloth allows it to operate at high temperatures seen during entry (1500°-2000° C). Several of the top layers of the carbon fabric are allowed to oxidize and recede away during the entry heat pulse, but the construction of the 3D woven fabric allows the deployable aeroshell to maintain its structural integrity.

Sounding Rocket Flight Test of ADEPT at ~ 1m scale: A recent major development highlight was the sounding rocket flight experiment of the SmallSat scale ADEPT, called ADEPT SR-1, successfully launched on Sept 12, 2018.[2] The flight experiment utilized many features intended for 1-meter scale space flight missions such as the carbon-fabric decelerator, two-stage spring system for deployment, and a payload geometry approximating a 3U CubeSat. The ADEPT SR-1 was the first fight test which matured ADEPT in the areas of deployment and structural integrity and improved aerodynamic knowledge of the ADEPT open-back configuration. When considered with all the previous ground test and analysis products for the ADEPT project, successful demonstration of the SR-1 flight test Key Performance Parameters (KPPs) supports a technology readiness level (TRL) claim of 5 for SmallSat scale ADEPT at the system-level.

The ADEPT team built and tested a 2m diameter ground test article to demonstrate deployment reliability and was evaluated for the delivery of a 1mT lander at Venus at 6m scale. That study demonstrated ADEPT can save considerable mass as well as maintain a low g-load during entry to accommodate sensitive instrumentation. More recently, wind tunnel and arc jet tests were performed prior to the SR-1 flight test to support smaller scale ADEPT applications for Mars as well as Venus.

ADEPT has been studied for a variety of Entry, Descent, and Landing (EDL) mission applications at Mars. The low ballistic coefficient, hypersonic deployable decelerator offers the potential for effective global access for landed payloads, overcoming the challenges of relatively high elevation landing sites currently inaccessible to higher ballistic coefficient entry systems. The stowable, packaging efficiency can enable multiple, network lander systems to be considered. Since ADEPT deploys prior to atmosphere entry, it also can significantly simplify EDL operations, possibly even delivery of robust landed payloads without parachutes or additional decelerators.

Small Sat Application and Drag Modulated Aerocapture: In addition to Mars EDL applications for ADEPT, there has been renewed focus on SmallSat orbiter missions using the aerocapture technique for orbit insertion.[3] One version of aerocapture is called Drag Modulated Aerocapture (DMA) which has been the focus of significant research and development in the last five years, focused on developing a simple and cost-effective atmospheric control method that is implementable on a small spacecraft within the constraints of a SIMPLEx-class mission. The simplest form of drag modulation aerocapture is the single-stage discrete-event architecture shown in Figure 2. The spacecraft enters the atmosphere in a high-drag/low-ballistic coefficient configuration with its drag skirt deployed, and then transitions to a low-drag/high-ballistic coefficient by jettisoning the drag skirt. The timing of the drag skirt jettison event is determined by a control algorithm with input from an onboard inertial measurement unit. The algorithm monitors the deceleration of the vehicle and triggers the release of the drag skirt based on predicted atmospheric exit conditions that result in capture to the target orbit. This form of drag modulation flight control provides the control authority needed for an interplanetary science mission with a simple enough implementation to be integrated as part of a small spacecraft.

Conclusion: The ADEPT deployable entry system is folded during launch and then deployed prior to atmospheric entry, enabling the entire flight system to be packaged into an ESPA compatible volume, meeting SIMPLEx and other mission launch and configuration constraints. The ADEPT system is uniquely capable as it can tolerate relatively high heating and pressure environments for deployable systems. ADEPT benefits from significant recent development, culminating in a successful suborbital flight test which demonstrated key aspects of the technology, including the ability to deploy in space and withstand aerodynamic loading during reentry. This has given an improved understanding of the flight system capabilities and benefits for a wide range of EDL and Aerocapture Low Cost Mars science mission applications.

References:

[1]Cassell, A., et al "ADEPT for Interplanetary Small Satellite Missions" Interplanetary Small Satellite Conference, 29-30 April, 2019, San Luis Obispo, CA.

[2]Cassell, A. M., et al "ADEPT Sounding Rocket One Test Overview" AIAA Aviation Conference, Dallas, TX, 17-21 June 2019.

[3]Austin, A. et al., "SmallSat Aerocapture: Breaking the Rocket Equation to Enable a New Class of Planetary Missions", 70th International Astronautical Congress, 21-25 October 2019.

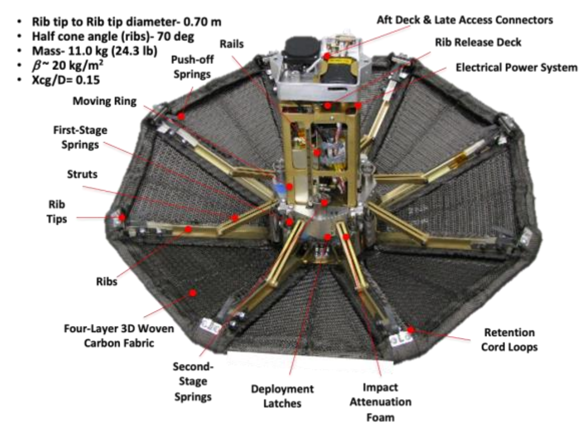

Figure 1. ADEPT SR-1 Vehicle Description

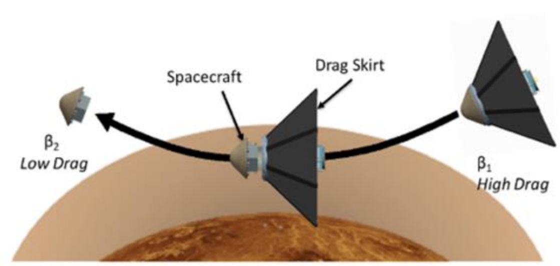

Figure 2. ADEPT Drag Modulated Aerocapture

LOW-COST MARS IN-SITU ASTROBIOLOGY MEASUREMENTS AND STRATEGY. M. B. Wilhelm[1], A. J. Ricco[1], C. Lee[2,3], K. L. Lynch[2], L. Beegle[4], A. Cassell[1], N. Barba[4], [1]NASA Ames Research Center, Moffett Field, CA 94035 (marybeth.wilhelm@nasa.gov), [2]Lunar and Planetary Institute/Universities Space Research Association, [3]NASA Johnson Space Center, [4]Jet Propulsion Laboratory, California Institute of Technology

Introduction: Identifying evidence of Martian life would revolutionize our understanding of biological processes and predictions about the likelihood of life elsewhere. Of all Solar System bodies, Mars remains a primary life-detection target because conditions during its first 500 million years resembled those on Earth when early life emerged [1]. The search for life on Mars should include identifying preserved remains of ancient life from this more habitable epoch in Martian history relative to today, as well as searching for evidence of potential modern survivors that could have found refuge in locations with available liquid water and protection from the harsh surface environment [2].

Low-Cost Astrobiology Mission Motivation & Potential Objectives: Low-cost astrobiology missions to Mars could search for indicators of extant organisms or preserved remains of ancient organisms and help improve our understanding of the modern habitability of Mars with a relatively simple and complementary set of analytical instrumentation. With lower-cost, smaller-size payloads, multiple high-priority astrobiology landing sites could be explored per mission with a distributed network [3]. Measurements made with low-cost instruments would be unlikely to provide conclusive evidence of life but could help determine which regions should be further investigated with follow-on missions (including human missions), either with more comprehensive in-situ instrumentation or sample-return. This mode of Mars exploration would represent a shift in the current paradigm away from site selection relying primarily on remote sensing to be more like the iterative exploration used in astrobiologically significant environments on Earth. In-situ screening of multiple candidate landing sites for organic content, geochemistry, and mineralogy would increase probability of life detection by prioritizing sites for resource-intensive, more-conclusive analyses. Low-cost surface networks would increase reconnaissance of organic matter as direct sample contact is required for the most definitive detection of organics.

Potential objectives for a low-cost Mars astrobiology mission include:

(O1) Determine the variability of astrobiologically-relevant gases at the surface. Methane is a primary astrobiology gas target [4], as well as other gases such as small hydrocarbons, water, hydrogen, and carbon dioxide. These gases could indicate the metabolic activity of an extant population, a reservoir of stored organics (*biotic or abiotic in origin*) undergoing thermogenic alteration, or abiotic reactions occurring (*e.g., via Fischer-Tropsch chemistry*) [5]. Trace gases could be detected through measurements made at the surface after disruption of regolith (e.g. impact or drilling plus thermal processing) at high-priority sites, which would increase likelihood of release. Methane release and sequestration would best be elucidated via surface measurements versus atmospheric measurements [6]. Thus, distributed network sensors would be beneficial in determining methane "hotspots."

(O2) Characterize organic material contained in regolith. One of the best indicators of ancient life on Mars may be preserved organic matter. On Earth, there are molecules that retain biogenic patterns and structures that elucidate the origin and evolution of life that is preserved over geological timescales [7]. Current understanding of the Martian organic inventory comes from studies of Martian meteorites [8] and the in-situ measurements of the Viking landers and Mars Science Laboratory rover [9]. These molecules, namely lipids and insoluble macromolecular material, require sample-processing steps and large analytical instrumentation to elucidate their origin [10]. However, simpler techniques may be used to first probe whether organics are present in soils before resource-intensive analysis.

(O3) Determine if liquid water and salts were or are present at geomorphologically significant sites. In the search for extant life, understanding water availability is paramount. In hyperarid terrestrial deserts, a concentration of organisms is typically found where water activity is the highest for the longest time relative to other features (e.g., deliquescent salts, in rock habitats that retain water) [11]. Additionally, lipids are found to be well preserved in salts over long geologic time periods [12]. On Mars, there are several promising geomorphologic features that are potentially associated with the presence of liquid water. They require in-situ investigations to follow up on remote sensing observations to gain a better understanding if and how liquid water was or is involved in their formation (e.g., gullies, recurring slope linea) [13]. This might be achieved through measuring local relative humidity, soil conductivity, and salt content.

Measurement Options: These objectives could be met using several types of analytical instrumentation in combination (**Table 1**). One key to developing a low-cost astrobiology relevant mission concept is to develop science measurements that are focused and are possible in a small, ruggedized package that requires simple ancillary support hardware, such as sample handling and processing hardware.

NASA programs such as PISCASO, ColdTech, ECI, and MATISSE are developing technology for future missions. Additionally, over the last few decades, Research and Technology development funding for non-NASA based analytical chemistry techniques has doubled ~ every 10 years due to needs in healthcare and environmental sciences [14]. While many of these developments are currently at low to mid-TRL, NASA researchers are beginning the process of raising their TRL for future flight opportunities.

A few techniques discussed here are examples but do not form an exhaustive list. Our focus was to identify potential instrumentation able to withstand high deceleration shock events (< 2000 g pulse) for low mission cost and mass ($100-300M; 5-12 kg) [15]. Contact with regolith is required in some instances, and penetration via an impactor would likely improve detection probability.

Carbon Nanotube (CNT) Based Gas Sensors. High-surface-area CNT chemiresistors have improved sensitivity and recovery time relative to traditional bulk material counterparts; they can detect trace (~ppm) CH_4, CO NH_3, NO, SO_2, and H_2O_2 [16,17]. Heritage derives from extensive use of similar gas sensors on the International Space Station [18]. These fingernail-sized sensors require minimal mass, power, and volume. Sensitivity, gas discrimination and selectivity might require improvement for Mars mission implementation.

Pyrolysis (Py) + CNT Gas Sensors. CNT sensors could also be used with basic pyrolysis. Regolith can be heated through a simple mechanism (e.g., contact with a heated wire) and volatile emissions detected in a compact instrument outfitted with CNTs as a simplified evolved-gas analyzer, particularly for simple hydrocarbons (e.g. ethane, propane, butane). They could be measured with commercially available technology (e.g., Sensirion's VOC Sensor SGP40). These measurements could be indicative of breakdown of larger organics in Martian regolith. To gain resolution between small aliphatic hydrocarbons, a simple, monolithic GC column [19] could be used.

Total organic carbon (TOC) would be a useful measurement to corroborate the presence/abundance of organic matter measured as evolved hydrocarbon volatiles by CNT gas sensors. TOC could be measured using a pyrolyzer coupled with a solid-state oxygen source [20] to oxidize all carbon species, the evolved CO_2 then measured with a ruggedized commercial sensor (e.g., mouser.com/c/ds/?q=IR15TT). TOC has also been measured in water systems using boron-doped diamond sensor electrodes at 10-100 mg/L [21].

Electrochemical Sensors. The electrochemical sensors on the Wet Chemistry Laboratory (WCL) flown on the Phoenix Mars mission [22] measured multiple ions including perchlorate. A microfluidic implementation (*low SWaP*) of WCL has been developed recently for Icy-Worlds applications [23] to measure a range of ions (Na^+, K^+, Mg^{2+}, Ca^{2+}, Cl^-, SO_4^{2}, CO_3^{2-}), and could be useful for geochemical characterization at astrobiologically-significant sites.

Miniature Raman. Raman remains an important tool in characterization of the bulk properties of carbonaceous matter contained in Martian soils (e.g., diagnostic functional groups) using a standoff technique [24]. Raman systems such as the Raman Laser Spectrometer (RLS) for ExoMars survived drop tests up to 2500 g [25], making them a potential candidate for "rough" landings. Additionally, miniature Raman probes have been recently developed for medical purposes [26] as well as planetary missions [27].

Payload Combinations: Science objectives (above) could be addressed using a combination of small, rugged sensors (**Table 1**).

Table 1: Astrobiology Objectives Addressed by Low-SWaP Instruments

	O1: Variability of Gases at Surface	O2: Organics in Regolith	O3: Liquid Water and Salts
Relevant to:	*extant or ancient life*	*extant or ancient life*	*extant life*
CNT Gas Sensors	X		
Py + CNTs		X	
Electrochemical Sensors for Ions			X
Electrochemical Sensors for TOC		X	
Miniature Raman		X	X

Blue X= standoff technique; **Red X**= contact with soil required

References: [1] Pollack, J. B., et al.,. *Icarus*, *71*(2). [2] Carrier, B. L., et al., (2020). Mars extant life: what's next? Conference report. [3] Squyres, S. W. (1995). *Adv. in Space Res.*, *15*(4).[4] Webster, C. R., et al., (2015). *Sci.* , *347*(6220). [5] Oehler, D. Z., & Etiope, G. (2017). *Astrobio.*, *17*(12). [6] Korablev, O., et al., (2019). *Nature*, *568*(7753). [7] Summons, R. E., et al., (2011). *Astrobio.*, *11*(2), 157-181.[8] Steele, A., et al., (2016). *Met. & Plan. Sci.*, *51*(11). [9] Eigenbrode, J. L., et al., (2018). *Sci.*, *360*(6393). [10] Lee, C., et al., (2019). *Org. Geochem.*, *132*. [11] Warren-Rhodes, K. A., et al., (2006). *Microb. ecology*, *52*(3). [12] Cockell, C. S., et al., (2020). *Astrobio.*, *20*(7). [13] Wray, J. J. (2021). *Ann. Rev. of Earth & Plan. Sci.*, *49*. [14] Dorsey, E. R., et al., (2010). *Jama*, *303*(2). [15] N. Barba, et al., (2021) IEEE Aero. Conf. (50100). [16] Hannon, A., et al., (2016). *Sensors*, *16*(8). [17] Meyyappan, M., et al., (2015). *MRS Bulletin*, *40*(10). [18] Stenzel, C. (2016). *Analytical & bioanalytical chem.*, *408*(24). [19] Svec, F. (2017). *Electrophoresis*, *38*(22-23). [20] Speidel, R., & Weidlich, E. R. (1988). *Vacuum*, *38*(2), 89-92.[21] Dweik, B., et al., (2019). [22] Hecht, M. H., et al., (2009). *Sci.*, *325*(5936). [23] Noell, A. C., et al., (2019). *AbSciCon*. [24] Wiens, R. C., et al., (2021). *Space Sci. Rev.*, *217*(1). [25] Moral, A. G., et al., (2020). *Jour. of Raman Spec.*, *51*(9). [26] McGregor, H. C., et al., (2018). *Jour. of biophotonics*, *11*(11). [27] Jehlička, J., et al., (2016). *Astrobio.*, *16*(12).

MISSION DESIGN HURDLES FOR LOW-COST MISSIONS TO MARS. R. C. Woolley[1] and N. Barba[1], [1]Jet Propulsion Laboratory, California Institute of Technology. 4800 Oak Grove, Pasadena, CA 91109. woolley@jpl.nasa.gov

Introduction: In order to reach their final destination, any low-cost mission to Mars must first determine how they are to overcome a series of mission design hurdles to get there, depicted broadly in Figure 1. These hurdles represent the challenges of multiple steps from departing Earth to arriving at or on Mars. The nature of the hurdles that must be cleared are dependent on such factors as whether the spacecraft will be manifested as a rideshare, piggy back, or dedicated launch. We present here methods and strategies for low-cost missions to address: 1) launch, 2) departure from Earth orbit, 3) interplanetary cruise, 4) Mars orbital insertion (MOI) or entry targeting, and 5) achieving final orbit or entry, descent and landing (EDL). The final two hurdles are bifurcated for orbiters vs. landers.

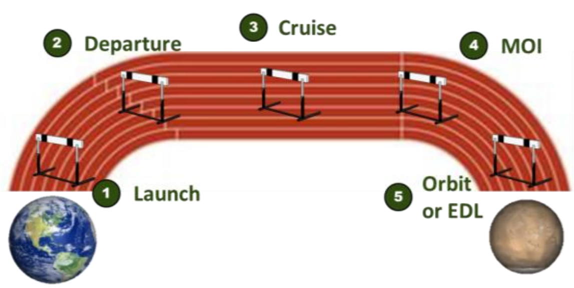

Figure 1- Mission Design Hurdles from Earth to Mars

For traditional missions to Mars, each of these hurdles requires a solution that often comes with considerable complexity and cost. Missions wishing to reach the Red Planet for a fraction of traditional costs must approach these challenges with ingenuity and creative solutions. The most recent example of this was the first CubeSat to reach Mars, MarCO, which was manifested in the aft bulkhead carrier (ABC) of the Atlas V that launched Insight [1]. MarCO avoided the high costs of launch and departure through rideshare, and flew by Mars rather than needing an MOI.

Methods: Each of the hurdles essentially represents the costs of providing the ΔV necessary to leave Earth's gravity well and to arrive at Mars. The amount of ΔV required is dependent upon the starting and ending points [2]. The ΔV is provided by either an integrated propulsion system, a tug or propulsion module, or another host spacecraft. (For near-Mars applications, the atmosphere can provide deceleration for aerobraking, aerocapture, or landing). In the cases of rideshares or piggyback missions, some or all of the mission design hurdles are cleared by the launch vehicle or propulsion systems of the primary.

Launch. For dedicated or direct missions to Mars, the launch vehicle typically launches to a temporary parking orbit, followed by an Earth departure burn to send the spacecraft directly to the interplanetary cruise phase. Launch vehicles capable of sending sufficient mass to the energies needed to reach Mars frequently cost $100M and above, which can be near or even greater than the cost of the small mission itself. A number of small, low-cost launch vehicles are emerging that can potentially provide dedicated launches for Mars mission with sufficiently low mass and an identified method to clear the next hurdle.

Earth Departure. Missions not launching to a positive C3, such as rideshares to GTO or launches to LEO, must find a way to provide the ΔV needed for a trans-Mars injection. Not only is this a large maneuver (typically a few km/s), but it also must be at the right time and in the right direction. This may require loitering, multiple maneuvers, and/or lunar gravitational assists. Such high ΔVs may also be provided more efficiently through the use of solar electric propulsion (SEP), however, the low thrust spirals can add many months to the transfer duration.

Interplanetary Cruise. Even the shortest transfers to Mars will take more than 6 months, where the spacecraft will require basic functions such as power, thermal, telecom, and maneuvering. These subsystems are typically part of most orbiters, but landers or simple orbiters may require an additional cruise stage or mothership to provide these functions. For SEP missions, much of the ΔV needed to make the transfer is provided through near-continuous thrusting during this phase.

Mars Orbital Insertion or Entry Targeting. Upon arrival at Mars, a spacecraft must provide a braking maneuver in order to be captured into the Martian gravity well. The magnitude depends on the incoming hyperbolic velocity and the desired capture orbit. Orbiters can choose from a large insertion burn directly to the final orbit, multiple burns, MOI to a large elliptical orbit followed by months of aerobraking, or even aerocapture. SEP missions will transition through the sphere-of-influence gradually as they begin a circular spiral in the planar inclination of their choice (e.g. polar or equatorial). Landed missions do not need to "hit the brakes" as they will use the atmosphere and other methods to decelerate before impact. They do, however need to target the entry interface and B-plane target with sufficient accuracy to ensure a save landing at their desired target.

Final Orbit Acquisition or EDL. After arriving at Mars, whether by MOI directly, a SEP spiral, or separation from a host, it will be necessary for the spacecraft to have sufficient propulsion to achieve the desired orbital parameters to carry out the mission objectives. In some cases, this may just mean a few 10's of m/s or taking advantage of natural orbital drifts. In other cases, this could require rather large maneuvers to change planes or circularize orbits. For landers, a strategy must be adopted for EDL. This can include a combination of heatshields, parachutes, propulsion, airbags, crushables, etc. Lower costs are likely achieved through the minimization of complexity, deployments, and strict requirements.

Format: This research will be best portrayed visually as a poster or short presentation. It is intended to illustrate a pathway of options for each hurdle and the potential solutions of each for a wide range of small, low-cost missions to Mars.

Acknowledgments: This research was carried out at the Jet Propulsion Laboratory, California Institute of Technology, under a contract with the National Aeronautics and Space Administration. Information about future mission concepts in this document is pre-decisional, and is provided for planning and discussion only.

References:

[1] Klesh, Andrew, et al. "MarCO: Early operations of the first CubeSats to Mars.," *Proceedings of the Small Satellite Conference,* SSC18-WKIX-04, (2018).

[2] Woolley, Ryan, Nathan Barba, and Lou Giersch. "Rideshare Strategies for Small Mars Missions." *2021 IEEE Aerospace Conference (50100)*. IEEE, 2021.

Toward Economically Addressing Surface Science Questions on Mars with Distributed Instruments.

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Background and Motivation: Robotic exploration of the solar system has relied heavily on large, single spacecraft missions equipped with many instruments. This has led to many important scientific discoveries, but some scientific questions are difficult to answer with data from a single state-of-the-art rover or orbiter. For example, the localization and analysis of seismic events or characterization of large-scale atmospheric phenomena is hard to perform with monolithic instruments; in contrast, these science questions can be sufficiently addressed with measurements from modest-quality, less-expensive instruments when sampled simultaneously from different spatial locations. Toward this goal, we explore Distributed Instruments (DIs). A DI is a collection of geographically dispersed sensors designed to strategically collect spatially and temporally correlated readings at known locations [1]. DIs are suitable (and in some cases, required) to gather the data needed for investigating dynamic, distributed phenomena. Furthermore, they involve manufacturing multiple copies of a single platform architecture and equipping this platform with off-the-shelf sensors. We explore which aspects of DIs lend themselves to lower-cost Martian surface science and discuss areas where further development is needed.

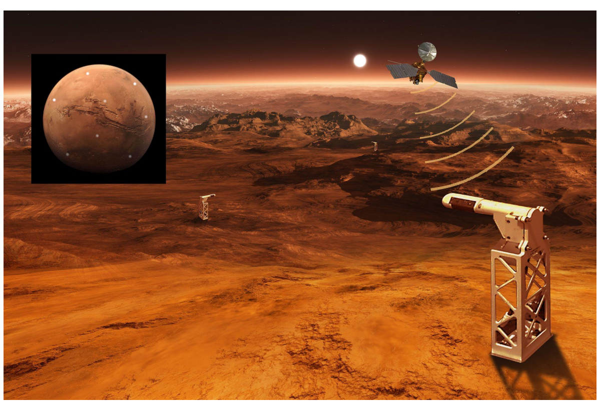

Figure 1. Artist's illustration of a DI to study Mars. Each node in the DI network contains a modular set of instruments to observe atmospheric, seismologic, and/or other phenomena.

Uniquely Addressable Science Questions: DIs are uniquely suited to answer science questions involving large-scale, surface-level phenomena. On Mars, there are at least four such high-priority areas of scientific inquiry. First, investigation into active geological processes is greatly simplified when multiple, distributed measurements are available for the same event. For example, the localization of seismic events (i.e., Marsquakes) is substantially easier when data is collected from multiple locations [1].

Second, cycling of dust, water, and CO_2 remains poorly understood. Climate modeling has been stymied by the absence of distributed, diurnal, atmospheric measurements (e.g., 3D surface wind speeds) [2]. A DI can support modeling and investigation into the Martian climate (e.g., seasonal variations in the atmospheric composition and characterization of transient dust storms) through simultaneous sampling of these dynamic phenomena from multiple locations. Again, important scientific advancements are achievable with relatively inexpensive sensors.

Third, trace gasses (e.g., methane) require measurements from multiple sensors to localize their source. On Earth, methane detection has long relied on arrays of sensors to better understand the shape and dynamic concentration of methane gas plumes. The investigation of Martian methane is important in our search for life as well as an indicator of hydrothermal activity, which could indicate favorable conditions for life [1].

Fourth, investigating the internal composition of Mars through magnetometry can benefit from multiple, landed sensors to measure its internal structure. DIs would provide information about the internal composition of Mars that can answer questions about atmospheric loss. Further, identification of any residual crustal magnetization could help shield future robotic or human landers from radiation.

Key Technologies: *EDL and Sensor Placement.* A significant technological and financial obstacle facing DI platforms is the deployment of the individual sensor platforms. Global distribution requires either multiple launches or independent EDL platforms for each sensor node because strategies for dispersing during EDL or after landing are not yet tenable. Multiple independent landers in the form of microlanders or ground penetrators are currently the most developed technologies to deliver the nodes of a DI. One such platform, the Small High Impact Energy Landing Device (SHIELD; Figure 2), supports global distribution of DI nodes for about \$50 million per lander. Three landers with a transit stage and launch has been projected to cost about $200 million [3]. With SHIELD, each node is packaged into an independent EDL platform and released at slightly different velocities after launch. Over the course of the journey to Mars, the spatial separation between nodes grows, so global coverage is assured by the time the microlenders begin EDL. Miniaturized sensors that can withstand ballistic impact are already in development, but others will require focused investments to improve their robustness to the high impact forces.

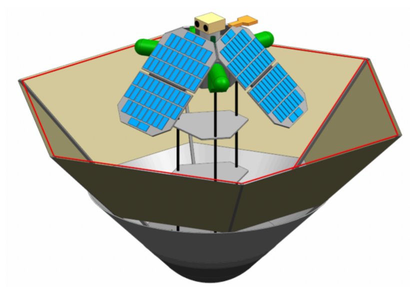

Figure 2. Ballistic SHIELD microlander concept capable of carrying up to 10 kg payload [3].

Power. Compact and long-life power sources are critical for the successful implementation of DIs. Selection of an appropriate power source depends on many factors, including the nature of the electrical loads (i.e., average and peak power levels), its location (i.e., latitude), and the environment of the instrument (i.e., time of year). The lowest cost option would feature the use of primary batteries; however, this approach would practically limit mission life to several months at most. To maintain low cost and increase mission life, a combination of solar arrays and rechargeable energy storage (secondary batteries and/or supercapacitors) offer the best approach. Selection of this option must be traded against other power technologies, based on the peak power needs and total energy required each day [1]. These are impacted by the sun angle and the amount of electrical energy required for heaters. Small radioisotope thermoelectric generators (RTGs) that utilize one or more (1 W_{th}) radioisotope heating units (RHUs) to provide both thermal and electrical power are another alternative, especially where access to adequate solar energy is limited and temperatures are low. However, the use of this technology increases the cost of each node in the DI. These sources would also require on-board energy storage to support peak power requirements, trickle charged by the small RTGs.

Science Autonomy. DIs can leverage onboard science autonomy software as a way to mitigate demands on the sensor platform. For example, content-based compression and prioritization are two related methods to ensure the most scientifically valuable data is sent back to Earth when the full raw data record is too large to transmitted. These methods ensure that data for compelling events (e.g., large magnitude Marsquakes) are fully captured while aggressively condensing or deprioritizing data from less interesting components of the data record. Adaptive sampling is a separate method to reduce power consumption by intelligently regulating data collection rates across the DI network. For example, a DI may operate with low-frequency sampling by default. However, after a sentinel sensor identifies a valuable phenomenon or anomaly (e.g., a growing dust storm), it can trigger the rest of the network to increase data sampling. Reducing data transmission and power spent collecting that data will lower mission costs by reducing demands on energy generation and communication hardware.

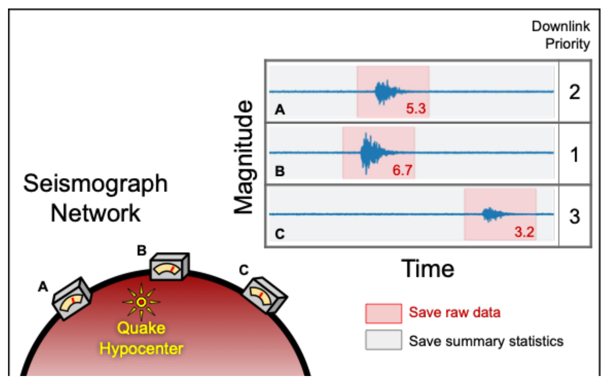

Figure 3. Instrument autonomy for a seismograph network. Multiple DI nodes record activity from a Marsquake. The phenomenon is identified by onboard autonomy (red boxes) and raw data is prioritized for downlink according to magnitude (right of example traces). Quiescent data is summarized with simple statistics to reduce transmitted data and save power.

Conclusions: DIs are valuable for investigating seismic activity, climate, magnetosphere, and trace gases on Mars. While some focused technology improvement is needed (especially deployment of sensor nodes), off-the-shelf sensor technology combined with a microlender concept could support a small DI mission (3-4 nodes) for under $300 million.

Acknowledgments: We acknowledge the thoughtful contributions and conversations with others who contributed to the related Blue-Sky Study on Distributed Instruments.

References: [1] A. Goel, et al. (2021) *Planetary Science and Astrobiology Decadal Survey, 53(4),* e-id 156. [2] C. Newman, et al. (2020) *ESSOA.* [3] N. Barba, et al. (2020) *LPI*, #2326, p. 2874.