Orbit Determination Sensitivity Analysis for the Europa Multiple Flyby Mission Concept

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This paper details the results of parametric variations on the notional Europa Mission Concept tour navigation strategy on orbit determination delivery and knowledge errors and the associated statistical ΔV consumption. Approach maneuver placement at encounter minus two and a half days and at encounter minus three and a half days is compared to the reference encounter minus three days location as well as variations to the data cutoff for approach maneuver design, which is baselined one day prior to maneuver execution. An execution error model with fixed and proportional components assigned to the magnitude and pointing directions is applied to each maneuver in a Monte Carlo simulation. Variations on the fixed and proportional contributions to both component errors are simulated and analyzed to show the effect of varying thruster characterization levels. The effects of varying levels of a priori satellite ephemeris errors are also characterized in this study.

Nomenclature

APR	Approach Maneuver
CU	Cleanup Maneuver
DCO	Data Cutoff
MONTE	Mission Analysis, Operations and Navigation Toolkit
RCS	Reaction Control System
SEP	Sun Earth Probe angle
TRG	Targeting Maneuver

I. Introduction

The National Research Council's 2011 Planetary Science Decadal Survey[1] identifies Jupiter's moon Europa as the most likely body in the Solar System to harbor extraterrestrial life. The Europa Mission Concept would evaluate the potential habitability of Jupiter's icy moon by employing a suite of in-situ and remote sensing instruments. Multiple flybys of Europa would serve to characterize the thickness of Europa's ice shell and confirm the existence of a subsurface liquid ocean. The Europa Mission Concept was selected by NASA for Phase A studies in 2015, with a planned launch in 2022. The tour phase of the current mission concept consists of forty-two low altitude Europa science flybys. This work will assess the sensitivity of orbit determination (OD) delivery and knowledge performance for an example Europa Mission Concept through parametric variation of a baseline tour navigation strategy. The instrument suite for the Europa Mission points nadir at close approach and is most sensitive to radial spacecraft ephemeris error. The percentage of flybys which have less than 1 km of radial ephemeris error are catalogued for each OD variation.

II. Europa Mission Navigation Concept

The current Europa Mission concept calls for a direct launch from Earth to the Jupiter system with a candidate launch year of 2022. Following the interplanetary cruise, a large Jupiter Orbit Insertion burn and a series of Ganymede flybys would place the spacecraft into Jupiter orbit at a 4:1 resonance with Europa.

The reference trajectory under study is named 15F10-S22, where the first number represents the year it was designed, the F designates a flyby mission, and the second number represents the number of trajectories that have been designed. The dash S designates the baselined launch vehicle, in this case the Space Launch System, and the final number shows the baseline launch year of 2022. After five years in orbit the spacecraft would be disposed via impact with Callisto, deemed acceptable by NASA's planetary protection standards. This tour contains five flybys of Ganymede, eight Callisto encounters including the final impact, and forty-two low altitude science flybys of Europa. In general, each transfer from encounter to encounter has three maneuvers to maintain the trajectory, two deterministic and one statistical.[2] 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.

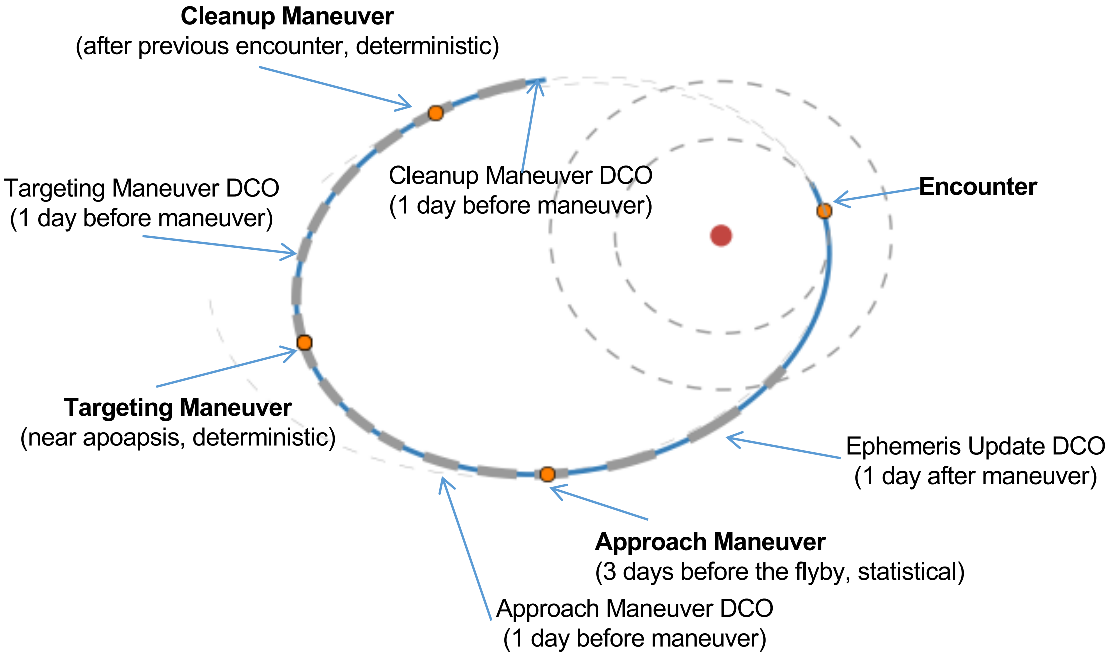

Figure 1. Typical orbit petal diagram

Transfers containing multiple revolutions of Jupiter may contain an additional targeting maneuver to limit dispersions. Tracking data are baselined as coherent two-way Doppler and range observations of the spacecraft with a schedule of eight hours on followed by eight hours off. The baseline flight system design carries eight 22N engines which fire in a group of four in RCS control and in a group of eight in main engine configuration. The strong magnetic field of Jupiter contributes to the choice of a multiple flyby mission and drives the spacecraft trajectory design such that 70% of the orbit is spent outside the harshest radiation environment.[3]

III. Orbit Determination Analysis

The methodology of orbit determination is used to assess the expected spacecraft ephemeris uncertainties in delivery and knowledge based on the current reference trajectory, notional tracking schedule, and physical models. Tracking data is modeled as an eight hour pass of range and Doppler observables accumulated every other eight hours. These simulated observables are processed in a least squares navigation filter to compute the expected spacecraft ephemeris uncertainties for the design of each maneuver, the delivery error including maneuver execution error, and the OD knowledge two days prior to encounter with additional tracking beyond the maneuver execution.

A. Processing Assumptions

Each orbit determination arc encompasses two flybys and is setup with an epoch near the apojove prior to the first flyby in 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. Generally, there is an approach maneuver to the first flyby and a cleanup maneuver after the first flyby to remove maneuver execution error in each arc. The cleanup maneuver together with the targeting maneuver make the target at the next flyby and the statistical approach maneuver accounts for execution error or force mis-modeling. Table 1 shows the background assumptions for each OD arc. Low SEP angles affect Doppler and range data types differently near solar conjunction and are masked accordingly. There is a no tracking zone from 12 hours before to 12 hours after each flyby. The data cutoff for the design of each maneuver is one day prior to maneuver execution for maneuvers targeting Europa flybys. Uncorrelated stochastic white noise, estimated in eight hour batches of constant acceleration, accounts for mis-modeling of small forces.

Table 1. Baseline 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 12 hours before to 12 hours after flyby
Un-modeled accelerations	4.5 x 10^{-6} mm/s per axis stochastic white noise, 8 hour batches
Nominal data cutoff for maneuvers	1 day before maneuver execution time

B. Filter Configuration

Table 2 shows the parameters present in the OD filter for each arc and designates which are estimated and updated, and which only have their error considered in the filter estimate. The uncertainty in the spacecraft state at the arc epoch containing the first Ganymede flyby is set to wide open, otherwise the each arc has the a priori state uncertainty in the table. The Jupiter barycenter ephemerides and individual states of the satellite system are estimated in each arc. The estimated satellite covariance from the previous arc is mapped forward to the next arc epoch and used as a new a priori. This full satellite covariance includes the GMs of the satellites as well as the Jupiter pole location and even zonal harmonics to degree six. A priori covariances 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. When mapped to the start of tour in 2025, the jup310 covariance yields uncertainties of 46 km in Ganymede position and 194 km in Europa position. 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.

Table 2. Filter parameter arc setup

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
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^3/sec^2	Estimated	jup310 covariance
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

IV. Maneuver Analysis

A Monte Carlo simulation of trajectory dispersions based on OD error and maneuver execution error is processed to determine the statistical $\Delta V99$ for each maneuver, the value for which 99% of maneuvers in the distribution will require less than that amount of ΔV. Starting with perfect OD knowledge, a spacecraft state is sampled from the OD covariance at maneuver execution time and the execution error model is sampled to produce an implemented maneuver. Each of the 173 maneuvers in the tour is executed 5000 times in a Monte Carlo analysis to find the mission $\Delta V99$. This process is iterated between the OD covariance analysis and Monte Carlo maneuver analysis until the $\Delta V99$ for successive iterations is within a specified tolerance of 5 m/s. A Gates Model[4] is used to describe the error due to maneuver execution. Table 3 gives the fixed and proportional components due to magnitude and pointing errors. These values assume that the guidance and navigation team has performed some in-flight calibration of the RCS engines during interplanetary cruise. Maneuver magnitudes less than 0.21 m/s are assigned the 4x22N error model representing RCS execution and maneuver magnitudes greater than 0.21 m/s are assigned the 8x22N error model representing main engine configuration.

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

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

Typical deterministic maneuvers, the cleanup and targeting maneuvers, range in size from hundreds of millimeters per second to meters per second in ΔV. The mean value of the statistical approach maneuvers determined from Monte Carlo analysis is shown in Appendix A. Mean values range from 100 to 200 mm/s with $\Delta V99$s in the same range except for particularly sensitive transfers such as the E29 arc with a 99% value of 1.8 m/s. This arc has a very short transfer time of 10 days and has no targeting maneuver, only one deterministic and one statistical maneuver are used to make the flyby target. This results in one fewer opportunity to correct flyby error and control maneuver execution dispersions.

V. Covariance Analysis

For each arc in the tour, a covariance analysis is implemented to determine the expected level of error in the spacecraft ephemeris at flybys and maneuver design data cutoffs. Simulated Doppler and range measurements in eight hour tracks are processed in a least squares navigation filter and the resulting covariance is mapped to times of interest. A useful set of encounter target coordinates are expressed in the plane perpendicular to the incoming asymptote of the trajectory, called the B-plane. The spacecraft ephemeris error is mapped to the target time as the semi-major and semi-minor axes of an error ellipse in the B-plane and the uncertainty in time of close approach completes the coordinate system. Figure 2 shows the time evolution of the B-plane coordinate uncertainties in an arc as tracking data is processed, maneuvers are executed, and encounters are passed. Gray bars show periods of tracking with the eight hours on, eight hours off schedule. Maneuver locations show a stochastic increase in uncertainty corresponding to execution error and flybys are generally accompanied by a steep drop in uncertainty since the potential satellite ephemeris error is no longer mapped ahead to the next encounter. The initial spacecraft state uncertainty is set at a very conservative 15 km at the start of each arc. When mapped in time to to the target encounter and including the potential errors in the first flyby of the arc, this results in very large (10^4 km) B-plane errors prior to the first flyby in the arc. Execution errors from large deterministic maneuvers and dispersions from approach maneuver execution are important sources of error in covariance analysis. Approach maneuver characteristics such as location and data cutoff are examined for sensitivities since the approach is the final maneuver to ensure good flyby performance. Figure 2 shows the semi-major axis uncertainties mapped to the encounter B-plane, with data tracks represented by gray bars. Maneuver execution error is applied stochastically, increasing the uncertainties at maneuver times and resulting in the slanted tracks where the uncertainty is lower at the beginning of track compared to the end of track. Semi-major axis uncertainties reduce significantly between the TRG and APR maneuvers, with missed data tracks a source of potential vulnerability in designing the approach maneuver.

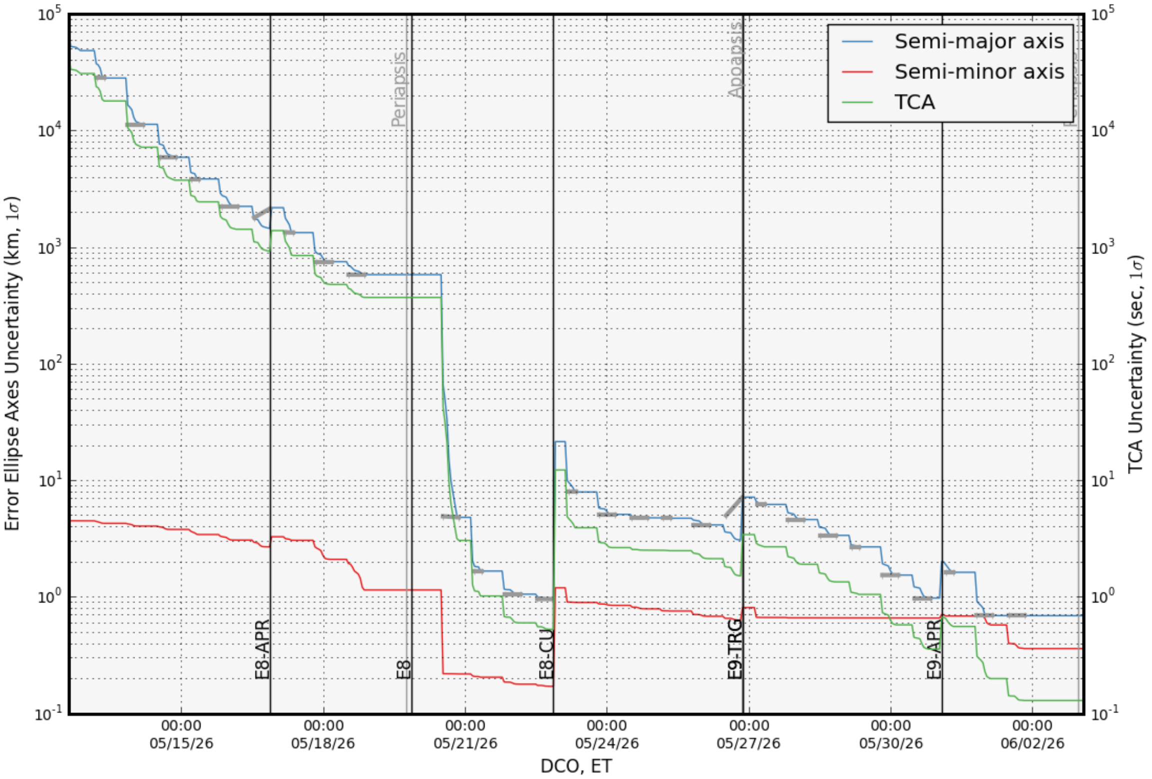

Figure 2. B-plane uncertainty evolution for a typical OD arc

Uncertainties in the Jupiter satellite system ephemeris are also critical components of the covariance analysis. Figure 3 shows the time evolution of estimated uncertainties in Europa's position and velocity for the same arc as above. The error in the ephemeris maps cyclically with Europa's 2:1 resonance with Io. The plot shows a reduction in the Europa ephemeris uncertainty when the first track of data is processed after each flyby. The evolution of the Ganymede and Io ephemeris uncertainty shows a similar pattern due to their mutual 4:2:1 orbital resonance, which is represented by correlation terms in the satellite system covariance.

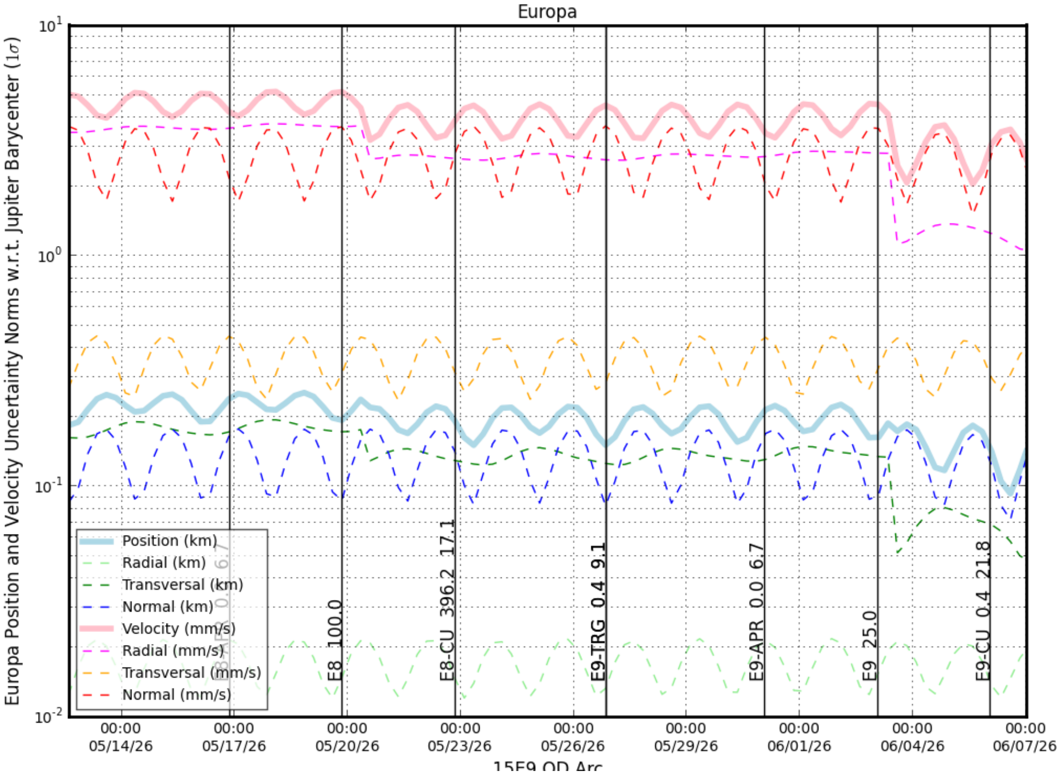

Figure 3. Europa position and velocity mapping for 15E9 arc

The primary metrics used to evaluate different filter strategies and execution error models are the OD knowledge at the approach maneuver design, the delivery error following approach maneuver execution, and OD delivery knowledge following an additional data track after approach maneuver execution, called the encounter update. This analysis is conducted using JPL's python-based MONTE software.[5]

VI. Sensitivity Analysis

This section details the results of parametric variations of the notional Europa Mission Concept 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 update delivery. The baseline tour strategy places the approach maneuver at three days prior to encounter in every arc, with the data cutoff for maneuver design at one day prior to execution. This section considers placing the approach maneuver at two and a half days prior to encounter and three and half days prior to encounter, also effectively moving the data cutoff for approach maneuver design. A sixteen hour margin in approach maneuver design is also considered, making the final data track in the baseline case a contingency track. Post-maneuver spacecraft telemetry data is used to constrain the a priori maneuver execution pointing error to 0.25°. This constraint is applied to only cleanup and targeting maneuvers in one variation and applied to all maneuvers in a second variation. The sensitivity to initial satellite ephemeris covariance is investigated by running a case with perfect knowledge of the satellite system, a case with the a priori uncertainties scaled up by a factor of five, and a case using the predecessor to jup310, the jup230 covariance. In addition, parametric variation of maneuver execution errors is studied by using combinations of half and double the values of the Gates Model errors.

A. Baseline Case

The OD knowledge of spacecraft ephemeris one-sigma uncertainty at the time of approach maneuver design is shown in Figure 4, plotted by Europa flyby. Europa flyby altitudes are computed from a reference ellipsoid with axes of 1562.6 km, 1560.3 km, and 1559.5 km. The blue bars show results for high flybys over 50 km altitude, red shows flybys at or near 50 km altitude, and yellow shows low flybys of 25 km altitude. The various payload instruments are interested in the altitudes of flybys with different uncertainties but the OD performance is not dependent on altitude. The uncertainties are shown in RTN coordinates representing the radial, transverse, and normal directions to the spacecraft trajectory at close approach. The black horizontal bar shows the 1 km level of uncertainty, as the performance level desired by the nadir-pointing instrument suite at close approach. When the E6 flyby is achieved, several arcs in a row have radial uncertainties below 1 km, but problem transfers arise with larger radial uncertainties. The transverse or along-track knowledge uncertainties are above 2 km for the majority of the tour and the cross-track uncertainties fall below 1 km for the majority of the tour.

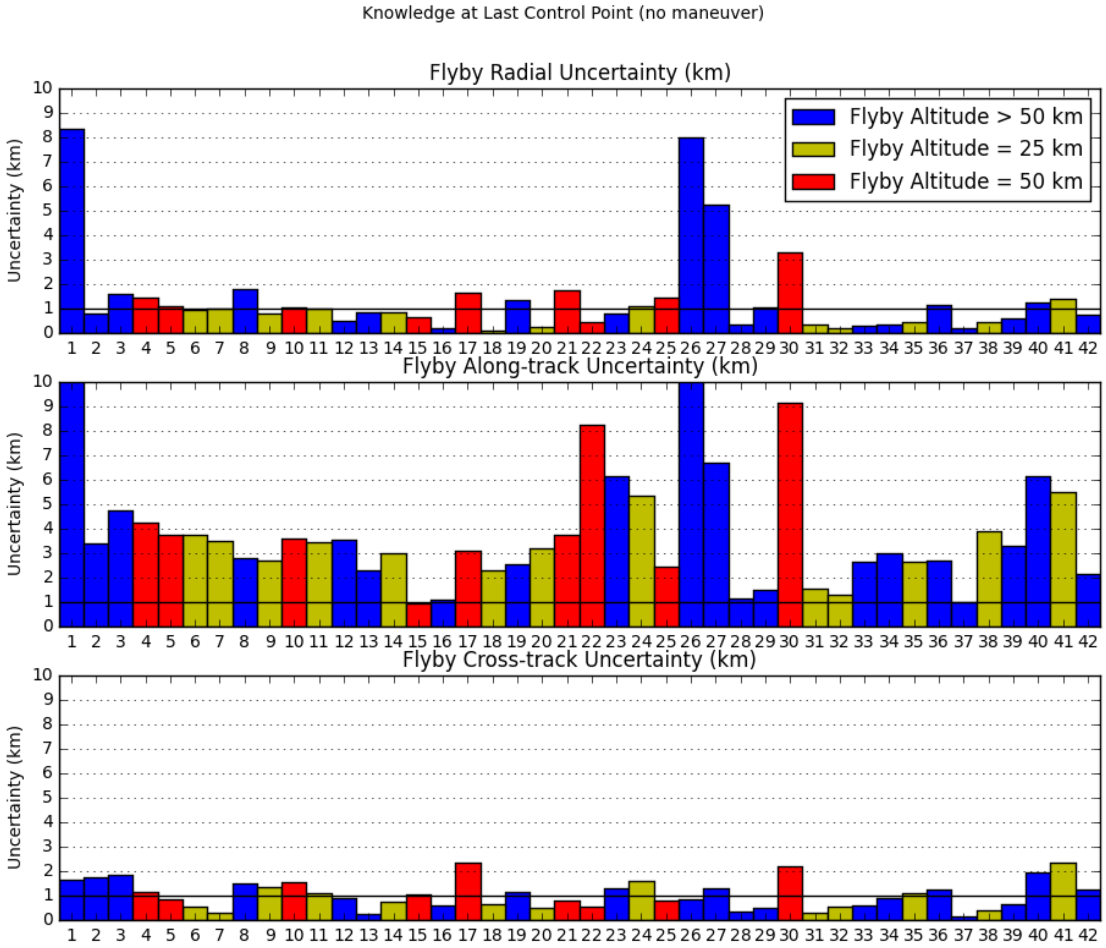

Figure 4. Baseline OD Knowledge at Approach Maneuver Design by Europa Flyby

The OD delivery errors shown in Figure 5 show the delivered uncertainties following approach maneuver execution. This increases the errors in all three components, with every arc having greater than 2 km uncertainty in the along-track direction.

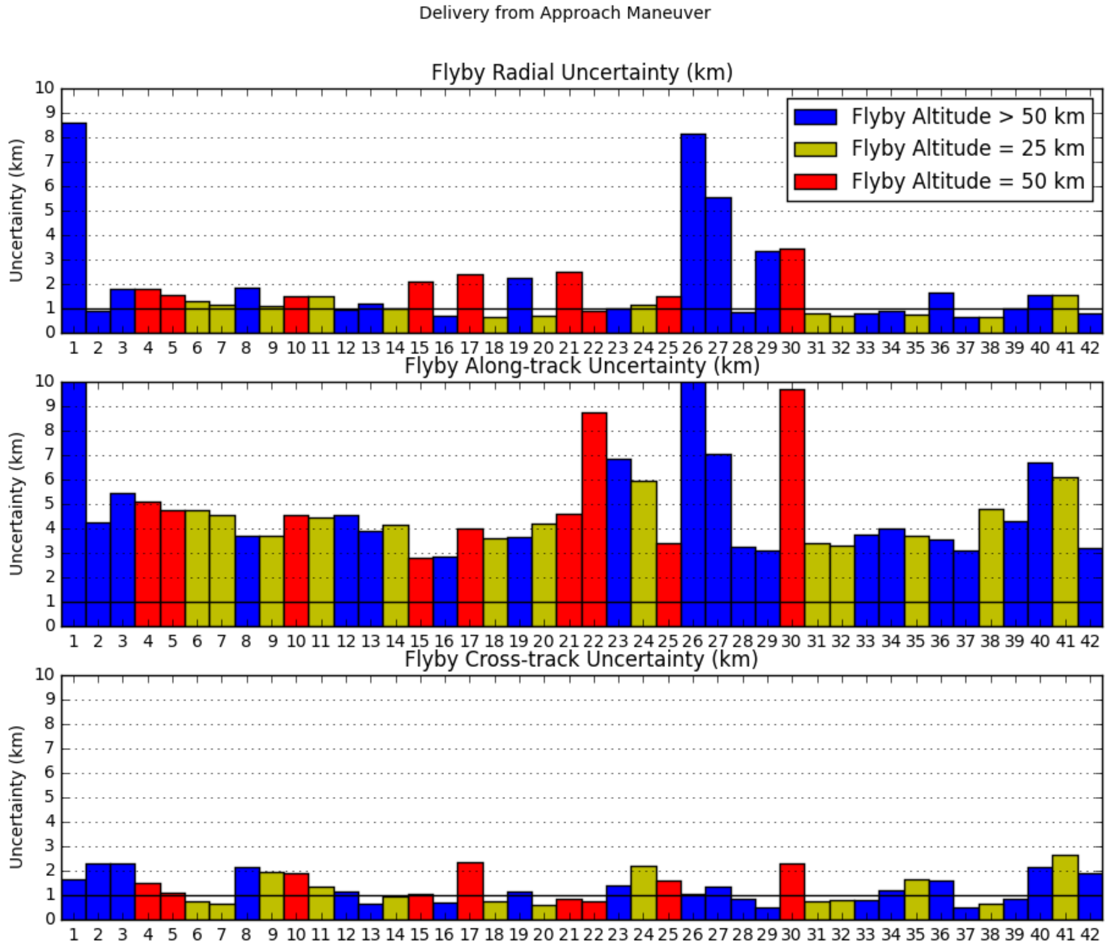

Figure 5. Baseline OD Delivery at Approach Maneuver Execution by Europa Flyby

Since so many transfer arcs in the baseline tour strategy deliver OD uncertainties above 1 km, a post maneuver update accumulating an additional data track is proposed.[6] This case allows some resolution of the executed approach maneuver and reduces the OD uncertainties prior to encounter. Figure 6 shows this case for an encounter minus two days OD update. Utilizing this additional data, all of the 25 km altitude flybys have radial and cross-track uncertainties less than 1 km and around 75% of all flybys have less than 1 km radial uncertainty. This error reduction allows more precise pointing of the spacecraft instrument deck and improves the quality of science measurements at close approach. In the following sections we examine the percentage of flybys that produce less than 1 km uncertainty in the radial, along-track, and cross-track error components as a result of parametrically varying inputs to the covariance analysis.

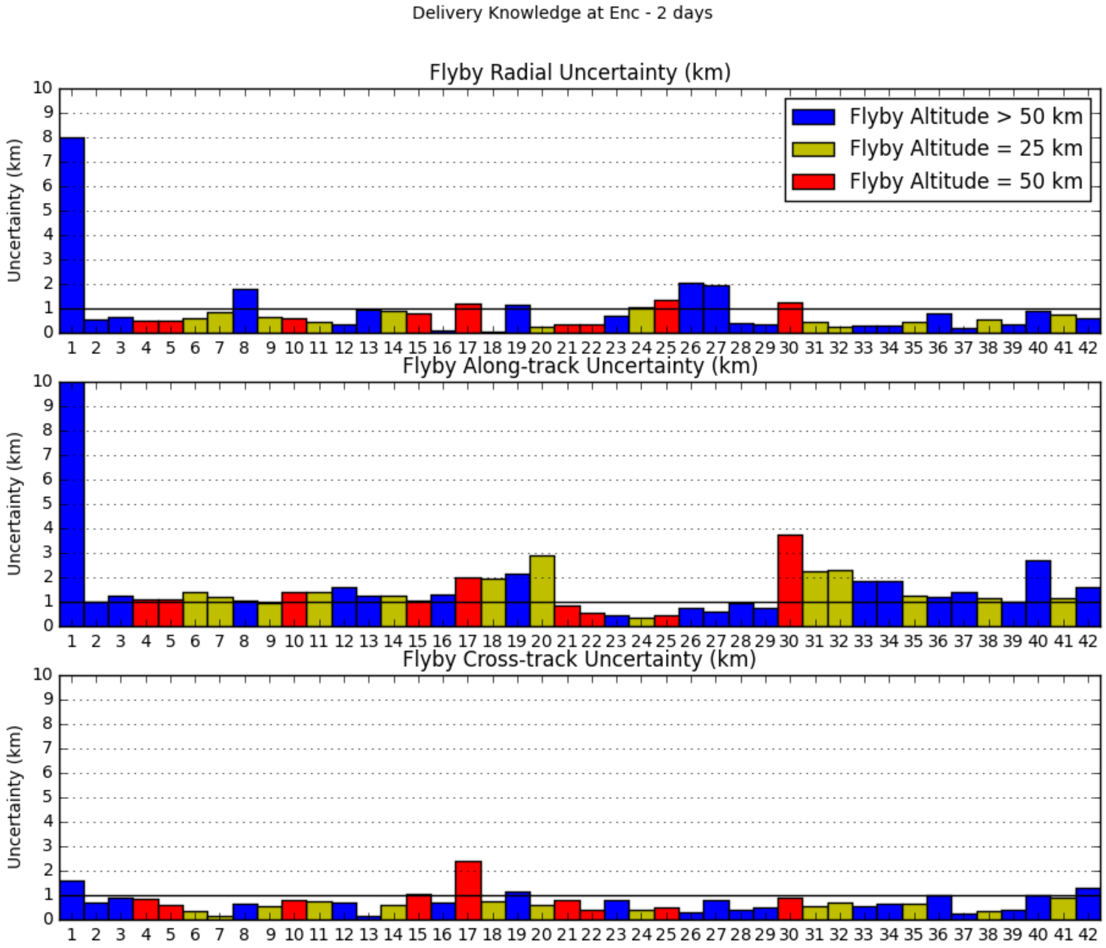

Figure 6. Baseline OD Knowledge at E-2day Encounter Update by Europa Flyby

B. OD Knowledge Results at Approach Maneuver Design

The instruments selected for the Europa Mission Concept are most susceptible to errors in the radial direction since the all instruments point nadir at close approach. A 1 km uncertainty level in the radial direction is of interest to these instruments, although specific requirements for navigation are preliminary and being iterated. Figure 7 shows percentage of flybys which have less than 1 km uncertainty in the radial, along-track, and cross-track orbit directions at approach maneuver DCO for variations on approach maneuver location and DCO, use of post-maneuver telemetry, and satellite ephemeris covariance usage.

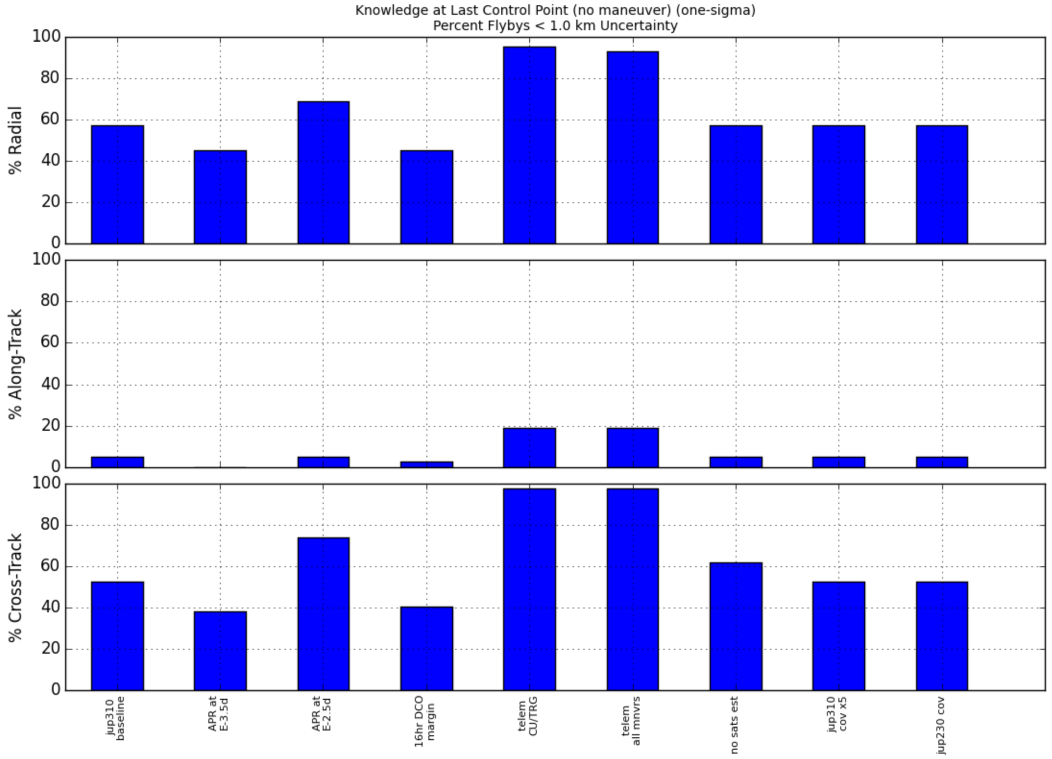

Figure 7. OD Knowledge at Approach Maneuver Design for Filter Variations: Percent of Flybys with <1km uncertainty in radial, along-track, cross-track coordinates

The greatest improvement in OD knowledge over the baseline case comes from the use of post maneuver telemetry. The figure shows that over 90% of the flybys achieve less than 1 km in radial uncertainty. Moving the approach maneuver location earlier to E-3.5 days produces a longer mapping time to the flyby and increases the knowledge uncertainty. Moving the approach maneuver closer to the encounter at E-2.5 days includes more data in the filter solution and a shorter map time to the flyby which raises the percentage of flybys with less than 1km uncertainty. Figure 8 shows the OD knowledge performance of the baseline case using the nominal Gates Model from Table 3 compared with eighteen variations of the four Gates error values. As expected, the case towards the middle of the plot which halves all Gates error values yields the largest reduction in OD knowledge uncertainty. For this case, 70% of low flybys have radial uncertainty at less than 1 km. Doubling the proportional error components increases uncertainties in a more pronounced way than doubling the fixed error components, specifically for low altitude flybys. There is little visible variation in the along-track uncertainties due to changes in the Gates Model parameters.

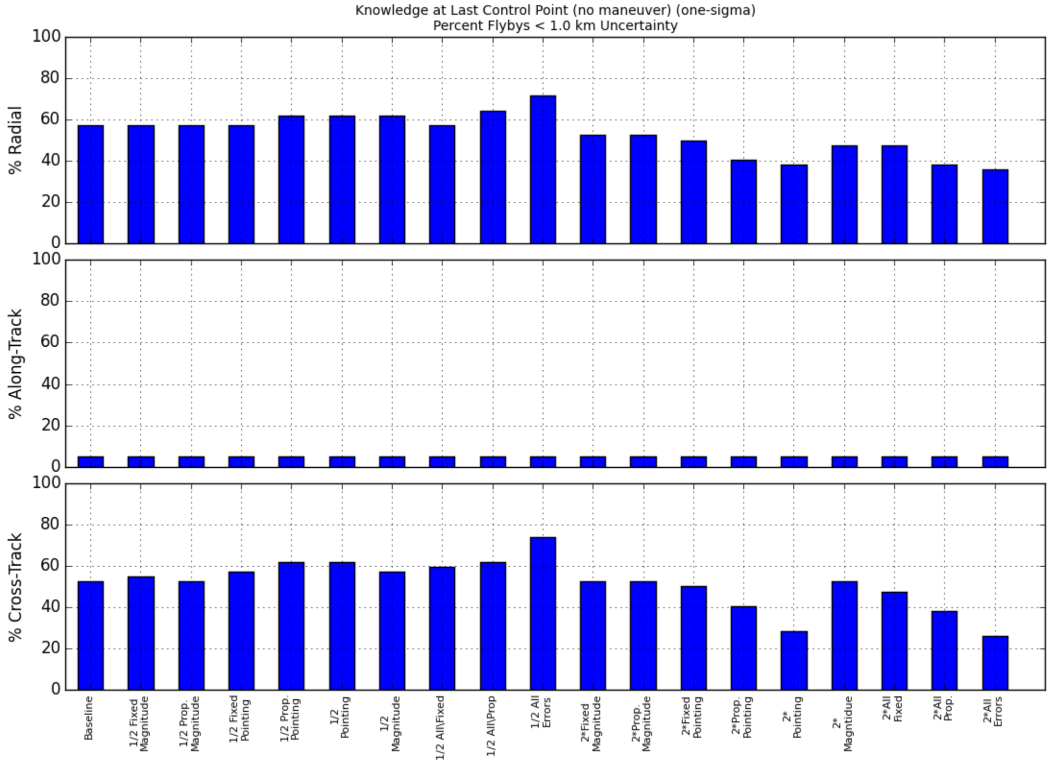

Figure 8. OD Knowledge at Approach Maneuver Design for Execution Error Variations: Percent of Flybys with <1km uncertainty in radial, along-track, cross-track coordinates

C. Delivery Results from Approach Maneuver Execution

The OD delivery case discussed in this section gives the one-sigma uncertainties expected immediately following approach maneuver execution. For the all maneuvers telemetry case, the post-maneuver pointing constraint is only applied to approach maneuvers of the previous arcs, and the reported OD delivery results do not include telemetry information for the current approach maneuver. In general, uncertainties increase due to including maneuver execution error in the mapping, and the percentage of flybys with less than 1 km uncertainty decreases but not equally across all variations. Particularly, the all maneuvers telemetry case gives a very high percentage of flybys below the 1 km mark while omitting the telemetry constraint from approach maneuvers causes a steep decline in all uncertainty components. The all maneuvers telemetry case is also the only variation which gives a non-zero percentage of flybys with along-track error performance better than 1 km, although this is the least sensitive direction affecting instrument performance. The case without estimation of the satellite states corresponding to perfect knowledge of their ephemeris outperforms the satellite estimation cases only slightly. This is because the majority of the error in the a priori ephemeris covariance reduces drastically after completion of the first Europa flyby in tour.

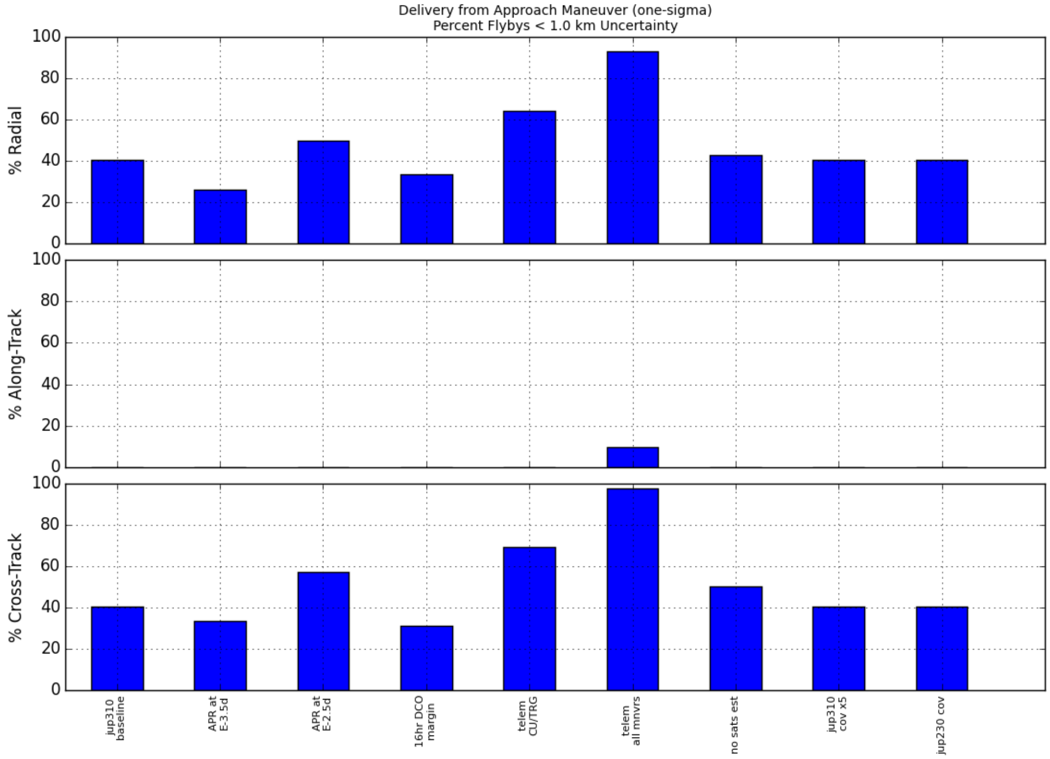

Figure 9. Delivery from Approach Maneuver for Filter Variations: Percent of Flybys with <1km uncertainty in radial, along-track, cross-track coordinates

Figure 10 shows the approach maneuver delivery errors for variations of the Gates Model execution errors. The half all fixed and pointing errors case gives the best performance but only clears 60% of flybys having 1 km uncertainty in the radial and cross-track directions. The second best performing case is that with all fixed errors halved, which produces over 50% of flybys having the desired 1 km or less radial uncertainty. These cases are ten and twenty percentage point improvements over the baseline case with nominal Gates Model errors. None of the cases produce flybys with under 1 km uncertainty in the along-track direction when varying the Gates error parameters.

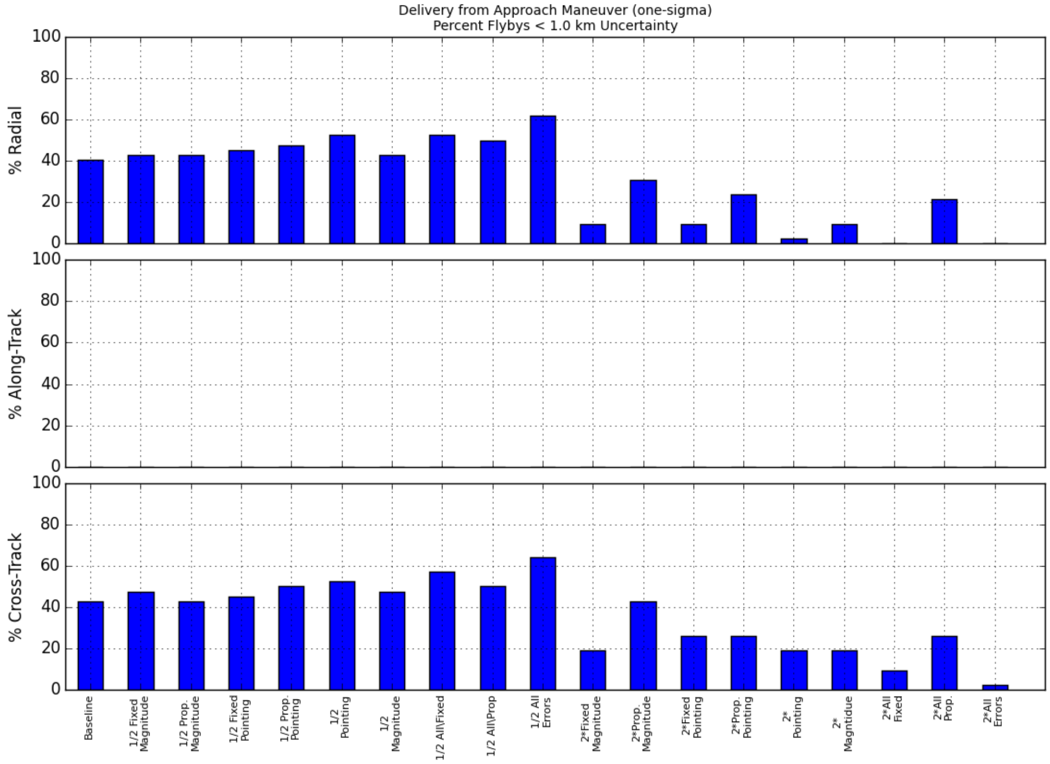

Figure 10. Delivery from Approach Maneuver for Execution Error Variations: Percent of Flybys with <1km uncertainty in radial, along-track, cross-track coordinates

D. Post-Approach Maneuver Knowledge Update Results

The post-approach maneuver knowledge update solution offers the most improvement in flyby performance over the baseline for most variations. This mapping includes one additional track of data since tracks are centered on maneuver execution time and the tracking schedule is every other eight hours. Utilizing the encounter minus two days knowledge update, even the baseline case delivers 80% of flybys with less than 1 km uncertainty in the radial and cross-track directions. Using pointing telemetry for all maneuvers and performing the post-approach maneuver knowledge update produces greater than 90% of flybys with 1 km uncertainty or better in all three directions. There are only ten percentage points of difference in performance between the different satellite covariance cases. The approach maneuver at three and a half days before encounter performs better than the analogous two and a half day case since there are more post-maneuver data tracks for the earlier maneuver case.

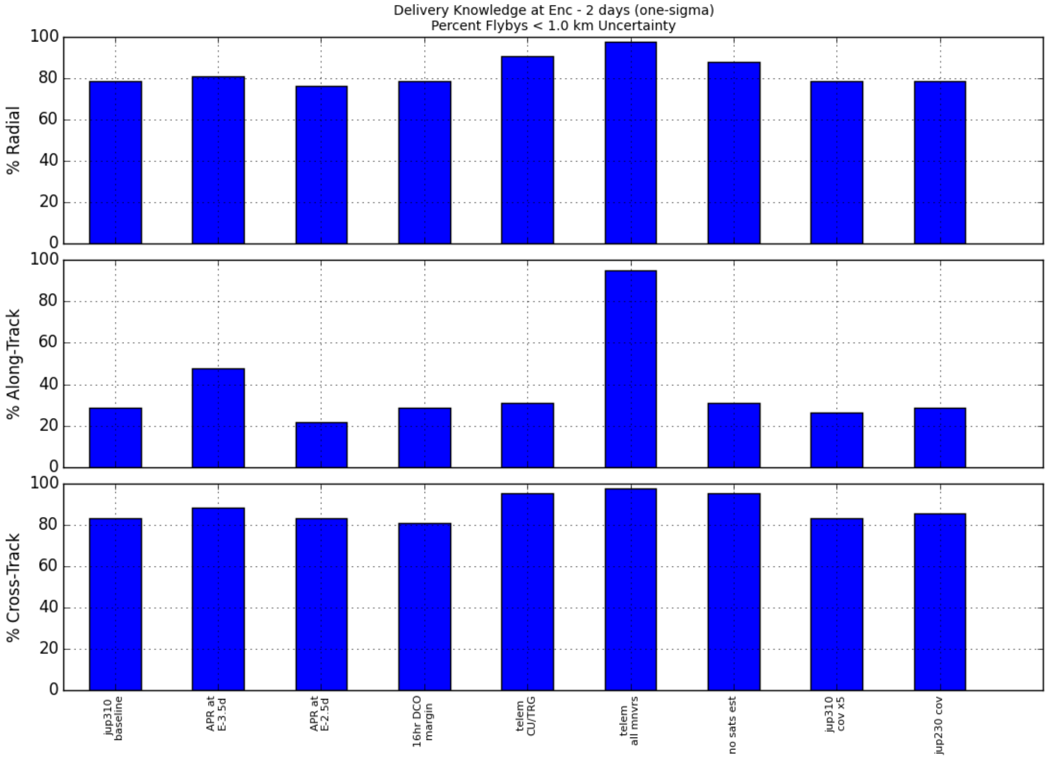

Figure 11. Delivery from Approach Maneuver for Filter Variations: Percent of Flybys with <1km uncertainty in radial, along-track, cross-track coordinates

E. Tour ΔV Performance Variations

Finally, the ΔV cost of implementing the various strategies is examined in a Monte Carlo analysis. Table 4 shows the mean, one-sigma, and 99th percentile ΔV values for the entire tour portion of the Europa Mission Concept. At each maneuver location a state is drawn from the OD covariance and a maneuver is targeted to the next encounter and executed with error drawn from the maneuver execution covariance. The later approach maneuver case (E-2.5) has a lower $\Delta V99$ by 20 m/s but would leave less schedule margin for maneuver uplink contingency. The use of post-maneuver telemetry to constrain burn pointing gives a significant ΔV reduction of 30 m/s whether approach maneuver telemetry is included or not. The no satellite estimation case with perfect satellite state knowledge improves the baseline slightly and shows that most of the satellite covariance error is estimated down early in the tour. The largest uncertainty in the maneuver ΔVs comes from the scaled satellite covariance case, which also shows the greatest $\Delta V99$ of any of the variations. Increasing the satellite uncertainty in this way widens the distribution of maneuvers targeting Jupiter Orbit Insertion and the first few Ganymede flybys. This growth of maneuver size ends once the spacecraft encounters Europa. Doubling the Gates Model errors results in an increase of maneuver $\Delta V99$ that is twice the size of the reduction in $\Delta V99$ due to halving the same parameters.

Table 4. Tour ΔV Performance Cases

Case	Mean (m/s)	Sigma (m/s)	ΔV99 (m/s)
Baseline	1309.508	19.056	1358.494
APR-2.5day	1298.568	15.182	1338.688
APR-3.5day	1315.538	16.782	1359.378
16hr DCO margin	1319.184	16.894	1362.763
CU/TRG telemetry	1289.015	12.800	1322.026
CU/TRG/APR telemetry	1288.911	12.804	1321.979
No satellite estimation	1300.370	14.058	1336.974
jup310 cov scaled x5	1356.182	57.271	1514.770
jup230 cov	1305.321	15.596	1346.217
2x all Gates errors	1375.536	30.986	1464.708
1/2x all Gates errors	1275.263	10.937	1302.513

VII. Conclusion

This work details the preliminary sensitivities of a baseline navigation strategy for the Europa Mission Concept. The examination of OD knowledge and delivery for the Europa approach maneuvers shows that 1 km radial uncertainties in spacecraft ephemeris, which are desirable from the instrument perspective, are achievable in only 50% of flybys with the baseline strategy. If an encounter minus 2 days knowledge update is performed where an additional data track is used in the solution, this increases to 80% of flybys with less than 1 km radial uncertainty for the baseline case. Additional modifications to the navigation strategy are explored in an orbit determination sensitivity analysis and the resulting tour ΔV99s are found from a maneuver Monte Carlo analysis. The cases with the best radial flyby uncertainty performance are the post-maneuver telemetry pointing and the half all Gates error parameters cases, both achieving 90% of flybys with less than 1 km radial uncertainty. The majority of the improvement from using post-maneuver telemetry was found in constraining the pointing of cleanup and targeting maneuvers only. The majority of the improvement in flyby performance from varying the Gates Model parameters was found in reducing the fixed error components by half. In general, the variations which improved flyby uncertainty also reduced the ΔV99 for the tour, with the lowest ΔV99 of 1302.513 m/s coming from the case with all Gates Model errors halved. The use of telemetry pointing information to improve spacecraft ephemeris knowledge is used by the Cassini Mission and should be feasible on a similar tour mission. The improvement of the Gates Model error parameters would be the result of ground testing or in-flight calibration and provides reduction in radial uncertainty similar to the use of maneuver pointing telemetry. The post-approach maneuver knowledge update improves uncertainties by a factor of two in some cases but represents a no-margin case in terms of maneuver uplink success. Future work will consider using reduced overall tracking schedules, using only one hour of range per pass, and de-weighting Doppler and range data.

Appendix A: Europa Approach Maneuver Size Statistics

Table 5. Approach Maneuver Size (m/s)

Maneuver	Mean (m/s)	Sigma (m/s)	99%ile (m/s)
E1-APR	3.781640579795181e-02	2.223829417823904e-02	1.053621904621081e-01
E2-APR	2.929922043450975e-02	1.881084963031284e-02	9.498338141625928e-02
E3-APR	1.023256990807536e-01	6.812274382900337e-02	3.081483696110590e-01
E4-APR	7.911427167782642e-02	5.637444827817259e-02	2.633554202301663e-01
E5-APR	5.870660793350801e-02	4.032239895703936e-02	1.813915847557122e-01
E6-APR	3.046461975123450e-02	2.003636072708449e-02	9.602888127230845e-02
E7-APR	7.574299667169056e-02	5.313850120680319e-02	2.400567970612785e-01
E8-APR	7.475623633428158e-02	3.967316096819327e-02	1.888826823253522e-01
E9-APR	3.770190859921819e-02	2.156347448982227e-02	1.039497168141613e-01
E10-APR	5.920467414325173e-02	4.092923505812501e-02	1.954125557003230e-01
E11-APR	7.599918099985832e-02	5.225150374857234e-02	2.344161126744257e-01
E12-APR	1.067862691627287e-01	7.443749390715083e-02	3.271025381528828e-01
E13-APR	1.825079824679030e-01	1.496382459266121e-01	6.707740113425996e-01
E14-APR	9.319386192663617e-02	6.382598225493351e-02	2.881224096561601e-01
E15-APR	9.586672876510306e-02	6.542105634327107e-02	3.217872684632367e-01
E16-APR	1.548107759964930e-01	1.191582924364703e-01	5.294411119494894e-01
E17-APR	7.173066803110791e-02	4.528922832167113e-02	2.164291236018604e-01
E18-APR	3.217326271218906e-02	1.965970055490467e-02	9.441331644910991e-02
E19-APR	5.984334850262524e-02	3.302241364454492e-02	1.583562399170192e-01
E20-APR	3.739632061358096e-02	2.369195017039310e-02	1.098050741789021e-01
E21-APR	5.101158072740616e-02	3.009598706718364e-02	1.470254328583749e-01
E22-APR	6.083055778350514e-02	4.147513715963325e-02	1.890315205451331e-01
E23-APR	1.969249103761779e-01	1.368454675972724e-01	6.069640866727367e-01
E24-APR	1.083298001622332e-01	7.043211841731076e-02	3.237456886672496e-01
E25-APR	4.338547815431618e-02	2.245074280926063e-02	1.067986135054302e-01
E26-APR	2.018237904914046e-01	1.305310312842804e-01	6.167235923678317e-01
E27-APR	7.428922561717198e-02	4.588798837798428e-02	2.135117143975761e-01
E28-APR	1.046873082989331e-01	8.380774091499821e-02	3.818524369377435e-01
E29-APR	4.932861576047126e-01	4.222331943991101e-01	1.814572407037683e+00
E30-APR	2.084382825763277e-02	1.313603567121114e-02	6.632465644786474e-02
E31-APR	6.149000982941293e-02	4.604856004006926e-02	2.075005817530916e-01
E32-APR	1.432747420246707e-01	1.293797251481470e-01	6.201301806518584e-01
E33-APR	4.354181107407896e-02	3.019693058048925e-02	1.398368011516056e-01
E34-APR	3.928244732729133e-02	2.731029343578200e-02	1.305385756026268e-01
E35-APR	6.409213223677754e-02	4.413083121154820e-02	2.089835922736545e-01
E36-APR	4.636967639576672e-02	2.500585433333865e-02	1.195510273795976e-01
E37-APR	4.843479123394526e-02	3.336069611634432e-02	1.568268776859686e-01
E38-APR	7.035436758921677e-02	4.695180059660783e-02	2.132110317691243e-01
E39-APR	5.598168505024519e-02	3.844153649001354e-02	1.740458485712061e-01
E40-APR	1.019140220506105e-01	1.081526324267600e-01	5.126378769416480e-01
E41-APR	1.249076164312076e-01	1.274858939037882e-01	6.362046658310916e-01
E42-APR	3.199638903715886e-02	1.676475115644379e-02	8.284391412702921e-02

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