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————— GODDARD SPACE FLIGHT CENTER —————
GREENBELT, MARYLAND

VARIATIONS OF THE LUNAR ORBITAL PARAMETERS
OF THE APOLLO CSM-MODULE

by
T. P. Timer*

February 1966

Goddard Space Flight Center
Greenbelt, Maryland

*This report prepared under the direction of the Mission Analysis Office, Code 507, by
Mr. T. P. Timer of the Advanced Projects Branch, Data Systems Division, Code 543.2

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VARIATIONS OF THE LUNAR ORBITAL PARAMETERS
OF THE APOLLO CSM-MODULE

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Goddard Space Flight Center

SUMMARY

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This report investigates the variation of the orbital parameters for the forty hour period after insertion into two reference Apollo Lunar Parking Orbits¹. It is found that while the variation of most of the parameters under the influence of a triaxial Moon and other perturbing forces is small, the change in pericyynthion height is significant. In Table 1 the amount of change in the various elements during this time is shown.

The most pertinent piece of information derived from this investigation is with regard to the choice of hypothetical lunar landing sites on the surface of the Moon (see Figure 1). Choosing a point on the earthward side of the trace which satisfies the constraint that it has a longitude of between 315° and 45° and a latitude of +5° and -5° with respect to a selenographic coordinate system one has a hypothetical landing site. It is found that any subsequent trace of the sub-module point at the same longitude will always lie within 0°5 in latitude of the initial landing site chosen during the forty hours under consideration. Therefore, landing sites chosen in the above manner meet the two requirements as described in Apollo Navigation Technical Report² which states that the two constraints on the lunar parking orbit mission are as follows:

- (1) the plane of the trajectory must contain a landing site vector on the earth side of the Moon which has a longitude of between 315° and 45° and a latitude of between +5° and -5° in selenographic coordinates.
- (2) the plane of the orbit must be oriented so that the lunar landing site doesn't move out of the orbital plane more than 0°5 during the period of 3 to 39 hours after lunar insertion.

¹pp. 3-10 Apollo Navigation Group Technical Report 65-AN-1.0, February 5, 1965.

²pp. 3-6, 3-7.

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INTRODUCTION

The basic concept behind this report was to see how the orbital parameters for the two reference lunar parking orbits behaved during the forty hour period after lunar insertion. To this end two 7090/7094 computer programs were used to generate this information which is presented as two series of graphs. Series A graphs are associated with the 1968 reference trajectory. Series B graphs are associated with the 1969 reference trajectory. It should be noted at the outset that several coordinate systems are in use throughout this report. The three coordinate systems in use are the following:

center: selenocentric
fundamental plane: parallel to the earth's equatorial plane
x-axis: mean equinox of date

center: selenocentric
fundamental plane: true equator (earth) of date
x-axis: true equinox of date

center: selenocentric
fundamental plane: true equator of the moon
x-axis: intersection of the prime meridian and the equator of the moon.

The two computer programs used as sources of data are the Jet Propulsion Laboratory's Space Trajectory program and the Goddard Interplanetary Trajectory Encke Method (Version 12-C) program. Both programs numerically integrate the orbit by the Encke Method hence one program serves as an independent check of the validity of the data generated by the other program.

I. General Description of the Reference Trajectories

The lunar parking orbit is constrained to be near-circular with a semi-major axis of 1018.5 nautical miles (1886 km) with an altitude above the lunar surface of 80 nautical miles \pm 5 nautical miles (148 \pm 9 km). The duration of this trajectory is constrained to be between two to sixty hours³. In this study both cases meet these requirements. The insertion conditions for the two reference⁴ trajectories under consideration (study) are:

Date of Lunar Insertion Reference Trajectory #1		Date of Lunar Insertion Reference Trajectory #2
May 9, 1968		September 20, 1969
15 hrs/54.0 mins/56.610 secs.		5 hrs/10 mins/12.176 secs.
X = -1012.437 0 n.mi.		X = + 165.639 36 n.mi.
Y = - 51.263 872 n.mi.		Y = - 919.376 95 n.mi.
Z = - 20.120 039 n.mi.		Z = - 415.861 51 n.mi.
\dot{X} = - 287.896 06 ft/sec		\dot{X} = -5208.366 5 ft/sec
\dot{Y} = +4914.267 5 ft/sec		\dot{Y} = - 817.043 16 ft/sec
\dot{Z} = +1967.337 7 ft/sec		\dot{Z} = - 268.213 99 ft/sec
X = -1875.033 324 km		X = + 306.764 095 km
Y = - 94.940 691 km		Y = -1702.686 111 km
Z = - 37.262 312 km		Z = - 770.175 517 km
\dot{X} = - 0.087 750 895 km/sec		\dot{X} = - 1.587 513 284 km/sec
\dot{Y} = + 1.497 871 730 km/sec		\dot{Y} = - 0.249 035 253 km/sec
\dot{Z} = + 0.599 645 730 km/sec		\dot{Z} = - 0.081 751 788 km/sec

conversion factors: p 4-8

COORDINATE SYSTEM

center: selenocentric
 fundamental plane: plane parallel to earth's mean equator of date
 x-axis: mean equinox of date at insertion.

³p 3-7.

⁴p 3-11.

In terms of orbital elements, the insertion conditions, using the same coordinate system above, are:

Reference Trajectory #A 1968				Reference Trajectory #B 1969			
a =	1878.569	2	km	a =	1894.578	3	km
e =	0.000	406	737 41	e =	0.000	419	706 10
i =	158°183	342		i =	155°804	726	
Ω =	180°056	736		Ω =	182°414	087	
ω =	357°743	31		ω =	262°877	900	
m =	359°196	573		m =	0°000	824	8

II. Discussion of the Graphical Results

The series of graphs A-1 through A-6, and B-1 through B-6 are related to the reference trajectories A and B respectively and show similar trends. Hence only the first set of graphs will be discussed in detail with much of the discussion being applicable to both sets.

By inspecting graphs A-1 to A-4 the graphs of the semi-major axis, eccentricity, inclination, and longitude of the ascending node it can be seen that the orbit chosen is relatively a very stable orbit. The semi-major axis varies at most about 0.5 kilometers from its original length during the 40 hours of investigation. The inclination changes less than 0.05 degrees. The eccentricity is plotted to a scale with a factor 10^{-3} . Its fluctuations during the forty hour period are of the order of magnitude of 0.3×10^{-3} as a maximum. The longitude of the ascending node for all practical purposes changes linearly with respect to time, varying less than 0.05 degrees during the time interval considered. The purpose of the preceding discussion was to show quantitatively how these various elements varied with time. Figure A-5 and Figure A-6, however, provide the most useful information directly affecting a lunar parking orbit. In Figure A-5, height (radius vector minus the mean lunar radius) versus hours from epoch, shows how the height varies periodically with the period being the time for one circumlunar orbit. This variation is less than 0.15 kilometers. Figure A-6 shows the limiting cases, the first and the last orbit data, of the trace of the command module on the lunar surface or the lunar sub-module point. It can be seen that for the worst case by choosing a particular point on the trace of the first trajectory and then choosing a point on the trace of the last trajectory at the same longitude, the variation in latitude would be at worst 0°2. A considerable portion of the time, this variation is less than 0°2. In graph B-5 a small secular difference is evident in the value of the ascending node as computed by the JPL

and Goddard Item programs. The reason for this slight difference has not been ascertained except that it is not due to numerical differences in the values of the physical parameters used by the program. (See Appendix A)

CONCLUSIONS

(1) Based on the graphical data presented in this report, either the 1968 or 1969 reference trajectory could provide an orbit stable enough to meet the mission requirements of having suitable landing sites on the lunar surface which do not vary more than 0°5 in latitude from the original landing site. This information is presented in graphs A-6 and B-6 respectively where arbitrary hypothetical landing sites have been chosen.

(2) The use of two computer programs, one to serve as an independent check on the data generated by the other, is justified as the inter comparison of the data on the various graphs indicates.

(3) During this lunar parking orbit phase it would seem that the orbital path may be considered a constant with regard to three station USBS ground tracking. This statement is based on the knowledge that 3σ errors in position including both measurement noise and station bias errors are 8,500 meters.⁵ The change in the semi-major axis as found by this report is at most 500 meters which would be undiscernible since it is less than the accuracy of the position measurements made.

In Table 1 the maximum changes in the parameters for the two cases are shown. Essentially, the results are identical.

⁵Apollo Navigation Working Group Technical Report No. 65-AN-2.0, pp. 6-5, September 1, 1965.

Table 1—Maximum Changes in Orbital Parameters

	Δa	Δe	Δi
Case #1 1968 Data	0.5 km	0.3×10^{-3}	0°05
Case #2 1969 Data	0.45 km	0.3×10^{-3}	0°05

	$\Delta \Omega$	ΔH_p^*	$\Delta \text{Latitude}$
Case #1 1968 Data	0°05	0.15 km	0°2
Case #2 1969 Data	0°20	0.20 km	0°5

* H_p = pericynthion height.

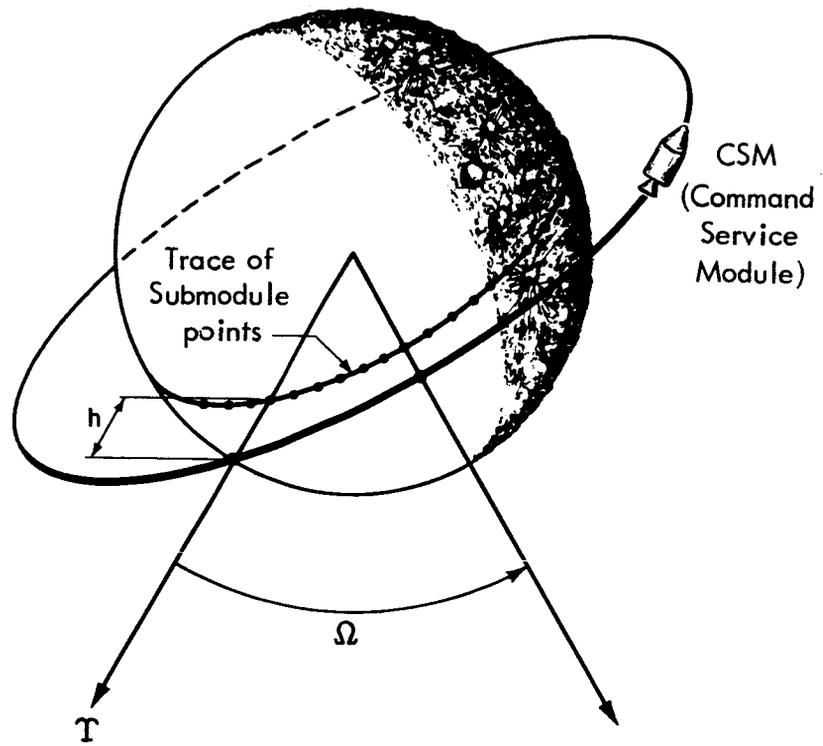
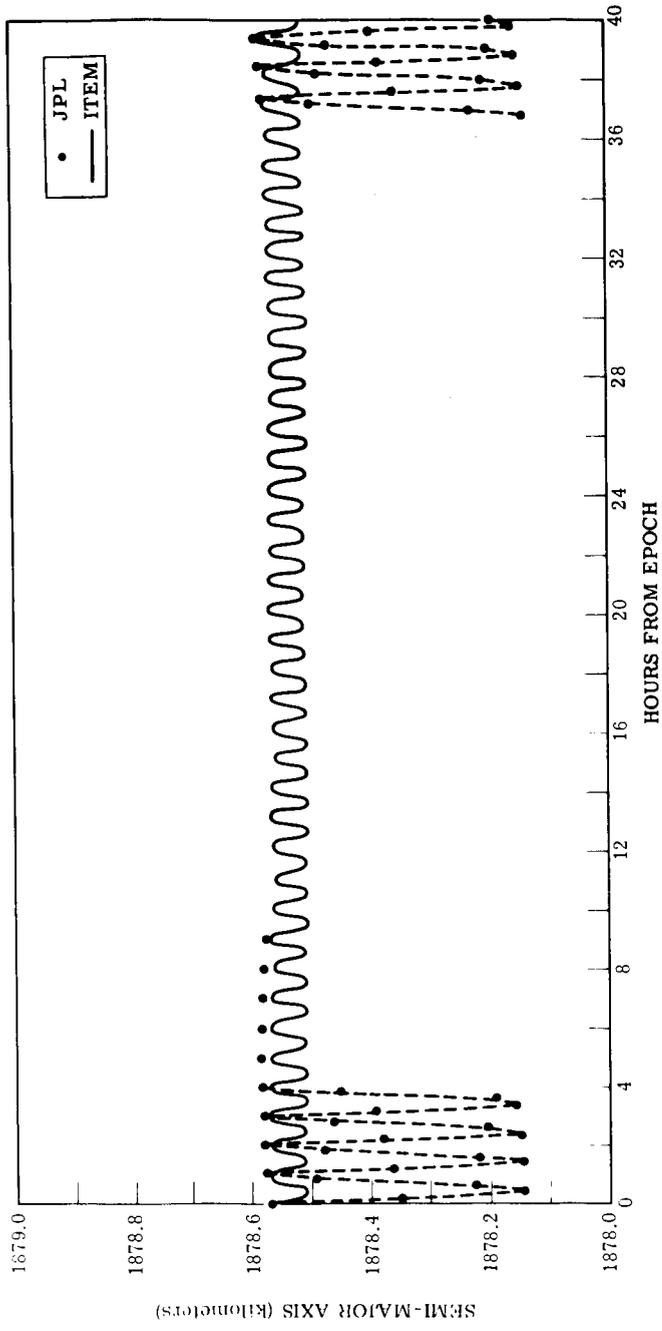


Figure 1



INJECTION CONDITIONS
 Semi-major Axis : 1878.5692 km
 Eccentricity : 0.00040673741
 Inclination : 158.18334
 Long. of Ascending Node : 180.056736
 Argument of Pericynthion : 357.74331
 Mean Anomaly : 359.196573

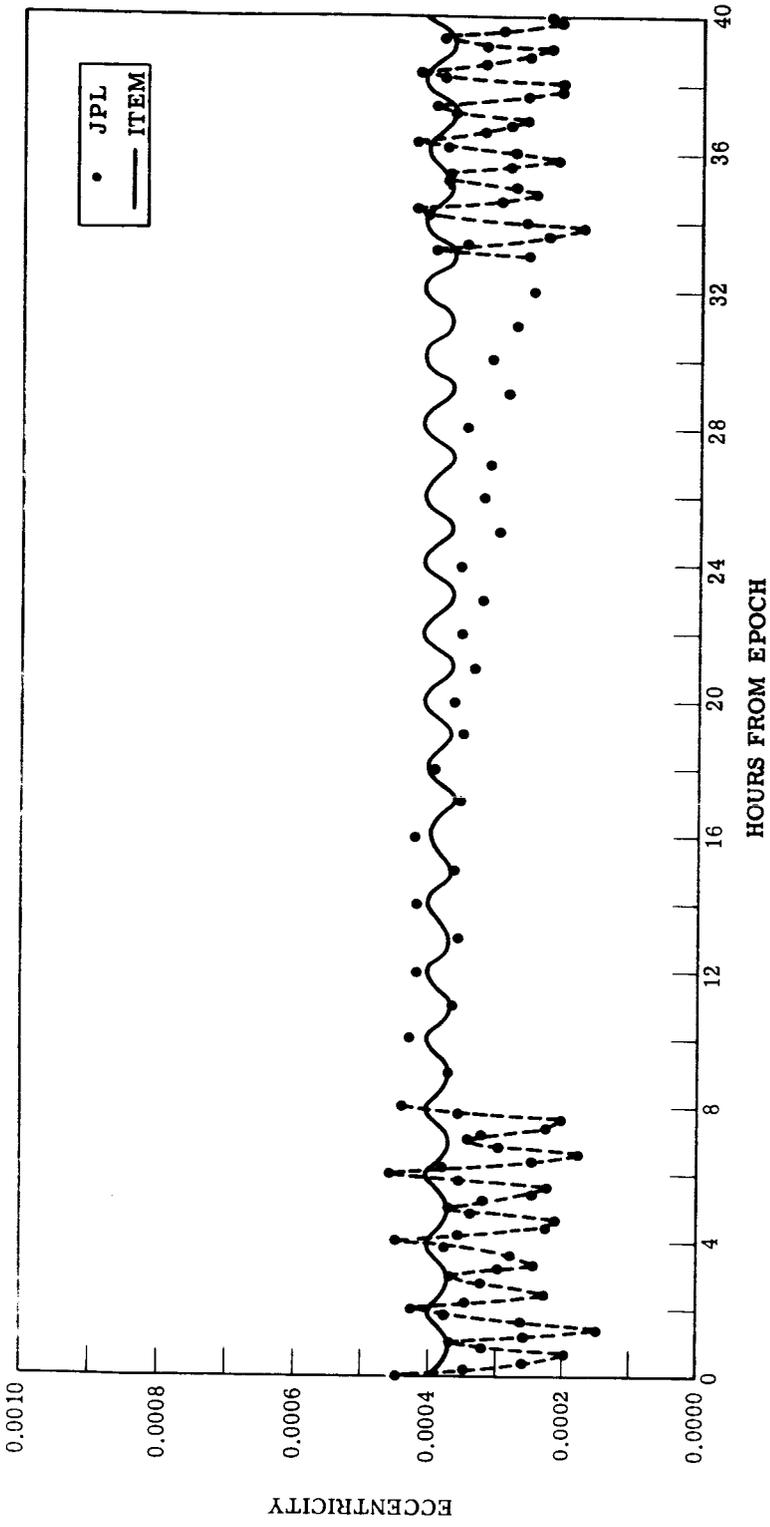
DATE OF EPOCH
 May 9, 1968
 15 hours/54.0 minutes/56.610 seconds

COORDINATE SYSTEM
 Center : Selenocentric
 Fundamental Plane : Parallel to the Earth's Equatorial Plane
 X-Axis : Mean Equinox of Date

Item Data
 Center : Selenocentric
 Fundamental Plane : True Equator of Date
 X-Axis : True Equinox of Date

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 Feb 1968

Figure A-1 Semi-major Axis (kilometers) Vs Hours from Epoch



INJECTION CONDITIONS
 Semi-major Axis : 1878.5692 km
 Eccentricity : 0.00040673741
 Inclination : 158°18334
 Long. of Ascending Node : 180°056736
 Argument of Pericynthion : 357°74331
 Mean Anomaly : 359°196573

DATE OF EPOCH
 May 9, 1968
 15 hours/54.0 minutes/56.610 seconds

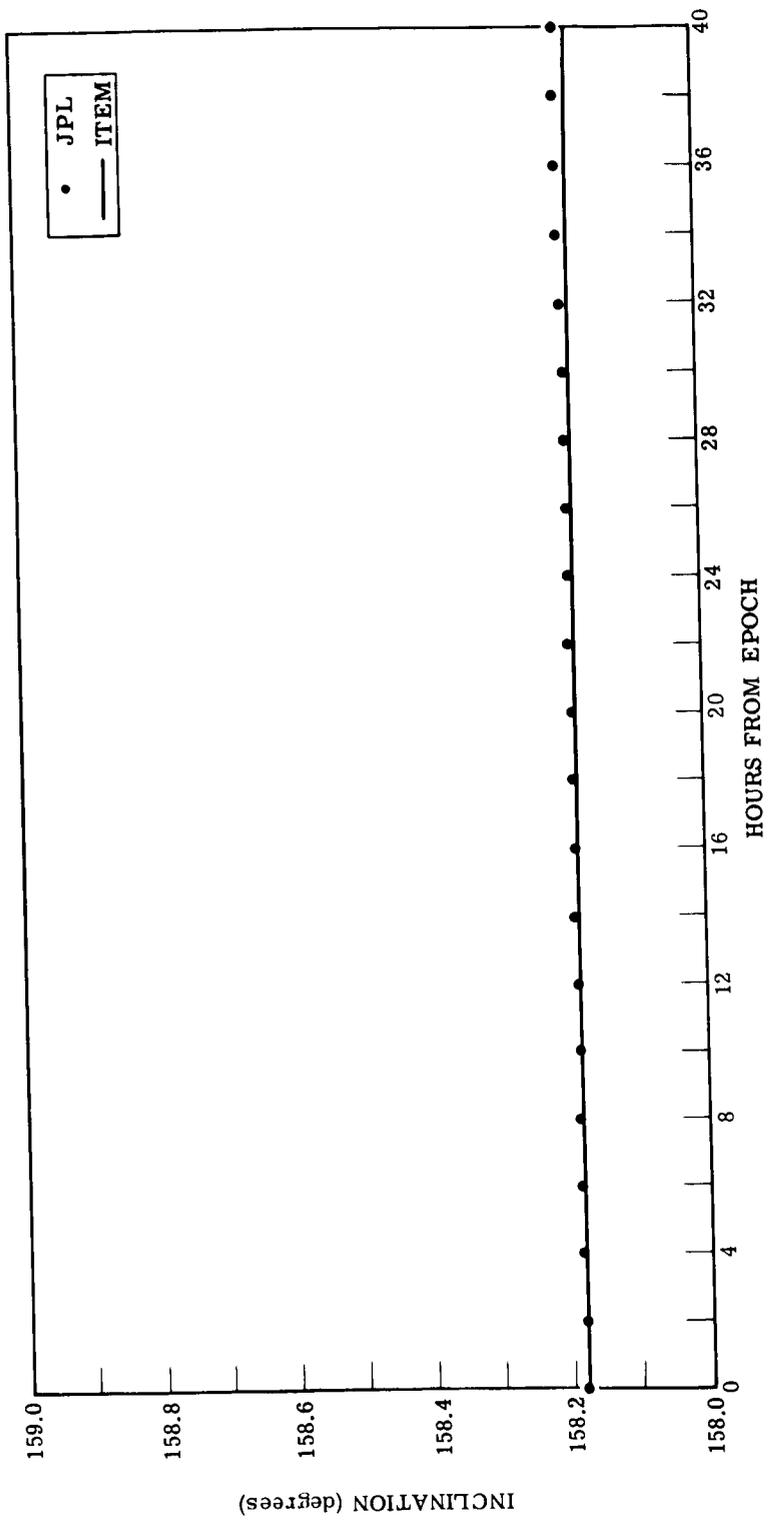
COORDINATE SYSTEM
 Center : Selenocentric
 Fundamental Plane : Parallel to the Earth's Equatorial Plane
 X-Axis : Mean Equinox of Date

JPL Data
 Center : Selenocentric
 Fundamental Plane : True Equator of Date
 X-Axis : True Equinox of Date

Item Data

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 Feb 1966

Figure A-2 Eccentricity Vs Hours from Epoch



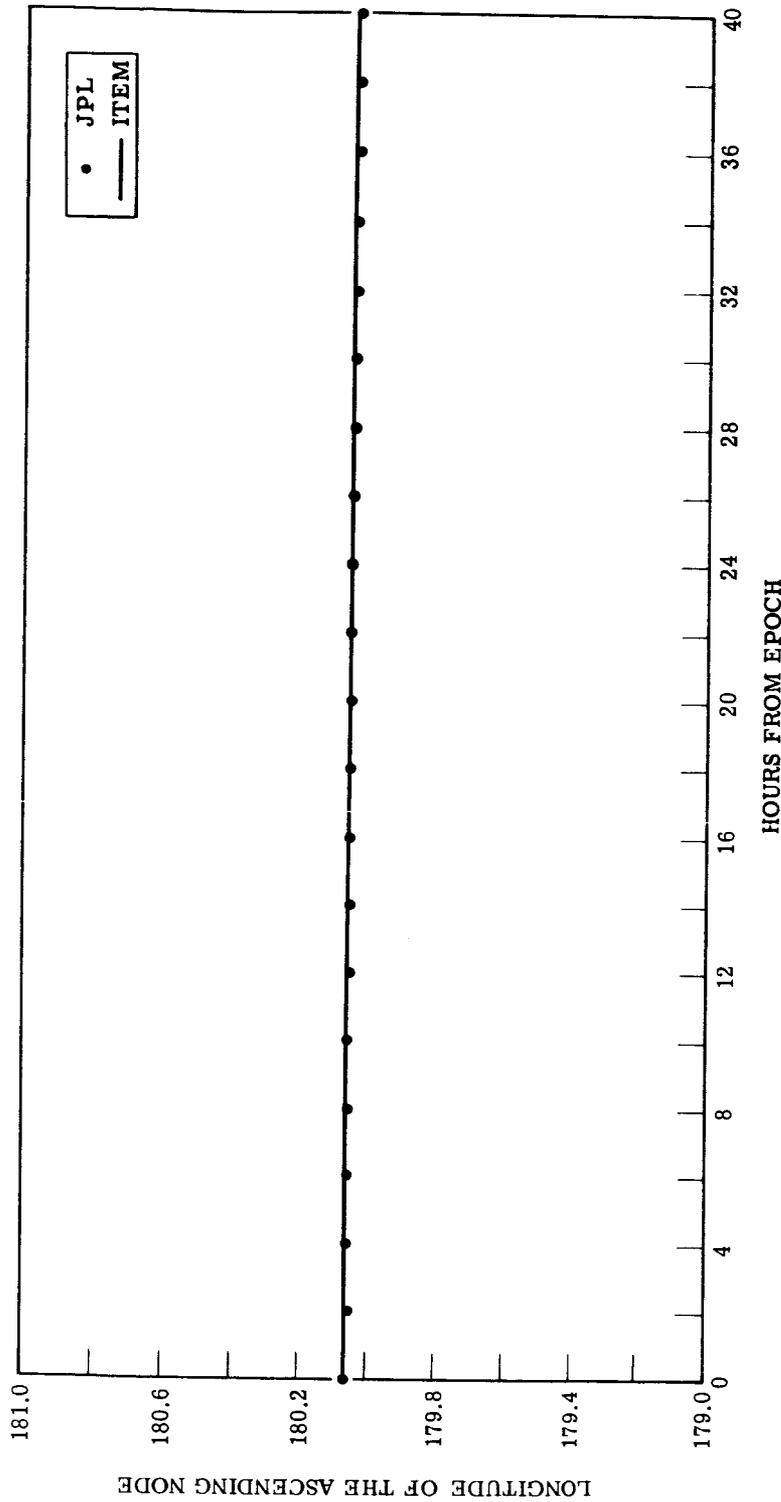
INJECTION CONDITIONS
 Semi-major Axis : 1878.5692 km
 Eccentricity : 0.00040673741
 Inclination : 158°18334
 Long. of Ascending Node : 180°056736
 Argument of Pericynthion : 357°74331
 Mean Anomaly : 359°196573

DATE OF EPOCH
 May 9, 1968
 15 hours/54.0 minutes/56.610 seconds

COORDINATE SYSTEM
 Center : Selenocentric
 Fundamental Plane : Parallel to the Earth's Equatorial Plane } Item Data
 X-Axis : Mean Equinox of Date
 Center : Selenocentric
 Fundamental Plane : True Equator of Date } JPL Data
 X-Axis : True Equinox of Date

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Figure A-3 Inclination (degrees) Vs Hours from Epoch



INJECTION CONDITIONS

Semi-major Axis : 1878.5692 km
 Eccentricity : 0.00040673741
 Inclination : 158°18334
 Long. of Ascending Node : 180°056736
 Argument of Pericynthion : 357°74331
 Mean Anomaly : 359°196573

DATE OF EPOCH

May 9, 1968
 15 hours/54.0 minutes/56.610 seconds

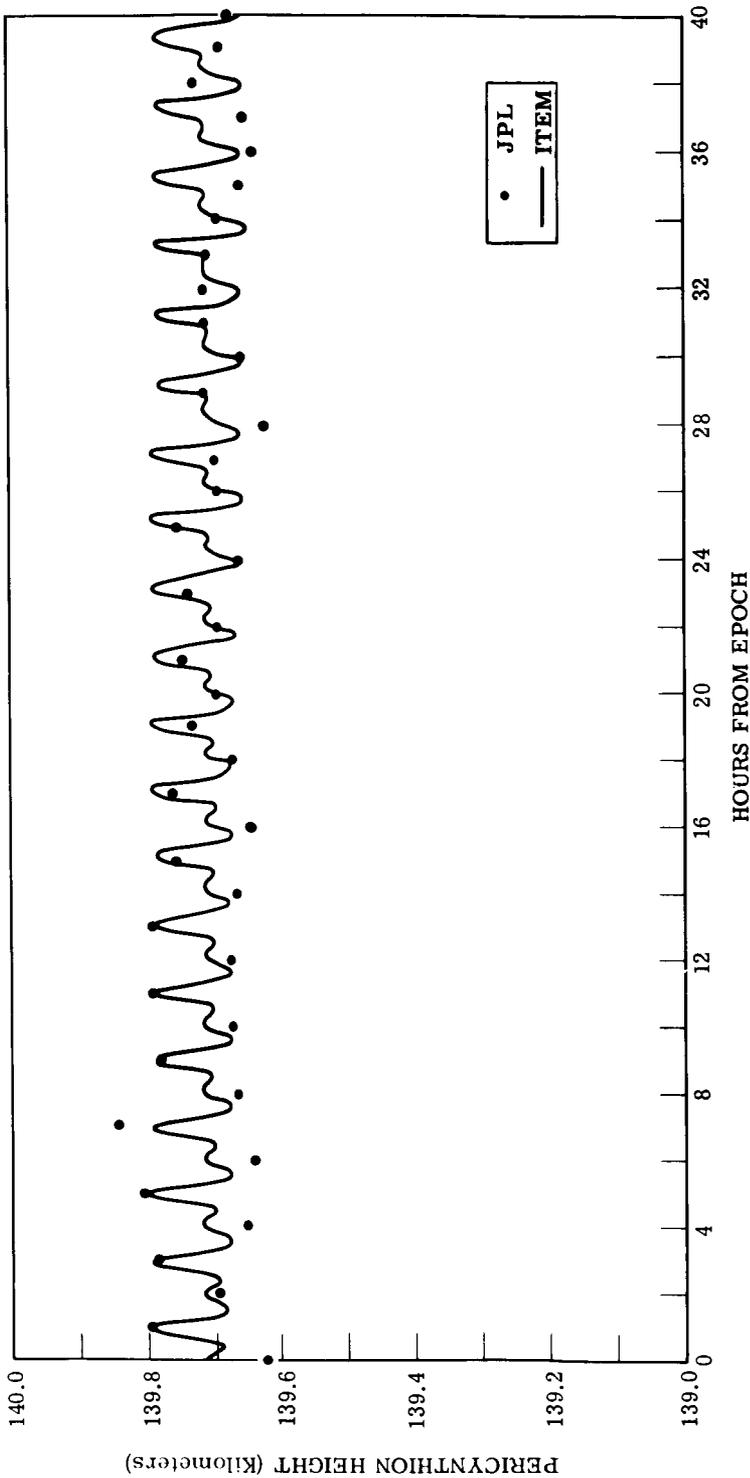
COORDINATE SYSTEM

Center : Selenocentric
 Fundamental Plane : Parallel to the Earth's Equatorial Plane } Item
 X-Axis : Mean Equinox of Date } Data

Center : Selenocentric
 Fundamental Plane : True Equator of Date } JPL Data
 X-Axis : True Equinox of Date }

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Figure A-4 Longitude of the Ascending Node (degrees) Vs Hours from Epoch



INJECTION CONDITIONS

Semi-major Axis : 1878.5692 km
 Eccentricity : 0.00040673741
 Inclination : 158°18334
 Long. of Ascending Node : 180°056736
 Argument of Pericynthion : 357°74331
 Mean Anomaly : 359°196573

DATE OF EPOCH

May 9, 1968
 15 hours/54.0 minutes/56.610 seconds

COORDINATE SYSTEM

Center : Selenocentric
 Fundamental Plane : Parallel to the Earth's Equatorial Plane } Item
 X-Axis : Mean Equinox of Date } Data

Center : Selenocentric
 Fundamental Plane : True Equator of Date } JPL Data
 X-Axis : True Equinox of Date }

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Figure A-5 Height (kilometers) Vs Hours from Epoch

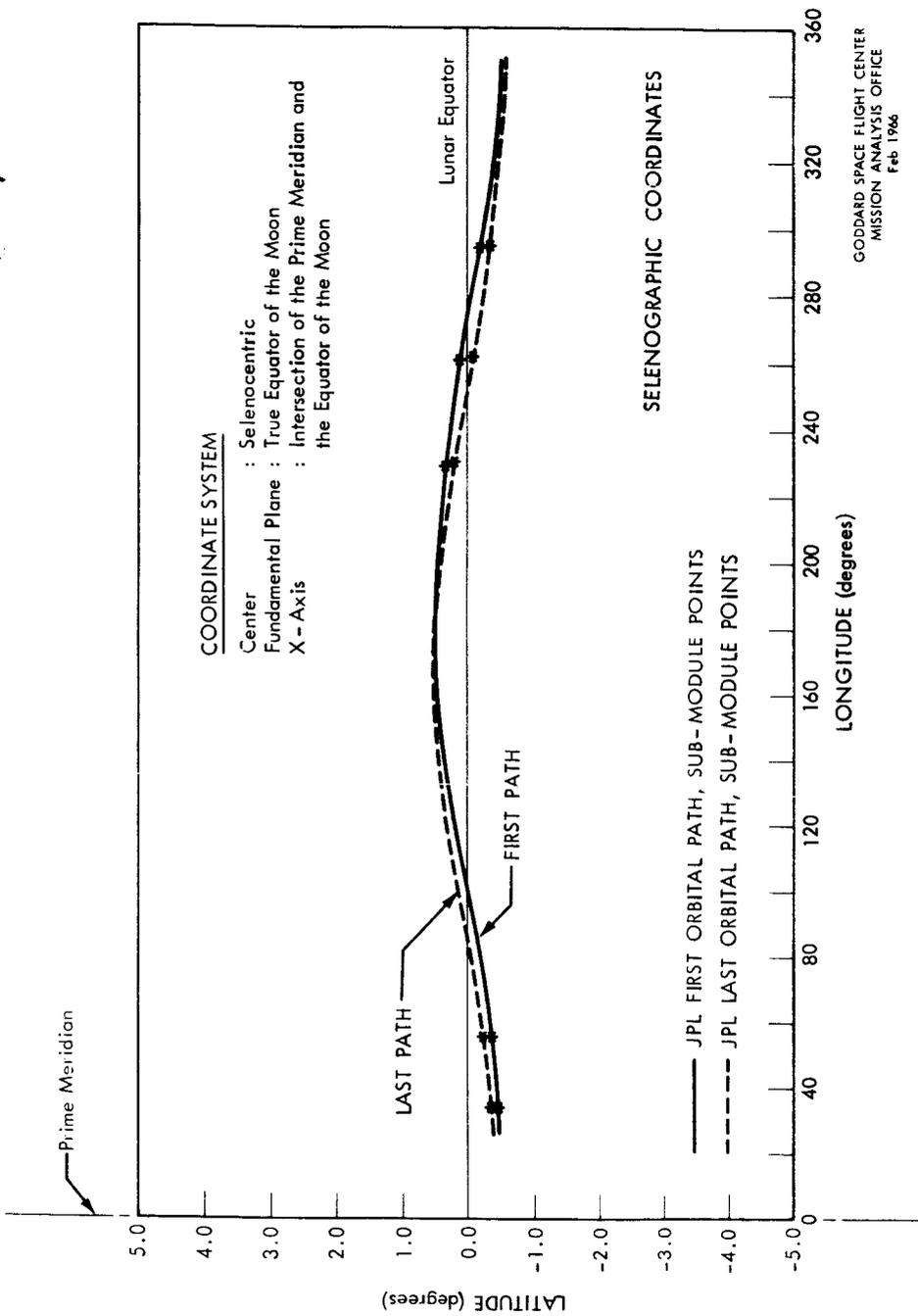
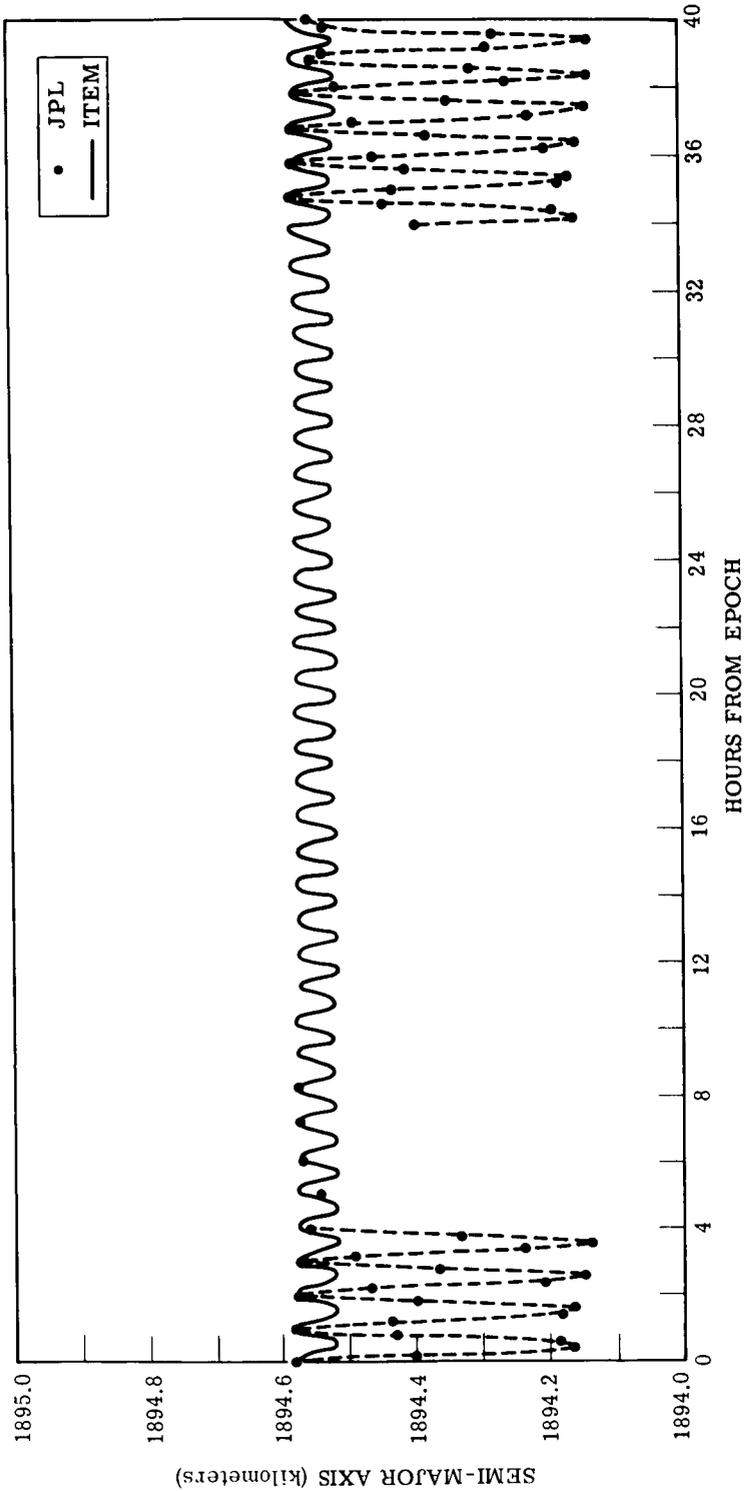


Figure A-6 MOON SUB-MODULE POINTS
 Latitude Vs Longitude



INJECTION CONDITIONS
 Semi-major Axis : 1894.5783 km
 Eccentricity : 0.00041970610
 Inclination : 155°80'47.26
 Long. of Ascending Node : 182°41'40.87
 Argument of Pericynthion : 262°87'71.6900
 Mean Anomaly : 0°00'08.24

DATE OF EPOCH
 September 20, 1969
 5 hours/10 minutes/12.176 seconds

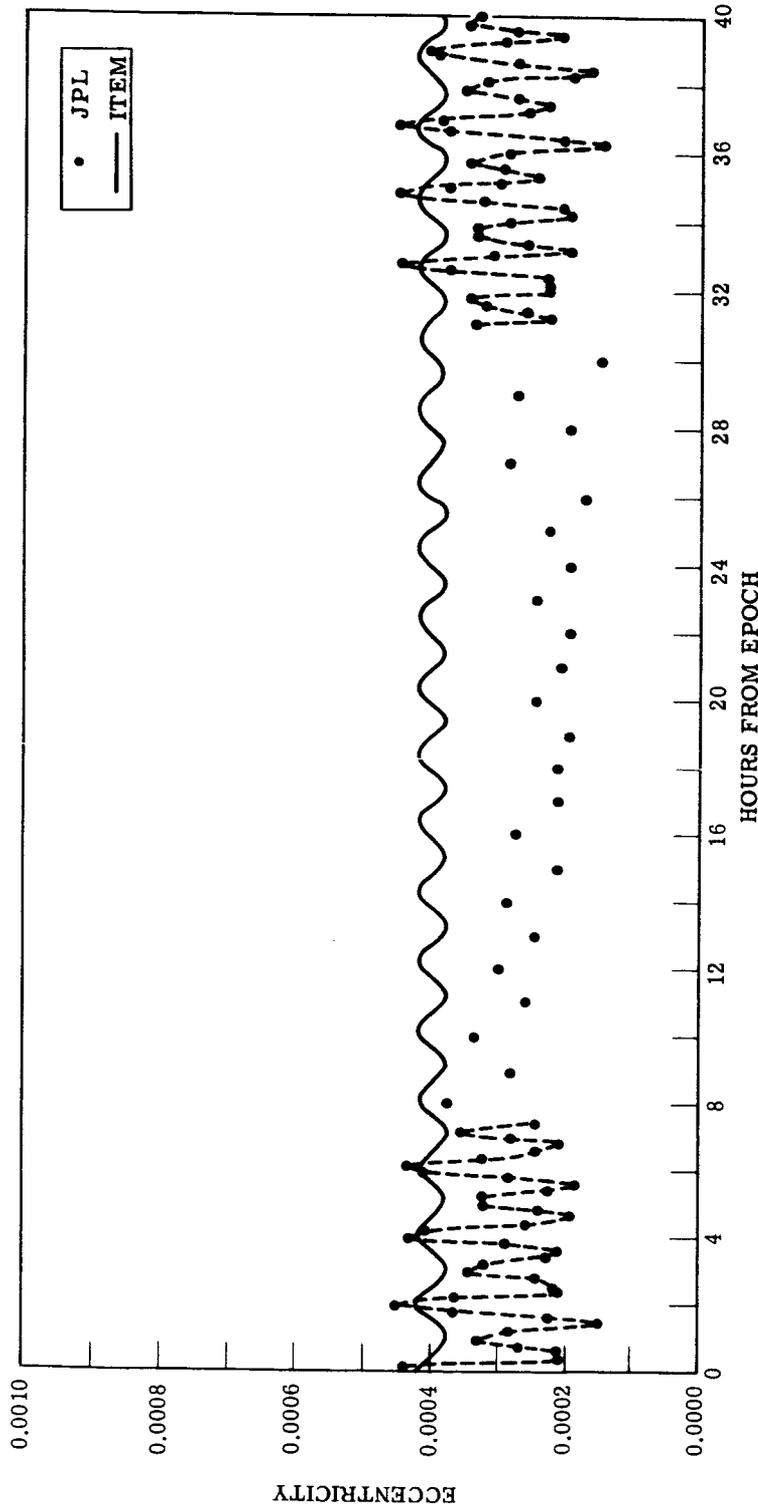
COORDINATE SYSTEM
 Center : Selenocentric
 Fundamental Plane : Parallel to the Earth's Equatorial Plane
 X-Axis : Mean Equinox of Date

Item Data
 Center : Selenocentric
 Fundamental Plane : True Equator of Date
 X-Axis : True Equinox of Date

JPL Data

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Figure B-1 Semi-major Axis (kilometers) Vs Hours from Epoch



INJECTION CONDITIONS

Semi-major Axis : 1894.5783 km
 Eccentricity : 0.00041970610
 Inclination : 155°804726
 Long. of Ascending Node : 182°414087
 Argument of Pericynthion : 262°87716900
 Mean Anomaly : 0°000824

DATE OF EPOCH

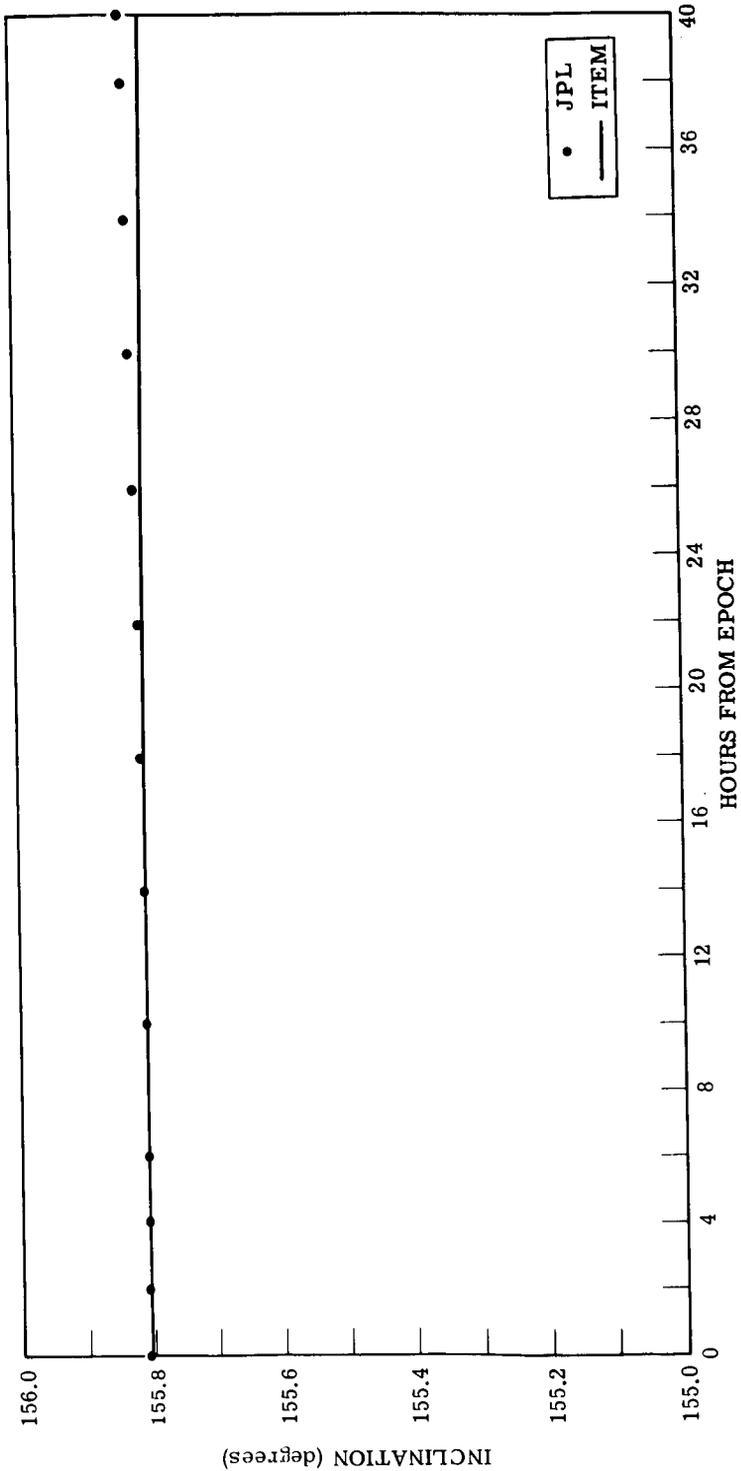
September 20, 1969
 5 hours/10 minutes/12.176 seconds

COORDINATE SYSTEM

Center : Selenocentric
 Fundamental Plane : Parallel to the Earth's Equatorial Plane } Item
 X-Axis : Mean Equinox of Date } Data
 Center : Selenocentric
 Fundamental Plane : True Equator of Date } JPL Data
 X-Axis : True Equinox of Date }

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Figure B-2 Eccentricity Vs Hours from Epoch



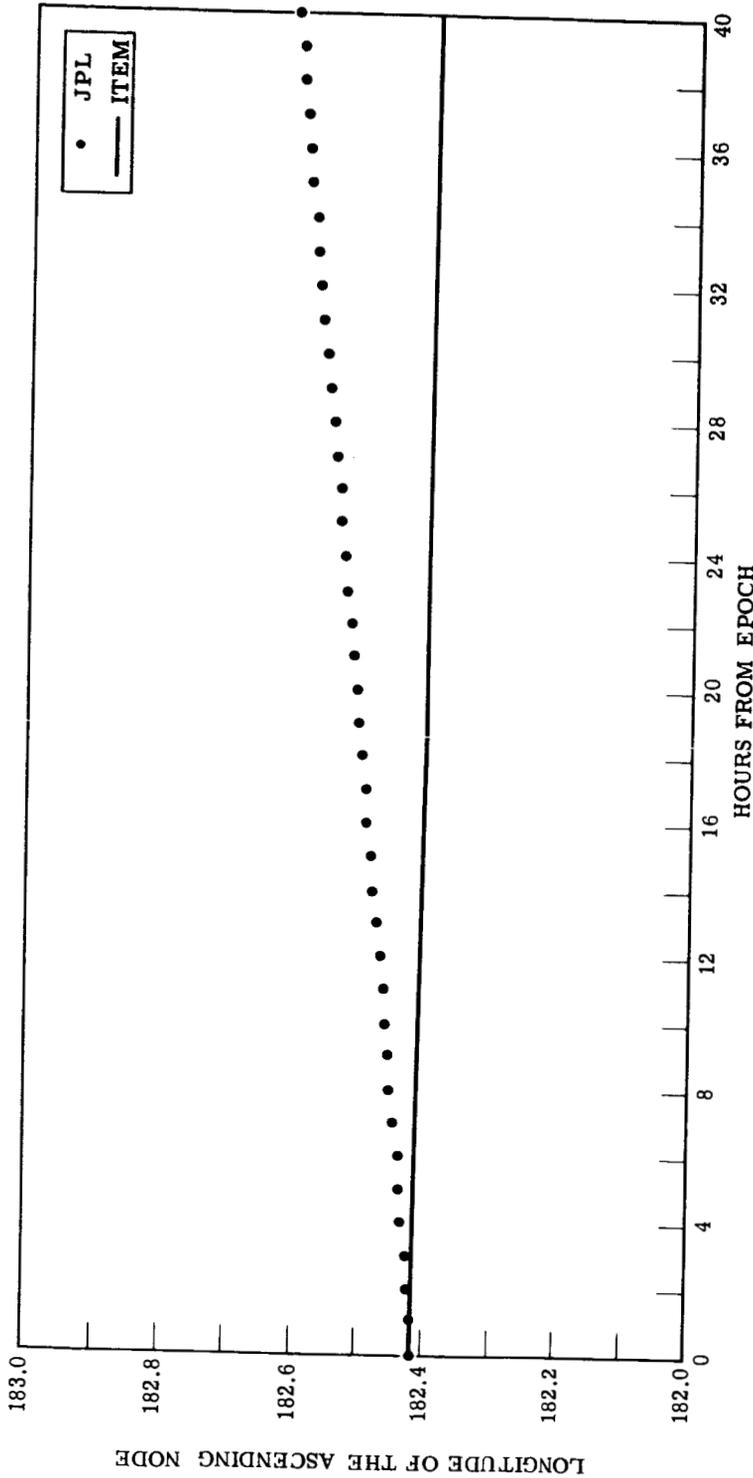
INJECTION CONDITIONS
 Semi-major Axis : 1894.5783 km
 Eccentricity : 0.00041970610
 Inclination : 155°80'47.26
 Long. of Ascending Node : 182°41'40.87
 Argument of Pericynthion : 262°8'77.16900
 Mean Anomaly : 0°00'08.24

DATE OF EPOCH
 September 20, 1969
 5 hours/10 minutes/12.176 seconds

COORDINATE SYSTEM
 Center : Selenocentric
 Fundamental Plane : Parallel to the Earth's Equatorial Plane } Item Data
 X-Axis : Mean Equinox of Date }
 Center : Selenocentric
 Fundamental Plane : True Equator of Date } JPL Data
 X-Axis : True Equinox of Date }

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Figure B-3 Inclination (degrees) Vs Hours from Epoch



INJECTION CONDITIONS

Semi-major Axis : 1894.5783 km
 Eccentricity : 0.00041970610
 Inclination : 155°80'47.26
 Long. of Ascending Node : 182°41'40.87
 Argument of Pericynthion : 262°87'16.900
 Mean Anomaly : 0°00'08.24

DATE OF EPOCH

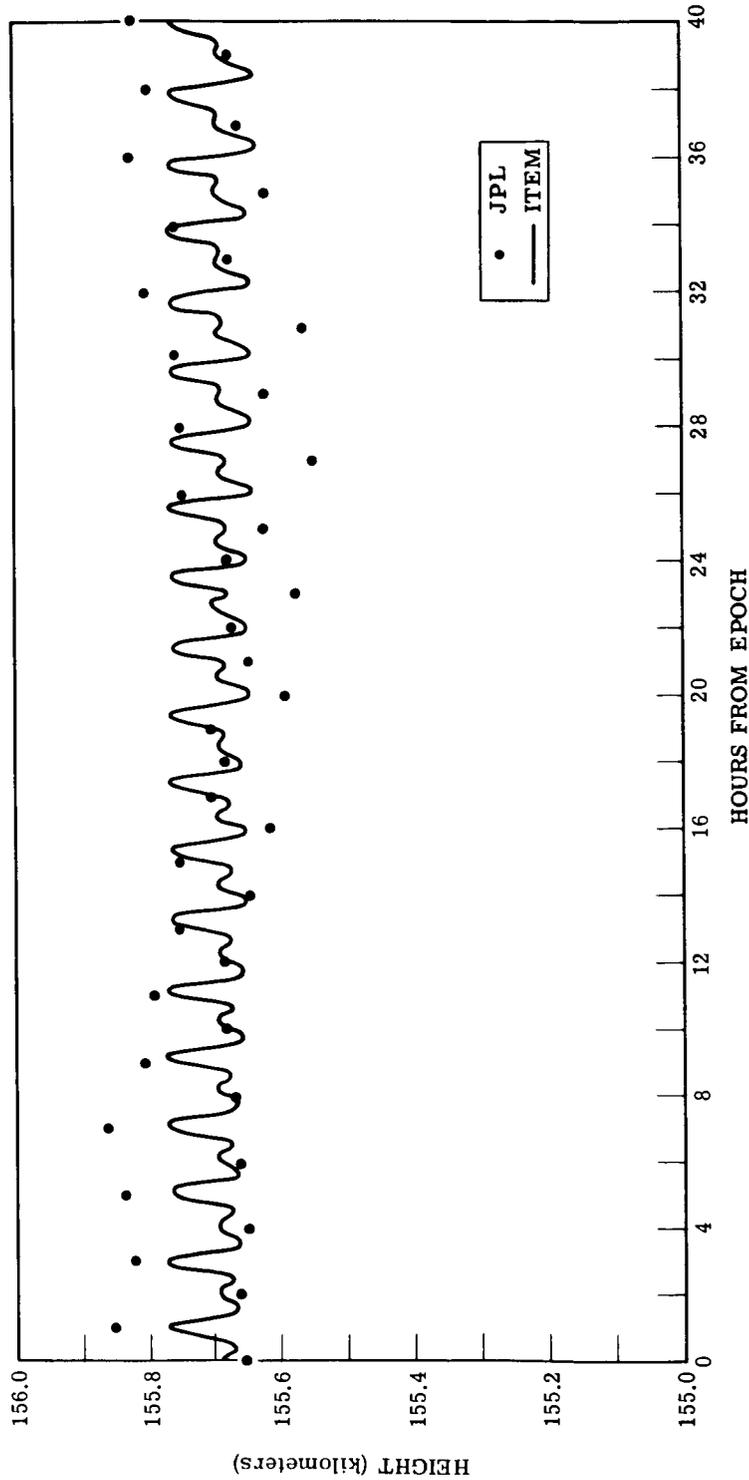
September 20, 1969
 5 hours/10 minutes/12.176 seconds

COORDINATE SYSTEM

Center	: Selenocentric	} Item Data
Fundamental Plane	: Parallel to the Earth's Equatorial Plane	
X-Axis	: Mean Equinox of Date	
Center	: Selenocentric	} JPL Data
Fundamental Plane	: True Equinox of Date	
X-Axis	: True Equinox of Date	

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Figure B-4 Longitude of the Ascending Node (degrees) Vs Hours from Epoch



INJECTION CONDITIONS

Semi-major Axis : 1894.5783 km
 Eccentricity : 0.00041970610
 Inclination : 155°30'47.26
 Long. of Ascending Node : 182°41'40.87
 Argument of Pericynthion : 262°87'16.900
 Mean Anomaly : 0°00'08.24

DATE OF EPOCH

September 20, 1969
 5 hours/10 minutes/12.176 seconds

COORDINATE SYSTEM

Center : Selenocentric
 Fundamental Plane : Parallel to the Earth's Equatorial Plane } Item
 X-Axis : Mean Equinox of Date } Data

Center : Selenocentric
 Fundamental Plane : True Equator of Date } JPL Data
 X-Axis : True Equinox of Date }

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Figure B-5 Height (kilometers) Vs Hours from Epoch

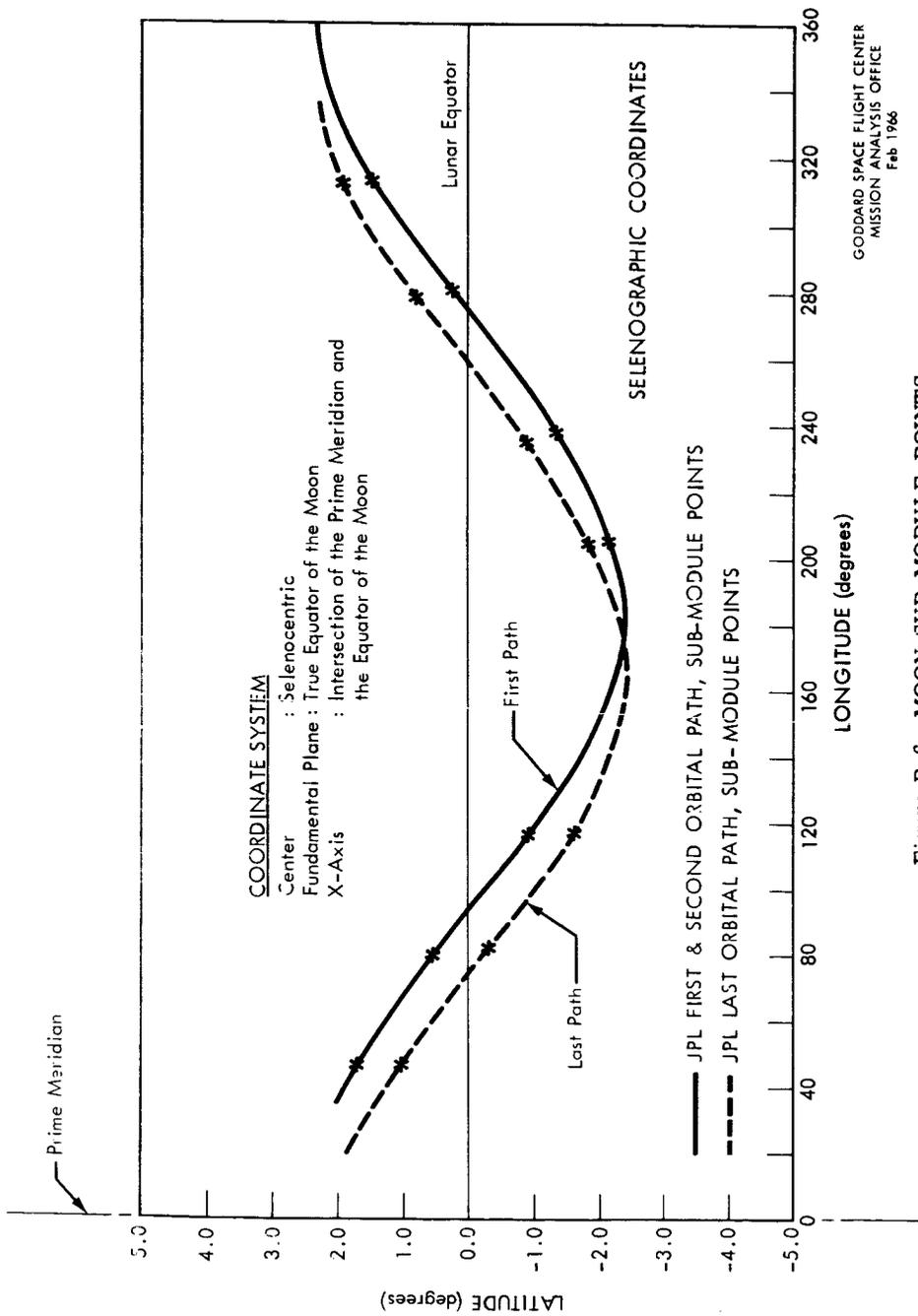


Figure B-6 MOON SUB-MODULE POINTS
 Latitude Vs Longitude

APPENDIX A

CONSTANTS

JPL NAME	QUANTITY	JPL VALUE	GSFC ITEM VALUE	ANWG APOLLO NAME	ANWG APOLLO VALUE & QUANTITY
GME	gravitational coefficient for earth	$3.986\ 0320 \times 10^5 \text{ km}^3/\text{sec}^2$	$19.909\ 4165 \text{ er}^3/\text{hr}^2$	μ EARTH	gravitational parameter for earth $3.986\ 032 \times 10^4 \text{ m}^3/\text{sec}^2$ $1.990\ 941\ 65 \times 10 \text{ er}^3/\text{hr}^2$
GMM	gravitational coefficient for moon	$4.900\ 7589 \times 10^3 \text{ km}^3/\text{sec}^2$	$0.244\ 782\ 8913 \text{ er}^3/\text{hr}^2$	μ MOON	gravitational parameter for moon $4.902\ 778 \times 10^{12} \text{ m}^3/\text{sec}^2$ $0.244\ 883\ 757 \text{ er}^3/\text{hr}^2$
GMS	gravitational coefficient for sun	$1.327\ 154\ 4 \times 10^{11} \text{ km}^3/\text{sec}^2$	$0.513\ 736\ 472 \times 10^{-6} \text{ au}^3/\text{hr}^2$	μ SUN	gravitational parameters for sun $1.327\ 154\ 45 \times 10^{20} \text{ m}^3/\text{sec}^2$ $6.628\ 865\ 88 \times 10^6 \text{ er}^3/\text{hr}^2$
GMA	gravitational coefficient for mars	$4.297\ 779\ 9 \times 10^4 \text{ km}^3/\text{sec}^2$	$0.166\ 365\ 411\ 7 \times 10^{-12} \text{ au}^3/\text{hr}^2$	n.a.	n.a.
GMV	gravitational coefficient for venus	$3.247\ 695\ 0 \times 10^5 \text{ km}^3/\text{sec}^2$	$0.125\ 717\ 034\ 3 \times 10^{-11} \text{ au}^3/\text{hr}^2$	n.a.	n.a.
GMB	gravitational coefficient for barycenter	$4.035\ 039\ 5 \times 10^5 \text{ km}^3/\text{sec}^2$	not in GSFC Item	n.a.	n.a.
GMJ	gravitational coefficient for jupiter	$1.267\ 106\ 0 \times 10^6 \text{ km}^3/\text{sec}^2$	$0.490\ 492\ 590\ 7 \times 10^9 \text{ au}^3/\text{hr}^2$	n.a.	n.a.
J	coefficient of the second harmonic in earth's oblateness	$1.623\ 4500 \times 10^{-3}$ non-dimensional	1082.3×10^{-6} non-dimensional	J C _{2,0}	constants associated with the gravitational potential of the earth $1.623\ 45 \times 10^{-3}$ -1082.30×10^{-6}
H	coefficient of the third harmonic in earth's oblateness	$-0.574\ 999\ 99 \times 10^{-5}$ non-dimensional	-2.3×10^{-6} non-dimensional	H C _{3,0}	constants associated with the gravitational potential for the earth -0.575×10^{-5} 2.3×10^{-6}
D	coefficient of the fourth harmonic in earth's oblateness	$0.787\ 499\ 99 \times 10^{-5}$ non-dimensional	-1.8×10^{-6} non-dimensional	D C _{4,0}	constants associated with the gravitational potential of the earth $0.787\ 5 \times 10^{-5}$ 1.8×10^{-6}
RE	earth's radius to be used in earth's oblate potential	6378.165 km	6378.165 km	Re	earth radius 6378.165 km
G	universal gravitational constant for lunar oblateness	$4.902\ 643 \times 10^{12} \text{ m}^3/\text{sec}^2$	$0.244\ 782\ 9 \text{ er}^3/\text{hr}^2$	μ MOON μ MOON	gravitational parameters for the moon $2.448\ 837\ 57 \times 10^{-1} \text{ er}^3/\text{hr}^2$ $4.902\ 778 \times 10^{12} \text{ m}^3/\text{sec}^2$
A	moment of inertia for the moon to be used in the lunar oblate potential	$0.887\ 459\ 98 \times 10^{29} \text{ kg}\cdot\text{km}^2$	$0.887\ 46 \times 10^{35} \text{ kg}\cdot\text{m}^2$	A	moment of inertia about principal rotational axis $0.887\ 817\ 983\ 4 \times 10^{35} \text{ kg}\cdot\text{m}^2$
B	moment of inertia for the moon to be used in the lunar oblate potential	$0.887\ 639\ 98 \times 10^{29} \text{ kg}\cdot\text{km}^2$	$0.887\ 64 \times 10^{35} \text{ kg}\cdot\text{m}^2$	B	moment of inertia about principal axis $0.888\ 001\ 9542 \times 10^{35} \text{ kg}\cdot\text{m}^2$
C	moment of inertia for the moon to be used in the lunar oblate potential	$0.888\ 0099\ 8 \times 10^{29} \text{ kg}\cdot\text{km}^2$	$0.880\ 1 \times 10^{35} \text{ kg}\cdot\text{m}^2$	C	moment of inertia about principal axis $0.888\ 369\ 781\ 7 \times 10^{35} \text{ kg}\cdot\text{m}^2$
OME	rotational rate of the earth	0.004 178 074 1 deg/sec	0.262 516 170 81 rads/hr	ω	angular velocity of the earth's rotation $4.178\ 074\ 16 \times 10^{-3} \text{ deg}/\text{sec}$ 0.262 516 142 rad/hr
au	astronomical unit to convert planetary ephemerides to km	$1.495\ 990\ 0 \times 10^8 \text{ km}/\text{au}$	$1.495\ 99 \times 10^8 \text{ km}/\text{au}$	au	astronomical unit $1.495\ 990\ 00 \times 10^{11} \text{ m}$
REM	earth radius to convert lunar ephemerides to kilometers	6378.165 km	6378.165 km	n.a.	n.a.

n.a. = not applicable.