Orbit Determination Covariance Analysis for the Europa Clipper Mission

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A new Jovian satellite tour is proposed by NASA, which would include numerous flybys of the moon Europa, and would explore its potential habitability by characterizing the existence of any water within and beneath Europa's ice shell. This paper describes the results of a covariance study that was undertaken on a sample tour to assess the navigational challenges and capabilities of such a mission from an orbit determination (OD) point of view, and to help establish a ΔV budget for the maneuvers needed to keep the spacecraft on the reference trajectory. Additional parametric variations from the baseline case were also investigated. The success of the Europa Clipper mission will depend on the science measurements that it will enable. Meeting the requirements of the instruments onboard the spacecraft is an integral part of this analysis.

I. Introduction

The Europa Clipper mission proposal is being developed jointly by the Applied Physics Laboratory (APL), Johns Hopkins University, and the Jet Propulsion Laboratory (JPL), California Institute of Technology.[1] The purpose of such a mission would be to investigate the existence of a sub-surface ocean, where life would be possible if the intense tidal forces from Jupiter created the heat necessary for chemical reactions between the sub-surface ocean's salty water and Europa's rocky core. The Galileo mission provided a wealth of information on the moon Europa after conducting twelve successful flybys of this moon. Its discoveries contributed to the selection of instruments that would be needed on the Europa Clipper payload for conducting more detailed measurements in search of life on Europa. Presently, there are eight candidate instruments on the spacecraft, five of which would be nadir pointed (an ice penetrating radar, IPR, a stereo topographical imager, TI, a shortwave infrared spectrometer, SWIRS, and a thermal imager, ThI), one instrument would be pointed in the Z-direction (neutral mass spectrometer, NMS), and two instruments would be on booms (a Langmuir probe, LP, and a magnetometer, MAG). The SWIRS and NMS would characterize the composition of subsurface landforms, or of ejected surface products during flybys at altitudes lower than 100 km. The IPR and ThI would acquire sub-surface sounding profiles, or detect anomalous surface temperatures. The TI and recon-camera would acquire high-resolution images of the surface of Europa.

The study presented in this paper is based on a launch in 2021. The cruise trajectory to Jupiter would take 6.5 years and would include one gravity assist from Venus, and two from Earth (VEEGA). Upon arrival at Jupiter, the spacecraft would first perform a flyby of the moon Ganymede before the Jupiter Orbit Insertion (JOI) maneuver. This would mark the beginning of a 3.5-year Jovian tour. The proposed tour would be designed such as to minimize the amount of radiation from Jupiter to which the Europa Clipper spacecraft would be exposed. The numerous petal orbits that contain flybys of the moon Europa are highly eccentric, which would allow the spacecraft to limit the amount of time spent close to the planet to the time it is conducting scientific observations of this moon.

Initial flybys of the moons Ganymede and Callisto would setup the necessary conditions for the first Europa encounter, and in the process, reduce the satellite ephemeris uncertainties to the levels necessary

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for subsequent low altitude flybys of the Jovian moons. The Jovian tour would include 45 Europa flybys, 5 Ganymede flybys, and 9 Callisto flybys. The tour analyzed was designed to provide good coverage of Europa under optimum lighting conditions that would allow the science instruments to assess the habitability of this moon. On approach to this satellite, the spacecraft would perform low-resolution global scans with its infrared spectrometer (SWIRS), followed by high-resolution scans in a pushbroom fashion near closest approach. At 1,000 km the ice-penetrating radar, IPR, the topographic imager, TI, and the mass spectrometer, NMS, would power up. The radar pass would occur from 400-km inbound altitude to 400-km outbound altitude, during which stereo imaging and mass spectrometer data would be acquired continuously. During departure, the infrared spectrometer would conduct additional high- and low-resolution scans as the spacecraft moves away from Europa.[1]

To ensure the success of the Europa Clipper mission, each aspect of the potential tour will have to be carefully planned and analyzed. From an OD point of view, this process would include predicting the accuracy with which the tour could be navigated in order to establish a ΔV budget. In addition, the navigation uncertainties would also have to meet the level of accuracy needed by the science instruments on board the spacecraft. Of the eight candidate instruments for the Europa Clipper payload, the shortwave infrared spectrometer (SWIRS) would place the most stringent requirements on navigation. The shortwave IR region (1-5 microns) is uniquely suited for determining the surface composition of Europa, which would include hydrates, brines, organics, and ice.[2] Modeling all the sources of navigation errors, and finding ways to minimize them in order to meet the pointing accuracy required by the instruments are among the navigational challenges presented in this paper.

II. Orbit Determination

The process of orbit determination involves estimating the spacecraft state from the tracking data by using the equations of motion, and a measurement model that accounts for all the sources of errors. In a covariance analysis, the measured and computed observables are equal. The analysis consists of minimizing the errors based on the available data. The uncertainties in parameters that can be improved with observations are estimated. All non-gravitational accelerations and all non-maneuver related errors are modeled with stochastic accelerations. Any systematic errors in modeling, which cannot be improved by the filter, are treated as "unmodeled" or consider parameters.

The Europa Clipper tour presents overall challenges not seen in the Cassini tour. The Jupiter satellites, Europa, Ganymede, and Callisto, which will provide the gravity assists to shape the spacecraft orbits, are large, comparable in size to Saturn's moon, Titan, yet the flybys occur at altitudes as low as 25 km, versus the 950 km minimum altitude for Titan. The short orbital periods of Europa and Ganymede of 3.5 days and 7.2 days, respectively, would result in flybys that occur only a few hours from a Jupiter periapsis, so any OD errors prior to the flybys would be magnified by the combination of a low altitude satellite flyby and the Jupiter periapsis passage. Europa's short orbital period also causes the length of the spacecraft orbital period to be about 14.2 days for a 4:1 resonance. This would result in placing the three maneuvers that shape the spacecraft orbit between the flybys at intervals of about 4 days, which could at times prevent full OD convergence by the data cutoff (DCO) for the design of the next maneuver. The tracking data schedule could be a factor in the OD convergence and the magnitude of the maneuver execution errors. The uncertainty in the pointing of the science instruments is directly tied to the uncertainty in the spacecraft position before a flyby.

A. Covariance Analysis Software

The software used for conducting this covariance analysis was transitioned to Python and C++ languages from a FORTRAN program and matlab scripts that had been written to perform OD covariance analyses throughout the Cassini Mission. The original software was used for predicting the uncertainties in the satellite and spacecraft ephemerides, and for arriving at a ΔV budget for the maneuvers to be performed during the Cassini Prime, Equinox, and Solstice Missions.[3] The new software runs with the navigation programs used presently at JPL, and has the same capability to perform OD covariance analysis for the Europa Clipper Mission as was done for the Cassini Mission, and thus evaluate the navigability of the proposed tours.

The inputs necessary for an OD covariance analysis are the following:

1. A reference spacecraft trajectory from launch until the end of the satellite tour,
2. A planetary ephemeris, a satellite ephemeris, and satellite partial derivatives,
3. Input covariances for the injection state, planets, and satellites,
4. The location, magnitude, and aim point for the maneuvers,
5. The times and location of all the targeted satellite flybys.

B. Measurement Model and Filter Configuration

This OD covariance analysis uses only radiometric data, which would be acquired by NASA's Deep Space Network (DSN). Two-way Doppler data measures the Earth-line-of-sight velocity of the spacecraft with respect to the tracking station. Two-way ranging data provides the spacecraft Earth-relative distance. No optical navigation data (OpNavs) were used for this analysis. In general, OpNavs provide a two-dimensional measurement of the satellite position against the background stars, which are assumed inertial. This measurement can reduce the uncertainty in the satellites ephemerides in the absence of a Doppler signature which would be obtained during a flyby. As a result, the initial satellite flybys in a Europa Clipper tour would prove to be somewhat more challenging because of the large uncertainty in the Jovian satellite ephemerides. This sample tour was specifically designed with a higher altitude for those flybys.

Delta-Differential One-Way Range (ΔDOR) measurements will be used only during cruise. The difference in the arrival times of the radio signal from the spacecraft is measured at two widely-spaced DSN stations. The same type of interferometric measurement is also obtained for a nearby quasar. The two angular measurements are then differenced. The result is a near-cancellation of station location, transmission media, and clock offset calibration errors. The measurement is accurate especially where Doppler fails near zero-degree declination.

For the purpose of this OD covariance analysis, the Europa Clipper tour is divided into trajectory arcs that begin at a Jupiter apoapsis and terminate at a satellite flyby. The overlap between the arcs allows comparison of OD solution between the arcs for greater confidence at the beginning of the new arc, before designing the post-flyby maneuver that targets the next encounter. While the covariance analysis makes use of the improvement in the satellite covariance at the beginning of each arc, the spacecraft uncertainties are reinitialized at epoch to 15 km and 50 mm/s .

The satellite ephemerides would be continuously updated at each Jupiter apoapsis, and the *a posteriori* satellite covariance at the apoapsis of a current arc would become the *a priori* covariance for the following arc. The tour consists of 5 Ganymede flybys, 9 Callisto flybys and 45 Europa flybys. The first Ganymede flyby, G0, would be prior to the onset of the tour, before JOI.

The spacecraft would be maintained on the reference trajectory by performing an average of three orbit trim maneuvers between the satellite flybys, of which the clean-up maneuver post-flyby, and the maneuver near the Jupiter apoapsis would be deterministic and target the next flyby, and only the approach maneuver would be statistical.

Tracking requirements for converging the OD after each maneuver are a function of the spacing between maneuvers, which in turn depends on the spacecraft orbital period. To achieve a 1:4 resonance with Europa's period, the spacecraft period would have to be about 14.2 days, during which time the three maneuvers needed to correct the spacecraft trajectory would be at about 4 day intervals. For the Europa Clipper tour, the frequency of tracking data would coincide with every other DSN tracking opportunity, which is higher than the daily passes for the Cassini Mission when the spacecraft orbital period was around 16 days based on a 1:1 resonance with Titan's orbit, and the maneuvers spaced about 5 days apart. Continuous tracking for the Europa Clipper will be necessary when the flybys are close together, as would be the case for this tour between Europa-28 followed by Callisto-3 just 5 days later. The OD uncertainties will have to be converged by the conclusion of the E28 flyby in order to allow the clean-up/targeting maneuver to be designed and uplinked to the spacecraft prior to the C3 flyby. It might not be possible to both collect science data and track

the spacecrft at the same time during the Europa-28 flyby due to limitations in the spacecraft power and the need to point the high-gain antenna to Earth. The current requirements on spacecraft tracking exclude it from 24 hours before until 12 hours after an Europa flyby, so that science observations and measurements can point the high-gain antenna to the satellite.

In this covariance analysis, two-way Doppler and range data weights are set at 0.1 mm/s and 3 m, respectively, except during solar conjunctions, at Sun-Earth-Probe (SEP) angles $\leq 15°$. During that time, the Doppler data are de-weighted to 1 mm/s for $7.5° < SEP \leq 15°$, and to 5 mm/s for $3° < SEP \leq 7.5°$. The ranging data become biased at SEP $\leq 7.5°$. In general, no tracking data can be acquired at $SEP \leq 3°$.

In this filter model, the parameters estimated are the planetary and satellite ephemerides and GM, Jupiter's oblateness and pole, the spacecraft state, and the maneuvers in the arc. Non-gravitational perturbations on the spacecraft trajectory other than from maneuvers come from errors in the predicted small forces imparted to the spacecraft such as residual Solar Radiation Pressure (SRP) errors, thruster firings, and errors in Radio-Isotope Thermal Generator (RTG) accelerations. All non-gravitational accelerations and all non-maneuver related errors are modeled as white noise, stochastic acceleration of $4.5 \times 10^{-12} km/s^2$ per axis, which are updated in 8-hour batches. Media corrections and earth orientation parameters are considered.

The OD covariance analysis is carried out in an iterative process. The first set of spacecraft covariances is generated with no maneuver execution errors. These OD covariances are given to the maneuver analyst, who estimates the maneuver execution errors based on the information provided. The maneuver execution errors are then input into the OD covariance program, which generates a new set of OD covariances. This iterative process between the OD and maneuver teams may be repeated as necessary in order to arrive at a set of converged execution errors.

III. Satellite Ephemeris Uncertainties

Unlike the Cassini Mission, which had no precursor tour of the Saturnian satellites, the Europa Clipper Mission would benefit from the wealth of information gathered by the Galileo Mission at Jupiter. The Galileo Mission performed an extensive tour of the Jovian satellites, which included among others 12 close flybys of the moon Europa. As a result, the approach satellite ephemeris covariance contains smaller uncertainties than the one for the Cassini Mission.

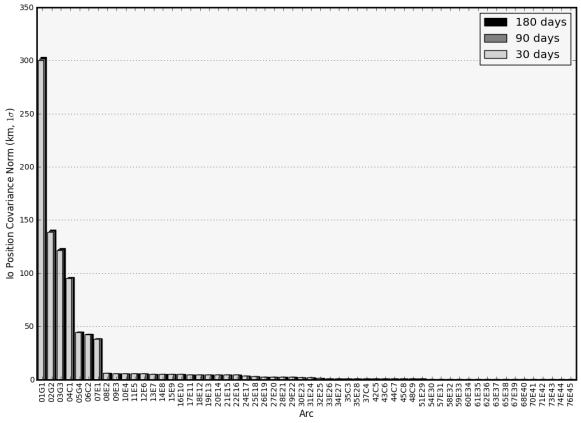
At the onset of the Jovian tour, the satellite ephemeris uncertainties are the dominant source of error in the OD uncertainties. However, after a few flybys of the moons Ganymede, Callisto, and Europa, the satellite ephemerides become well determined through the satellite Doppler signature. Presently, there are no plans to have a camera on board the spacecraft to enable OpNav measurements of the satellites, which would reduce the uncertainties in the satellite ephemerides prior to the onset of the tour. For this sample tour, the planetary and satellite covariances were estimated on the approach to Ganymede-0, G0, prior to JOI. The combined covariance became the *a priori* covariance for the tour. By using the *a posteriori* satellite covariance from one trajectory leg as an *a priori* input for the next trajectory leg, the satellite covariance is continuously updated, and the satellite correlations are preserved.

The orbital resonance of 4:2:1 between Io, Europa and Ganymede greatly contributes to rapidly reducing these satellite ephemeris uncertainties whenever a flyby of any of these moons occurs. The Europa orbital resonance with Callisto is 36:7, which means that a flyby of Callisto would also improve Europa's ephemeris uncertainties slightly.

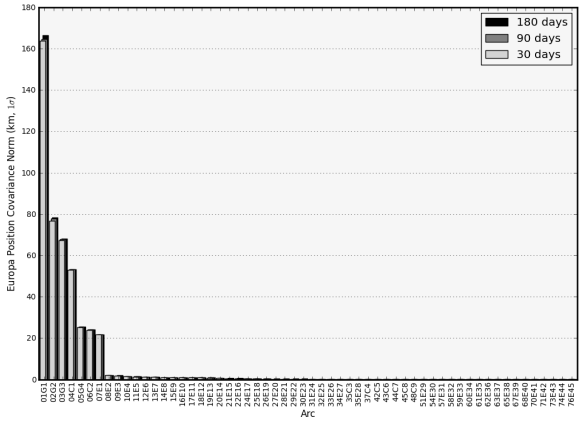
The estimated satellite ephemeris uncertainties for this sample tour are shown in Figures 1-2. The information in the figures is obtained by taking the solution at the apoapsis DCO and mapping it forwad over an interval of 30, 90, and 180 days respectively, in time increments of fractions of the satellite period, such that there would be good coverage of the satellite uncetainties as a function of its position in the orbit. The maximum RSS value of the position components found in each time-interval is then plotted in the bar plot. The difference between the uncertainties obtained for each arc is an indication of secular growth in

the absence of flyby data, which would otherwise reduce the ephemeris uncertainties. Because of the Io, Europa, and Ganymede orbital resonance of 4:2:1, the uncertainty in the Io ephemeris is improved as well (Figure 1(a)).

The sample tour analyzed would begin with several flybys of the moons Ganymede and Callisto, in order to set up the necessary conditions for an Europa flyby. The flybys will be stepped down from a higher altitude towards a lower altitude as the satellite ephemeris uncertainties are reduced. The results obtained in this analysis show that the Ganymede mapped ephemeris uncertainties are reduced from about 30 km at G0 to the 2 km level at G3, which occurs in the third flyby in the tour (03G3, Figure 2(a)). The moon Callisto would also be used to shape the spacecraft orbit. The initial flyby of Callisto would occur in the forth flyby in the tour (04C1). At that time, the Callisto mapped ephemeris uncertainties would be in the range of 40 km. By the sixth flyby in the tour which coincides with the second Callisto flyby (06C2), these ephemeris uncertainties would have dropped to just 12 km (Figure 2(b)). The next flyby, 07E1, would mark the first Europa flyby in the tour, with mapped ephemeris uncertainties of the order of 20 km at a flyby altitude of 753 km. The following flyby of Europa would occur in the next arc, 08E2, at an altitude of 250 km. At this time, the Europa mapped ephemeris uncertainties would have dropped to a mere 2 km (Figure 1(b)), thus no longer being the dominant source of error in the OD uncertainties.

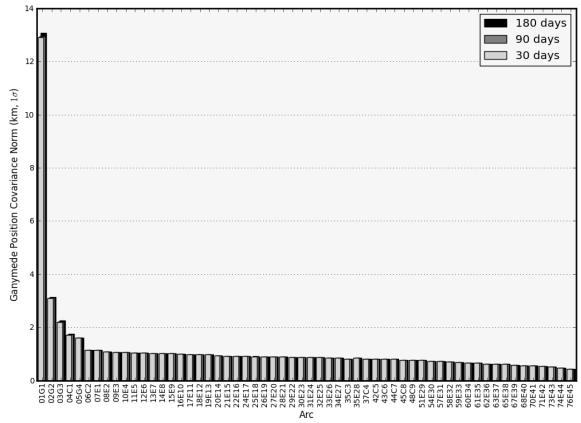


(a) Io

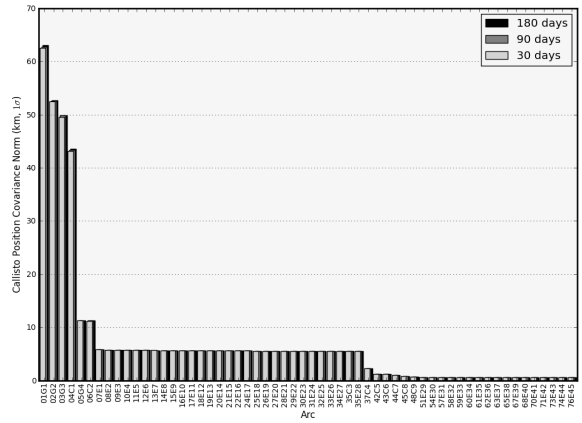


(b) Europa

Figure 1. Io and Europa 1-σ Ephemeris Uncertainties



(a) Ganymede



(b) Callisto

Figure 2. Ganymede and Callisto 1-σ Ephemeris Uncertainties

IV. B-Plane Uncertainties: Baseline Case

The Europa Clipper Mission will be a fast-paced tour, that will try to answer the question of existence of life on Europa. Based on the scientific heritage from the Galileo Mission, the science instruments on board the spacecraft will take specific measurements of the surface of Europa for reconnaissance sites, and investigate the existance of a subsurface ocean for habitability. The altitude of the flybys will be at times as low as 25 km, which would require that the navigation uncertainties be small for science measurements. As discussed in the previous section, lowering the altitude of the flybys gradually until the satellite ephemeris uncertainties are reduced, would allow characterization of the Jovian system while safely navigating the spacecraft through Jupiter's large moons. By G3, C2, and E2, the satellite ephemeris uncertainties are no longer the major contributor to the OD uncertainties as can be seen from Tables 1-3 and Figure 3. The OD uncertainties shown are for the baseline case at the DCO of two days before the approach maneuver to a flyby, which is the last control point. Figure 3 groups the B-plane, downtrack, and radial uncertainties by satellite. For most of the flybys, these uncertainties are under 5 km once the satellite ephemeris uncertainties no longer dominate. However, for the Europa flybys, Figure 3(c), the downtrack uncertainties are larger than the other uncertainties. These uncertainties are related to the time of periapse uncertainties through v_∞.

Table 1. B-Plane and Encounter 1σ Uncertainties for the Ganymede Flybys

Flyby	Arc	Date, Time (ET)	Altitude (km)	DCO (days)	Semi-major Axis (km)	Semi-minor Axis (km)	Theta (deg)	Radial (km)	Down-track (km)	Time of Flight (sec)
G1	01G1	22-OCT-2028,17:14:57	100.0	-5.040	12.4	6.7	173	7.5	4.6	0.71
G2	02G2	18-DEC-2028,23:07:27	100.0	-5.035	5.3	2.7	173	3.2	1.8	0.28
G3	03G3	16-JAN-2029,13:49:11	1035.6	-4.190	4.1	1.8	4	1.9	0.7	0.11
G4	05G4	27-FEB-2029,18:42:49	523.6	-5.178	5.4	3.1	16	3.1	1.1	0.21

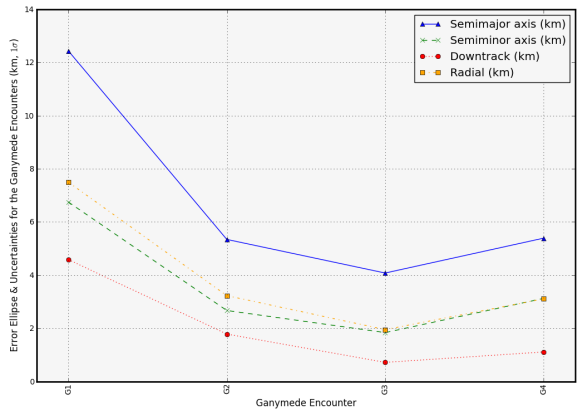
Table 2. B-Plane and Encounter 1σ Uncertainties for the Callisto Flybys

Flyby	Arc	Date, Time (ET)	Altitude (km)	DCO (days)	Semi-major Axis (km)	Semi-minor Axis (km)	Theta (deg)	Radial (km)	Down-track (km)	Time of Flight (sec)
C1	04C1	31-JAN-2029,12:29:58	911.6	-5.168	38.6	14.5	143	34.5	6.5	1.18
C2	06C2	16-MAR-2029,06:22:26	2635.9	-5.031	11.8	1.3	1	1.3	0.4	0.10
C3	35C3	01-JUN-2030,20:43:22	466.6	-4.548	4.7	0.3	0	3.0	2.9	0.99
C4	37C4	21-JUL-2030,21:11:53	100.0	-5.029	0.5	0.4	169	0.5	0.6	0.19
C5	42C5	07-AUG-2030,12:47:16	1828.3	-4.340	6.1	2.1	141	5.7	6.1	2.12
C6	43C6	15-AUG-2030,18:43:55	100.0	-4.032	5.1	0.3	109	4.4	2.1	0.71
C7	44C7	01-SEP-2030,10:18:28	50.0	-5.301	1.2	0.4	54	0.5	0.8	0.27
C8	45C8	04-OCT-2030,17:52:49	25.0	-5.369	0.5	0.3	0	0.4	0.2	0.08
C9	48C9	07-NOV-2030,06:37:48	3673.1	-5.037	2.9	0.3	179	0.3	0.2	0.07

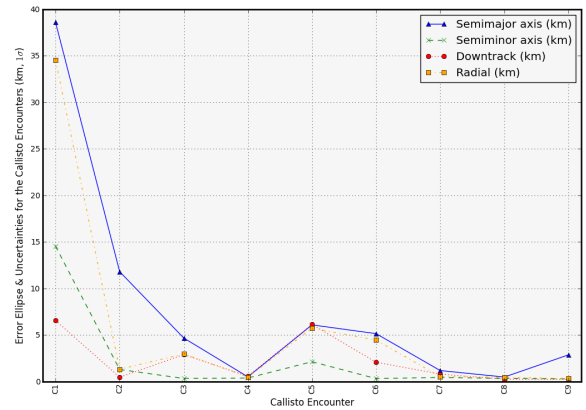
In this sample Jovian satellite tour, one of the more difficult navigational challenges would be the E28-C3, back-to-back flybys. In order to improve lighting conditions at Europa, the Clipper spacecraft will execute a "switch flip" or pi-transfer, which would result in encountering Callisto only 5 days after an Europa flyby. Because of the short interval between the two flybys, only one orbit trim maneuver could be executed during this time, which would have a DCO at the conclusion of the E28 flyby. This maneuver will be necessary to clean-up any flyby errors incurred at E28 at an altitude of only 25 km and target the next flyby. Even though the Callisto flyby would be at an altitude of 467 km, and thus less sensitive to larger flyby uncertainties, converging the OD by the DCO for this maneuver would require continuous tracking through the E28 flyby. In the span of 5 days, the location of this DCO is necessary to allow time for the design and uplinking of the maneuver to the spacecraft, so that the maneuver could be executed 2.5 days before the C3 flyby. Figure 4 illustrates the OD convergence of B-Plane uncertainties for the E28 arc (a), and the C3 arc (b). The figure for the C3 arc shows that the OD uncertainties remain large until E28, and the combined effect of the flyby and continuous tracking reduces the B-plane uncertainties from about 1000 km to about 10 km by the DCO for the maneuver. (For an explanation of the B-Plane see the Appendix).

Table 3. B-Plane and Encounter 1σ Uncertainties for the Europa Flybys

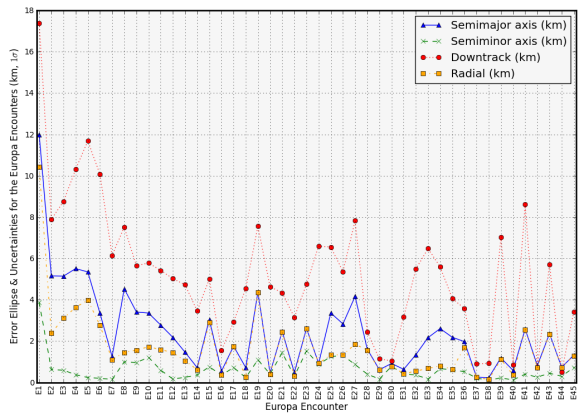
Flyby	Arc	Date, Time (ET)	Altitude (km)	DCO (days)	Semi-major Axis (km)	Semi-minor Axis (km)	Theta (deg)	Radial (km)	Down-track (km)	Time of Flight (sec)
E1	07E1	25-MAR-2029,22:26:46	752.8	-5.405	12.0	3.9	95	10.4	17.4	4.33
E2	08E2	09-APR-2029,02:40:14	250.0	-5.029	5.2	0.6	98	2.4	7.9	2.00
E3	09E3	23-APR-2029,07:42:55	100.0	-5.197	5.1	0.6	81	3.1	8.8	2.20
E4	10E4	07-MAY-2029,12:42:32	100.0	-5.027	5.5	0.4	58	3.6	10.3	2.58
E5	11E5	21-MAY-2029,17:42:12	50.0	-5.087	5.3	0.2	35	4.0	11.7	2.92
E6	12E6	04-JUN-2029,22:42:15	25.0	-5.337	3.3	0.2	11	2.8	10.1	2.53
E7	13E7	19-JUN-2029,03:44:28	100.0	-5.031	1.2	0.1	166	1.1	6.1	1.55
E8	14E8	03-JUL-2029,15:16:07	100.0	-5.394	4.5	1.0	86	1.4	7.5	1.88
E9	15E9	17-JUL-2029,20:14:27	25.0	-5.034	3.4	1.0	106	1.6	5.6	1.41
E10	16E10	01-AUG-2029,01:15:16	50.0	-5.212	3.4	1.2	130	1.7	5.8	1.43
E11	17E11	15-AUG-2029,06:11:33	25.0	-5.034	2.8	0.6	151	1.6	5.4	1.34
E12	18E12	29-AUG-2029,11:07:49	50.0	-5.078	2.2	0.2	174	1.4	5.0	1.25
E13	19E13	12-SEP-2029,16:00:57	25.0	-5.310	1.5	0.2	19	1.0	4.7	1.18
E14	20E14	26-SEP-2029,21:15:21	565.3	-5.039	0.7	0.4	35	0.6	3.5	0.88
E15	21E15	11-OCT-2029,09:12:54	1872.3	-5.399	3.0	0.8	88	2.9	5.0	1.26
E16	22E16	12-NOV-2029,01:39:22	2710.3	-5.161	0.5	0.4	154	0.4	1.6	0.38
E17	24E17	26-NOV-2029,14:57:33	50.0	-5.076	1.8	0.7	91	1.7	2.9	0.72
E18	25E18	14-DEC-2029,04:40:31	50.0	-5.362	0.7	0.2	174	0.2	4.5	1.13
E19	26E19	28-DEC-2029,17:39:58	81.3	-5.934	4.4	1.1	92	4.4	7.6	1.86
E20	27E20	15-JAN-2030,07:07:06	50.0	-5.538	0.4	0.4	11	0.4	4.6	1.14
E21	28E21	29-JAN-2030,20:00:01	100.0	-5.035	2.5	1.4	84	2.4	4.3	1.07
E22	29E22	16-FEB-2030,09:40:09	50.0	-5.051	0.5	0.3	0	0.3	3.1	0.77
E23	30E23	02-MAR-2030,22:49:07	50.0	-5.032	2.6	1.5	88	2.6	4.8	1.16
E24	31E24	20-MAR-2030,12:05:36	100.0	-5.233	0.9	0.9	105	0.9	6.6	1.61
E25	32E25	04-APR-2030,01:17:20	50.0	-5.167	3.4	1.3	87	1.3	6.5	1.59
E26	33E26	18-APR-2030,06:13:36	50.0	-5.070	2.8	1.3	111	1.3	5.4	1.29
E27	34E27	02-MAY-2030,11:03:14	50.0	-4.982	4.2	0.9	130	1.8	7.8	1.89
E28	35E28	27-MAY-2030,07:36:51	25.0	-5.241	1.6	0.4	147	1.6	2.4	0.59
E29	51E29	09-DEC-2030,22:16:02	546.7	-5.040	0.6	0.2	90	0.6	1.1	0.28
E30	54E30	14-JAN-2031,21:03:57	1009.1	-5.065	0.9	0.8	1	0.8	1.0	0.26
E31	57E31	28-JAN-2031,18:06:20	100.0	-5.035	0.6	0.4	90	0.4	3.2	0.79
E32	58E32	11-FEB-2031,23:08:16	100.0	-5.212	1.3	0.4	153	0.5	5.5	1.37
E33	59E33	26-FEB-2031,04:12:04	50.0	-5.453	2.2	0.2	6	0.7	6.5	1.63
E34	60E34	12-MAR-2031,09:13:49	50.0	-5.033	2.6	0.7	35	0.8	5.6	1.40
E35	61E35	26-MAR-2031,14:15:55	25.0	-5.276	2.2	0.6	65	0.6	4.1	1.02
E36	62E36	09-APR-2031,18:29:44	303.5	-5.031	2.0	0.5	85	1.7	3.6	0.91
E37	63E37	04-MAY-2031,06:22:08	50.0	-5.367	0.2	0.2	2	0.2	0.9	0.23
E38	65E38	29-MAY-2031,03:37:22	25.0	-5.668	0.2	0.1	18	0.1	0.9	0.24
E39	67E39	12-JUN-2031,07:37:02	50.0	-5.876	1.2	0.2	152	1.1	7.0	1.83
E40	68E40	07-JUL-2031,04:32:13	25.0	-5.487	0.6	0.1	174	0.4	0.9	0.22
E41	70E41	21-JUL-2031,08:16:16	50.0	-5.025	2.6	0.4	134	2.5	8.6	2.25
E42	71E42	15-AUG-2031,05:17:42	50.0	-5.313	0.8	0.3	172	0.7	0.7	0.19
E43	73E43	29-AUG-2031,08:56:27	25.0	-5.028	2.4	0.4	115	2.3	5.7	1.51
E44	74E44	23-SEP-2031,05:37:40	50.0	-5.097	0.7	0.3	171	0.7	0.5	0.13
E45	76E45	07-OCT-2031,08:47:52	25.0	-5.262	1.3	0.7	96	1.3	3.4	0.92



(a) Ganymede Flybys



(b) Callisto Flybys



(c) Europa Flybys

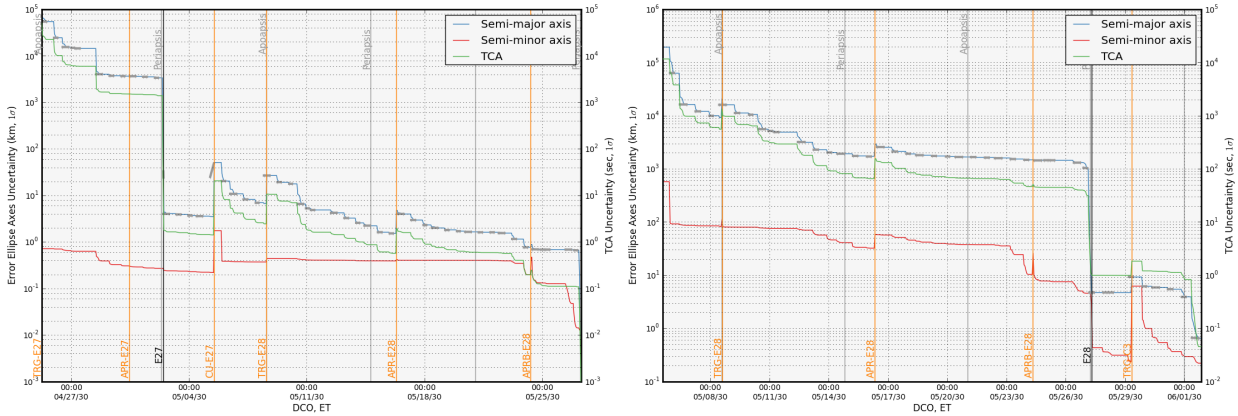
Figure 3. B-Plane, Downtrack, and Radial 1-σ Uncertainties at Approach Maneuver-2days

V. Science Instruments Requirements on OD

The OD uncertainties for the Europa Clipper have to be small enough to meet the level of accuracy needed by the notional science instruments. An analysis of radial and downtrack errors during a low flyby concluded that only the SWIRS instrument is significantly affected by the expected errors. The SWIRS mirror has a scanning range of $\pm 45°$ in the downtrack direction. The notional instrument operations profile is to image lines on the surface in the crosstrack direction, at a resolution of 300 m/pixel, with a downtrack separation of 300m between successive lines. The mirror is used to control the imaging location in downtrack, since the spacecraft velocity is higher than the rate of advance of the instrument observations. Errors in radial, downtrack (i.e closest-approach timing), and attitude cause the line spacing to deviate from 300m. A line spacing error of up to 10% (i.e 30m) is thought to be acceptable. Figure 5 shows that a 1 km error in downtrack is not very significant, but a 1 km error in the radial direction exceeds the 30m requirement at a few points (at about $\pm 60s$ from closest approach). In addition, Figure 5 shows that the effect of the expected 2-mrad pointing control capability is not very significant.

For most flybys the 1-sigma radial uncertainty at the last control point, which occurs at the approach maneuver-2days, exceeds the 1 km level desired by the SWIRS instrument. However, the instrument pointing profile could be updated based on a DCO of one day before the satellite encounter. This late DCO would allow convergence of the maneuver execution errors after the approach maneuver had been performed. This update is only a knowledge update of the on-board ephemeris. No further corrections of the trajectory can be executed at this time, but it would result in the science instruments being pointed more accurately.

The spacecraft position errors were evaluated in the downtrack and radial directions at closest approach



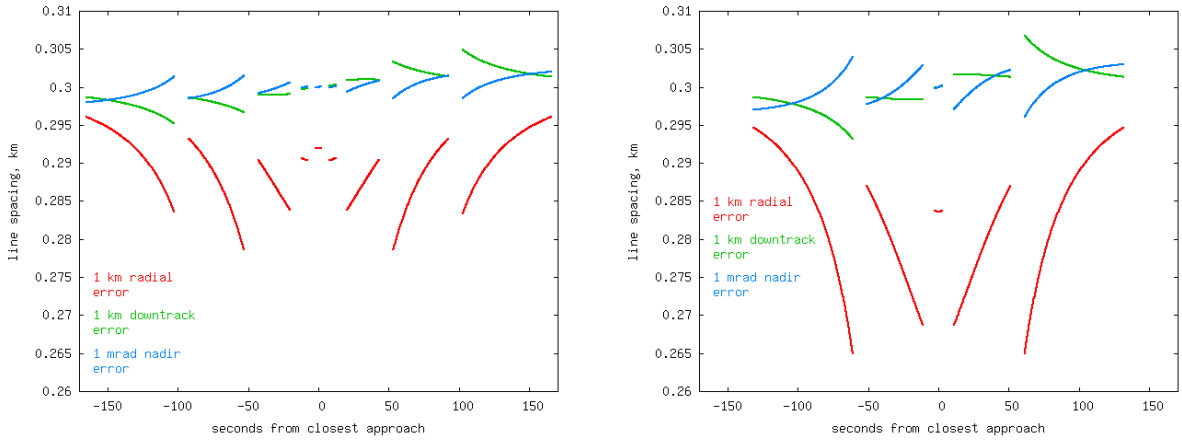
(a) Europa-28 Arc

(b) Callisto-3 Arc

Figure 4. B-Plane and Time of Closest Approach 1-σ Uncertainties

for all the Europa flybys, for a DCO of encounter-1day. Figure 6 shows the results for all of the 25 and 50 km flybys, and it can be seen that in most cases, the radial error is much smaller than 1 km, and only slightly exceeds 1 km in a few cases. While these are 1-σ results, it is not currently thought to be necessary to ensure that all scientific measurements could be made in the presence of worst-case (e.g 3-σ) errors, since most of the time the errors would be much smaller, and some small loss of science data is acceptable. More analysis remains to be done in order to understand the source of the larger radial errors on a few of the flybys, which could be deterministic maneuvers, a short arc that does not allow the OD uncertainties to converge sufficiently between maneuvers, or insufficient tracking data due to low SEP or occultations.

The requirements for the other instruments do not appear to be as stringent, and presently, the magnitude of the OD uncertainties estimated for this sample tour are believed to be adequate for carrying out the planned science measurements.



(a) 25 km Flyby Altitude

(b) 50 km Flyby Altitude

Figure 5. Europa 1-σ Flyby Errors for SWIRS

VI. Parametric Studies

Parametric studies of the filter model were conducted to better understand the impact on the OD uncertainties. It was found that the largest impact to the OD uncertainties came from the satellite ephemeris uncertainties, the level of stochastic accelerations which account for unmodeled accelerations, the amount of radiometric tracking, and the Doppler data accuracy. Figure 7 and Figure 8 show the 1-σ maximum

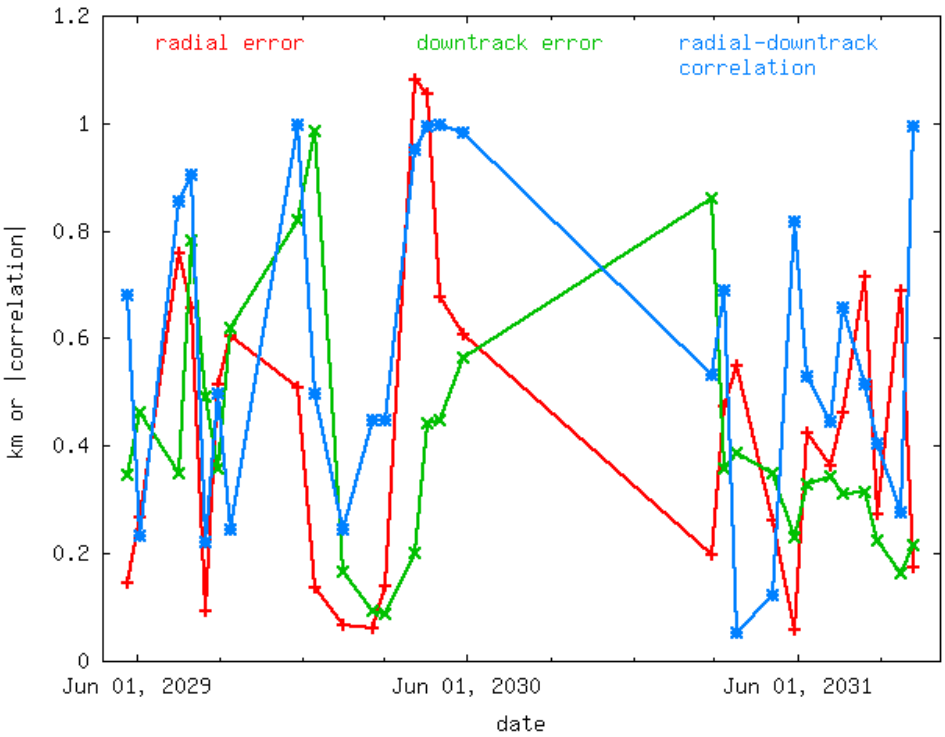


Figure 6. OD Uncertainties for the Low Altitude (25 km & 50 km) Europa Flybys

radial and pointing dispersion sensitivity, respectively, to the filter model. The pointing uncertainties are calculated in the nadir direction at an altitude of 20,000 km from the closest approach to the satellite.

VII. Conclusion

The covariance analysis performed has demonstrated the feasibility of navigating the proposed sample Europa Clipper Mission from an orbit determination point of view. The study helped determine a statistical ΔV budget, and predict the OD accuracy for all the satellite flybys and for the SWIRS instrument. Radiometric data taken with a frequency of one out of every two tracking opportunities will be sufficient in most cases to achieve the B-plane uncertainties needed to accurately navigate the proposed tour. In order to meet the OD accuracy required by SWIRS, an update of the OD knowledge would be necessary for the Europa flybys at a DCO of encounter-1day. The analysis identifies flybys which would be challenging for both OD and maneuver. These are the back-to-back flybys of E28-C3, which are separated by only 5 days, during which time only one targeting maneuver could be designed and executed. Continuous tracking data would be necessary in order to converge the OD uncertainties faster. The analysis also predicts the improvement that would be achieved in the satellite ephemeris uncertainties during the proposed tour, and the contribution of these uncertainties to the spacecraft ephemeris uncertainties. The decision to not use OpNavs for this mission is two-fold: the ephemerides for the Jovian satellites are better known than those for the Saturnian satellites for the Cassini Mission, and given how much larger the major Jovian moons are, the Doppler signature at the flyby combined with the resonance between the moons would rapidly reduce the ephemeris uncertainties. The second factor comes from the science need to explore Europa with instruments other than a camera while in search of existence of life.

VIII. Acknowledgment

This research was carried out at the Jet Propulsion Laboratory, California Institute of Technology, under a contract with the National Aeronautics and Space Administration. Reference to any specific commercial product, process, or service by trade name, trademark, manufacturer or otherwise, does not constitute or

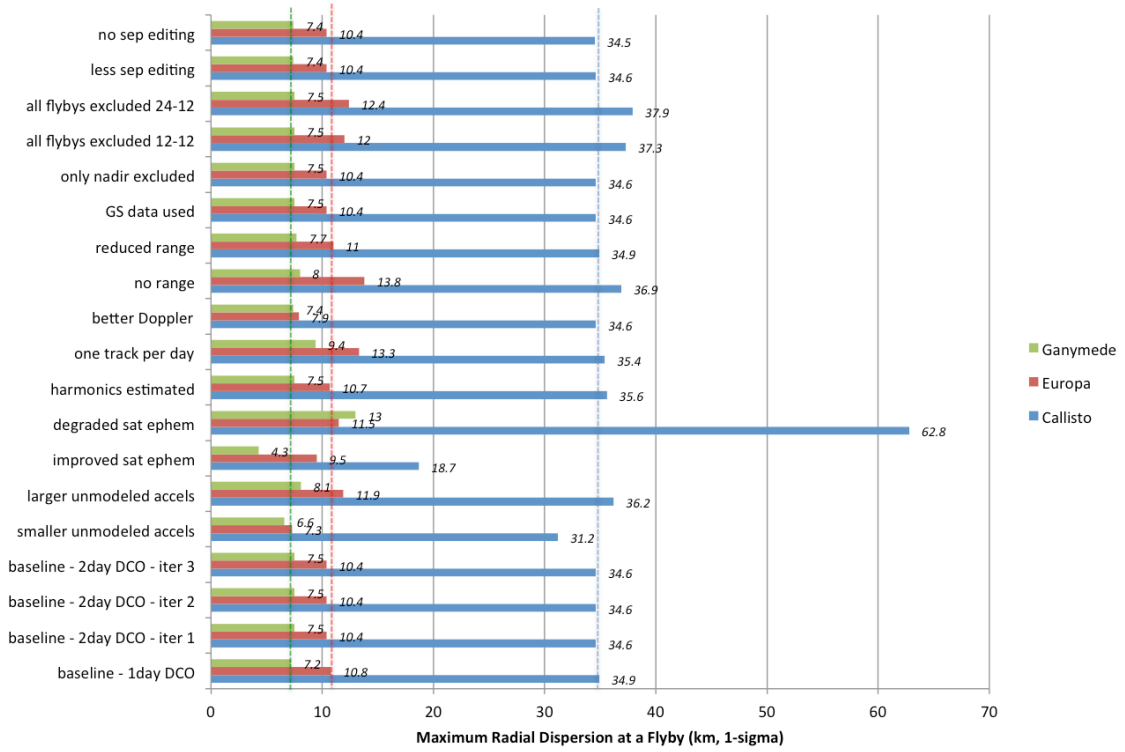


Figure 7. Maximum Radial 1-σ Uncertainty (km) at a Flyby

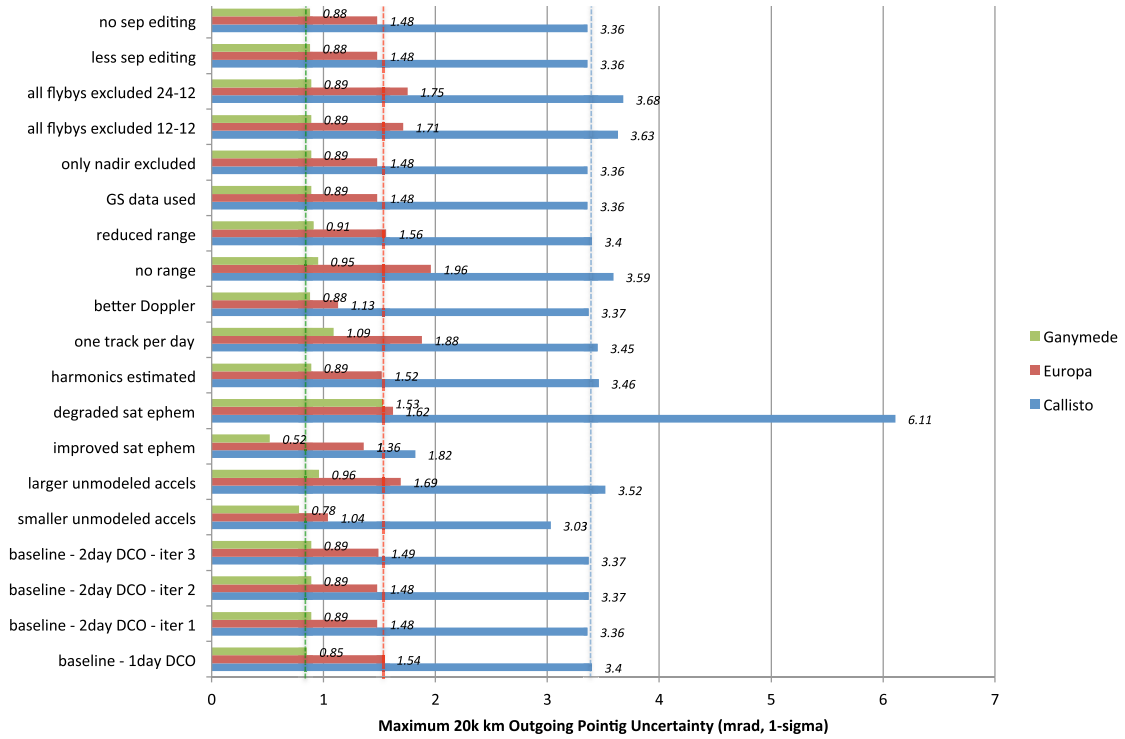


Figure 8. Maximum 20k Pointing 1-σ Uncertainty (km) at a Flyby

imply its endorsement by the United States Government or the Jet Propulsion Laboratory, California Institute of Technology.

William Folkner provided the planetary covariance. Robert A. Jacobson provided the Jupiter satellite ephemeris and covariance.

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Appendix

The B-plane (Figure 9[4]) passes through the center of the target body and perpendicular to the incoming asymptote of the hyperbolic flyby trajectory. Coordinates in the plane are given in the **R** and **T** directions, with **T** being parallel to the Earth Mean Orbital plane of 2000) in the direction defined by crossing **S** into the pole vector). The angle θ determines the rotation of the semi-major axis of the error ellipse in the B-plane relative to the T-axis and is measured positive right-handed about S.

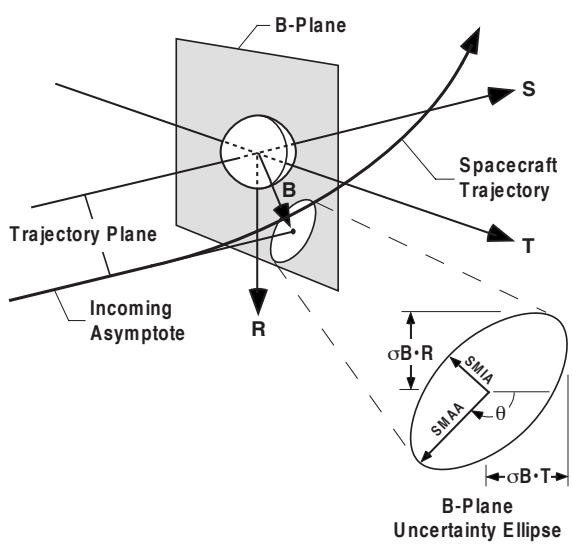

Figure 9. The B-plane coordinate system