ALSEP SOLAR WIND SPECTROMETER PLASMA DATA AS OBSERVED AT THE APOLLO 12 AND 15 LANDING SITES

by

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This paper presents the results of one phase of research carried out at the Jet Propulsion Laboratory, California Institute of Technology, under contract No. NAS7-100, sponsored by the National Aeronautics and Space Administration.

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I. INTRODUCTION

The JPL Solar Wind Spectrometers are part of the Apollo Lunar Surface Experiment Packages operating at the Apollo 12 and 15 landing sites. The data are now available from the National Space Science Data Center in several forms. There are plots of hourly average values for solar wind bulk speed, direction, proton density, thermal speed, and alpha particle to proton ratio. Positive ion data are available on magnetic tape, both in the form of hourly averages and as unaveraged individual measurements. Plots of unaveraged data and electron data are not available from NSSDC; requests for this information should be directed to the experimenters.

II. INSTRUMENT DESCRIPTION

The basic sensor in the solar wind spectrometer is a Faraday cup that measures the charged particle flux entering the cup. By collecting these ions and using a sensitive current amplifier, the resultant current flow is determined. Energy spectra of positively and negatively charged particles are obtained by applying fixed sequences of square wave ac retarding potentials to a modulation grid and measuring the resulting changes in current. Similar detectors have been flown on a variety of space probes, and are described in Hundhausen (1968). Further descriptions of the solar wind spectrometer experiments are given in Snyder *et al.* (1970), and Clay *et al.* (1972).

To be sensitive to solar wind plasma from any direction (above the horizon of the Moon), and to ascertain the solar wind angular distribution, the solar wind spectrometer has an array of seven cups. Since the cups are identical, an isotropic particle flux would produce equal currents in each cup. If the flux is not isotropic but appears in more than one cup, analysis of the relative amounts of current in the collectors can provide information on the direction of plasma flow and its anisotropy. The central cup faces vertically, and the remaining six cups symmetrically surround the central cup (Fig. 1), facing 60° off vertical. The combined acceptance cones of all cups cover most of the upward hemisphere. Each cup has a circular opening, five circular grids, and a circular collector (Fig. 2). The functions of the grid structures are to apply an ac modulating field to incoming particles and to screen the modulating field from the inputs to the sensitive preamplifiers. The entrance apertures of the cups were protected from damage or dust by covers that remained in place until after the departure of the lunar module. The angular sensitivity of the Faraday cup sensor to collimated ion beams has been measured by laboratory plasma calibration. The result, averaged over all seven cups, is shown in Fig. 3 and for positive ions, agrees quite well with the measured optical transparency.

The electronics for the solar-wind spectrometer is in a temperature controlled container that hangs below the sensor assembly. The electronics includes power supplies, a digital programmer that controls the voltages in the sensors as required, current measuring circuitry, and data conditioning circuits.

On the Moon, the instrument is hung from a pair of knife edges so that it is free to swing about an east-west horizontal axis and, hence, is self leveling in one dimension. Rotations about the north-south axis and the vertical axis are determined from shadow patterns on photographs and, for Apollo 12, from the effect of sunlight on a sensor.

III. INSTRUMENT SITE, OPERATION, DATA COVERAGE

The Apollo 12 Solar Wind Spectrometer is located 3° south and 23° west on the lunar surface. The Apollo 15 Solar Wind Spectrometer is 26° north and 4° east. Orientations of the instruments at the local sites are determined from photographs of instrument shadow patterns. The Apollo 12 orientation is known within 0.5° and the Apollo 15 orientation within 1.5°.

Data coverage for the Apollo 12 Solar Wind Spectrometer begins on day 323 of 1969; the instrument is still (day 60 of 1973) operational. The Apollo 15 SWS began operations on day 212 of 1971 and failed on day 182 of 1972. During these periods data coverage was essentially complete, but the data supplied to NSSDC exclude times during lunar night when no currents were measurable.

IV. DATA ACQUISITION SEQUENCE

The solar wind spectrometer operates in an invariable sequence in which a complete set of plasma measurements is made every 28.1 sec. The sequence consists of 14 energy steps spaced a factor of $\sqrt{2}$ apart for positive ions and seven energy steps spaced a factor of 2 apart for electrons. A large number of internal calibrations are provided, and every critical voltage is read out at intervals of 7.5 min or less.

In the reduced data records and the analyzed data that are supplied to the NSSDC, this data acquisition sequence does not appear, since only a small fraction of the readings in the 186-measurement sequence represent meaningful data at any given time. For most purposes of data analysis the details of this sequence are irrelevant, but they do become important when the precise time of a particular measurement is of interest. The following partial description of the sequence will enable the determination of the time of a measurement to a precision of about one second.

The sequence begins with the positive-ion measurements, the energy steps proceeding from the lowest to the highest. At each step 8 measurements are made. The first is the sum of the currents in all 7 cups; then the 7 cups are sampled in sequence. There are 112 measurements in the positive ion subsequence, followed by 16 calibration measurements and a 56-measurement electron subsequence. The sequence ends with two data words which provide a sequence counter. In the ground data processing each sequence is tagged with a time corresponding to the earth receipt time of the end of the last data word in the sequence. Application of a light-transit-time correction provides the time at which the sequence terminated on the Moon. In the reduced data records the time is rounded off to the nearest whole second.

The time at which the measurement of the plasma properties was actually made can be inferred as follows. Using the calibration data presented in Table 1 and knowing the gain state of the instrument, the proton bulk velocity will indicate which energy step provided the largest current readings. (If the plasma was incident at a large angle from the cup, a correction by the cosine of the incidence angle will be necessary.) Then knowing which cup or cups and which energy step or steps were involved in the measurement, the measurement time is obtained by subtracting from the sequence-end time the function Δt:

$$\Delta t = 28.13 - 0.15094 \times (\text{STEP} \times 8 + \text{CUP}).$$

V. DATA ANALYSIS

For each proton spectrum the cup with the greatest total current was found. The currents in the individual energy channels were then least squares fit to the data model. This model assumed a convected Maxwell-Boltzmann proton distribution with unknown parameters — bulk velocity, most probable thermal speed, and density. An alpha particle distribution with the same velocity and thermal speed as protons was assumed with alpha particle density unknown. For these preliminary estimates the velocity vector was assumed perpendicular to the collector plate. Due to the relatively broad energy channels it was difficult to distinguish between alpha particles and energetic protons when the ratio of most probable thermal speed to proton speed was greater than 0.25. Thus a jump in alpha/proton ratio across a shock might be estimated. The broad channels also prevented accurate measurement of thermal speeds less than 10% of the bulk speed.

The estimates as described above are uncorrected for angular direction of the plasma. Angles were estimated from examination of current in other cups as described later in this section. After the angle between the plasma beam and the cup axis was determined, corrections were made to all parameters to account for the angular response of the Faraday cup and aberration effects.

Several definitions are required as a preliminary to the description of the angular analysis. Side cups are all cups except cup 7 (the vertical cup). The side cup with the greatest current (summed over all channels) is referred to as Cup A. The adjacent cup in the counterclockwise direction from Cup A (as viewed from above) is Cup B, the clockwise cup is Cup C. A noise level was chosen based upon fluctuations in zero level currents. If Cup 7, Cup A, and Cup B or Cup C are above noise, the solar wind direction is determined. Otherwise, assumptions are required.

The angle between the plasma and the normal to Cup 7 is defined as β. The plasma direction projected downward onto the instrument and measured clockwise from a line between cups 1 and 7 is defined to be the azimuthal angle α (Fig. 4). If no current above noise is measured in Cup 7, the β angle required by assuming radial flow of the solar wind from the sun is assumed. If this assumption, however, implies that current should be measured in Cup 7, the assumed angle is limited to increasingly larger angles until the predicted current in Cup 7 decreases to the noise level value. Similarly, no current in Cup A leads to assuming β or limiting β to smaller values.

The α angle is similarly predicted, measured, or limited. If current is available only in Cup A, then the α angle for radial flow from

from the sun is assumed. If this requires currents above noise in Cups B or C, the assumed α angle is limited closer to the Cup A direction. If currents in Cup B or C are available, the α angle is measured directly. After angles were determined, conversion was made to solar ecliptic coordinates taking into account the known orientations of the instruments; i.e., the direction of the bulk velocity is given by DELE and DELNE, the angle in the ecliptic and the angle north of the ecliptic.

VI DESCRIPTION OF VARIABLES ON TAPE

The variables provided on the data tapes are listed here with a brief definition. Refer also to the discussion of variables in the previous section.

Symbol	Description
DP	Proton density (protons/cm^3).
AP	Ratio of alpha-particle density to proton density.
VEL	Solar wind proton speed (km/sec).
THERMV	Most probable thermal speed (km/sec)

Thus, the fitted proton distribution function, f_p, is

$$f_p(\bar{v}) = \frac{DP}{THERMV^3\sqrt{\pi^3}}\, e^{-(\bar{v} - VEL\bar{n})^2/THERMV^2} ,$$

where $\bar{n}$ is a unit vector in the solar wind direction.

DELE: East-West angle in solar ecliptic coordinates in degrees; no correction has been made for aberration due to orbital velocity. A positive value means a plasma velocity component directed opposite to the earth's orbital motion; i.e., an average $+5^{\circ}$ due to aberration is typical.

DELNE: North-South angle in solar ecliptic coordinates in degrees. This number is positive if the plasma velocity has a northward component; i.e., positive values for flow coming from south of the ecliptic.

FLAG: FLAG is a 36 bit word, the definition of which is given in Table 2. Bits are numbered 0 to 35 with bit 0 being the high-order bit. Most of these bits will be of no interest to the users of the data; exceptions to this rule are explained here. Bits 15 and 16 are IA which has values from zero to three; bits 17 and 18 are IB. Bit 19 is IDISCP. IA is the angle code indicating how the angle α was derived as explained in the previous section. If IA = 0, α is measured. If IA = 1, α is assumed. If IA = 2, α is limited. If IA = 3, then also IB = 3 and the cup observing the protons is too far from the sun direction to be plausible. Similarly, IB is the angle code for the β angle. If IB = 0, β is measured, and so on. IDISCP = 1 indicates a side cup not adjacent to Cup A had current above noise and greater than current in Cup B or Cup C. Bit 30 indicates the instrument gain level that determines the value of the energy steps; 0 is low gain, 1 is high gain.

RMS: Percentage error in current fitting program.

KUPA: Cup with the largest current excluding Cup 7.

CURA: Current in picoamps in Cup A.

CURB: Current in picoamps in Cup B.

CURC: Current in picoamps in Cup C.

CUR7: Current in picoamps in Cup 7.

For definitions of A, B, and C, see the section on data analysis.

FACTD: Correction factor for Maxwell-Boltzmann least squares estimates of density to account for decrease in transparency of cup with increasing angle of plasma beam from cup normal; typical values range between 1.2 and 3.5.

PD is a product of the preliminary density estimate and the correction factor. VEL is similarly corrected for the cosine of the angle between the plasma beam and the cup normal.

XNOISE: Noise level in picoamperes used in estimating angles.

VII. FORMAT OF FULL TIME RESOLUTION DATA TAPES

The resultant parameters from analysis of each plasma spectrum (each 28 seconds) are written onto these tapes. Several months of data are placed on each digital magnetic tape. These tapes are written in BCD format on 7 tracks at 800 characters per inch and even parity.

All physical records contain 384 words which are blocked from 32 logical records of 12 words each. There are 4 types of logical records: (1) plasma data for one spectrum, (2) label information, (3) pseudo end of file, and (4) fill data.

The plasma data have the following format for each logical record. There are 72 BCD characters in the 12 words.

Character	Parameter
1 - 6	Not significant (used by input/output of specific computer)
7	BLANK
8 - 16	TIME DDDHHMMSS
17 - 20	DP*10
21-22	AP*100
23 - 26	VEL
27 - 29	THERMV
30 - 33	DELE*10
34 - 37	DELNE*10

Character	Parameter
38 - 49	FLAG
50 - 51	RMS
52	KUPA
53 - 56	CURA
57 - 59	CURB
60 - 62	CURC
63 - 66	CUR7
67 - 69	FACTD*100
70 - 72	XNOISE*10

The 9 characters of TIME have the day-hour-minute-second of year at the end of spectrum measurement in form of (DDDHHMMSS). The first day of the year is Day 1. The 12 characters of FLAG are an octal representation of the 36 bit word.

One can use FORTRAN format controlled READ, and the following example could be successfully used:

```
      READ (Unit, 10) ITIM, DP, AP, VEL, THERMV, DELE, DELNE,
     *FLAG, RMS, KUPA, CURA, CURB, CURC, CUR7, FACTD, XNOISE
10    FORMAT (6X, 1X, I9, F4.1, F2.2, F4.0, F3.0, 2F4.1, Ø12,
     *F2.0, I1, F4.0, 2F3.0, F4.0, F3.2, F3.1)
```

NOTE: The format supplied decimal points reduce the appropriate variables by factors of 10 to yield correct values.

The label records are used to identify the information contained on the tape and can be ignored by the general user. The first logical record will always be a label and may be followed by other label records.

Each label record has the same format as the plasma data with certain parameters redefined. Label records are identifiable by the illegal time of DDDHHHMMSS = 000999999. For this record, DP*10 is the spacecraft number (12 indicates Apollo 12 instrument and 15 indicates Apollo 15), AP*100 is the year for the first data (e.g., 70 indicates year 1970), VEL is the starting day for processing, THERMV is the starting hour of processing, DELE*10 is the last day of processing, and DELNE*10 is the last hour.

The pseudo-end-of-file record is a logical record with the illegal time of DDDHHMMSS = 499000000. All 15 remaining variables contain fill data. This record always follows the last plasma data and precedes the two hardware produced EOF marks on the tape.

Fill-data may be used at any time but its primary use is to complete the end block. Fill data has the illegal time of +0, -0 or all blanks. All other 15 variables also contain values of +0, -0, or blanks.

VIII. FORMAT OF DATA TAPES OF HOURLY AVERAGES

The averaged values of parameters from analysis of plasma spectra are placed on a digital magnetic tape. This tape is written in BCD format on 7 tracks, at 800 characters per inch and even parity. The averaged values are the result of combining individual spectral results into hourly averages.

There are 4 sets of criteria to determine which spectra to combine. The first set allows all spectra where results from analysis give an answer. The average values of 6 basic parameters (proton density, alpha-proton ratio, plasma velocity, plasma thermal speed, and plasma angle from the sun's direction in and out of ecliptic plane), their 6 RMS deviations and the number of spectra are included.

The second set of hourly averages are similar to the first except that each spectrum has been screened to pass the requirements of small RMS error on curve fitting (RMS < 20) and that thermal speed be less than 1/2 bulk velocity. This set is a subset of set one.

The third set is a subset of set two, and has the further requirement that one and only one of the angles be measured (as compared to merely consistent with assumed solar plasma direction).

The fourth set is also a subset of set two, and has the requirement that both angles are measured. This set is quite small for Apollo 12 data and is disjoint with subset three.

The hourly average tape has two logical records of 18 words for each hour of data analyzed, and is blocked 2 logical records per physical record of 36 words. There are two types of records: 1) data and 2) pseudo-end-of-file.

Data records have the following format for the 108 BCD characters of each logical record:

Logical Record One

Char.	Parameter	Comments
1 - 6	Not significant	Input/output control for computer used
7	Blank	
8 - 9	ISC	Spacecraft number
10 - 11	IYR	YEAR
12 - 18	TIME	Day-Hour-Min DDDHHMM
19 - 21	NSI	Number of spectra in average set one
22 - 25	DP1*10	Ten times average proton density (P/cm^3)

Logical Record One (cont.)

Char.	Parameter	Comments
26 - 27	AP1*100	100 times alpha-to-proton density ratio.
28 - 31	VEL1	Velocity of protons (km/sec)
32 - 34	THV1	Thermal velocity (km/sec)
35 - 38	DE1*10	Ten times DELE (degrees)
39 - 42	DNE1*10	Ten Times DELNE (degrees)
43 - 46	DDP1*10	Ten times the RMS deviation of DP1.
47 - 48	DAP1	RMS deviation of AP1*100
49 - 52	DVELI	RMS deviation of VEL1
53 - 55	DTHV1	RMS deviation of THV1
56 - 59	DDE1*10	Ten times RMS deviation of DE1
60 - 63	DDNE1*10	Ten times RMS deviation of DNE1
64 - 108	SAME 13 variables for Average set 2	

Logical Record Two

Char.	Parameter	Comments
1 - 6	Not significant	Used for I/O control
7	Blank	
8 - 18	Blank	
19 - 63	Same 13 variables for averages set 3.	
64 - 108	Same 13 variables for averages set 4.	

If one uses format control for reading each logical record, a FORTRAN READ statement to place data into ISC (Spacecraft), IYR (year), ITIM (Time = DDDHHMM), NS(4) (number of spectra in each of 4 averages), and AVE(2,6,4) (average values of parameter, its RMS deviation for 6 variables and for 4 average sets) is:

```
          READ(UNIT,10) ISC, IYR, ITIM, (NS(K), ((AVE(I,J,K),J=1,6),
        *  I = 1,2),K = 1,4)
    10    FORMAT(6X, 1X, 2I2, 2(I3, 2(F4.1, F 2.2, F4.0, F3.0, 2F4.1)),
        *  1, 6X, 12.X, 2(I3, 2(F4.1, F2.2, F4.0, F3.0, 2F4.1)) )
```

NOTE: The format supplied decimal point reduces the appropriate variables by factors of 10 to yield correct values.

The last physical record has the same format but is a psuedo end-of-file and has the illegal time of DDDHHMM = 4990000. ISC and IYR are the same as for data, but all 52 variables which follow have fill data of blanks. Following the psuedo end-of-file are 2 hardware EOF marks.

IX. FORMAT OF PLOTS

Plots provided to NSSDC show hourly averages of selected data (the second set of data described in the section on hourly average data tapes). Proton velocity is in km/sec. Most probable thermal speed, $v = \sqrt{2kT/m_p}$ is in km/sec. Density is measured in protons cm^{-3}. The angles DELE and DELNE are discussed in the section "Description of Variables on Tape," and are measured in degrees. Alpha/Proton ratio is the ratio of alpha particle number density to proton number density. January 1 is Day 1. Figure 5 is a sample plot that illustrates the available information.

X. USE OF DATA

Users should reject all fitted parameters for which RMS = 99., IA = 3, or DP = 0.0. A somewhat stronger set of criteria for rejecting bad data is RMS > 20, IA = 3, IDISCP = 1, THERMV > $\frac{1}{2}$ VP, or DP = 0.0.

Changes in assumptions involving angles can cause unrealistic discontinuities in plasma direction, speed, and density. The user is advised to study the section on data analysis. FACTD, CURA, CURB, CURC, CUR7, and XNOISE are provided to allow the user to remove the effects of changes in estimated angle if he so desires.

A final warning is that plasma velocities and densities measured at the Apollo 12 site are often perturbed from solar wind values. Velocity decreases of 50 km/sec and density increases of 30% due to the 38γ field at the Apollo 12 site have been observed. This topic is discussed by Neugebauer *et al.* (1972). At present we have no reason to believe that plasma parameters at the Apollo 15 site differ significantly from the values in the unperturbed solar wind.

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TABLE 1

Position and Width of SWS Energy Steps in Terms of Proton Velocity for Normal Incidence (Velocities expressed in km/sec).

SWS APOLLO 12					
	LOW GAIN			HIGH GAIN	
STEP	MEAN	WIDTH	MEAN	WIDTH	STEP
1	62	20	112	21	1
2	91	18	143	25	2
3	120	22	175	30	3
4	156	28	216	37	4
5	191	32	259	43	5
6	235	40	314	53	6
7	285	48	377	62	7
8	337	57	446	74	8
9	400	67	527	87	9
10	480	79	629	104	10
11	569	92	744	122	11
12	682	114	893	149	12
13	807	132	1055	172	13
14	968	157	1266	206	14

SWS APOLLO 15					
	LOW GAIN			HIGH GAIN	
STEP	MEAN	WIDTH	MEAN	WIDTH	STEP
1	66	13	105	20	1
2	90	17	135	25	2
3	120	20	169	28	3
4	151	26	208	35	4
5	188	31	252	42	5
6	230	38	305	51	6
7	280	46	370	60	7
8	333	55	439	71	8
9	395	64	519	83	9
10	469	77	616	103	10
11	557	91	730	119	11
12	666	109	874	144	12
13	791	130	1039	170	13
14	946	154	1235	218	14

TABLE 2 - SIGNIFICANCE OF FLAG WORD

Bit	Values	Significance
0	0	Unused
1	0	Unused
2	0,1	1 = no current detectable
3	0	Unused
4	0,1	1 = peak current too small to determine spectrum
5	0,1	1 = peak current in cup not near sun
6,7	0,1,2,3	Number of cups with measurable current (0 = 4 cups)
8	0,1	1 = no proton analysis (see other bits for reason)
9	0,1	1 = spurious negative currents at low energies
10	0,1	1 = spectrum too broad (hot) for meaningful analysis
11	0,1	1 = current in analyzed cup marginally small (<7 pa)
12	0,1	1 = RMS fit worse than 25%
13	0,1	1 = peak current in lowest or highest energy level
14	0,1	1 = proton energy levels 13 and 14 unused
15,16	0,1,2,3	Angle code for alpha (see text)
17,18	0,1.2.3	Angle code for beta (see text)
19	0,1	1 = discrepancy in cup currents (IDISC)
20	0,1	1 = RMS fit worse than 60%
21	0,1	1 = pickup current from modulator higher than normal
22	0,1	1 = value of DELE or DELNE > 30
23	0,1	1 = electrometer zero level shifted by > 0.8 pa
24	0,1	1 = no electron data for this time
25	0,1	1 = electron currents marginally small
26	0	Unused
27	0	Unused
28	0	Unused
29	0	Unused
30	0,1	0 = low gain, 1 = high gain
31	0,1	No proton data for this time
32	0,1	No proton data for this time (bit errors)
33	0,1	1 = no electron data for this time
34	0,1	1 = no electron data for this time (bit errors)
35	0	Unused

FIGURE CAPTIONS

FIGURE 1:

Orientation of Apollo 12 SWS on the lunar surface. The Apollo 15 SWS is rotated 180°.

FIGURE 2:

Faraday-cup sensor.

FIGURE 3:

Angular response of the Faraday cup.

FIGURE 4:

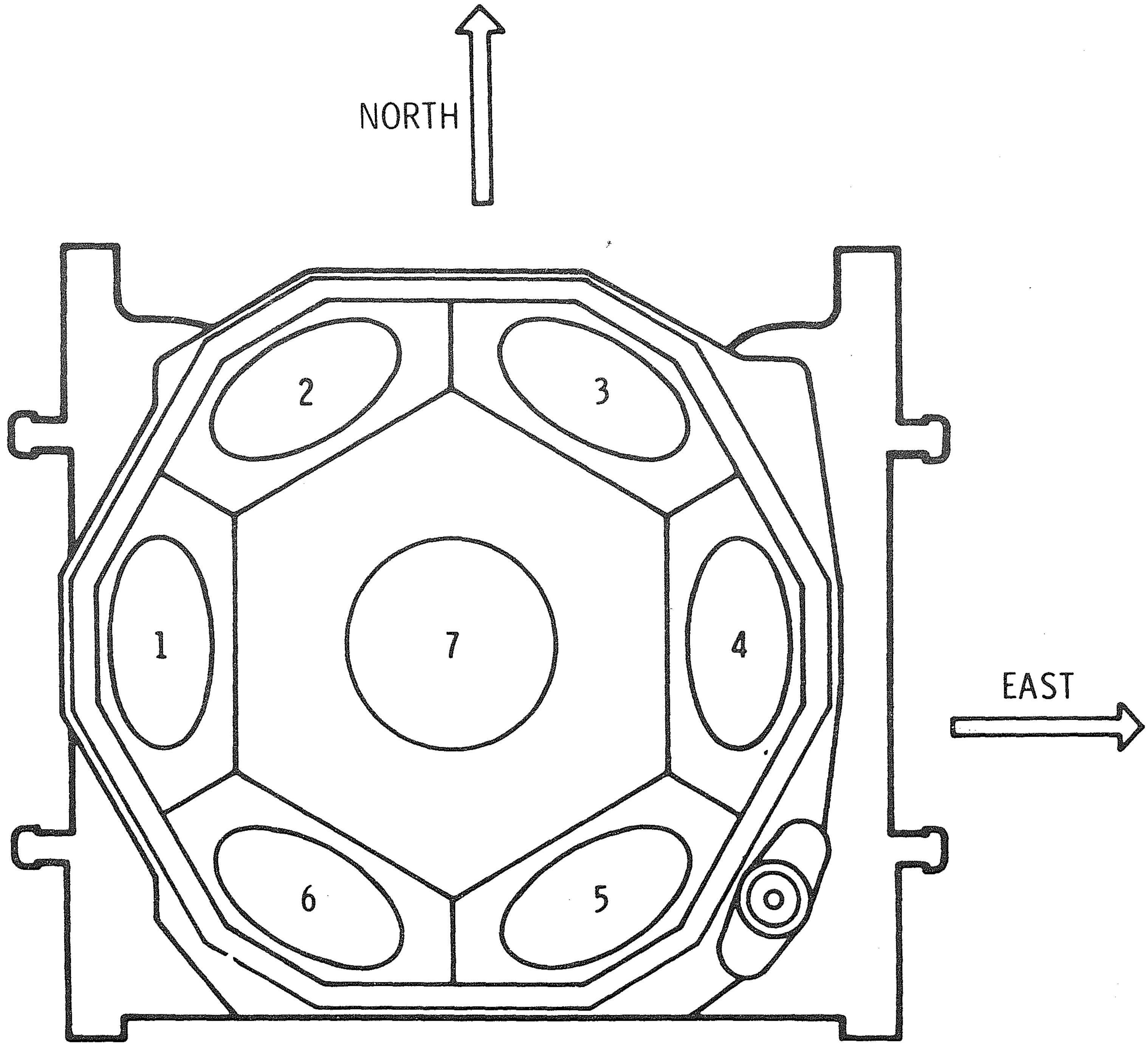
Illustrations of the α and β angles.

FIGURE 5:

Sample plot of hourly averages.

Lunation is the number of lunations following Apollo 12 turn-on in November 1969. Year and Day are the time for local noon at Apollo 12 site. Thermal speed is located below the bulk velocity in velocity graphs and Alpha/Proton density ratio is located below Proton density in Density graph.

Data are plotted only for hours which contain 25 or more spectra.



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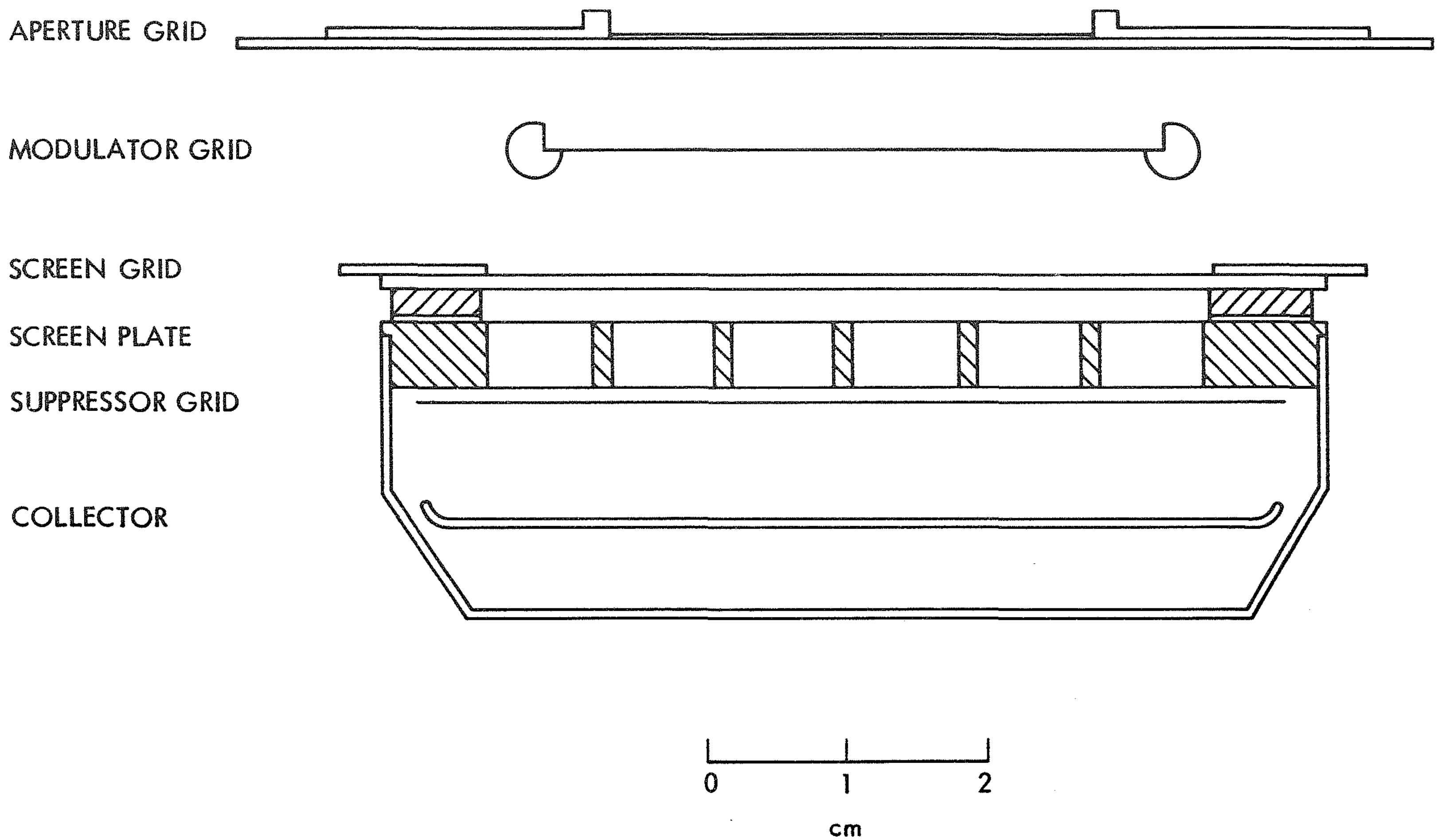
3
4
5
6
7



APERTURE GRID
MODULATOR GRID
SCREEN GRID
SCREEN PLATE
SUPPRESSOR GRID
COLLECTOR
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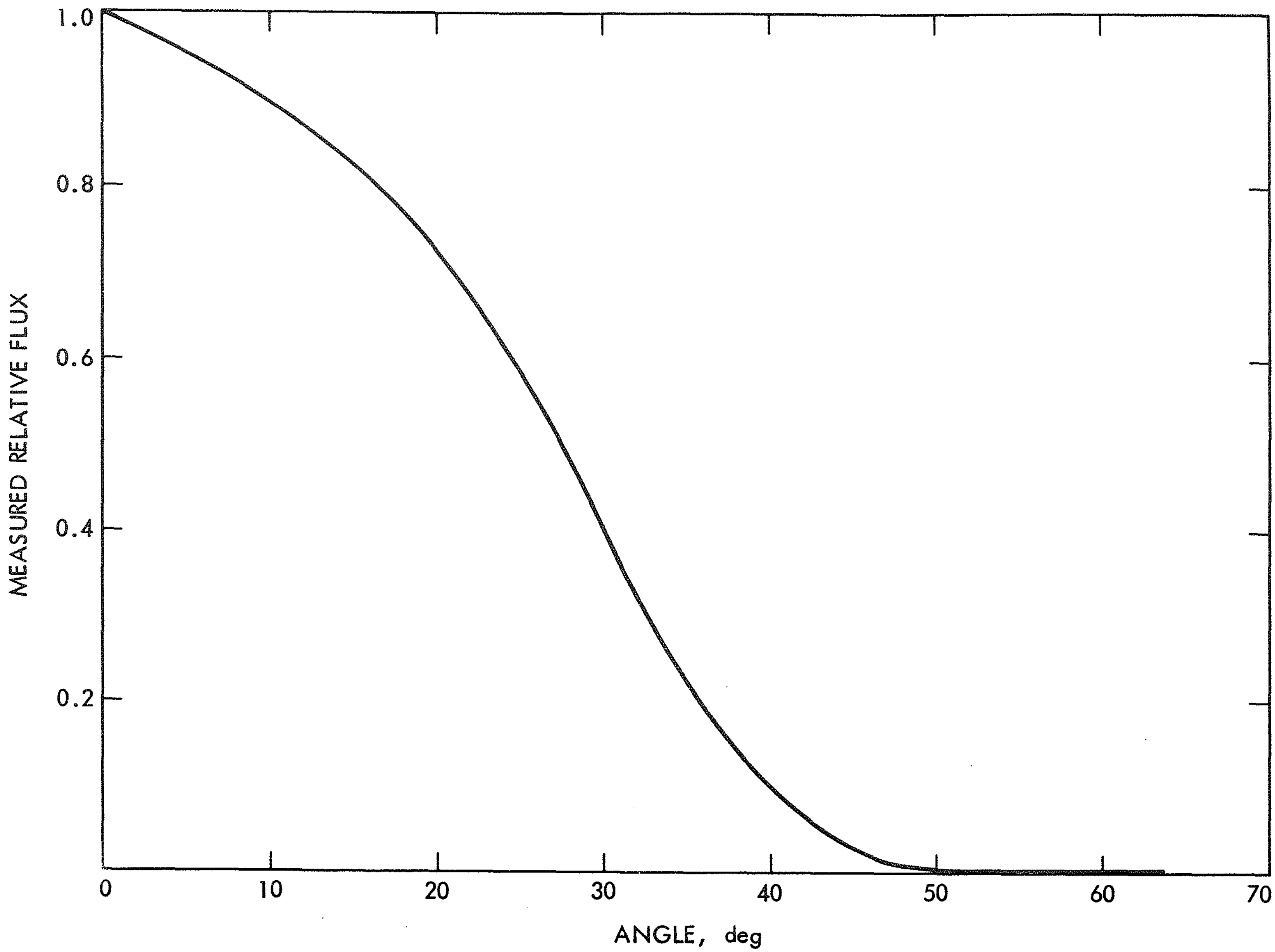
1
2
cm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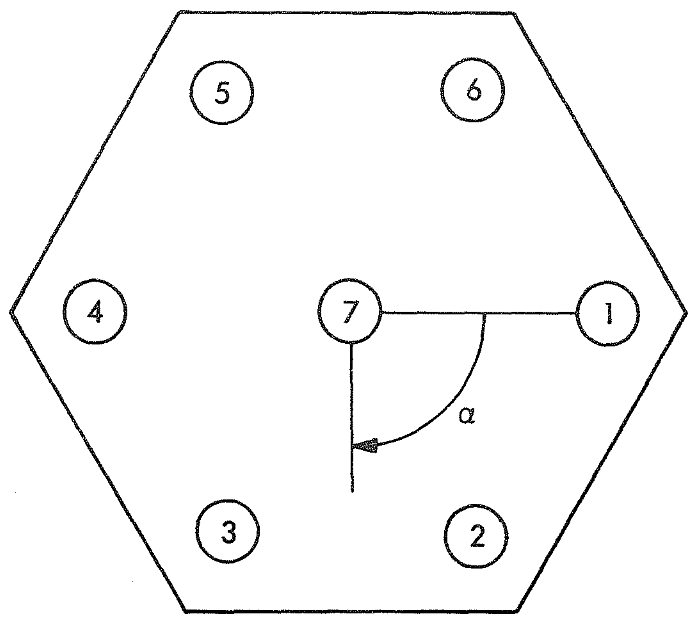
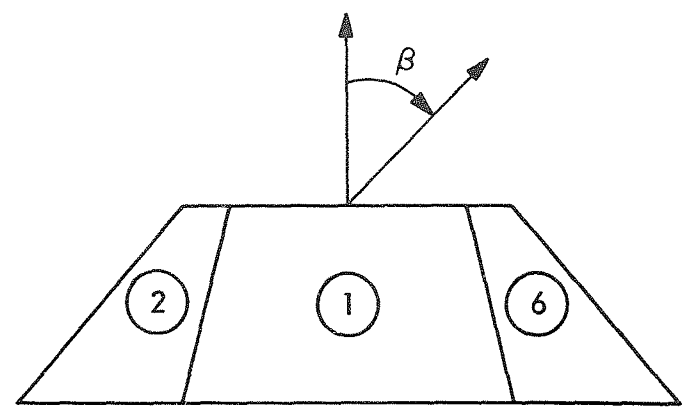
ANGLE, deg



TOP VIEW



SIDE VIEW