Data Set Catalog # 222

Apollo 14, 15 and 16

BISTATIC RADAR EXPERIMENT
71-008A -04A, 04B, 04C
71-063A -14A, 14B, 14C
72-031A -12A, 12B, 12C

9 tapes

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1. INTRODUCTION:

The documentation for this data set was originally on paper, kept in NSSDC's
Data Set Catalogs (DSCs). The paper documentation in the Data Set Catalogs have been
made into digital images, and then collected into a single PDF file for each Data Set
Catalog. The inventory information in these DSCs is current as of July 1, 2004. This
inventory information is now no longer maintained in the DSCs, but is now managed in
the inventory part of the NSSDC information system. The information existing in the
DSCs is now not needed for locating the data files, but we did not remove that inventory
information.

The offline tape datasets have now been migrated from the original magnetic tape to
Archival Information Packages (AIP's).

A prior restoration may have been done on data sets, if a requestor of this data set has
questions; they should send an inquiry to the request office to see if additional
information exists.

2. ERRATA/CHANGE LOG:

NOTE: Changes are made in a text box, and will show up that way when displayed on screen with a PDF reader.

When printing, special settings may be required to make the text box appear on the printed output.

Version	Date	Person	Page	Description of Change
01				
02				

3 LINKS TO RELEVANT INFORMATION IN THE ONLINE NSSDC
INFORMATION SYSTEM:

http://nssdc.gsfc.nasa.gov/nmc/

[NOTE: This link will take you to the main page of the NSSDC Master Catalog. There you will be able to perform searches to find additional information]

4. CATALOG MATERIALS:

    a. Associated Documents   To find associated documents you will need to know the document ID number and then click here.

http://nssdcftp.gsfc.nasa.gov/miscellaneous/documents/

    b. Core Catalog Materials

13 CM BISTATIC RADAR LUNAR OBS.

71-008A-04A

This data set has been restored. There was originally one
9-track, 1600 BPI tape written in Binary. There is one restored tape.
The DR tape is a 3480 cartridge and the DS tape is 9-track, 6250 BPI.
The original tape was created on a 930 computer and the restored
tape was created on an IBM 9021 computer. The DR and DS numbers
along with the corresponding D number are as follows:

DR#	DS#	D#	FILES	TIME SPAN
DR005628	DS005628	D011596	1	02/06/71 - 02/06/71

116-CM BISTATIC RADAR LUNAR OBS.

71-008A-04B

THIS DATA SET HAS BEEN RESTORED. IT ORIGINALLY CONTAINED ONE

9-TRACK, 800 BPI TAPE WRITTEN IN BINARY. THERE IS ONE RESTORED TAPE.

THE DR TAPE IS A 3480 CARTRIDGE AND THE DS TAPE IS 9-TRACK, 6250 BPI.

THE ORIGINAL TAPE WAS CREATED ON AN IBM 360 COMPUTER AND WAS RESTORED

ON THE MRS. THE DR AND DS NUMBER ALONG WITH THE CORRESPONDING D

NUMBER AND TIME SPAN IS AS FOLLOWS:

DR#	DS#	D#	FILES	TIME SPAN
DR003596	DS003596	D011595	1	02/06/71 - 02/06/71 (a)

(a) TWO READ ERRORS ON RECORDS 10 AND 7214

13 CM BISTATIC RADAR LUNAR OBS.

71-063A-14A

This data set has been restored. There were originally two 7-track, 800 BPI tapes written in Binary. There is one restored tape. The DR tape is a 3480 cartridge and the DS tape is 9-track, 6250 BPI. The original tapes were created on a 930 computer and the restored tapes were created on an IBM 9021 computer. The DR and DS numbers along with the corresponding D numbers are as follows:

DR#	DS#	D#	FILES	TIME SPAN
DR005637	DS005637	D011591	1	08/01/71 - 08/01/71 (a)
		D011592	2	08/01/71 - 08/01/71

(a) D011591: Read error occurred in record 3147 of file 1.

PSPG 00584

116-CM BISTATIC RADAR LUNAR OBS.

71-063A-14B

This data set has been restored. There was originally one
7-track, 800 BPI tape written in Binary. There is one restored tape.
The DR tape is a 3480 cartridge and the DS tape is 9-track, 6250 BPI.
The original tape was created on an IBM 930 computer and the restored
tape was created on an IBM 9021 computer. The DR and DS numbers along
with the corresponding D number are as follows:

DR#	DS#	D#	FILES	TIME SPAN
DR005894	DS005894	D011593	1	08/01/71 - 08/01/71

13-CM BISTATIC RADAR LUNAR OBS.

72-031A-12A

This data set has been restored. There were originally two 7-track, 800 BPI tapes written in Binary. There is one restored tape. The DR tape is a 3480 cartridge and the DS tape is 9-track, 6250 BPI. The original tapes were created on a XDS computer and the restored tapes were created on an IBM 9021 computer. The DR and DS numbers along with the corresponding D numbers are as follows:

DR#	DS#	D#	FILES	TIME SPAN
DR005649	DS005649	D011589	1	04/23/72 - 04/23/72 (a)
		D011588	2	04/23/72 - 04/23/72

(a) D011589: Read error occurred in record 309 of file 1.

71-008A-04A

Apollo 14, 13 CM Bistatic Radar Lunar Obs.

The data is contained on one 800 BPI, 9 track, binary XDS-sigma V tape with one file. A 7track C copy was made.

D-11596   C-09246   2/06/71 - 2/06/71

71-008A-04B

Apollo 14, 116 CM Bistatic Radar Lunar Obs.

The data is contained on one 800 BPI, 9 track, Binary, XDS-sigma V tape with one file. A 7 track C copy was made.

D-11595   C-09247   2/06/71 - 2/06/71

71-063A-14A

Apollo 15, 13 CM Bistatic Radar Lunar Obs.

The data is contained on two 800 BPI, 9 track, Binary, XDS-sigma V tapes with one file each. Two 7 track C copy's were made.

D-11591   C-09248   1 of 2   8/01/71 - 8/01/71
D-11592   C-09249   2 of 2   8/01/71 - 8/01/71

71-063A-14B

Apollo 15, 116 CM Bistatic Radar Lunar Obs.

The data is contained on one 800 BPI, 9 track, Binary, XDS-sigma V tape with one file. A 7 track C copy was made.

D-11593   C-09250   8/01/71 - 8/01/71

72-031A-12A

Apollo 16, 13 CM Bistatic Radar Lunar Obs.

The data is contained on two 800 BPI, 9 track, Binary, XDS-sigma V tapes with one file each. Two 9 track C copy's were made.

D-11589   C-09251   1 of 2   4/23/72 - 4/23/72
D-11588   C-09252   2 of 2   4/23/72 - 4/23/72

Apollo 16, 116 CM Bistatic Radar Obs.

The data is contained on one 800 BPI, 9 track, Binary, XDS-sigma V tape
with one file each. A 7 track C copy was made.

D-11590   C-09253   4/23/72 - 4/23/72

71-008A-04C

71-063A-14C

72-031A-12C

D-12324

Apollo 14, 15, 16 Combined Bistatic Radar Obs. C-09582

This data is contained on one 800 BPI, 9 track, Binary, XDS-sigma V tape
with 6 files. A 7 track C copy was made.

D#		C#	FILE	CONTENTS	DATE DATA WAS TAKEN
D-1	12324	C- 09582	1	Apollo 14, 116CM	2/06/71
D-		C-	2	Apollo 14, 13 CM	2/06/71
D-		C-	3	Apollo 15, 116CM	8/01/71
D-		C-	4	Apollo 15, 13 CM	8/01/71
D-		C-	5	Apollo 16, 116CM	4/23/72
D-		C-	6	Apollo 16, 13 CM	4/23/72

July 24, 1973

To: Data Repository

From: ADP Services

Subject: Apollo 14, 15, 16 Combined Bistatic Radar tape.

Please release tape DD11594 and the corresponding DC number and

return to G. R. Dow as per attached letter. A replacement tape

DD12324 has been received, processed and placed in the NSSDC

library.

July 24, 1973

Mr. G. R. Dow
Center for Radar Astronomy
Dept. of Electrical Engineering
Stanford University
Stanford, California 94305

Subject: Your letter and shipment of June 25, 1973, concerning
the Bistatic Radar data tape.

Dear Mr. Dow,

We are returning, under separate cover, the magnetic tape
containing Apollo 14, 15 and 16 Bistatic Radar data which
you sent to us earlier this year. The replacement tape has
been duplicated and placed in the NSSDC library. If you
have any questions please call us.

Yours truly,

Joseph R. Johns
Manager, ADP Services

Under Separate Cover:
  Magnetic tape containing
  Apollo 14, 15 and 16 data (1)

May 11, 1973

To: C. Wende

From: ADP Services

Subject: Apollo 16 Bistatic Radar data tapes

There is a data word discrepancy in the header record of the
Apollo 16, Bistatic Radar data tapes. Words 43 and 44 indicate
day and year that the data were collected in integer format.
Word 45 and 46 also indicate Julian Ephemeris day at 00.00.00
GMT or day the data was collected in double precision format.
Based on our conversion of words 43 and 44 the time the data
were collected is 4/23/72. When data for words 45 and 46 were
calculated on the ephemeris day program (Julian) we came up with
a time that data were collected as 4/22/72. The tapes were
processed using the first date; 4/23/72. If there are any
objections please contact ADP Services.

From S.M. Butstin - Roden Zr (S-170)   Draft

APOLLO 14, 15, 16
13 c m [illegible] LUN... [illegible]
116 c m [illegible] LUNA [illegible]

Appendix IV

JM Doptrack Tape Formats

    This appendix describes the tape formats for the JM Doptrack Tapes generated in Subtask 6 of the text. Tapes are 9 track, 800 BPI, binary in XDS Sigma 5 machine images. These tapes contain the output of the polarimeter in Subtask 4, the corrected fractional polarization obtained from Subtask 5, MSC trajectory data, and certain ancillary quantities computed at Stanford. All records within the given file are the same length. There may be more than one tape per file. Files are identified by a header record which contains a brief description of the tape contents. This Appendix describes the tape organization, the file organization, and the record formats for the JM Doptrack tapes. Definitions of the tape contents are either given here or described by reference.

A. Tape Organization

File	No. Tapes	Contents	Record Length
1	1	Apollo-14 116 cm	514
2	1	Apollo-14 13 cm	514
3	1	Apollo-15 116 cm	1026
4	2	Apollo-15 13 cm	514
5	1	Apollo-16 116 cm	1026
6	2	Apollo-16 13 cm	514

B. File Organization

    1. Header Record
    2. Data Record #1
    3. Data Record #2
    4. Data Record #3   Observational Data   Data Frame
    5. Data Record #4
    6. Data Record #5
    7. Data Record #6   ephemeris data
          ⋮
    8.
    9. EOF (End of File Word)

Files may be continued across the end of a tape.

C. Header Record Formats

Word No.	Contents	Units	Machine Type[α]
1 : : 42	Alphanumeric Tape Identifier	--	A
43	Day of year on which data were collected (January 1 = day 1)		I
44	Year data were taken		I
45) 46)	Julian Ephemeris Day at 00:00:00 GMT on the day the data were taken	(days)	DPR
47) 48)	Julian Ephemeris Day of reference epoch	(days)	DPR
49	Time increment between data frames	(sec)	R
50	Number of data records following the Header Records (Number of data frames = Number of Data Records ÷ by 6)	--	I
50 : : end	No meaningful data		

Appendix IV (cont.)

α A - Alpha numeric

I - Integer

R - Real

DPR - Double precision real

D. Data Frame Formats

1. Data Record Organization

Record No.	Contents	Note:
1	$J_{11}(k)$	116 cm data
2	$J_{22}(k)$	$J_{11}(k)$ - <u>Left</u> circular polarization
3	Real part of $J_{12}(k)$	
4	Imaginary part of $J_{12}(k)$	$J_{22}(k)$ - <u>Right</u> circular polarization
5	$\gamma(k)$	
6	Spacecraft ephemeris and ancillary data	13 cm data
		$J_{11}(k)$ - <u>Right</u> circular polirization
		$J_{22}(k)$ - <u>Left</u> circular polarization

2. Format Records 1-5 (all machine type REAL)

Word No.	Contents
1	Data described under D.1 above
$\vdots$	
513/1025	
514/1026	Sequential Record No.

3. Format Record 6 (all machine type Real)

Word No.	Contents	Units
1	Frame No. (data record no. mod 6)	
2	UT2	(sec)
3	Difference of reflected and direct dopplers, > 0 for reflected doppler > directed doppler	(Hz)
4	Predicted bandwidth for 0.1 radian rms surface slope	(Hz)

3. Format Record 6 (all machine type Real) (cont.)

Word No.	Contents	Units
5	Angle of incidence	(deg)
6	Spacecraft altitude (mean lunar radis assumed 1736 km)	(km)
7	Spacecraft speed	(m/sec)
8	Radar cross section predicted for smooth conducting moon	(dim)
9	(Radar cross section)/ (received power)	(m^2/w)
10	X ⎱ Components of Seleno-	
11	Y ⎰ graphic unit position vector of spacecraft	
12	Z ⎰ location	(dim)
13	X ⎱ Components of Seleno-	
14	Y ⎰ graphic unit position vector of specular	
15	Z ⎰ point location	(dim)
16	Latitude of sub-spacecraft position	(deg)
17	Longitude of sub-spacecraft position	(deg)
18	Component of doppler shift due to earth roatation	(Hz)
19	Total doppler shift of reflected signal	(Hz)
20	Latitude of specular point	(deg)
21	Longitude of specular point	(deg)
22	Speed of the specular point on the lunar surface	(M/sec)
23	Vehicle look angles to earth	(deg)
24	α_e β_e	
25	Euler angles of local horizon	(deg)
26	θ	
27	φ coordinates	
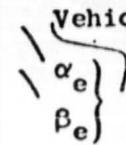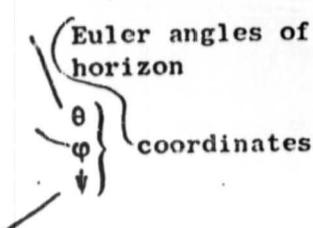
3. Format Record 6 (all machine type Real) (cont.)

Word No.		Contents	Units
28	X	Spacecraft selenographic	
29	Y	unit velocity vector	(dim)
30	Z		
31	X	Selenographic unit vector	
32	Y	to earth	(dim)
33	Z		

The data frames are repeated each 6 records. The first data frame occupies records 2-7, the next 8-13, etc.

Note: Data do not always progress uniformly in time. Occasionally, data frames will reverse slightly in time for one frame, and then continue forward. This effect is caused by the sampling procedure in which a small deliberate overlap was inserted. Time tags on data are correct.

E. Definition of Contents

1. Data - the data have been defined under Subtasks 4 and 5 of the text.

2. Ephemeris and Ancillary Data - the formulae used in computing trajectory related parameters are given in Appendix VI.

From S.U. Bristol - Radon 2x. (S-170)   Draft
APOLLO 1. 1.
Combined
71-008A-04C
71-063C-14C
72-021A-

Appendix VI

Integral Tape Format

The integral tape contains reduced data records generated in Subtasks 7, 8 and 9 (of Block Diagram I). This appendix gives the detailed formating of that tapes and describes all ancillary computations.

A. Tape Organization

The table below gives the file contents and data record length for the integral tape.

File No.	Contents	Record Length
1	Apollo-14 116 cm	50 words
2	Apollo-14 13 cm	50 words
3	Apollo-15 116 cm	50 words
4	Apollo-15 13 cm	50 words
5	Apollo-16 116 cm	50 words
6	Apollo-16 13 cm	50 words

The tape is 9 track, 800 BPI, binary in XDS Sigma V machine images.

B. File Organization

1. Header Record

2. Data Record

3. :

4. (EOF) (End of File)

5. Header Record

6. :

A - Alpha numeric

I - Integer

R - Real

DPR - Double precision real

to bottom of next page

C. Header Record Format

Word No.	Contents	Units	Machine Type α
1/ 42	Alphanumeric File Identifier	--	A
43	Integer Day Number (Jan. 1 = 1)	(day)	I
44	Integer Year (GREGORIAN)	(year)	I
45 46	Double precision Julian emphermis day number at 00:00 GMT on day data were taken	(day)	DPR
47 48	Double precision Julian ephermis day of reference epoch	(day)	DPR
49	Time increment between data records	(sec)	R
50	Number of data records following this header record		I

D. Data Record Format (all machine type real)

Word No.		Contents	Units
1		Data frame number from JM Doptrack tape	
2		Time data were taken:	UT2- (sec)
3	X ⎫	Components of seleno- graphic unit position	
4	Y ⎬	vector of spacecraft	(dim)
5	Z ⎭	location	
6	X ⎫	Components of seleno- graphic velocity unit	
7	Y ⎬	vector	(dim)
8	Z ⎭		
9		Speed: Magnitude of space- craft velocity vector	(m/sec)
10	X ⎫	Components of seleno- graphic unit vector from	
11	Y ⎬	center of the moon to	(dim)
12	Z ⎭	center of the earth	

D. Data Record Format (all machine type real) (cont.)

Word No.	Contents		Units
13	X	Components of seleno-	
14	Y	graphic unit position vector of specular	(dim)
15	Z	point location	
16	θ	Euler angles of space-	
17	ψ	craft attitude and local horizon frame	
18	ϕ		

$$\bar{A}_{veh}] = \begin{bmatrix} \phi \\ (x) \end{bmatrix} \begin{bmatrix} \psi \\ (z) \end{bmatrix} \begin{bmatrix} \theta \\ (y) \end{bmatrix} \begin{bmatrix} \bar{A}_1 \end{bmatrix}$$

(cw rotation looking in + axes direction)

Word No.	Contents		Units
19	α_s	Vehicle look angles to specular point	(deg)
20	β_s		
21	δ	Angle between plane of incidence and plane-containing vehicle x axis and direction vector to specular point	(deg)
22	α_e	Vehicle look angles to earth	(deg)
23	β_e		
24		Selenographic latitude of spacecraft position	(deg)
25		Selenographic longitude of spacecraft position	(deg)
26		Selenographic latitude of specular point	(deg)
27		Selenographic longitude of specular point	(deg)
28		Angle of incidence	(deg)
29		Instantaneous speed of specular point on lunar surface	(m/sec)
30		Predicted bandwidth for .1 radian rms surface slope	(Hz)
31		Difference between reflected and direct doppler shifts	(Hz)
32		Total doppler shift reflected signal	(Hz)

Appendix VI (cont.)

D. Data Record Format (all machine type real) (cont.)

Word No.	Contents	Units
33	Component of doppler shift due to earth's rotation	(Hz)
34	Altitude of spacecraft above lunar surface: Radius of center of the moon-1736 Km	(Km)
35	Normalized bistatic-radar cross-section	(dim)
36	Sigfac	(m^2/w)
37	Polarized power	(arb)
38	Normalized polarized power	(^{o}k)
39	Unpolarized power	(arb)
40	Normalized unpolarized power	(^{o}k)
41	Equivalent area bandwidth	(Hz)
42	Normalized absolute moment bandwidth	(dim)
43	Normalized second moment bandwidth	(dim)
44	Centroid of the echo spectrum	(Hz)
45	RMS slopes inferred from equivalent area bandwidth	(deg)
46	Spare if value equals zero, otherwise handscaled one-half power echo bandwidths	(Hz)
47	Data validity flag	(-)
48	Spare if value = 0, otherwise value of spacecraft antenna gain in α_s, β_s, direction (cf Word No. 19, 20)	(dim)
49	Spare	(-)
50	Data record sequence number	(-)

Note: Data do not always progress uniformly in time. Occasionally, data records will reverse slightly in time for one record, and then continue forward. This effect is caused by the sampling procedure in which a small deliberate overlap was inserted. Time tags on data are correct. Overlapping data correspond to the same time interval but different sampling passes. Slight differences arise from variation in exact times averaged.

E. Data Parameter Definitions

The remainder of this section defines the contents of the data records just described above. The individual subsection numbers correspond to the word numbers in Section D (Data Record Format). If a particular quantity has been described at length elsewhere a reference will be given. Otherwise, the quantity is defined here.

1. Frame Number - identifies the JM Doptrack tape frame number corresponding to the Integral tape record number.

2. Time - gives the UT2 at which the data were taken. This time corresponds to the mid-point of the averaging interval, as described under Subtask 4. All trajectory parameters have been interpolated to this time, so that geometrical quantities corresponds to the location of the specular point on the mean lunar surface at the middle of the averaging interval.

3, 4, 5. Selenographic Unit Position Vector - is defined with respect to the lunar surface. This vector is a unit vector directed from the center of the moon for the instantaneous location of the spacecraft. The X, Y, Z directions are defined as follows:

$$X = \text{Mean Earth direction}$$
$$Y = \text{Mean direction of the following limb}$$
$$Z = \text{North polar direction}$$

The selenographic coordinants are obtained by rotation from the selenocentric geoequaltorial units of the epoch given in the Header Record. Procedures are described elsewhere (Tyler, 1968).

6, 7, 8. Selenographic Unit Velocity Vector is a unit vector in the direction of the spacecraft velocity. The coordinant system is the same as that given in items 3, 4, 5 above.

9. Speed - is the magnitude of the spacecraft velocity vector.

10, 11, 12. Selenographic Unit Vector to Earth - is a unit vector giving the direction from the lunar center of mass to the center of mass to the earth in the selenographic coordinant system described in the 3, 4, 5 above.

13, 14, 15. Selenographic Unit Position Vector of Specular Point -
is a unit vector from the center of mass of the moon to the loca-
tion of the specular point on the mean spherical lunar surface.
For this computation the lunar radius is taken as 1736 km. The
specular point is the location on the mean lunar surface where the
angles of incidence and reflection are equal (cf Tyler, [1968]).

16, 17, 18. Euler Angles of Spacecraft Attitude -- connect the space-
craft altitude with a local horizon reference frame. Both the local
horizon and the Euler angles are defined in Appendix IX.

19, 20. Look Angles to Specular Point - are the vehicle polar coordinance
These quantities are defined in Appendix IX.

21. Plane of the Vehicle - orientation with respect to the plane of
incidence is given by the angle δ. This quantity is necessary to
define the vehicle attitude with respect to the plane incidence.
The angle δ is defined in Appendix IX.

22, 23. Look Angles to Earth - are the vehicle polar coordinance of a
unit vector in the earth center of mars direction. These quantities
are computed in the same manner as item 19, 20 above using the unit
vector to earth.

24. Selenographic Latitude of Spacecraft Position - is the selenographic
latitude of the sub-spacecraft point computed from the Z component
unit vector given in items 3, 4, 5.

25. Selenographic Longitude of Spacecraft Position - is the selenographic
longitude of the spacecraft of the sub-spacecraft position computed
from item 3, 4, 5 according to astrometric convention, western limb
of the moon leading.

26. Selenographic Latitude of Specular Point - is the selenographic
latitude of the specular point on a mean spherical lunar surface
computed from item 15.

27. Selenographic Longitude of Specular Point - is the selenographic
longitude of the specular point on the mean spherical lunar surface
computer from items 13, 14, 15.

Appendix VI (cont.)

28. Angle of Incidence - is the angle of incidence on mean spherical lunar surface at the specular point (cf Tyler, 1968).

29. Speed of the Specular Point - is the speed with which the instantaneous specular point moves across the mean lunar surface (Tyler, 1968).

30. Predicted Bandwidth - is the one half spectral width predicted for a 0.1 radian rms surface slope, based on the instantaneous angle of incidence and specular point velocity. Computation is after Fjeldbo (1964), also described in Tyler (1968). Fjeldbo gives a theoretical expression for the 1/2 power echo bandwidth

$$\Delta f = 4(2\ln 2)^{1/2} \frac{vs}{\lambda} \frac{h_o}{d_o} \cos \phi$$

where ϕ_s = velocity of the specular point on the mean lunar surface, λ = wavelength of the radiation (either 116 cm or 13 cm), ϕ = angle of incidence at the specular point, and the quantity $\frac{h_o}{d_o}$ = the mean lunar rms slope.

The quantity Δf is the 1/2 power bandwidth predicted for guassian spectrum. Such a spectrum would result from a gently undulating surface with gaussian autocorrelation function.

31. Difference Between Reflected and Direct Doppler Shifts - is the predicted frequency difference between a wave reflected from the specular point and the signal traveling directly from the spacecraft to earth. Sign convention is such that the difference is positive for a reflected doppler shift greater than that of the direct doppler shift.

32. Doppler Shift - is the total doppler shift expected fro the reflected signal. Computation of this doppler shift includes spacecraft motion and the earth's rotation, but does not include the rate of change of distance between the earth and the moon.

33. Doppler due to Earth's Rotation - is the component of the doppler shift for a signal arriving from the direction of the moon due to the earth's rotation.

34. **Altitude** - of the spacecraft above the lunar surface has been compu-
ted assuming a lunar radius equal to 1736 km. The magnitude of the
spacecraft radius vector from the lunar center of mass is obtained
by adding the contents of word no. 34 to 1736 km.

35. **Normalized Bistatic-Radar Cross-Section** - is the bistatic-radar
cross-section of a smooth conducting sphere of the same radius
and relative geometry as the moon. Following Fjeldbo (1964) this
cross-section is given by

$$\sigma_B = \frac{4\pi \, R_1^2 \, \cos\phi}{\left(\cos\phi + \frac{2d_{or}}{R}\right)\left(1 + \frac{2d_{or}}{R}\cos\phi\right)}$$

where

R_1 = distance from transmitter to the center of the moon

R = lunar radius (1.736×10^6 m)

ϕ = angle of incidence (cf item 28)

d_{or} = distance from the transmitter to the specular
point on the mean lunar surface.

36. **Sigfac** - is a multiplicative constant relating instantaneous geometry
and received power to surface reflectivity.

$$SIGFAC = \frac{(4\pi)^2 \, R_1^2 \, R_2^2}{A \, P_T \, G_T \, \sigma_B}$$

where

R_1 = distance from transmitter to center of the moon

R_2 = distance from receiving site to center of the moon

A = effective aperture of receiving antenna

P_T = transmitted power

G_T = transmitting antenna gain in specular point
direction

σ_B = bistatic-radar cross-section for a perfectly
conducting moon

For convenience, this expression is evaluated with the following
numerical values for the quantities above:

R_1 = instantaneous value from MSC trajectory

σ_B = instantaneous value from item 35 above

R_2 = 4×10^8 m

A = $0.5 \, (22.5)^2 \pi$

G_T = 1

P_T = .2.5 w

These values give only order of magnitude results for this experiment.

37. <u>Polarized Power</u> - is the experimenter's best estimate of the polarized component of the received echo total power. Extraction of the polarized power is discussed elsewhere (cf Subtask 8).

Denote the polarized power spectrum $P_p(k)$. Consider the figure below. Polarized power is determined from

$$P = \sum_{k=B_1}^{B_2} (P_p(k) - n)$$

The $P_p(k)$ is a polarized power spectrum. In the determination of P, the signal limits B_1, B_2 and n are selected by the experimenter. The quantity n is chosen on the basis of

$$\sum_{B_1'}^{B_2'} (P_p(k) - \hat{n}) \sim 0$$

where B_1', B_2' represent spectral limits containing no echo signal, and $\hat{n}$ represents a sequence of trials of n. The limits B_1, B_2, B_1', B_2', are varied as is necessary to follow the changing echo signal.

38. <u>Normalized Polarized Power</u> - the quantity contained in item 37
divided by the average power spectral density of the system noise
level. This quantity has been discussed in detail elsewhere
(cf Subtask 3).

Using the notation introduced under item 37,

$$\text{Normalized Polarized Power} = P/n$$

where P and n have the same meaning as above.

Note: P/n is extremely sensitive to the choice of n. Thus, polarized
power is considered the best overall measure of received polari-
zed echo power. But, P/n provides the only method, through the
measure of system temperature, of obtaining an absolute power
calibration. Similarly, the value of n may be determined from
the ratio of polarized power to P/n, so that the variations and
system temperature and/or gain may be estimated.

39. <u>Unpolarized Power</u> - is the analogous quantity to item 37, for the
unpolarized power spectrum. The unpolarized power is obtained in
a manner similar to that used to compute polarized power. Letting

$P_u(k)$ represent the unpolarized power spectra, and refering to the figure below, the unpolarized power is given by

$$U = \sum_{\tilde{B}_1}^{\tilde{B}_2} (P_u(k) - \tilde{n})$$

where the tilda's refer to the values of B and n used in the unpolarized power spectrum. In general, the limits for the polarized and unpolarized echoes will be different, as will the value of the system noise level. The difference in frequency limits arises from the difference in the spectral distribution of the unpolarized power; the difference in system noise temperature arises from the signal processing used to separate these quantities (cf Subtask 4, 5). The value of $\tilde{n}$ is chosen in a manner similar to that of n in item 37. In some cases, it is not clear that all the unpolarized power is contained in the receiver passband. In this event, $\tilde{B}_1$ or $\tilde{B}_2$ is set equal to the upper or lower frequency limit as appropriate.

40. <u>Normalized Unpolarized Power</u> - is the analogous quantity to item 39, for the unpolarized power spectrum. The normalized unpolarized power is defined as

$$\text{Normalized Unpolarized Power} = U/\tilde{n}$$

where the symbols have the same meaning as in item 39. Comments given under item 38 are also germaine to normalized unpolarized power.

41. <u>Equivalent Area Bandwidth</u> - the spectrum of a bistatic-radar echo from a well behaved surface may be written as (<u>Fjeldbo</u>, 1964).

$$S(f) = e^{-\pi f^2 \left[4 v_s (\pi/\lambda) \cos \phi \left(\frac{h_o}{d_o} \right) \right]^{-2}} = e^{-f^2/2\tilde{\sigma}^2}$$

where

    f = frequency measured from the centroid of the echo spectrum

    v_s = speed of the specular point across the mean lunar surface

    λ = wavelength

    ϕ = angle of incidence, and

    h_o/d_o = rms slope

_____

*The three machine calculated bandwidths, i.e., the equivalent area bandwidth, the absolute moment bandwidth, and the second moment bandwidth, provide three quasi-independent methods of determining the spectral width of the received echoes. The equivalent area bandwidth provides a standard result that is not particularly sensitive to the gaussian, or non-gaussian nature of the echo spectrum. The absolute moment bandwidth and the second moment bandwidth so emphasize departures from gaussian because of the increasing importance given to the wings of the spectrum.

Equivalent area bandwidths have been used to determine lunar rms slopes. The absolute moment bandwidths and the second moment bandwidths, when normalized by the equivalent area bandwidth, give a sensitive measure of the departures of the echo spectra from the gaussian conditions. RMS slopes derived from these measures are termed "gaussian equivalent slopes" in that they would correspond to true surface conditions for a surface with gaussian statistics and a gaussian autocorrelation function with the same equivalent widths. A more complete description of the lunar slopes requires additional analysis (e.g., see <u>Parker and Tyler</u>, 1973).

Solving for rms slope in terms of measured values of standard deviation, $\hat{\sigma}$, of an experimental spectrum yields

$$h_o/d_o = \frac{\hat{\sigma}}{2(v_s\Lambda)\cos\phi}$$

Thus, the rms slope may be readily determined from a experimental curve in terms of the e^{-1} width of that curve. The equivalent area bandwidth is a measure of $\hat{\sigma}$ based on an equivalent rectangular spectrum of the same area as the experimental spectrum. This width is computed as

$$\hat{\sigma}_{ea} = \frac{\sum\limits_{C_1}^{C_2} F_p(k)}{\max P_p(k)} \cdot (2\pi)^{-1/2}$$

$$C_1 < k < C_2$$

Referring to the figure which follows, the quantity $\hat{\sigma}_{ea} = \sigma$ if the observed curve is gaussian and noiseless. For non-gaussian data $\hat{\sigma}_{ea}$ is still a measure of the bandwidth, albeit the interpretation must be modified. rms slopes determined from $\hat{\sigma}_{ea}$ and expression above will be referred to as equivalent area slopes. The quantity $\hat{\sigma}_{ea}$ is the equivalent area bandwidth.

42. **Normalized Absolute Moment Bandwidths** - are based on an equivalent value of $\hat{\sigma}$ computed from the absolute moment of the data. That is,

$$\hat{\sigma}_{am} = \frac{\sum\limits_{k=C_1}^{C_2} P_p(k)\,|k-\bar{k}|}{\sum\limits_{k=C_1}^{C_2} P_p(k)} \cdot \sqrt{\frac{\pi}{2}}\;; \quad \bar{k} = \frac{\sum\limits_{k=C_1}^{C_2} P_p(k)\,k}{\sum\limits_{k=C_1}^{C_2} P_p(k)}$$

for a gaussian spectrum the equivalent area moments and the absolute moments will be equal

$$\hat{\sigma}_{am} = \hat{\sigma}_{ea} = \sigma$$

where the symbols have the same meaning as in item 41.

The normalized absolute moment bandwidth is

$$\hat{\sigma}_{am}/\hat{\sigma}_{ea}$$

For a gaussian echo spectrum this ratio will be unity.

43. <u>Normalized Second Moment Bandwidth</u> - the second moment bandwidth is also based on gaussian equivalence. This bandwidth is defined as

$$\hat{\sigma}_{sm} = \frac{\sum\limits_{k=C_1}^{C_2} P_p(k)(k-\bar{k})^2}{\sum\limits_{k=C_1}^{C_2} P_p(k)} \quad ; \quad \bar{k} = \frac{\sum\limits_{k=C_1}^{C_2} P_p(k) \cdot k}{\sum\limits_{k=C_1}^{C_2} P_p(k)}$$

Again, for a gaussian echo spectrum

$$\hat{\sigma}_{sm} = \hat{\sigma}_{am} = \hat{\sigma}_{ea} = \sigma$$

where the symbols have the same meaning under items 42 and 41.

The normalized second moment bandwidth is given by

$$\hat{\sigma}_{sm} / \hat{\sigma}_{ea}$$

Again, departures of this ratio from unity are indicative of a non-gaussian received echo spectrum

44. **Centroid of the Echo Spectrum** - the centroid of the echo spectra are defined in the standard way

$$\bar{k} = \frac{\sum\limits_{k=C_1}^{C_2} P_p(k) \cdot k}{\sum\limits_{k=C_1}^{C_2} P_p(k)}$$

where the symbols have the same meaning as in 41, 42 and 43. The values of C_1, C_2 are held constant throughout items 41, 42, 43 and 44. The echo spectrum centroid is used in the computations of the absolute moment bandwidths and the second moment bandwidths. It is also useful for estimation of the observed doppler difference (cf item 31). However, the centroid has no direct meaning in an

absolute sense in that the transmitter frequencies from the space-craft are not known precisely.

45. rms Slopes - are obtained from the equivalent area bandwidths according to

$$\frac{h_o}{d_o} = \frac{\hat{\sigma}_{ea}}{2(v_s/\lambda)\cos\phi}$$

and

$$\text{rms slope} = \tan^{-1}(h_o/d_o)$$

where the results are expressed in degrees for convenience. The quantities v_s, λ, ϕ and $\hat{\sigma}_{ea}$ have been defined in item 41.

46. Handscaled 1/2 Power Echo Bandwidths - handscaling of polarized echo bandwidths has been discussed previously under Subtask 10. A 1/2 power echo bandwidth is defined by the quantity "B" in the figure which follows. In practice, this value is obtained by handscaling data from plots. The handscale bandwidths provide a rapid, simple technique for the evaluation of lunar rms surface slopes. The handscaled bandwidths were also used as a controlling parameter in development of automated techniques for obtaining echo bandwidths. rms slopes may be obtained from the handscaled bandwidths by

$$\text{rms slope} = 5.7^o \times B/(\text{predicted 1/2 power bandwidth for 0.1 rms slopes})$$

As before, in item 45, the result is given in degrees for convenience. Predicted 1/2 power bandwidths for 0.1 rms slopes are given in Word No. 30 of the integral tape data records (cf item 30).

47. Flag - the flag word contains a seven level binary code that indicates data quality. A bit in the "1" condition indicates the existance of a special condition in the data. A bit position in the "0" state carries no meaning other than that the data are normal.

The interpretation of the bit positions is as given below.

Bit in "1" Condition	Implication
1	Polarized power data questionable or no good
2	Unpolarized power data questionable or no good
3	Polarized noise level, n, (cf item 37) changed this data record
4	Polarized integration bounds B_1, B_2, (cf item 37) changed this data record
5	Unpolarized noise level, $\tilde{n}$, (cf item 39) changed this data record
6	Unpolarized integration bounds, $\tilde{B}_1$, $\tilde{B}_2$, (cf item 39) changed this data record
7	System gain changed this data record

Explanation

Bit Position "1"

Polarized data may be flagged for any one of a number of reasons. The presence of interference, an error in setting the integration bounds, or a tape drive error in the data processing are examples of difficulties that would result in such a flag. In case of gross errors the flag represents an objectively known bad data point. In the case of more subtle phenomena such as interference, the flag represents an experimenters subjective opinion. For the 116 cm data interference is the predominant cause of a data bad flags. Data users who wish to examine this question for themselves may do so by reprocessing the data from the JM Doptrack tapes, however, it is very strongly recommended that no flagged data be used without taking this precaution.

Bit Position "2"

Unpolarized data may be flagged for the same reasons as those given for the polarized data under bit position "1" above. However, because gross errors for polarized and unpolarized data may be independent, and because the unpolarized data possess a certain immunity to interference, which tends to be polarized, the flags in bit position "1" and "2" are not necessarily coincident. As before, in the case of interference, the investigator's judgment is involved.

Bit Position "3"

This flag is set when the noise level, i.e., n in item 37 is changed during the data reduction process. This flag serves to alert the user that such a change has been made. Any discontinuity that occurs when this bit is set is likely to result from this cause. In the case of the polarized power such discontinuities are generally quite small, on the order of 1%. However, in the case of the normalized polarized power such discontinuities may be large, on the order of two. Obviously, no physical significance should be attached to such discontinuities.

Bit Position "4"

Changes in the integration bounds are flagged for reasons similar to those given under bit position "3". The bounds, B_1, B_2, vary with the changing width and location of the polarized echo. Usually, such changes are very small and their effect is not noticable in the data.

Bit Position "5"

Changes in the unpolarized noise level, $\tilde{n}$, are made for the same reasons as those described under bit position "3". As before, changes in the unpolarized power, and especially the normalized unpolarized power, that occur with these changes in $\tilde{n}$ are non-physical.

Bit Position "6"

The comments that apply to the polarized integration bounds given under bit position "4" also apply here.

Bit Position "7"

System gain changes may occur during data reception in the receiving systems or during data playback in the record reproduction system. Such changes are flagged since they will appear as a change in the polarized and unpolarized signal levels. Gain changes do not affect measures of echo bandwidths.

48. **Antenna Gain** - is the gain of the spacecraft antenna in the α_s, β_s direction determined from *this needs completing*

Where is 49?

Stanford Apollo Bistatic-Radar Experiment (S-170):
National Space Science Data Center Data Description

G. L. Tyler
H. T. Howard
G. R. Dow

February 15, 1973

Technical Report No. 3282-1

CENTER FOR RADAR ASTRONOMY
RADIOSCIENCE LABORATORY

STANFORD ELECTRONICS LABORATORIES

STANFORD UNIVERSITY · STANFORD, CALIFORNIA

STANFORD APOLLO BISTATIC-RADAR EXPERIMENT (S-170):

NATIONAL SPACE SCIENCE DATA CENTER DATA DESCRIPTION

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Contents

Introduction

The Stanford Apollo Bistatic-Radar Experiment (S-170) was carried out during the lunar orbit phase of the Apollo 14, 15, and 16 flights. The experiment was unique in that no special equipment was placed onboard the Apollo vehicles and carried to the moon, and that the principal observations were carried out on the ground. Radio-frequency transmissions from the orbiting command-service-module were directed toward the moon and received on the earth after reflection from the lunar surface. Two wavelengths, 13 cm (2287.5 MHz, S-band) and 116 cm (259.7 MHz, VHF), were used. The best data were obtained during periods when the spacecraft was maneuvered to maintain a predetermined, although changing, attitude with respect to the earth and moon. During these periods, data were obtained at the two wavelengths simultaneously. Data were also obtained at the 116 cm wavelength during periods of inertial hold and SIM bay attitude maneuvers. Data reception took place at two sites on the earth, the NASA-DSN 64 m antenna facility located near Barstow, California and the Stanford Research Institute/ Stanford University 46 m antenna facility located on the campus of Stanford University, Stanford, California. The NASA facility was used for reception of the 13 cm data, the Stanford facility for the 116 cm data. In both cases the elements of the receiving system critical to the experimental objectives were under direct control of the experimenters. At the DSN, a Signal Conditioning Unit designed and constructed at Stanford was inserted as a critical series element in the data receiving system and used to set system bandwidths, levels and timing information for the analog recording system. Input signal levels, bandwidths, and

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frequencies to the Signal Conditioning Unit from the DSN were specified
and monitored in real-time during data collection by the experimenters.
Data reduction was carried out at the Stanford Sigma 5 Real-Time Computa-
tion Facility. With two exceptions (cf. Notes on Block Diagram I, 4d,
and Appendix V) identical programs and procedures were used for 13 cm
and 116 cm data. Also, with one exception, the same programs were used
for all three flights (cf. Subtask 2). However, certain parameters, de-
fined elsewhere in the report, were varied for data at the two wavelengths.

Good data were obtained from the three flights. In the data sets
accompanying this report we include the simultaneous 13 cm and 116 cm
observations, but not the 116 cm data obtained in the inertial hold and
SIM bay attitudes. Data are given in two forms:

a) A complete set of observations reduced to short time averages
   of the electromagnetic wave spectra for the 13 cm and 116 cm
   observations. These observations have been corrected for
   instrumental effects, and are unedited. Tapes containing
   these data are referred to as JM Doptrack tapes. The
   observations have been merged with trajectory data obtained
   from the Manned Space Flight Center in Houston, and certain
   ancillary data computed from the trajectory.

b) A complete set of reduced data records, called Integral tapes,
   obtained from the JM Doptrack tapes, which describe certain
   properties of the JM Doptrack data, such as moments of the
   echo spectra, and inferred properties of the lunar surface,
   such as rms slopes.

There is one-to-one correspondence between the Integral data and the JM
Doptrack data; an interested investigator may use either the reduced
data records given on the Integral tapes, or use the JM Doptrack tapes
to verify the reduction procedure and perform additional reductions.

The remainder of this report describes the data collection and
reduction system in some detail, attempts to give cautioning notes to

the data user, and describes the tape contents and formats for JM Dop-track and Integral tapes. However, no particular attempt to explain the motivation for the overall data reduction procedures will be made, except as it affects individual steps not described elsewhere. A more general understanding of the experiment, its goals, limitations, and preliminary results may be obtained from the references listed below:

Howard, H. T. and G. L. Tyler, "Bistatic-Radar Studies of the Lunar Surface," Apollo 14 Preliminary Science Report, NASA publication SP-272, 1971.

Howard, H. T. and G. L. Tyler, "Bistatic-Radar Investigation," Apollo 15 Preliminary Science Report, NASA publication SP-289, p. 23-1, 1972.

Howard, H. T. and G. L. Tyler, Apollo 16 Preliminary Science Report, NASA publication SP-315, p. 25-1, November, 1972.

Tyler, G. L. and H. T. Howard, "Bistatic Radar Observations of the Lunar Surface with Apollos 14 and 15," paper presented at Third Lunar Science Conference, Houston, Texas, January, 1972.

Tyler, G. L. and D. H. H. Ingalls, "Functional Dependence of Bistatic Radar Frequency Spectra on Lunar Scattering Laws," J. Geophys. Res., Vol. 76, No. 20, pp. 4775-4785, July, 1971.

Synopsis of Observations

A synopsis of the observations included with this report is given in
Table I, "Stanford Apollo Bistatic-Radar Experiment Parameters." The
definitions of the columns in Table I are given below:

SPACECRAFT - Designation of flight number

ORBIT - NASA-MSC orbit numbers, counted from lunar orbit
insertion

WAVELENGTH - Either 13 cm or 116 cm, wavelength of electromag-
netic radiation from command-service-module,
corresponds to frequencies 2287.5 MHz and 259.7 MHz
respectively.

ANTENNA - Command-service-module antenna in use. Quantities
in ( ) are NASA-MSC designation. Antenna patterns
used in data reduction obtained from NAA (1966a,
1966b, 1969), and MSC (1967). Apollo 14 experiment
required compromise in spacecraft attitude to
accomodate patterns from two fixed antennas.

3 db BEAMWIDTH - One-half power antenna beamwidths

POLARIZATION - Of command-service-module antenna

GAIN - Command-service-module antenna gain

POWER - Transmitted power, from command-service-module

SYSTEM TEMPERATURE - Equivalent temperature of receiving system on the
earth, looking at cosmic background radiation
perpendicular to plane of galaxy.

TABLE I

Stanford Apollo Bistatic-Radar Experiment Parameters

SPACECRAFT	ORBIT	WAVELENGTH	ANTENNA	3 db BEAMWIDTH	POLARIZATION	GAIN[β]	POWER[γ]	SYSTEM TEMPERATURE[δ]
Apollo 14	25	13 cm	Cavity backed helix (OMNI C)	~60°	Right elliptical axial ratio ~7 db	-1.5 db	~4 W	27°K ± 3°
Apollo 14	25	116 cm	Scimitar (VHF LEFT)	α	Linear, maintained in plane of incidence	~0 db	~2.5 W	~1000°K ± 50°
Apollo 15	28	13 cm	Steerable crossed dipoles (HIGH GAIN, WIDE)	~40°	Right circular axial ratio ≲1.0 db	-1.5 db	~4 W	27°K ± 3°
Apollo 15	28	116 cm	Scimitar (VHF RIGHT)	α	Linear, varies with respect to plane of incidence	~0 db	~2.5 W	~1000°K ± 50°
Apollo 16	40	13 cm	Steerable crossed dipoles (HIGH GAIN, WIDE)	~40°	Right circular axial ratio ≲1.0 db	-1.5 db	~4 W	27°K ± 3°
Apollo 16	40	116 cm	Scimitar (VHF LEFT)	α	Linear, maintained in plane of incidence	~0 db	~2.5 W	~1000°K ± 50°

α   beamwidth of scimitar not defined
β   includes circuit losses, nominal values ± 3 db
γ   in carrier signal, nominal values, actual values not measured in flight
δ   varies with orbital position of spacecraft, cold sky values given

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Data Collection, Processing, Reduction

Block Diagram I, located at the rear of the report, depicts the flow of data through collection, processing, and reduction. Annotations and notes (circled numbers) give brief comments or descriptive titles as guides for reference. The overall data flow is divided into 11 subtasks, indicated by horizontal brackets. The remainder of the report is subdivided according to the subtasks. It is assumed that the reader has general familiarity with analog-to-digital and digital techniques for data reduction and analysis. Critical data reduction parameters are given in Table II and antenna parameters are given in Tables III and IV.

Each subtask description provides a general explanation of that subtask function. An attempt has been made to maintain independent description, with minimum reference to other functions. Highly technical details, such as magnetic tape formats and coordinate descriptions, are reserved for the appendixes. In this way a careful reading of the subtask descriptions, in connection with Block Diagram I, should provide a good overview of the data reduction process. The appendixes may be read at a later time, or for details.

A THOROUGH STUDY OF BLOCK DIAGRAM I PRIOR TO THE USE OF REPOSITORY DATA IS VERY HIGHLY RECOMMENDED.

TABLE II

STANFORD APOLLO DUAL-FREQUENCY BISTATIC-RADAR DATA SUMMARY

	APOLLO 14		APOLLO 15		APOLLO 16	
	116 cm (VHF)	13 cm (S-BAND)	116 cm (VHF)	13 cm (S-BAND)	116 cm (VHF)	13 cm (S-BAND)
Julian Ephemeris Day (00:00 UT2 Preceding Data)	2440988.5		2441164.5		2441430.5	
Reference Epoch for Coordinate Systems	2440952.509		2441317.752		2441317.752	
CALENDAR DATE	February 6, 1971		August 1, 1971		April 23, 1972	
Orbit Number (From Lunar Orbit Insertion)	25		28		40	
Transmitter Frequency	259.7 MHz	2287.5 MHz	259.7 MHz	2287.5 MHz	259.7 MHz	2287.5 MHz
UT2 START/STOP TIME	06:37:17/07:30:34	06:38:30/07:32:28	01:23:00/02:23:58	01:16:30/02:29:00	01:16:30/02:16:26	01:17:00/02:27:05
Spacecraft Antenna (MSC Designation)	VHF LEFT	OMNI C	VHF RIGHT	HIGH GAIN (WIDE)	VHF LEFT	HIGH GAIN (WIDE)
High Gain Antenna Pointing Angles						
α	-	-	-	144.°	-	145.°
β	-	-	-	122.°	-	302.°
Data Source	Stanford 10.003 MHz i.f. rcvr	DSN/STANFORD Closed Loop rcvr	Stanford 10.003 MHz i.f. rcvr	DSN/STANFORD Closed Loop rcvr	Stanford 10.003 MHz i.f. rcvr	DSN/STANFORD Closed Loop rcvr
Receiver Bandwidth	~3.5 kHz	~20.0 kHz	~3.5 kHz	~20.0 kHz	~3.5 kHz	~20.0 kHz
Data Sampling Frequency	10.0 kHz	43.0 kHz	10.0 kHz	43.0 kHz	10.0 kHz	43.0 kHz
Total Analysis Bandwidth	5.0 kHz	21.5 kHz	5.0 kHz	21.5 kHz	5.0 kHz	21.5 kHz
N, Number of Analysis Bins	1024	1024	2048	1024	2048	1024
Analysis Resolution	9.8 Hz	42.0 Hz	4.9 Hz	42.0 Hz	4.9 Hz	42.0 Hz
Length of Data Window/Transform	0.1024 sec.	0.02381395 sec.	0.2048 sec.	0.02381395 sec.	0.2048 sec.	0.02381395 sec.
L, Number of Transforms Averaged per JM Record (see Subtask 4)	26	100	23	99	23	99
Frame Length	2.6624 sec.	2.381395 sec.	4.7104 sec.	2.357581 sec.	4.7104 sec.	2.357581 sec.

TABLE III

Stanford Research Institute 46 m Antenna Performance (116 cm)

Aperture	Efficiency	Feed System	Mount	Pointing Loss
46 m dia.	~35% ±5%	Crossed dipole array axial ratio ~1. db ± 0.5[α] isolation ~16 db ± 1.0	el/az	< 0.1 db

TABLE IV

NASA DSN 64 m Antenna Performance (13 cm)[*]

Aperture	Efficiency	Feed System	Mount	Pointing Loss
64 m dia.	58% ±4%	Waveguide horn axial ratios $\gtrsim$ 0.8 db[β] isolation $\lesssim$ 26 db[γ]	el/az	< 0.03 db

---

[α] estimated

[β]
[γ] } Private communication, D. Bathker, JPL, 1973.

[*] <u>DSN</u>, 1972

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Subtask 1

Data Collection

a) 116 cm. A detailed block diagram of the 116 cm receiver is given in Appendix I. The receiver is a super-heterodyne of standard design. An unusual feature of this system is the summed second local oscillator signal used to produce offset 9.0 and 10.003 MHz intermediate frequency signals. In operation, the 10.003 MHz channel was tuned to the downlink signal carrier and its accompanying echo, while the 9.0 MHz channel was tuned to the subcarrier signal displaced $\pm$ 31.6 KHz from the 259.7 MHz carrier. This procedure was adopted to provide frequency dispersive redundancy against locally generated interference at the main carrier frequency. The receiver passband characteristics are given in Appendix II. However, all data given here were obtained through the main 10 MHz channel. Receiver outputs were multiplexed with standard frequency references and clock signals and recorded on analog tape. Parameters of the Stanford Research Institute 46 m dish are given in Table III.

(b) 13 cm. A detailed block diagram of the 64 m 13 cm receiving system is given in Appendix II. Again, standard superheterodyne techniques are employed. All 13 cm data were obtained from a phase-locked loop signal tracking system using manual tracking when the direct signal dropped below threshold of the phase-locked loop. The receiver passband characteristics are given in Appendix III. The NASA-DSN station configuration for this experiment is given elsewhere (DSN, 1970, 1971). Again, analog signals from the receiver output multiplexed with clock and reference frequencies were recorded. Parameters of the NASA DSN 64 m dish are given in Table IV.

Subtask 1 (cont.)

(c) Critical Bandwidths. Appendix III gives the power spectral
    densities obtained at the receiver outputs for the three
    Apollo experiments with uniform power spectrum (white)
    noise input. These curves were obtained in Subtask 4,
    and were used in the data normalization. For the 116 cm
    system additional checks made with coherent signals within
    $\pm$ 5 MHz either side of the 10 MHz intermediate frequency
    and within $\pm$ 20 MHz of the first intermediate frequency
    verified the absence of spurious responses that would not
    be detected by the noise calibration technique. Similar
    tests have been carried out by the DSN and the experimenters
    at the 64 m facility. Thus, the curves in Appendix III
    accurately represent the receiver response to signals near
    the frequency to which the receivers were tuned. Image
    rejection in the 116 cm system was greater than 100 db.

Subtask 2

Sampling

Data sampling was carried out using standard techniques
on the Stanford Sigma 5 Real-Time Computation Facility.
Right circular and left circular polarization signal
channels were sampled simultaneously in synchronism with
the multiplexed time reference signals. Sampling was
initiated at the start of an even 10 sec. interval (UT2)
by a start pulse derived from the recorded time code.
The sampling programs were improved between the Apollo 15
and 16 experiments to obtain higher playback rates for the
13 cm data (see Block Diagram I, Notes, 4d). With this
exception, the same computer programs were used for data
reduction from the three sets of observations. A small
overlap was provided between subsequent sample data tapes.
These overlaps were carried through the remainder of the
data processing. Tape recorder playback levels were
adjusted for equality between left circular and right
circular polarization using the controlled reference
signal levels for calibration. The playback recorder
electronics were equalized for the particular tape source
(FR1400 A, FR1400 B, HP3955B) prior to sampling data from
that source. Output from the data sampling process was
stored on magnetic tape. The quantization level was 8 bits.
The ith data sample generally will be denoted $\hat{d}_i$: data
from the left circularly polarized antenna $_1\hat{d}_i$, data from
the right circularly polarized antenna $_2\hat{d}_i$.

Conversion to Frequency Domain

All data have been rendered in the frequency domain in the form of modified complex Fourier coefficients (Blackman and Tukey, 1958). A sequence of data samples was multiplicatively weighted with a sine-squared (Hanning) data window and then Fourier analyzed using fast Fourier transform techniques. Analytically, the data samples were grouped, separately for each polarization, according to

$$d_j^n = \hat{d}_i, \tag{1}$$

where $i = nN + j$, $j \le N$; n, N, j positive integers or zero. The modified complex Fourier coefficients are

$$f_k^n = \sum_{j=0}^{N-1} \sin^2\left(\frac{2\pi}{N} j + \frac{\pi}{N}\right) d_j^n \, e^{-i(2\pi/N)jk}, \tag{2}$$

where $i = \sqrt{-1}$, $0 \le k \le N-1$. In the Apollo data reduction programs, N was either 1024 or 2048 (see Table II). Each set of coefficients corresponds to a time interval $T = N \cdot (\text{sampling interval})$ (see Table II for values). The outputs of the transformation are the f_k^n above.

Generation of Coherency Matrix

The coherency matrix (Born and Wolf, 1959) was determined directly from the f_k^n by forming the summed products

$$
\begin{bmatrix}
\sum\limits_{n=1}^{L} |{}_1 f_k^n|^2 & \sum\limits_{n=1}^{L} {}_1 f_k^n \; {}_2 f_k^{n*} \\[2em]
\sum\limits_{n=1}^{L} {}_1 f_k^{n*} \; {}_2 f_k^n & \sum\limits_{n=1}^{L} |{}_2 f_k^n|^2
\end{bmatrix}
\tag{3}
$$

where $*$ denotes complex conjugate. Each sum is a function of the frequency index k. In order to compensate for the non-uniform effects of the receiving system filters, we further form

$$
{}_1\hat{q}_k^2 = \langle {}_1 q_k^2 \rangle = \sum_{n=1}^{M} |{}_1 q_k^n|^2
$$

$$
{}_2\hat{q}_k^2 = \langle {}_2 q_k^2 \rangle = \sum_{n=1}^{M} |{}_2 q_k^n|^2
\tag{4}
$$

where $q_k^n = f_k^n$ for periods with signal absent. The $\hat{q}_k^2$ are the receiving system output power spectra for a noise input. The upper bound M was chosen to reduce the fluctuations in $\hat{q}_k^2$ to a small value. Typically $M \stackrel{\sim}{<} 10^4$, for which $\hat{q}_k^2$ is determined to approximately one percent. The coherency matrix, corrected for receiver power transfer characteristics is

$$
\underline{J}_k =
\begin{bmatrix}
J_{11} & J_{12} \\
J_{21} & J_{22}
\end{bmatrix},
\tag{5}
$$

Subtask 4 (cont.)

where

$$J_{11} = \frac{1}{\hat{q}^2} \sum_{n=1}^{L} |_1 f_k^n|^2$$

$$J_{22} = \frac{1}{2\hat{q}_k^2} \sum_{n=1}^{L} |_2 f_k^n|^2 \tag{6}$$

$$J_{12} = \frac{1}{1\hat{q}_k \, 2\hat{q}_k} \sum_{n=1}^{L} {}_1 f_k^n \, {}_2 f_k^{n*}$$

$$J_{21} = J_{12}^* \, .$$

The fractional polarization of the received signal may be computed directly from the $\underline{J}_k$ as

$$\gamma_k = \left\{ 1 - \frac{4 \ \text{Det} \ \underline{J}_k}{\text{Trace}^2 \ \underline{J}_k} \right\}^{1/2} \tag{7}$$

Again γ_k is a function of the frequency index k. The output of Subtask 4 consists of the spectra $\underline{J}_k$, γ_k. The parameters L and N used in the reduction of the several sets of observations are included in Table II. Completion of the $\underline{J}_k$ (Subtasks 2, 3, and 4) represented the greatest portion of the computational expense for this experiment. Additional results may be obtained directly from $\underline{J}_k$ and γ_k. For example, the power in the polarized and unpolarized parts of the echo is:

Subtask 4 (cont.)

polarized power $\qquad P_p(k) = \gamma_k \cdot \text{Trace } \underline{J}_k$

$$(8)$$

unpolarized power $\qquad P_{\bar{u}}(k) = (1-\gamma_k) \cdot \text{Trace } \underline{J}_k \; .$

Other parameters of the echo spectra may be obtained simi-
larly (<u>Born and Wolf</u>, 1959; Appendix 10).

Correction for System Polarization Parameters

The quantities $\underline{J}_k$ and V_k discussed in the previous section under Subtask 4 were derived directly from the sample data as they came from the analog tapes. As discussed under Subtask 4 certain corrections have been made for the receiver filter characteristics. However, the data were treated as though they were derived from perfect antennas. That is, the antennas were assumed to consist of a pair of right and left circularly polarized elements. It was further assumed that, with the exception of the filter corrections already applied, the gains in the two receiver channels were equal. In the case of the 13 centimeter data this assumption was very good. The isolation of the DSN 64 m antenna has been measured as > 26 db with an axial ratio of $\tilde{<} 0.8$ db (private communication, D. Bathker, JPL, 1973). At 116 cm the properties of the SRI 46 m antenna are not nearly so well known. Polarization of the 46 m antenna was controlled principally through the constraints applied to the construction of the feed system. The feed system consisted of a crossed dipole array of linear elements connected through a standard hybrid to obtain a circular polarization. The array elements were mechanically and electrically identical. The hybrid combiner and associated phase shift elements were adjusted to within 1° and 1 db of the ideal transfer function for such a device. Coupling between the orthogonal linear array elements was less than 40 db with the feed removed from the dish. Cross-coupling between the two circular polarizations, observed at the hybrid output with the feed in place at the focus of the dish, was 16 db. We were unable to measure the axial ratio of the overall system with the feed in place in the dish. We estimate axial ratio of the 116 cm system as approximately 1 db for either polarization. For certain received polarizations axial ratios

of this magnitude can introduce significant errors
in the calculation of fractional polarization.
Consequently, a correction for this uncertainty was applied
in Subtask 5. This correction was applied to the 116 cm
Apollo 14 and 16 data only. The output tapes from Subtask
5 preserve the original J_{-k} computed earlier.

The corrections were determined as follows (cf Tyler, 1970).
Consider the signals arriving at the antenna terminals in
terms of their right and left circularly polarized compo-
nents, which we will denote E_r, E_1, respectively. The
relationship between the arriving signals and the signals
at the antenna terminals may be expressed as a matrix
multiplication

$$
\begin{bmatrix} E_r' \\ E_1' \end{bmatrix} = \begin{bmatrix} c_{11} & c_{12} \\ c_{21} & c_{22} \end{bmatrix} \begin{bmatrix} E_r \\ E_1 \end{bmatrix} \qquad (0)
$$

where the c's are complex and arbitrary. The matrix
elements may be thought of as the transmission coefficients
of the four port network consisting of pairs of antenna
elements and terminals. Physically, the c's may represent
attenuation, gain, and cross-coupling. In an ideal system
$c_{11} = 1$, $c_{12} = c_{21} = 0$, $c_{22} = 1$.

The effect of such a transformation on the coherency matrix $\underline{J}$ is easily shown to be

$$
\begin{bmatrix} J'_{11} \\ J'_{12} \\ J'_{21} \\ J'_{22} \end{bmatrix}
=
\begin{bmatrix}
|c_{11}|^2 & c_{11}c_{12}^* & c_{11}^*c_{12} & |c_{12}|^2 \\
c_{11}c_{21}^* & c_{11}c_{22}^* & c_{12}c_{21}^* & c_{22}^*c_{12} \\
c_{11}^*c_{21} & c_{21}c_{12}^* & c_{22}c_{11}^* & c_{22}c_{12}^* \\
|c_{21}|^2 & c_{22}^*c_{21} & c_{22}c_{21}^* & |c_{22}|^2
\end{bmatrix}
\begin{bmatrix} J_{11} \\ J_{12} \\ J_{21} \\ J_{22} \end{bmatrix}
\qquad (10)
$$

where $\underline{J}'$ is the coherency matrix of the wave associated with $\underline{J}$ observed at the antenna terminals. The k subscripts have been suppressed for convenience. However, it is assumed that the c's are independent of frequency over the spectrum of interest. Given $\underline{J}'$ and the c's, the original $\underline{J}$ may be recovered through an inverse matrix manipulation. In the present case $\underline{J}'$ is observed, but the c's are unknown.

The c's may be estimated from an observation of an unpolarized signal (Tyler, 1970). System noise inputs to the 116 cm receiver system were used to estimate the c's and perform a correction. The method was based on an experimenter selection of these portions of the receiver output spectrum that contained only receiver noise. If it is assumed that the noise input is unpolarized, then

$$
J'_{11} = (|c_{11}|^2 + |c_{12}|)^2\, J_o
$$

$$
J'_{12} = (c_{11}c_{21}^* + c_{22}^*c_{12})\, J_o
$$

$$
J'_{21} = J'^*_{12} \qquad\qquad (11)
$$

$$
J'_{22} = (|c_{21}|^2 + |c_{22}|^2)\, J_o,
$$

Subtask 5 (cont.)

where

$$J_o = k\, T_{sys}/2$$

$$k = 1.38 \times 10^{-23} \text{ (Joules/deg. Kelvin)} \quad (12)$$

$$T_{sys} = \text{system temperature.}$$

The signal will appear unpolarized if

$$J_{12}' = 0 \text{ and } J_{11} = J_{22}$$

or

$$c_{11}c_{21}^* = -c_{22}^* c_{12} \qquad (13)$$

and

$$|c_{11}|^2 + |c_{12}|^2 = |c_{21}|^2 + |c_{22}|^2 ,$$

from which the required inverse transformation can be
obtained. In practice, a numerical estimate of the
correction matrix was obtained as described above. This
estimate was then used as a starting point in a search to
find the c's which minimized the apparent polarization of
the corrected J_k' in the noise portions of the spectrum.
The corrections in the form just described were then used
to compute the corrected J_k' for the entire spectrum. A
corrected fractional polarization γ_k' based on J_k' was then
obtained.

The output tapes from Subtask 5 contain the <u>original</u> J_k
and the <u>new, corrected</u> γ_k'. A data user may easily
recompute the original γ_k from the J_k which have been pre-
served and which are available on the tapes supplied
(see Subtask 6, Appendix IV). The correction factors
employed in the generation of the γ_k' are given in
Appendix VIII.

Subtask 5 (cont.)

In summary, steps in this subtask are:

a) Read $\underline{J}_k$ source tapes from Subtask 4

b) Determine elements of the correction matrix based on minimization of the polarized part of the noise.

c) Compute γ'_k.

d) Generate new tape containing the <u>original</u> $\underline{J}_k$ and <u>new</u> γ'_k.

This process was applied to the Apollo 14 and 16 116 cm data: 13 cm data are uncorrected, i.e., for 13 cm data $\gamma'_k = \gamma_k$. In subsequent steps the γ'_k were used in all computations of the polarized and unpolarized parts of the 116 cm echo spectrum.

Merging Observations with Trajectory

The output of Subtask 5, the $\underline{J}_k$, γ_k' tapes, represents the experimenter's best estimate of the received spectra, averaged over the time intervals previously defined: that is, a complete second order description of the received echo signal. In the present step this data, which was previously processed without regard to lunar coordinates or other geophysical considerations, was combined with the Apollo command-service-module ephemeris. The emphemeris was first interpolated to the mid-point of the averaging period used in the computation of the $\underline{J}_k$, then certain ancillary quantities were computed. The interpolated ephemeris and the derived quantities were then merged with the experimental data to form a basic set of source tapes designated JM Doptrack. After further processing in Subtask 10, these tapes became the primary source tapes supplied with this report to the NSSDC.

The ephemeris based quantities added to the observational data were:

a) Time corresponding to mid-point of averaging period

b) Predicted difference between reflected and direct doppler shifts

c) Predicted echo bandwidth for a moon with rms slope of 0.1

d) Angle of incidence on mean spherical moon

e) Spacecraft altitude above mean spherical surface

f) Speed of the spacecraft

g) Bistatic-radar cross-section of a smooth, perfectly conducting, spherical moon for the current spacecraft-moon-earth geometry

h) Normalized signal strength for a conducting moon and instantaneous geometry

i) Spacecraft position in selenographic coordinates

j) Specular point position on a mean spherical lunar surface in selenographic coordinates

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k) Selenographic latitude and longitude of space-craft position

l) Doppler shift due to rotation of the earth

m) Total doppler shift of the reflected signal

n) Selenographic latitude and longitude of specular point on the mean spherical lunar surface

o) Speed of the specular point on the mean lunar surface

p) Look angles to earth in spacecraft coordinates

q) Euler angles of spacecraft attitude in local horizon system

r) Selenographic unit velocity vector of spacecraft

s) Selenographic unit vector location of earth.

These tapes are organized in groups of six data records, referred to as a data frame, corresponding to each time interval. A complete description of the JM Doptrack tape formats and contents is given in the appendixes (see Appendix IV).

Computation of Polarized and Unpolarized Parts, Carrier Suppression

JM Doptrack tapes contain spectrally analyzed 13 cm and 116 cm receiver outputs. No provision was made within the receivers or Subtasks 2, 3, 4, 5, or 6 for removal of the directly propagating telemetry carrier from the echo data. In terms of the polarization parameters, this signal cannot be removed completely. However, much of the data analysis is based only on the low order moments of the polarized part of the echo. Subtask 7 computed polarized and unpolarized spectra from relation (8), Subtask 4, then used an empirically derived algorithm to remove the carrier signal from the polarized spectra; these data together with the ephemeris data described in Subtask 6 constitute the intermediate data set generated by Subtask 7. The algorithm for carrier suppression is described in Appendix V. Carrier suppression was also applied to unpolarized data. However, the carrier was largely suppressed in those data by coherency matrix processing, since it was a polarized signal. The output of this subtask, the P tapes, contain the experimenter's best estimate of the power spectra of the polarized and unpolarized components of the echo signal.

Computation of Total Received Power, Echo Moments

Inputs to this subtask were the polarized and unpolarized power spectra derived from the JM Doptrack source tapes (Subtasks 6, 7). The purpose of Subtask 8 was to derive numerical measures of the echo spectra. Certain measures of the echo spectra were corrected for predictable trajectory effects and converted into scientific units. In all cases, the designation of the echo signal location in a spectrum was made by the experimenter's visually scanning plots of the polarized and unpolarized power spectra. The values of the k indices bounding the echo were input to a computer program that did the actual data reduction. An average noise level, determined from a region of the spectra not containing echo, was also input to the computer program. The data were monitored at approximately 30 sec. intervals and the echo limits reset to account for motion of the echo in the receiver passband. It was also necessary to occasionally reset the noise level as it also varied during the experiment, principally due to the scan of the receiving antenna across the lunar terminator. The derived quantities are given below:

a) Polarized echo power -- the integral of the polarized power spectra between the frequency limits set by the experimenter and above the system noise level. This quantity is the best measure of the polarized echo power received.

b) Normalized polarized echo power -- the quantity described in a) above, divided by the polarized system noise level.

c) Unpolarized echo power -- the integral of the unpolarized power spectra between the frequency limits set by the experimenter and above the system noise level. This quantity is the best measure of the unpolarized echo power received.

d) Normalized unpolarized echo power -- the quantity described in c) above, divided by the unpolarized system noise level.

e) Equivalent area bandwidth -- the bandwidth of the polarized echo signal between the frequency limits set by the experimenter and above the polarized system noise level as determined by the ratio of the total polarized echo power to the peak polarized echo power.

f) Normalized absolute moment bandwidth -- the bandwidth of the polarized power echo as described in e) above, computed from a gaussian equivalent absolute moment, and divided by e).

g) Normalized second moment bandwidth -- the bandwidth of the polarized power echo as described in e) above, computed from a gaussian equivalent second moment, and divided by e).

h) Centroid of echo spectrum -- the centroid of the polarized power echo as described in e) above.

i) RMS slope -- the rms slope of the lunar surface inferred from the value of e) above and the predicted bandwidth for an rms surface slope of 0.1, using linear interpolation.

Formulas for the computation of the above quantities and a brief explanation of their use may be found in Appendix VI. The trajectory data added in Subtask 6 were retained throughout this subtask. A simple correspondence between the output of this subtask and the JM Doptrack tapes was maintained through inclusion of ephemeris data in both data sets.

Final Editing of Data

Final editing of the output from Subtask 8 resulted in a set of reduced data records designated Integral tapes. These tapes constitute the second form of data supplied to the NSSDC.

Final editing of data included the following steps:

a) Addition of hand-scaled bandwidths as a partial independent check on Subtask 8 (see Subtask 10).

b) Addition of spacecraft antenna gain in the direction of specular reflection.

c) Notation of operational or data processing changes

  i) Polarized band bad

  ii) Unpolarized data bad

  iii) Change in polarized noise level

  iv) Change in polarized k indices for echo limits

  v) Change in unpolarized noise level

  vi) Change in unpolarized k indices for echo limits

  vii) Change in system gain

Caution: Some integral data, primarily at the beginning or end of a transmission, have been deleted. Large overlaps in the 13 cm data caused by the use of two analog tape recorders have also been deleted. In all other cases bad data, for example when interference is present, are flagged on the edited Integral tapes as described in c) above (see Appendix VI, E47). The data contained on the Integral tapes are still the experimenter's best estimates of the values. However, in the case of flagged data, that estimate may be very poor. No flagged data should be used without examining the spectra on the corresponding JM Doptrack tapes. For example, in the 116 cm data occasional interference produced marked increases in the apparent polarized echo power, but evidently left the unpolarized

power unaffected. A flag for polarized power thus may also cast suspicion on the unpolarized power. The experimenters have evaluated these cases and indicated their opinions accordingly in the data. Other individuals may arrive at different conclusions. It is primarily for this reason that the JM Doptrack/Integral tape frame-to-record correspondence (through ephemeris data) has been maintained: reduced data records on the Integral tapes may, if questioned, be re-evaluated from the JM Doptrack source tapes. A complete description of the Integral tape formats and the flags is given in Appendix VI.

Displaying, Scaling, and Copying the Data

Output from Subtask 6, the JM Doptrack tapes, is used in miscellaneous programs in preparation for data analysis and distribution. An important step in producing the final Integral tapes (Subtask 9) took place here. Polarized power spectra obtained from JM Doptrack tapes are computer plotted and visually examined to determine specifically

a) proper receiver operation

b) proper receiver tuning

c) presence of interference.

Such plots are also used to determine the one-half power, hand-scaled bandwidths added to the data set in Subtask 9. This bandwidth is determined by measuring the width of the polarized echo spectrum at a point one-half the distance from the apparent system noise level to the mean echo peak. The measured distance is scaled by the appropriate factor to determine the width in Hertz. Such measures can be related to the rms slope of the lunar surface from the quasi-specular scattering theory (see Appendix VI). The hand-scaled values are used to verify the machine algorithms used in computing lunar rms slopes and as a simple means of quickly estimating the slope.

Finally, this subtask included copying of the JM Doptrack tapes for shipment to the NSSDC. These tapes were not edited.

Utility Routines

Integral tapes have been organized as a sequence of records describing the data and experimental geometry at successive instances of time. It is then a simple matter to determine any set of variables from this tape with time as a parameter. We suggest that data users consider this data as a set of dependent functions parameterized in time and hope that such a presentation is found useful.

Stanford Apollo 116 cm (VHF) Bistatic-Radar Receiving System:
Major Elements
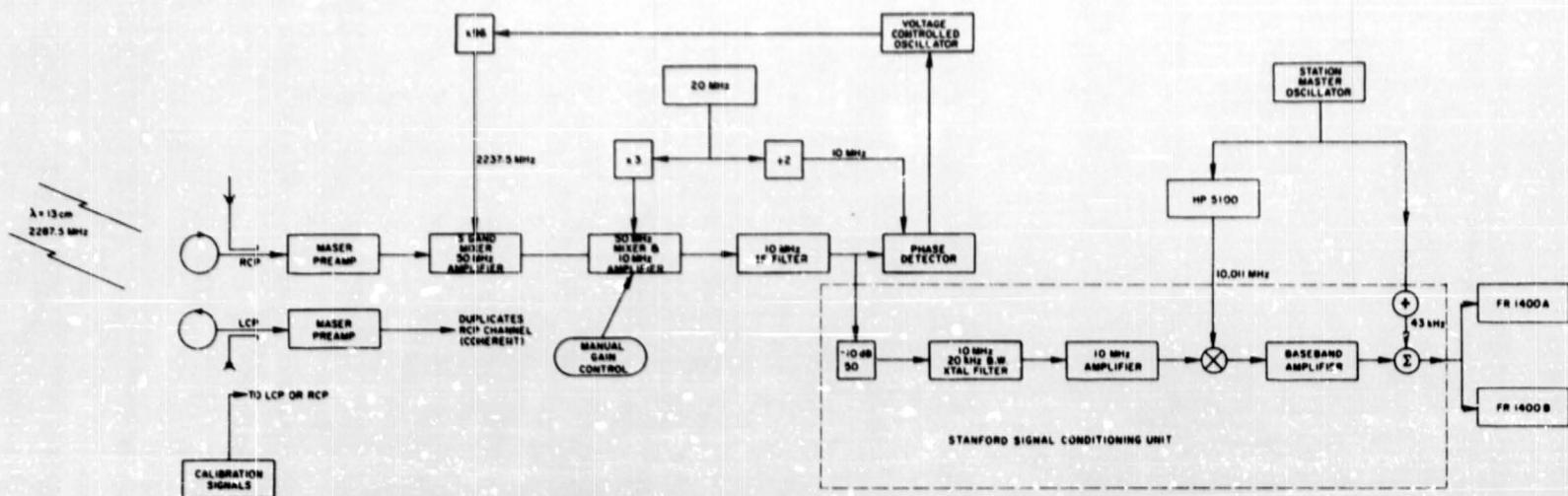
Stanford Apollo 13 cm (S-Band) Bistatic-Radar Receiving System:
Major Elements

| 0 Hz | CHANNEL 0 | 5000 Hz |

| 0 Hz | CHANNEL 1 | 5000 Hz |
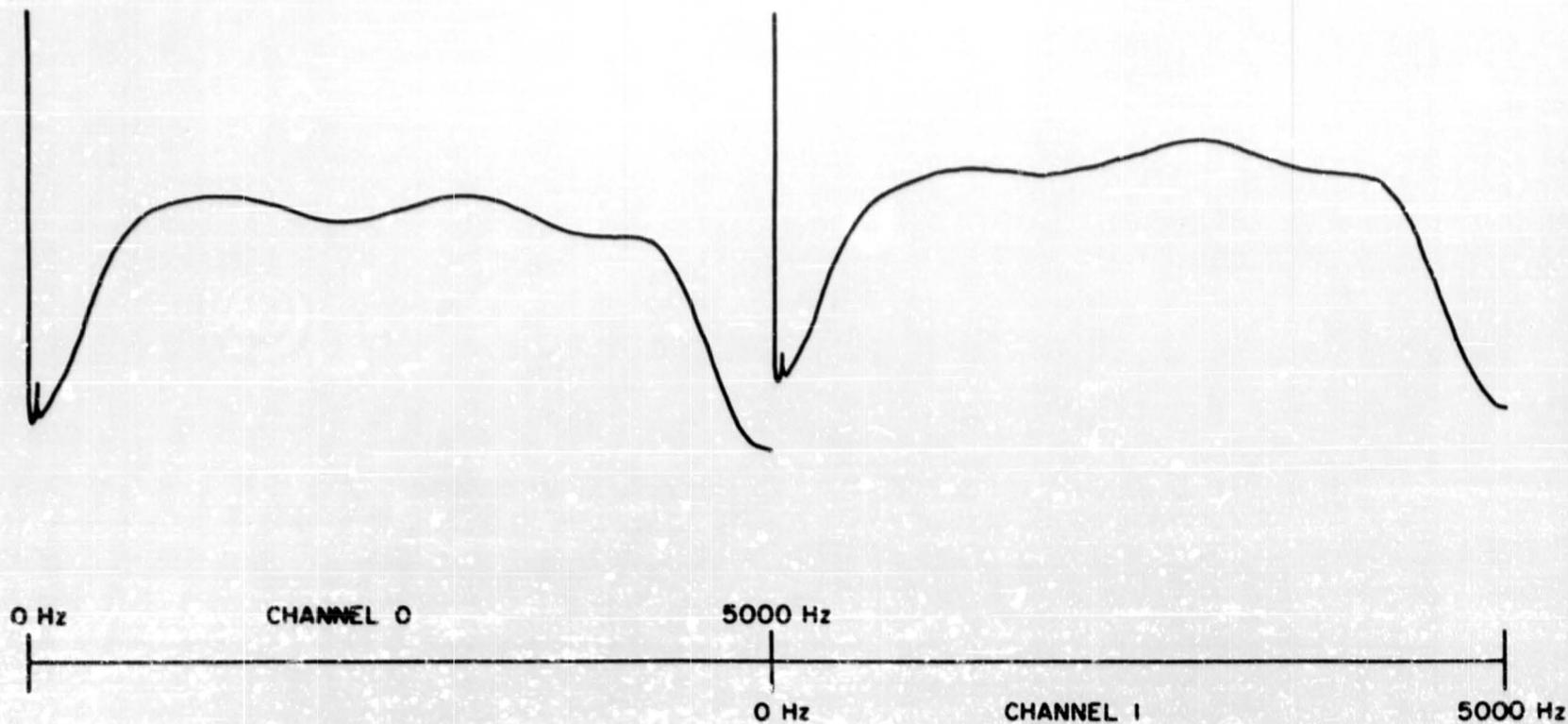
Apollo Bistatic-Radar Receiving System
116 cm Uncorrected Frequency Response

0 Hz	CHANNEL 0	21500 Hz	

Apollo Bistatic-Radar Receiving System
13 cm Uncorrected Frequency Response

Appendix IV

JM Doptrack Tape Formats

This appendix describes the tape formats for the JM Doptrack Tapes generated in Subtask 6 of the text. Tapes are 9 track, binary in XDS Sigma 5 machine images[α]. These tapes contain the output of the polarimeter in Subtask 4, the corrected fractional polarization obtained from Subtask 5, MSC trajectory data, and certain ancillary quantities computed at Stanford. All records within the given file are the same length. There may be more than one tape per file. Files are identified by a header record which contains a brief description of the file contents. This appendix describes the tape organization, the file organization, and the record formats for the JM Doptrack tapes. Definitions of the tape contents are either given here or described by reference.

A. File Organization

File	No. Tapes	Contents	Record Length
1	1	Apollo-14 116 cm	514 words
2	1	Apollo-14 13 cm	514 words
3	1	Apollo-15 116 cm	1026 words
4	2	Apollo-15 13 cm	514 words
5	1	Apollo-16 116 cm	1026 words
6	2	Apollo-16 13 cm	514 words

B. File Organization

1. Header Record

2. Data Record 1
   Data Record 2
   Data Record 3 } Observational Data } Data Frame
   Data Record 4
   Data Record 5
   Data Record 6 Ephemeris Data

   ⋮
   < Many Data Frames >
   ⋮

3. EOF (End of File Mark)

[α]See Appendix XI for a description of Sigma 5 machine images.

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If more than one tape was needed to contain the JM Doptrack
file, the file was continued across the end of the tape to the
next tape without interruption; there is only one header record
per file, at the beginning of the first tape of the file.

Once again, even though the files are physically nothing more
than a continuous string of records, all of equal length, it
is helpful to think of them (see figure below) as being composed
of a header record followed by groups (frames) of six records.
The ephemeris data record concludes the frame and, since each
JM data frame is a short-time average, the ephemeris data have
been calculated using the midpoint of the frame as the instan-
taneous time reference point.

JM Doptrack File Containing N Data Frames

Rec. No.:	1	2	3	4	5	6	7
Header Record	Data Rec. 1	Data Rec. 2	Data Rec. 3	Data Rec. 4	Data Rec. 5	Eph. Rec. 6	Data Rec. 1

DATA FRAME 1

8	9	10	11	12	13	14	15
Data Rec. 2	Data Rec. 3	Data Rec. 4	Data Rec. 5	Eph. Rec. 6	Data Rec. 1	Data Rec. 2	Data Rec. 3

DATA FRAME 2   DATA FRAME 3

6N-1	6N	
Data Rec. 5	Eph. Rec. 6	EOF

DATA FRAME N

35
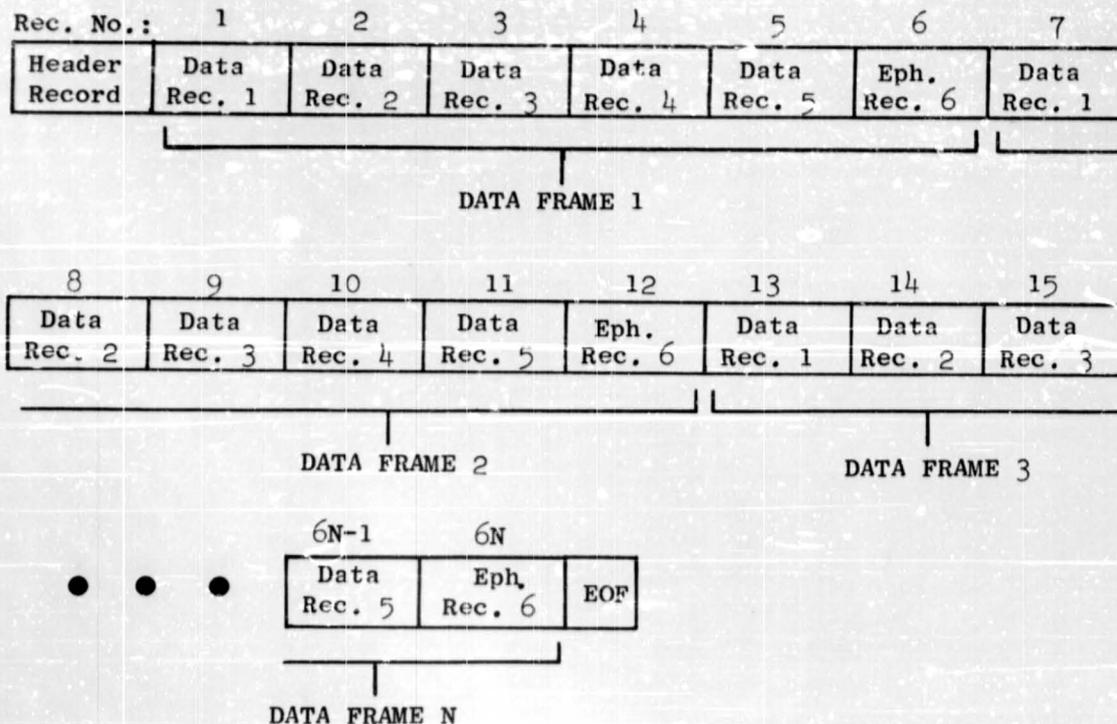
Appendix IV (cont.)

C. Header Record Formats

Word No.	Contents	Units	Machine Type[α]
1-42	Alphanumeric file identifier	--	A
43	Day of year on which data were collected (January 1 = 1)	(days)	I
44	Year data were taken (Gregorian)	(year)	I
45-46	Julian Ephemeris Day at 00:00 UT2 on the day the data were taken	(days)	DPR
47-48	Julian Ephemeris Day of reference epoch	(days)	DPR
49	Time increment between centerpoint of data averaging frame	(sec)	R
50	Number of data records following this header record (Number of data frames = number of data records divided by 6)	--	I
51-514/1026	Not used		

D. Data Frame Formats

1. Data Record Organization

Record No.	Contents	Note:
1	$J_{11}(k)$	**116 cm data**
2	$J_{22}(k)$	$J_{11}(k)$ - Left circular polarization
3	Real part of $J_{12}(k)$	
4	Imaginary part of $J_{12}(k)$	$J_{22}(k)$ - Right circular polarization
5	$\gamma(k)$	
6	Spacecraft ephemeris and ancillary data	**13 cm data**
		$J_{11}(k)$ - Right circular polirization
		$J_{22}(k)$ - Left circular polarization

[α]A - Alphanumeric
I - Integer
R - Real
DPR - Double Precision Real

D. 2. Format Records 1-5 (all machine type <u>real</u>)[1]

Record No.	Contents
1-513/1025	Data described under D.1 above
514/1026	Meaningless

3. Format Record 6 (all machine type <u>real</u>)

Word No.	Contents	Units
1	Meaningless	
2	UT2 at midpoint of frame	(sec)
3	Reflected doppler minus direct doppler	(Hz)
4	Predicted bandwidth for rms surface slope of 0.1	(Hz)
5	Angle of incidence	(deg)
6	Spacecraft altitude (mean lunar radius assumed 1736 km)	(km)
7	Spacecraft speed	(m/sec)
8	Radar cross section predicted for smooth conducting moon	(dim)
9	(Radar cross section)/ (received power)	(m^2/w)
10	X ⎫ Components of seleno-	
11	Y ⎬ graphic unit position vector of spacecraft	
12	Z ⎭ location	(dim)
13	X ⎫ Components of seleno-	
14	Y ⎬ graphic unit position vector of specular	
15	Z ⎭ point location	(dim)
16	Selenographic latitude of subspacecraft position	(deg)
17	Selenographic longitude of subspacecraft position	(deg)
18	Component of doppler shift due to earth rotation	(Hz)

[1] Due to a hardware problem in the data processing, words 1-15 are zero in the Apollo-14, 116 and 13 cm, and Apollo-15 13 cm files.

D. 3. Format Record 6 (all machine type <u>real</u>) (cont.)

Word No.	Contents	Units
19	Total doppler shift of reflected signal	(Hz)
20	Selenographic latitude of specular point	(deg)
21	Selenographic longitude of specular point	(deg)
22	Speed of specular point on the lunar surface	(M/sec)
23	α_e ⎫ Vehicle look angles	
24	β_e ⎬ to earth	
25	θ ⎫	
26	ψ ⎬ Euler angles of local horizon coordinates	(deg)
27	φ ⎭	
28	X ⎫	
29	Y ⎬ Spacecraft selenographic unit velocity vector	(dim)
30	Z ⎭	
31	X ⎫ Selenographic unit	
32	Y ⎬ vector from center of moon to center of	
33	Z ⎭ earth	(dim)
34-514/1026	Not used	

Note: Data do not always progress uniformly in time. Occasionally, data frames will reverse in time for one frame, and then continue forward. This effect is caused by the sampling procedure in which deliberate overlap was inserted. Time on data is correct.

E. Definition of Contents

1. Data -- defined under Subtasks 4 and 5 of the text.

2. Ephemeris and Ancillary Data -- described in greater detail in Appendix VI.

Appendix V

Carrier Suppression Algorithm

This appendix describes the algorithm used to remove the direct signal from the polarized and unpolarized parts of the bistatic-radar echo spectrum (see Subtask 7). This algorithm was used on each frame of polarized and unpolarized data which the JM Doptrack tapes yield according to relation (8), Subtask 4. Two slightly different procedures were used for the 116 cm and 13 cm data. These differences constituted the only difference in procedure between the 116 cm and 13 cm data. Both data sets were processed by the same computer program, with different program branches for the two cores. The direct signal observed at 13 cm was free of spurious sidebands to the level of our observations. At 116 cm, the direct signal contained two weak sidebands symmetrically displaced approximately 20 db below the direct signal. Consequently, during periods of strong direct signal at the 116 cm wavelength, it was also necessary to correct for the presence of these sidebands. The procedures described below were developed empirically but were found to give good results. The approach was to find the maximum of the power spectrum and to assume that this maximum represented the direct signal. This assumption was tested by determining the height of the maximum with respect to the fluctuations in the spectrum in the immediate vicinity of the maximum. If the maximum exceeded the fluctuation criteria then an interpolation procedure was used to provide a smoothed estimate of the spectrum. In the case of the 116 cm data, sideband suppression was achieved by reducing the local maximum on either side of the direct signal by an amount proportional to the strength of the direct signal. A detailed summary of this procedure is given below.

Initial Test

1. Find the absolute maximum of all the data, MAX (see figure which follows).

2. Find the adjacent local maxima, MAX12 and MAX34.

3. Test MAX to determine whether or not it represents the direct signal.

   i) $SUM = \dfrac{MIN1 + MIN2}{8} + \dfrac{MAX12}{4} + \dfrac{MIN3 + MIN4}{8} + \dfrac{MAX34}{4}$

Initial Test (cont.)

    ii)   CRIT = 1.2·SUM

    iii) (MAX.LT.CRIT) $\Rightarrow$ no direct signal present, terminate procedure; go to next frame, initial test 1.
          (MAX.GE.CRIT) $\Rightarrow$ direct signal present, continue.

4. Check data type. If data is 116 cm then go to step 8, otherwise continue with step 5.
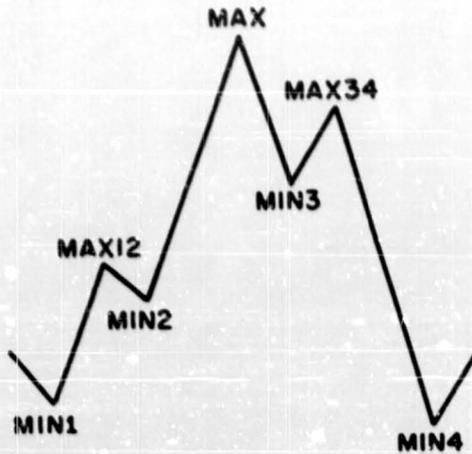
13 cm Procedure

5. Test for a smooth direct signal.

    IF (2.0·MIN1.GE.MIN2)
            and $\Rightarrow$ smooth direct signal.
    (2.0·MIN4.GE.MIN3)

If the direct signal is smooth then all values between MIN2 and and MIN3 which are greater than CRITC are set equal to CRITC and the procedure is terminated; initial test 1 is then begun on the next frame. If the test for smoothness is failed, then continue with step 6.

6. This procedure is applied only if the direct signal is spread through several frequency analysis bins. Determine the first minimum on either side of the direct signal which

Initial Test (cont.)

satisfies the following condition:

(MIN(I).LT.MIN(I-1)·2.0)   Where I indexes the left side of
                          the direct signal

(MIN(J).LT.MIN(J+1)·2.0)   and J indexes the right side of
                          the direct signal (see fig. below).

If the conditions are not satisfied in 15 minima, choose the 15th minima. Denote the extreme minima $\hat{I}$, $\hat{J}$. MIN($\hat{I}$) and MIN($\hat{J}$) locate the extent of the spread direct signal. Denote the minima adjacent to the direct signal $\tilde{I}$, $\tilde{J}$. Then replace the data D( ) with D'( ) calculated as follows:

$$D'(L) = D(L) - \frac{D(\tilde{I}) - D(\hat{I})}{\tilde{I} - \hat{I}} \cdot (L-\hat{I}); \quad \hat{I} + 1 \leq L \leq \tilde{I} - 1$$

$$D'(L) = D(L) - \frac{D(\hat{J}) - D(\tilde{J})}{\hat{J} - \tilde{J}} \cdot (L-\hat{J}); \quad \tilde{J} + 1 \leq L \leq \hat{J} - 1$$

$$D'(L) = D(\tilde{I}) + \frac{D(\tilde{J}) - D(\tilde{I})}{\tilde{J} - \tilde{I}} \cdot (L-\tilde{I}); \quad \tilde{I} \leq L \leq \tilde{J}.$$

7. Terminate procedure; go to next frame, initial test 1.
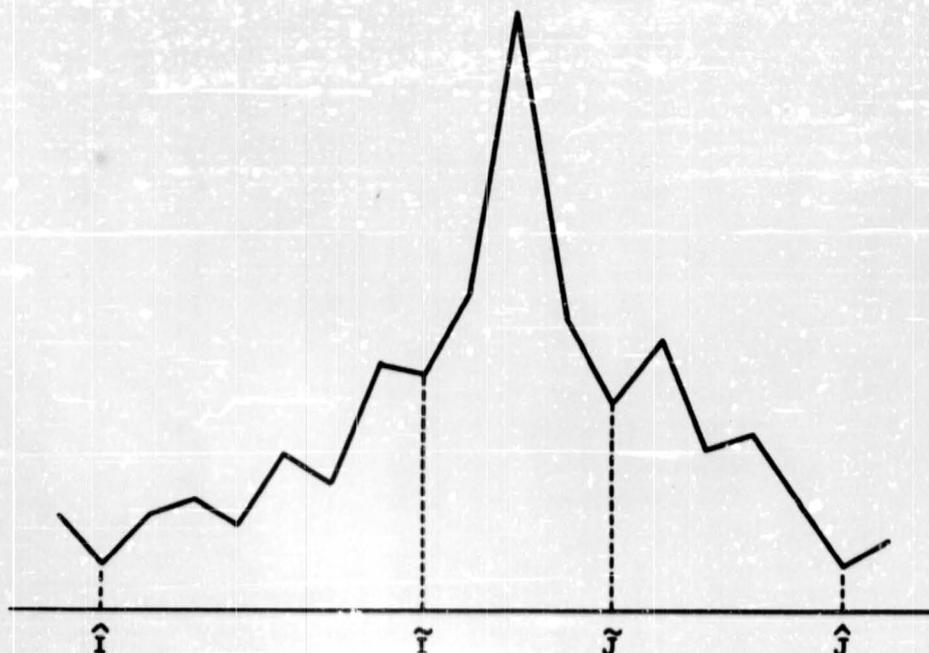
116 cm Procedure

8. Find the largest local maximum within 60 Hz of the direct signal on first the left side and then on the right side of the direct signal. Designate these maxima MAXL, MAXR, respectively.

9. Determine relative magnitude of the direct signal.

$$CRITSB = 200.0 \cdot SUM$$

If (MAX.GE.CRITSB) then the direct signal is sufficiently large to require compensation for the sidebands. Replace MAXL and MAXR by the average value of their respective adjacent minima.

10. If (MAX.LT.CRITSB) the direct signal is small. Subtract a constant from the maxima MAXL and MAXR, defined above. The constant is

$$ESUB = (MAX - SUM)/500.0$$

The subtraction is performed only if the data value is greater than ESUB.

11. Replace MAX by the average of MIN2 and MIN3.

12. Terminate procedure and go to next frame, initial test 1.

Appendix VI

Integral Tape Format

The Integral tape contains reduced data records generated in Subtask 7, 8 and 9 (see Block Diagram I). This appendix gives the detailed formatting of that tape and describes all ancillary computations.

A. Tape Organization

The table below gives the file contents and data record length for the Integral tape.

File No.	Contents	Record Length
1	Apollo-14 116 cm	50 words
2	Apollo-14 13 cm	50 words
3	Apollo-15 116 cm	50 words
4	Apollo-15 13 cm	50 words
5	Apollo-16 116 cm	50 words
6	Apollo-16 13 cm	50 words

The tape is 9 track, 800 BPI, binary in XDS Sigma 5 machine images. See Appendix XI for a description of Sigma 5 machine images.

B. File Organization

   1. Header Record

   2. Data Record
      .
      .
      <many data records>
      .
      .

   3. (EOF) End of File

   4. Header Record

   5. .
       .
       .

Appendix VI (cont.)

C. Header Record Format

Word No.	Contents	Units	Machine Type [α]
1-42	Alphanumeric file identifier	--	A
43	Day of year on which data were collected (January 1 = 1)	(days)	I
44	Year data were taken	(year)	I
45-46	Julian Ephemeris Day at 00:00 UT2 on the day the data were taken	(days)	DPR
47-48	Julian Ephemeris Day of reference epoch	(days)	DPR
49	Time increment between center-point of data averaging frame	(sec)	R
50	Number of data records following this header record	--	I

D. Data Record Format (all machine type **real**)

Word No.		Contents	Units
1		Meaningless	
2		UT2 at midpoint of frame	(sec)
3	X	Components of seleno-	
4	Y	graphic unit position vector of spacecraft	(dim)
5	Z	location	
6	X	Components of seleno-	
7	Y	graphic velocity unit vector	(dim)
8	Z		
9		Speed: Magnitude of spacecraft velocity vector	(m/sec)
10	X	Components of seleno-	
11	Y	graphic unit vector from center of the moon to	(dim)
12	Z	center of the earth	

[α] A - Alphanumeric
 I - Integer
 R - Real
DPR - Double Precision Real

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Appendix VI (cont.)

D. Data Record Format (all machine type real) (cont.)

Word No.		Contents	Units
13	X	Components of seleno-	
14	Y	graphic unit position vector of specular	(dim)
15	Z	point location	
16	θ	Euler angles of space-	
17	ψ	craft attitude and local horizon frame	(deg)
18	Ø		

$$\bar{A}_{veh}] = \begin{bmatrix} \phi \\ (x) \end{bmatrix} \begin{bmatrix} \psi \\ (z) \end{bmatrix} \begin{bmatrix} \theta \\ (y) \end{bmatrix} \begin{bmatrix} \bar{A}_1 \end{bmatrix} \left(\begin{array}{c} \text{cw rotation look-} \\ \text{ing in + axis} \\ \text{direction} \end{array} \right)$$

19	α_s	Vehicle look angles to specular point	(deg)
20	β_s		
21	δ	Angle between plane of inci- dence and plane containing both the vehicle x axis and direction vector to specular point	
22	α_e	Vehicle look angles to earth	(deg)
23	β_e		
24		Selenographic latitude of space- craft position	(deg)
25		Selenographic longitude of space- craft position	(deg)
26		Selenographic latitude of specu- lar point	(deg)
27		Selenographic longitude of specular point	(deg)
28		Angle of incidence	(deg)
29		Instantaneous speed of specu- lar point on lunar surface	(m/sec)
30		Predicted bandwidth for rms surface slope of 0.1	(Hz)
31		Reflected doppler minus direct doppler	(Hz)
32		Total doppler shift of reflec- ted signal	(Hz)
33		Component of doppler shift due to earth rotation	(Hz)

D. Data Record Format (all machine type _real_) (cont.)

Word No.	Contents	Units
34	Altitude of spacecraft above lunar surface: Radius of the moon assumed to be 1736 Km	(Km)
35	Radar cross-section predicted for smooth conducting moon	(dim)
36	(Radar cross-section)/ (received power)	(m^2/w)
37	Polarized power	(arb)
38	Normalized polarized power	$(^{\circ}k)$
39	Unpolarized power	(arb)
40	Normalized unpolarized power	$(^{\circ}k)$
41	Equivalent area bandwidth	(Hz)
42	Normalized absolute moment bandwidth	(dim)
43	Normalized second moment bandwidth	(dim)
44	Centroid of the echo spectrum	(Hz)
45	RMS slope inferred from equivalent area bandwidth	(deg)
46	Spare if value equals zero, otherwise handscaled one-half power echo bandwidth	(Hz)
47	Data validity flag	
48	Spare if value = 0, otherwise value of spacecraft antenna gain in α_s, β_s, direction (see word no. 19, 20)	(dim)
49	Not used	
50	Data record sequence number	

Note: Data do not always progress uniformly in time. Occasionally, data records will reverse in time for one record, and then continue forward. This effect is caused by the sampling procedure in which a small deliberate overlap was inserted. Time tags on data are correct. Overlapping data correspond to the same time interval but different sampling passes. Slight differences arise from variation in exact times averaged.

E. Data Parameter Definitions

The remainder of this section defines the contents of the data records described just above. The individual subsection numbers correspond to the word numbers in Section D (Data Record Format). If a particular quantity has been described at length elsewhere, a reference will be given. Otherwise, the quantity is defined here.

1. Meaningless

2. Time is the UT2 in seconds at which the data were taken. This time corresponds to the mid-point of the averaging interval, as described under Subtask 4. All trajectory parameters have been interpolated to this time, so that geometrical quantities correspond to the location of the specular point on the mean lunar surface at the middle of the averaging interval.

3, 4, 5. Selenographic Unit Position Vector is defined with respect to the lunar surface. This vector is a unit vector directed from the center of the moon for the instantaneous location of the spacecraft. The X, Y, Z directions are defined as follows:

X = mean earth direction

Y = mean direction of the following limb

Z = north polar direction.

The selenographic coordinates were obtained by rotation from the selenocentric geo-equatorial units of the epoch given in the header record. Procedures are described elsewhere (Tyler, 1968).

6, 7, 8. Selenographic Unit Velocity Vector is a unit vector in the direction of the spacecraft velocity. The coordinate system is the same as that given in items 3, 4, 5 above.

9. Speed is the magnitude of the spacecraft velocity vector.

10, 11, 12. Selenographic Unit Vector to Earth is a unit vector giving the direction from the lunar center of mass to the center of mass to the earth in the selenographic coordinate system described in the 3, 4, 5 above.

13, 14, 15. **Selenographic Unit Position Vector of Specular Point**

is a unit vector from the center of mass of the moon to the loca-
tion of the specular point on the mean spherical lunar surface.
For this computation the lunar radius was taken as 1736 km. The
specular point is the location on the mean lunar surface where the
angles of incidence and reflection are equal (cf Tyler, 1968).

16, 17, 18. **Euler Angles of Spacecraft Attitude** connect the space-
craft altitude with a local horizon reference frame. Both the
Local Horizon system and the Euler angles are defined in Appendix IX.

19, 20. **Look Angles to Specular Point** are in vehicle polar coordinates.
These quantities are defined in Appendix IX.

21. **Plane of the Vehicle** , the orientation with respect to the plane of
incidence , is given by the angle δ. This quantity is necessary to
define the vehicle attitude with respect to the plane of incidence.
The angle δ is defined in Appendix IX.

22, 23. **Look Angles to Earth** are the vehicle polar coordinates of a
unit vector in the earth center of mass direction. These quantities
were computed in the same manner as items 19, 20 above using the unit
vector to earth.

24. **Selenographic Latitude of Spacecraft Position** is the selengraphic
latitude of the subspacecraft point computed from the Z component
of the unit vector given in items 3, 4, and 5.

25. **Selenographic Longitude of Spacecraft Position** is the selenographic
longitude of the subspacecraft position computed from items 3, 4,
and 5 according to astrometric convention, western limb of the moon
leading.

26. **Selenographic Latitude of Specular Point** is the selenographic
latitude of the specular point on a mean spherical lunar surface
computed from item 15.

27. **Selenographic Longitude of Specular Point** is the selenographic
longitude of the specular point on the mean spherical lunar surface
computed from items 13, 14, 15.

28. **Angle of Incidence** is the angle of incidence on mean spherical lunar surface at the specular point (cf Tyler, 1968).

29. **Speed of the Specular Point** is the speed with which the instantaneous specular point moves across the mean lunar surface (Tyler, 1968).

30. **Predicted Bandwidth** is the one-half power spectral width predicted for an rms surface slope of 0.1, based on the instantaneous angle of incidence and specular point velocity. Computation is after Fjeldbo (1964), also described in Tyler, (1968). Fjeldbo gives a theoretical expression for the 1/2 power echo bandwidth:

$$\Delta f = 4(2\ln 2)^{1/2} \frac{v_s}{\lambda} \frac{h_o}{d_o} \cos \phi \, ,$$

where v_s = velocity of the specular point on the mean lunar surface, λ = wavelength of the radiation (either 116 cm or 13 cm), ϕ = angle of incidence at the specular point, and the quantity $\frac{h_o}{d_o}$ = the mean lunar rms slope.

The quantity Δf is the 1/2 power bandwidth predicted for a gaussian spectrum. Such a spectrum would result from a gently undulating surface with gaussian autocorrelation function.

31. **Difference Between Reflected and Direct Doppler Shifts** is the predicted frequency difference between a wave reflected from the specular point and the signal traveling directly from the spacecraft to earth. Sign convention is such that the difference is positive for a reflected doppler shift greater than the direct doppler shift.

32. **Doppler Shift** is the total doppler shift expected from the reflected signal. Computation of this doppler shift included spacecraft motion and the earth's rotation, but did not include the rate of change of distance between the earth and the moon.

33. **Doppler Due to Earth's Rotation** is the component of the observed doppler shift due to the earth's rotation, for a signal arriving from the direction of the moon.

34. <u>Altitude</u> of the spacecraft above the lunar surface has been computed assuming a lunar radius equal to 1736 km. The magnitude of the spacecraft radius vector from the lunar center of mass is obtained by adding the contents of word no. 34 to 1736 km.

35. <u>Normalized Bistatic-Radar Cross-Section</u> is the bistatic-radar cross-section of a smooth conducting sphere of the same radius and relative geometry as the moon. Following <u>Fjeldbo</u> (1964) this cross-section is given by

$$\sigma_B = \frac{4\pi R_1^2 \cos\phi}{\left(\cos\phi + \dfrac{2d_{or}}{R}\right)\left(1 + \dfrac{2d_{or}}{R}\cos\phi\right)} \; ,$$

where

R_1 = distance from transmitter to the center of the moon

R = lunar radius (1.736×10^5 m)

ϕ = angle of incidence (cf item 28)

d_{or} = distance from the transmitter to the specular point on the mean lunar surface.

36. <u>(Radar Cross Section)/(Received Power)</u> is a multiplicative constant relating instantaneous geometry and received power to surface reflectivity.

$$\frac{\text{radar cross-section}}{\text{received power}} = \frac{(4\pi)^2 R_1^2 R_2^2}{A \, P_T \, G_T \, \sigma_B}$$

where

R_1 = distance from transmitter to center of the moon

R_2 = distance from receiving site to center of the moon

A = effective aperture of receiving antenna

P_T = transmitted power

G_T = transmitting antenna gain in specular point direction

σ_B = bistatic-radar cross-section for a perfectly conducting moon.

<u>For convenience</u>, this expression was evaluated with the following numerical values for the quantities above:

Appendix VI (cont.)

R_1 = instantaneous value from MSC trajectory

σ_B = instantaneous value from item 35 above

$R_2 = 4 \times 10^8$ m

$A = 0.5 \ (22.5)^2 \pi$

$G_T = 1$

$P_T = 2.5$ w.

These values give only order of magnitude results for this experiment.

37. <u>Polarized Power</u> is the experimenter's best estimate of the polarized component of the received echo total power. Extraction of the polarized power is discussed elsewhere (cf Subtask 8).

Denote the polarized power spectrum $P_p(k)$. Consider the figure below. Polarized power is determined from

$$P = \sum_{k=B_1}^{B_2} (P_p(k) - n) .$$

The $P_p(k)$ is a polarized power spectrum. In the determination of P, the signal limits B_1, B_2 and n were selected by the experimenter. The quantity n was chosen on the basis of

$$\sum_{B_1'}^{B_2'} (P_p(k) - \hat{n}) \sim 0$$

where B_1', B_2' represent spectral limits containing no echo signal, and $\hat{n}$ represents a sequence of trials of n. The limits B_1, B_2, B_1', B_2', were varied as is necessary to follow the changing echo signal.

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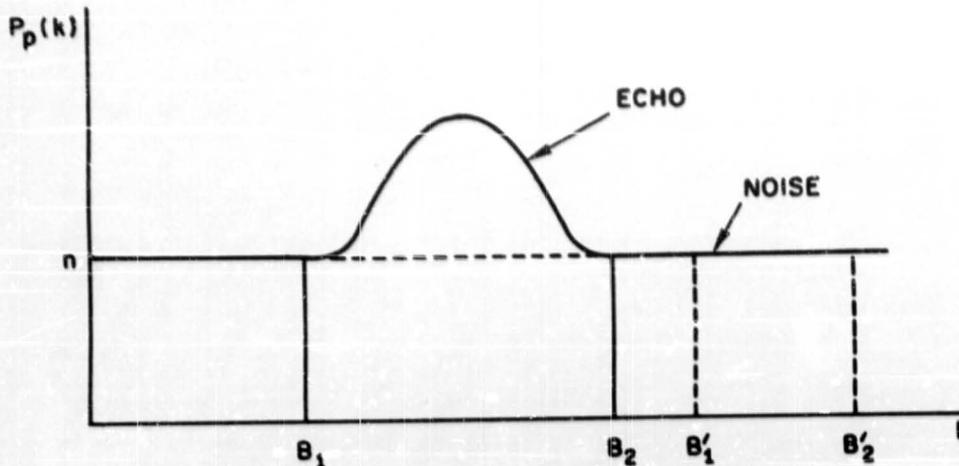
38. <u>Normalized Polarized Power</u> is the quantity contained in item 37 divided by the average power spectral density of the system noise level. This quantity has been discussed in detail elsewhere (cf Subtask 8).

Using the notation introduced under item 37,

normalized polarized power $= P/n$,

where P and n have the same meaning as above.

Note: P/n is extremely sensitive to the choice of n. Thus, polarized power is considered the best overall measure of received polarized echo power. But P/n provides the only method, through the measure of system temperature, of obtaining an absolute power calibration. Similarly, the value of n may be determined from the ratio of polarized power to P/n, so that the variations and system temperature and/or gain may be estimated.

39. <u>Unpolarized Power</u> is the analogous quantity to item 37, for the unpolarized power spectrum. The unpolarized power was obtained in a manner similar to that used to compute polarized power. Letting

$P_u(k)$ represent the unpolarized power spectra, and referring to the figure below, the unpolarized power is given by

$$U = \sum_{\tilde{B}_1}^{\tilde{B}_2} (P_u(k) - \tilde{n}),$$

where the tildas refer to the values of B and n used in the unpolarized power spectrum. In general, the limits for the polarized and unpolarized echoes were different, as was the value of the system noise level. The difference in frequency limits arose from the difference in the spectral distribution of the unpolarized power; the difference in system noise temperature arose from the signal processing used to separate these quantities (cf Subtask 4, 5). The value of $\tilde{n}$ was chosen in a manner similar to that of n in item 37. In some cases, it was not clear that all the unpolarized power is contained in the receiver passband. In this event, $\tilde{B}_1$ or $\tilde{B}_2$ was set equal to the upper or lower frequency limit as appropriate.
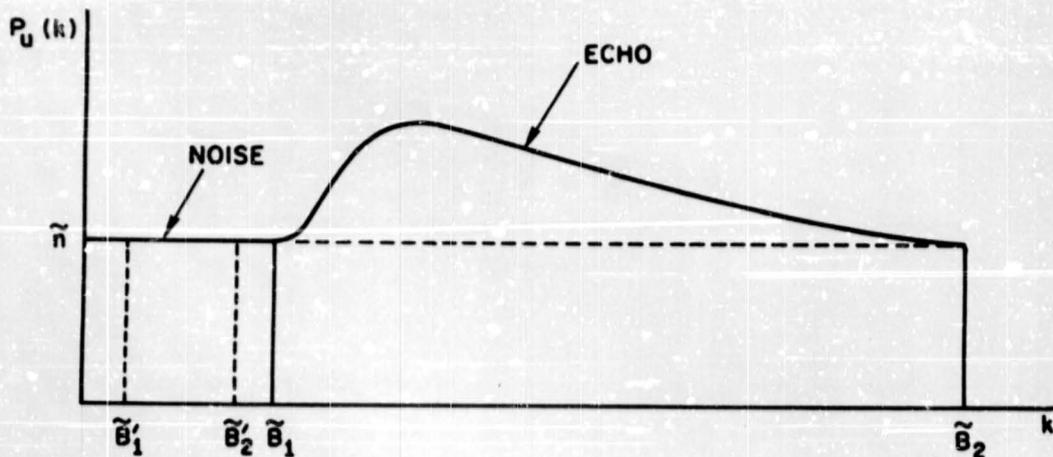
40. <u>Normalized Unpolarized Power</u> is the analogous quantity to item 38, for the unpolarized power spectrum.   The normalized unpolarized power is defined as

$$\text{normalized unpolarized power} = U/\tilde{n}$$

where the symbols have the same meaning as in item 39.   Comments given under item 38 are also germane to normalized unpolarized power.

41.* <u>Equivalent Area Bandwidth</u>: the spectrum of a bistatic-radar echo from a well behaved surface may be written as (<u>Fjeldbo</u>, 1964):

$$S(f) = e^{\frac{-\pi^2 f^2}{2} \left[4v_s(\pi/\lambda) \cos \phi \left(\frac{h_o}{d_o} \right) \right]^{-2}} = e^{-f^2/2\tilde{\sigma}^2},$$

where

f = frequency measured from the centroid of the echo spectrum

v_s = speed of the specular point across the mean lunar surface

λ = wavelength

ψ = angle of incidence, and

h_o/d_o = unidirectional rms slope.

---

*The three machine calculated bandwidths, i.e., the equivalent area bandwidth, the absolute moment bandwidth, and the second moment bandwidth, provide three quasi-independent methods of determining the spectral width of the received echoes. The equivalent area bandwidth provides a standard result that is not particularly sensitive to the gaussian, or non-gaussian nature of the echo spectrum. The absolute moment bandwidth and the second moment bandwidth so emphasize departures from gaussian because of the increasing importance given to the wings of the spectrum.

Equivalent area bandwidths have been used to determine lunar rms slopes. The absolute moment bandwidths and the second moment bandwidths, when normalized by the equivalent area bandwidth, give a sensitive measure of the departures of the echo spectra from the gaussian conditions. RMS slopes derived from these measures are termed "gaussian equivalent slopes" in that they would correspond to true surface conditions for a surface with gaussian statistics and a gaussian autocorrelation function with the same equivalent widths. A more complete description of the lunar slopes requires additional analysis (e.g., see <u>Parker and Tyler</u>, 1973).

Solving for rms slope in terms of measured values of standard deviation, $\hat{\sigma}$, of an experimental spectrum yields

$$h_o/d_o = \frac{\hat{\sigma}}{2(v_s/\lambda)\cos\phi} \quad .$$

Thus, the rms slope may be readily determined from an experimental curve in terms of the e^{-1} width of that curve. The equivalent area bandwidth is a measure of $\hat{\sigma}$ based on an equivalent rectangular spectrum of the same area as the experimental spectrum. This width is computed as

$$\hat{\sigma}_{ea} = \frac{\sum\limits_{C_1}^{C_2} P_p(k)}{\max P_p(k)} \cdot (2\pi)^{-1/2}, \quad C_1 < k < C_2.$$

Referring to the figure which follows, the quantity $\hat{\sigma}_{ea} = \sigma$ if the observed curve is gaussian and noiseless. For non-gaussian data $\hat{\sigma}_{ea}$ is still a measure of the bandwidth, although the interpretation must be modified. RMS slopes determined from $\hat{\sigma}_{ea}$ and the expression immediately above will be referred to as equivalent area slopes. The quantity $\hat{\sigma}_{ea}$ is the equivalent area bandwidth.

42. <u>Normalized Absolute Moment Bandwidths</u> are based on an equivalent
value of $\hat{\sigma}$ computed from the absolute moment of the data. That is,

$$\hat{\sigma}_{am} = \frac{\displaystyle\sum_{k=C_1}^{C_2} P_p(k)\,|k-\bar{k}|}{\displaystyle\sum_{k=C_1}^{C_2} P_p(k)} \cdot \sqrt{\frac{\pi}{2}}\;;\quad \bar{k} = \frac{\displaystyle\sum_{k=C_1}^{C_2} P_p(k)\,k}{\displaystyle\sum_{k=C_1}^{C_2} P_p(k)}$$

for a gaussian spectrum the equivalent area moments and the absolute
moments will be equal

$$\hat{\sigma}_{am} = \hat{\sigma}_{ea} = \sigma$$

where the symbols have the same meaning as in item 41.

The <u>normalized absolute moment bandwidth</u> is

$$\hat{\sigma}_{am}/\hat{\sigma}_{ea}\,.$$

For a gaussian echo spectrum this ratio will be unity.

43. <u>Normalized Second Moment Bandwidth</u>: the second moment bandwidth is
also based on gaussian equivalence. This bandwidth is defined as

$$\hat{\sigma}^2_{sm} = \frac{\sum\limits_{k=C_1}^{C_2} P_p(k)(k-\bar{k})^2}{\sum\limits_{k=C_1}^{C_2} P_p(k)} \; ; \quad \bar{k} = \frac{\sum\limits_{k=C_1}^{C_2} P_p(k)\cdot k}{\sum\limits_{k=C_1}^{C_2} P_p(k)} \; .$$

For a gaussian echo spectrum

$$\hat{\sigma}_{sm} = \hat{\sigma}_{am} = \hat{\sigma}_{ea} = \sigma,$$

where the symbols have the same meaning as under items 42 and 41.
The <u>normalized second moment bandwidth</u> is given by

$$\hat{\sigma}_{sm}/\hat{\sigma}_{ea}.$$

Again, departures of this ratio from unity are indicative of a
non-gaussian received echo spectrum

44. <u>Centroid of the Echo Spectrum</u>: the centroid of the echo spectrum is
defined in the standard way:

$$\bar{k} = \frac{\sum\limits_{k=C_1}^{C_2} P_p(k)\cdot k}{\sum\limits_{k=C_1}^{C_2} P_p(k)}$$

where the symbols have the same meaning as in 41, 42 and 43. The
values of C_1, C_2 are held constant throughout items 41, 42, 43 and
44. The echo spectrum centroid is used in the computations of the
absolute moment bandwidths and the second moment bandwidths. It is
also useful for estimation of the observed doppler difference
(cf item 31). However, the centroid has no direct meaning in an

absolute sense because the transmitter frequencies from the space-craft are not known precisely.

45. RMS Slopes are obtained from the equivalent area bandwidths according to

$$\frac{\overset{.}{h}_o}{d_o} = \frac{\hat{\sigma}_{ea}}{2(v_s/\lambda)\ \cos\ \phi}$$

and

unidirectional rms slope (deg.) $= \tan^{-1}(h_o/d_o)$,

where the results are expressed in degrees for convenience. The quantities v_s, λ, ϕ and $\hat{\sigma}_{ea}$ have been defined in item 41.

46. Handscaled 1/2 Power Echo Bandwidths: handscaling of polarized echo bandwidths has been discussed previously under Subtask 10. A 1/2 power echo bandwidth is defined as the quantity "B" in the figure which follows. In practice, this value was obtained by handscaling data from plots. The handscaled bandwidths provide a rapid, simple technique for the evaluation of lunar rms surface slopes. The handscaled bandwidths were also used as a controlling parameter in development of automated techniques for obtaining echo bandwidths. RMS slopes may be obtained from the handscaled bandwidths by

$$\text{rms slope} = 5.7^o \times \frac{B}{(\text{predicted 1/2 power bandwidth for rms slope of 0.1})},$$

where the result is given in degrees for convenience. Predicted 1/2 power bandwidths for 0.1 rms slopes are given in word no. 30 of the integral tape data records. Hand measurements were made only for selected segments of the data.

47. **Flag:** the flag word contains a seven level binary code that indicates data quality. A bit in the "1" condition indicates the existance of a special condition in the data. A bit position in the "0" state carries no meaning other than that the data are normal.

The interpretation of the bit positions is as given below.

Bit in "1" Condition	Implication
1	Polarized power data questionable or no good
2	Unpolarized power data questionable or no good
3	Polarized noise level, n, (cf item 37) changed this data record
4	Polarized integration bounds B_1, B_2, (cf item 37) changed this data record
5	Unpolarized noise level, $\tilde{n}$, (cf item 39) changed this data record
6	Unpolarized integration bounds, $\tilde{B}_1$, $\tilde{B}_2$, (cf item 39) changed this data record
7	System gain changed this data record

Explanation

Bit Position "1"

Polarized data may be flagged for any one of a number of reasons.
The presence of interference, an error in setting the integration
bounds, or a tape drive error in the data processing are examples
of difficulties that would result in such a flag. In case of gross
errors the flag represents an objectively known bad data point.
In the case of a more subtle phenomenon such as interference, the flag
represents an experimenter's subjective opinion. For the 116 cm data
interference is the predominant cause of a data bad flags. Data
users who wish to examine this question for themselves may do so by
reprocessing the data from the JM Doptrack tapes. It is
very strongly recommended that no flagged data be used without taking
this precaution.

Bit Position "2"

Unpolarized data may be flagged for the same reasons as those
given for the polarized data under bit position "1" above. However,
because gross errors for polarized and unpolarized data may be inde-
pendent, and because the unpolarized data possess a certain immunity
to interference, which tends to be polarized, the flags in bit
position "1" and "2" are not necessarily coincident. As before,
in the case of interference, the investigator's judgment is involved.

Bit Position "3"

This flag is set when the noise level, i.e., n in item 37, is
changed during the data reduction process. This flag serves to
alert the user that such a change has been made. Any discontinuity
that occurs when this bit is set is likely to result from this cause.
In the case of the polarized power such discontinuities are generally
quite small, on the order of 1%. However, in the case of the
normalized polarized power such discontinuities may be large, on the
order of two. Obviously, no physical significance should be attached
to such discontinuities.

Bit Position "4"

Changes in the integration bounds are flagged for reasons similar to those given under bit position "3". The bounds, B_1, B_2, vary with the changing width and location of the polarized echo. Usually, such changes are very small and their effect is not noticable in the data.

Bit Position "5"

Changes in the unpolarized noise level, $\tilde{n}$, are made for the same reasons as those described under bit position "3". As before, changes in the unpolarized power, and especially the normalized unpolarized power, that occur with these changes in $\tilde{n}$ are non-physical.

Bit Position "6"

The comments that apply to the polarized integration bounds given under bit position "4" also apply here.

Bit Position "7"

System gain changes may occur during data reception in the receiving systems or during data playback in the record reproduction system. Such changes are flagged since they will appear as a change in the polarized and unpolarized signal levels. Gain changes do not affect measures of echo bandwidths.

48. **Antenna Gain** is the gain of the spacecraft antenna in the α_s, β_s direction determined from antenna patterns contained in NAA (1966b) (116 cm), MSC (1967) (Apollo 14, 13 cm), or NAA (1969) (Apollos 15 and 16, 13 cm).

49. Not Used

50. **Sequence Number**, where the first data record=1.

Appendix VII

Cross-Reference Table for JM Doptrack/Integral Tape Trajectory Parameters

The table below provides a cross-reference between the JM Doptrack trajectory parameter records and the Integral tape data records. JM Doptrack tapes are described in Appendix IV. That appendix gives the detailed format for those tapes, but does not define all of the trajectory parameters. Integral tapes are described in detail in Appendix VI. That appendix does include a detailed description of the various trajectory parameters. All of the trajectory parameters given on the JM Doptrack tapes are also found on the Integral tapes. This appendix provides a convenient means for determining the location of a given JM Doptrack tape trajectory parameter in the Integral tape format. For reference, the trajectory parameters are found in the sixth record of a data frame on the JM Doptrack tape (i.e., in record number N·6, N = 1, 2, 3, ..., where the first data record = 1).

JM Doptrack Word No.	is found in	Integral Tape Word No.
1		1
2		2
3		31
4		30
5		28
6		34
7		9
8		35
9		36
10		3
11		4
12		5
13		13
14		14
15		15
16		24
17		25
18		33

JM Doptrack Word No.	is found in	Integral Tape Word No.
19		32
20		26
21		27
22		29
23		22
24		23
25		16
26		17
27		18
28		6
29		7
30		8
31		10
32		11
33		12

Units and scale factors are identical on JM Doptrack and Integral tapes.

Appendix VIII

Matrix Correction Factors

The tables below give the matrix correction factors (c-matrix) that were applied to the 116 cm data in Subtask 5 (cf text). No corrections were applied to the 13 cm data.

In all cases, the following values were used for C_{12} and C_{22}

$$C_{12} = 0.0 + j \ 0.0$$
$$C_{22} = 1.0 + j \ 0.0$$

Only C_{11} and C_{21} were varied. Start times shown below refer to the time on the first frame to which the particular c-matrix was applied; the same c-matrix was used on all succeeding frames with times less than the next entry in the table.

Apollo 14

Time UT2 (sec) start	C-matrix	
	C_{11}	C_{21}
23338.35	1.100 + j 0.0	0.0 + j 0.0
25155.63	1.960 + j 0.0	0.050 + j 0.200
25166.28	1.230 + j 0.0	0.070 + j 0.150
25168.94	1.100 + j 0.0	0.0 + j 0.0
25190.24	1.200 + j 0.0	0.0 + j 0.07
25192.91	1.960 + j 0.0	0.050 + j 0.200
25198.23	1.200 + j 0.0	0.0 + j 0.070
25206.22	1.100 + j 0.0	0.0 + j 0.0
26348.41	0.929 + j 0.0	0.189 + j 0.0

Apollo 15

	C-matrix	
	C_{11}	C_{21}
all data	1.000 + j 0.0	0.0 + j 0.0

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Appendix VIII (cont.)

Apollo 16

Time UT2 (sec) start	C-matrix	
	c_{11}	c_{21}
4592.35	$0.913 + j\ 0.0$	$-0.134 - j\ 0.045$
4780.77	$0.958 + j\ 0.0$	$-0.040 - j\ 0.010$
5432.35^α	$0.944 + j\ 0.0$	$-0.055 - j\ 0.032$
5587.79	$1.000 + j\ 0.0$	$-0.060 + j\ 0.020$
5983.46	$0.900 + j\ 0.0$	$-0.100 - j\ 0.050$
6272.35^α	$0.830 + j\ 0.0$	$-0.100 - j\ 0.040$
6484.32	$0.870 + j\ 0.0$	$-0.090 + j\ 0.0$
7030.72	$0.860 + j\ 0.0$	$-0.060 - j\ 0.050$
7112.35^α	$0.871 + j\ 0.0$	$-0.072 - j\ 0.490$
7333.74	$0.815 + j\ 0.0$	$-0.066 + j\ 0.010$
7701.15	$0.778 + j\ 0.0$	$-0.060 - j\ 0.040$
7952.35^α	$0.740 + j\ 0.0$	$-0.100 - j\ 0.040$

[α]These changes are located in overlap areas described in Appendix IV (D3).
The change takes effect on the frame with the time (word 2, record 6;
cf Appendix IV) closest to that shown here.

Appendix IX

Coordinate Transformations

A. General Definitions

$\bar{r}$ = specular point position vector

$\bar{p}$ = spacecraft position vector

$\bar{v}$ = spacecraft velocity vector

$\bar{a}_{\Delta H}$ = vector in local horizon system

$\bar{a}_{\Delta V}$ = vector in vehicle reference frame

$\bar{a}_{\Delta P}$ = vector in primary or principal reference system

$\left.\begin{array}{l}\phi \\ \psi \\ \theta\end{array}\right\}$ defined in C below (Euler angles between local horizon and vehicle systems)

$\left.\begin{array}{l}\alpha \\ \beta\end{array}\right\}$ look angles to specular point in vehicle system

$\left.\delta\right\}$ orientation of vehicle along α, β direction (defined below)

B. Data supplied by MSC gives spacecraft attitude in "Local Horizontal" coordinate system.

Definition of "Local Horizontal" system (see figure which follows):

$$\bar{a}_{ZH} = -\frac{\bar{p}}{/\bar{p}/}$$

$$\bar{a}_{YH} = \frac{\bar{v} \times \bar{p}}{/\bar{v} \times \bar{p}/}$$

$$\bar{a}_{XH} = \bar{a}_{YH} \times \bar{a}_{ZH}.$$
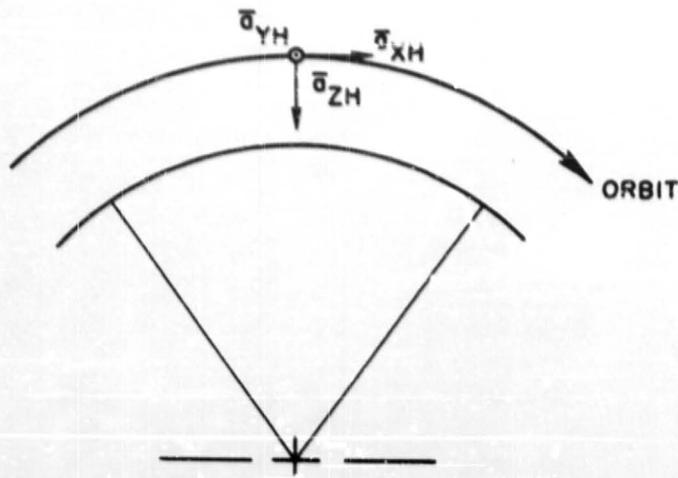
$\bar{a}_{ZH}$ is directed toward the nadir.

$\bar{a}_{YH}$ is directed along angular momentum vector.

$\bar{a}_{XH}$ is in the plane of the orbit roughly along $\bar{v}$.

C. Specification of spacecraft attitude

The Euler angles $\emptyset$, Ψ, θ specify the sequence of rotations required to transform Local Horizontal coordinates to Vehicle coordinates as follows:

$$\begin{bmatrix} X_V \\ Y_V \\ Z_V \end{bmatrix} = \begin{bmatrix} \emptyset \\ (X) \end{bmatrix} \begin{bmatrix} \Psi \\ (Z) \end{bmatrix} \begin{bmatrix} \theta \\ (Y) \end{bmatrix} \begin{bmatrix} X_H \\ Y_H \\ Z_H \end{bmatrix}$$

where the matrix $\begin{bmatrix} (ang) \\ (axis) \end{bmatrix}$ denotes a rotation of (ang) about the current (axis). Rotations are in the sequence (Y, Z, X). The sense of rotation is clockwise when looking in the + (axis) direction. For instance, consider:

$$\begin{bmatrix} x'_1 \\ x'_2 \\ x'_3 \end{bmatrix} = \begin{bmatrix} \alpha \\ (x_1) \end{bmatrix} \begin{bmatrix} x_1 \\ x_2 \\ x_3 \end{bmatrix}$$
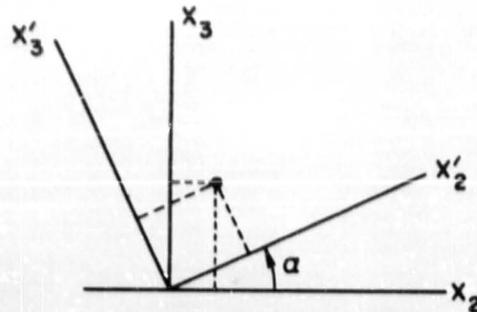
$$x'_1 = X_1$$

$$x'_2 = X_2 \cos\alpha + X_3 \sin\alpha$$

$$x'_3 = -X_2 \sin\alpha + X_3 \cos\alpha$$

then the transformation is

$$\begin{bmatrix} x'_1 \\ x'_2 \\ x'_3 \end{bmatrix} = \begin{bmatrix} 1 & 0 & 0 \\ 0 & \cos\alpha & \sin\alpha \\ 0 & -\sin\alpha & \cos\alpha \end{bmatrix} \begin{bmatrix} x_1 \\ x_2 \\ x_3 \end{bmatrix}$$

Thus

$$\begin{bmatrix} \emptyset \\ (X) \end{bmatrix} \begin{bmatrix} \Psi \\ (Z) \end{bmatrix} \begin{bmatrix} \theta \\ (Y) \end{bmatrix} = \begin{bmatrix} R \end{bmatrix}$$

$$[R] = \begin{bmatrix} \cos\Psi \cos\theta & \sin\Psi & -\cos\Psi \sin\theta \\ \sin\emptyset \sin\theta - \cos\emptyset \sin\Psi \cos\theta & \cos\emptyset \cos\Psi & \cos\emptyset \sin\Psi \sin\theta + \sin\emptyset \cos\theta \\ \sin\emptyset \sin\Psi \cos\theta + \cos\emptyset \sin\theta & -\sin\emptyset \cos\Psi & \cos\emptyset \cos\theta - \sin\emptyset \sin\Psi \sin\theta \end{bmatrix}$$

D. Conversion of Reference Coordinate to Local Horizontal System

Quantities that are known in the principal reference system may be converted to the Local Horizon system through the directional cosines connecting the two. These are given by the vector components of the $\bar{a}_{\Delta H}$, expressed in the primary system. The $\bar{a}_{\Delta H}$ form the rows of the

transformation (rotation only) matrix. Thus

$$
\bar{\bar{x}}_H \Big] = \begin{bmatrix} a_{XH_1} & a_{XH_2} & a_{XH_3} \\ a_{YH_1} & a_{YH_2} & a_{YH_3} \\ a_{ZH_1} & a_{ZH_2} & a_{ZH_3} \end{bmatrix} \begin{bmatrix} \bar{x}_P \end{bmatrix}
$$
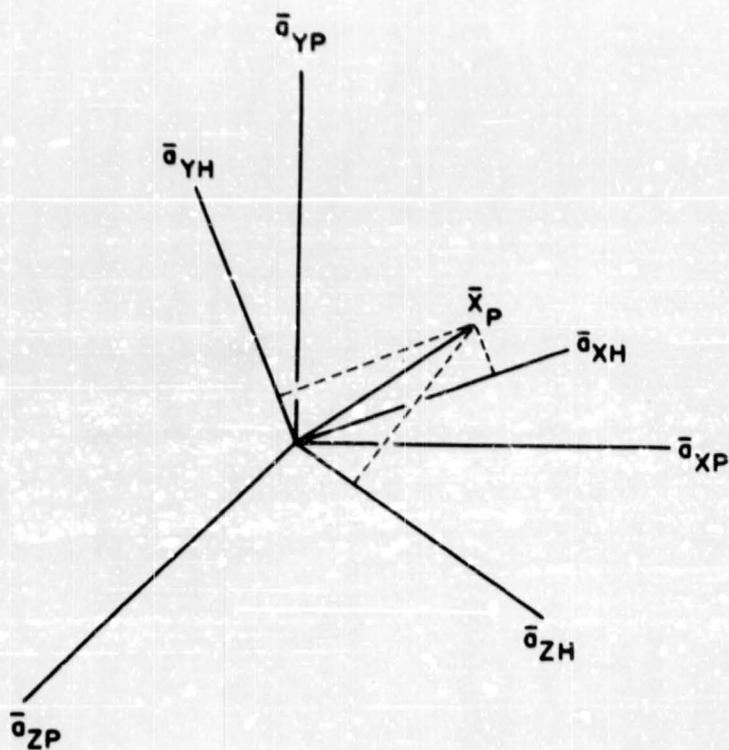
Components in sub -H system are
projections onto reference axes
of that system.

E. Conversion of Reference Coordinates for Vehicle Coordinates

Conversion from principal coordinates to Vehicle coordinates may be made by two successive rotations, principal coordinates ⟶ Local Horizontal coordinates Local Horizontal coordinates ⟶ Vehicle coordinates.

or

$$\bar{X}_V\Big] = \Big[R_{VH}\Big]\Big[X_H = \Big[R_{VH}\Big]\Big[R_{HP}\Big]\Big[\bar{X}_P$$

where R_{ij} implies a rotation from the j to i system. Thus $\Big[R_{VP}\Big] = \Big[R_{VH}\Big]\Big[R_{HP}\Big]$.

F. Computation of spacecraft to specular point look angles, α_s, β_s.

1. The direction to the specular point from the spacecraft is

$$\frac{\bar{r} - \bar{p}}{|\bar{r} - \bar{p}|} = \bar{\gamma}.$$

In Vehicle coordinates

$$\bar{\gamma}_V\Big] = \Big[R_{VP}\Big]\Big[\bar{\gamma}_P.$$

The quantity α is measured from the + X direction,

$$\therefore \alpha_s = \arccos(\gamma_{XV}), \quad 0 \le \alpha \le \pi.$$

The quantity β_s is the azimuthal angle (minimum angle to $\bar{\gamma}$, X_V plane) measured from the $-Z_V$ axis, positive towards $+ Y_V$:

$$\beta_s = \text{signum}\,(\gamma_{YV}) \cdot \arccos(-\gamma_{ZV}), \quad -\pi \le \beta \le \pi,$$

where $\text{signum}(X) = \dfrac{X}{|X|}$. These quantities are depicted in the figure which follows:

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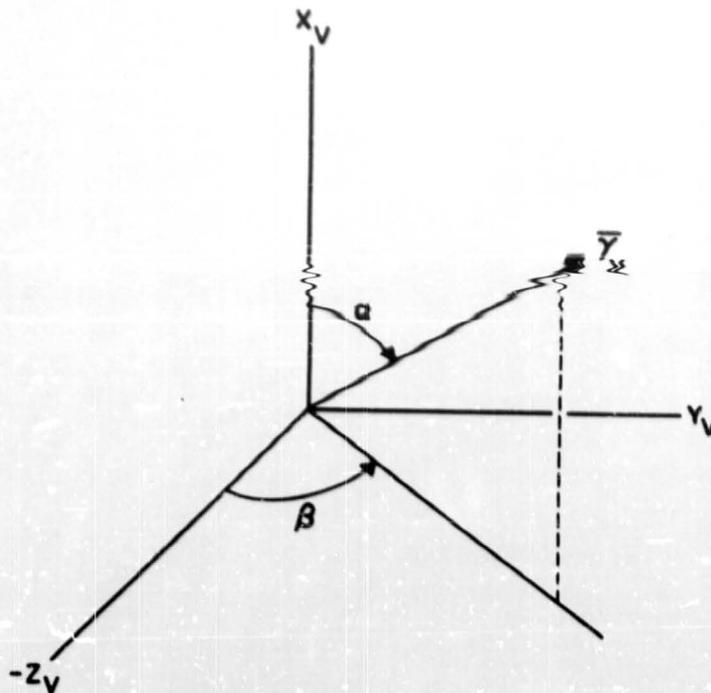
G. Definition and Computation of δ.

The angle δ is the included angle between the $\bar{\gamma}$, $\bar{a}_{XV}$ plane and the plane of incidence, the $\bar{\gamma}$, $\bar{p}$ plane (see figure which follows):

$$\delta = \text{signum}\left(\bar{\bar{p}} \cdot \bar{a}_{XV} \otimes \bar{\gamma}\right) \cdot \arccos\left(\frac{\bar{\gamma} \otimes \bar{p}}{\bar{\gamma} \otimes \bar{p}} \cdot \frac{\bar{a}_{XV} \otimes \bar{\gamma}}{\bar{a}_{XV} \otimes \bar{\gamma}}\right),$$

$$-\pi \le \delta \le \pi.$$
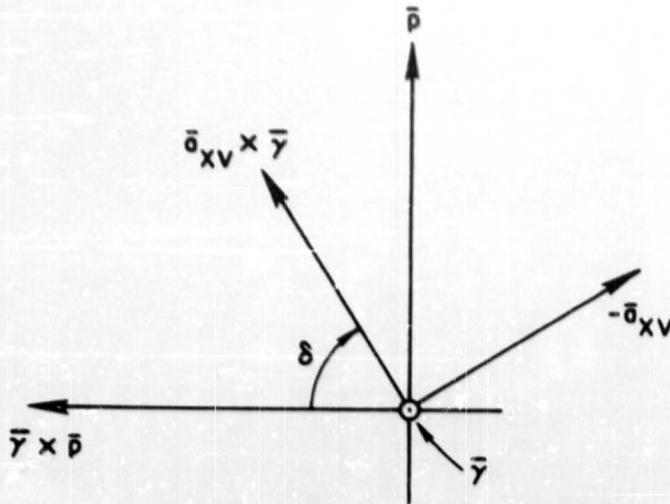
H.   Sources

Additional information regarding the definitions of Local Horizon and Vehicle coordinates may be found in MSC publications describing trajectory tapes (MSC, 1970).   Input for α_s, β_s, δ computations are MSC supplied experimenter trajectory tapes.   The principle reference frame is selenographic.

Appendix X

Relationship Between the Coherency Matrix and Other Specifications of
Polarization

The methods used to estimate the polarization state of Apollo
bistatic-radar data are those described by Tyler and Simpson, (1970).
This appendix describes the relationship of the coherency matrix to
the more common descriptors intensity, axial ratio and orientation of
the polarization ellipse.

The coherency matrix is from Born and Wolf, (1959).

$$\bar{e}_1(t) = \text{Re}\left\{ E_1\ e^{j\omega t} \right\} \bar{e}_1$$

$$\bar{e}_2(t) = \text{Re}\left\{ E_2\ e^{j\omega t} \right\} \bar{e}_2$$
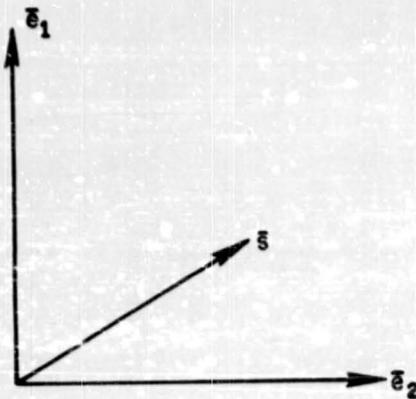
$$\underline{J} = \begin{bmatrix} <E_1 E_1^*> & <E_1 E_2^*> \\ <E_1^* E_2> & <E_2 E_2^*> \end{bmatrix}$$
where E_1, E_2 are complex magnitudes associated
with any pair of orthogonal linear polarizations.

$$\underline{J} = \begin{bmatrix} J_{11} & J_{12} \\ J_{21} & J_{22} \end{bmatrix} ; \quad J_{ij} = <E_i E_j^*>$$

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$$\underline{\rho} = \text{Tr}(\underline{J}) \begin{bmatrix} \rho_{11} & \rho_{12} \\ \rho_{21} & \rho_{22} \end{bmatrix} \quad ; \quad \text{Tr}(J) = J_{11} + J_{22} = \text{total received power}$$

Born and Wolf show that the percentage polarization γ, i.e., the fraction of $\text{Tr}(\underline{J})$ that may be described by a deterministic polarization ellipse, is

$$\gamma = \sqrt{1 - 4\,(\rho_{11}\,\rho_{22} - \rho_{12}\,\rho_{21})}.$$

Then any $\underline{J}$ may be written as

$$\underline{J} = \underbrace{\frac{1}{2}\,(1 - \gamma)\,\text{Tr}(\underline{J}) \begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix}}_{\text{unpolarized part}} + \underbrace{\gamma\,\text{Tr}(\underline{J}) \begin{bmatrix} q_{11} & q_{12} \\ q_{21} & q_{22} \end{bmatrix}}_{\text{polarized part}}$$

where

$$q_{ii} = \frac{1}{\gamma}\,(\rho_{ii} - \frac{1}{2}\,(1-\gamma)) \; ; \; q_{ij} = \frac{1}{\gamma}\,\rho_{ij}.$$

Ko (1962) gives the relationship between $\underline{q}$ and the Poincaré sphere (Beckmann, 1968) as: (shown schematically in the figure which follows)

$$q_{11} = \cos 2\omega, \qquad 0 \leq \omega \leq \pi$$

$$q_{12} = \sin\omega\,\cos\omega\,e^{j2X} \implies \tan 2X = \frac{\text{Im}(q_{12})}{\text{Re}(q_{12})} \, , \, -\frac{\pi}{2} < 2X < \frac{\pi}{2}.$$

Also note:

$$\tan\omega = \sqrt{\frac{q_{22}}{q_{11}}}, \quad \tan X = \frac{M}{N} \, , \qquad \tan X > 0 \implies \text{right elliptical polarization.}$$
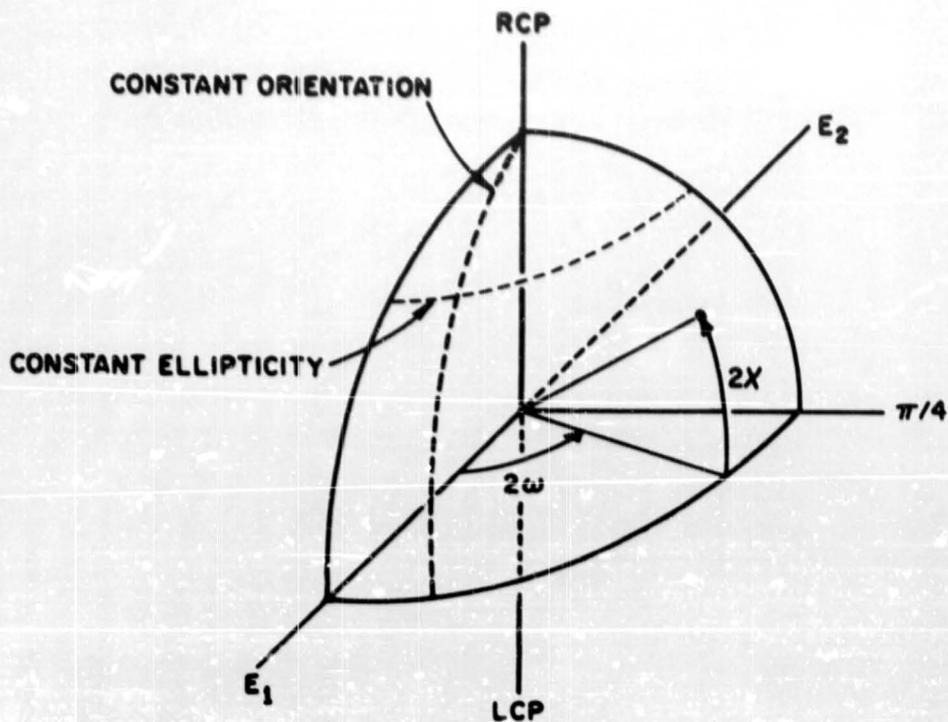
For Apollo, a similar matrix $\underline{J}_c$, where the sub-c designates decomposition of the incident wave into circular components, is used:

$$\underline{J}_c = \begin{bmatrix} <E_\ell E_\ell^*> & <E_\ell E_r^*> \\ <E_\ell^* E_r> & <E_r E_r^*> \end{bmatrix} \qquad \begin{bmatrix} J_{c11} & J_{c12} \\ J_{c21} & J_{c22} \end{bmatrix}$$

where E_ℓ and E_r denote <u>l</u>eft and <u>r</u>ight circular waves.

Defining $\underline{\rho}_c$ and $\underline{q}_c$ in an analogous manner:

$$\underline{J}_c = \begin{bmatrix} \rho_{c11} & \rho_{c12} \\ \rho_{c21} & \rho_{c22} \end{bmatrix} = \frac{1}{2}(1-\gamma)\ \mathrm{Tr}(\underline{J}_c) \begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix} + \gamma\ \mathrm{Tr}(\underline{J}_c) \begin{bmatrix} q_{c11} & q_{c12} \\ q_{c21} & q_{c22} \end{bmatrix}, \quad \text{where}$$

as before $\gamma = \sqrt{1 - 4\left(\rho_{c11}\,\rho_{c22} - \rho_{c12}\,\rho_{c21}\right)}$.

However, the interpretation of the $\underline{q}_c$ is modified in accordance with the new definition:

$$\tan X = \frac{M}{N} = \frac{-\sqrt{q_{c11}} + \sqrt{q_{c22}}}{\sqrt{q_{c11}} + \sqrt{q_{c22}}}$$

$$\omega = \frac{1}{2}\ \arg\,(q_{12}),$$

where ω is referenced to instantaneous E_ℓ position at time $t = 0$.

The invariance of $\mathrm{Tr}(\cdot)$, $\mathrm{Det}\,(\cdot)$, and γ under transformations to circular coordinates can be verified by direct computation.

Appendix XI

XDS Sigma 5 Machine Images

All data on the JM Doptrack and Integral tapes are in the form of
XDS Sigma 5 machine images. One word is 32 bits, one byte, 8 bits.
The data are either real (floating-point), integer, or alphanumeric.
The machine images are as follows:

A. Real

A single precision real number consists of a sign bit (bit 0), a
biased[α], base 16 exponent called a characteristic (bits 1-7), and
a 24 bit fraction. A double precision number consists of a single
precision number followed by an additional 32 bits of fractional
significance (cf figure below). Unless otherwise noted, all numbers
referred to in this report as "real" are single precision.

```
          (·)
 +|Characteris-|                                              |
 -|tic (C)     |          Fraction (F)                        |
 0            7          15           23                      31

 |                                                            |
 | Extra Fraction Bits for Double Precision Only              |
 32                                                          63
```
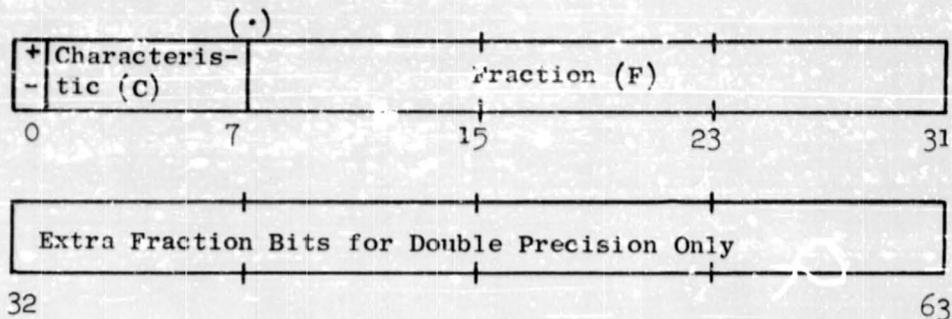
[α] The bias value of 64_{10} is added to the exponent to make it possible
to compare the absolute magnitude of two numbers without reference to
a sign bit.

A real number (N) is defined as follows:

$N = F \times 16^{C-64}$ where

$F = 0$ or

$2^{-24} \leq |F| < 1$ (single precision) or

$2^{-56} \leq |F| < 1$ (double precision)

and $0 \leq C \leq 127$

A negative real number is the two's complement of its positive representation. (Note that this differs from the IBM 360.)

B. Integer

Integers are written in full-word, two's complement representation.

C. Alphanumeric

Alphanumeric data, strings of characters, are represented in Extended Binary-Coded-Decimal Interchange Code (EBCDIC). Each character occupies one byte (8 bits), so each word of alphanumeric data contains four characters.

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Block Diagram I: Block Diagram of

Stanford Apollo Bistatic-Radar Data Processing and Reduction

(1) a) Receiving system described in Appendix I.

   b) Critical filter response given in Appendix III.

   c) RCP, LCP, coherency maintained through entire system.

   d) Antenna pointing maintained toward center of moon using
       Stanford Research Institute lunar ephemeris.

   e) Absolute phase in LCP, RCP channels not controlled, relative
       phase maintained.

   f) Spectral purity of downlink signals measured for Apollo
       equipment type (MSC, 1970).

(2) a) Deep space network station under NASA control, used standar-
       dized procedures except as noted.

   b) Apollo operational system used for 64 m dish pointing, closed
       loop receiver acquisition. Station configuration for bistatic-
       radar experiment described elsewhere (DSN, 1970, 1971).

   c) Absolute phase in RCP, LCP not controlled, relative phase
       maintained.

(3) a) Stanford Signal Conditioning Unit provided critical control
       over system frequency response. Filter characteristics
       given in Appendix III.

   b) FR1400 tape recorders A, B used to provide continuous data
       across tape changes.

(4) a) H.P. 3955B frequency response adjusted for a maximally flat
       frequency response on playback using calibration tapes from
       data source machine (H.P. 3955B for 116 cm data; FR1400 A, B
       for 13 cm data).

   b) Coherent sampling maintained. Reference signal from tape
       used to synchronize samples.

   c) Actual time recovered by use of time code translator clock
       output to establish start times. Time from start main-
       tained by counting sampling pulses.

(4) d) Actual sampling rates: (cont.)

Flight	Wavelength	Sampling Rate	Ratio of Effective Sampling Rate to Actual Sampling Rate
Apollo 14	13 cm	10.75 kHz	4
Apollo 14	116 cm	10.00 kHz	1
Apollo 15	13 cm	10.75 kHz	4
Apollo 15	116 cm	10.00 kHz	1
Apollo 16	13 cm	21.5 kHz	2
Apollo 16	116 cm	10.00 kHz	1

(5) a) Fourier coefficients computed from successive groups of weighted data: data group length either 1024 or 2048 samples, weighting function is $\sin^2 (\pi t/T)^T$, where t is time and T is duration of sample group length.

b) Data analysis lengths

Data Source	Sample Length	Analysis bandwidth (Hz)
Apollo 14 S-band	1024	42.0
Apollo 14 VHF	1024	9.8
Apollo 15 S-band	1024	42.0
Apollo 15 VHF	2048	4.9
Apollo 16 S-band	1024	42.0
Apollo 16 VHF	2048	4.9

(6) Polarimeter computed elements of signal covariance matrix (see Subtask 5).

(7) a) Normalizing data obtained from data runs employing noise input. Purpose was to compensate for variations in receiver passband.

b) Normalizing tapes contain smoothed power spectra from noise source data.

(8) a) C-matrix correction was polarization coordinate transformation to correct for errors in receiver antenna system. Applied to 116 cm data only.

b) Criterion for choosing c-matrix was to minimize polarized part of system noise.

(9) a) Merge combined data tapes with geometrical parameters obtained from MSC (Best-Estimate-Trajectory) Post-Flight tapes.

b) MSC data are interpolated to center of data averaging window.

c) JM Doptrack tapes constitute primary data source for analysis.

(10) Carrier suppression deleted direct signal from the data by means of an empirical algorithm (see Subtask 7 and Appendix V).

(11) a) Tapes edited for changes indicated in operational logs and interference.

b) Handscaled data added to tape from card source.

c) Edited integral tapes constitute reduced data records.
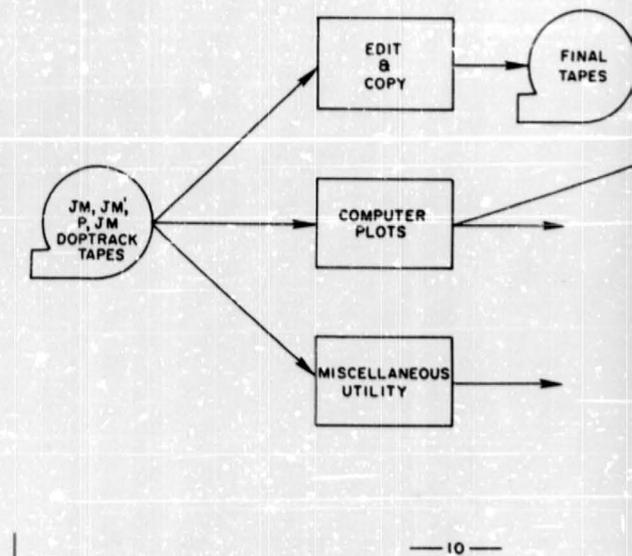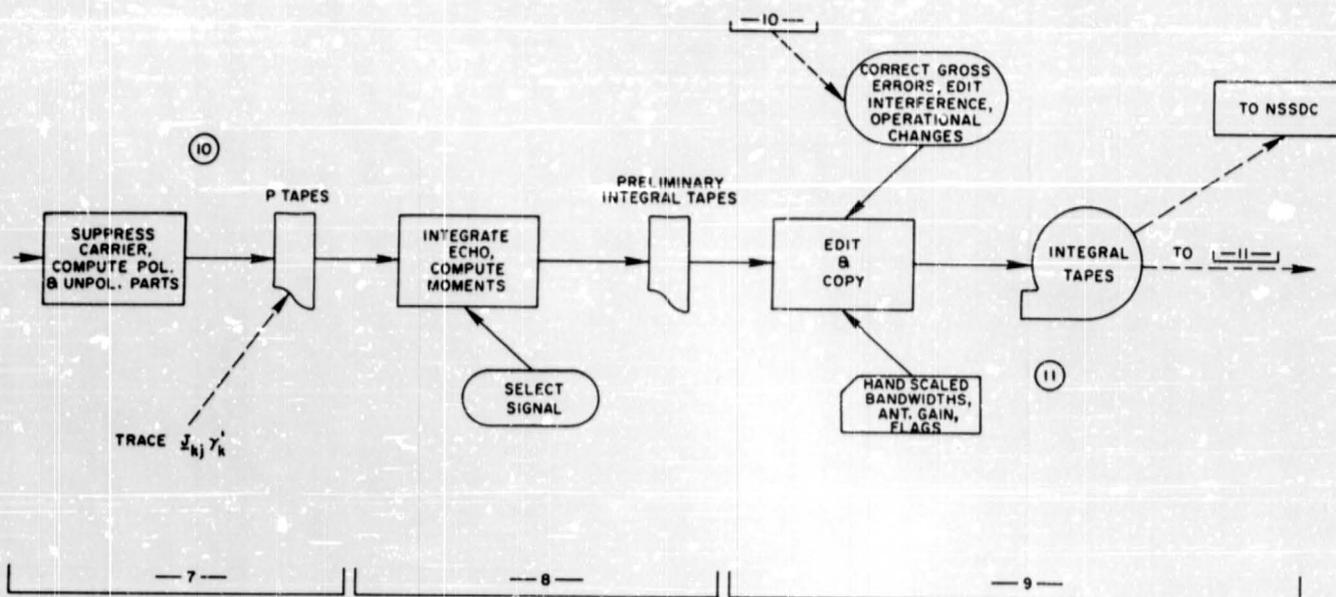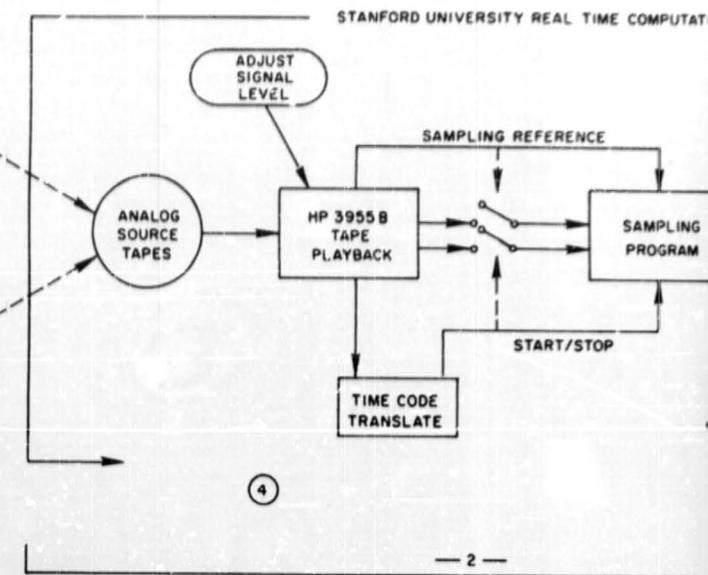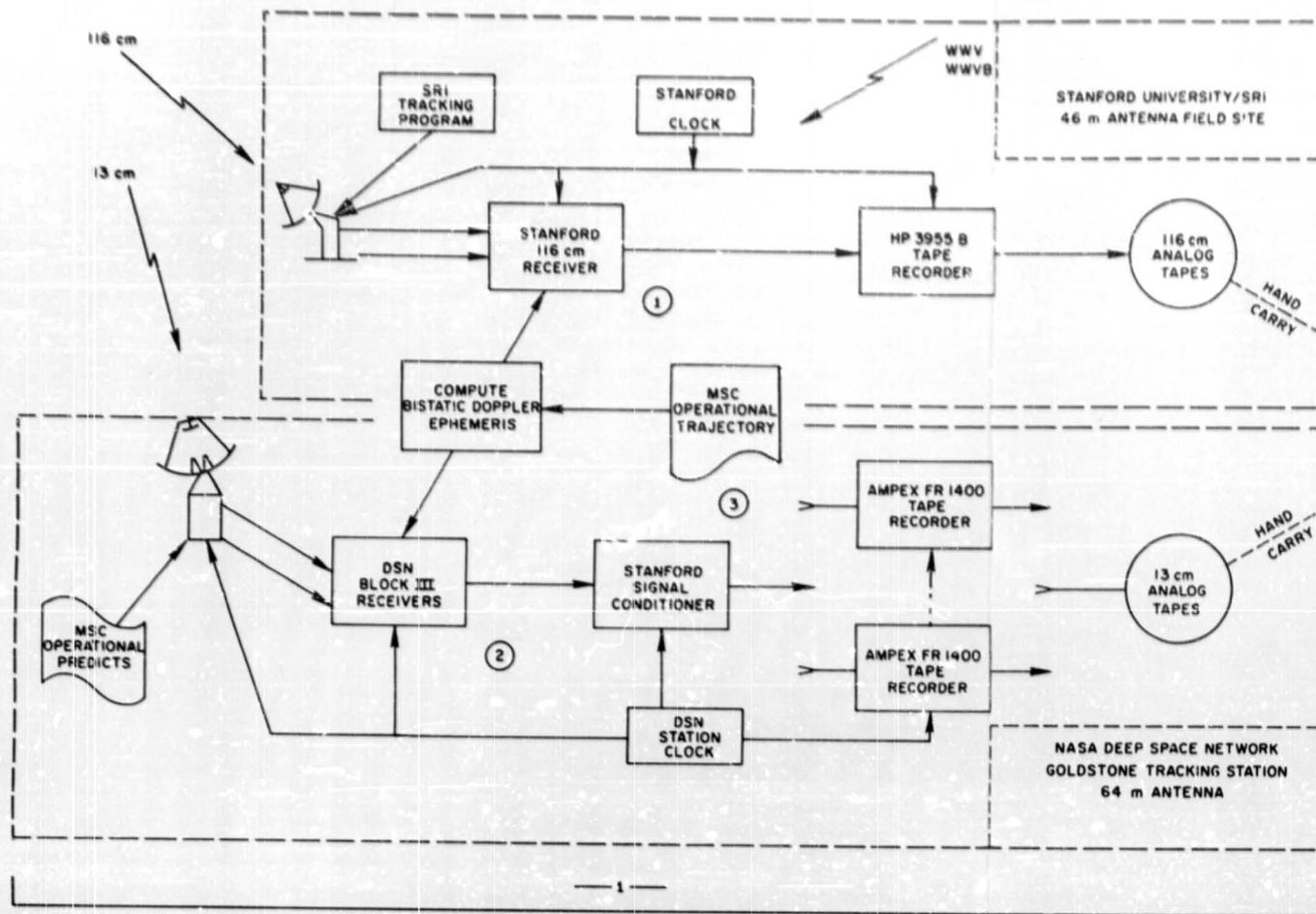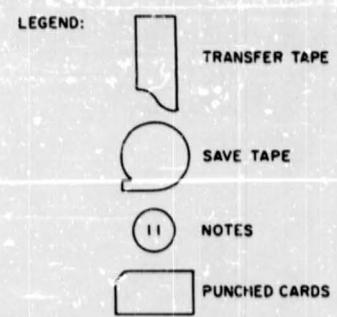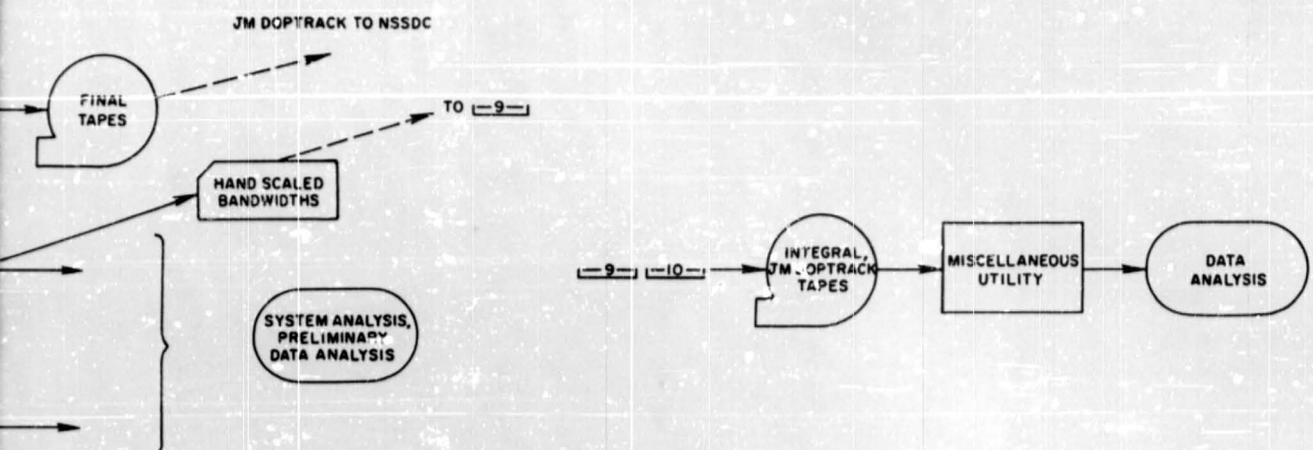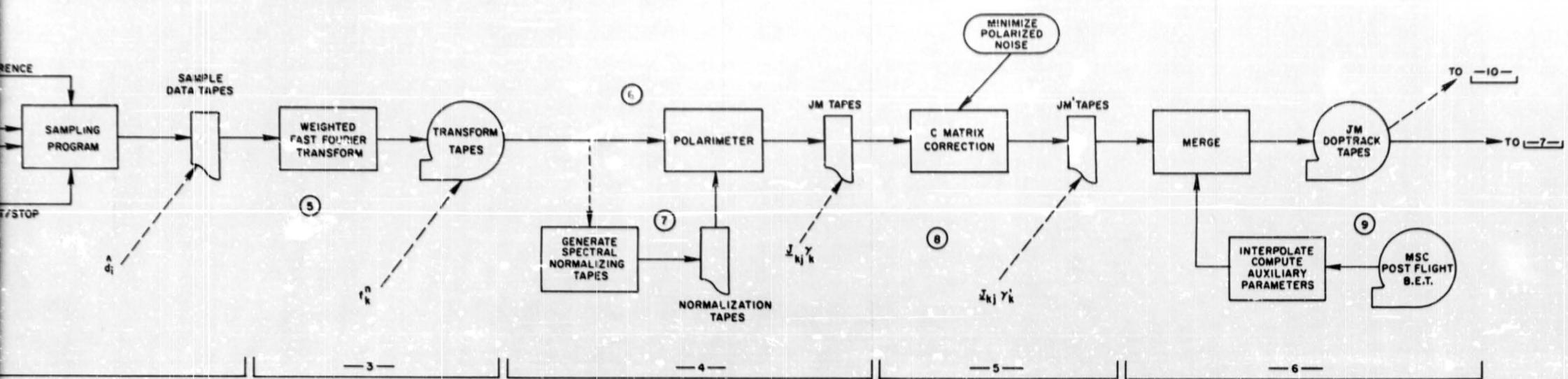
BLOCK DIAGRAM I:

SIMPLIFIED BLOCK DIAGRAM

STANFORD APOLLO BISTATIC-RADAR

DATA PROCESSING AND REDUCTION

STANFORD DON NIL HAFOL GOB HUB/STATIC HR RADAR EXP B(5 70)

E2... (hex data dump)

REC   1. LENGTH 2056

40D10440C4D6D7E3D9C1C3D240E3C1D7C540C6C9D3C56740F1F540C30440C4C1E3C161C7C5D9C5D9C1E3C5C440F2F140C6C5
C240F1F9F7F361C74BD94BC4D6E66BE2E3C1D5C6D6D9C440E4D5C9E561C3C64B40E2E3C1D5C6D6D9C440E4D5C9E540D9C5D7
D6D9E340E2E440E2C5D3F7F360F0F0F64040000000250000007B34625231C000000006253BF8824DD2F1412588A500020EE
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2DE76800 26316A8026F632002AF 368 3026163A200 0E25F4000 0220FFF013040000003A4000043290 2AEF32000 04250000 78
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...
1C8122000000

REC   2. LENGTH 2056

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...
0CD6412DE093413164A4 4139EA5341369ACE412D7F624128 1CC941 2E89C341 3123EE41 2CA441 41 26EEAF41 22FF4241 1FA809

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A0 3841 197E534 16EA9E 411 75ADD 411 7F6D 34117DF 51411155FB8411 4753541 13945241 16ACF54115 56DEA411458C541 15550C
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4129B1AE41 3216834133 2A2A41 364DBA41 2D650E41 2AD1B6 41 2470B0 41 299F63 41 263B2441 2338F3412347A24 12817804125
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FC384129 8E414 12E04CD 412A67FA4129255C41290 38C4128 A22C413290D341 2AB9 1041 2CFF7C4127A1A84 1267A584 12D6C 16
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48A642 60 55DB41F2E807 41B 455A 641ABC1EC418D2DD4418B0DC941A6EA 634194E60E4 190860 341A658C44193FA71 41B0E2B7
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31F641 5B B56A416 6E0 794 154EFBE41 5550904146 11FE413CF20441 3BD14F41 402BA24 13D5D10414A4C4A4 15171E24140A910
41383C434 13D19BB41 40 9EFB41 4340364 13D2591 41 31 7FE0 412D5BFD413 0 A8064 129C447 41 331FC44 1301 D0F41 2A3DAD4126
9455412 4F238412AE7BF 412244 0E4120E58 7412012 994121 3C304120 D0794 11E710A41 1E1975411BF61241 18C6B74 11AF7DA
41243A55 4123F4274 123 26B6 411F20 384 11 ACBBE411 1B9CB41 1EB5 AB4127289B41 2786C24 1238572411D7AFB412188634 11F
F81F411 1FA5BB41 21499 7412 3B9E241 25 4A8141 2048C9 411B3E4341 1E14 32412 13603411 1FD3F341 1F134A4 11F5773412212 3D
412 15968411ACC1341 1C 43BE4120 8D2E41 2181F041 1FC075411E82684 1 1D1884411 1CC6DE41 1B417 44120D71741218DD241 1 E
44A94 119EF3541 217BA1 41 221F9C411 1EF8DC4120 026E41 1DEBF241 1F8 8E6441 1C269B41 1F6E95411D6DE4411BD 72E411B77 3
411FE80 34 11D54EA411 1EC51241 1D82714120 0DD0741 278C80412545734120 B6A1 41 1B50354119942C411EF56941224A40411D
CC77411DA9714121825D 411B0B0D411D49C94121D76541 1EEC50411721D1 411A77054 1 1C46C2 411D5EA941 1DEAE341228907
1222348411EFE3641 20 2D2B41 1EA 6EE411FDA764 1 19A93C41 1A44 1D411D16D141 1FA6E5412211DF4 11A97D2411C242A411C
A57941228E0841 1BC4A8411 AFB6D411D810441 21 7827411 1E5A7C41 1D2E0D411 FEA2741 209 A1C411 8E58F4 119E2B8411 74892
411C38E5412 37F4E 41 1F DC3A411 F4347411 C1DA841 1BBD1A411CD467411DC137411 1CC1 1E411F5FEE4120A1084120F2B141 1B
F15D411D6C2C4125B2F7411C55C44 11B95CC411EE731411CE1D541 1B8 AD74119E0 4F411B2E06411 9D2DB41 186AB34 11C447C
411E5B8A4122431C4121 4F0E412 16D6841 1CDC30411 9FBB7411 1BC8AA41192E964 11C0369 4 1A6A094 11CE2DB411 F2A48411D
41D241 2241EF41219BEE411C2A 0E412 2068 54128D49041235F1541 1C591241 18A3B6412125C04124ACDD411 D13BF4119 9C6C

REC   3, LENGTH   2056

E2E3C1D5C6D5D9C440E4D5C9E540C1D7D6D3D3D640F1F640C2C9D0E2E3C1E3C9C340D9C1C4C1D940C5E7D7404P 2F1F 7F05D   REC   1, LENGTH   200
40404040C9D5E3C5C7D9C1D340E3C1D7C54 0C6C9D3C56140F1F340C3D440C4C1E3C101C7C5D5C5D9C1E3C5C44 0F 2F1 40D1E4
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DCD9E340E2E440E2C5D3F7F360F0F0F64040000000720000007B4462540D68000000046254065C083126E4125B8A50000069E

D1100000441200I2DBFDE2E3040FD779A3FC1B0C040FA42E740242674BFD80545453658E8B40FE39AC4019D72D3FF6AE404014   REC   2, LENGTH   200
01AC40FE807B3FF2FFF042719 4CDBFD 90A89BD736BFE4287DFC0BDC8105A42ADUD2042672A480BDCAD616412B42E842019722
41366B0C42554C854 24F5331433F8498432A4 0BABCC369D0443 28DAA4371EC1642 74F810411331BA5881F1764416FAD244B0
C477426E761D428F74D2431B053F41228F7B4127E8BD44261EC1413A548D00000000000000000040A147AE000000041100000

412000004412 0F88BFDEB2D640FD8A303FC05DA040FA552A40239FECBFD7FEC943658E5A40FE39A74019D7883FF6B1004015   REC   3, LENGTH   200
47D440FEAA8B3FF176F0427179FCBFD9C056BD7371624287D061BDC6238C42AD1E0C427 2CBABDCAD648412AF73A4261790E
413612F24255392A424F400E433F9A94432A9A4DBCC3304044328A664371E63A4274FB224113534958B1F1E34417839844B4
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4130000044121 1E4BFDF387540FD9C953FBF0A1040FA6 742402 3186BBFD7F8594 3658E2D40FE39AD4019D6EB3FF6B3E04015   REC   4, LENGTH   200
A0204 0FEA4D33FEFEF2042715F37BFDA76E2BD7376BD4287BD7EBDC80F4742AD1E49427234FFBDCAD0754 12AAB8242615AFB
41 35BB1542552554424F2CB5433FB098432AF4E8BCC2F7B0443287234371E0664274FE76411374D15881F25B4419A4AC44C5
417A4270B34C42925D37431BEE444126DB26412D6E474426 14E34134EDFC000000000000090000000000000000041300000

414000004412 143F8FDFBD2240FDAE9B3FBDB67040FA78F3402291D9BFD7F1F54 3658DFC40FE39A64019D7443FF6B6B04015   REC   5, LENGTH   200
F7704 0FE9EBC3FEE67704271447EBFDB2DFABD737C0E4287AE6EBDC8267342AD30A74271FD4FBDCAD69C412A5FC14261 3CE7
413563484255 11B4424F1952433FC6A2432B4FE2BCC2BEB0443283CE4371DA8242750189411 3965E5881F2C84419145944C0
EB4A42729 34142 94CC89431CB735412217F9412A005F44265E64413C770B0000000000000000000000000000041400000

4150000044121 69BBFE042D240FDC0793FBC62C040FA8A8140220A48BFD7EB9C43658DCC40FE39AF4019D6A83FF6B9604016   REC   6, LENGTH   200
4F6440FE98873FECE040427129D2BFD8E5B1BD73815642879BCFBDC8107A42AD30174271C5AABDCAD6BE412A13F642611ED5
41350B944254FDF0424F060F433FDCAA432BAA8BBCC28680443280754371D4A14275049B4113B7E35881F3384416E2A044B0
0A59426ADAF4428AC5E9431C2EAC4121FE5D412847D34426102F413ADC4000000000000000000000000000000041500000

4160000044121 8F6BFE0C78C40FDD1E53FBB0ED040FA9BA5402183A8BFD7E54C43658D9D40FE39A84019D7033FF6BC304016   REC   7, LENGTH   200
66940FE923F3FEB58B04271 0F32BFDC9E06BD73869542878B0DBDC80F AF42AD387142718E0FBDCAD6DA4129C82242610 0C2
4134B3CC4254E A62424EF2BA433FF2B2432CQ5AABCC24EE044327D1F4371CEC4427507EF4113D9695881F3804415D3A944A7
E60042749ECF4297747A431E8B03411F980D4125B47A44260EC8413FA9F1000000000000000000000000000000041600000

417000004412 1B52BFE14C494 0FDE30E3FB9BAA040FAAC844020FD0 3BFD7DF0B43658D6D40FE39974019D75E3FF6BF004016   REC   8, LENGTH   200
FE5140FE8BD43FE9D22042 70F49EBFDD56F8BD73 8DCA42877C28BDC8268842AD4A674271567FBDCAD6F141297C454260E2B0
41345C3B4254D6A1424EDF3E4 34008C5432C619ABCC217F0443279BB4371C8DA42750B434113FAF05881F4274415C35344A7
68574279674242 9DAAAC43225D5C411CD5934122373144260282414B9DD600000000000000000000000000000041700000

418000004412 1DAD8FE1D20640F DF 40F3FB8666040FABD394020756 1BFD7D8D343658D3E40FE39A84019D6C53FF6C1D04017   REC   9, LENGTH   200
568840FE85233FE84B704 270DA16BFDE1088BD7390F6428769D5 BDC8104442AD49CA42711EFBBDCAD70241293050426 0C49E
413404A94254C2CC424ECBDB43401EDC432CBD5BBCC1E0804432 76494371C30E42750E5641141C6F5881F49544170ACD44B1
3F644276640 94299C118431E0964411F991 54125D6D04426123 9413D3A6A0 000000000000000000000000041800000

419000004412 2009BFE256D140FE04A43FB711D040FACD8 64 1FEEAEBFD7D2A54 3658D0F40FE39A14019D7223FF6C4904017   REC   10, LENGTH   200
ADFD40FE7E693FE6C5004270BF9ABFDEC AB6BD73961842875B6CBDC8287442AD5C0E4270E7 81BDCAD70E4128E 46D4260A68C
4133AD244254AF244424EB06D4 34034EC432D1 970BCC1AA30443272DC4371BD2D4275 11A941143DF15881F50C441549A144A3
C0394270BEB542926C09431C29C741228A92412963DE44260AEA413BF397000000000000000000000000000000041900000

41A000004412 2264BFE2DCAF40FE151B3FB5BD3040FADDAE401F66E3BFD7CC8643658CE140FE39AA4019D66C3FF6C7504018   REC   11, LENGTH   200
06E640FE77813FE53F104270A52ABFDF8582BD739B31 4287493DBDC8124942AD5B784270B011BDCAD71541289872426 0887B

42260000442136 67BFDAFA40BF02B174C10D6100BF062A034025051A4029CD7243661914 40FDFA8A401C00DB3FFB3D204027   REC   1, LENGTH   200
5E58BF0313043F3D1870BE1C19C7BF338DD1BD73E991428FECODBDC43BEDBDEBBB2D4294C227BDCOBED53FC860E4BD9DAC6A
40DACA52BDAED8E7425765B34337160A428FBB3B43148ACOBBD80DC84349F5E7426B276C404BA2CF588091FC422F3F2A42D1
FC6C412BD7D341330C44426A120041165CFA411C2740442C0A1F41434DB1000000000C0000000000000000000004369900 0

42270000442136C3BFDA749F8F02C50DC123BA00BF063E3640258C0F4029CDDE4366193940FDFA87401C0113 3FFB3B604027   REC   2, LENGTH   200
5ABBF03082F3F3ECD00BE1AE7A2BF357E37BD73ECF9428FE056BDC4540EBDEBD9874294 93ADBDCOD8B8BFCD7C07BD9DBE15
40E0E5DBBDAEC874425775CD4337056A428C186043141B40BBD80CEE4349EEDF426B2 51E4049C44F588091A9423F0CB04311
838641312 3BB41422E67425E2CC741181789411DFE7E442BFFCC413D4E760000000000C00000000000000000000004369A000

42280000442141 1FBFD9EE0EBF02D911C13A1400BF0652D84026 13F14029CE3C4366195F40FDFAA2401C00543FFB39C04026   REC   3, LENGTH   200
CCBFBF02FD5A3F408330BE19B55ABF376C95BD73F0 6B428FC98EBDC4390 1BDEBC2F042946529BDCOF2413FD27735BD9D6FBF
40E70723BDAE37F3425785BC4336F50A4288817F 313AB30BBD80C1B4349E7DA426B228F4047EA465BB0914E423D096D4310
F465413491F44146CD31426D0A32411BC12A4120D910442C03C44148D985000000042280000 0000000000000004369B000

42290000442143 7ABFD96871BF02ED33C15071 00BF0667A64026 9AEB4029CE864366198640FDFA9F401C00703FFB38704026   REC   4, LENGTH   200
845BBF02F2C53F4239C0BE1882F0BF3958ECBD73F3E6428FBD63BDC44F29BDEBDF5B4294369CBDC10B6EBFD772 6EBD9D516A
40ED29DDBDAE7954257 95BC4336E4B64284E8D143133AF0BBD80B504349E0DC426B1FBE40460F5E58809 0E9423E472D4311
4CA9413CF4FB415218D04273DC424114D822411A3902442BF212414F805100000000000000000000000000000004369C000

422A0000442145D6BFD8E204BF0301CEC166CD00BF067CD2402722B44029CED14366 19AA40FDFAB8401BFFB33FFB36E04026   REC   5, LENGTH   200
3B2EBF02E8183F43F0F0BE175064BF3B4 33ABD73F76B428FA75EBDC4384DBDEBCD3A4294080 4BDC12440BFEC6DB4BD9D3314
40F34ECCBDAE97094257A5B64336D474428153E14312CA00BBD80A894349D9EC426B1D7040443 5AD588090984238D77142FC
A1154131567F414272C6425EEF61411 8F9D0411EE613442BE50A4142F902000000000000000000000000000000004369D000

422B0000442146 31BFD35C8DBF03168AC17D2500BF069229402 7A97F4029CF0C436619D040FDFAB6401BFFE93FFB3520402 5   REC   6, LENGTH   200
F3088F02DDBC3F45A850BE161DD2BF3D2B07BD73FB06428F950BBDC4328EBDEBCCE8429 3D964BDC13CA8BFE1690BBD9D14BF
40F9746BBDAE8 6B54257B5AF433 6C446427DC10A43125880BBD809C54349D2EA426B1AE140425C8F588090 3D4235B9F042ED
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