JET PROPULSION LABORATORY **INTEROFFICE MEMORANDUM**

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TO: Distribution

FROM: E. A. Belbruno and J. K. Miller

SUBJECT: A Ballistic Lunar Capture Trajectory For The Japanese Spacecraft Hiten

References:

[1] Belbruno, E.A., "Examples of the Nonlinear Dynamics of Ballistic Capture and Escape in the Earth-Moon System," AIAA Paper #90-2896, August 1990. (In Progress)

[2] Belbruno, E.A., "Lunar Capture Orbits, a Method of Constructing Earth-Moon Trajectories and the Lunar GAS Mission," AIAA/DGLR/JSASS Inter. Elec. Propl. Conf., Paper AIAA-87-1054, May 1987.

Summary: The purpose of this memo is to document two integrated trajectories which go from the present elliptic orbit for the Hiten S/C to ballistic lunar capture at a periapsis altitude of 100 km requiring between 30 m/s - 169 m/s. This is within the propellant budget which is approximately 250 m/s. Because of this constraint, the trajectories are nonlinear and are found by utilizing the nonlinear four-body interaction between the Sun-Earth-Moon-S/C. Approximately four months are required to transfer from the present Hiten S/C orbit to ballistic lunar capture. The captured orbit needs to be stabilized. The trajectories are generated with DPTRAJ. The construction of trajectories with more current mission data and time frames is in progress.

1. Introduction. The Japanese S/C Hiten is presently orbiting the Earth in an elliptic orbit with an apoapsis of 759,843 km, a periapsis of 29,417 km, which gives an eccentricity of .93. The period of this orbit is 28.6 days. This S/C was previously called MUSESA which was launched on January 24, 1990 from Kagashima in Japan. It has been desired to get the Hiten S/C into an orbit about the Moon in order to perform gravity field measurements. The desired captured orbit for this S/C is required to have a periapsis of 100 km. This condition is difficult to achieve since the S/C only has 250 m/s available for maneuvers. One purpose of this memo is to provide a trajectory which transfers from the present Hiten S/C trajectory to an elliptic ballistic lunar capture orbit with a periapsis of 100 km within the propellant requirements where approximately 169 m/s is required. The transfer time is approximately four months. A sensitivity analysis for this trajectory is not carried out. Another integrated

trajectory is described which shows that under suitable conditions only 30 m/s is required for lunar capture.

→ Ref 2 – The 1987 AIAA Paper

The methodology for finding these trajectories is described below in Section 2. The utilization of weak stability boundaries [1,2] is the key to the solution. These boundaries estimate transition regions due to the four-body Sun-Earth-Moon-S/C interaction where the gravitational interactions tend to balance, and provide a more realistic estimation of these regions than is possible with the classical sphere of influence. The weak stability boundaries are estimated by accurately measuring the distance from a planetary body in question where elliptic motion breaks down due to other perturbations. This distance is a function of both the radial orientation from the body that the elliptic initial conditions are taken, and the ellipticity. The breakdown occurs when the trajectory is no longer able to orbit completely around the body in question and instead escapes this body and orbits another. This process is schematically shown in Figure 0 in the planar case for measuring the boundary about the Moon. The breakdown distance is labeled r_1 in this figure. The boundaries yield locations where ballistic capture at the Moon is possible with minimal propellant usage. Most of the capture is ballistic, however, deterministic maneuvers are performed prior to lunar capture in order to carry out the complete transfer. The largest maneuver is done in the Earth-Sun transition region. This maneuver is done to counter the Sun's perturbative effect. The perturbative effect of the Sun is instrumental in reducing the size of the maneuvers required for lunar capture.

The trajectories are simulated using a version of DPTRAJ called FAST. It is necessary to design the trajectories with this precision software in order to realize the subtle four-body effects. The motions of the planets are modeled by the ephemeris DE118. Solar radiation pressure is also modeled. Key trajectory events are listed in Section 3. The starting time is taken at the periapsis of the initial lunar flyby which begins to alter the trajectories by increasing their energy. The trajectories then have an apoapsis at approximately 1.5 million km from the Earth after about two months. This turns out to be near the weak stability boundary for the Earth due to the Sun. A maneuver is performed at this point in order to make each of the trajectories fall back towards the Moon in about two months. This maneuver is the crucial one since it causes the trajectories fall into a ballistic capture orbit which ballistically transfer to an ellipse at the Moon with a periapsis of 100 km from the lunar surface and with an eccentricity of about .94. The ellipse is unstable and must be stabilized, otherwise the trajectory will leave the Moon. This capture orbit starts from the 1.5 million km point and was found by starting from the desired weakly captured ellipse at the Moon and integrating backwards in time. The weakly captured ellipse and its qualitative behavior were known from previous theoretical studies. The apriori knowledge of the dynamics of this orbit by backwards integration was key in being able to match it with a maneuver at the 1.5 million km point with the portion of the trajectory which came from the lunar flyby.

A complete transfer trajectory is plotted in Figures 1-6 for different projections. A blow up of the capture portion is indicated.

The more direct approach using traditional transfer constructions is briefly described in Section 4.

The FAST runstreams for these trajectories can be found in the files 08787*EAB.HITEN1 and 08787*EAB.HITEN2 on the Univac B machine. The trajectory printouts are available upon request.

2. Trajectory Design Methodology. The idea of constructing a trajectory from the Hiten S/C elliptic orbit to lunar capture is to first modify the original elliptic orbit with a lunar flyby. This can be done by phasing with two small maneuvers on the order of 10-20 m/s. The lunar flyby increases the orbital energy. This increased energy raises its apoapsis to approximately 1.5 million km. This apoapsis distance was required in order to be at the desired position in the Earth's weak stability boundary where very small maneuvers will cause large changes to the trajectory due to the balancing of the Earth and Sun perturbative effects. As will be described, a small maneuver will cause the trajectory to return to the

Moon and achieve ballistic capture. This return trajectory is found by beginning with a desired capture ellipse at the Moon with a periapsis of 100 km, and then by integrating backwards in time. In order to insure that integration backwards in time from a lunar capture ellipse will lead to escape from the Moon to the 1.5 million km point, it is necessary that this ellipse is suitably unstable. This is done by requiring that the ellipse be in the weak stability boundary (WSB) of the Moon due to the Earth and Sun. In order that the lunar capture ellipse of a periapsis of 100 km be in the WSB with the given orientation, its eccentricity should be approximately .95.

Once the trajectory is integrated back to the 1.5 million km point, a small maneuver is done in order to match it with the other piece which came from the lunar flyby. This maneuver is the largest performed and is also in an unstable region. If the trajectories went too much beyond this distance, say 1.7 million km, the solar perturbations would be too strong and pull the S/C away from the Earth-Moon system into orbit about the Sun. Matching trajectories in this region is sensitive.

Thus, the trajectory construction can be viewed as the following process:

a.) Escape from the original S/C elliptic trajectory by a lunar flyby to the Earth WSB in two months at 1.5 million km from the Earth.

b.) Perform a maneuver at the 1.5 million km point in the Earth's WSB in order to phase into a lunar capture trajectory.

c.) Follow the lunar capture orbit from the Earth WSB for two months to ballistic lunar capture at 100 km from the lunar surface at the lunar WSB.

Additional maneuvers are performed along this trajectory in order initially match the Hiten trajectory and to stabilize the capture ellipse. These are described in the next section for each of the examples labeled Example #1 and Example #2. They were found by the following shooting method:

The initial data is taken from the values given by weak stability theory for the capture ellipse and from the actual Hiten conditions prior to lunar flyby. The proper phasing and trajectory integration was first carried out with software developed by J. Miller. These converged solutions were input into FAST where final targeting was performed. FAST was also used to manually optimize the maneuver at the 1.5 million km point by breaking it up into two maneuvers and retargeting from one maneuver to the other.

The construction of lunar capture orbits to the lunar WSB were successfully carried out in [2] for the Lunar GAS mission study with a similar technique by backwards integration. However, that problem was simpler than the one reported on in this memo.

3. Key Trajectory Events

Example #1:

1.	Lunar Flyby	Periapsis Altitude	=	19,767 km
	T= 08/05/1990	Velocity at Periapsis	=	1.36 km/s
	01:19:49 (ET)	V_∞	=	1.18 km/s
		B-Plane Angle	=	-1.6 degrees (EME50)
2.	Maneuver #1	ΔV	=	43 m/s
	T= 09/03/1990	Radius	=	1,379,211 km (EC)
	23:33:45			
3.	Apoapsis	Radius	=	1,463,634 km (EC)
	T= 09/27/1990	Velocity	=	233 m/s
	04:15:15			

4.	Maneuver #2 T= 10/24/1990 00:00:00	ΔV Radius	= =	126 m/s 1,315,555 km (EC)
5.	Lunar Capture T= 12/19/990 02:51:52	Periapsis Altitude Velocity at Periapsis Semi-major Axis Eccentricity	= = = =	100 km 2.28 km/s 32,361 km .94

A plot of this trajectory is shown in Figures 1-6 for different views. An ecliptic coordinate system (EMO50) is used throughout where the X-axis points to the vernal equinox of 1950, and the XY-plane is the ecliptic plane. These plots were generated from a FAST P-File. The program FAST was run with all planetary perturbations obtained via DE118. Solar radiation pressure was also modeled. Approximately, 10-20 m/s should be alloted for the actual Hiten trajectory in order to phase into the trajectory given by Example #1.

Example #2:

1.	Start T= 08/03/1990 14:59:10 (ET)	Radius Velocity	= =	36,124 km 4.61 km/s
2.	Lunar Flyby T= 08/05/1990 22:35:48	Periapsis Altitude Velocity at Periapsis V_∞ B-Plane Angle	= = = =	38,971 km 1.49 km/s 1.42 km/s 70 degrees (EME50)

3.	Maneuver #1 T= 09/10/1990 21:14:07	ΔV Radius	= =	30 m/s 1,423,261 km
4.	Apoapsis T= 09/23/1990 02:29:06	Radius Velocity	= =	1,451,839 km 226 m/s
5.	Lunar Capture T= 12/19/1990 02:42:27	Periapsis Altitude Velocity at Periapsis Semi-major Axis Eccentricity	= = = =	100 km 2.28 km/s 33,033 km .94

This example as it stands is not exactly phased with the actual Hiten trajectory. However, it demonstrates that if it were possible to have better phasing the ΔV could be reduced to 30 m/s with our approach. Thus, the value of 169 m/s obtained in Example #1 should be able to be improved.

Example #2 is plotted in Figure 7.

4. Classical Hohman Transfer Approach

The direct and more obvious approach to achieve lunar capture is to maneuver the Hiten spacecraft into an orbit that is as close to rendezvous with the Moon's orbit as possible, and then perform an orbit insertion maneuver at lunar periapsis. The concept here is to reduce the hyperbolic excess velocity at the Moon to as low a value as possible and insert at periapsis which is the most energy efficient transfer point. A flyby of the Moon can be designed to reduce the apoapsis altitude of the spacecraft orbit to the radius of the Moon's orbit. The resulting orbit resembles a Hohman transfer orbit from the Earth to the Moon. The periapsis altitude at the Earth is around 20,000 km and there is little one can do to raise the periapsis altitude without changing the apoapsis altitude. It would be desirable if the resulting orbit were circular. Then, we could phase with the Moon's orbit and drop into orbit around the Moon in an ellipse of eccentricity of approximately 0.9 for about 120 m/s. However, since the transfer orbit has a periapsis altitude of around 20,000 km relative to the Earth, it should take around 225 mps to achieve orbit around the Moon with a periapsis of 100 km and an eccentricity of 0.9. This analysis ignores weak stability boundary effects due to the Sun and Earth in the vicinity of the Moon. It may be possible to design a transfer orbit that takes into account the interplay between the Sun, Earth and Moon gravity fields to achieve an orbit with less delta-V.

5. Orbit Trim and Stabilization

The initial capture orbit about the Moon is in the weak stability region and must be stabilized to prevent escape. Stabilizing the orbit involves performing a small maneuver at periapsis to reduce the orbital energy such that the spacecraft is well within the Moon's gravity well. A maneuver of between 10-20 m/s to reduce orbital eccentricity to around .90 should suffice. Before performing this maneuver, it may be desirable to trim the orbit to an orbit that improves gravity harmonic determination. The ideal orbit is a low circular orbit at high inclination relative to the Moon's equator such that global coverage of the Moon's gravity field may be obtained. The delta velocity required to circularize a highly eccentric orbit at 100 km altitude is several hundred meters per second. This is far beyond the roughly 250 m/s available from the Hiten spacecraft. A good compromise would be a high inclination orbit with a periapsis altitude of 100 km provided the periapsis point is near the equator. This would provide excellent coverage of the equatorial region and coverage of both poles at less than two Moon radii for high eccentricity orbits. The 100 km altitude orbit is no problem since the capture orbit is designed to have this value. Placing the periapsis point on the equator may pose a problem; however, we have some latitude in the capture orbit design and precession of the orbit due to J_2 may achieve this condition in time. The initial orbit inclination may also be controlled by capture orbit design. A propulsive maneuver to raise inclination may be needed though and this is best performed at apoapsis in the initial capture orbit. A maximum of 50 m/s is required to raise inclination to a polar orbit. Thus, the scenario for mission operations would be an inclination raise maneuver immediately after capture, if required, followed by an orbit stabilization maneuver several days later. The inclination raise maneuver may be designed to provide enough stabilization to hold the spacecraft in lunar orbit for several weeks.

Remarks - Jim Miller has made a comparison of the trajectory construction procedure to riding the crests of waves while on a surfboard. The crests can be thought of as WSB's. A recommendation to the trajectory verification process is to test this analogy at a local beach.

Acknowledgements:

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TRANSITION REGION ESTIMATION
FOR THE MOON

PLANAR CASE

DIRECT WEAK STABILITY BOUNDARY

Propogate Trajectories Along Radial Line From The Moon
With Initial Elliptic State at Periapsis of Eccentricity e

Fix e, θ

Measure Breakdown Distance r_1

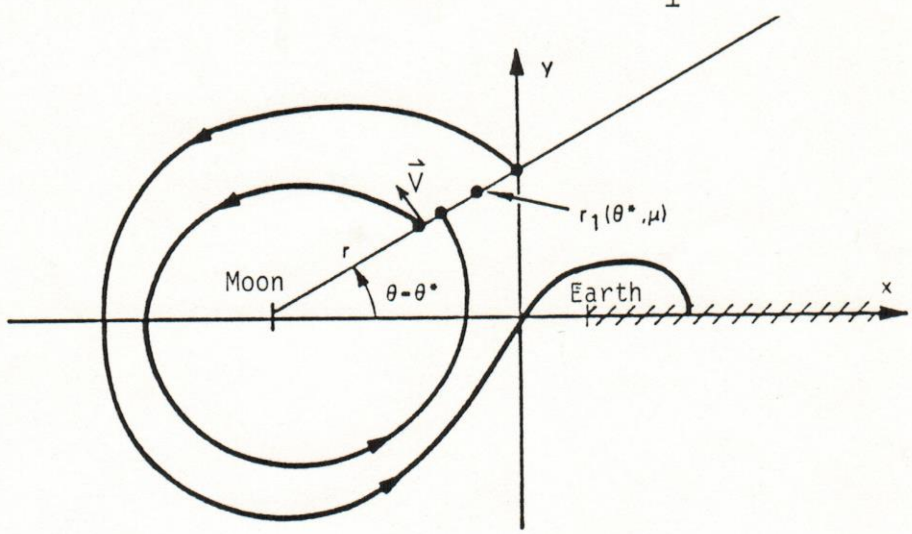
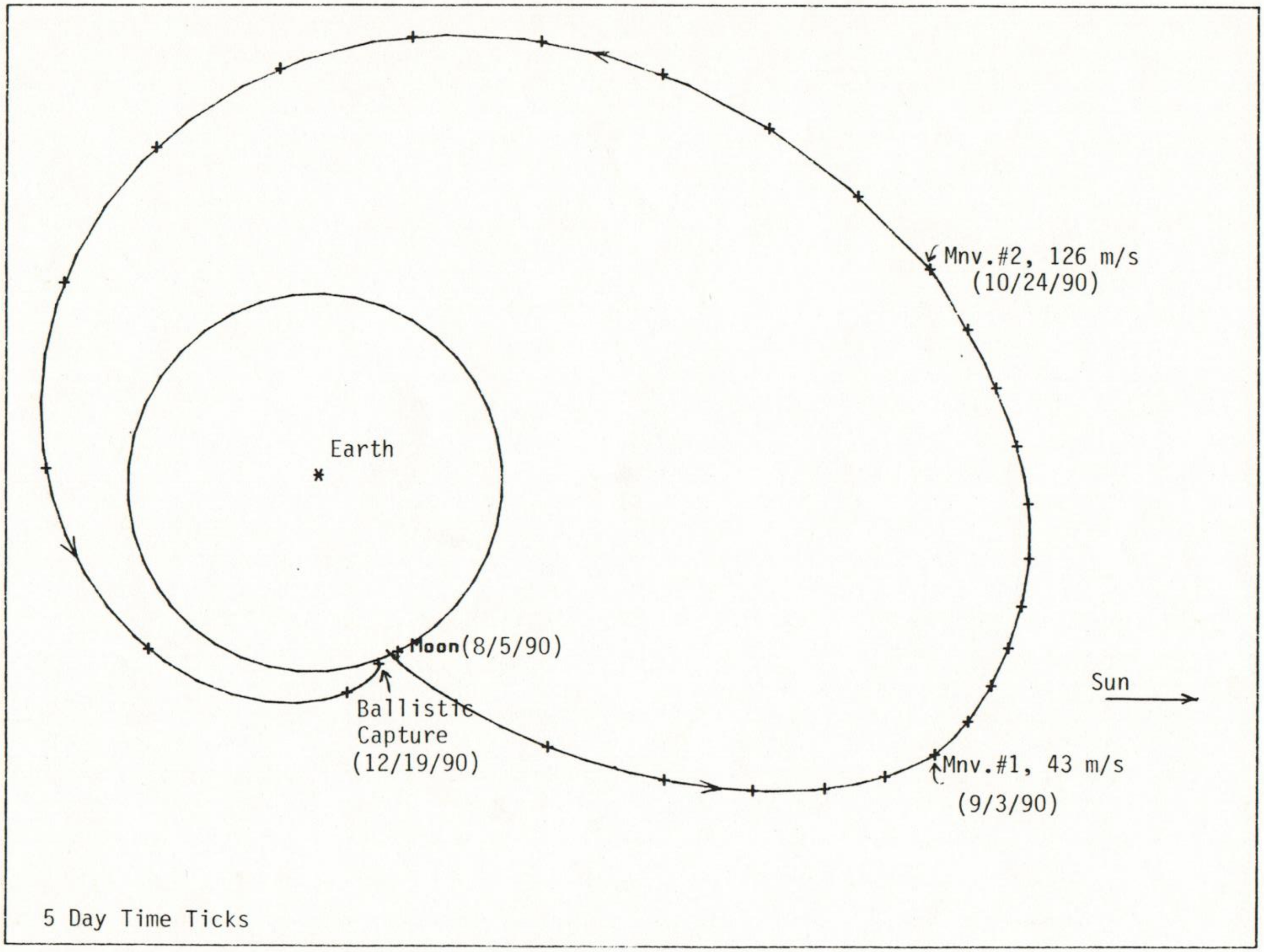


Figure 0.

$$WSB = \left\{ r_1 \;\middle|\; \theta \in [0, 2\pi] \;,\; \vec{V} \text{ counterclockwise} \right\}$$

As $e \uparrow 1$, $r_1 \downarrow 0$.

MUSES LUNAR CAPTURE ORBIT



Ecliptic Plane (XY) Projection (EM050), FAST Integrated
Capture at 100 km Altitude

Figure 1.

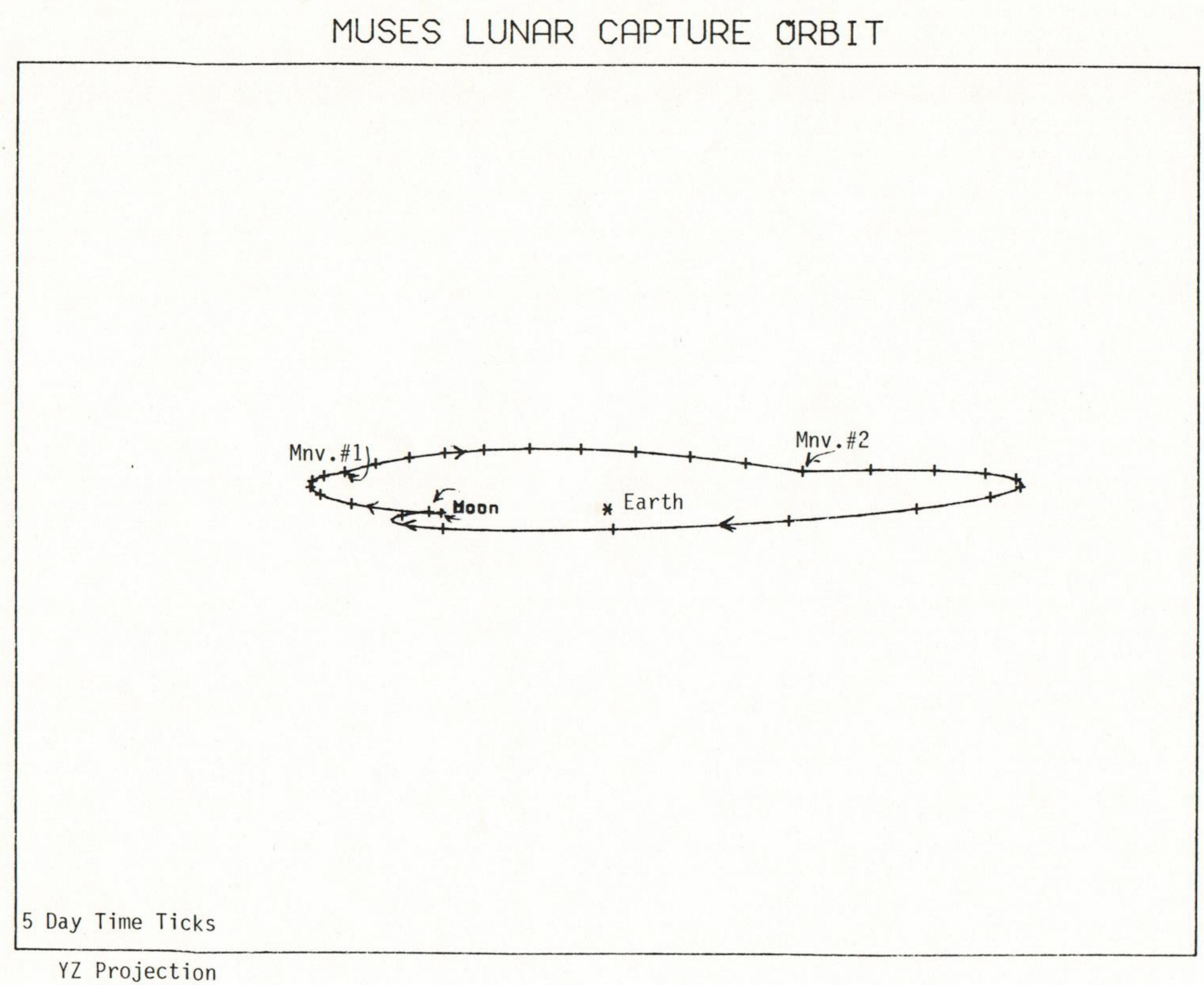
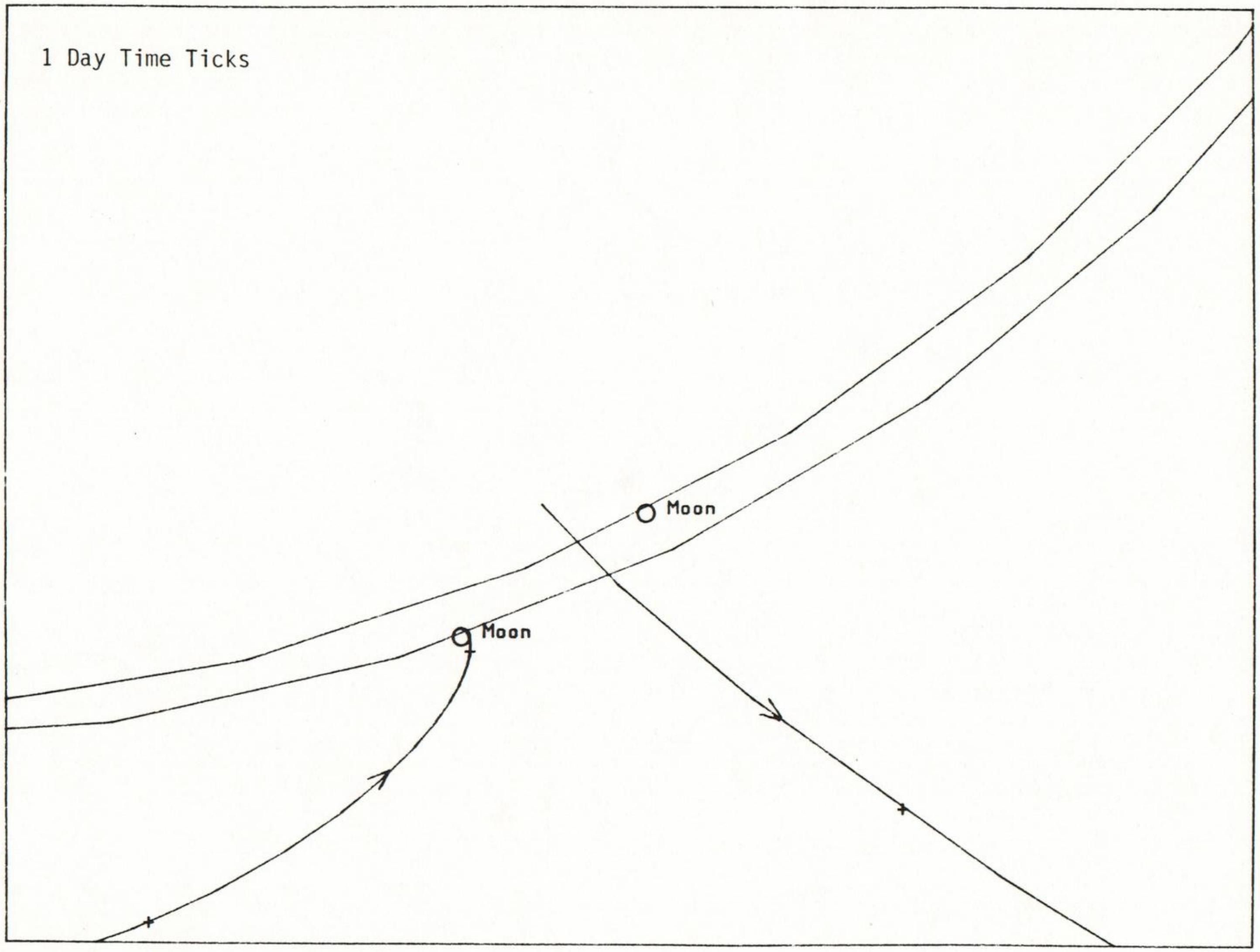

MUSES LUNAR CAPTURE ORBIT
Mnv.#1
Mnv.#2
Moon
Earth
5 Day Time Ticks
YZ Projection

Figure 2.

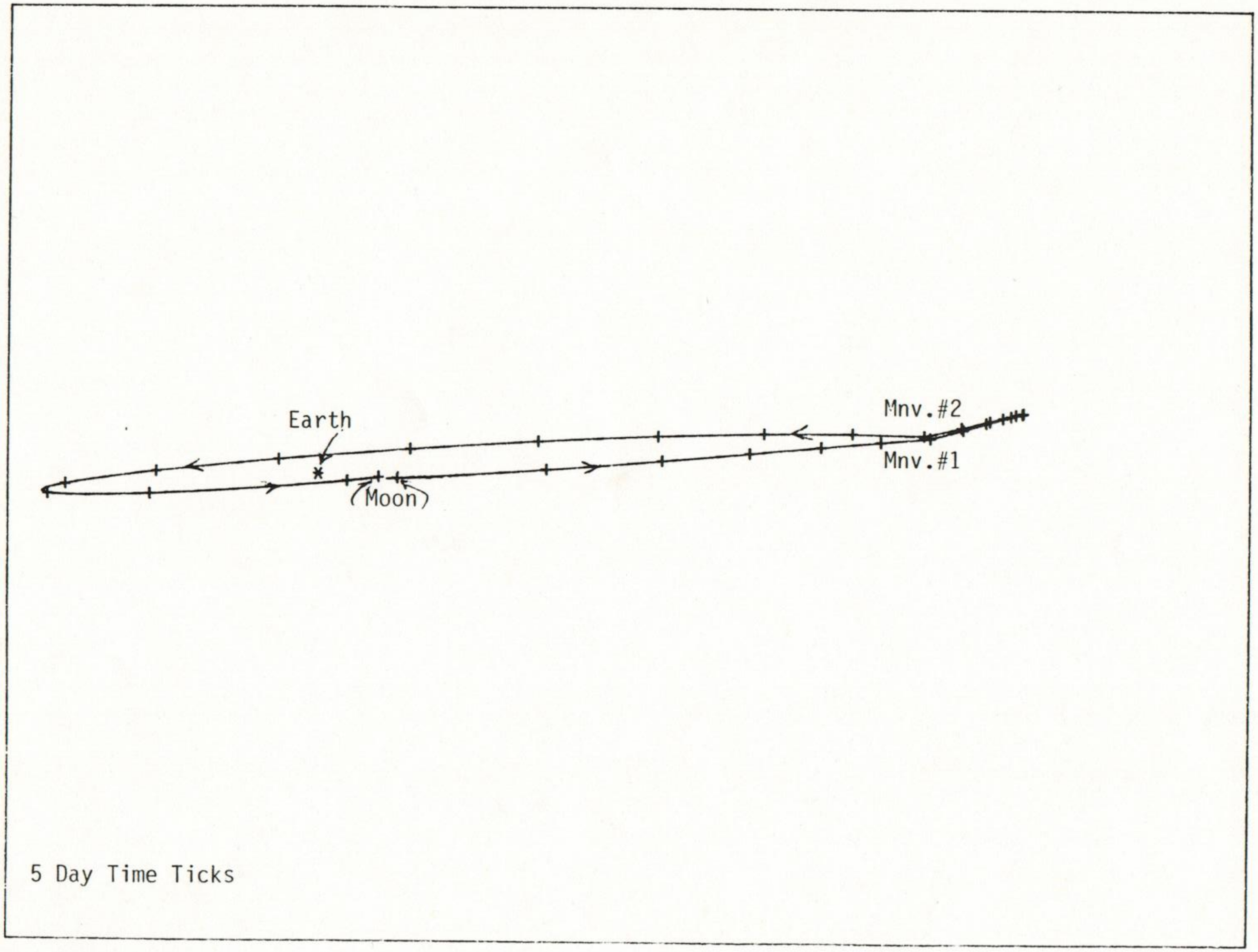
MUSES LUNAR CAPTURE ORBIT



Ecliptic Plane (XY) Projection

Figure 3.

MUSES LUNAR CAPTURE ORBIT



XZ Projection

Figure 4.

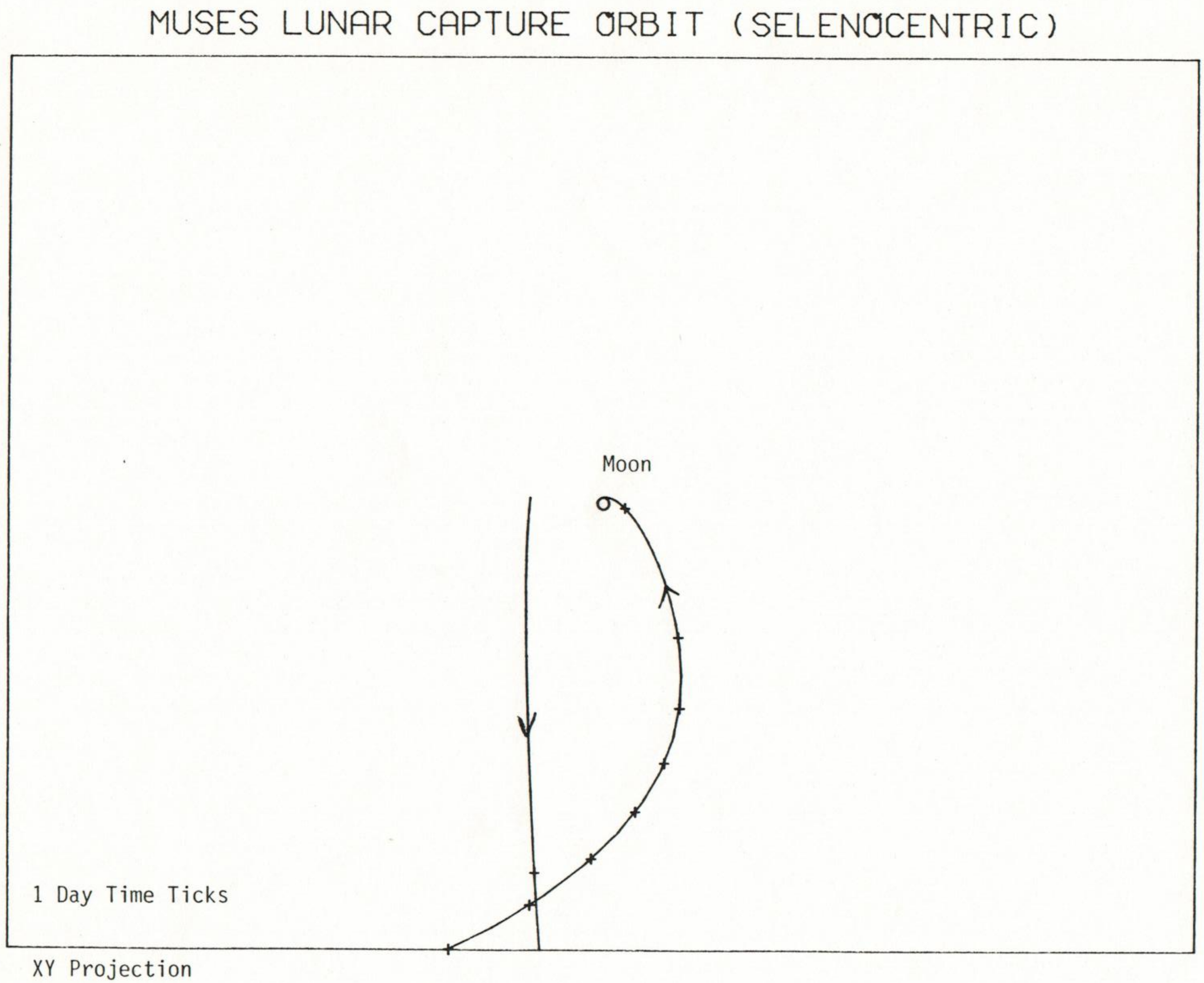
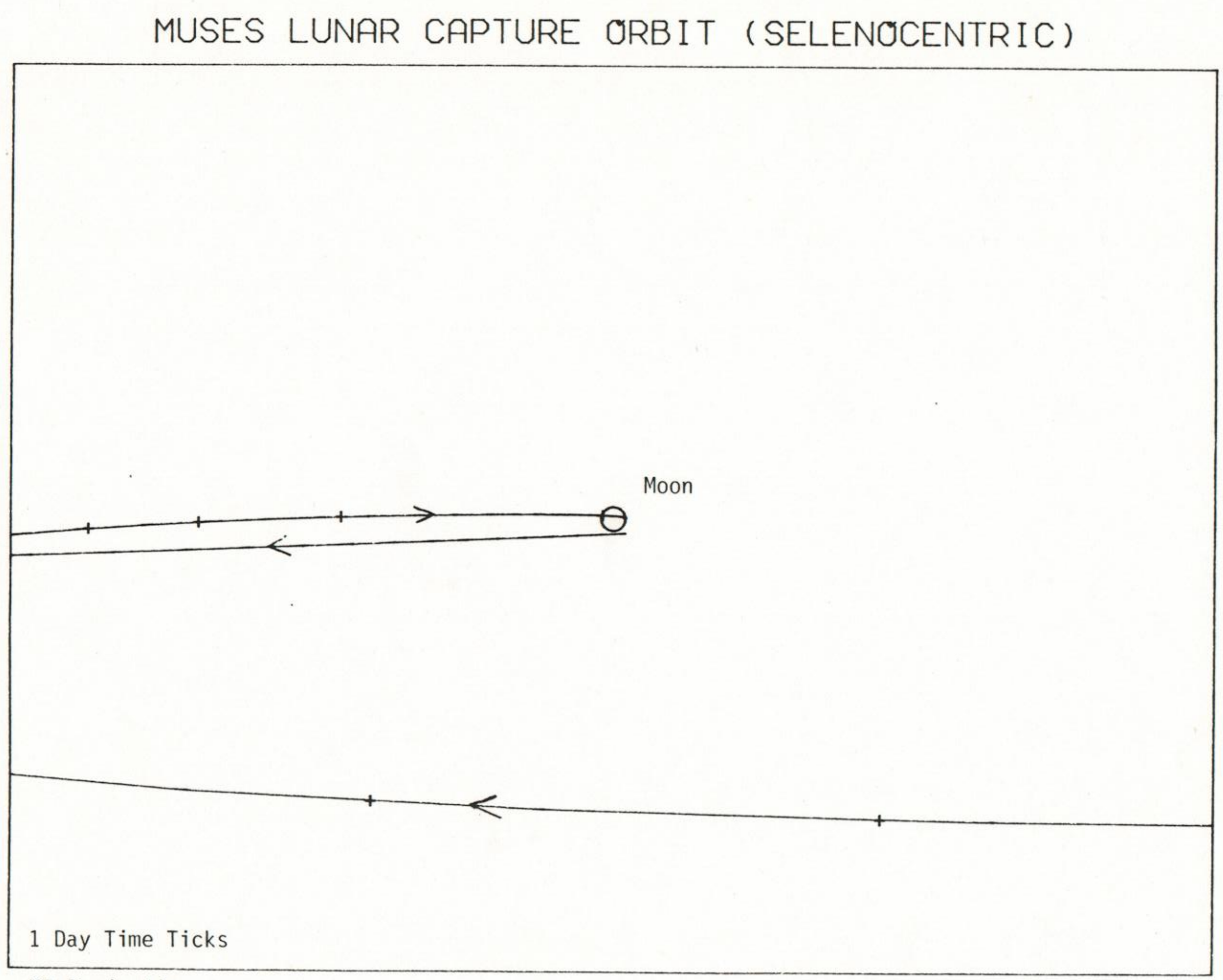
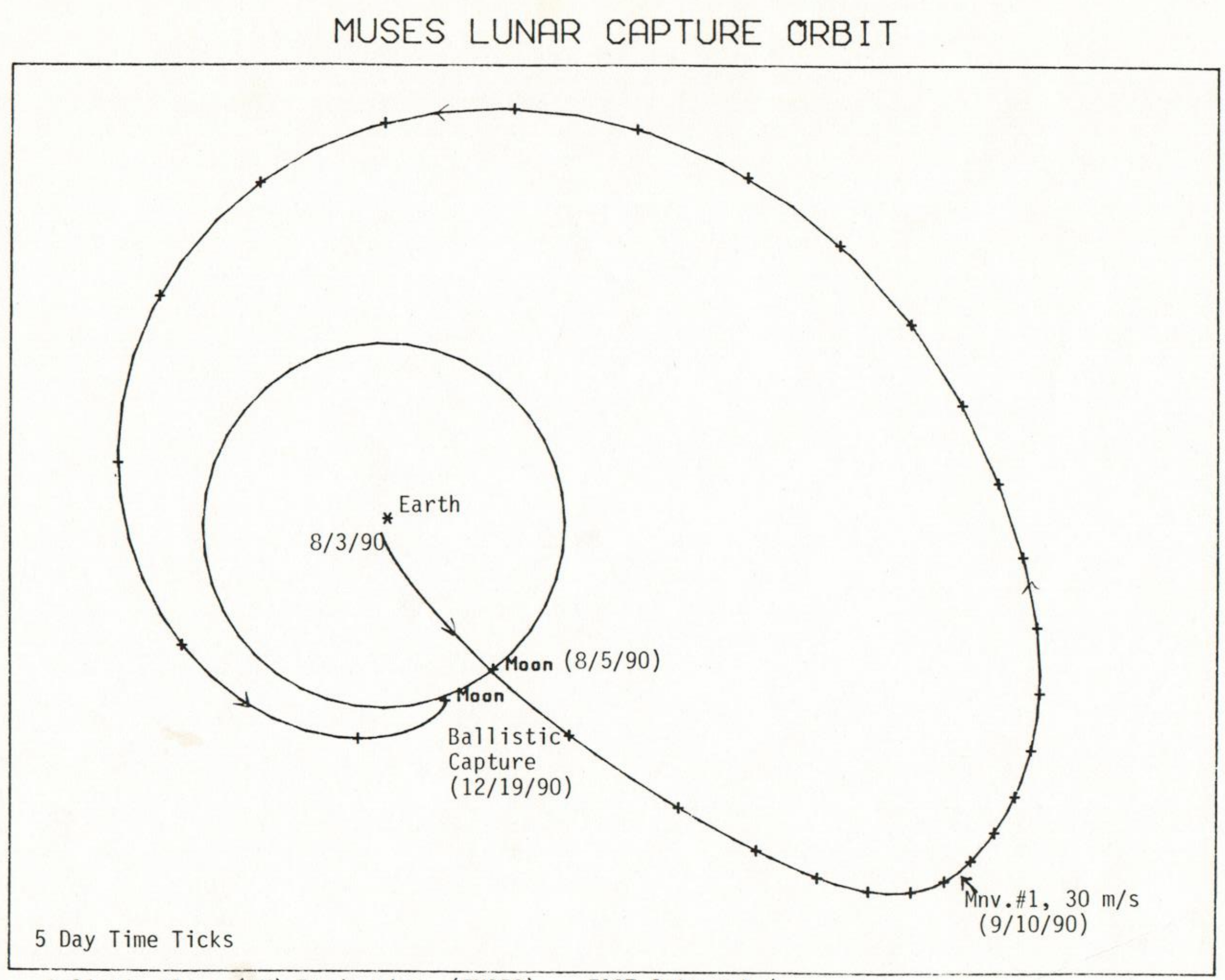

MUSES LUNAR CAPTURE ORBIT (SELENOCENTRIC)
Moon
1 Day Time Ticks
XY Projection

Figure 5.



YZ Projection

Figure 6.



Ecliptic Plane (XY) Projection (EM050), FAST Integrated
Capture at 100 km Altitude

Figure 7.