NAVIGATIONAL CHALLENGES FOR A EUROPA FLYBY MISSION

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Abstract: *Jupiter's moon Europa is a prime candidate in the search for present-day habitable environments outside of the Earth. A number of missions have provided increasingly detailed images of the complex surface of Europa, including the Galileo mission, which also carried instruments that allowed for a limited investigation of the environment of Europa. A new mission to Europa is needed to pursue these exciting discoveries using close-up observations with modern instrumentation designed to address the habitability of Europa. In all likelihood the most cost effective way of doing this would be with a spacecraft carrying a comprehensive suite of instruments and performing multiple flybys of Europa. A number of notional trajectory designs have been investigated, utilizing gravity assists from other Galilean moons to decrease the period of the orbit and shape it in order to provide a globally distributed coverage of different regions of Europa. Navigation analyses are being performed on these candidate trajectories to assess the total ΔV that would be needed to complete the mission, to study how accurately the flybys could be executed, and to determine which assumptions most significantly affect the performance of the navigation system.*

Keywords: *Navigation, tour, Europa, flyby.*

1. Introduction

Europa, the smallest of Jupiter's four Galilean moons, is a prime candidate in the search for present-day habitable environments outside of the Earth. Europa is unique among other large planetary satellites because it most probably has a global liquid ocean beneath its outer ice shell. Energy from tidal heating and irradiation of its surface could provide Europa a rich source to fuel chemical reactions that could use the water and dissolved salts of its liquid ocean, and the minerals of its mantle, to produce the complex molecules that are a precursor to life [1]. NASA's Pioneer and Voyager spacecraft, and its Galileo mission, provided increasingly detailed images of the complex surface of Europa. Galileo, a mission that performed an extensive tour of the Jovian system, included 12 close flybys of Europa, and used its cameras and other instruments to investigate the surface and environment of the moon. The Galileo mission provided tantalizing samples of data at Europa, but a new mission to Europa would be needed to pursue those exciting discoveries using close-up observations with modern instrumentation designed to address habitability. After performing trade studies, it was found that the most cost effective way to do this is with a spacecraft carrying a comprehensive suite of instruments and performing multiple flybys of Europa [1]. The mission concept currently being studied by NASA would perform a series of flybys of Europa in order to investigate its habitability by characterizing its ice shell and possible subsurface water, by studying its composition and chemistry, and by mapping its surface. A number of notional trajectory designs have been performed, utilizing gravity assists from other Galilean moons to decrease the period of the orbit and shape it in order to provide a globally distributed coverage of different regions of Europa. Navigation analyses are being performed on these candidate trajectories to assess the total velocity change (ΔV) that would be needed to complete the mission, and to study how accurately the flybys could be executed.

2. The Case for Europa

Four hundred years ago, Galileo Galilei's discovery of four objects moving around Jupiter helped change our view of the universe by showing that the Earth was not the center of all celestial motion. Those four moons, now known as the Galilean satellites, could only be studied in depth much later, when space probes were sent to investigate the Jupiter system. Large linear features detected in the pictures taken by Voyager 1 were first assumed to be deep cracks generated by rifting or tectonic processes. More detailed images returned by Voyager 2 provided evidence for a moving ice shell that could be explained by the existence of a liquid ocean under the ice shell, but the low resolution and poor coverage provided by the Voyager spacecraft did not allow for a full understanding of the processes that created the features seen in the surface of Europa [2]. The Galileo orbiter, arriving to Jupiter in 1995, performed a seven-year tour of the Jovian system that allowed for multiple close flybys of Europa [3]. Magnetic data and detailed images provided strong support for the existence of a salty ocean under the ice surface of Europa. Recent discoveries of many Jupiter-like planets orbiting other stars, and the fact that all the gas-giant planets of the solar system possess sizeable satellites, make the study of icy moons like Europa more important in order to understand the habitability of icy worlds throughout the universe.

As Europa orbits Jupiter, and due to the eccentricity of its orbit, it experiences strong tidal forces. The tidal forces cause Europa to contract and stretch. This continuous flexing creates heat, which makes Europa's interior warmer. The tidal forces also make Europa's icy outer shell flex, likely causing the long, linear cracks seen in images of its surface. Most scientists think it is probable that Europa has a salty ocean beneath a relatively thin and geologically active icy shell. Although evidence exists for oceans for several other large icy satellites in the outer solar system, Europa is unique because its ocean is believed to be in direct contact with its rocky interior, where conditions could be similar to those on Earth's biologically rich ocean floor. Our planet has geologically active places on its sea floor, called hydrothermal zones, where water and rock interact at high temperatures. These zones are known to be rich with life, powered by energy and nutrients that result from reactions between the seawater and the warm, rocky ocean floor.

Life as we know it depends upon three key ingredients: liquid water, to create an environment that facilitates chemical reactions; essential chemical elements that are critical for biological processes; and a source of energy that could be utilized by living things. Europa appears to possess all three of these key ingredients for life. It is special among the bodies of our solar system in having a potentially enormous volume of liquid water, along with geological activity that could promote the exchange of useful chemicals from the surface with the watery environment beneath the ice. However, the flow of material within and beneath Europa's icy crust is not well understood. Even the existence of a subsurface ocean, while strongly suspected, is not yet proven.

3. The Europa Clipper Mission Concept

The Europa Clipper mission concept, being developed jointly by the Applied Physics Laboratory (APL), Johns Hopkins University, and the Jet Propulsion Laboratory (JPL), California Institute of Technology, would send a spacecraft to the Jupiter system to perform repeated close flybys of the giant planet's moon Europa to investigate its potential habitability. The spacecraft would collect information on Europa's ice shell thickness, composition and surface geomorphology. The notional science payload consists of six instruments: a shortwave infrared spectrometer, an ice penetrating radar, a stereo topographical imager, a mass spectrometer, Langmuir probes, and a magnetometer.

While other mission concepts are possible, such as an orbiter or a lander, the APL-JPL team found that a multiple flyby tour would be the most cost effective way to address the science objectives listed in the latest Planetary Science Decadal Survey [4]. A flyby mission can potentially carry a heavier instrument payload, while increasing the time available for data transmission, and reducing the time spent in a high radiation environment [5]. The proposed Europa Clipper mission would minimize the hazards posed by Jupiter's intense particle radiation environment by spending most of its time well outside the most intense regions of radiation, only diving in close to Europa for brief periods to collect precious science data during flyby encounters.

The current concept of the Europa Clipper mission would include 45 flybys of Europa at altitudes varying from 2700 km to 25 km. In the course of setting up these flybys, the mission would also fly by the Jovian moons Ganymede and Callisto, although these flybys are done solely to shape the orbit and would not drive science requirements.

Both a direct launch using the Space Launch System (SLS), and a Venus-Earth-Earth Gravity Assist (VEEGA) cruise using an Evolvable Expendable Launch Vehicle (EELV) are being considered currently. The VEEGA option would spend 6.5 years traveling to Jupiter, while the SLS option could arrive to Jupiter in less than 3 years. Upon arrival at Jupiter, the spacecraft would perform a nearly 2-hour main engine burn to allow capture into Jovian orbit. The spacecraft would then perform a number of Ganymede and Calisto flybys to reduce orbital energy and align its trajectory with Europa.

The Europa flyby campaign would be composed of a number of segments each designed to provide good coverage of a wide region on Europa with consistent lighting conditions [5]. During each flyby, a preset sequence of science observations would be executed. On approach the spacecraft would perform low-resolution global scans with its infrared spectrometer ("nodding" the instrument field of view back and forth across the moon), followed by high-resolution scans with that instrument. At 1,000 km the ice-penetrating radar, topographic imager and mass spectrometer 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 are acquired continuously. During departure, the infrared spectrometer would conduct additional high- and low-resolution scans as the spacecraft moves away from Europa.

Once the nominal mission has been completed – 45 Europa flybys for its current design – the mission could continue to execute Europa flybys during an extended mission, if propellant is available. The spacecraft would eventually be decommissioned via targeted impact on Ganymede or Jupiter before its propellant runs out or radiation damage compromises its electronics.

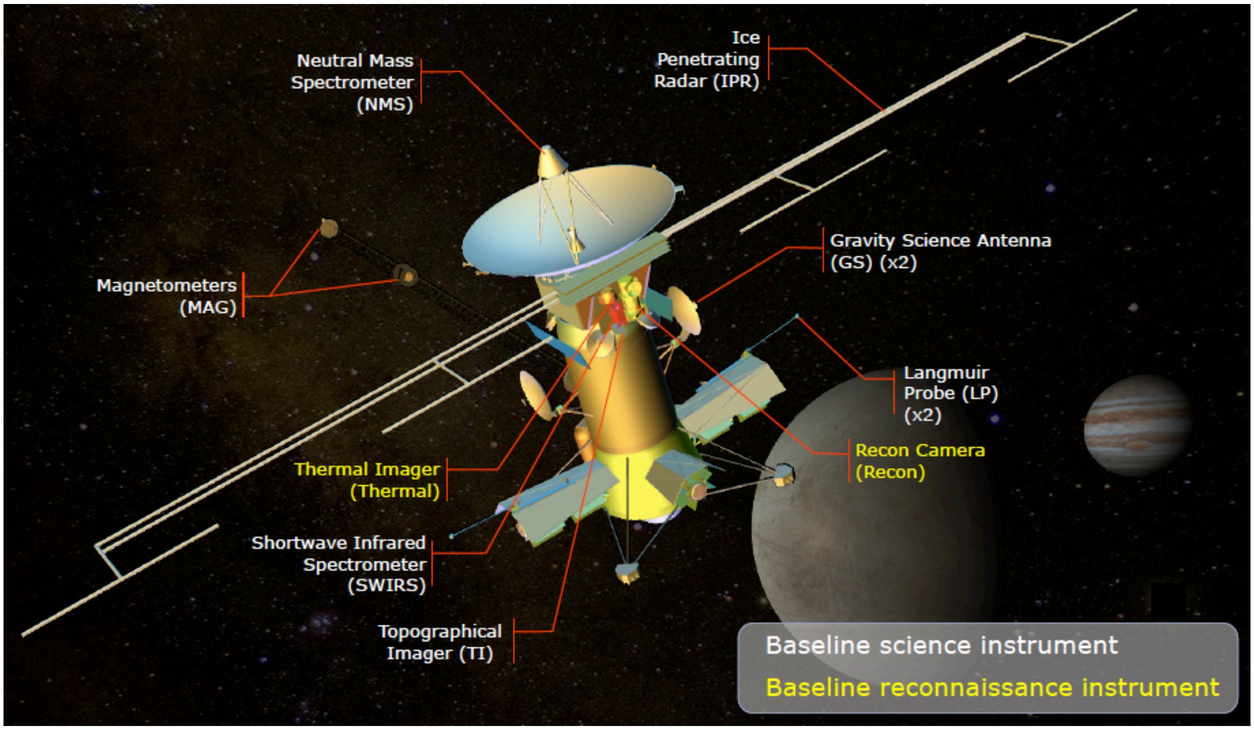

Figure 1. Notional Europa Clipper Spacecraft

3.1 Notional Spacecraft

The notional spacecraft (Fig. 1) assumed for the navigation analysis described in the paper would use radioisotope thermal generators for power. It would communicate using X-band for uplink, command, and engineering downlink, and Ka-band for science data downlink. A high gain antenna (HGA), aligned with the +Z axis of the spacecraft, would be used to communicate during the tour. Most instruments would be bore sighted with the +Y axis of the spacecraft, which would point in the nadir direction during science flybys, precluding tracking using the HGA for several hours before and after the flyby. The propulsion system would consist of a Reaction Control System (RCS) and a Main Engine (ME). The Reaction Control System, used for attitude control and small trajectory control maneuvers, would be equipped with eight 1-N thrusters, with attitude control about the Z-axis performed with balanced thrusters and control about the other two axes with unbalanced thrusters. The Main Engine would be a 400 N thruster with the thrust vector nominally aligned with the +Z direction. The Main Engine would be used for maneuvers with a total commanded magnitude of more than 1.3 m/s. The RCS thrusters would be used for smaller maneuvers. For the satellite tour analysis the maneuver execution errors listed in Table 1 have been assumed. During the satellite tour the spacecraft is assumed to use reaction control wheels to turn except when using the Main Engine. Due to power limitations, the notional spacecraft may or may not be power positive during science downlink, and may need to recharge its batteries after each tracking pass. The baseline for this analysis is that the ground would be able to track the spacecraft during every other DSN tracking opportunity.

Table 1. Tour Maneuver Execution Errors

		Main Engine	RCS
Magnitude	Proportional (%)	0.07	1.0
	Fixed (mm/s)	10.0	1.17
Pointing (per axis)	Proportional (mrad)	3.5	6.0
	Fixed (mm/s)	17.5	1.33

4. Navigation Analysis

An important part of the concept study for any space mission is to analyze whether the trajectory designed for the mission can actually be flown, when one considers the usual sources of uncertainty and errors involved in the operation of a mission. The tentative spacecraft design and the mission operation scenarios reflect a compromise between competing priorities. Cost, mass, and risk need to be minimized across the spacecraft, achieving a compromise design that maximizes the science return for the desired cost. These constraints affect the navigation planning in a number of ways.

The amount of tracking data depends on the availability of sufficient power to operate the communications equipment. For a mission to the outer solar system continuous tracking would not be possible if the spacecraft is not power positive while it is sending data to the ground. While we can think of adding power sources – solar panels or radioisotope thermal generators - to make the spacecraft always power positive, the mass required by those additional sources is mass that will not be available for instruments or propellant.

There may be times at which the spacecraft is going to optimize its orientation to point its science instruments. If the communications antenna is fixed to the spacecraft, it may not be possible to point the instruments to the science target and the antenna to the Earth. Having an articulating antenna could solve this conflict, but it would also add mass that could otherwise be used for instruments or propellant.

Missions communicating with the ground using radio frequencies can easily produce Doppler measurements as part of the routine signal tracking process. Ranging requires modulating a signal that may subtract from the power used to communicate. Additional navigation measurements, such as optical images, can improve navigation performance, but require the spacecraft to carry additional equipment that could compete, in mass and power, with other needs of the mission.

The navigation analysis is performed in order to determine what is the best way to fulfill the requirements imposed on the navigation system in order to achieve the mission objectives, and to contribute to the design of the spacecraft and the mission operations concept. The spacecraft needs to fly over the science targets at the required altitude and, in order to properly operate the scientific instruments, the spacecraft needs to point to the science targets precisely, so the actual relative position of the spacecraft with respect to the target also needs to be known. The analysis also provides an estimate of the location and magnitude of the trajectory maneuvers that would be needed to perform the tour, so the propellant that the spacecraft would need to carry can be calculated.

The navigation analysis requires orbit determination analysis and maneuver analysis. The orbit determination analysis needs to take into account the uncertainties in the ephemeris and other parameters that model the Jovian system, as well as other dynamic and measurement modeling uncertainties. The maneuver analysis needs to model the execution errors of the orbit shaping maneuvers in order to estimate the flyby trajectory errors and the required propellant for the mission. The navigation analysis is an iterative process between trajectory design and navigation, in which navigation assesses new trajectory designs and proposes changes in order to make the mission less difficult to navigate.

4.1 Navigation Concept

Europa has an orbital period of just 3.55 days, compared with about 15.9 days for Titan, so a Europa flyby mission could be more challenging than the Cassini mission [6] because it could have a much more compressed operational timeline. Every flyby of a sizeable moon amplifies the trajectory errors that were present before the flyby. A number of maneuvers, typically three, are scheduled between consecutive flybys. The first maneuver after a flyby is called the cleanup maneuver, as it is typically used to remove the perturbation introduced by the previous flyby due to trajectory and moon modeling errors, but it could have a deterministic component; the second maneuver is called the targeting maneuver as it removes trajectory and maneuver execution errors to target for the next flyby; the third maneuver is called the approach maneuver, a final opportunity to correct the trajectory prior to the flyby. Not all of these maneuvers would have a deterministic component, but all of them would have to be designed including data taken after the previous flyby or maneuver, in order to target the next flyby. Certain trajectory shaping strategies, such as pi-transfers or a flyby of one moon closely followed by a gravity assist by another moon, could be very challenging from the point of view of operations, since they would consist of a close succession of flybys, orbit determinations, and maneuvers. Failure in performing all the required tasks could require a redesign of the rest of the tour, or even mean the end of mission if the spacecraft would impact a flyby target.

The current tour navigation concept for the Europa Clipper mission being studied uses coherent two-way radiometric data collected by the Deep Space Network (DSN) to perform orbit determination. The data types used are coherent two-way Doppler and range data. The current spacecraft architecture uses the X band for uplink and the X and Ka bands for downlink. Ka-band downlink would be used for high-volume science data transmission, and X-band for engineering telemetry. The addition of optical measurements is being studied, in order to potentially improve the spacecraft trajectory knowledge during the science flybys. It is assumed that most of the navigation tasks would be performed on the ground, possibly with a high degree of automation. The most critical navigation task may be the design of maneuvers to keep the spacecraft in the planned tour, either planned velocity changes to achieve new orbital conditions, or trajectory correction maneuvers to compensate for trajectory modeling errors, both for the spacecraft and the moons, and maneuver execution errors. The fast pace of the tour would require a short time between the collection of the tracking data after a previous maneuver or flyby, and the design, testing, and approval of the next maneuver, so it can be commanded to the spacecraft and be executed on time.

4.2 Orbit Determination Analysis

The orbit determination analysis needs to take into account the uncertainties in the ephemeris and other parameters that model the Jovian system, as well as other dynamic and measurement modeling uncertainties. The analysis starts when a new trajectory design is created, together with the set of deterministic and statistical maneuvers that will be used to achieve and maintain the planned trajectory. The trajectory design is based on a particular set of planetary and satellite ephemerides that are also used by the orbit determination analysis. The error of these ephemerides can be estimated and this uncertainty is included in the orbit determination process. For this one can also include future planned observations up to the time of the mission in consideration, either from the ground or by other future space missions, such as Juno in the case of the Jovian system. Other orbit determination assumptions specific to this tour analysis are listed in Table 2. Un-modeled accelerations soak up the effect of a number of dynamic error contributions that cannot be accurately predicted: attitude control thrusting for momentum desaturation and reaction control wheel speed biasing, thermal and solar radiation pressure accelerations, and higher order and degree terms of the moon's gravity fields. In addition to those assumptions the spacecraft, planet and satellite ephemerides are estimated, as are the gravitational parameters of the planet and satellites, and the trajectory maneuvers in the data arc. DSN station coordinates, media corrections, and UT1 and polar motion are considered in the orbit determination analysis.

Table 2. Tour Baseline Orbit Determination Assumptions

Tracking data	2-way Doppler and range collected every other pass
Doppler data weight	0.1 mm/s for 60s sampling for Sun-Earth-Probe (SEP) angles higher than 15°; 1 mm/s between 7.5° and 15°; 5 mm/s below 7.5°; no data used below 3°
Range data weight	3 m for SEP angles higher than 7.5°; no data used below 7.5°.
Tracking exclusion around Europa flybys	No tracking data collected from 24 hours before to 12 hours after the flyby
Un-modeled accelerations	4.5×10^{-6} mm/s^2 per axis estimated stochastically as white noise in 8-hour batches
Nominal data cut off for maneuvers	2 days before the maneuver execution time

The orbit determination analysis is performed arc by arc, where an arc typically starts some time before the approach maneuver for a flyby and ends after the following flyby. The tracking data during the arc is used to perform orbit determination for the design of the maneuvers between the two flybys and to predict the spacecraft trajectory at the second flyby. The planetary and satellite ephemeris and gravity parameter uncertainties are obtained from the previous arc using as the data cut off (DCO) the time of the start of the new arc.

The orbit determination analysis is first performed assuming no maneuver execution errors, and orbit determination covariances are produced for the expected DCO time of each maneuver. Those covariances are then used in the maneuver analysis to calculate the distribution of expected maneuver designs, and from those a distribution of maneuver execution errors for each maneuver is computed. These errors are used in a new iteration of the orbit determination analysis to calculate new orbit determination errors at the maneuver DCO times, and the process is continued until it converges.

Once the process converges, additional mappings and cases are computed to determine the accuracy with which each flyby can be executed. Table 2 shows an example of the results that are obtained. The values listed are the B-plane and encounter uncertainties for the first 18 Europa flybys when mapping from the approach maneuver DCO. These values represent the orbit determination delivery errors, since they do not include the execution errors of the approach maneuver. Delivery performance improves as more flybys are executed, since the satellite ephemeris errors are reduced, but eventually they can be different from flyby to flyby depending on the particular geometry of the flyby in relation to the Earth direction. Similar computations also need to be performed using a DCO after the approach maneuver is executed and some tracking data is collected, in order to assess the trajectory knowledge at the flyby, which will be used to point instruments to their targets on Europa.

Table 3. Sample B-Plane and Encounter 1-Sigma Uncertainties at the Approach Maneuver DCO for 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	753.3	-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	5.3	0.8	97	2.4	8.2	2.07
E3	09E3	23-APR-2029,07:42:55	100.0	-5.197	5.2	0.6	81	3.1	8.9	2.24
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	0.2	166	1.1	6.2	1.55
E8	14E8	03-JUL-2029,15:16:07	100.0	-5.394	4.5	1.1	86	1.5	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	131	1.7	5.8	1.44
E11	17E11	15-AUG-2029,06:11:33	25.0	-5.034	2.8	0.6	151	1.6	5.4	1.35
E12	18E12	29-AUG-2029,11:07:49	50.0	-5.078	2.2	0.2	174	1.4	5.1	1.27
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	33	0.6	3.5	0.88
E15	21E15	11-OCT-2029,09:12:54	1872.3	-5.399	3.1	1.4	88	2.9	5.0	1.26
E16	22E16	12-NOV-2029,01:39:22	2710.3	-5.161	0.6	0.4	158	0.4	1.6	0.38
E17	24E17	26-NOV-2029,14:57:33	50.0	-5.076	1.8	1.7	105	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	4.6	1.13

After the baseline orbit determination analysis is performed, additional orbit determination cases are run using different assumptions, usually changed one at a time. Figure 2 shows an example for recent Europa Clipper analyses. These cases show the sensitivity of the baseline results to changes in the assumptions, highlighting which assumptions are more critical to get the required performance, and which assumptions can be changed without significantly affecting the performance. In the case of a satellite tour, delivery errors are mostly affected by the maneuver execution error assumptions, by the initial satellite ephemeris uncertainties – for early flybys, and by the level of the un-modeled accelerations.

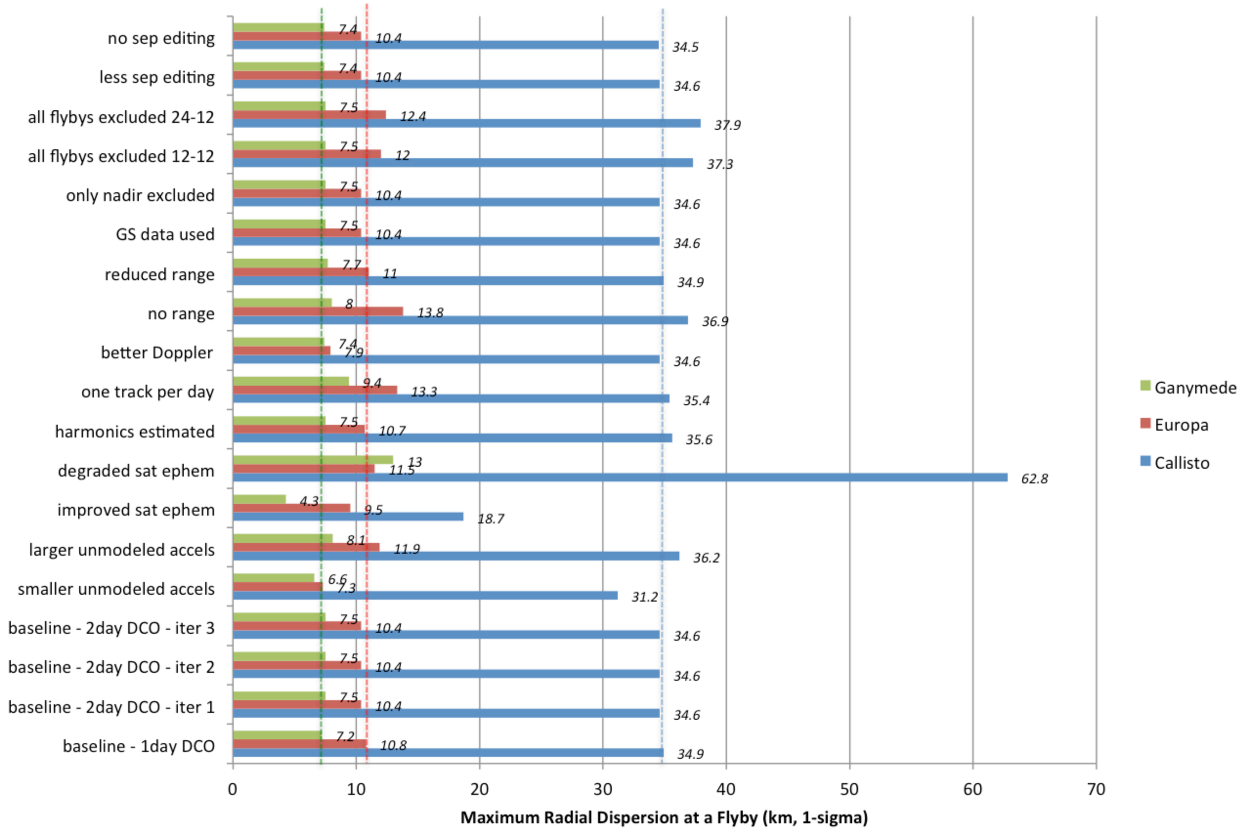

Figure 2. Sample Tour Flyby Variations at the Approach Maneuver DCO

A particularly challenging requirement for the Europa Clipper mission could be the necessary pointing accuracy during the flyby. Navigation affects the pointing accuracy because the spacecraft attitude control system needs to know the position of the spacecraft with respect to Europa in order to correctly point the instruments toward targets of interest. The relatively low altitude of some flybys, nominally down to as low as 25 km, makes position knowledge errors a potentially large contributor to pointing errors. The trajectory needs to be predicted using data before the flyby. The study team is investigating ways to improve the position knowledge for the flybys. One option is to collect radiometric data after the last maneuver executed before the flyby, and use it to better predict the trajectory at the flyby. The challenge is that the last maneuver is typically performed three days before the flyby, so a 4 mm/s error in the executed maneuver could map to a 1 km position error at the flyby. Enough tracking data needs to be processed before the flyby, but time also needs to be allocated to generate the ephemeris update and reliably upload it to the spacecraft. A possible alternative is to perform on-board processing at the spacecraft; either by using one-way data from the ground assuming the spacecraft is equipped with a sufficiently stable frequency reference, or by using optical navigation.

4.3 Maneuver Analysis

The maneuver analysis uses orbit determination errors and maneuver execution error models in order to estimate the distribution of expected maneuver designs for every maneuver opportunity. These estimates in turn provide maneuver execution error values for each maneuver that are used for orbit determination analysis, while the maneuver magnitude distributions are used to calculate the propellant required to reliably complete the mission. The maneuver analysis also assesses the best possible placement for trajectory shaping and correction maneuvers, in order to reduce flyby delivery errors and the total propellant needed to execute the mission. Maneuver analysis randomly samples the covariance provided by orbit determination in order to perform Monte Carlo sampling of the maneuvers needed to fly the mission. Maneuvers are designed based on the initial state and the desired flyby targets, and maneuver execution errors are then also sampled for the resulting maneuver designs. These errors are reported and then used to drive the next iteration of the orbit determination process.

In the case of Europa Clipper, maneuvers would be executed in one of two different modes. Smaller maneuvers would be executed using the RCS thrusters, and the slew to the maneuver attitude would be performed using reaction control wheels. Larger maneuvers would be performed using the main engine, the engine that is also used for the Jupiter Orbit Insertion (JOI) maneuver, and the slew to the maneuver attitude would be, in this case, performed using the RCS thrusters. The maneuver magnitude threshold between using RCS thrusters or the main engine could be chosen in order to minimize the maneuver execution error. As shown in Table 1, RCS maneuvers have a smaller fixed error but a larger proportional error than main engine maneuvers. Making the error as small as possible does not only reduce the delivery errors, it also reduces the size of subsequent maneuvers and the overall propellant needed for the mission. An additional consideration is that in the current architecture, the RCS uses monopropellant thrusters, with a smaller specific impulse, while the main engine uses bipropellant with a higher specific impulse. This makes using the main engine more efficient in terms of propellant mass for a given maneuver magnitude, so this effect should also be included in calculating the optimal maneuver magnitude to transition between using the RCS thrusters and the main engine.

For the current design of the Europa Clipper tour, the total deterministic maneuver ΔV required after the periapsis raise maneuver is 164 m/s, and when orbit determination uncertainties and maneuver execution errors are included at the baseline level in the analysis, the total ΔV increases to 497 m/s, for a 99% confidence level. As a comparison, more than 800 m/s are needed for the Jupiter Orbit Insertion maneuver, and about 120 m/s for the periapsis raise maneuver. When the analysis is run varying the orbit determination assumptions, the results shown in Figure 3 are obtained. As it was the case with delivery errors, the highest sensitivity is with respect to satellite ephemeris uncertainty and the level of the un-modeled accelerations. Not shown in Figure 3 are the effects of increased and decreased maneuver execution errors, but they should also significantly affect the statistical ΔV.

Part of the maneuver analysis is to identify the number and location of maneuvers between flybys. For the current tour design, consecutive Europa flybys are typically separated by about 14 days, since the spacecraft is in a 4:1 resonant orbit with Europa, providing sufficient time for the three maneuvers planned between flybys. More challenging is the location of maneuvers when consecutive flybys involve different moons. In some of those cases, for the current tour design, the time between flybys can be as short as just five days. For that case only one maneuver is planned between the two flybys, with a reduced time between the maneuver data cut off and maneuver execution, and with additional tracking planned in order to ensure that sufficient data is available to reliably design the maneuver.

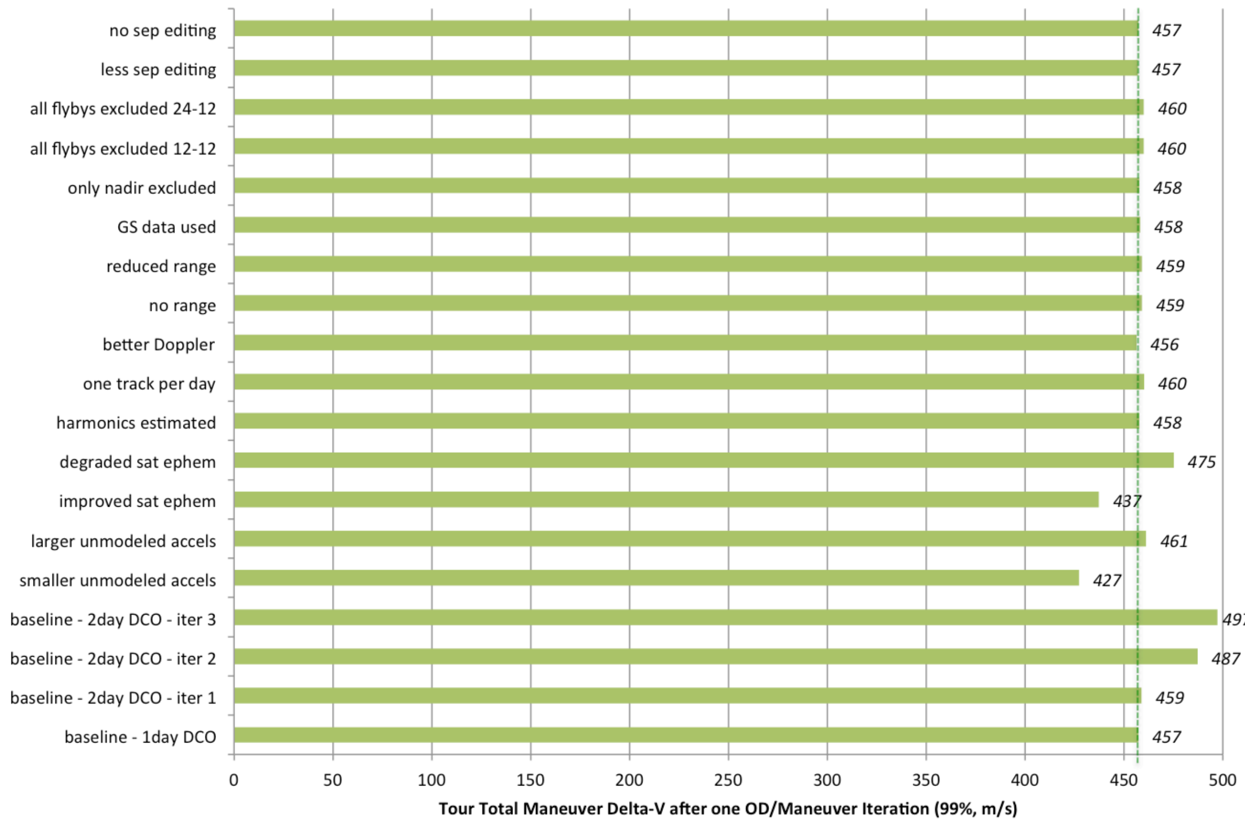

Figure 3. Total Tour 99% ΔV Required

5. Conclusion

The design of a flyby mission to Europa can be more challenging than that of a flyby mission to Titan, from the point of view of navigation. The shorter orbital period of Europa would require a more rapid succession of orbit determinations and maneuvers. Navigation analyses have established the baseline delivery performance and statistical ΔV needed to fly the current reference tour. As expected for an outer planet tour, managing maneuver execution error uncertainties – and satellite ephemeris uncertainties early in the tour – are key considerations in order to stay at these performance levels. Work continues on establishing the science drivers for navigation performance; these drivers are important in determining the recommended turn-around times for navigation deliveries and the roles of ground and on-board autonomy in meeting those turn-around times. The analysis performed so far has shown that ground processing of radiometric data would most probably be able to fulfill most of the expected mission requirements. Stringent trajectory knowledge requirements, beyond those levied against Cassini, could make the navigation task for Europa Clipper more challenging than that for

Cassini. They could require a trajectory knowledge update right before the flyby, either by using high-paced ground processing, or by performing on-board autonomous navigation.

6. Acknowledgment

The authors would like to thank Dr. L Alberto Cangahuala for thoroughly reviewing the paper and providing suggestions to improve it.

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 herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise, does not constitute or imply its endorsement by the United States Government or the Jet Propulsion Laboratory, California Institute of Technology.

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