
SURVIVE AND OPERATE
THROUGH THE LUNAR NIGHT
WORKSHOP
November 13, 2018
Columbia, Maryland

Program

Survive and Operate Through the Lunar Night Workshop

November 13, 2018 • Columbia, Maryland

Institutional Support

NASA Solar System Exploration Research Virtual Institute
NASA Lunar Exploration Analysis Group
Lunar and Planetary Institute
Universities Space Research Association
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Andrew Petro
NASA Headquarters

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Greg Schmidt
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Renee Weber
NASA Marshall Space Flight Center

Alison Zuniga
NASA Ames Research Center

Lunar and Planetary Institute   3600 Bay Area Boulevard   Houston TX 77058-1113

Abstracts for this workshop are available via the workshop website at

https://www.hou.usra.edu/meetings/survivethenight2018/

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Survive and Operate Through the Lunar Night Workshop
Tuesday, November 13, 2018
USRA Headquarters, Columbia, MD

Agenda	Time	Speakers
Welcome and Workshop Objectives	8:30–8:40 a.m.	Co-Chairs: Andrew Petro, NASA HQ Renee Weber, NASA MSFC
Overview of Lunar Day/Night Environmental Conditions — Including Various Latitudes, Polar Regions, Permanently Shadowed Regions, Peaks of Eternal Light	8:40–9:00 a.m.	Brett Denevi, JHU APL
Lessons Learned from Missions that Have Survived Lunar Night (Surveyor, ALSEP, Lunokhod)	9:00–9:20 a.m.	Ron Creel, NASA Retired
Panel Discussion: Evolving Requirements from Survival to Continuous Operations for Science, Exploration, and Commercial Activities	9:20–10:20 a.m. BREAK 10:40–11:40 a.m.	Science Perspective Sam Lawrence, NASA JSC: ASM/NEXT-SAT Briefing Exploration Perspective Ben Bussey, NASA HQ Panel Greg Chavers, NASA MSFC/HQ Dave Blewett, JHU APL Dana Hurley, JHU APL James Carpenter, ESA
LUNCH	11:40 a.m.– 1:00 p.m.	On your own
Panel Discussions: State of the Art, Potential Solutions, and Technology Gaps Panel 1: Power Generation, Storage, and Distribution Panel 2: Thermal Management Systems, Strategies, and Component Design Features	1:00–2:00 p.m. BREAK 2:15–3:15 p.m.	Power Panel Moderator: Lee Mason, NASA STMD Len Dudzinski, NASA HQ: RPS and Fission Bob Sievers, Teledyne: Fuel Cells, RTGs Erik Brandon, JPL: Batteries Paul Alburtus, ARPA-e: Energy Storage Thermal Management Panel Moderator: Rubik Sheth, NASA JSC Eric Sunada, JPL: Robotic Missions Chad Bower, Paragon: Commercial Systems Kust Sacksteder, NASA GRC: Thermal Wadi
Commercial Space Panel: Understanding the Economic Business Case for Creating Lunar Infrastructure Services and Lunar Markets	3:15–4:00 p.m.	Moderator: Alison Zuniga, NASA ARC George Sowers, Colorado School of Mines Dennis Poulos, Poulos Air and Space, Inc. Dennis Wingo, SkyCorp Inc. Mahamed Ragab, iSpace Technologies, Inc. Rolf Erdmann, PT Scientists
International Space University Summer Project Presentation "Lunar Night Survival"	4:00–4:20 p.m.	Matt Henderson and Ilaria Cinelli, ISU
Open Discussion and Conclusions	4:20–5:30 p.m.	Co-Chairs, All Workshop Participants
Poster Session **Wednesday Evening, November 14**	5:00–7:00 p.m.	Posters Presented on Wednesday Evening During the 2019 LEAG Meeting

Wednesday, November 14, 2018
POSTER SESSION: SURVIVE AND OPERATE THROUGH THE LUNAR NIGHT WORKSHOP
5:00–7:00 p.m. USRA Education Gallery

Authors	Title and Summary
Evans M. E. Ignatiev A.	*Lunar Superconducting Magnetic Energy Storage (LSMES)* **[#7001]** This study seeks a method to efficiently store electrical energy without using chemical batteries, by applying terrestrial technology based on a superconducting coil and a persistent magnetic field located in a lunar permanently shadowed crater.
Nandini K. Usha K. Srinivasan M. S. Pramod M. Satyanarayana P. Sankaran M.	*Passive Survivability of 18650 Lithium-Ion Cells Through Lunar Night Environment Scenario* **[#7002]** Present study describes passive survivability of commercially-off-the-shelf 18650 lithium-ion cells tested in an environmental scenario similar to onset and progress of lunar night that is at cryogenic temperatures under vacuum for 336 earth hours.
Poulos D. D.	*Data Encoded Laser Wireless Power (DELWP) for Lunar Polar Applications* **[#7003]** Data encoded high power fiber lasers illuminating specialized tuned photovoltaic panels designed for power transfer will provide reliable, continuous power and data during periods of limited solar illumination, including into the dark polar craters.
Van Cleve J. E. Weinberg J. D. Neal C. R. Elphic R. C. Weed K. Mills G. Dissly R.	*Darkness Visible: Instrumentation and Thermal Design to Access the Hidden Moon* **[#7005]** We show mission concepts for a long-lived geophysical network and in-situ investigation of volatiles in the lunar polar cold traps, and Ball instrument and thermal technology enabling survival, situational awareness, and operations in the dark Moon.
Herring J. S. Mackwell S. Pestak C.	*Small Modular Fission Reactors that Enable Affordable and Sustainable Lunar Enterprise* **[#7006]** We will present the results of a study looking at the use of a LEU-based Small Modular Fission Reactor (SMFR) in the 40 to 100 kW range for lunar activities, building on the results of NASA's HEU-based KiloPower project.
Colaprete A. Elphic R. C. Shirley M. Siegler M.	*Multi-Lunar Day Polar Missions with a Solar-Only Rover* **[#7007]** The lunar poles offer opportunities for solar-only rovers to survive and operate many lunar days. Presented here are examples of rover traverses that take advantage of the unique polar illumination environments to operate across multiple lunar days.
Eppler D. B. Budden N. A.	*Lighting Constraints to Lunar Surface Operations* **[#7008]** An investigation into lunar surface ambient lighting levels indicates that, for most nearside locations, illumination will be adequate throughout a large portion of the lunar night to conduct surface activities.
Bugby D. C. Clark P. E. Hofmann D. C.	*High Performance Thermal Switch for Lunar Night Survival* **[#7009]** A high performance differential thermal expansion (DTE) thermal switch was developed to enable solar/battery powered lunar surface science payloads. The measured thermal switch performance is: 5 W/K ON, 0.002 W/K OFF, and 2500:1 ON/OFF ratio.
Nunes D. C. Carpenter K. Haynes M. de la Croix J. P.	*Shifting the Paradigm of Coping with Nyx on the Moon — a Ground-Penetrating Radar Case* **[#7012]** A multi-static, autonomous ground-penetrating radar instrument, MARGE, will incorporate strategies to be more tolerant of the lunar diurnal thermal cycle.
Wani S. C. Shah U. B. Kothandhapani A. Garg P. Sahai M. Garg M. Nair S.	*Requirement Analysis and Night Survival Concept for Z-01 Landing Mission Using Fuel Cell* **[#7014]** Only three missions have survived the lunar night, using Radioisotope Thermo-Electric Generators and Radioisotope Heating Units. This paper discusses the challenges to survive lunar night and presents a fuel cell-based concept as an alternative.
Plata D. S.	*Lunar Roads: Strategies for Remaining in the Sunlight* **[#7017]** By driving westward on the slowly rotating Moon, telerobots could remain in the sunlight while compressing the regolith in order to make basic, reduce-dust roads.

Authors	Title and Summary
Powell T. M. Siegler M. A. Molaro J. L. Paige D. A.	*Leveraging In-Situ Regolith Properties for Nighttime Heating* **[#7018]** Despite large temperature fluctuations at the lunar surface, thermally coupling to warm nighttime materials (rocks, subsurface, etc.) present in-situ might provide some heating and reduce the engineering payload necessary for surviving the night.
Dillon R. P. Borgonia J-P. C. Roberts S. N. Hofmann D. C. Kennett A. Firdosy S. A. Wilcox B. H. Hales S. Smith J. D. Schuler J. McEnerney B. Shapiro A. A.	*Bulk Metallic Glass Gears for Lunar Night Capable Actuators* **[#7019]** BMG Gears is developing unheated, cold-capable gearboxes for use in cryogenic environments such as lunar night. The enabling alloy properties, cryogenic test performance, part processing, qualification, TRL, and infusion challenges are discussed.
Carroll K. A.	*Lunar Surface Gravimetry Surveying Through the Lunar Night* **[#7020]** Lunar surface gravimetry is a powerful technique for probing the Moon's subsurface structure, using a gravimeter on a static lunar lander or on a lunar rover. Measurements spanning multiple lunar days will increase accuracy and resolution.
Guven U. G. Singh A. K. S.	*Utilization of Nuclear Power for Moon Missions: Nuclear Power Generation Using Helium Cooled Reactor for Moon Habitats* **[#7021]** Abstract discusses using helium cooled nuclear reactors in Moon habitats to supply continuous power to the habitat as well as any future processing/manufacturing plants on the Moon.
Nieczkoski S. Dreyer C. B. Blair B. Rostami J.	*Material Selection for Mechanical Mechanism Survival and Use in the Lunar Night* **[#7023]** Survival of spacecraft mechanisms is challenging due to low polar temperatures. Structural and cutting materials enabling drilling and mining under deep cryogenic conditions are currently being tested under the NASA Early Stage Innovation program.
Guzik M. C. Gilligan R. P. Smith P. J. Jakupca I. J.	*Regenerative Fuel Cell-Based Energy Storage Systems for Lunar Surface Exploration* **[#7024]** The data presented in this paper provides a method to determine the critical parameter values of a Regenerative Fuel Cell (RFC) system in order to perform high-level mission architecture trades, with a focus on surviving the lunar night.
Williams J.-P. Greenhagen B. T. Paige D. A.	*Seasonal Temperature Variations in the Polar Regions of the Moon* **[#7026]** Mapping of temperatures in the south polar region with LRO's Diviner Lunar Radiometer Experiment shows how temperatures within 5 degrees of the pole vary considerably with season.
Eubanks T. M.	*MilliWatt Lunar VLBI Beacons: Surviving the Lunar Night* **[#7027]** MilliWatt radio beacons could establish a lunar VLBI network for science and navigation in cislunar space, ideally operating for decades. Small, gm-scale Americium-241 batteries are proposed to meet the power and longevity needs of these networks.
Fuqua Haviland H. Poppe A. R. Fatemi S. Delory G.	*The Importance of Nightside Magnetometer Observations for Electromagnetic Sounding of the Moon* **[#7010]** Nightside Time Domain Electromagnetic Sounding has the capability to advance the state of knowledge of the field of lunar science. This requires magnetometer operations to withstand the harsh conditions of the lunar night.
Ignatiev A.	*The Use of Lunar Resources for Energy Generation on the Moon* **[#7013]** The resources of the Moon can be used to develop an electrical energy system for the Moon. This can be accomplished by leveraging vacuum deposition technology and lunar resources to fabricate a low-cost and scalable lunar power grid.
Baiden G. R. Blair B. R.	*Adapting Terrestrial Technology to the Design of a Night-Survivable 10 Meter Lunar Polar Prospecting Drill* **[#7016]** This paper will explore the possibility of a 10 meter cryogenic lunar polar drill that could 'survive the night' and that would enable the collection of scientific data that could validate current models for polar resources.

Authors	Title and Summary
Vaughan R.	*Mission Design and Implementation Considerations for Lunar Night Survival* **[#7029]** We present some of the design, development, cost, and schedule impacts of dealing with problematic night time lunar conditions, whether for near-equatorial or near-polar landed lunar missions.
Farmer J. F. Alvarez-Hernandez A. Breeding S. P. Lowery J. E.	*Advanced Thermal Techniques and Systems Design Enable Long Duration, Continuous Day/Night Operation of Robotic Science Landers and Payloads on the Lunar Surface* **[#7030]** Recent developments in NASA and commercial space capabilities and plans support and call for increased exploration of the lunar surface. Lunar exploration objectives vary widely from geophysical research to human exploration and resource prospecting.
Clark P. E. Bugby D. C. Hofmann D. C.	*Low-Cost Distributed Lunar Surface Networks Enabled by High Performance Thermal Components* **[#7031]** Credible opportunities for delivery of small payloads to the lunar surface via commercial landers are emerging in the coming decade.
Cataldo R. L. Mason L. S.	*Lunar Night Survivability Achieved by Radioisotope and Fission Power System Technology* **[#7032]** Options for advanced RPS and Kilopower systems will be discussed and compared to alternate power system solutions.
Morrison C. G. Deason W. Eades M. J. Judd S. Patel V. Reed M. Venneri P.	*The Pylon: Near-Term Commercial LEU Nuclear Fission Power for Lunar Applications* **[#7033]** Nuclear energy provides not only the ability to survive the 354-hour lunar night, but the ability to thrive.
Hecht M. H. Lubin P.	Satellite Beamed Power for Lunar Surface Assets **[#7034]** The confluence of several factors now make beamed power systems practical for solar system exploration in the near-term. This is particularly true for lunar exploration.
Barnhard G.	*Challenges of Space Power Beaming: Mission Enabling Technology for Continuous Lunar Operations* **[#7035]** This presentation will outline opportunities to leverage and extend the Xtraordinary Innovative Space Partnerships, Inc. (XISP-Inc) Technology Development, Demonstration, and Deployment (TD3) mission for Space-to-Space Power Beaming (SSPB).

CONTENTS

ADAPTING TERRESTRIAL TECHNOLOGY TO THE DESIGN OF A NIGHT-SURVIVABLE 10 METER PLUS LUNAR POLAR PROSPECTING DRILL. G. R. Baiden[1] and B. R. Blair[2], [1]CEO, Penguin Automated Systems Inc., Sudbury, Ontario, Canada, <gbaiden@penguinasi.com>, [2]Penguin Automated Systems US Inc., Denver, Colorado, <planetminer@gmail.com>.

Introduction: This paper will explore the possibility of combining the Lunar and terrestrial drilling needs together for lunar polar exploration. While drilling in varying gravity environments is only theoretical at this point, the creation of a 10 metre or deeper Lunar polar drill that can survive through the night would represent a remarkable breakthrough if accomplished, enabling the collection of priceless scientific data that could validate current models for polar resources. Current lunar drill designs are limited to 1 meter or less. Novel drilling technology in mining and oil & gas exploration could fill the void and increase sampling depth. Penguin ASI is a patent holder of a new type of drill that grips the rock and thrusts based on ground pressure rather than gravity, enhancing its operational capabilities for lunar and asteroidal applications.

Cryogenic Drill Design: The focus of this presentation will be on the engineering steps needed to design, certify and de-risk drilling technology for lunar cryogenic applications. Moreover, the operational requirements to setup the drill, drill the hole and then move to the next drill site while managing the consumables for multi-day operation will be explored.

Spinoff Technology: Rock drilling is a key societal technology both terrestrially and extra-terrestrially. Advances in terrestrial drilling technology have been slowing to date as consumable designs for bits, steel and machines have not had an impetus to improve due to the nature of their in production rather than research. Therefore, significant commercial potential is also anticipated for technical breakthroughs.

Challenges of Space Power Beaming: Mission-Enabling Technology for Continuous Lunar Operations

Gary Pearce Barnhard, XISP-Inc, gary.barnhard@xisp-inc.com

This presentation will outline opportunities to leverage and extend the Xtraordinary Innovative Space Partnerships, Inc. (XISP-Inc) Technology Development, Demonstration, and Deployment (TD^3) mission for Space-to-Space Power Beaming (SSPB), planned for implementation on the International Space Station (ISS) for subsequent application to lunar surface operations. This presentation extends the paper CHALLENGES OF SPACE POWER BEAMING: FORGING PRODUCTION SERVICES FROM THE TECHNOLOGY DEVELOPMENT TRADE SPACE presented at IAC 2018 Bremen. The SSPB mission builds on foundational research in the field as well as mission development work accomplished to date by the proposed Principal Investigator (PI), XISP-Inc, and the XISP-Inc SSPB Consortium participants. This mission is a unique opportunity to foster the development of power and ancillary services beaming technology, by leveraging ISS resources to create a SSPB testbed environment on and near the ISS that supports the development of frequency-agnostic radiant energy beaming technology. The overarching objective of this mission is to hasten the development of viable applications of SSPB technology and ancillary services through focused incremental efforts that bridge the technology development “valley of death” as well as substantially mitigate perceived and actual cost, schedule, and technical risk associated with applications of the technology. The SSPB mission objectives include the technology development necessary to support the unbundling of a commercially relevant space power system (i.e., the separation of power generation, transmission, distribution, and loads) along with the multiplexing of ancillary services (e.g., data, communications, navigation, time) to enable Space-to-Space and Space-to-Alternate Surface, as well as Surface-to-Surface Power Beaming.

The ability to provide power and ancillary services when and where needed is essential to virtually all aspects of human endeavor and enables all forms of space development/settlement. The SSPB mission will deliver significant commercial value in the form of power and bi-directional ancillary services to a growing number of customers interested in co-orbiting with the ISS and lay the foundation for a myriad of Cislunar applications.

The first phase of the SSPB mission is Technology Development. This includes lab/ground test work (XISP-Inc & teammate Internal Research and Development (IRaD) and leverageable contract research & development) which will transition into highly configurable space-qualified instances of cognitive Software Defined Radio (SDR) transceivers, rectennas, and related control systems. These elements will have mutable/switchable apertures (frequency-agnostic radiant energy beaming source), separate and converged conformal rectenna/solar array/antenna constructs that are configurable/tunable (combination of phased array, reflectarray, and multi-layer/junction, and related technologies), and software-driven controls. The elements will be integrated to form an on-orbit testbed consisting of an ISS-based transmitter, a co-orbiting CubeSat flight test article, and related management operations control applications. The testbed will support the near–real-time characterization, optimization, and operationalization of an unbundled power and ancillary services beaming system.

In the second phase of the SSPB mission, Technology Demonstration, the results from the testbed will be used to create an enhanced technology demonstration of the commercial application of the SSPB technology by providing an additional source of power and ancillary services to a specially configured Cygnus pressurized logistics commercial cargo carrier, thereby enabling Cygnus to support crew-tended co-orbiting operations while the ISS resumes normal operations. The combination of the Phase I technology development and the Phase II technology demonstration will raise the Technology Readiness Level (TRL) of SSPB technology from the existing TRL of 4 to 8/9.

The third Phase of the SSPB mission, technology deployment, entails fielding an interface deployment kit for the use of space-based power and ancillary services that would be suitable for multiple space-to-space, space-to-lunar surface, and surface-to-surface applications. One of the addressable markets this deployment kit will be designed to facilitate is lunar surface operations through multiple lunar nights.

HIGH PERFORMANCE THERMAL SWITCH FOR LUNAR NIGHT SURVIVAL. D. C. Bugby[1], P. E. Clark[1], and D. C. Hofmann[1], [1]Jet Propulsion Laboratory, California Institute of Technology, 4800 Oak Grove Drive, Pasadena, CA 91109, david.c.bugby@jpl.nasa.gov, pamela.e.clark@jpl.nasa.gov, douglas.c.hofmann@jpl.nasa.gov.

Introduction: A high performance differential thermal expansion (DTE) thermal switch was developed to enable solar/battery lunar surface science payloads. Previous DTE thermal switches (e.g., MSL SAM) are ON/cold, OFF/warm. For lunar night survival, this "normal-operation" DTE thermal switch must be reversed to OFF/cold, ON/warm. This paper describes a patent-pending JPL-developed "reverse-operation" DTE thermal switch that performs as follows: ON conductance of 5 W/K, OFF conductance of 0.002 W/K, and ON/OFF switching ratio of 2500:1.

Background: The thermal design challenge facing lunar solar/battery-powered instruments is how to reject payload heat during the day yet isolate the payload enough during the night for battery mass launch viability. A Lunar Geophysical Network (LGN) study indicated a 400:1 thermal switching ratio is required for battery mass viability. The ratio must be even higher for compact lunar payloads under development at JPL. The NASA 2015 technology roadmap TA14 indicates a need for a thermal switch 10X better than the state-of-the-art 100:1 MER paraffin thermal switch.

Concept: Two prototypes were designed, built, and tested. Their basis of operation is the mating/de-mating of parallel (near mirror finish) flat metal surfaces. The physical mechanism causing the motion is the DTE of mid-CTE, high thermal conductivity (k) metallic end-pieces compared to a low-CTE, low k two-piece metal/polymer support beam. The requirements of operation were to be fully ON above 300 K with 1335 N force and fully OFF below 260 K.

Design: The thermal switches were designed for seamless integration into box-type instrument enclosures. Each prototype easily slides into a small 25-35 mm circular enclosure opening such that most of the 80-120 mm long thermal switch lies within the enclosure and just two small circular 25-45 mm diameter, 6 mm thick discs (one connects to a radiator) are visible from the outside of the enclosure. Figure 1 illustrates how the design would be integrated into a notional IR camera. Also shown is a prediction of the instrument thermal response during a 10º latitude lunar day.

Fabrication: A technique was developed that ensures the mating surfaces are highly parallel to promote a high uniformly applied ON force and a flat uniform OFF gap, where the OFF thermal path is solely through the low k support beam. To achieve high ON force at room temperature, the support beam is sized (δ) shorter than the space between the end-pieces. During assembly, the support beam is stretched by δ to provide the ON pre-load. To ensure highly parallel surfaces, a sequence of machining operations and digital profilometer readings obviates the need for metallic shims.

Modeling: Pre-test predictions of reverse-operation DTE thermal switch prototype performance indicated ON conductance of 2.5 W/K based on the metal contact heat transfer coefficient correlations [1] and OFF conductance of 0.002 W/K assuming just conduction through the assembly with a completely open gap (radiation ignored). An open gap was predicted to occur at 273 K for one prototype and 283 K for the other.

Testing: Two testing stages were carried out. The first stage (on lab bench) sprayed aerosol freeze-spray onto each prototype and measured temperature. Electrically non-conductive polymers in the OFF condition flow path allowed electrical resistance to indicate the ON/OFF transition, which verified the pre-test predictions. The second stage (in thermal vacuum) was conducted with a calibrated Q-meter, which demonstrated performance that doubled pre-test ON conductance and was in-line with pre-test OFF conductance predictions. The two prototypes are illustrated in Figure 2.

Conclusion: A high performance reverse-operation DTE thermal switch was developed that will enable future lunar/planetary solar/battery instruments to survive/operate through the lunar/planetary night.

References:

[1] Hattori, T. , et. al (2001), *Transactions on Engineering Sciences, 32*, WIT Press, ISSN 1743-3533.

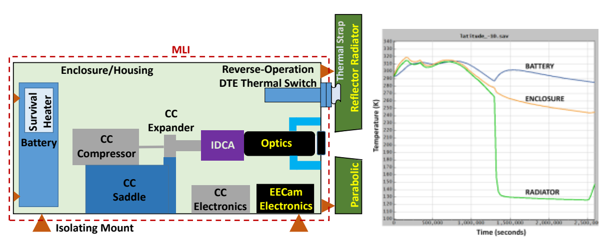


Figure 1. Reverse-Operation DTE Thermal Switch Enables Notional IR Camera to Stay Warm Through Lunar Night

Figure 2. Reverse-Operation DTE Thermal Switch Prototypes

LUNAR SURFACE GRAVIMETRY SURVEYING THROUGH THE LUNAR NIGHT. K.A. Carroll, Gedex Systems Inc., 407 Matheson Blvd., Mississauga, Ontario, Canada L4Z 2H2, kieran.carroll@gedex.com

Introduction: Making gravimetry measurements on the Lunar surface is a powerful technique for determining characteristics of the Moon's subsurface structure. The most useful types of measurements are long-term monitoring of the Moon's gravity at one or more static locations, and surveys over extensive lines and/or areas in which measurements are made at a large number of different locations. In both cases, limiting the data-taking to a single Lunar day-time significantly restricts the dataset sizes, limiting the science results that can be obtained. We discuss how Lunar landers and rovers capable of surviving the Lunar night would enhance the science achievable for Lunar surface gravimetry.

Lunar Surface Gravimetry Background: The well-known terrestrial geophysics technique of surface gravimetry surveying is one of the few techniques that can provide information about the composition and structure of the lunar subsurface. This has been used once on the Moon, with Apollo 17's Traverse Gravimeter Experiment (TGE) [1]. Gravimetry surveys carried out on the Lunar surface can achieve sub-km spatial resolution, far finer than the ~12 km resolution achievable by the best gravity measurements made from Lunar orbit [2]. New gravimeter technology opens the prospect of conducting lunar surface gravimetric surveys using small lunar rovers [3].

Gravimetry can be used to determine the size and extent of interesting subsurface features such as lava tubes [4][5], ice deposits, buried craters and boulders, and volcanic intrusive features such as those that may cause the magnetic anomalies associated with lunar swirls. They can augment and enhance interpretation of local and global seismological signals collected by Lunar Geophysical Network stations [6]. Long-term gravimetry monitoring at one or more static locations on the Moon may provide a means to probe the structure of the Moon's mantle.

Surveying Through The Lunar Night: One application for gravimetry on the Lunar surface is *gravimetry surveying*, in which a gravimeter is carried to a sequence of measurement stations, typically either along a traverse line (as in the TGE survey), or spread throughout a two-dimensional area (e.g., along a set of parallel survey lines). Such surveys aim to estimate density variations in the subsurface structure below the survey area, to help understand the local geology.

The more measurements that are made in such a survey, the larger the area that can be covered, and/or the finer the spatial resolution that can be achieved in the resulting geological models. Obviously, surveys that are carried out by rovers that can survive the Lunar night can make measurements at a greater number of stations, by making measurements over a period of multiple Lunar days, covering more survey area.

Modern Lunar rovers (; e.g., CNSA's Yutu rover) are expected to have a speed of ~0.2 km/hour, allowing up to ~70 km of travel during one Lunar day, Taking into account time that must be spent making each gravimetry measurement (expected to be 10-20 minutes per station), such a rover could traverse as much as 40 km of survey line length, with 100 m between stations, over the course of one Lunar day, allowing an area of 2x2 km to be surveyed with line spacing of 100 m.

A rover capable of surviving the Lunar night could cover more survey line length and/or area. E.g., over the course of 2 years (24 Lunar days) a total distance of perhaps 1000 km could traversed, allowing an area of 10x10 km to be surveyed at 100 m resolution.

Long-Duration Gravity Monitoring: Another application for gravimetry on the Lunar surface is *long-duration monitoring* of the gravity strength at one or more static locations on the Moon, to probe the structure of the Moon's mantle. As discussed in [7], some of the Moon's hemispherically asymmetric features may be explained by the Lunar mantle having a laterally inhomogeneous structure. Long-duration gravimetry measurements at a well-selected static location on the Lunar surface, using a gravimeter on a Lunar lander, could investigate this by detecting the non-degree-2 elastic response of the Moon to tidal forcing from the Earth and the Sun. Measurement series longer than one Lunar day will span multiple cycles of these signals, and produce more data points to fit to a Lunar elasticity model, resulting in improved estimates of mantle inhomogeneity parameters.

References: [1] Talwani M. (2003) The Leading Edge v.22 no.8, 786-789, doi: 10.1190/1.1605083. [2] Lemoine, F.G. et al. (2014) *Geophys Res Lett., 41,* 3382–3389. [3]. Jawin, E.R. et al., "Lunar Science for Landed Missions Workshop Findings Report," SSERVI. [4] Carroll, K.A. et al. (2015) *LPS XLVI*, Abstract #1746. [5] Urbancic, N. et al. (2017) *JGR: Planets, 122*, 1181-1194. [6] Carroll, K.A., "Lunar Surface Gravimetry Science Opportunities," poster at SSERVI/LEAG Lunar Science for Landed Missions workshop, NASA Ames Research Center, 10-12 Jan. 2018. [7] Zhong, S. et al. (2012) *Geophys Res Lett., 39,* 3382–3389.

Lunar Night Survivability Achieved by Radioisotope and Fission Power System Technology

Robert L. Cataldo and Lee S. Mason, NASA Glenn Research Center, Cleveland, OH 44116

The Moon's surface environment offers a significant challenge for most space systems and, particularly, for power technologies. A complete lunar day cycle is 354 hours of sunlight and 354 hours of darkness. Equatorial diurnal surface temperatures range from about 400K at lunar noon to 100K during the night. Surviving the long lunar night poses a significant challenge for photovoltaic arrays and energy storage systems. Providing the required energy for both nominal operations and for electric heaters to maintain keep-alive temperatures for electronics and other vital systems would necessitate a massive photovoltaic power supply and storage system, thereby reducing the amount of landed payload available for exploration and science investigations. Radioisotope power systems (RPS) produce power by converting the heat produced by natural isotopic decay into electricity. For example, the 110 We multi-mission radioisotope thermoelectric generator (MMRTG) has been powering the Mars Curiosity rover and is also planned for the Mars 2020 mission rover. RPS is ideally suited for lunar surface applications eliminating the need for large batteries, thus saving 100's kg of mass even for modest science missions while providing waste heat to maintain components and systems in required temperature ranges. The US uses plutonium-238 as the fuel source and it offers a high energy density along with an 88-year half-life. Eventual human habitats, crewed rovers, in-situ resource production demonstration, etc., will require significantly greater levels of power not practical for a RPS system or photovoltaic systems. For these higher power needs, nuclear fission systems would be a viable solution. Recent developments in smaller scale reactor systems called Kilopower are envisioned as an initial step in powering near term human lunar surface systems. Options for advanced RPS and Kilopower systems will be discussed and compared to alternate power system solutions.

Low-Cost Distributed Lunar Surface Networks Enabled by High Performance Thermal Components. P.E. Clark[1], D.C. Bugby[1], and D. C. Hofmann[1], [1]Jet Propulsion Laboratory/California Institute of Technology, , 4800 Oak Grove Drive, Pasadena, CA 91109, pamela.e.clark@jpl.nasa.gov

Purpose: Credible opportunities for delivery of small payloads to the lunar surface via commercial landers are emerging in the coming decade. Characterization of the highly interactive environment of the lunar surface and subsurface, requires continuous operation. Due to the uniquely extreme lunar surface conditions (high radiation, 2-week <100 K night, 2-week up to 400 K day), radioisotopes have been required for either full day and night operation (Apollo Lunar Surface Experiment Package using RTGs) or day operation and night survival only (all others including Lunakhod, Yutu, proposed commercial designs using RHUs). Compact in situ measurement packages with one or more scientific instruments capable of sustaining stand-alone day/night lunar operation could enable science investigations that heretofore required unaffordable dedicated landers with radioisotopes. Successfully demonstrating the feasibility of such a concept would represent a major breakthrough by enabling studies of the dynamic activities on lunar and other extreme environment solar system surfaces via distributed, lower cost platforms. In situ measurement//monitoring packages of 1 to 3 instruments, deployed on or from landers or rovers, could address high priority science goals and strategic knowledge gaps by providing dynamic measurements of the Moon's environment or interior.

Background: The most challenging problem is creating a thermal design to allow a low-cost, compact (cubesat-scale) package without radioisotopes to, at minimum, survive lunar night, and preferably operate on limited duty cycle during lunar night. Preliminary environmental modeling indicates that the availability of a reverse thermal switch (to maintain a thermal control box) with 1000:1 switching ratio, 10 times better than state of the art MER ratio of 100:1, would be required to allow cubesat-scale package (<20 kg, <2W during lunar night) to survive lunar night. The special parabolic radiator/reflectors required to survive the solar and lunar surface thermal emissions during lunar day have already been demonstrated on the Apollo Lunar Surface Experiment Packages (ALSEPs). Recently, Bugby and coworkers [1] have demonstrated the capability of a reverse thermal switch with a 2500:1 switching ratio.

Examples: The Surface Imaging of Lunar Volatiles in the InfraRed (SILVIR), based on a ruggedized version of JPL's EECam (Enhanced Engineering Camera) optics and electronics [2] updated with a JPL cryo-cooled HOTBIRD (High Operating Temperature Barrier InfraRed Detector) focal plane array [3] and filters for selection of water-related absorption bands, would provide snapshots of water-related features as a function of time of day, shadow, and slope, at a given landing site, and thus local 'ground truth' for the orbital observations over many lunar cycles. The SILVIR package would also include instrument electronics, a battery assembly, and the Bugby thermal switch. SILVIR would be most suitable, equipped with a gimbal, for a lander network, but could be used as a water feature 'mapper' on a rover as well. The principal thermal challenge is making sure the battery temperature is within operational limits to operate the cryocooler for at least two hours before the first observation of the day, at dawn.

The Lunar Interior Magnetic Sounder (LIMS) [4], based on fluxgate and vector helium magnetometers and their associated electronics on short booms, would provide, in conjunction with the orbital ARTEMIS magnetometer, would provide measurements of lunar magnetic induction varying over the course of several lunar cycles (including traverses through the Earth's magnetotail) from which the lunar interior temperature profile could be derived, and models for the origin and formation of the core constrained. The fluxgate magnetometer would be calibrated with the thermally stable vector helium magnetometer. The LIMS package would also include instrument electronics, a battery assembly, and the Bugby thermal switch. LIMS would be most suitable for a lander network. The principal thermal challenges are maintaining the fluxgate magnetometer and battery within operational limits, and vector helium magnetometer within survival limits during lunar night.

Results: Our thermal modeling demonstrates that both packages, representing a range of instrument requirements and incorporating the new thermal switch, should be able to meet their requirements for survival and/or operation during lunar night [1].

References: [1] Bugby, Clark, and Hofmann (2018), these proceedings; [2] McKinney, C. et al (2018) LPSC 2018, 2857.pdf; [3] Ting, D. et al (2011) NASA Tech Briefs, NPO-46477, 16; [4] Clark, Bugby, and Chin (2018) LPSC 2018, 1269.pdf

Multi-Lunar Day Polar Missions with a Solar-Only Rover. A. Colaprete[1], R. C. Elphic[1], M. Shirley[1], M. Siegler[2], [1]NASA Ames Research Center, Moffett Field, CA, [2]Planetary Science Institute, Tucson, AZ

Introduction: Resource Prospector (RP) was a lunar HEOMD/Advanced Exploration Systems volatiles prospecting mission developed for potential flight in the early 2020s. The mission includes a rover-borne payload that (1) can locate surface and near-subsurface volatiles, (2) excavate and analyze samples of the volatile-bearing regolith, and (3) demonstrate the form, extractability and usefulness of the materials. The primary mission goal for RP is to evaluate the In-Situ Resource Utilization (ISRU) potential of the lunar poles, to determine their utility within future NASA and commercial spaceflight architectures. While the current RP rover design did not require a system that could survive lunar nights, it has been demonstrated that the current design could conduct multi-lunar day missions by taking advantage of areas that receive prolonged periods of sunlight (short lunar nights).

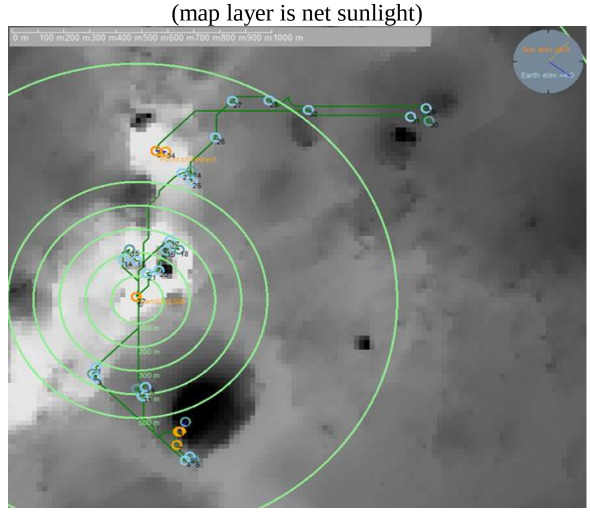
Mission Goals and Rover System Design: While it is now understood that lunar water and other volatiles have a much greater extent of distribution, possible forms, and concentrations than previously believed, it is essential to fully understand how viable these volatiles are as a resource to support human exploration of the solar system. Specifically, the distribution and form needs to be understood at a "human" scale. That is, the "ore body" must be better understood at the scales it would be worked as a mining operation before it can be evaluated as a potential architectural element within any evolvable lunar or Mars campaign. To this end the primary mission goals for RP are to (1) provide ground truth for models and orbital data sets, including temperatures at small scales, subsurface temperatures and regolith densities, surface hydration and hazards (rocks and slopes), (2) correlate surface environments and volatiles with orbital data sets to allow for better prediction of resource potential using orbital data sets, and (3) address key hypotheses regarding polar volatile sources and sinks, retention and distribution, key to developing economic models and identifying excavation sites

The RP rover system was designed to be as simple as possible (low cost and risk) while still meeting these requirements. Detailed analysis of traverses, including rover models that include power, data and mobility models, has found that a solar powered rover with Direct to Earth (DTE) communications could meet all mission goals within one Lunar day (mission length 10-12 Earth days). Therefore, the simplest design utilizes only solar power with no radiogenic heating (e.g., Radioisotope Thermoelectric Generators or RHUs) or other non-solar power systems.

Polar Solar "Oases": Numerous studies have identified regions near the lunar poles that have sustained periods of solar illumination. In some places these periods of sustained sunlight extend across several lunations, while others have very short (24-48 hours) nights. A study was conducted to evaluate if the RP rover system could take advantage of these "oases" to survive the lunar night. While the Earth would set, as seen by the rover, every approximately 2-weeks, these "oases" could provide sufficient power, and have lunar-nights short enough, for the rover system to survive.

Results: The study focused in the area surrounding the north pole crater Hermite-A (primarily due to the fidelity of existing traverse planner data sets in this area). Several possible locations in the area showed short nighttime periods (<48hours). Two examples were studied in detail, including power modeling, both surviving a single polar night, extending the total mission duration to over 46 Earth days. These examples saw considerable increase in overall science return, increasing the number of drill sites from 16 to as many as 40. It was concluded that these traverse types were available at both the north and south pole, and likely can extend to 2.5 to 3 lunations while not making any modification to the existing RP rover system design. However, relatively minor augmentation/changes to the RP rover design, including the use of passive thermal switches and a modest number of RHUs, would likely greatly expand the number of locations and mission durations. This talk will summarize the approach for identifying these areas and review the two examples cited above.

Example of a North Pole Multi-Lunar Day Traverse
(map layer is net sunlight)



Bulk Metallic Glass Gears for Lunar Night Capable Actuators.
R.P. Dillon[1], J-P.C. Borgonia[1], S.N. Roberts[1], D.C Hofmann[1], A. Kennett[1], S.A. Firdosy[1], B.H. Wilcox[1], S. Hales[2], J.D. Smith[3], J. Schuler[3], B. McEnerney[1], and A.A. Shapiro[1]
[1]NASA Jet Propulsion Laboratory, 4800 Oak Grove Drive, Pasadena, CA 91109, [2]NASA Langley Research Center, 1 NASA Drive, Hampton VA 23666, [3]NASA Kennedy Space Center, M7-0409, Kennedy Space Center, FL 32899.

Introduction: The Bulk Metallic Glass (BMG) Gears project is a NASA Game Changing Development project that has been co-funded by the Space Technology Mission Directorate and Science Mission Directorate to develop unheated, cold capable, BMG-based gearboxes (Fig.1) for use in cryogenic environments such as Lunar night. Cryo-environment capable gearboxes which do not require ancillary equipment, including the heaters and associated circuitry, found on current state-of-the-art cryogenic gearboxes are enabled by a CuZr-based bulk metallic glass (BMG) alloy. This alloy exhibits surface wear behavior ~1/3 that of maraging steel. In this poster, the enabling alloy properties and cryogenic test performance, both unlubricated and dry lubricated, are considered relative to the current state-of-the-art. Component processing, material qualification, technology readiness, and infusion challenges are also presented. Background on the early development of BMGs for gearbox applications has been published in [1] for planetary gears and [2] for strain wave gears.

Fig 1. BMG-based planetary gearbox

References:

[1] Hofmann, DC et. al, Advanced Engineering Materials (2016) DOI: 10.1002/adem.201600541

[2] Hofmann, DC et. al, Scientific Concepts (2016) DOI: 10.1038/srep37773

LIGHTING CONSTRAINTS TO LUNAR SURFACE OPERATIONS; Dean B. Eppler, The Aerospace Corporation, Houston, TX [dean.b.eppler@aero.org]; and Nancy Ann Budden, Naval Postgraduate School, Monterey CA [nbudden@nps.edu].

Introduction: Human exploration of the moon's surface will be performed during 14-day lunar days and 14-day lunar nights. An investigation into the levels of ambient lighting on the lunar surface indicates that for most nearside locations, illumination will be adequate throughout a large portion of the lunar night to conduct most surface activities, including driving, extravehicular activities (EVAs) and potentially spacecraft arrival and departure. It is expected that special illumination may be required for specific tasks where the area of activity is shadowed by natural or manmade structures. An example would be vehicle landing sites, where surface orientation or location is critical.

Surface Lighting Conditions: Because of the captured rotation of the Moon around the Earth, the location of the Earth in the lunar sky will be constant (no Earth rise or set), but the resultant illumination will vary over the course of the lunar night due to the shifting phase angle of the Earth. At the sub-Earth point, the illumination at sunset will be 1 order of magnitude brighter than illumination under a full Moon on Earth, or about 2.8 lumens m^{-2}[1]. At the same location, the illumination will rise to a maximum of 13.5 lumens m^{-2} at lunar "midnight", and decrease back down to 2.8 lumens m^{-2} at sunrise. This maximum will be similar to the light level on a July evening at 8:00 p.m. in the southern United States, equivalent to the illumination occurring about 15 minutes after sunset. Numerous orbital experiments conducted during Apollo, (e.g., [2]), showed that with 1600 ISO film, Earthshine was sufficient to photograph surface features from orbit.

As surface locations shift toward the eastern or western limbs, illumination will vary from nominal sub-Earth illumination. At surface locations on the far western limb, the maximum illumination from Earthshine (13.5 lumens m^{-2}) will occur at sunset and decrease to zero at dawn. The reverse sequence (zero illumination at sunset, maximum illumination at sunrise) will occur at the far eastern limb. The lunar farside will experience no illumination other than starlight during the lunar night, requiring artificial lighting or night-vision hardware for external operations. Polar locations will experience illumination conditions similar to the sub-Earth point, but the lighting will be at angles < 10°, making artificial illumination necessary for most exterior activities (P. Spudis, personal communication).

Apollo surface operations conducted during late lunar morning illumination suggests that activities conducted around lunar noon may be difficult due to low sun angles yielding reduced shadowing with decreased surface definition. Extremely low sun angles (< 20 degrees) are likely to make meter-scale irregular topography, typical of the lunar surface, difficult to see, similar to flat lighting conditions in Antarctica. In conclusion, Earthshine will enable effective exploration during the lunar night. However, lighting limitations 2-3 days around lunar noon may complicate or deter full-scale surface operations.

[1] Eppler, D. (1991) NASA TM-4271; [2] Lloyd, D. (1971) Unpubl. Bellcom Rpt., https://ntrs.nasa.gov/archive/nasa/casi.ntrs.nasa.gov/19720006805.pdf.

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MILLIWATT LUNAR VLBI BEACONS: SURVIVING THE LUNAR NIGHT T. Marshall Eubanks[1], [1]Space Initiatives Inc, Clifton, VA 20124 USA; tme@space-initiatives.com;

Introduction: The exploration of the Solar System can be enhanced by the use of femtospacecraft, small autonomous units which can be used to provide multiple observation points or in hazardous environments where there is a strong risk of loss of individual nodes. In order to meet the more demanding requirements of operation in deep space and to create true spacecraft swarms to meet various operational goals we are developing the Pixie femtospacecraft [1] (see Figure 1). A Pixie is 80 x 40 x 9 mm with a mass $<$ 80 grams. These small units can act as autonomous spacecraft, or as modular nodes attached to or integrated with other spacecraft, rovers and equipment send to or near the Moon.

Lunar VLBI Networks: Low power ($<$ 1 milliW) Pixie transmissions could be used as a source for differential Very Long Baseline Interferometry (VLBI) observations from Earth [2, 3] using the new VGOS VLBI system [4]. The scientific goals would be to provide nanoradian accuracu astrometry and transverse positions with a single-observation accuracy of $/sim$50 cm. Each Pixie would broadcast a unique code-multiplex signal so that same beam interferometery could be performed with multiple beacons on and off the lunar surface.

These measurements would meet a number of scientific goals, including improvements in the Lunar ephemeris (transverse VLBI measurements of lunar rotation would nicely complement the on-going program of radial measurements from Lunar Laser Ranging). These beacons would serve as geodetic control points on the Lunar surface, directly tying the Lunar, planetary and extra-galactic reference frames and also allowing for differential position measurements of rovers and smallsat lunar orbiters.

Surviving the Lunar Night:

The scientific and programmatic goals of a lunar geodetic VLBI network would be best met with beacons able to survive the Lunar night. EThe Pixie would provide a battery, solar power and also computer control of beacon broadcasts (either on a regular schedule, or in response to local conditions or uplinked commands).

The minimum sustained power consumption of a Pixie beacon would be order 10 milliWatt. This amount of power can be provided from a roughly 1 gm Americium-241 battery [5] which, with an ultracapcitor for short term power needs, should suffice to power a continuous permanent VLBI network on the lunar surface for decades to come. This deployment would also serve as a test of small nuclear batteries likely to become increasingly important for small spacecraft missions into the outer solarsystem and interstellar space [6, 7].

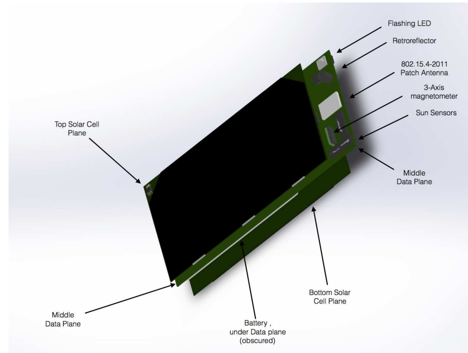


Figure 1: The Asteroid Initiatives Pixie Asteroid Instrumentation set (without insulation).

References: [1] T. M. Eubanks, et al. (2017) in *Lunar and Planetary Science Conference* vol. 48 of *Lunar and Planetary Science Conference* 1577. [2] G. Klopotek, et al. (2017) in *EGU General Assembly Conference Abstracts* vol. 19 of *EGU General Assembly Conference Abstracts* 433. [3] S. V. Pogrebenko, et al. (2004) in *Planetary Probe Atmospheric Entry and Descent Trajectory Analysis and Science* (Edited by A. Wilson) vol. 544 of *ESA Special Publication* 197–204. [4] R. Haas, et al. (2015) *IAU General Assembly* 22:2257511. [5] L. Cordingley, et al. (2011) in *9th European Space Power Conference* vol. 690 of *ESA Special Publication* 130. [6] A. M. Hein, et al. (2017) *ArXiv e-prints* (1711.03155). `arXiv:1711.03155`. [7] A. M. Hein, et al. (2017) *ArXiv e-prints*. `arXiv:1708.03556`.

Lunar Superconducting Magnetic Energy Storage (LSMES). M. E. Evans[1] and A. Ignatiev[2], [1]NASA Johnson Space Center, michael.e.evans@nasa.gov, [2]University of Houston, ignatiev@uh.edu.

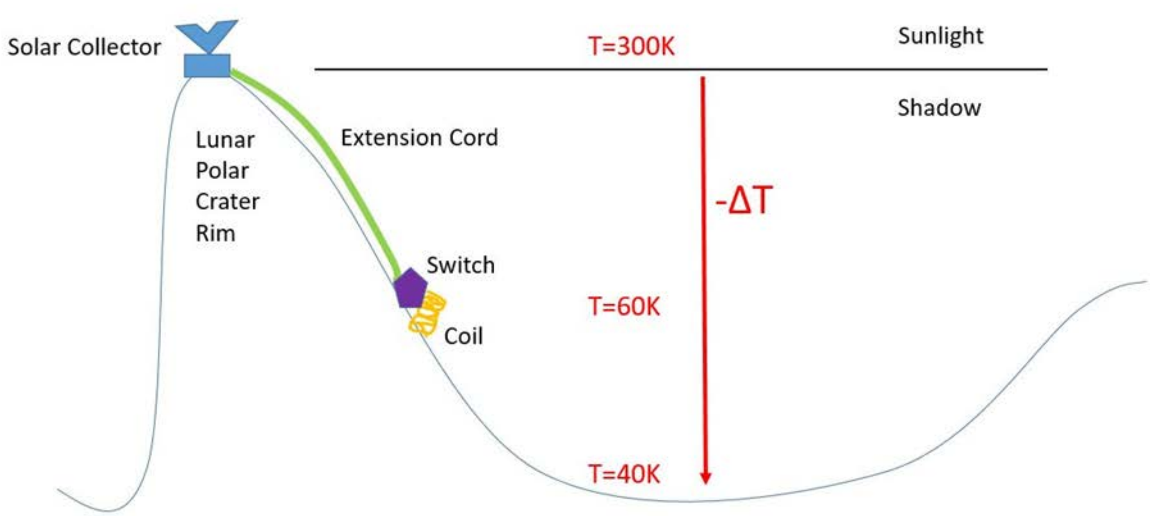
Introduction: Superconducting Magnetic Energy Storage (SMES) is an energy storage system that stores electrical energy in the form of a magnetic field by passing direct current through a superconducting coil. The conductor for carrying the current operates at cryogenic temperatures where it becomes a superconductor and thus has virtually no resistive losses as it produces the magnetic field. [1]. The energy can be stored in a persistent mode until required [2]. The main terrestrial challenge for SMES is the need for a cryo-cooling system and the cost associated with its deployment, operation and maintenance. For lunar and planetary exploration, this challenge is totally mitigated using the cold environment of the mission to sustain superconductivity temperatures. The permanently shadowed craters on the moon have regolith temperatures between 50-60K (3), which is the operating temperature for High Temperature Superconducting (HTS) wire. SMES provides several advantages over traditional chemical batteries that: 1) incur much energy loss in extremely cold environments due to power needed for heaters, 2) are inefficient due to their inherent redox and side reactions, and 3) fail over time due to charge/discharge cycling changes in their chemical processes.

Study for Application on Moon: Generally, a SMES system consist of four parts: 1) superconducting magnet; 2) cryogenic system; 3) control system; and 4) power conditioning system. This study initially identifies guidelines for a candidate mission using LSMES. Next, the study addresses the feasibility of using HTS wire in either a solenoid or toroid configuration, designs the magnet support structure considering the current carrying capacity of the magnet wire and the mechanical stresses associated with the high magnetic fields, and evaluates concepts for grid power conditioning and an electronic switch to charge/discharge the coil. The study also develops a hardware concept of the coil and tests energy storage in a magnetic field at expected lunar temperatures in the Permanently Shadowed Regions (PSRs).

Summary: LSMES could provide for energy storage with negligible electrical energy loss (>95% system efficiency) [4] at cryogenic temperatures (<100K) over very long lifetimes. Integrating LSMES into a mission architecture could enable creation of distributed electrical "recharge stations" for lunar surface components in both human and robotic missions. This technology is independent of the energy source and could be applied to architectures with either networks of solar arrays or nuclear fission reactors on the lunar surface. It could also be applied to other lunar regions with appropriate thermal gradients that support constant cryogenic temperatures outside the PSRs.

References:

[1] Onnes, H.K. (1911) *Comm. Phys. Lab. Univ. Leiden*, 124 [2] Chen, H. et al (2009) *Progress in Natural Science*, 291-312 [3] Williams, J.P. et al (2016) *Icarus 283*, 300-325 [4] Cheung, K.Y.C.et al (2002) *Imperial College London: ISE v2*.



Advanced Thermal Techniques and Systems Design Enable Long Duration, Continuous Day/Night Operation of Robotic Science Landers and Payloads on the Lunar Surface. J. F. Farmer[1], A. Alavarez-Hernandez[2], S. P. Breeding[1], J. E. Lowery[1], [1]NASA MSFC, Huntsville AL, [2]NASA JSC, Houston TX.

Introduction: Recent developments in NASA and commercial space capabilities and plans support and call for increased exploration of the lunar surface. Lunar exploration objectives vary widely ranging from geophysical research to human exploration and resource prospecting. The slow rotation of the Lunar surface and polar orientation relative to the sun along with the regolith thermo-optical and thermos-physical properties and vacuum conditions combine to create a unique and very challenging thermal environment for any extended lunar surface activity requiring operation during the approximately 28 earth day lunar day/night cycle, where day time temperatures of the lunar surface can reach 400K (near the equator) and night time temperatures can drop to 100K (even colder in permanently shadowed regions and craters). A set of risk reduction studies were performed in support of early phase mission design activities for various science and exploration missions, one of which was the ILN (International Lunar Network), to investigate potential approaches that enable continuous operation in this environment. These studies have led to the development of advanced thermal control technologies and designs, extended testing of battery capabilities, and a viable systems approach to survive the night for extended mission durations. This report summarizes the targeted missions, the overall design approach, the enabling technologies, and the risk reduction studies including the associated analyses and testing used to investigate their viability.

Driving Missions: The first mission that drove the initial investigations was ILN. This mission was intended to develop and position robotic landers equipped with an array geophysical and electromagnetic experiments, globally dispersed on the lunar surface. These landers were required to operate continuously during lunar day/night cycles for up to 6 years.

General Assumptions and Design Approach: Both of these missions targeted a minimum cost approach and, as such, high energy, continuous power generation options including a nuclear reactor and a radio-isotope power source were prohibited. Consequently, lunar cycle variant photovoltaic power was assumed, and thermal based solutions that conserved heat during the cold lunar night were critical. The general approach for achieving this consisted of using a warm electronics enclosure that contained all critical electronic components and energy storage batteries expected to operate over the duration of surface portion of the mission. This enclosure was insulated with high performance thermal insulation and isolated with low conductance structural mounts to minimize heat loss and gain. The components within this enclosure were mounted on a baseplate designed to share heat between the components and acquire heat to be rejected when necessary. The plate was connected via an advanced variable thermal link to a lunar radiator to reject this heat. The variable link would passively vary between a highly conductive heat transport path and a thermal isolator as the conditions dictated.

Enabling Thermal Technology Options: While the insulation and isolation techniques and the thermal baseplate used in the design were high performance and somewhat novel, the more advanced technologies investigated for this application were those related to the variable link. The technologies investigated included: (1) a hybrid wick, variable conductance heat pipe, (2) a loop heat pipe with a passive bypass valve, and (3) a hybrid loop heat pipe with variable conductance heat pipe. Each of these technologies provides efficient two phase heat transport when “on” to support heat rejection during lunar day, but also provides a passive, temperature driven means of isolation to conserve heat. This “turn-down” feature of these links along with the insulation/isolation features of the enclosure minimizes the amount of power used during the long lunar night to minimize the mass of the battery required; analysis during these mission studies estimated that each watt of power used during the lunar night required approximately 5kg of battery to supply the needed energy.

Risk Reduction Activities: A variety of activities have been performed to assess this lunar night survival capability. *Thermal trade studies* were conducted to identify and select overall thermal approaches and technologies. *System level thermal and power analyses* have been conducted to predict night time heat loss, daytime heat rejection, and power management performance. *Ground and in-space thermal development testing* have been conducted to assess the performance of the variable link technologies, and their integration with baseplate and radiator concepts, as well as to assess long term battery performance and lifetime at more extreme temperatures and depths of discharge necessary for this application.

THE IMPORTANCE OF NIGHTSIDE MAGNETOMETER OBSERVATIONS FOR ELECTROMAGNETIC SOUNDING OF THE MOON. H. Fuqua Haviland[1] and A. R. Poppe[2], S. Fatemi[3], G. T. Delory[2], [1]NASA Marshall Space Flight Center, MSFC, AL 35812 (heidi.haviland@nasa.gov), [2]Space Sciences Laboratory, University of California, Berkeley, CA 94720. [3] Swedish Institute of Space Physics, Sweden.

Introduction: Understanding the current day structure, state, and composition of the lunar interior provides insight into origin and formation processes of the Moon. Knowledge of the lunar interior builds on an array of disciplines, observations, and various types of analyses such as geochemistry, geophysics, geodynamics. Current understanding of the lunar interior lacks precise constraints on the composition and structure including layers of mantle material (upper mantle, middle mantle, and lower mantle regions), a possibly partially molten ilmenite layer, above a differentiated core enriched in light elements [1-4]. Additional observations and analyses are required to be able to answer fundamental planetary science questions including the thickness of the Procellarum KREEP terrane, the existence of a melt layer at the core mantle boundary, and the thickness of the inner and outer core layers. Electromagnetic (EM) Sounding is capable of answering these key questions through analysis of magnetometer observations at the surface of the Moon and surrounding environment. EM Sounding isolates induced magnetic fields to remotely deduce lunar material properties at depth [2,5].

Recent analyses of plasma and field observations provide a wealth of understanding about the dynamics of the lunar plasma environment [6-8]. These characterizations improve the boundary conditions acting on induced magnetic fields from the interior. Plasma hybrid models suggest the induced fields are not confined within the lunar wake cavity [9-11] as previously proposed [5]. Thus, the first step of performing Time Domain EM (TDEM) Sounding at the Moon is to characterize the dynamic plasma environment, and to be able to isolate geophysically induced currents from concurrently present plasma currents. The TDEM Sounding transfer function method focuses on analysis of the nightside observations when the Moon is immersed in the solar wind. This method requires two simultaneous observations: an upstream reference measuring the pristine solar wind, and one downstream at or near the lunar surface [2]. This method was last performed during Apollo and assumed the induced fields on the nightside of the Moon expand as in an undisturbed vacuum within the wake cavity [12]. TDEM sounding is particularly well suited for measurements from moving satellite platforms directly accounting for changing altitudes [2].

Our approach is to isolate induction from the plasma wake cavity by fully and self consistently characterizing both of these fields [11]. Thus, improving the accuracy of existing TDEM methods. Our models compare a plasma induction model capturing the kinetic plasma environment within the wake cavity around a conducting Moon, to an analytic expression of the geophysical forward model capturing induction in a vacuum. This method can be applied to any two point magnetometer measurement of the Moon or similar airless bodies. Nightside TDEM sounding has the capability to advance the state of knowledge of the field of lunar science forward. This requires magnetometer operations to withstand the harsh conditions of the lunar night.

Apollo and ARTEMIS Magnetometer specification comparison: For comparison, we include the specifications of two magnetometers that have been used to perform TDEM: Apollo 12 Lunar Surface Magnetometer with orbiting reference magnetometer, Explorer 35 [12,13], and currently orbiting twin ARTEMIS satellites. TDEM Sounding requires the use of a reference probe measuring the pristine and undisturbed solar wind conditions near the Moon.

Apollo 12 Lunar Surface Magnetometer [13, see Table 1]: Range 0-+/-400 nT, Resolution 0.2 nT, Frequency Range dc to 3 Hz, Power 3.4 W average daytime, Weight 8.9 kg, size 25 X 28 x 63 cm.

ARTEMIS Fluxgate Magnetometer [15, 16 see Tables 1 and 2]: DC magnetic field, Sampling rate & resolution: DC-128 Samples/s & 3 pT, Offset stability <0.2 nT/12 hr. Resources requirements: **Mass**: Sensor (75 g), Harness (150g or 60 g/m) Electronics(150g). **Dimensions:** Sensor (diameter 70 mm, height 45 mm), Board (100 mm × 120 mm). **Power consumption**: 800 mW. Temperature range: Sensor (−100◦ to 60◦ C), Electronics, (−55◦ to 80◦ C).

References: [1] Garcia R.F., et al., (2011) *Phys. Earth Planet. Inter.* 188, 96–113. [2] Grimm R.E., Delory G.T., (2012) *ASR*. 50, 1687–1701. [3] Hood L.L., et al., (1999) *GRL*. 26, 2327–2330. [4] Weber R.C., et al., (2011) *Sci*. 331, 309–312. [5] Sonett C.P., (1982) *Rev. Geophys. Sp. Phys*. 20, 411–455. [6] Halekas J.S., et al., (2005) *JGR*. 110, A07222. [7] Halekas J.S., et al., (2010) *PSS*. [8] Poppe A.R., et al., (2014) *GRL*. 41, 3766–3773. [9] Fatemi S., et al., (2015) *GRL*. 42 6931–6938. [10] Fatemi S., et al., (2017) *J. Phys. Ser. J. Phys. Conf. Ser*. 837. [11] Fuqua Haviland H., et al., (2017) *LPSC XLVIII*. [12] Dyal P., Parkin C.W., (1971) *JGR*. 76, 5947–5969. [13] Dyal P., Parkin C.W., (1971) *Proc. 2nd LPSC.* 3, 2391–2413. [14] Dyal P., et al., (1974) *Rev. Geophys. Sp. Phys.* 12, 568–591. [15] Angelopoulos V., (2010) *Space Sci. Rev.* 165, 3–25. [16] Auster H.U., et al., (2008) *Space Sci. Rev.* 141, 235–264.

UTILIZATION OF NUCLEAR POWER FOR MOON MISSIONS: NUCLEAR POWER GENERATION USING HELIUM COOLED REACTOR FOR MOON HABITATS

Ugur GUVEN[1] and Anand Kumar Singh[2]
[1]UN Center for Space Science and Space Technology Education in Asia Pacific (CSSTEAP)
drguven@live.com
[2]UPES Aerospace Engineering Department

Introduction: As the closest space based natural satellite in space, the moon has been one of the main interests of mankind since the dawn of the civilization. To overcome certain difficulties with power requirements, nuclear power sources will be more advantageous in long term point of view. On the moon, it is essential to have extensive support to create power for the various logistical requirements such as life support, communications, lights, waste removal, etc. as well as for the scientific experiments and for the facilities that will process materials. Thus, functional power sources are needed which can function reliably in long term. Due to its basic properties, chemical or thermal means of generating electricity would be quite difficult under reduced gravity conditions. Moreover, it would create several control and stability issues as well and furthermore they would require excessive amounts of fuel to be either mined or transported from Earth in a continuous manner.

However, with the availability of a nuclear reactor, all of the power requirements in a moon based station (with reduced gravity conditions) can be met for several years without any difficulty. Nuclear reactor power systems can support human exploration at surface outposts and space stations. A nuclear reactor on the surface of the Moon can be a source of reliable power to provide life support, and to supply the large power demands of facilities processing materials.

Naturally, there are different options for utilization of nuclear power for moon based missions. Unfortunately, the standard types of reactors found on Earth such as the Heavy Water Pressurized Reactor or the Light Water Pressurized Reactor systems will not be feasible on the moon. Since the moon has the $1/6^{th}$ gravity of the Earth, the fission kinetics would be harder to control and using water as a coolant will not be practical as having thousands of tons of water on the moon will not be logistically feasible. In addition, the circulation of waste water will be extremely difficult due to subzero temperatures as well as the vacuum outside of the Moon Habitat

Since the operation of normal water cooled nuclear reactors would be a challenge due to limited availability of water and due to behavior of water under reduced gravity and vacuum conditions in the Moon, it will be necessary to utilize more advanced types of nuclear reactors. One such example would be the utilization of a ***Helium Cooled Nuclear Reactor*** where Helium will be used both as a neutron moderator and as a coolant. Since helium is a noble gas, it will not be chemically reactive and also several studies suggest that Helium circulation would function well under reduced gravity conditions and even under microgravity conditions. In addition, the pumping and the cycling of Helium would be easier and the logistics of wastewater will not be a problem as well.

Thus, by using a helium cooled reactor, the challenges of using a water cooled reactor can be overcome and the necessary long term power supply can be provided to a Moon Habitat. The paper will discuss the issues while addressing moon based criteria such as the reduced gravity, lack of atmosphere, availability of large amounts of moon dust and lack of natural resources necessary for operation of such a system.

References:

[1]. Claudio Bruno, "Nuclear Space Power and Propulsion Systems", Volume 225, Progresses in Astronautics and Aeronautics, American Institute of Aeronautics and Astronautics, 2008.

[2]. Paul A. Czysz, Claudio Bruno, Future Space Craft Propulsion Systems: Enabling Technologies for Space exploration, Second Edition, Praxis Publishing Ltd, Chichester, UK, 2009.

[3]. Gurunadh Velidi, Ugur Guven, "Usage of Nuclear Reactors for Space Applications: Space Propulsion and Space Power Concepts", in *proc. International Conference on Mechanical and Aerospace Engineering*, New Delhi, 2011, P.356-360.

[4]. Ugur Guven, Piyush Kuchhal "Nuclear Fusion and then Moon as a Source of Power for the World", in *proc. International Conference on Mechanical and Aerospace Engineering*, New Delhi, 2011, P.356-360.

[5]. Stanley Schmidt, Robert Zubrin, "Islands in The Sky: Bold New Idea Colonizing Space", Wiley, First Edition, 1996.

[6]. Giancarlo Genta, Michael J. Rycroft, "Space, the final frontier?", Cambridge University Press, 2003.

REGENERATIVE FUEL CELL-BASED ENERGY STORAGE SYSTEMS FOR LUNAR SURFACE EXPLORATION. Monica C. Guzik[1], Ryan P. Gilligan[1], Phillip J. Smith[1], and Ian J. Jakupca[1], [1]NASA John H. Glenn Research Center, Cleveland, OH, 44011, United States

Abstract: The National Aeronautics and Space Administration (NASA) continues to develop technologies to satisfy the persistent need for consistent and reliable power systems that enable Lunar surface exploration. The traditional power architecture solution sizes a photovoltaic solar array to both power the customer load and charge an energy storage system while sunlight is available. When sunlight is unavailable during the lunar night, the energy storage system discharges to support the customer loads. In the past, batteries have met the energy storage needs over short charge/discharge durations with the lowest overall mass and fewest system complications compared to other technologies. However, the lengthy eclipse durations and challenging thermal environments inherent in many lunar surface exploration locations result in longer discharge periods with higher energy storage requirements to survive the cold temperatures during the lunar night. For such missions, the battery mass quickly becomes prohibitively large, necessitating an alternative energy storage method. One such alternative is the Regenerative Fuel Cell (RFC).

A Proton Exchange Membrane (PEM)-based RFC system integrates a fuel cell, an electrolyzer, and a multi-fluid reactant storage system into an energy storage device. The energy capacity of the RFC is determined by the amount of available hydrogen and oxygen storage. Typically, hydrogen and oxygen are stored as gases at elevated pressure, due to the advantage of decreased system volume and simplified thermal requirements. Previous system trades suggest that the optimum gaseous storage pressure is in the range of 1000 to 1800 psia, but may vary based on the mission requirements, particularly when overall volume minimization is required in addition to system efficiency.

The RFC discharges power through a fuel cell that converts the stored chemical energy of oxygen and hydrogen into direct-current electricity, heat, and water. This product water is accumulated until it is later consumed in the charging portion of the cycle. Fuel cells are, inherently, a current-producing device with the resulting electrical potential (voltage) indicating the reaction efficiency. Increasing the system pressure and temperature increase the reaction efficiency by increasing the molecular concentration and reaction kinetics. For PEM fuel cells, the standard operational regimes are 40 to 65 psia and 20 to 80°C.

Unlike RFC systems, batteries incorporate energy conversion (power) and energy capacity (storage) into one package that encompasses both the energy storage mass and the power production mass. An RFC dissociates the two masses, thereby enabling independent sizing of each. Because an RFC stores chemical energy as gases, it is able to store energy in large quantities with a relatively low mass penalty. This advantage becomes more pronounced as energy storage levels increase. NASA continues to evaluate RFC systems for lunar surface exploration, inclusive of lunar night survival and operations, as the sub-systems and individual technology elements mature.

This presentation highlights the updated results of a recent NASA study funded under the Advanced Exploration Systems (AES) Modular Power Systems (AMPS) project using an analysis method previously developed under the AMPS project. Both manned and robotic exploration of the lunar surface will require optimized energy storage solutions that minimize system mass and volume, while maintaining the capability to provide power and heat to survive the lunar night. Each mission has a unique set of requirements based on its location and application that may result in different technology solutions. Performing high-level analysis of the available energy storage options may allow mission designers to converge on a technology solution early in the architecture definition process, allowing for more effective optimization of the final system design. Using the data presented, high-level system sizing of an RFC energy storage system for a given lunar mission can be performed to aid in architecture trade studies. Following the selection of an RFC system as a viable solution for a given mission, the detailed models used to generate the presented data can be used for system optimization and further efficiency gains.

SATELLITE BEAMED POWER FOR LUNAR SURFACE ASSETS. M. H. Hecht[1] and Philip Lubin[2]. [1]MIT Haystack Observatory, Westford, MA, [2]Univ. of California at Santa Barbara.

Introduction: Solar power satellites have long been promoted for terrestrial use [1], but the advantage over ground-based assets has never been convincingly demonstrated. In contrast to the terrestrial case, however, orbiting infrastructure for space power satellites is less expensive and simpler to emplace than ground facilities for use on other worlds. Moreover, a cost-effective architecture is one that minimizes the surface footprint at the expense of resources in space. The confluence of several factors now make beamed power systems practical for solar system exploration in the near-term. This is particularly true for lunar exploration, where the night is 14 Earth days long and there is both scientific and exploration interest in visiting permanently shadowed regions.

Mission architecture: For the architecture described here, the orbital element collects solar radiation with photovoltaic panels and uses the electrical power to direct a high power laser at a photovoltaic array on the surface. This allows surface instruments to maintain full operation without access to sunlight.

Since the divergence of the power beam is proportional to the wavelength, the need to limit the size of the surface receiver favors optical over microwave transmission. With a coherent optical beam, the angular dispersion can be made equal to or less than the pointing accuracy of the projector, which is typically of order 1 arcsecond. That limitation suggests placing the satellite in a low orbit rather than in a stationary location, transmitting only when the orbiter passes over the ground station. The result is low duty cycle transmission and high duty cycle solar collection, which eliminates the need for an oversized solar collector for the orbiter and makes it possible to deliver significant power to the ground from a modest sized spacecraft with a small aperture (20-50 cm for 1 arcsecond).

To meet the power needs of larger missions (such as crewed surface operations), the best scaling strategy is to position a necklace of solar power satellites in a common orbit, each radiating to the surface in turn. These satellites could also provide near-continuous communications and GPS-like navigational support to a ground station. We also note that the same technology can be applied with little modification to point-to-point power beaming across the lunar surface.

Orbital element: For the orbital element we postulate a self-contained small spacecraft with ~ 6 m^2 of solar arrays in a low lunar orbit, nominally 200 km perilune. The solar panels would charge a battery during most of each orbit, except when in eclipse, and would discharge for ~4 minutes during each pass over the landed station while homing in on a retroreflector mounted on the station. With a 2.2 hr orbital period, this strategy corresponds to a 3.2% duty cycle. An optical system with ~1 arcsecond pointing accuracy could project ~6 kW to the surface with 1 arcsecond dispersion using a 20-50 cm mirror, illuminating a spot on the surface as small as 1 m (though in practice, 2-3 m is more realistic allowing for jitter, aberration, and elongation from an angle up to 45º). On the surface, this flux density is comparable to overhead sunlight.

Laser power of 3-6 kW can be readily achieved today by joining the outputs of multiple fiber lasers via spectral combining [2], a technique capable of producing tens of kW of output. Other components needed for an operable system, including steerable optics compatible with high power loads, are commercially available for space applications. The telescope, pointing and tracking elements, radiator, battery, and solar panels are high TRL commercial components that can be adapted to a free-flyer platform.

Landed element: Assets on the ground need not be different from those used on a typical solar-powered mission, such as the UltraFlex family of deployable solar arrays such used for the Phoenix and InSight missions. Those missions used 2.1 m diameter arrays, but up to 6m implementations have been developed by the manufacturer, Orbital STK (the specific size needed would depend on the dispersion and pointing accuracy of the incident beam). With the orbital element described above, such an array would produce nearly 3 kW-hr for the surface every 24 hrs, comparable to an MMRTG such as on the Curiosity mission at Mars. Moreover, the conversion efficiency of photovoltaics tuned to a specific laser wavelength can significantly surpass that of solar spectrum conversion.

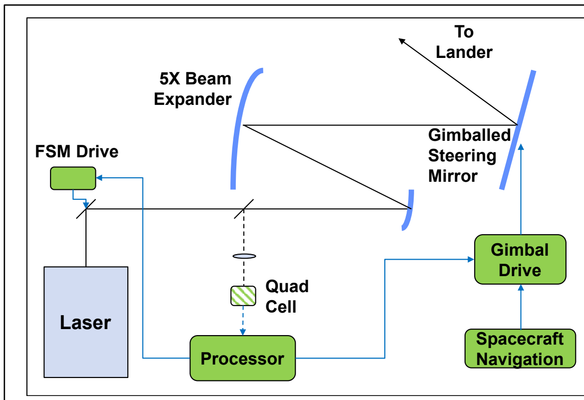


Fig. 1 Notional optical train showing focusing and pointing systems. The dotted line indicates quad cell feedback assuming a beacon or retroreflector on the surface.

Design approach: Notional optics are shown schematically in Fig. 1. An off-axis 5X beam expander provides high efficiency without obscuration while a flat gimballed coarse steering mirror requires minimal moving mass, and hence offers fast response. A fast steering mirror (FSM) for fine pointing is controlled by a PID loop based on detection of a tracking signal from a retroreflector at the center of the photovoltaic receiver. A 5 cm reflector aperture would collect at least 5W from the beam, corresponding to ~12.5 mW within the minimum 20 cm aperture of the orbiter. A quad cell detector would then use this signal to generate a feedback response to the fine steering mirror (FSM). To detect the reflected signal while radiating 3-6 kW to the ground is straightforward if the radiating beam is time gated.

An alternative approach to acquisition and tracking provides the feedback signal digitally from the ground. In this case, the photovoltaic array itself is configured in quadrants, or a set of 4 small photodiodes is overlain on the array to the same effect. The power measured in each of these quadrants is then used to generate a feedback signal, which is radiated digitally to the spacecraft whenever the beam drifts too far from the optimal position (but no faster than a 1 kHz cadence). If the signal is lost entirely, it may be re-acquired by expanding or rastering the beam.

Acknowledgements: We appreciate the advice and guidance of T.Y. Fan and Alan Wirth of MIT Lincoln Laboratory in formulating this concept and helping us understand the available technology.

References: [1] Glaser, P.E., Davidson, F.P, Csigi, K.I., (1997) Solar Power Satellites: A Space Energy System for Earth, Wiley-Praxis. [2] S. Redmond, K. Creedon, T. Y. Fan, A. Sanchez, C. Yu, and J. Donnelly (2013), in Coherent Beam Combining, A. Brignon ed. Chapter 4 (Wiley-VCH).

SMALL MODULAR FISSION REACTORS THAT ENABLE AFFORDABLE AND SUSTAINABLE LUNAR ENTERPRISE. J. S. Herring[1], S. Mackwell[1] and C. Pestak[1], [1]Universities Space Research Association, 7178 Columbia Gateway Drive, Columbia, MD 21046 (jherring@usra.edu)

Common to all the robotic and human activities planned for the lunar surface is the need for abundant and reliable electrical power. Effective robotic exploration and sustained human presence will require electrical power in the 40kW to 100kW range that is continuously available throughout the entire lunar day/night cycles. A power plant capable of meeting this need would form the basis for establishing commercial electrical utility services on the lunar surface. Such services will jump start the exploration, resource mapping, commercial exploitation, and colonization of the Moon by a broad mix of public and private users that include space agencies, industries, adventurers, and entrepreneurs.

To address the challenges and opportunities of establishing in-space commercial electrical utilities, Universities Space Research Association (USRA) recently began an Internal Research and Development (IRAD) project to perform a concept study of a new Small Modular Fission Reactor (SMFR) that uses Low Enriched Uranium (LEU) for use on the Moon. SMFRs have significant advantages over other potential power sources being considered for the Moon.

By selecting LEU as the fuel, USRA is addressing design issues for a SMFR for use on the lunar surface that can be developed commercially, thus enabling greater industry participation in current and future initiatives for the exploration, habitation, and exploitation of the Moon. Our study will build upon the progress made by NASA’s HEU-based KiloPower project and make use of DOE’s experience in the development of compact reactor systems.

Using a variety of possible energy conversion techniques, SMFRs powered by LEU can enable a commercial enterprise to provide both the heat and electricity needed for human and robotic activities, including outposts, habitats, fleets of exploration rovers, ISRU systems, and excavation/mining operations.

This presentation describes our concept for a commercially viable SMFR for use on the Moon by 2028, if properly resourced.

The Use of Lunar Resources for Energy Generation on the Moon Dr. Alex Ignatiev, Lunar Resources (alex@lunarresources.space)

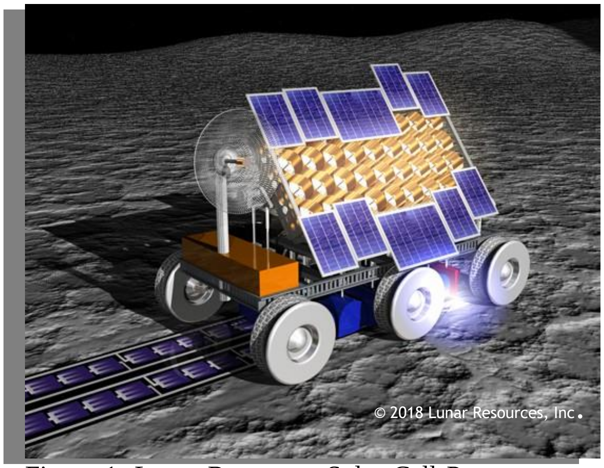


Figure 1, Lunar Resources Solar Cell Paver concept surface vehicle

Introduction: The indigenous resources of the Moon can be used to develop an electrical energy system for the Moon. Based on available lunar resources a lunar power system founded on the fabrication of solar cells by thin film growth technology in the vacuum environment of the Moon can be generated. This can be accomplished by the deployment of a moderately-sized (~200kg) crawler/rover on the surface of the Moon with the capabilities of preparation of the lunar regolith for use as a substrate, evaporation of the appropriate semiconductor materials for the solar cell structure directly on the regolith substrate, and deposition of metallic contacts and interconnects to finish off a complete solar cell array. The direct fabrication of an electric power system on the Moon would require the transportation of a much smaller mass of equipment to the Moon than would otherwise be required to install a complete electric power system brought to the Moon from the Earth and emplaced there. It would also result in an electric power system that was repairable/replaceable through the simple fabrication of more solar cells, and that would yield an energy-rich environment for the Moon and cis-lunar space.

References:

[1] A. Cohen “Report of the 90-Day Study on Human Exploration of the Moon and Mars”, NASA, Nov. 1989

[2] A. Freunlich, T. Kubricht, and A. Ignatiev: “Lunar Regolith Thin Films: Vacuum Evaporation and Properties,” AP Conf. Proc., Vol 420, (1998) p. 660

[3] Sadoway, D.R.: “Electrolytic Production of Metals Using Consumable Anodes,” US Patent No. 5,185,068, February 9, 1993

[4] Duke, M.B.: Blair, B.: and J. Diaz: “Lunar Resource Utilization,” Advanced Space Research, Vol. 31(2002) p.2413.

[5] A. Ignatiev, A. Freundlich.: “The Use of Lunar Resources for Energy Generation on the Moon,”

The Pylon: Near-Term Commercial LEU Nuclear Fission Power for Lunar Applications. C. G. Morrison[1], W. Deason[1], M. J. Eades[1], S. Judd[1], V. Patel[1], M. Reed[1], P. Venneri[1], [1]Ultra Safe Nuclear Corporation, Seattle, WA, 98199 (c.morrison@usnc.com)

Introduction: Nuclear energy provides not only the ability to survive the 354-hour lunar night, but the ability thrive. The exploration of Lunar resources in permanently shadowed craters and utilization of thermal energy to process local resources are task well-suited to nuclear energy. Yet, despite exceptional potential, nuclear energy is often omitted from further consideration due to technology development and policy considerations. However recent developments demonstrate that the technology development and policy challenges are surmountable and a near-term solution for nuclear energy in the Lunar environment is available.

Terrestrial Technology Suited for Lunar Environments: USNC is a commercial company that is developing a terrestrial gas-cooled micro-modular reactor (MMR) for off-grid and rugged locations on Earth. The MMR utilizes a novel refractory carbide nuclear fuel technology designed to optimize safety.

For the same reasons why the technology excels in remote terrestrial regions, it also excels in the space environment. The Pylon is a low enriched uranium (LEU) fission reactor system utilizing the core technology of the MMR for electricity on the Moon.

The Pylon is a near-term technology building upon the expertise and success of the MMR. The Pylon is a 4500 kg 125-150 kWe radiatively-cooled system Approximately 800 kW of waste heat at temperatures between 300-500 K is available for in-situ resource exploration and acquisition. In addition, up to 1150 K process heat is available. The Pylon design is such that it can be delivered to the Lunar Surface on a large CLPS class lander such as the Blue Moon. The temperature ranges are well-suited to utilize currently available directly-cycle Brayton energy conversion technology.

Conclusion: The Pylon fission power system can enable sustainable, power-abundant exploration, and lead to meaningful development on the Lunar surface.

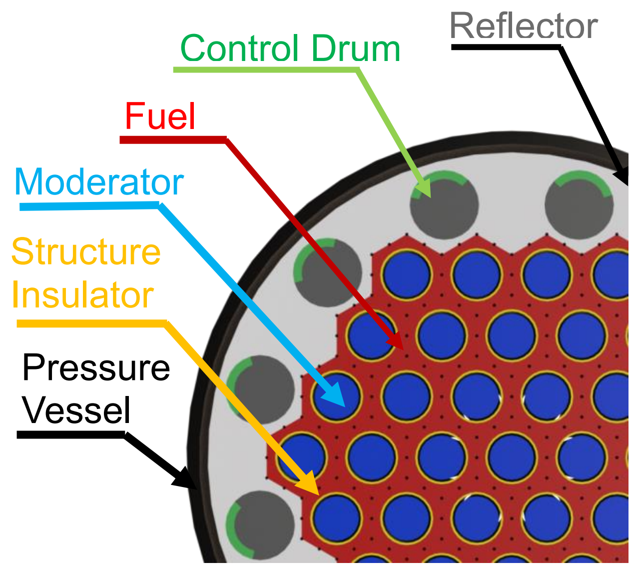


Figure 1: Reactor Core Design

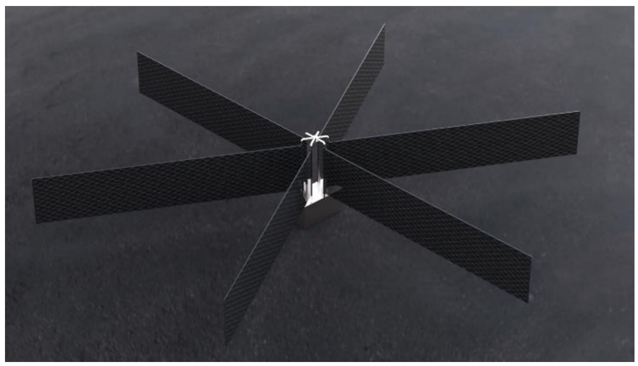


Figure 2: Notional Lunar Configuration

PASSIVE SURVIVABILITY OF 18650 LITHIUM-ION CELLS THROUGH LUNAR NIGHT ENVIRONMENT SCENARIO.

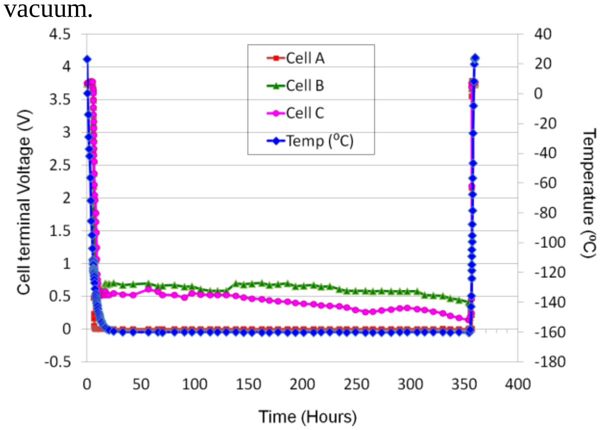
K. Nandini[1], K. Usha[2], M. S. Srinivasan[3], M. Pramod[4], P. Satyanarayana[5] and M. Sankaran[6], [1] Battery Division Power Systems Group U R Rao Satellite Centre HAL Airport Road, Bangalore – 560017 India Phone: 080-2508-3668 nandinik@isac.gov.in, [2-4] Battery Division Power Systems Group U R Rao Satellite Centre HAL Airport Road Bangalore – 560017 India, [5] Power Systems Group U R Rao Satellite Centre HAL Airport Road Bangalore – 560017 India, [6]Communication and Power Area U R Rao Satellite Centre HAL Airport Road Bangalore – 560017 India.

Introduction: Every space exploration mission is unique in its design, approach and mission management and battery too, as a subsystem in any of such space-craft, has to cater to exceptional demands. A lunar rover mission for instance, requires the battery to support the peak power load when the power generation through solar panels is in-sufficient. At all such operations during lunar day, the battery pack temperature can be efficiently managed with-in the optimal window, using rover's thermal management elements. The real challenge is to endure passively through the lunar night, at prevailing temperatures as harsh as -180 ºC for duration of 336 hours [1], to be able to operate in the subsequent lunar day. From a battery point of view this challenge is only one of its kind, where battery is required to operate (charge or discharge) at ambient temperatures and is required to survive passively (without any load) an exposure to extremely low temperatures, preferably, without any permanent loss or damage. Even though the works cited in literature [2-4] addresses the ways to tackle inferior charge/discharge characteristics of Li-ion batteries by altering electrolyte composition, there is hardly any information about the passive survivability of already existing chemistry of commercialized Li-ion cells, at extreme low temperatures below -150 ºC and the present work aims to throw some light at this ambiguity.

Present study describes passive survivability of commercially-off-the-shelf (COTS) 18650 lithium-ion cells tested in an environmental scenario similar to lunar night (cryogenic temperatures at vacuum). Survivability of the cells in particular and battery pack in general is crucial for resumption of function of any lunar exploration rover after hibernation at every lunar night. The test is designed to include a batch of Commercial lithium-ion cells from different manufactures, with different nameplate capacities and different States of Charge. The cell behavior during the test is monitored in-situ using cell terminal voltage measurements. Complementary tests like, visual examination, dimensional measurements, Residual Gas Analysis to detect any leakage, electrical tests to appraise electrical performance and 3 dimensional x-ray computed tomography analysis to view cell internal features, are carried out at ambient conditions, on all cells both prior-to and after soaking at low temperatures, to comprehend the effect of exposure to extreme low temperatures.

Results indicate successful survivability of tested commercial Lithium-ion cells after extreme thermal soak without any significant physical or internal damage or electrical performance degradation. Variation in cell terminal voltage with temperature is a reversible change attributed to the reversible phenomenon of freezing of cell electrolyte, which furthermore is confirmed through ex-situ measurement of freezing point of electrolyte extracted from tested cells.

Digital Formats: The plot below shows the variation of recorded cell terminal voltage with time and temperature for sample COTS Li-ion cells: Cell A, Cell B and Cell C, during thermal soak at -160ºC soak for 336 hours inside liquid nitrogen cooled shroud under vacuum.



References: [1] Christie R.J. Plachta D.W and Hasan M.M. (2008) *NASA-TM*, 215300. [2] Zhang S.S. (2006) *J. Power Sources*, *162*, 1379-1394. [3] Li J. Yuan, C.F. Guo Z.H. Zhang Z.A. Lai Y.Q. Liu J. (2012) *Electrochim. Acta*. *59*, 69-74. [4] Cho Y-G. Kim Y-S. Sung D-G. Seo M-S. Song H-K. (2014) *Ener. Enviorn. Sci. 7*, 1737-1743. [5] Kim K.M. Ly N.V. Won J.H. Lee Y-G. Cho W.I. Ko J.M. Kaner R.B. (2014) *Electrochim. Acta. 136*, 182-188. [6] Won J.H. Lee H.S. Hamenu L. Latifatu M. Lee Y.M. Kim K.M. Oh J. Cho W.I. Ko J.M. (2015) *J. Indus. Eng. Chem. 37*, 325-332. [7] Hamenu L. Lee H.S. Latifatu M. Kim K.M. Park J. Baek Y.G. Ko J.M. Kaner R.B. (2016) *Cur. Appl. Phy. 16*, 611-617.

MATERIAL SELECTION FOR MECHANICAL MECHANISM SURVIVAL AND USE IN THE LUNAR NIGHT. S. Nieczkoski [1] C. B. Dreyer[2], B. Blair[3], and J. Rostami[4], [1]Thermal Space Ltd. (1333 Yarmouth Ave., Suite #1, Boulder, CO 80304, steve@thermal-space.com), [2]Colorado School of Mines (1600 Illinois St, Golden, CO 80401, cdreyer@mines.edu), [3]Plantary Resource Engineering (planetminer@gmail.com), and [2]Colorado School of Mines (1600 Illinois St, Golden, CO 80401, rostami@mines.edu).

Introduction: The lunar night presents challenges for the survival of spacecraft mechanisms due to extreme low temperatures, typically 100 K at low latitudes [1] and less near the poles [2]. Some spacecraft components, such as those in a rover or lander body, can be protected from the extremely low temperature by use of heaters and adequate thermal design. However, those mechanisms on the appendages of a rover or lander, such as robotic arms, drills, scopes, lander legs, and rover wheels cannot be easily protected in this way because they are directly exposed to the ambient lunar thermal and vacuum environment. These mechanisms would be challenging to keep warm by applied heat and insulation because they must contact the lunar surface or otherwise be exposed to the radiative environment of the Moon by design. It is desirable to find design solutions that will allow mechanisms to function at the natural temperature of the lunar night. In this paper, we discuss materials and design approaches that allow such mechanisms to not only survive the lunar night, but have complete functionality in the lunar night environment. Our team is currently developing a drilling system capable of operating in the permanently shadowed regions on the lunar surface under an Early Stage Innovation (ESI) Program funded by NASA.

Challenges: ---- Adequate designs must encompass not only the low temperature vacuum environment on the lunar surface, but also the transition from Earth ambient. In mechanized systems, primary considerations include material mechanical properties (strength, modulus, hardness, wear resistance, etc.), efficient use of both good thermal-conducting and thermal-insulating materials, mechanical stresses induced by materials of varying thermal contraction behaviors, exposure or isolation of electrical components and subsystems, suitable lubricants, hermetic sealing or venting, and abrasion resistance or shielding.

Solutions: ---- Fortunately, there are common materials such as 300-series stainless steel and 6000-series aluminum that have been used for decades in aerospace systems that will lay the foundation for the mechanical and thermal designs of mechanized lunar systems. Fiber-reinforced composite structures formulated with resin systems that are compatible with the cryogenic environment are also of high value. Our drilling system is being designed to utilize these materials in combination with other subsystem specific materials such as polycrystalline diamond compact (PDC) bits on the drill head that have shown excellent wear resistance while operating at cryogenic temperature [3].

Conclusions: Design solutions exist that enable mechanisms to not only survive direct exposure to the lunar thermal environment, but continue to function without failure. Operation of drills, scopes, robotic arms, rover wheels, and other mechanical appendages during the lunar night are desirable for science and prospecting activities. This paper discusses the material approaches that we are developing to assure that drilling can be conducted and characterized in the harsh cryogenic vacuum environment on the lunar surface.

References: [1] Vasavada, A.R., Bandfield, J.L., Greenhagen, B.T., Hayne, P.O., Siegler, M.A., Williams, J.P. and Paige, D.A., 2012. *Journal of Geophysical Research: Planets*, 117(E12). [2] Paige, D.A., Siegler, M.A., Zhang, J.A., Hayne, P.O., Foote, E.J., Bennett, K.A., Vasavada, A.R., Greenhagen, B.T., Schofield, J.T., McCleese, D.J. and Foote, M.C., 2010. *Science*, 330(6003), pp.479-482. [3] Evans, C., and Bryan, J. B., 1991, "Cryogenic Diamond Turning of StainlessSteel," CIRP Ann. – Manuf. Technol., 40(1), pp. 571–575.

Shifting the Paradigm of Coping with Nyx on the Moon – a Ground-Penetrating Radar Case. D. C. Nunes[1], K. Carpenter[1], Mark Haynes[1], Jean Pierre de la Croix[1]. [1]Jet Propulsion Laboratory, California Institute of Technology (4800 Oak Grove Drive, Pasadena CA 91109, Daniel.Nunes@jpl.caltech.edu)

Introduction: Radar has played a key role in characterizing the properties and geology of the Moon, from ground-based [1] to bi-static [2], sounders [3] and a ground-penetrating radar [4]. Currently, a higher level of fidelity in data is needed to fully characterize and interpret the lunar geologic and to be able to exploit its resources. Radar will continue to be a key tool in this effort, and this belief is supported by the needs outlined in the Lunar Exploration Road Map and the Lunar Knowledge Gaps document.

Detection and mapping of polar volatiles, of pyroclastic deposits and regolith stratigraphy, and of lunar lava tubes are among the primary science cases for ground-penetrating radar instruments. Aside from the ice deposits expected in and around the permanently shaded areas near the poles, primary science targets are distributed around the Moon in the equatorial and tropical latitudinal bands.

MARGE: We are currently developing a ground-penetrating radar (GPR) instrument that is an intrinsic part of a compact, autonomous rover. The size of the Multi-static Autonomous Roving Ground-penetrating-radar Explorer (MARGE) is driven by the size of the GPR antenna, which is approximately 50×50 cm and capable of transmitting and receiving an ultra-wide frequency band from 120 MHz to 2 GHz. This operational band permits penetrations of up to ~20 m while providing depth resolution of for typical lunar regolith and rock dielectric constants [5] and a dynamic range of 120 dB; see Figure 1 for the link analysis.

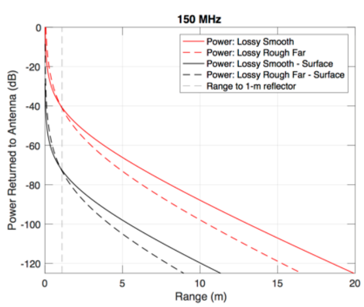


Figure 1- *Link analysis for a reflection arising from a regolith/rock dielectric interface for increasing depth (range).*

Common strategies: Since Sojourner, survivability has depended on active and passive thermal management, through a combination of battery-powered heaters, small radiogenic sources and thermal insulation like aerogel [6]. These have worked reasonably well in the past. The long dark period on the moon makes heating a power hungry option. Commercial landers will not allow radioisotope heating units at least in the beginning. Our heritage solutions for Mars or the past lunar missions may not apply to this new opportunity.

New Strategy: To survive the relatively long lunar night we propose to shift the strategy from one of full dependence on thermal management to one of increasing thermal tolerance. For example, special components and electrical traces that are tolerant to variations on the order of 300°C can be used. This comes down to material and alloy selection and architecture. Specific power storage solutions tailored to survival of freeze/thaw cycles and the heat of the lunar day as well as concepts of operations that allow for opportunistic operation between thermal extremes are needed. We will present some possible solutions to these challenges based off our current effort on MARGE.

Expanding Surveys: An average speed of 2.5 cm/sec for autonomous planetary rovers [6,7] may allow traverses comparable to ~1 km during a lunar day, depending on operational constraints, such as data storage and downlink and 6 earth-days of amenable thermal conditions.

The biggest benefit for a GPR to survive the night is expanding the survey area to multi-km, which would maximize science and characterization in the vicinity of the landing site.

References:

[1] Hagfors, T. (1970), *Radio Sci., 5*(2), 189-227. **[2]** Nozette, S. et al. (1996), *Science, 274*(5292), 1495. 10.1126/science.274.5292.1495. **[3]** Phillips, R. J. et al. (1973),*LPSC Proceedings*, Houston, TX. **[4]** Fa, W. et al. (2015), *GRL 42*(23), 10,179-110,187. **[5]** Olhoeft, G. R., & Strangway, D. W. (1975), *Earth Planet. Sci. Lett., 24*, 394-404. **[6]** Crisp, J. A. et al. (2003), *JGR 108*(E12), 10.1029/2002JE002038. **[7]** Grotzinger, J. P et al. (2012), *Space Sci. Rev. 170*(1), 5-56.

LUNAR ROADS: STRATEGIES FOR REMAINING IN THE SUNLIGHT. D. S. Plata[1], Space Development Network, developspace1@gmail.com.

Introduction: The slow rotation of the moon on its axis results in lunar nights lasting about 14 Earth days. This poses a significant challenge to robotic exploration due to the lack of solar power and the need for the hardware to survive the cryogenic temperatures of the lunar night.

Because of the slow rotation of the moon on its axis, lunar days are also 14 Earth days long. Telerobots could construct basic lunar roads by compacting the regolith. In this context, they could also increase their lunar day by driving in a westerly direction. The speeds necessary to remain at a the same time of lunar day appear within reach of telerobots by driving west at high latitudes.

The Challenge: The moon's slow rotation on its axis results in long lunar nights of about 14 Earth days. The resulting lack of solar power creates the challenge of surviving the lunar night [1]. During this time, solar power is lost, temperatures plummet, and power requirements may increase in order to provide body heat. However, the moon's slow rotation also increases the length of the lunar day.

Speeds Necessary to Remain in Lunar Daylight: To remain at the same time of day on the moon, vehicles would have to drive west at 15.4 km/hr at the equator, 10.4 km/hr at 45 degrees latitude, and 8.0 km/hr at 58.5 degrees latitude. For comparison, the Apollo rovers were designed with a maximum speed of 12.9 km/hr with the maximum speed measured at 18.0 km/hr.

Strategies for Developing a Network of Lunar Roads: This paper examines the question of how telerobots could be used to create a network of roads starting at the poles and extending towards the equator. Basic lunar roads could simply involve the compressing of regolith in order to reduce the amount of dust kicked up when vehicles pass over them. These roads could be of use for exploration and resource development.

Strategies for remaining within the sunlight include driving from the poles in the morning, and then making longitudinal roads while driving west. As sunset slowly develops, the telerobots could drive back towards the poles at higher speeds using the very roads that they created and then either head west at speeds greater than the moon's rotation or even pass over the pole to morning on the other side of the moon.

Challenges to Overcome: Challenges for the implementation of this approach are discussed including maintaining the telerobots operating in the setting of abrasive regolith dust [2], ensuring that the telerobots are adequately charged, and maintaining communications between Earth and the telerobots [3,4].

References: [1] Ungar E. and Fruitwala N. (2011) AIAA SPACE 2011 Conference & Exposition, AIAA SPACE Forum. [2] Hyatt M. et al. (2007) 45th AIAA Aerospace Sciences Meeting and Exhibit, Aerospace Sciences Meetings. [3] Farquhar R. W. (1967), JSR, Vol. 4, No. 10, pp. 1383-1384. [4] Malmström et al. (2006) Space 2006, AIAA SPACE Forum, https://doi.org/10.2514/6.2006-7453.

Data Encoded Laser Wireless Power (DELWP) For Lunar Polar Applications. Dennis Poulos, Poulos Air & Space, Inc., 4084 Preservation Cir, Melbourne, Fl 32934; dpoulos@pouloscorp.com

Background: Laser wireless power (LWP) for Lunar exploration was proposed by the Communications Working Group (WG2) of the 2008-2009 International Lunar Network (ILN) Study. Jim Schier, NASA, Chief Architect, Space Communications and Navigation, Human Exploration and Operations Mission Directorate described the ILN findings in a "Concept for Lunar Power and Communications Utility" briefing on Oct 14, 2015[1]. Critical technologies have matured to the point where this architecture is commercially viable and could be deployed to support Lunar missions.

High Power Fiber Laser for Wireless Power: Fiber laser technology has evolved so that power levels of 10's of kW can be efficiently generated and transmitted with very high quality and wall plug efficiencies (WPE) approaching 30% or higher[2,3]. Assuming power satellite use conventional solar panels, with an efficiency of 25%, to generate power, the size of a solar panel assembly to support a 10 kW fiber laser is 100 m^2. [For comparison, the area of the ISS solar panel assembly is 3,246 m^2 and the ISS generates 120 kW to 84 kW.] A high-power fiber laser can be modulated with a high data rate signal and multiple channels of data can be multiplexed into a single beam using wavelength division multiplexing (WDM).

Advanced High Efficiency, High Power Tuned Photovoltaic Power Receivers: Photovoltaic (PV) cells are being developed for power transfer. Mature Vertical Multijunction (VMJ) cell technology is currently used for commercial applications. VMJ cells receive monochromatic (laser) power at irradiancies greater than 18.6 W/cm^2 (150 times more intense than sunlight) at 975 nm (IR band) with efficiencies of over 36%[4]. Newer technology Vertical Epitaxial Heterostructure Architecture (VEHSA) PV technology has demonstrated operation at irradiance levels 1,000 times solar intensity, with power efficiencies of 70%[5]. VMJ or VEHSA power panels on mobile rovers or at fixed Lunar outposts illuminated by high intensity monochromatic laser light would provide hundreds or thousands of times the power of equivalent solar panels.

Aperture and Landed Mass: Diffraction limited gaussian laser power beams with no atmospheric absorption loss focus 86% of the transmitted power in the central beam (the beam "spot"). An 850 nm laser beam from a 1 m aperture transmitter on a satellite with an apoapsis of 9,381 km would have a 17.9 m diameter (251 m^2) spot on the lunar surface. A VMJ or VEHSA optical power receiver that size could generate hundreds or thousands of kW of power. The spot size for an equivalent 10 GHz (X Band) RF power beam with a 30 m transmitting antenna would be 21 km (346 km^2).

"Frozen" Elliptical, Inclined Polar Orbits: Classes of "Frozen" Lunar polar orbits were identified by Dr Tod Ely[6] and Erica Lieb[6] as part of the 2004 Vision for Space Exploration (VSE) studies. These frozen elliptical orbits are long-term stable. Nominal eccentricity is between 0.6 and 0.7 with an apoapsis between 6,111 km and 9,381 km. Inclination is between 51° and 56° (or higher) and they have line-of-sight (LOS) coverage of the complete polar region. Pointing and tracking at those ranges to rovers or outposts on the lunar surface is challenging but doable. A constellation of three laser power satellites deployed in a "Frozen" orbit will provide simultaneous coverage of polar regions by two power satellites for enhanced safety and reliability.

Survival and Operation through the Lunar Night. These technologies, combined into a Data Encoded Laser Wireless Power (DELWP) system, will generate significantly more power than equivalent Solar panels and provide bi-directional high-speed data links, both key enablers for exploration of the dark Lunar polar regions and operation and survival through Lunar night. Deployed on the polar crater rims, DELWP will provide LOS power and data deep into the permanently dark craters enabling extended range and time on station for prospecting rovers without relying of large, heavy batteries for mere survival, cabling, or radioisotope thermoelectric generators (RTG). Waste heat will be harvested to provide thermal conditioning for rovers. A three-satellite constellation of laser power satellites flown in "Frozen" Lunar orbits would provide continuous (day/night) optical wireless power across the Lunar polar regions. Laser systems, compared to RF, minimize transmitting and receiving apertures, minimize landed mass, and maximize data transfer speeds. Multiple sites or rovers can be serviced simultaneously by additional beam transmitting apertures or by beam scanning.

References: [1] Jim Schier (NASA) (Oct, 14, 2015) Concept for Lunar Power and Communications Utility briefing. [2] Kuniharu Himeno (2016), Fujikura Technical Review, No 44, March 2016. [3] John Wallace (2016), LaserFocusWorld, Vol 52 #3, 29-26. [4] Mico Perales (02/17/2015) LaserFocus-World, Vol 51 #2, 29-32. [5] York M. C. A. and Fafard S. 2017 J. Phys. D 50 173003. [6] Dr Tod Ely and Erica Lieb, Jet Propulsion Laboratory, The Journal of the Astronautical Sciences, Vol 53, No3, July-September 2005, "Stable Constellations of Frozen Elliptical Inclined Lunar Orbits"; pp. 301-316.

LEVERAGING IN-SITU REGOLITH PROPERTIES FOR NIGHTTIME HEATING. T. M. Powell[1], M. A. Siegler[2], J. L. Molaro[2], D. A. Paige[1], [1]Earth, Planetary, and Spaces Sciences, University of California, Los Angeles CA, 90095, USA (tylerpowell@ucla.edu), [2]Planetary Science Institute based in Tucson AZ, 85719, USA.

Introduction: The Diviner instrument on-board the Lunar Reconnaissance Orbiter [1] is a thermal infrared radiometer that has characterized the lunar surface temperature and thermophysical properties globally. Most of the lunar surface is covered in a highly porous and thermally insulating regolith layer which results in dramatic temperature swings from roughly 400 K at noon to less than 100 K at night at the equator: a challenging environment for a spacecraft. Despite the large fluctuations at the near surface, significant stores of sensible heat might still be accessible by leveraging temperature variations with depth and thermophysical property variations on the surface. Thermally coupling to warm materials already present on the Moon might provide some nighttime heating and reduce the engineering payload necessary for surviving the lunar night.

Subsurface heat: The temperature fluctuation observed at the surface propagates to depth based on the diffusivity of lunar regolith κ and the length of the diurnal period P: $z_s = (\kappa P/\pi)^{0.5}$ where z_s is the skin depth, at which temperature amplitudes decrease to 1/e of the surface value. Typically this is about 4-10 cm. Below about ¼ m depth, the temperature is roughly constant throughout the diurnal cycle at about room temperature, 255 K at the equator (Figure 1).

This high temperature at depth is due to a 'solid state greenhouse effect' from radiative heat transfer within the regolith. The granular nature of regolith and lack of atmosphere cause radiative transfer between grains to be a significant component of regolith conductivity: $K = K_c + BT^3$ where K_c is the phonon conductivity and B is a radiative transfer constant. The temperature dependence of conductivity results in more efficient pumping of heat into the subsurface during the day than out at night, resulting in the diurnal average temperature at 10 cm depth being ~50 K higher than at the near surface.

Rocks and high thermal inertia material: Diviner observations show that high thermal inertia material at the surface like exposed melt or coherent rocks remain warmer throughout the lunar night.

This study uses known lunar thermophysical properties and thermal modeling to determine feasibility of using in-situ materials as nighttime thermal sources.

Methodology: We used COMSOL to model the temperature of a simple lander as a high conductivity box surrounded by an insulating layer. We compare the nighttime temperature of a lander placed on a typical lunar regolith column to a spacecraft thermally coupled to the subsurface and surface rocks. In the subsurface experiment, a conductive rod was added to the lander to a 0.5 m depth

Results: Preliminary results of show that a conductive rod penetrating to a depth of 0.5 m can keep the spacecraft a few 10s of degrees K warmer during the lunar night. This shows that in-situ lunar materials may provide a valuable store of heat that can be utilized for future lander missions.

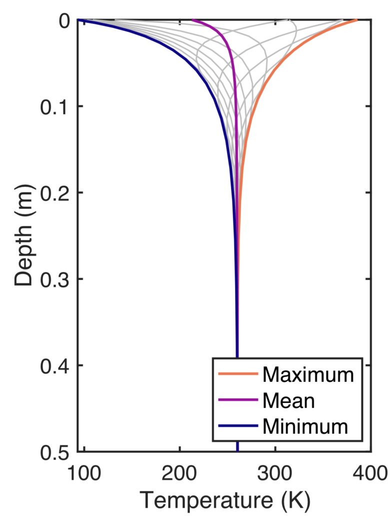


Figure 1. Modeled temperature profile of typical equatorial lunar regolith over a diurnal period. Grey lines show instantaneous profiles every 2 lunar hours.

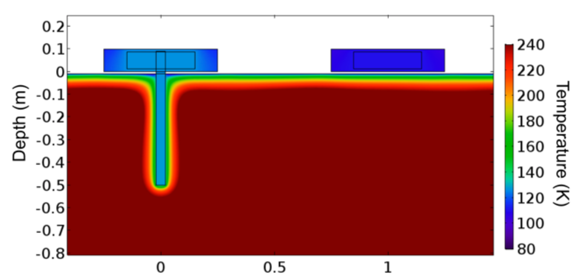


Figure 2. Preliminary model results of thermally coupling to a depth of 0.5 m.

References:

[1] D. A. Paige, *et al.* The Lunar Reconnaissance Orbiter Diviner Lunar Radiometer Experiment. *Space Sci. Rev.,* 150:125-160, 2010.

Darkness Visible: Instrumentation and Thermal Design to Access the Hidden Moon

Jeffrey E. Van Cleve[1], Jonathan D. Weinberg[1], Clive R. Neal[2], Richard C. Elphic[3], Kevin Weed[1], Gary Mills[1], Rich Dissly[1]

[1]Ball Aerospace, Boulder CO [2]Notre Dame [3]NASA-Ames

Abstract:
In poetic language, people often talk about "The Dark Side of the Moon," while their astronomical meaning is the "Far Side of the Moon." In this workshop, we are literally discussing the dark Moon – the entire Moon during the 14-day lunar night at the equator, and the regions of eternal darkness in polar craters which may be rich in volatiles for use as resources, and as a valuable record of the Moon's history. The dark Moon has been hidden for most of the history of spaceflight, as no human missions and few robotic missions have persisted through even one lunar night, and no missions whatsoever have landed in the permanently-shadowed regions. In this poster, we discuss "Night" mission concepts, previously developed by the authors with NASA funding, that remain directly relevant to NASA robotic and human science and exploration of the Moon - a long-lived (> 6 y) lunar geophysical network [1] and a Discovery-class mission for the in-situ investigation of volatiles in the lunar polar cold traps [2].

We also discuss Ball instrument and thermal technology enabling survival, situational awareness, and operations in the dark Moon, including low-light and thermal cameras, flash lidars, advanced multi-layer insulation (MLI)[3], and phase-change material "hocky pucks" that can damp out thermal transients to help moving platforms scuttle through dark regions for 24 h or so on their way between illuminated area such as "the peaks of eternal light" near the lunar south pole, without expending precious stored electrical power for heat.

References:
[1] NLSI Lunar Science Conference (2008) abstract 2058, Weinberg, Neal, et al.
[2] NLSI (2008) abstract 2142, Elphic, Weinberg, et al.
[3] Commercial and Government Responsive Access to Space Technology Exchange (CRASTE)(2016): An Overview of Next Generation Multilayer Insulation. Gary Mills BATC

Mission Design and Implementation Considerations for Lunar Night Survival. R. Vaughan[1], [1]Mission Design Division, NASA Ames Research Center, Moffett Field, CA

Introduction: Lunar night survival, while being a technical design challenge, also has an impact on mission planning and execution during the flight system development phases (Phases A-D). Depending on mission objectives, different locations on the lunar surface result in different challenges to technical formulation of a comprehensive mission design and implementation. Equatorial regions have temperature extremes between day and night (<100K to >380K) but are somewhat cyclical and predictable. Polar regions can have milder thermal environments in terms of overall surface temperature swing and opportunities for extended durations for solar power but pose unique challenges in temporal and spatial availability of both sunlight and direct-to-Earth communications. Options for surviving the night will depend heavily on mission objectives, lunar location and program cost and schedule constraints.

Lunar Night as a Mission Variable: Whether the primary purpose of the mission is scientific, mapping and prospecting, or demonstrating capabilities and technologies, surface traverse planning and concepts of operation will heavily influence the necessary capabilities of the flight system. Lunar night will be one of the variables to consider but may not be the biggest driver of system complexity. Clear flow-down of mission objectives, combined with surface mission planning and operations will ultimately lead to determining where, and how much lunar night survival will impact system design, as well as programmatic cost and schedule resources necessary to carry out the project.

Lunar Night Survival Planning; Equatorial: Equatorial regions of the moon experience a consistent and regular ~14 Earth-day duration of night-time. During the day, overhead sun limits the radiative view to cold space and during the night, temperatures plummet, increasing the demand for energy for survival. Nuclear energy sources are typically considered due to the extended duration of darkness. This approach will have an impact on the system design, having to deal with both hot and cold temperature extremes, but will also require additional cost and schedule resources for analysis, design, test and paperwork/process (Presidential Directive-25). Other technical solutions may be possible as well but they also may require additional resources for achieving technological readiness and incorporation. Understanding these mission drivers will be a crucial step in scoping out the development activity and allocating resources for successful execution.

Lunar Night Survival Planning; Polar: The definition of "night" becomes less distinct at near-polar latitudes. Latitude and local topography play a critical role in defining the duration of local shadows. It varies from locations of near-perpetual sunlight all the way to permanently shadowed regions. This presents a more open trade space for missions requiring more than 14 Earth days. Determining an appropriate landing site for both mission objectives and required shadow survival time, combined with an appropriate flight system design requires careful mission planning analysis.

Operating Through the Night: Planning to operate through the night could significantly increase the demand for energy depending on the concept of operations. Depending on local topography, polar locations (above ~80 deg) can also lose line of sight communications for 2 weeks or more every month, so either increased levels of autonomy or reliance on communications relays will be required. The flight system design approach and mission/traverse planning will be impacted by these frameworks, as well as additional technology maturation and design and testing activities during development.

Mission Design/Planning for Lunar Night Survival: An existing set of lunar mission planning tools, utilized by the Resource Prospector Mission Development team at NASA Ames, provide the capability to understand the trade space and mission drivers to bridge the gap between mission objectives and designing a reference mission that results in understanding the technical system design drivers and ultimately, formulating the project execution plan and resource requirements. As always, tools are just a part of a broader process in concept maturation, planning and execution. Understanding lunar night survival mission requirements, within the context of the mission objectives and planned against an project execution framework will result in a comprehensive approach to ensure successful progress and completion of the mission.

We present some of the design, development, cost and schedule impacts of dealing with problematic night time lunar conditions, whether for near-equatorial or near-polar landed lunar missions.

REQUIREMENT ANALYSIS AND NIGHT SURVIVAL CONCEPT FOR Z-01 LANDING MISSION USING FUEL CELL

Satishchandra C Wani[1], Udit Shah[2], Adithya Kothandapani[1], Prateek Garg[1], Mrigank Sahai[1], Mannika Garg[1], Sunish Nair[1]
[1]TeamIndus - Axiom Research Labs Pvt Ltd (adithya.kothandhapani@teamindus.in, Bangalore, KA-560092, India)
[2]StarLiner Engineering Inc. (udit.shah@starliner.com, 1279 Washington Valley Rd, Bridgewater, NJ 08807, USA)

Introduction: Space exploration missions have ramped up with improvements in technology. Where it was previously impossible to access certain bodies in the Solar System, advances in material science, power systems and communication, to name a few, have enabled longer and more productive scientific lunar missions. Of many lunar missions only few were intended to land. Solar-powered missions today are limited to short durations (max 14 days), due to availability of sun light on Lunar surface. In addition to harsh surface temperatures during the day, lunar night is even more challenging due to duration of night (14 Earth days near equatorial sites, higher near poles). In absence of any planetary or sun heating during night, the spacecraft experience cold environment viz. Lunar soil reaching -170C (Equator) and space at -269C [1]. Only three missions were able to survive lunar night, but using Radioisotope Thermo-Electric Generators and Radioisotope Heating Units. This paper presents an fuel cell based concept to extend life of existing mission Z-01 by surviving Lunar night.

Challenges to energy methods: Nuclear energy has advantage of high energy density hence needs less mass, but there are many disadvantages viz. difficult to source hence costly, transport, handle & storage. In such situation it is evident to explore non-nuclear energy sources for generating energy not only for single but many lunar nights. With present limitations in energy density from non-nuclear methods, the spacecraft should hibernate during lunar night and maintain at storage temperatures using survival heaters. After night it should function again as nominal during lunar day. This strategy reduces the cost of landed lunar missions to a large extent. To survive lunar night, one must minimize heat lost to space, enhance low temperature survival of spacecraft components and use heater power to maintain components at storage temperature limits.

Case study and proposed concept: To quantify the requirement of energy, present mission i.e. Z-01 is used. Z-01 is thermally designed to survive lunar day, hence energy requirements are expected to be higher. Thermal simulation compute the requirement as 90W heater power to maintain components at storage temperatures. This energy has to be supplied for 350 hours or net energy requirement is 31.5KW-hr. On comparison of available options viz. Mechanical (Flywheel) Electro-chemical (Battery), Electrical (Super capacitor), Thermal (PCB, Wadis), Chemical energy methods using parameters viz. Energy Capacity, Density, Discharge time & Maturity of Technology (Space qualified), Fuel cell is a potential energy method.

Figure 1 describes one such concept of using Fuel Cell as energy storage system to survive lunar night.

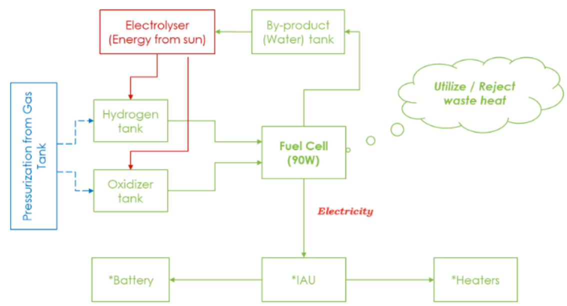


Figure 1: Energy Storage System using Fuel Cell

The fuel cell (PEM) powered by hydrogen and oxygen, is used to generate electricity and waste heat is tapped using heat pipes. The by-product i.e. water is collected in separate tank. During the day, electrolyser or reversible fuel cell is used to generate hydrogen and oxygen. Power for electrolyser is used from existing solar panels. The reactants are stored in separate tanks and be used in night for energy generation. Hence this concept can supply power for many lunar nights. The overall mass of the system to generate 90W for 350 hours is 50.3 kg, that is 25% of Z-01 dry mass.

Other technologies viz. Internal PCB Heater, Lunar Soil heating and Variable Conductance Loop Heat Pipe that help to reduce overall energy requirement are also presented.

Conclusion: Overall the paper presents historic missions that survived lunar night, overall challenges to survive lunar night, computation of energy requirement on actual project using thermal simulations. Due to disadvantages of nuclear energy method, alternative energy storage system using fuel cell is conceptualized. Due to its space heritage, simplicity of operation and regenerative capability, Fuel cell is most promising of all energy methods available

References: [1] Ashwin R. Vasavada, David A. Paige, Stephen E. Wood (1999), "Near-Surface Temperatures on Mercury and the Moon", *Icarus 141,* Page 179-193

SEASONAL TEMPERATURE VARIATIONS IN THE POLAR REGIONS OF THE MOON. J.-P. Williams[1], B. T. Greenhagen[2], and D. A. Paige[1], [1]Earth, Planetary, and Space Sciences, University of California, Los Angeles, CA, [2]Johns Hopkins University Applied Physics Laboratory, Laurel, MD.

Introduction: The Diviner Lunar Radiometer Experiment onboard the Lunar Reconnaissance Orbiter (LRO) has been systematically mapping the moon since July of 2009 [1]. The solar reflectance and mid-infrared radiance measurements acquired by Diviner provide information on how regoliths on airless bodies store and exchange thermal energy with the space environment [2][3][4]. The density of coverage in the polar regions is reaching a level where seasonal variations can begin to be characterized.

The maximum angle of the spin pole of the Moon and the normal to the ecliptic plane is 1.54°. Though modest enough to have minimal influence on surface temperatures at mid-to-low latitudes, in the polar regions where solar illumination is perpetually at grazing angles, seasonality can have a large influence. The polar regions are of significant interest for *in situ* exploration for the possibility of permanently shadowed regions (PSRs) cold-trapping water [5][6]. Mission planning for landing and operating in these regions will require understanding the extreme thermal environment and illumination conditions.

Mapping: We have begun generating seasonal maps of the poles. The initial mapping effort has focused on a 5° cap centered on the south pole. All data from the start of the mission thru to the end of 2017 has been split into summer and winter (defined by the subsolar latitude) and gridded at 240 m/pix in polar stereo projection and constant local time at 0.25 hour resolution. Our preliminary maps demonstrate the variation in seasonal temperatures across the south polar region which is strongly influenced by topography. Figure 1 shows maximum bolometric temperatures for summer and winter seasons. The extent of shadowed areas varies considerably between seasons. The maximum temperatures below 110 K in the summer map, denoted by the black contour, corresponds to the PSRs with an area of 7,453 km^2 (~10% of the mapped area). In the winter, the shadowed areas extend to an area of 18,653 km^2 (~26% of the mapped area).

References: [1] Paige D. A. et al. (2010) *Space Sci. Rev., 150*, 125–160. [2] Paige D. A. et al. (2010) *Science, 330*, 479–484. [3] Vasavada A. R. et al. (2012) *JGR, 117,* E00H18. [4] Williams J.-P. et al. (2017) *Icarus, 283,* 300–325. [5] Watson K. et al. (1961) *JGR, 66*, 3033–3045. [6] Arnold J. R. (1979) *JGR, 84*, 5659–5668.

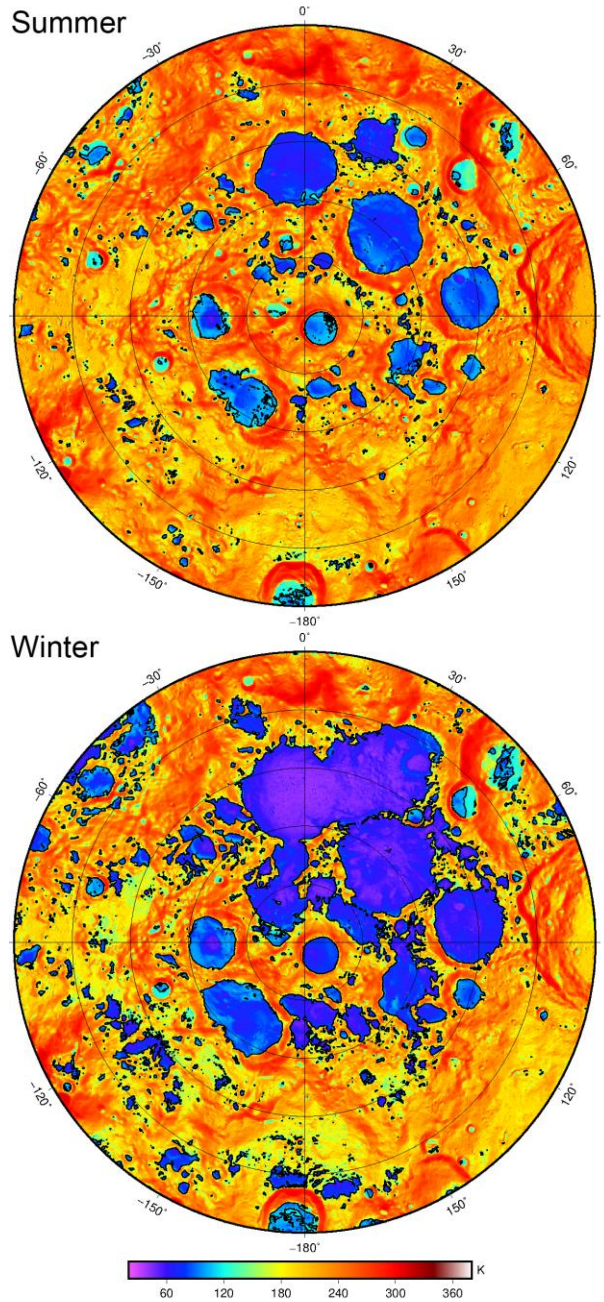


Fig. 1: Diviner maximum bolometric temperatures of the south pole 85°-90° S split into summer (top) and winter (bottom) seasons. The contours marks 110 K which approximates the boundary of regions shadowed throughout the season.