AAS 19-271

ORBIT DETERMINATION SENSITIVITY ANALYSIS FOR THE EUROPA CLIPPER MISSION TOUR

Zahi Tarzi[*], Dylan Boone*, Nickolaos Mastrodemos†, Sumita Nandi*, and Brian Young‡

The 2011 Planetary Science Decadal Survey identifies Europa, the fourth largest moon of Jupiter, as the most likely body in the Solar System to harbor extra-terrestrial life.[1] The Europa Clipper mission will orbit Jupiter and investigate Europa's habitability utilizing data collected during multiple close flybys of Europa by a set of five remote sensing and five in-situ instruments. The measurements set is designed to confirm the existence of a subsurface liquid ocean and characterize the thickness of its ice shell. The tour phase of the current mission plan consists of forty-six low altitude Europa science fly-bys. Sufficiently accurate predicted and reconstructed spacecraft orbit determination (OD) is needed to support spacecraft pointing, measurement planning and interpretation of measurements. After briefly discussing expected OD capability, this paper will assess the sensitivity of OD delivery and knowledge performance for the current Europa Mission trajectory through parametric variation of a baseline tour navigation strategy.[2] Variations of several parameters are run, one at a time, to determine the impact on spacecraft ephemeris uncertainties at OD knowledge, delivery, and encounter reconstruction times. There are two basic categories of sensitivity runs considered: variations of tracking data type and amount, and variations to dynamic parameters. The results of these parameter and data variations are compared against the values necessary to achieve accurate instrument pointing and observation planning.

INTRODUCTION

The Europa Clipper mission will explore Europa and investigate its habitability utilizing a set of five remote sensing instruments that cover the electromagnetic spectrum from thermal emission through the ultraviolet, four in-situ fields and particles instruments, a two-channel radar, and a gravity science investigation. Key mission objectives will be to produce high-resolution images of Europa's surface, determine its composition, look for signs of recent or ongoing activity, measure the thickness of the icy shell, search for subsurface lakes, and determine the depth and salinity of Europa's ocean. Over 40 flybys of Europa, with closest-approach altitudes varying from several thousand kilometers to as low as 25 kilometers, will be executed over an approximately 3.5 year Prime Mission.

[*] Navigation Engineer, Outer Planet Navigation Group, Jet Propulsion Laboratory, California Institute of Technology, 4800 Oak Grove Dr Pasadena, CA 91109.

[††] Navigation Engineer, Solar System Dynamics Group, Jet Propulsion Laboratory, California Institute of Technology, 4800 Oak Grove Dr Pasadena, CA

[‡‡] Navigation Engineer, Flight Path Control Group, Jet Propulsion Laboratory, California Institute of Technology, 4800 Oak Grove Dr Pasadena, CA

At the time this study was conducted, launch was scheduled to occur as early as June 2022, with backup opportunities in 2023. The launch timeframe has since been updated to utilize the 2023 opportunities as the new baseline. Two Jupiter system delivery options are currently being considered: 1) The baseline mission is an Earth-Jupiter direct trajectory that would arrive at Jupiter as early as December 2024 utilizing NASA's Space Launch System (SLS) launch vehicle, and, 2) The secondary mission is an Earth-Venus-Earth-Earth gravity assist interplanetary trajectory (EVEEGA) that would arrive at Jupiter in January 2030 utilizing a non-SLS expendable launch vehicle (ELV). The tour phase of the mission, which begins after arrival in the Jovian system, can be designed to have similar characteristic for any arrival year. This study is primarily concerned with the tour phase and, in this paper, "baseline" refers to a tour stemming from a 2022 launch direct to Jupiter trajectory.

After Jupiter capture, the tour begins with a series of Ganymede flybys which serve to reduce the orbit period and produce the desired phasing with respect to Europa to initiate the first Europa science campaign. Europa Campaign 1 is designed to survey the sun-lit anti-Jovian hemisphere of Europa and consists of roughly two-dozen flybys, most at altitudes at or below 100 km. This campaign is followed by a five-month period of orbit shaping utilizing Callisto flybys that sets up Europa Campaign 2 (another roughly two dozen flyby), which is primarily a survey of the sun-lit sub-Jovian hemisphere of Europa, but also executes a sub-set of flybys to cover the unlit anti-Jovian hemisphere of Europa. Most of the transfers from one Europa encounter to the next use a 4:1 resonance, which means Europa orbits Jupiter four times in the same amount of time the spacecraft orbits Jupiter once (approximately 14.2 days). These highly elliptical orbits afford time for Europa science data playback while outside Jupiter's high radiation environment, extending the lifetime of the mission and maximizing the total science return.

The flight system is comprised of a spacecraft and the aforementioned payload. The spacecraft is solar-powered with large batteries for use during the encounter and downlink periods, uses reaction wheels for precise attitude control, and has a bipropellant system for propulsion and coarse attitude control. The telecom system is comprised of a high-gain antenna (HGA) for communication at X- or Ka-band, a co-aligned medium-gain antenna (MGA), two low-gain antennas (LGAs) and three fan beam antennas for the gravity experiment and engineering purposes. All instruments are body mounted, and the spacecraft points the remote sensing instruments toward nadir during most of the flyby, and points the instruments designed to sample material from Europa itself in the velocity-facing direction at closest approach.

REFERENCE TRAJECTORY DESCRIPTION

The baseline trajectory used for Europa Clipper at the time of this study is referred to as 17F12 and is described in detail in Lam, et. al.[3] 17F12 is a high-fidelity, numerically integrated end-to-end trajectory that begins at Earth departure and ends with Callisto impact after the prime mission has been completed. 17F12 utilizes an Earth-Jupiter direct interplanetary trajectory launching in mid-2022, with arrival to the Jupiter system as early as December 2024. Once in the Jupiter system, 17F12 will obtain global-regional coverage of Europa via a complex network of 46 flybys over the course of 3.7 years. In addition, 4 Ganymede and 9 Callisto flybys are used to manipulate the trajectory relative to Europa. Upon arrival to the Jupiter system, a 300 km altitude Ganymede gravity assist will be utilized to significantly reduce the ΔV magnitude of the Jupiter Orbit Insertion (JOI) maneuver that will begin approximately 11 hours later. The Tour Phase of the mission begins immediately after the Jupiter Orbit Insertion burn (JOI) and continues through end of mission.

EUROPA CLIPPER TOUR NAVIGATION STRATEGY

During the tour phase of the mission, the close satellite encounters are of prime interest for science instruments and most stressing in terms of trajectory safety. Given those characteristics, the strategy that has been developed for tour navigation is to return the spacecraft to a reference trajectory at the time of targeted flybys, allowing the spacecraft position to deviate from the reference between targeted encounters. Since each tour petal contains one or two deterministic maneuvers in the time period between the early encounter and apojove, the key implementation is to place a purely statistical maneuver, called the approach maneuver, targeting the upcoming encounter at three days prior to the encounter. While all maneuvers will have a statistical component when expected errors are analyzed, a deterministic maneuver is one that is in the reference trajectory, while a statistical maneuver is added during navigation analysis to manage dispersions. The placement at three days before an encounter allows time to determine the spacecraft position in the presence of dispersions from the earlier maneuvers and correct accumulated orbit determination (OD) errors, while close enough to the upcoming encounter to limit error growth from dispersions in the approach maneuver itself. The desire to limit engineering activity near the encounter period, constrains the plausible placement of the approach maneuver on one side, while the observability of the dispersions from the earlier maneuvers in the petal using Earth-based tracking constrains the location on the other. While this strategy is similar to that employed in the Cassini tour of Saturn, the timelines are slightly shorter. Away from encounters, it is still necessary to maintain ephemeris knowledge to the level required to acquire spacecraft signal from Earth at any time, support science performed away from encounters, and design planned maneuvers.

The navigation analysis includes two components, used in concert. The first uses an OD covariance study to predict ephemeris uncertainties for varied tracking assumptions and modeling uncertainty levels for a reference trajectory. The second uses a Monte Carlo method to compute expected dispersions in deterministic and statistical maneuvers in the reference trajectory given a modeled maneuver execution behavior and expected ephemeris knowledge along the reference trajectory. Fuel mass allocation is based on ΔV99, the value for which 99% of the dispersed trajectories use less ΔV. The Monte Carlo results provide the mission ΔV99, individual maneuver ΔV99, and a maneuver covariance that may be used in the OD covariance study. Typically, the injection of the maneuver covariance statistics into the OD covariance study initially results in larger ephemeris uncertainties, and the process must be iterated until both ephemeris errors and maneuver statistics converge. Both the Monte Carlo-based maneuver analysis and the OD covariance study presented here were performed using the Mission Design and Operations Navigation Toolkit Environment (MONTE) software developed at JPL. [4]

In general, each transfer from encounter to encounter (called an arc) has three maneuvers to maintain the trajectory, two deterministic and one statistical. The first deterministic maneuver cleans up (CU) trajectory dispersions from the previous flyby, the second deterministic targets (TRG) the next encounter, and the statistical maneuver three days before each flyby accounts for OD and maneuver execution errors prior to approach (APR). Figure 1 shows a typical orbit petal with the three maneuvers and associated data cutoffs targeted to a Europa encounter. The inner dashed line represents the orbit of Europa and the outer dashed line that of Ganymede. Transfers containing multiple revolutions of Jupiter may contain an additional targeting maneuver to limit dispersions.

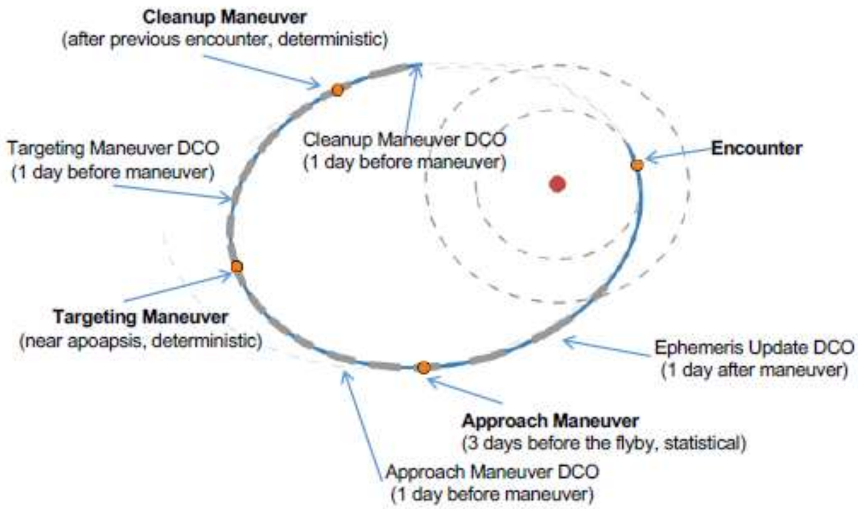

Figure 1. Typical Orbital Petal Diagram

ORBIT DETERMINATION

An OD covariance analysis is used to predict the expected uncertainty in the spacecraft ephemeris as a function of time given errors in dynamical models, tracking data schedule, and tracking data errors. The state partial derivatives of dynamic model parameters and measurement data are calculated about their nominal values and used to predict the impact of errors in those parameters and data on the ephemeris. [5] The state uncertainties can then be used as an input to the maneuver ΔV99 study and mapped forward from times when solutions would be available in operations to times of interest for instrument observations. In general, observing scenarios could be sensitive to both delivery (the expected error compared to a reference trajectory) and knowledge (the expected error compared to the last OD ephemeris available at the time of an observation). Orbit determination requirements for Europa Clipper are tied to knowledge only. However, since the delivery uncertainty affects the ΔV99 performance of the trajectory, it is still of interest in this analysis.

Each orbit determination arc encompasses two flybys and is setup with an epoch near the apojove prior to the first flyby in the arc. The epoch is placed near apojove in order to start the arc with an open state at a point with low dynamics. The first flyby then provides body-relative data to accurately estimate the ephemeris before delivery to the second flyby, which is the target of the arc. Arcs are labeled by the body they target and the number of times that body has been encountered, i.e. E29 represents the twenty-ninth targeted encounter of Europa. Assessing expected OD performance of each arc separately simulates an operations strategy that would reduce the propagation of systematic modeling errors.

Table 1 shows the data schedule assumed for each OD arc. The every other eight hours tracking schedule, designed to return the expected data volume, provides a rich data set for determining the spacecraft state throughout the arc. While Earth-based Doppler and range data instantaneously provide information primarily in the line-of-sight, the dynamics of the spacecraft orbit about Jupiter during the tour allow determination of all state components. ΔDOR tracking, which produces an near-instantaneous measurement of spacecraft plane-of-sky position by determining the angular offset between the spacecraft and a natural radio source is not employed during the tour (though it is employed during the interplanetary portion of the mission). Once a year during the tour, when the line-of-sight to Earth passes near the sun, Doppler and range data will be degraded due to solar plasma scintillations. This affect is characterized by appropriately de-weighting or removing simulated radiometric data at low Sun-Earth-Probe (SEP) angles as noted in Table 1. Since the spacecraft will point remote sensing instruments toward the flyby body near satellite flybys, the Earth-to-radio antenna geometry may not permit tracking data to be available in all cases. Therefore, tracking is excluded between 24 hours before and 12 hours after all flybys for the baseline case. In many cases, some Doppler tracking may be available employing a low-gain antenna to be used for Radio Science, and the effect of using this tracking is examined as one of the sensitivity study variations. The data cutoff for the design of each maneuver is one day prior to maneuver execution for maneuvers targeting Europa flybys.

In order to obtain better satellite ephemeris knowledge, the radiometric data can also be supplemented with images taken of the Jovian satellites and used as optical navigation (OpNav) data. The images can be processed (along with background stars used to precisely measure the camera pointing direction) to obtain the satellite position relative to the spacecraft. Used in conjunction with radiometric data, OpNav measurements can be used to produce better satellite ephemeris knowledge which is especially useful for close encounters with the satellites. Since there is no engineering camera, OpNav data are not included as part of the baseline data set, but the effect of using EIS-NAC (Europa Imaging System – Narrow Angle Camera) instrument images to augment radiometric data is studied as a sensitivity variation. Details on the optical navigation measurements are described in a later section.

Table 1. Orbit Determination Assumptions

Tracking Data	2-way Doppler and range collected every other 8 hour pass
Doppler data weight	0.1 mm/s per 60-sec integration for SEP > 15° 1 mm/s for 7.5° < SEP < 15° 5 mm/s for SEP < 7.5°, no data SEP < 3°
Range data weight	3 m for SEP angles > 7.5°, no data SEP < 7.5°
Tracking exclusion near Europa flybys	No data from 24 hours prior to 12 hours after flyby
Nominal data cutoff for maneuvers	1 day before maneuver execution time

Simulated tracking data are processed in an epoch state least squares navigation filter to compute the expected spacecraft state and parameterized model uncertainties. Table 2 shows the model parameters employed in the OD filter for each arc and designates which are estimated and updated, and which have their error considered in the filter estimate. Considered parameters are those corresponding to models which are not expected to have a strong independent signature in the data, but have uncertainties that affect state uncertainty. The initial spacecraft state uncertainty is set at a conservative 15 km at the start of each arc. The Jupiter barycenter ephemeris and individual states of the satellite system, their GMs and the pole orientation of Jupiter are estimated in each arc. To model the improved knowledge of these parameters in subsequent arcs, the estimated covariance of these parameters is mapped forward to the next arc epoch and used as a new *a priori*. *A priori* covariances at the start of tour for the Jupiter barycenter and satellite ephemerides are provided by the Solar System Dynamics Group at JPL, with the most current forms named de430 for the barycenter and jup310 for the satellites. The initial (pre-tour) satellite covariance is scaled so that it yields uncertainties of 11 km in Ganymede position and 55 km in Europa position, when mapped to the start of tour in 2025, which is conservative. The Jupiter barycenter and satellite ephemeris are estimated in each arc with the estimated satellite covariance mapped forward to the next arc epoch and used as a new *a priori*. A lower limit, or "floor", on this estimated uncertainty is put in place to avoid unrealistic increases in accuracy from many repeated observations. Uncorrelated stochastic white noise, estimated in eight hour batches of constant acceleration, accounts for mis-modeling of small forces such as solar radiation pressure. Uncertainty in parameters affecting radiometric tracking measurements such as errors in the DSN station locations, atmospheric delay, and Earth polar motion are considered in the filter. Impulsive burns are used to model expected momentum wheel desaturation via thrusters (referred to as "wheel biasing") prior to approach and cleanup maneuvers.

Table 2. OD Filter Parameters

Parameter	Unit	Estimated/Considered	***a priori* σ**
Epoch state S/C position – X/Y/Z	km	Estimated	15
Epoch state S/C velocity – X/Y/Z	cm/s	Estimated	5
Maneuvers	km/sec	Estimated	Monte Carlo covariances
Jupiter Ephemeris Set III parameters	-	Estimated	de430 covariance
Jupiter Satellite States pos/vel	km & km/s	Estimated	jup310 covariance
Jupiter Harmonics and Pole	-	Estimated	jup310 covariance
Jupiter and Satellite GMs	km^2/sec^3	Estimated	jup310 covariance
Impulsive RWA Bias, 4 per arc	mm/sec	Estimated	0.8 (spherical)
Solar Pressure Scale Factor	-	Estimated	5% of SRP accel
Stochastic accelerations X/Y/Z	km/sec^2	Estimated	1.5E-13 @ 8 hour batches
Earth polar motion X/Y	arcsec	Considered	3E-04
UT1 bias	sec	Considered	4.25E-05
DSN station locations	cm/arcsec	Considered	3/1E-03
Troposphere path delay – wet/dry	cm	Considered	1/1
Ionosphere path delay – day/night	cm	Considered	55/15

MANUEVER DESIGN

A linear Monte Carlo analysis is used to compute ΔV statistics for both individual maneuvers and the ensemble of maneuvers. The results can be used to plan mission fuel requirements and spacecraft constraints on individual maneuvers. As a necessary first step, an experience-based strategy is used to determine locations for pure statistical maneuvers and adjust deterministic maneuver placement and targeting strategy. Judicious placement accounts for the time of dynamic events that tend to magnify dispersions in the spacecraft ephemeris, such as close flybys and large deterministic maneuvers, as well as accounting for expected tracking schedule. Placement variations are assessed to find a suitable strategy.

The maneuver strategy for Europa Clipper is to perform three maneuvers per transfer between encounters: a post-encounter cleanup (CU) maneuver, an apoapsis targeting (TRG) maneuver, and a statistical pre-encounter approach (APR) maneuver. The CU maneuver, performed 3 days after an encounter, when sufficient data has been collected to reconstruct the flyby adequately, is designed to re-optimize the trajectory, optimizing the CU and TRG maneuvers for the next four transfers, minimizing total ΔV while achieving the targeted B-plane range, angle, and time of flight from the reference trajectory (see Appendix for a definition of B-plane geometry). The TRG maneuver, near apoapsis for maximum ΔV effectiveness, is a simpler design, targeting the reference B-plane location and time of flight; this is a deterministic maneuver, with a baseline ΔV resulting both from the reference trajectory and from the redesign as part of the CU re-optimization. Finally, the APR maneuver, three days before the encounter, retargets the encounter B-plane components and time of flight, removing execution errors from the TRG maneuver and applying any improvements in OD knowledge. This pattern was employed during the Cassini mission tour. Some transfers, used to shape the tour, have adjusted maneuver locations relative to the typical 4:1 resonant transfer depicted in Figure 1.

Once a maneuver location has been determined, a Monte Carlo analysis is performed starting with initial states from a sampled state covariance at a time prior to the maneuver. A maneuver is searched for each sample using the implemented targeting strategy. Finally, an execution error model is sampled to provide the final distribution of that particular maneuver. The two main inputs to the Monte Carlo analysis are the engine error model, which determines the uncertainty of the maneuver samples compared to their desired values, and the expected data cutoff (DCO) for OD knowledge used to design the maneuver, which determines the distribution of initial states for the Monte Carlo. For the purposes of this study, maneuver execution errors were modeled parametrically with a Gates Model.[6] Table 3 gives the fixed and proportional components due to magnitude and pointing errors. These values assume that the guidance and control team has performed some in-flight calibration of the engine system during interplanetary cruise. The Europa Mission flight system is currently being designed to perform maneuvers by slewing to the maneuver attitude and firing a set of four 22 N thrusters for maneuvers less than 0.21 m/s or eight 22 N thrusters for larger maneuvers.

Table 3. Gates Maneuver Execution Error Model Parameters (1σ) for Tour

	Error Component	8x22N Configuration	4x22N configuration
Magnitude	Fixed Error (mm/s)	4.67	4.67
	Proportional Error (%)	0.33	1.00
Pointing (per axis)	Fixed Error (mm/s)	3.33	3.33
	Proportional Error (mrad)	6.67	6.67

In operations, acceleration telemetry can give information regarding the executed maneuver which exceeds the accuracy specified by the Gates model. The Gates error model parameters can be used to derive an expected maneuver pointing reconstructed accuracy that would be achieved employing this telemetry. It is assumed that such telemetry information is used to assist in reconstructing executed maneuvers by constraining the components of the maneuver covariance transverse to the burn direction. The expected reconstructed accuracy for those components of maneuvers and consistent with the Gates model of Table 3 is enveloped by values given in Table 4. These values are smaller than the expected reconstructed accuracy employing post-maneuver radiometric tracking data alone for maneuvers with magnitude over 50 mm/s.

Table 4. ΔV Pointing Telemetry Accuracy (1σ) per Average Executed Magnitude

ΔV Magnitude (m/s)	Constraint (deg)
$\Delta V_{mag} \leq 0.05$	None
$0.05 < \Delta V_{mag} \leq 0.1$	0.5
$\Delta V_{mag} > 0.1$	0.25

In the covariance analysis, maneuvers are modeled as impulsive burns with magnitude, right ascension (RA), and declination (DEC) components, with an error covariance derived from the Monte Carlo analysis. The RA and DEC components of the Monte Carlo covariance are modified to simulate the incorporation of acceleration telemetry data using the values shown in Table 3. Constraining the magnitude component of the maneuver is not considered as it is expected that the absolute magnitude of the accelerometer data will be difficult to calibrate independent of the Doppler tracking data. This constraint is applied to all maneuvers in the tour phase of the mission large enough that useful maneuver pointing can be derived from expected telemetry. Delivery results are reported without the effect of telemetry in the estimation while knowledge update results include the effect of the telemetry accuracy constraint.

EUROPA ENCOUNTER DELIVERY RESULTS

Using the configuration discussed in the Orbit Determination Section, encounter delivery performance is determined for each arc in the tour. The expected uncertainty in the flyby target as a function of time can be calculated by mapping the state uncertainty at times within the arc forward to the encounter time. Figure 2 shows the time evolution of the B-plane coordinate (which are the maneuver target parameters) uncertainties in a typical arc (E9) as tracking data is processed, maneuvers are executed, and encounters are passed. When the 15 km initial state uncertainty is mapped in time to the targeted encounter and including the potential errors in the first flyby of the arc, this results in very large (104 km) B-plane errors prior to the first flyby in the arc. Flybys are generally followed by a steep drop in uncertainty since the potential satellite ephemeris error is no longer mapped ahead to the next encounter. Maneuver locations show an increase in uncertainty corresponding to introducing the execution error at the maneuver epoch. Post-maneuver tracking data then improves the state uncertainty. The post-maneuver drop-off is much steeper in Figure 2a which includes the effects of pointing telemetry which allows for a better estimate of the executed maneuver. The blue vertical lines labeled with “Bias” represent the times where momentum wheel bias events are modeled.

To assess OD performance against instrument position knowledge needs, the OD knowledge of spacecraft ephemeris uncertainty mapped to the time of the upcoming flyby is shown in Figure 3 for three epochs: the time of approach maneuver DCO, 2 days before encounter (which is one day after the Approach maneuver), and 1 day before the encounter. The uncertainties are shown in coordinates representing the radial, transverse, and normal directions (RTN) to the spacecraft trajectory at close approach for each flyby. The red dashed line shows the 1 km and 2 km levels of uncertainty in radial and transverse direction, respectively, as the performance requirement level at the time this study was conducted. The knowledge uncertainties are larger at the time of the approach maneuver DCO, and then typically shrink after the maneuver is performed and tracking data and pointing telemetry allow for estimations of the executed maneuver. In some cases, such as out-of-plane for E14-18, the uncertainties are not reduced significantly in one of the directions even with the post-maneuver knowledge update due to the geometry of those encounters. In this study, OD performance against this metric (predicted knowledge uncertainty at the flyby) is used to assess the risk associated with loss or degradation of tracking data or benefit of adding additional data or data types as observables in state estimation. Two examples of these variations using continuous tracking and taking OpNav measurements prior to a flyby, substantially improve knowledge performance of several flybys having poor performance with the current baseline tracking.

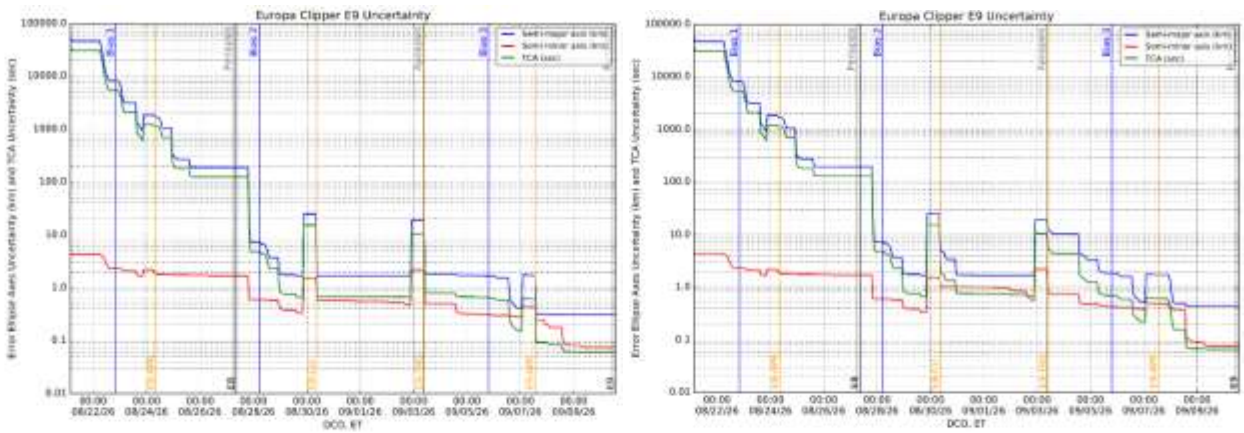

Figure 2. B-plane Uncertainty Evolution for a Typical Arc (E9): a) with Maneuver Pointing Telemetry b) without Maneuver Pointing Telemetry

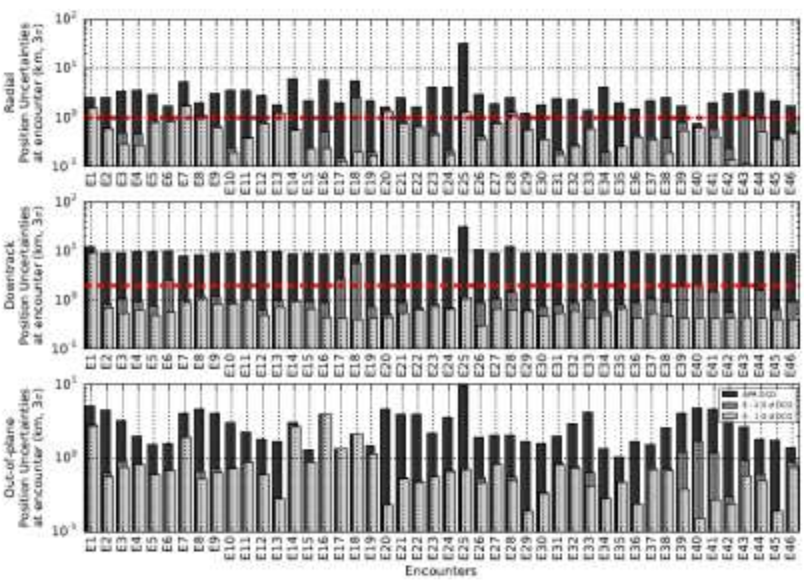

Figure 3. Europa Encounter 3σ Uncertainties in RTN Coordinates

EUROPA ENCOUNTER OD KNOWLEDGE SENSITIVITY STUDIES

This section details the results of parametric variations of the Europa Clipper tour navigation strategy. The baseline case implements a covariance analysis for each arc in the tour using the filter configuration described in preceding sections. Variations of several parameters are run one at a time to determine the impact on spacecraft ephemeris uncertainties in approach maneuver OD knowledge, delivery, and encounter reconstruction. There are two basic categories of sensitivity runs considered: variations of data type and amount, and variations to dynamic parameter uncertainties.

Variation on the data type and amount are described in Table 5. The nominal tracking plan consists of receiving radiometric Doppler and range measurements in 8 hour on/off increments. Some variations consist of eliminating radiometric ranging data or increasing the amount of coverage to allow for continuous tracking. Another alteration is performed by increasing or decreasing the radiometric data weights by a factor of ten, thus degrading or improving the quality of the tracking data. Sensitivity to maneuver pointing telemetry is analyzed by removing it entirely or improving the quality of the received telemetry. Margin is added to the data cutoff times used for maneuver designs in order to judge the impact of outdated data on the delivery errors. The effects of optical navigation (OpNav) data are considered, especially on the quality of encounter reconstruction, by adding optical measurements before and after each Europa encounter. A detailed description of the OpNav strategy and observables can be found in the optical navigation section. The inclusion of two hours of Doppler data during each Europa encounter is also analyzed as a method of improving the encounter reconstruction.

Table 5. Variations on Data Type and Amount

Doppler Only	Only Doppler data, no range
Continuous Tracking	Continuous Doppler/range during the tour, excluding occultations and Encounters
Data Weights 0.1x/10x	Increase/reduce the Doppler and range data weights by a factor of 10
No Telem	No maneuver pointing telemetry available
Capability Telem	Improved ‘Capability’ level of telemetry available – without GNC margins
TRG mnvrs DCOs-2days	DCO for targeting maneuvers is moved back to 2 days before maneuver execution
All mnvrs DCOs-2days	DCO for all maneuvers is moved back to 2 days before maneuver execution
Flyby Data	2 hours of de-weighted (10x) Doppler data centered at Europa Encounter (Excl: E28,E32,E39,E43)
OpNav Data	Optical data used, details of optical data in later section (E-2 case)

The dynamic parameter uncertainties are also adjusted to inspect the robustness of spacecraft ephemeris uncertainties to their modifications. Table 6 shows a summary of these variations. The sensitivity to systematic errors in the natural satellite ephemeris estimation process is examined by running cases with half and double the baseline satellite position knowledge lower limit (floor). In addition, the impact of changes to maneuver execution errors is studied by varying the components of the Gates Model, a parametric representation of expected maneuver execution error. OD performance when error levels associated with accumulated sources of force mis-modeling, represented as a stochastic acceleration, are evaluated for factors of two and ten increases. The sensitivity to prediction error for small impulse burns employed to bias momentum wheel rates is also studied.

Table 6. Variations on Dynamic Parameters

Gates Errors 0.5x/2x	Increase/reduce the maneuver execution errors by a factor of 2
Sat Floor 0.5x/2x	Increase/reduce the satellite knowledge floor by a factor of 2
Stochastics 2x/10x	Increase the background stochastic error by a factor of 2/10
Wheel Bias 2x/10x	Increase the error level associated with wheel biases by a factor of 2/10

The figures in this section show Europa Encounter delivery and knowledge uncertainties averaged over all encounters in the tour, with results shown in the radial, along-track, and cross-track coordinates for each variation studied. The dotted line represents the nominal value to make comparisons easier.

Approach Maneuver Delivery Sensitivities

Figure 4a displays delivery uncertainties mapped from the approach maneuver DCO to the encounter for the variations on data type and amount. These variations do not change the average uncertainties significantly outside of a few cases. Slight improvements are seen with continuous tracking and better weighted data, while slight increases are induced by removing pointing telemetry and moving back the maneuver DCOs. The largest change is produced by de-weighting the tracking data which causes a large increase in the uncertainties. The addition of optical data and tracking data during the encounter both reduce the average uncertainties compared to the nominal.

Figure 4b shows delivery uncertainties mapped from the approach maneuver DCO to the encounter for the variations on the dynamic parameters. The largest impact on the delivery uncertainties is produced by changes to the maneuver execution errors. The 2x increase in the execution errors result in a very large increase in uncertainties, while the reduction of execution errors nearly halves the uncertainties. This large dependency on the maneuver execution errors is expected since it is the largest source of uncertainty between the DCO and the encounter. Increasing the wheel bias errors by a factor of 10 also results in a large increase in the delivery uncertainty. The wheel biases are placed just prior the last tracking pass before the approach maneuver DCO, and thus there is not much tracking data after the bias to estimate down the errors. The limited tracking available becomes inadequate to fully reduce the uncertainty when large increases are made to the wheel bias errors. Increasing the stochastic errors by a factor of 10 has a small effect on the uncertainties, while there is little effect from changes to the satellite ephemeris floor of 0.5/2x. The largest improvement in OD delivery capability would be produced by improved maneuver execution modeling.

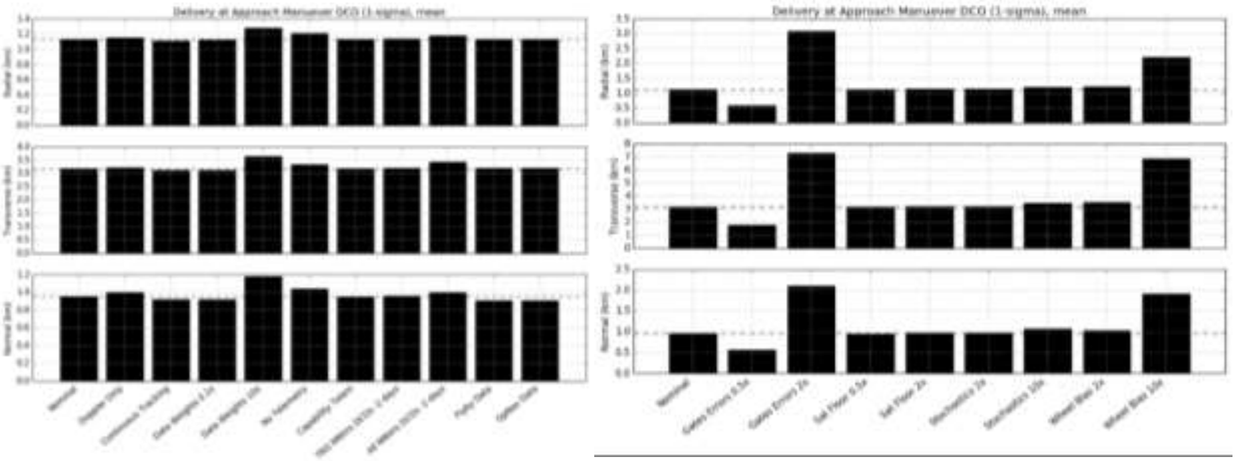

Figure 4. Mean Delivery Uncertainties: Variations on a) Data Type and Amount b) Dynamic Parameters

Predicted Flyby Knowledge Update Sensitivities

Figure 5a shows the averaged OD uncertainties mapped to each Europa encounter from 2 days prior to the encounter (the knowledge update) for variations on the data type and amount. It shows that the knowledge update is more sensitive to changes to the data quality and quantity than the delivery. This is expected, as the data received after the maneuver is used to estimate the execution errors and bring down the uncertainty. This is more difficult with less or lower quality data. Thus, the uncertainties decrease as compared to nominal in the cases with continuous tracking, a reduction of the data weights, inclusion of tracking data during the flyby, or inclusion of optical data. Cases with elimination of range data, an increase of the data weights, or elimination of telemetry data all result in larger uncertainties compared to the nominal values. The largest increase in uncertainty is produced by a degradation of the radiometric tracking data by a factor of 10, followed by the removal of maneuver pointing telemetry. Without the maneuver pointing telemetry, the approach maneuver errors could not be estimated down as seen in Figure 2. However, improving the telemetry to "capability" level does not result in much of a reduction in the uncertainty of the nominal case.

Figures 5b displays the averaged OD knowledge uncertainties for variations on the dynamic parameters. Changes to the maneuver execution error Gates model have a small effect on the knowledge uncertainty levels. This is again due to the availability of tracking after the maneuver which helps estimate down the execution errors. Changes to the satellite ephemeris floor also only affect the uncertainty levels slightly. Very large increases in the stochastic and wheel bias errors also result in increased uncertainty levels. In general, Figure 5 shows that efforts to improve the knowledge update uncertainties should focus on the quality and quantity of data available.

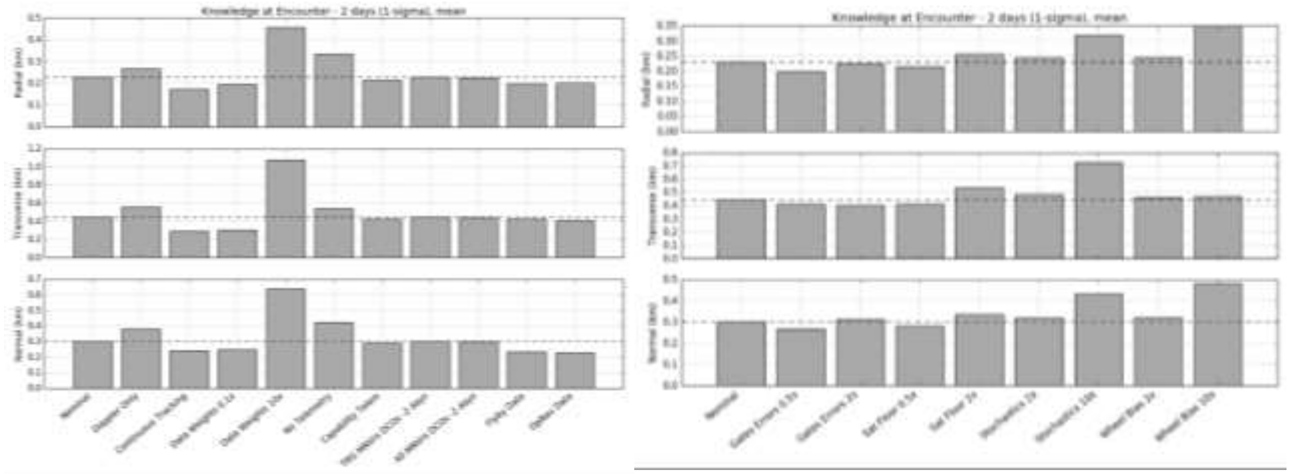

Figure 5. Mean Knowledge Uncertainties: Variations on a) Data Type and Amount b) Dynamic Parameters

RECONSTRUCTED ENCOUNTER KNOWLEDGE

Flyby reconstructed OD knowledge capability is assessed by mapping the spacecraft position uncertainty after the encounter time back to the encounter time. The uncertainty is mapped to each Europa encounter from two days after the event, representing a preliminary reconstruction that could be available after a few tracking passes. The parametric variations of the navigation strategy shown in the previous section can also be applied to assess the reconstruction capability sensitivity. Figure 6a shows the averaged OD uncertainty mapped to each Europa encounter from two days after the encounter for the variations to data type and amount shown previously. The uncertainties are highly sensitive to the quantity and quality of tracking data received after the encounter. The accuracy is improved by continuous tracking and the reduction of data weights. The uncertainties grow large if Range data is not utilized or if the tracking data is degraded by a factor of 2. The inclusion of tracking data during the encounter and optical data reduce the uncertainties by a large factor. The accuracy of the reconstruction is not affected much by changed to the maneuver pointing telemetry or DCOs. This is expected as there are no maneuvers within two days after the encounter. Figure 6b shows the averaged reconstruction uncertainties for the variations on the dynamic parameters. The solution is slightly improved by the better ephemeris knowledge produced by a reduction of half to the satellite ephemeris floor, and similarly degraded by a doubling of the floor. A large increase in the stochastic errors also causes large increases in the reconstruction uncertainty. Changes to the maneuver execution and wheel bias error do not impact the uncertainties much since there are no maneuvers or wheel biases within two days after the encounters. Overall, the best way ensure a high quality encounter reconstruction delivery is to utilize optical data and radiometric tracking during the encounter in addition to obtaining valuable post-encounter tracking and minimizing stochastic uncertainties.

Although Figure 6 shows that some parametric variations do not have much effect on the average uncertainties, they can be greatly increased for specific problem encounters with unfavorable geometry. The utilization of optical navigation data and radiometric tracking data during the encounters are effective in reducing uncertainties for these unfavorable flybys. In particular, two stressing cases were studied: satellite ephemeris floor increased by a factor of 4 (to 1km) to represent degraded satellite ephemeris knowledge, and no approach maneuver telemetry available to represent missed telemetry. Results for the increased satellite ephemeris floor are shown in Figure

7 as 3σ knowledge in radial, along-track and cross-track coordinates with a red dashed line representing the requirement level. The optical data and radiometric data during the encounter both still provide some reduction in the reconstructed uncertainty in the case of the increased satellite ephemeris floor. They are especially effective at reducing uncertainties for the encounters with unusually high uncertainties (E6, E7, E12, E13, E27), bringing them down closer to the average case. The same effect was seen in the case with no approach maneuver telemetry. The optical data is also able to reduce the uncertainties when flyby data is unavailable (E28, E32, E39, E43). Targeted optical measurements or encounter data at problem encounters would be useful in reducing abnormally large uncertainties even in cases with degraded ephemeris knowledge or missing telemetry.

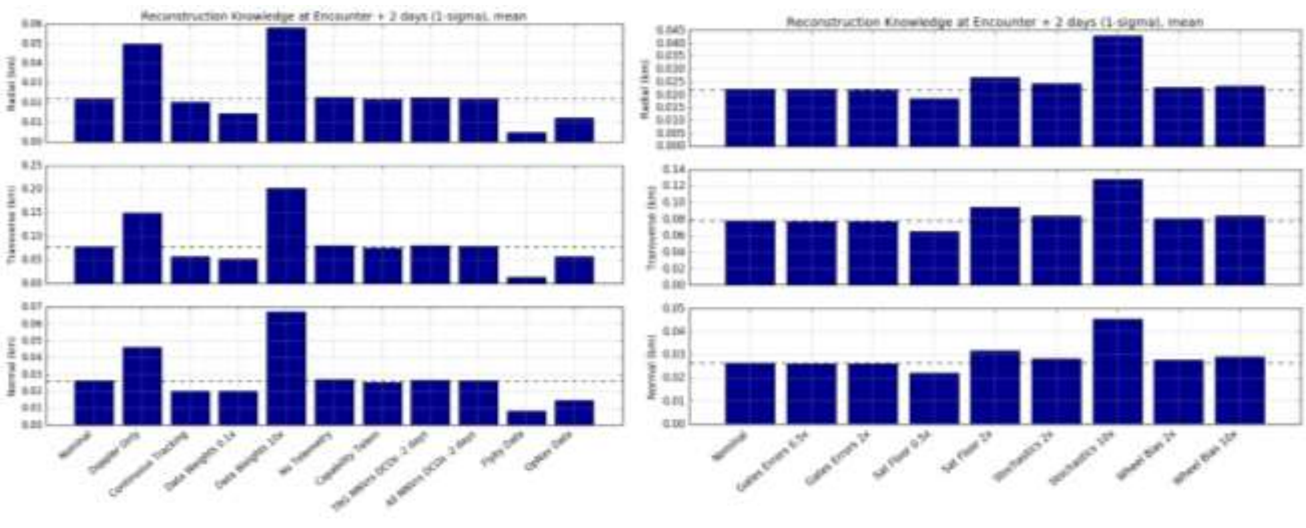

Figure 6. Mean Reconstruction Uncertainties: Variations on a) Data Type and Amount b) Dynamic Parameters

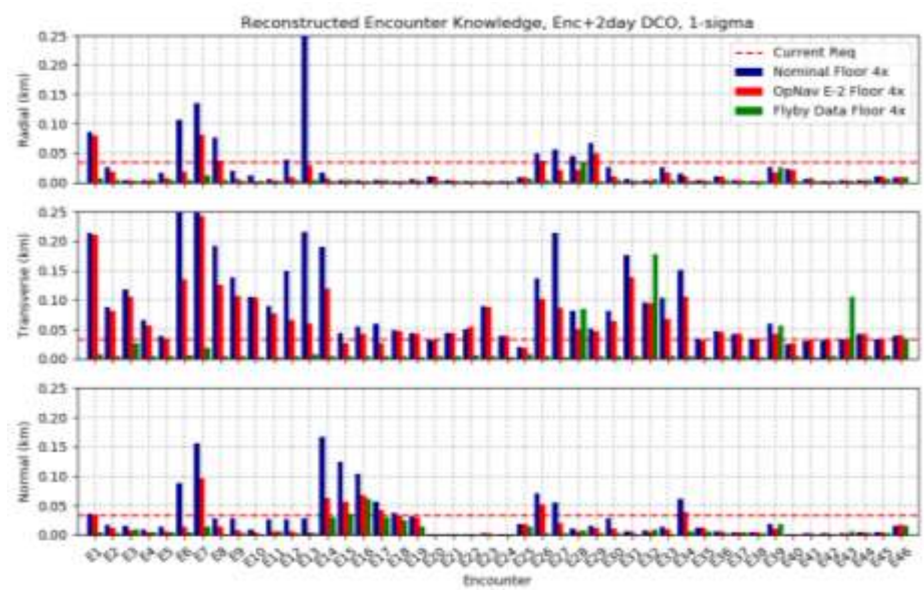

Figure 7. Reconstruction Uncertainty

OPTICAL NAVIGATION STUDIES

The current navigation baseline is based entirely on radiometric data types. However, use of optical data is also being considered in a number of scenarios. In general, optical data are complementary and independent to radiometric data providing visibility in directions often orthogonal to the tracking data. The spacecraft would acquire Europa astrometric observations that could add to navigational margin and robustness and also improve the accuracy of the encounter delivery or the OD knowledge update prior to closest approach science observations.

Optical Navigation Data Description

The Narrow Angle Camera (NAC) of the Europa Imaging System (EIS) will be used for all Europa imaging. The NAC has sufficient resolution to image Europa as an extended target during all above encounters and sufficiently large FOV to include background stars. Stars are used to estimate the camera's inertial orientation, as a correction to an initial estimate of the reconstructed attitude provided by the Attitude Control System (ACS). The updated camera pointing is delivered as part of the OpNav input to the OD analysis. Center of figure (CoF) estimates are also taken for extended bodies. For bodies such as Europa and the Galilean satellites that are described accurately by a triaxial ellipsoid model, the preferred method to establish the CoF is via limb-scans. This method has been used extensively with Cassini for all satellites and also with Dawn on approach to Vesta and Ceres. The input to the OD analysis in this case is a sample,line pair of the CoF of the extended body per image. Landmarks on Europa are also planned to be utilized, though they were not included in this preliminary study.

All OpNav sessions are assumed to take place during an imaging window of 2 hours with a total of 16 Europa observations. The approach geometry varies greatly over different flybys. Typically, image acquisition begins at large phase angles with the early encounters and end at low phase angles towards the end of the tour. Two cases were examined: pre-Encounter optical data simulated at Encounter minus 2 days (E-2 case), or Encounter minus 3 days (E-3 case). In both cases, post-encounter optical data is also simulated at Encounter plus 2 days (E+2). The E-3 case simulates data that can be used in time for the approach maneuver delivery, whereas the E-2 case produces data in time to be used for the Encounter minus 2 day knowledge update. The E+2 data is used for reconstruction knowledge. The phase angle for the E-3 case often exceeds 150 - 160 degrees. Although there were no mature flight rules for instrument Sun avoidance angles at the time of this study, it is expected that phase angles of 150 degrees or larger may violate eventual flight rules. Thus, it is assumed that imaging will not be performed at phase angles greater than 150 degrees. With the geometry in this tour, that leads to no OpNav sessions to support the E-3 case during the E1 to E14 flybys.

The inertial orientation of the camera will be estimated from the background stars in the image. The expected brightness contrast between Europa and stars in the 6th-11th visual magnitude range of the background star field is expected to exceed the dynamic range of the detector. A technique called alternating frames will be used whereby a series of images are acquired in alternating long and short exposures. The attitude for the short exposures will be interpolated from the long exposures. This method is not a linear interpolation, but rather an attitude propagation with an exponentially decreasing time correlation, with a time constant typically of the order of the time separation of the long exposure images. Each OpNav session therefore includes 16 images at short exposures and 17 images at long exposures. This technique has been used frequently and successfully with Dawn on approach to Vesta and Ceres which showed 1-sigma pointing accuracy at the short exposures of 0.2-0.25 pixels.[7,8] This work assumes 0.25 pixels 1-sigma per image.

For covariance studies the key parameter is the centerfinding error associated with a limb scan processing of an image. In this regard the important parameters are the size of the image in the FOV, the viewing geometry and the phase angle. The expectation is that a lower phase angle will result in a smaller centerfinding error and that a larger body in the FOV, e.g. greater than 400 pixels diameter will produce a larger centerfinding error compared to a body in the 100-200 pixel diameter range.

Simulated images were generated and processed to produce optical observables. The absolute differences between the estimated and true CoF are extracted and the mean absolute sample, line error is computed and the RSS (residual sum of squares) determined to produce the final sample,line centerfinding error for that particular OpNav session (used as 1-sigma values). These results are shown in Table 7. One tentative empirical conclusion from these results is that the centerfinding error is smaller for the very high (> 130 deg) and very low (< 30 deg) phase angles and increases somewhat for intermediate phase angles. Also there is an expected increase in centerfinding error with the body diameter but it remains well under 1 pixel. For the remaining OpNav sessions, centerfinding errors were interpolated from those in the nearest phase angle bins and apparent diameter. The RSS of the centerfining errors with the assumed 0.25 pixel 1-sigma inertial camera pointing error are computed to produce the final sample,line uncertainty per image. The predicted observations with their associated aggregate camera pointing and centerfinding errors are merged with the radiometric tracking data and analyzed in the OD covariance studies.

Table 7. Centerfinding Errors from Processing Simulated Images for 8 OpNav Sessions

Flyby/OpNav Session	Diameter Range (pixels)	Phase Angle Range (deg)	Limb-Scan Sample,Line, Centerfinding 1σ Error (pixels)
E1, E-2 days	100-200	140-150	0.240
E6, E-2 days	100-200	130-140	0.242
E20, E-3 days	100-200	110-120	0.399
E20, E-2 days	100-200	60-70	0.507
E32, E-3 days	100-200	20-30	0.283
E20, E+1 day	>400	130-140	0.551
E6, E+1 day	>400	70-80	0.679
E1, E+1 day	>400	40-50	0.619

Optical Navigation OD Results

The Europa Encounters covariance study was re-analyzed with the addition of simulated optical data. Two cases were examined: pre-encounter optical data simulated at encounter minus 2 days (E-2 case), or encounter minus 3 days (E-3 case). Refer to the previous section for more details on the optical data.

Figure 8 shows the spacecraft ephemeris uncertainties mapped to the encounter time in radial, alongtrack and cross-track coordinates. The uncertainties are mapped from encounter minus 2 days for an OD knowledge update. The E-2 case shows initial improvement from the nominal as expected. The E-3 case also shows some improvement from the nominal, though less than E-2. This is expected as the first 14 Europa encounters do not have any pre-encounter optical data in the E-3 case. However, the E-3 cases still benefits from the reduction in the Europa ephemeris uncertainty provided by the post encounter optical data. The later encounters do not show much improvement over the nominal due to encountering a limit in the ability to further increase knowledge of the Europa Ephemeris (satellite ephemeris floor discussed earlier).

Figure 9 shows Europa encounter delivery uncertainties mapped from the approach maneuver DCO time. There is much less improvement in uncertainties from nominal in this case than the knowledge mappings. None of the pre-encounter optical data from the E-2 case is used since the data comes after the approach maneuver DCO. However, some improvements from nominal can still be seen from the reduction in Europa Ephemeris uncertainty provided by the post-encounter optical data. For the E-3 case, pre-encounter data is available for use after E14 (and excluding E25). The E-3 case shows some improvement over nominal after E14, but uncertainties in later arcs are not affected much.

Both cases are able to use the post-encounter optical data, but E-2 shows greater reduction in uncertainties, especially early in the tour, due to the extra pre-encounter optical data during E1-14. Thus, the "OpNav" variation shown in the previous sections is for the E-2 case. Future work will be needed in order to create a more detailed optical navigation strategy that takes advantage of optical measurements in different locations based on the geometric and physical considerations described in the previous section as well as the impact they have on the OD uncertainties.

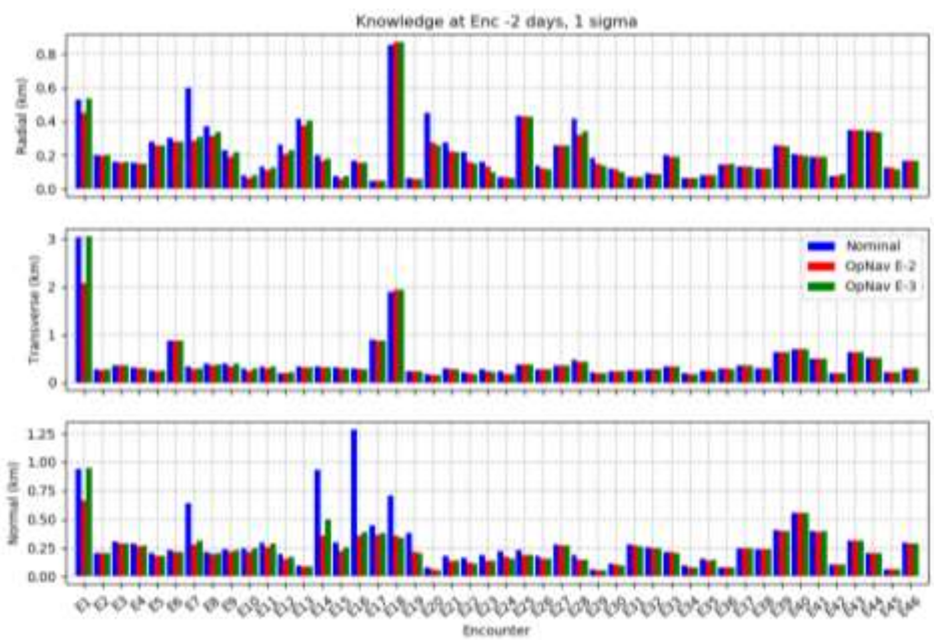

Figure 8. Optical Data Effect on Uncertainties Mapped From Knowledge Update

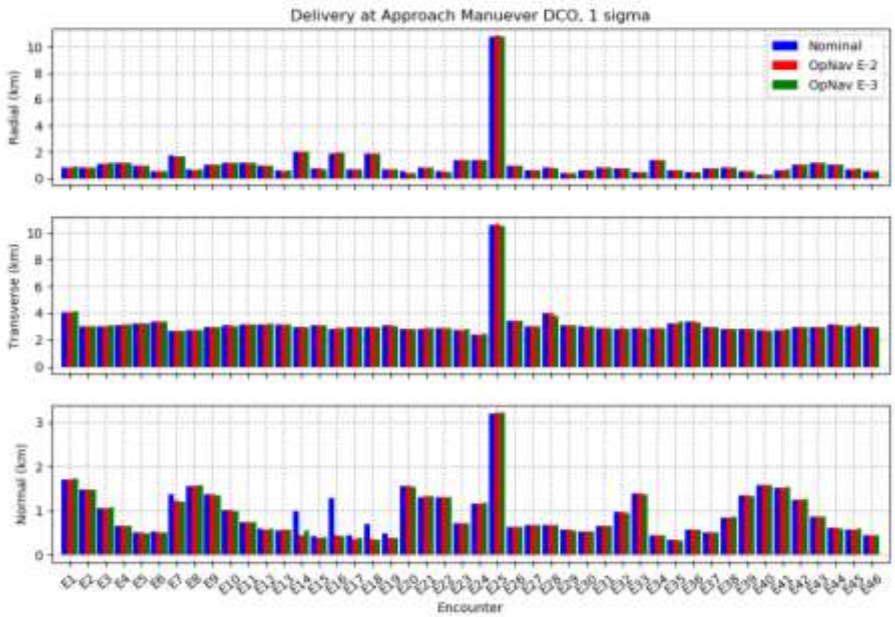

Figure 9. Optical Data Effect on Uncertainties Mapped From Delivery

CONCLUSION

This paper studied the OD uncertainty sensitivity of the Europa Clipper Mission navigation strategy to variations in a number of key parameters in two categories: tracking data type and amount, and variations to dynamic parameters. The results of these variations where studied for three key times when state knowledge would be assessed: approach maneuver design data cutoff time (delivery), pre-encounter knowledge update, and post-encounter reconstruction.

The approach maneuver delivery uncertainties were shown to be largely insensitive to changes to the data type and amount. They are most affected by the approach maneuver execution and momentum wheel bias uncertainty levels. Improvements in the maneuver execution modeling would lead to the greatest improvement in OD delivery capability.

While the encounter knowledge update uncertainties displayed little sensitivity to improvements in the quality and quantity of radiometric data over the baseline level, large degradations to the data quality or large data outages (though unlikely) would result in unacceptable increases to the uncertainty values. Acquiring maneuver pointing telemetry at the expected accuracy contributes significantly to lower knowledge uncertainties, and is clearly necessary to maintain acceptable uncertainty levels. The addition of optical data and radiometric tracking data during the encounters was shown to be noticeably beneficial in reducing uncertainties, especially for outlaying problem encounters.

The encounter reconstruction uncertainties improved greatly with increased data near the encounter, while unexpected large non-gravitational uncertainties degraded the reconstruction. The utilization of optical data within three days of the encounter and radiometric tracking during the two hours centered on the encounter were both very effective at improving reconstruction OD, especially for problem encounters with abnormally large uncertainties due to unfavorable geometry. This was true even in cases with degraded ephemeris knowledge or missing telemetry.

ACKNOWLEDGMENTS

This study was carried out at the Jet Propulsion Laboratory, California Institute of Technology, under a contract with the National Aeronautics and Space Administration.

APPENDIX: B-PLANE GEOMETRY

The B-plane is the plane perpendicular to the asymptote of the incoming trajectory, with the B-vector defined as the vector which joins the body center and the point where the asymptote meets the B-plane. Figure 2 shows the B-plane geometry. Three coordinate vectors are also defined: S along the incoming velocity, T lying in the ecliptic plane, and R completing the triad. Using this geometry, the target point is described by the R and T components of the B-vector, B•R and B•T. The B-plane error is expressed in terms of those quantities, and the time of flight.

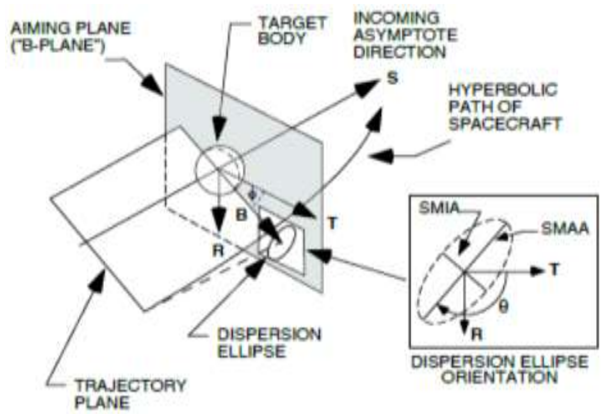

Figure 12. B-plane Geometry

REFERENCES

[1] National Research Council. "Visions and Voyages for Planetary Science in the Decade 2013-2022." Washington, DC: The National Academic Press, 2011.

[2] Dylan R. Boone, Sumita Nandi, Julie Kangas, and Brian Young, "Orbit Determination Sensitivity Analysis for the Europa Multiple Flyby Mission Concpet" AIAA/AAS Astrodynamics Specialist Conference, Long Beach, California, September 13-16, 2016

[3] Lam, Try, Brent Buffington, and Stefano Campagnola. "A Robust Mission Tour for NASA's Planned Europa Clipper Mission." AIAA/AAS Space Flight Mechanics Meeting, Kissimmee, Florida, January 8-12, 2018

[4] Evans, Scott, et al. "MONTE: THE NEXT GENERATION OF MISSION DESIGN AND NAVIGATION SOFTWARE." 6th International Conference on Astrodynamic Tools and Techniques, Darmstadt, Germany, March 2016.

[5] Moyer, Theodore D. Formulation for observed and computed values of Deep Space Network data types for navigation. Vol. 3. John Wiley & Sons, 2005.

[6] C. R. Gates. A simplified model of midcourse maneuver execution errors. Technical Report 32-504, JPL, Pasadena, CA, October 1963.

[7] Mastrodemos, N., Rush, B., Vaughan, D., & Owen Jr, W. “Optical navigation for the dawn mission at Vesta”, 23rd International Symposium on Space Flight Dynamics, Pasadena, California, October 29 - November 2, 2012

[8] Han, D., Smith, J., Kennedy, B., Mastrodemos, N., & Whiffen, G., “Dawn Navigation and Mission Design at Dwarf Planet Ceres” *Space Operations: Contributions from the Global Community* (pp. 517-541). 2017