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NAVIGATION FEASIBILITY STUDIES FOR THE EUROPA ORBITER MISSION

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This paper describes preliminary navigation analyses for the proposed Europa Orbiter mission. To quantify achievable navigation accuracies, orbit uncertainties are computed for simulated range and Doppler tracking coverage from NASA's Deep Space Network stations. In addition, optical communication range tracking is simulated to assess its capabilities against those of traditional radiometric tracking. Emphasis is placed on the operations phase of the mission for which additional navigation considerations are investigated; these include spacecraft safety shortly after Europa orbit insertion and sensitivity to various orbit configurations.

INTRODUCTION

The proposed NASA/JPL Europa Orbiter Mission has gained increasing importance recently because of speculations that liquid water oceans may exist below the ice surface of the Jovian moon Europa. It is believed that the subsurface oceans could be thermally supported by the intense tidal forces of Jupiter. The existence of liquid water is thought to be an integral part to the formation of life, so identifying a liquid water ocean elsewhere in the Solar System would be of great significance.

The fundamental objective of the Europa Orbiter Mission is to place a spacecraft into orbit around Europa for the purpose of obtaining evidence as to the existence of such an ocean using a number of scientific instruments and precise orbit determination. Scientific measurement capabilities being considered for the Europa Orbiter mission include[1]: 1) precise radiometric or optimetric navigation of the spacecraft to determine the time-varying gravity field corresponding to Europa's response to Jupiter's tidal potential; 2) radar sounding data to ascertain the thickness of Europa's ice surface; 3) laser altimetry and precise orbit determination for measuring height and phase characteristics of Europa's tidal bulge; and 4) optical imaging to characterize features of Europa's ice surface.

The purpose of this study is to quantify attainable navigation accuracies for the Europa Orbiter Mission. Since the design of the mission is currently in a phase of ongoing development, the assumptions used in this analysis may not reflect characteristics of the final design. Therefore, results given here represent a preliminary navigation assessment that may be refined upon completion of the design.

TRAJECTORY DESIGN

Several trajectory design options are currently being considered for the Europa Orbiter Mission, with possible launch dates ranging from 2001 to 2004. The mission is characterized by four distinct phases[2]: 1) an Earth/Jupiter transfer phase (*cruise phase*); 2) a multisatellite tour phase in the Jupiter system (*tour phase*); 3) a Europa insertion phase (*endgame phase*); and 4) a Europa *operations phase* .

The cruise trajectory will be either a direct transfer or a multiple planetary gravity assist trajectory to the Jupiter system. The duration of the cruise phase is dependent on the type of transfer, ranging from about 3 years for a direct transfer to 5 or more years for a gravity assist trajectory. Upon reaching the Jupiter system, the spacecraft will start a multi-satellite tour, similar to the one performed in the Galileo mission, in order to reduce the energy of the spacecraft orbit around Jupiter. When the spacecraft's orbit is almost inside Ganymede's orbit, the endgame phase begins, whereby consecutive Europa flybys in conjunction with deterministic maneuvers bring the spacecraft's orbit into near-resonance with Europa's orbit. The spacecraft then executes a Europa orbit insertion maneuver and additional maneuvers to achieve the desired orbit for the operations phase. The operations phase calls for a 50 km to 200 km altitude, circular orbit around Europa with an inclination of 45° to 90°. This phase will last 30 to 60 days (or as long as the severe radiation environment allows for) during which time the spacecraft will collect and downlink science data.

Navigation assessments of Jupiter multi-satellite tours similar to the tour and endgame phases of the Europa Orbiter Mission have been conducted in several previous studies[3,4,5]. In this investigation, analyses of the cruise and operations phases of the mission have been performed.

INTERPLANETARY CRUISE OD ANALYSIS

Trajectory

An orbit determination analysis has been completed for a representative direct interplanetary trajectory to Jupiter. As shown in Figure 1, the trajectory requires a Deep Space Maneuver (DSM) with a ΔV of approximately 184 m/s one year after injection. Also, an Io gravity assist with a flyby altitude of 500 km is implemented four hours before Jupiter orbit insertion to reduce the amount of ΔV required for capture into the Jovian planetary system.

Tracking Data

For the cruise OD analysis, radiometric data and images of satellites with stars in the background were simulated. Radiometric data, which included X-band range and Doppler data, were distributed equally between DSN tracking stations in the United States, Australia, and Spain. Satellite images were distributed roughly equally between Io, Europa, Ganymede, and Callisto.

Continuous radiometric tracking was simulated between injection (I) and I+30 days. Two passes per week were simulated between I+30 days and Jupiter closest approach (J_{CA}) minus 60 days. Continuous tracking was again simulated between J_{CA}-60 days and J_{CA}. To simplify the analysis, Doppler data was compressed to 60 minute intervals and one range point was simulated per pass.

Because of the relatively wide field of view of the onboard camera envisioned when this analysis was performed, satellite images shuttered earlier than Io-17 days were not useful. Also, because of the large pixel size (50 µrad/pixel) and Europa's brightness, it was difficult to find background stars bright enough to prevent saturation of Europa's image. Based on a dynamic range comparable to Galileo's and Cassini's narrow angle cameras and a pixel size of 50 µrad, the dimmest star that could be imaged without saturating the image of Europa would be around magnitude 4.4. Generally, two to three optical navigation images were simulated each day for a total of thirteen optical navigation frames (the last data cutoff, for an Io-5 day maneuver, was Io-12 days). Io, Ganymede, and Callisto each appeared on five frames while Europa appeared on six frames. The brightest star appearing on these frames was magnitude 4.6.

Optical communication range tracking was also simulated for the first 60 days after injection. An analysis of this data type, never before flown on an interplanetary spacecraft, was undertaken to determine if it could be used as a viable replacement for the traditional radiometric data types. Optical ranging data was simulated as a high precision, high frequency RF range data type. As with the radiometric data, continuous optical range tracking from the three DSN locations was simulated until 30 days after injection. For the next 30 days, two passes per week were simulated. The data was simulated at the rate of about one point every 10 seconds.

Filter Setup

The filter setup for the cruise OD analysis is described in Table 1, which lists the estimated, considered, and stochastic parameters along with their *a priori* uncertainties. "Considered" parameters are used to account for systematic errors in modeling which cannot be improved by the filter. Table 1 also lists the data weights.

Table 1
CRUISE PHASE FILTER SETUP

Estimated Parameters	*A priori* uncertainty
Spacecraft epoch state position	1000 km per axis
Spacecraft epoch state velocity	10 m/s per axis
Solar Pressure (bus model)	0.15 m^2 (10% of nominal area)
Non-gravitational acceleration	2×10^{-12} km/s^2 per axis
DSM execution error	1.8 m/s per axis (1% spherical)
Jupiter planet ephemeris	DE-405 precursor (1)
Jupiter satellite ephemeris	E5 theory values (2)
Jupiter GM	51.5 km^3/s^2
Io GM	1.0 km^3/s^2
Considered Parameters	
Station locations	0.5 m per axis
Troposphere (dry)	1 cm
Troposphere (wet)	4 cm
Ionosphere (day)	75 cm
Ionosphere (night)	15 cm
Earth-Moon barycenter ephemeris	DE-405 precursor (1)
Stochastic Parameters	

Non-gravitational acceleration	2×10^{-12} km/s^2 per axis (3)
Scan platform pointing about L axis	0.3° (4)
Scan platform pointing about M, N axes	1.0° (4)
Data Weights	
Doppler	0.5 mm/s (for 60 sec. compression)
Range	10 m
Satellite images	0.35 pixels
Optical Comm Range	10 cm

Notes:
(1) Reference 6.
(2) Reference 7. Also, Jupiter and satellite masses have been updated with data from the Galileo mission.
(3) Updated every hour, white noise. Accounts for unmodeled thruster activity.
(4) Updated every optical frame, white noise.

Results

Covariances have been mapped to the Io B-plane at closest approach to Io in Earth mean equator of J2000 coordinates (a definition of the B-plane coordinate system is provided in the Appendix). Figures 2 and 3 show the B-plane uncertainty and error ellipse orientation as a function of time from injection to Io closest approach.

Optical navigation images based on the camera design under consideration when this analysis was performed did not significantly reduce orbit uncertainties. For the Io-10 day maneuver (Io-17 day data cutoff) OD uncertainties based on radiometric data plus optical images and radiometric data only were nearly identical. For the Io-5 day maneuver (Io-12 day data cutoff) OD uncertainties based on radiometric data plus optical images were about 10% smaller than uncertainties based on radiometric data only.

Substituting optical communication ranging data in place of the X-band range and Doppler data appears to be a viable alternative. Orbit uncertainties from the first sixty days after injection mapped to the Io B-plane are presented in Figures 4 and 5 for both tracking types. The optical range tracking offers a marginal improvement over radiometrics for each of the three components of the orbit uncertainty.

OPERATIONS PHASE OD ANALYSIS

Nominal Orbit Configuration

The nominal orbit characteristics used for the operations phase analysis are listed in Table 2. These parameters correspond to a 100 km altitude, circular orbit around Europa with an inclination of 60°. The Earth-Europa-spacecraft angle at epoch (ascending node crossing) is 74°.

Table 2
OPERATIONS PHASE ORBIT CHARACTERISTICS

a	1665 km
e	0
i	60°
ω	0°
Ω	0°
f	0°
Epoch (start of orbit phase)	20 Jan 2007 12:00:00 ET

Tracking Data

Radiometric data and optical communication ranging data were simulated for the operations phase. Radiometric tracking was distributed equally between DSN stations in the United States and Australia, resulting in two 14-hour passes per day. Doppler data was compressed to 1 minute intervals and one range point was simulated per pass.

Single-station optical ranging data was analyzed for comparison to radiometric tracking. One 4-hour tracking pass per day was simulated with a data rate of about one point every 10 seconds.

Filter Setup

The filter setup for the operations phase is described in Table 3, which lists data weights and the estimated, considered, and stochastic parameters along with their *a priori* uncertainties. Because characteristics of the gravity field of Europa are almost entirely unknown, the gravity field model used in this analysis is a 40th degree and order normalized lunar gravity field scaled to the radius of Europa[8]. Gravity field coefficients up to degree and order 14 were estimated, with *a priori* uncertainties for most of the coefficients assumed to be 1000% of their nominal values. Coefficients under degree 3 are given smaller *a priori* uncertainties, based on current Galileo Mission estimates of those coefficients from flybys of Europa. Degree and order 15 through 20 coefficients were treated as considered parameters with *a priori* uncertainties at 100% of their nominal values.

Table 3
OPERATIONS PHASE FILTER SETUP

Estimated Parameters	***A priori* uncertainty**
Spacecraft epoch state position	10 km per axis
Spacecraft epoch state velocity	1 m/s per axis
Non-gravitational acceleration	2×10^{-12} km/s^2 per axis
Jupiter planet ephemeris	DE-405 precursor (1)
Jupiter satellite ephemeris	E5 theory values (2)
Jupiter J_2, J_4, pole orientation	E5 theory values (2)
Jupiter GM	51.5 km^3/s^2
Europa GM	0.5 km^3/s^2
Europa normalized gravity field, up to degree & order 14	20% for coefficients up to degree & order 2; 1000% all others
Considered Parameters	
Europa normalized gravity field, degree & order 15 through 20	100%
Station locations	0.5 m per axis
Troposphere (dry)	1 cm
Troposphere (wet)	4 cm
Ionosphere (day)	75 cm
Ionosphere (night)	15 cm
Stochastic Parameters	
Non-gravitational acceleration	2×10^{-12} km/s^2 per axis (3)
Data Weights	
Doppler	0.5 mm/s (for 60 sec. compression)
Range	10 m
Optical Comm Range	10 cm

Notes:
(1) Reference 6.
(2) Reference 7. Also, Jupiter and satellite masses have been updated with data from the Galileo mission.

(3) Updated every hour, white noise. Accounts for unmodeled thruster activity.

Results - Nominal Orbit Configuration

OD uncertainties have been computed over a 3.5-day interval, corresponding to one sidereal period of Europa's rotation (which is also its sidereal orbit period about Jupiter). This interval represents one *cycle*, during which time the spacecraft achieves nearly uniform coverage of Europa's surface. Figure 6 shows radial, downtrack and crosstrack one-sigma orbit errors for varying amounts of radiometric tracking over the 3.5 day cycle. For each case, the radial component is smallest and the downtrack greatest. The case with 3.5 days of tracking shows the uncertainty in each direction reduced by about an order of magnitude when compared to the case with one day of tracking.

Results for the optical range tracking cases are presented in Figure 7. Similar to the radiometric tracking cases, the optimetric results show the smallest orbit errors in the radial direction and the largest in the downtrack. In general, the values computed for the optical ranging cases are several times larger than for the radiometric tracking. Even so, the optimetrics, despite having single-station, 4-hour-per-day tracking, are quite comparable to the radiometrics (two station, 14-hour-per-day tracking). In practice, however, relying on single-station tracking is also more risky for navigation. Finally, the results for both the radiometric tracking cases and the optical range tracking cases suggest that a few days of continuous tracking is very important early in the operations phase.

Results - Other Orbit Configurations

Additional results for the operations phase have been compiled for several different orbit configurations. Combinations of the following variations on the nominal orbit have been considered: 1) altitude = 200 km; 2) inclination = 90°; 3) longitude of ascending node = 90° (corresponding to an Earth-Europa-ascending node angle of 164°). The analysis was performed using one day of radiometric tracking in each case. For each scenario, the maximum one-sigma uncertainty over the 3.5 day cycle was calculated; these values are listed in Table 4 along with the results from the baseline case.

Table 4
OPERATIONS PHASE OD UNCERTAINTIES FOR SEVERAL ORBIT CONFIGURATIONS

Orbit Characteristics			One-Sigma OD Uncertainties (km)		
Altitude (km)	Inclination (deg)	Earth-Europa-Ascending Node Angle (deg)	Radial	Downtrack	Crosstrack
* 100	60	74	4.75	25.09	12.39
100	60	164	5.56	20.72	8.76
100	90	74	4.74	44.23	3.56
100	90	164	2.74	17.44	3.52
200	60	74	1.76	11.54	5.59
200	60	164	2.36	8.93	3.88
200	90	74	2.33	17.38	1.58
200	90	164	1.29	7.22	1.48

*Baseline case as described in Table 2.

The results in Table 4 show that, with other things equal, the uncertainties tend to improve with 200 km altitudes compared to 100 km altitudes. The reason for this is two-fold: first, the effect of significant gravity field errors is reduced in the higher altitude orbits and second, the amount of occultation is diminished, allowing for an effective increase in the tracking coverage.

Another trend observed in Table 4 is the considerable reduction in downtrack error for Earth-Europa-ascending node angles of 164° compared to the 74° cases. The explanation for this is that the orbit plane orientation is much more edge-on to the Earth in the 164° cases, making the downtrack dynamics of the spacecraft more directly observable through the Doppler measurements.

EUROPA ORBIT INSERTION CONSIDERATIONS

A covariance analysis was performed to address the issue of spacecraft safety in the critical period immediately following Europa orbit insertion. To simulate post-insertion orbit determination, it was assumed that there would be no orbit update until a specified time past insertion; the period was assumed to be 12 hours in one set of cases and 32 hours in another. For the specified period, no tracking data was processed, and uncertainties were allowed to propagate.

The orbit configuration used in these computations was the same as defined in Table 2, with the exception that several cases were conducted for different altitudes from 50 km to 500 km. Figure 8 shows the results of this analysis. The maximum three-sigma radial orbit uncertainty over the 12-hour and 32-hour periods were plotted versus orbit altitude. As expected, the 32-hour line lies above the 12-hour line since orbit uncertainties propagated for a longer duration until an orbit update could be made. The dotted line at 100% shows the level at which the three-sigma radial uncertainty is as great as the orbit altitude. At a 100 km altitude orbit, for example, the three-sigma radial uncertainty is ~50% of the altitude, which may be considered risky in the face of anomalies that could be experienced at that time. Alternately, the option exists to first insert into a higher altitude and then transfer to the operational orbit when the spacecraft state has been determined to an acceptable level of accuracy.

There are a couple of points to consider about the orbit insertion analysis just described. A large portion of the orbit uncertainty was contributed from Jupiter satellite ephemeris *a priori* uncertainties. The Jupiter satellite ephemeris, especially for Europa, is likely to be much better known after the Galileo Europa Mission is completed and after the Europa Orbiter spacecraft completes its tour and endgame phases. Autonomous navigation, if included in the mission design, will theoretically decrease the time period past insertion for which orbit updates are not possible. These two factors make it reasonable to believe that the curves shown in Figure 8 could be significantly lower.

ACKNOWLEDGEMENT

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APPENDIX

Definition of the B-plane coordinate system.

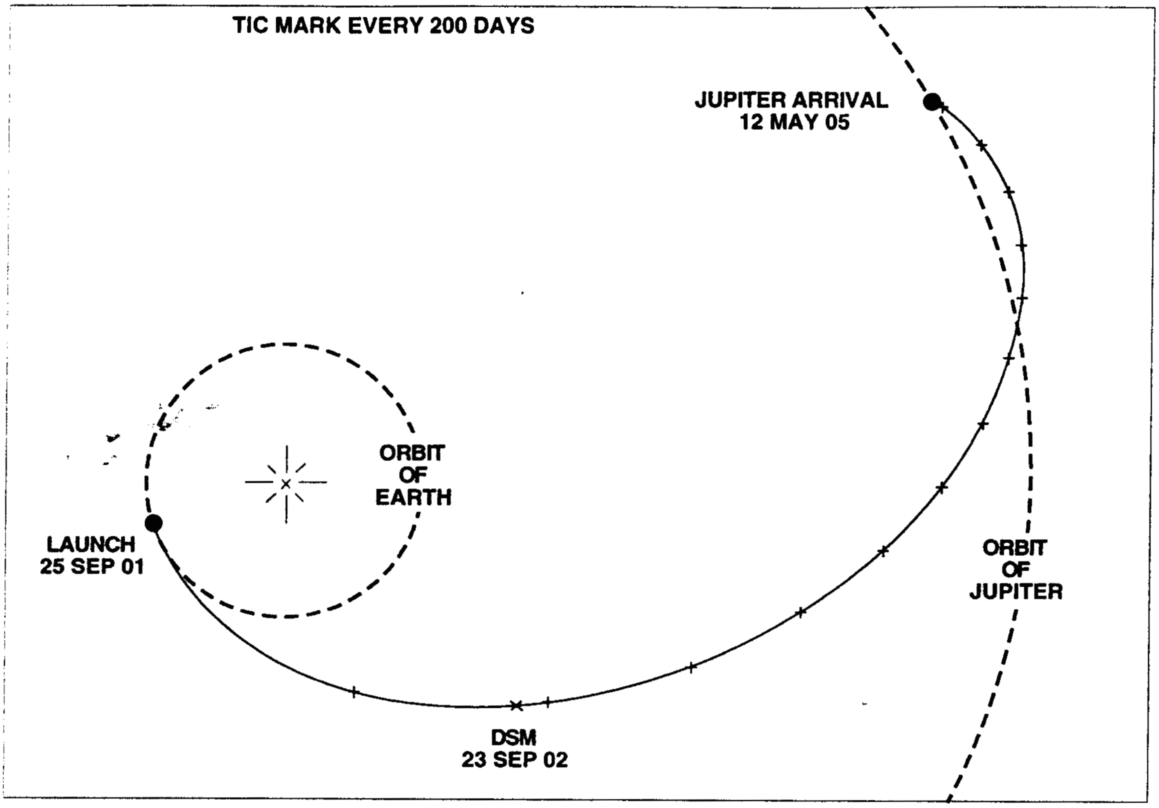


Figure 1. A direct Earth-Jupiter transfer with launch in 2001 and arrival in 2005.

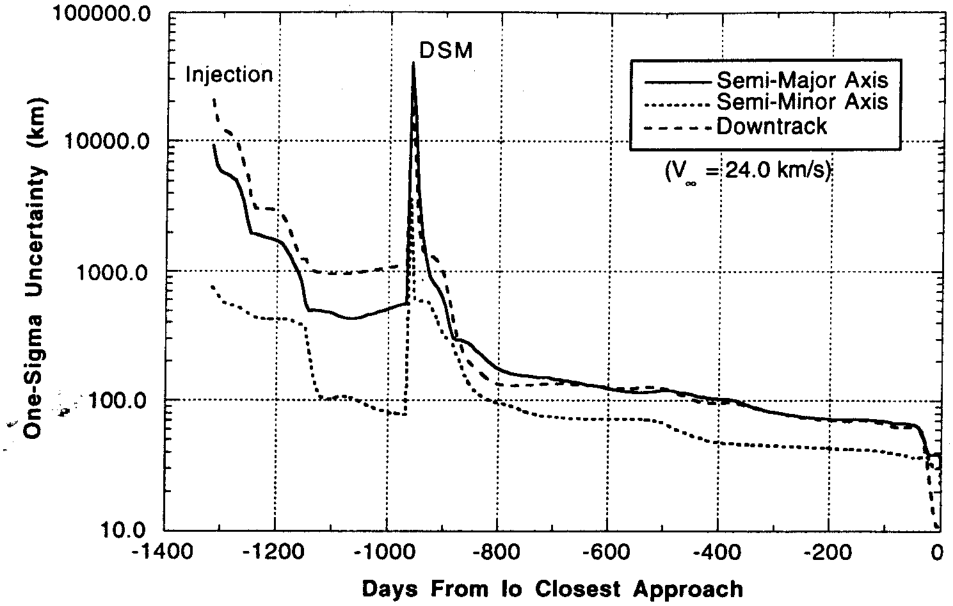


Figure 2. Cruise Phase B-plane uncertainties mapped to Io closest approach.

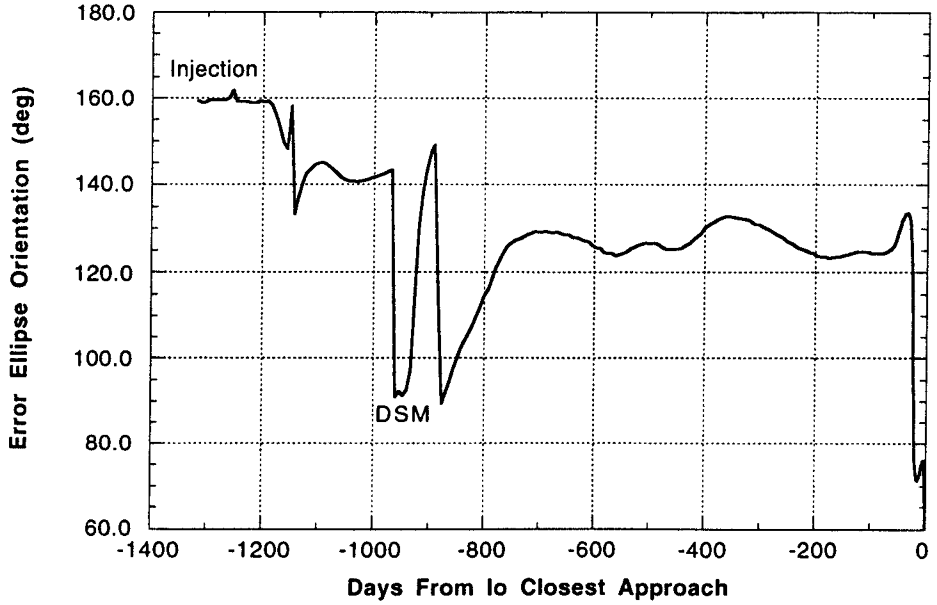


Figure 3. Cruise Phase B-plane error ellipse orientation mapped to Io closest approach.

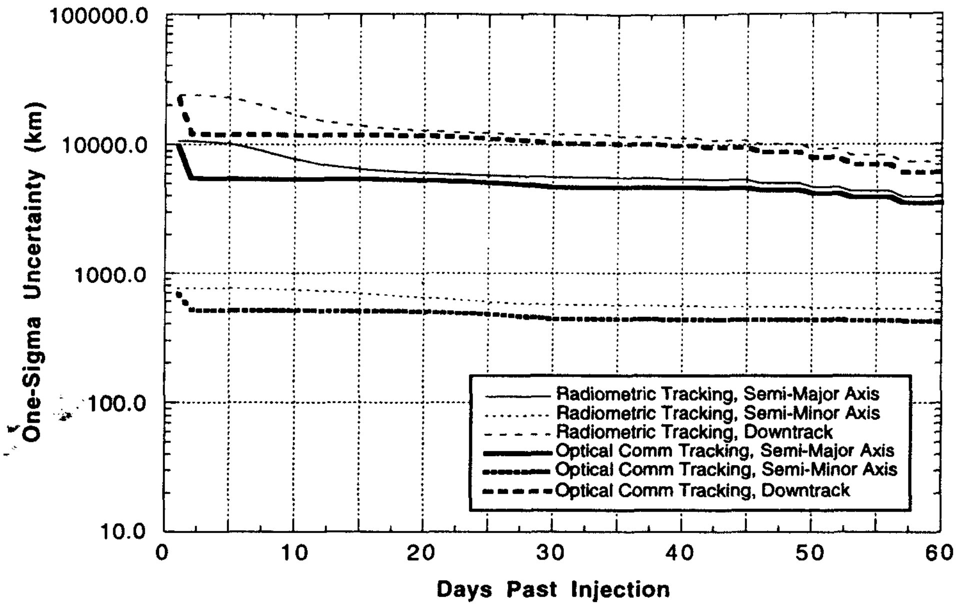


Figure 4. Cruise Phase B-plane uncertainties mapped to Io closest approach. Radiometric and optical communication tracking types are compared for the first sixty days after injection.

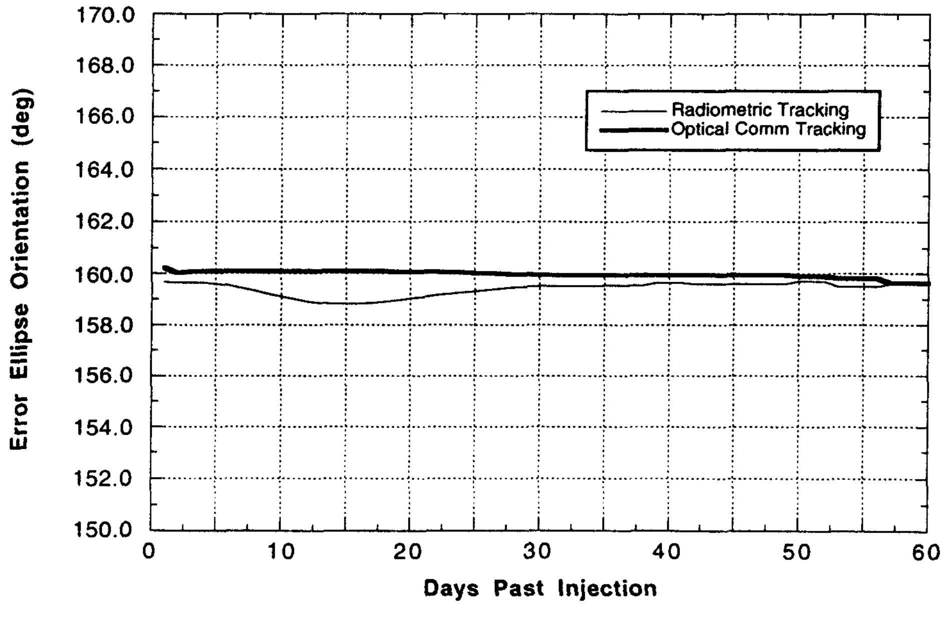


Figure 5. Cruise Phase B-plane error ellipse orientation mapped to Io closest approach. Radiometric and optical communication tracking types are compared for the first sixty days after injection.

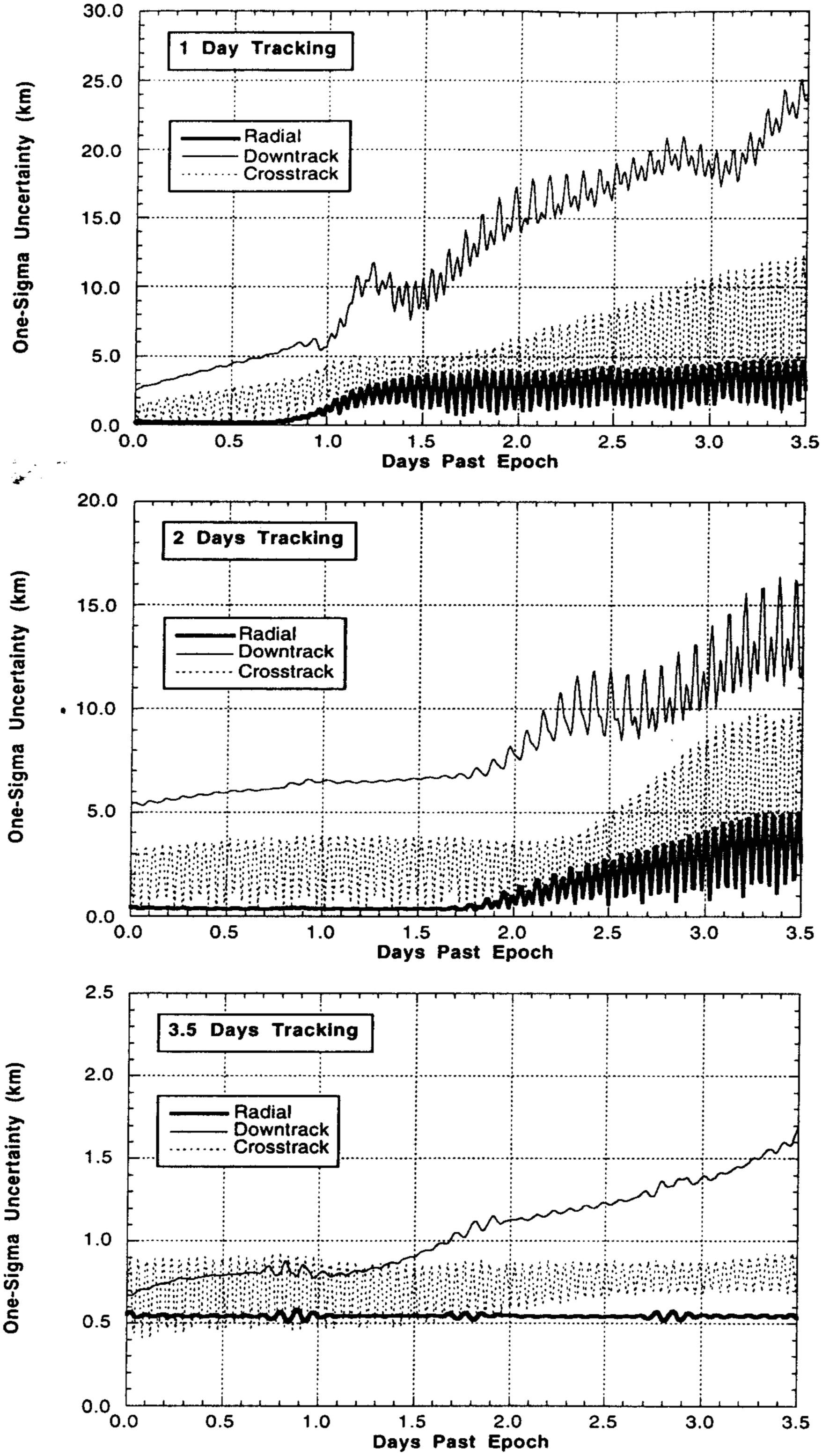


Figure 6. Orbit Phase uncertainties based on 1, 2, and 3.5 days of radiometric tracking.

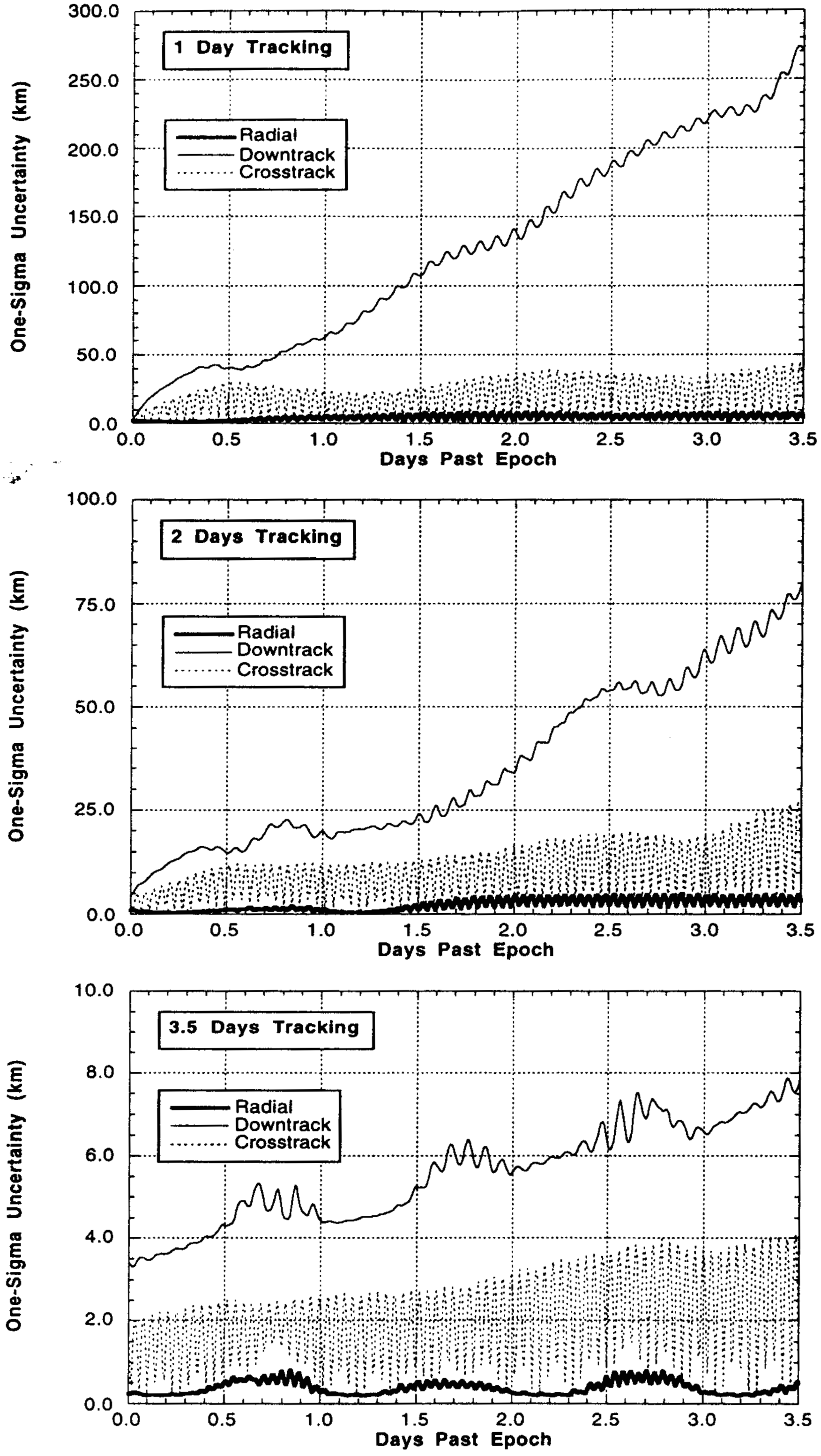


Figure 7. Orbit Phase uncertainties based on 1, 2, and 3.5 days of optical communication range tracking.

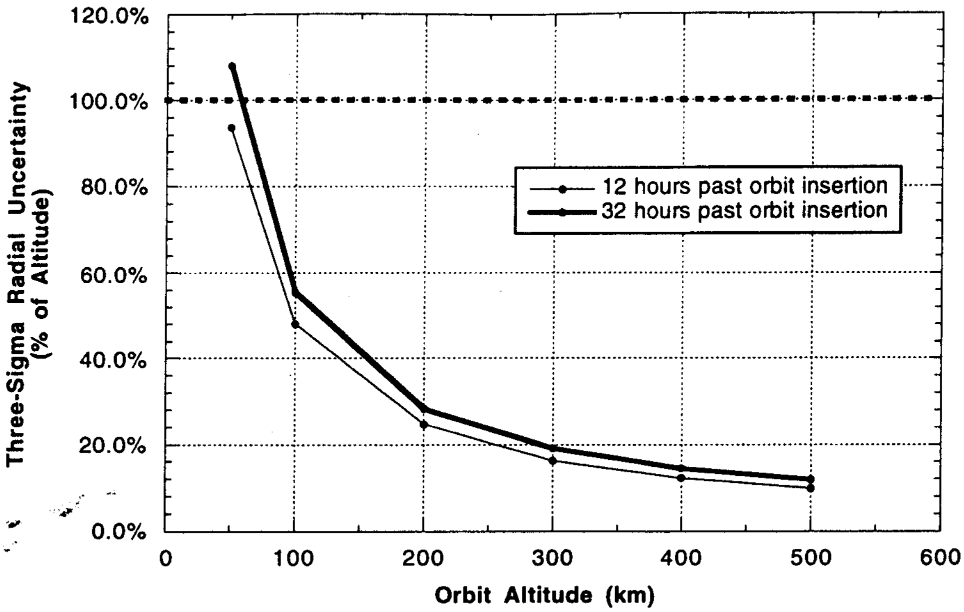
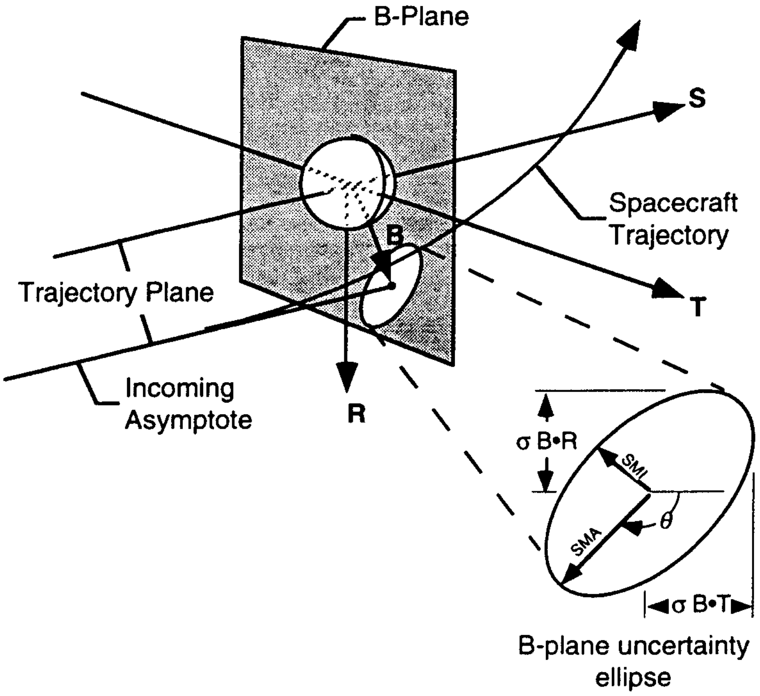


Figure 8. Radial orbit uncertainties determined for different orbit insertion altitudes. The times past insertion (12 hours and 32 hours) represent periods when it would not be possible to update the spacecraft orbit.



Appendix Figure