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EUROPA CLIPPER POINTING STABILITY: CHALLENGES ON A MULTI-INSTRUMENT MISSION TO JUPITER*

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Europa Clipper Mission is developing a flight system carrying an array of NASA-selected instruments to execute numerous flybys of the moon Europa while orbiting Jupiter. The Europa Clipper flight system is being jointly implemented by the Jet Propulsion Laboratory (JPL) and the Applied Physics Laboratory (APL), with a launch planned for 2023. The project completed the preliminary design review (PDR) in August 2018.

A multiple flyby design has enabled the mission, by reducing the amount of time the flight system spends in the harsh radiation environment near Europa. Conversely, the flyby architecture results in science observations taking place during a highly dynamic period as the spacecraft swings by Europa. These narrow periods of peak Europa science opportunities, result in complex interactions between all instruments, that must be managed during compressed windows to enable maximum science data collection. Pointing Stability and Jitter is one of the key characteristics that needs to be met during this time to ensure quality science data.

The imaging requirements for the Europa Clipper mission result in jitter requirements that are challenging to meet in concert with other instrument requirements. Developing a new flight system to accommodate the Europa environment and hosting 10 unique instruments has led to design fluctuation. Instrument, subsystem, and project PDR's have brought together a more complete design to provide better assessment of the expected Line-of-Sight jitter. This paper will discuss assessment methodologies, current challenges, and strategies for meeting jitter requirements of the Europa Clipper Mission.

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INTRODUCTION

The Europa Clipper mission will investigate Jupiter's moon, Europa, to better understand this unique body in the solar system. This investigation is joint partnership between the Jet Propulsion Laboratory and the Applied Physics Laboratory that will launch in 2023. Two Jupiter delivery options are being considered, either a direct trajectory (utilizing an SLS launch vehicle) with ~2.5 year cruise, or a longer cruise (utilizing alternate launch vehicles) that takes advantage of multiple gravity assists in the inner solar system. A Prime Mission of approximately 3.5 years will be spent orbiting Jupiter with over 40 flybys of Europa.

The Europa flyby approach allows for a longer mission by minimizing the time spent in the harsh radiation near Europa's orbit. Flybys with a closest-approach ranging from 25 kilometers to a few thousand kilometers will allow for excellent Europa Science. Primary objectives of the Europa Clipper mission are to assess habitability by generating high-resolution images, determining composition, and assessing any current or recent activity. The mission will investigate Europa using a set of five remote sensing instruments, four in-situ fields and particles instruments, a radar, and a gravity science investigation. [1,2]

The 3-axis-stabilized Europa Clipper Spacecraft provides a stable platform to accommodate the suite of instruments and provides acceptable pointing stability and knowledge as the Clipper Spacecraft flies by Europa. As a solar powered spacecraft it is quite large with over 100 square meters of solar array area to power all the sensors and actuators. When deployed is it over 25 m in length, or about the length of a basketball court. The spacecraft design centers on a core propulsion module that contains the propellant tanks, and propulsion plumbing, and supports both the solar arrays and telecommunication antennas. A protective vault enclosure sits atop the propulsion module and houses most of the Spacecraft electronics and provides protection from the harsh radiation environment at Europa.

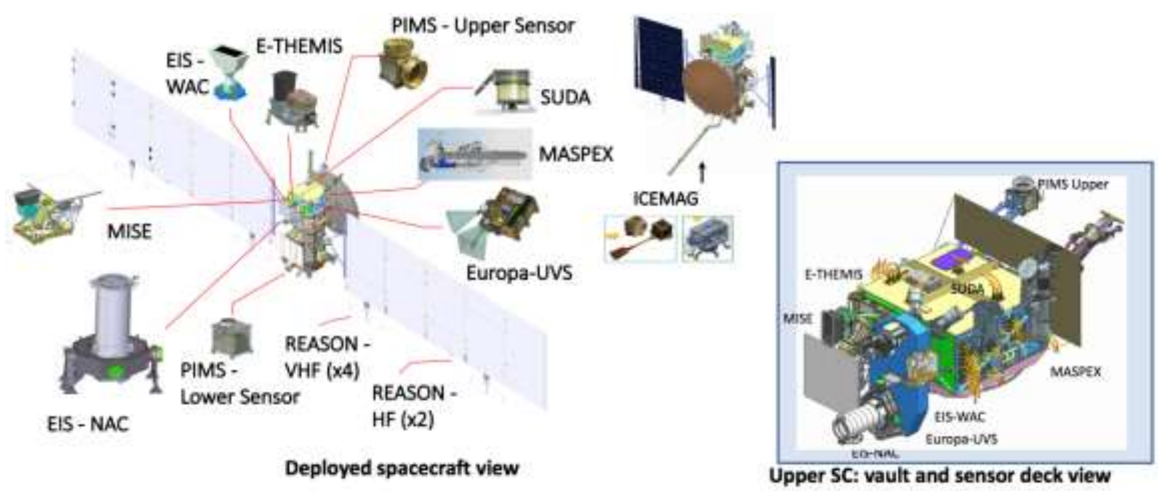


Figure 1 Spacecraft Overview

The single-fault tolerant, redundant GNC design has a sensor suite of two Sodern Stellar Reference Units (SRU), two Northrop Grumman Scalable Space Inertial Reference Unit (SSIRU), and four Adcole Digital Sun Sensors (DSS). For controlling the spacecraft there is a 12 engine bi-propellant system for either coarse attitude control or momentum management, four Honeywell Reaction Wheels (RWA) in a pyramid configuration for precise attitude control, and a Solar Array Drive Assembly for single axis rotation of the solar panels.

The science payload consists of a set of five remote sensing instruments, four in-situ fields and particles instruments, and a radar. All instruments are body mounted so 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. Although it is body mounted, the narrow-angle camera has a 2-axis gimbal to allow for off-nadir target observations and stereo imaging. The full instrument suite can be seen in Figure 1, though this paper will focus on those impacted by jitter requirements: the Europa Imaging System Narrow Angle Camera (EIS-NAC or simply NAC), the Mapping Imaging Spectometer for Europa (MISE), and the MAss SPectrometer for Planetary EXploration (MASPEX). The relative location of these three instruments can be seen in Figure 2.

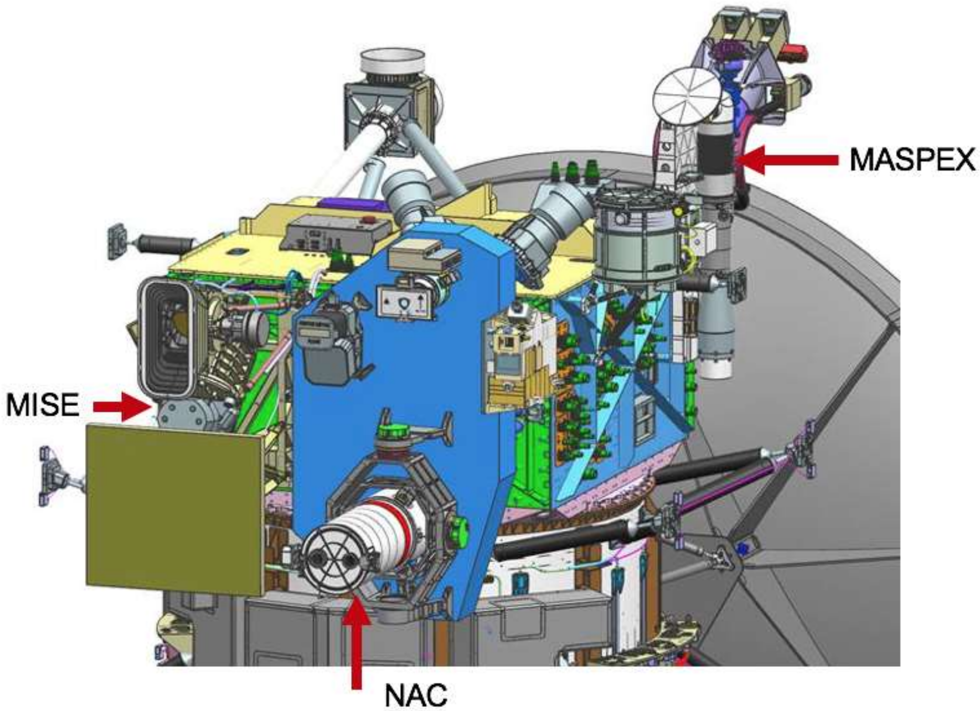


Figure 2 NAC, MISE, and MASPEX locations

FLYBY SCENARIO

The Europa Clipper Mission is a Europa flyby style mission not an orbiting mission.[3] This provides some significant benefits and some challenges to the operations including the impacts on jitter analysis. Figure 3 shows a cartoon that represents the typical Europa flyby trajectory during the science campaign. Here the orbit of Europa and the spacecraft around Jupiter can be seen in orange, with the blue arrows indicating the primary function of the different parts of the trajectory. Highly elliptical orbits lead to dedicated science data collection and data playback periods. This architectures has the benefit of data playback occurring while outside of Jupiter's high radiation environment, which helps extend the total mission lifetime. The spacecraft will have an orbit period of approximately 14 days, with most of the Europa science occurring within the 24 hours centered on the flyby closest-approach time. The relatively short time period for prime Europa observations results in all the instruments observing concurrently and must have compatible requirements. This flyby architecture presents a challenge when addressing jitter requirements because the spacecraft is actively changing attitude and most disturbances sources (such as reaction wheels, cyrocoolers, and heat pumps) cannot be deconflicted from the observations that have tight jitter needs.

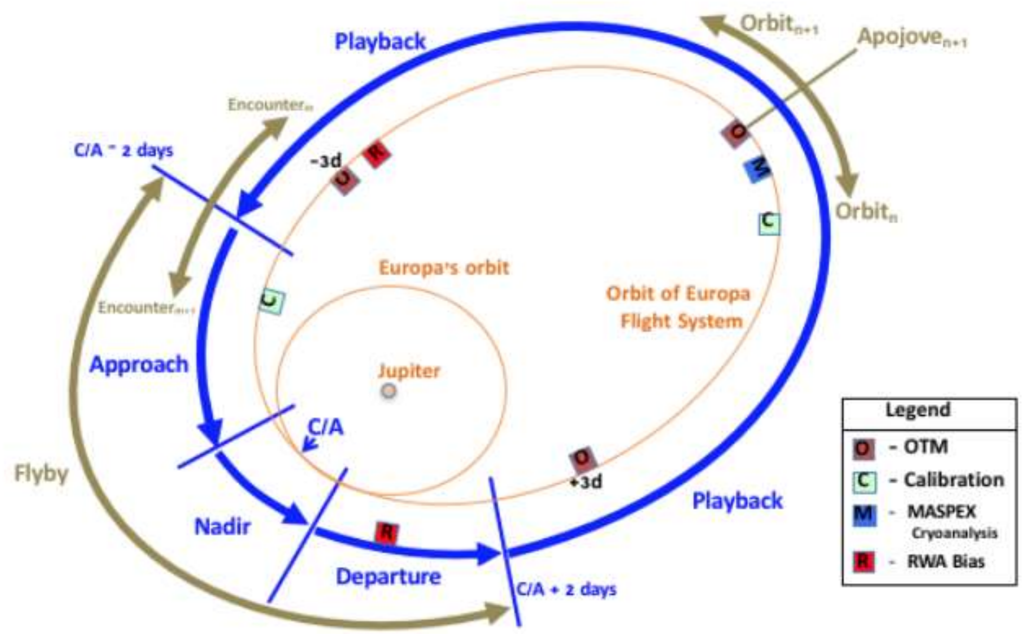


Figure 3 Europa Flyby Scenario

DRIVING JITTER REQURIEMENTS

With multiple optical instrument, each has its own line-of-sight (LOS) jitter requirements derived from either a resolution or data quality need. The optical instruments all start with a top level 'image smear' requirement which is broken down into the various components that would contribute to this image smear need. Figure 4 shows how this is broken down for allocations to be levied on the different components that will allow for the high level science need to be met. You can see in the figure, outline in red, the jitter contribution and the disturbances that contribute.

The NAC is the driving instrument for all flight system jitter and disturbance requirements. The NAC is a visible light imager that uses a detector that operates in two modes; for low altitude imaging, 'push-broom' mode using Time Delayed Integration (TDI), or for higher altitude imaging a 'framing' mode. The TDI is used at the lower altitudes to partially compensate for the spacecraft ground speed and improve the signal, and is the driving scenario. The camera has a top level 1-pixel 2σ (10 μrad 2σ) total image stability requirement for exposures of 10 ms and 100 ms. This 10 μrad number accounts for all the effects seen in Figure 4. The high frequency jitter was expected to be challenging and thus resulted in this contribution being allocated two-thirds of the total allocation. Other instrument jitter requirements are also managed but are 2-10 times less demanding than the NAC and do not drive the design.

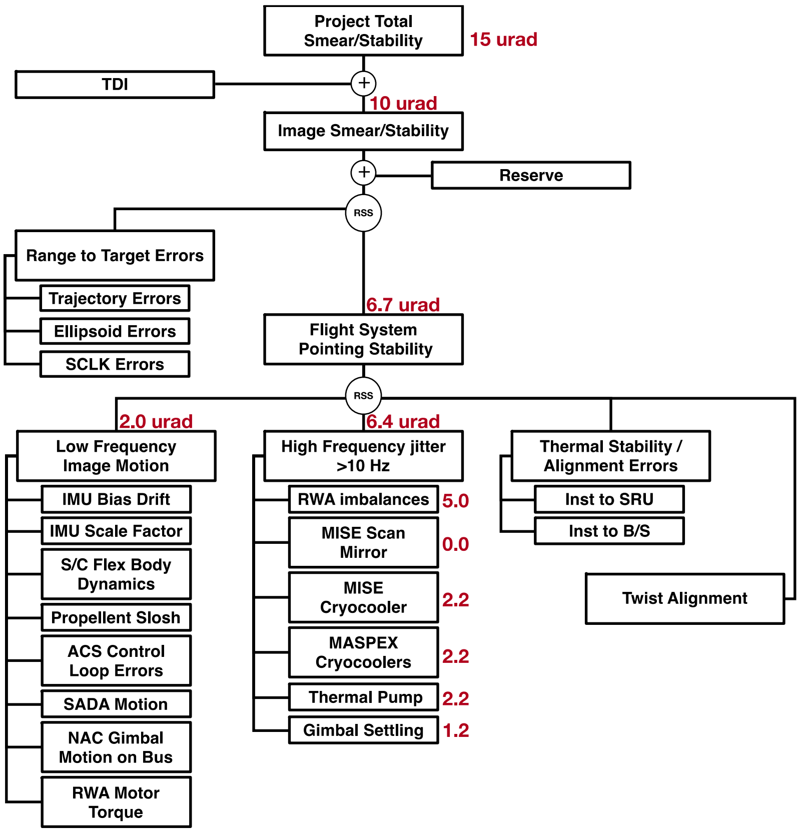


Figure 4 Image Smear / Pointing Stability Error Budget

PRIMARY DISTURBANCE SOURCES

The primary disturbance sources on the Europa Clipper spacecraft are the reaction wheels (RWA), the cryocooler on MISE, the cryocooler on MASPEX, the pump on the heat redistribution system (HRS), and the solar array drive assembly (SADA). These disturbance sources operate in different enough regimes that they are all treated independently.

The RWA are a dominant source of disturbances, and are designed to operate over a wide range of speeds. This complexity makes it difficult to isolate a specific condition under which they meet or exceed the jitter requirement. Careful analysis over a wide range of expected operating modes must be considered. The RWA are mounted on the bottom of the spacecraft, near the launch vehicle separation plane. The NAC is near the top of the spacecraft, however there is still significant disturbance from wheel harmonics on the NAC. The 5 μrad 2σ allocation was negotiated to apply to 95% of the expected wheel speeds. This negotiation allowed for removing the need to show compliance with each wheel at the worst case disturbance and the same time, a very low likelihood event. While a significant disturbance source, the RWA could also be damaged by the launch loads environment, and thus a dual purpose isolation system is being developed to help mitigate both issues.

The second most prominent disturbance is the MISE instrument which needs a cryocooler for imaging spectrometry. The MISE instrument is mounted to the vault wall next to the imaging platform attachment, see Figure 2 indicating the location of MISE and NAC. Although it is a disturbance source, it is also tunable in flight, and therefore that feature can be used to reduce the disturbance impact. This inflight adjustability provides the opportunity for de-tuning if a resonant interaction between the drive frequency and the NAC telescope is identified in flight. The cryocooler is designed with a nominal drive frequency of 135 Hz, although it has in-flight adjustability of ±10 Hz.

The MASPEX instrument is also a cryogenic instrument with a Stirling engine style cryocooler. The cryocooler does not have a fixed frequency but will vary based on cooling demand, from approximately 40-70 Hz. This complexity requires a wide range of flight scenarios to be analyzed to verify the jitter requirement is met. Unlike the MISE cryocooler the frequency is not tunable in flight, so varying frequency can be counted on to mitigation of the disturbance. MASPEX is mounted on an adjacent side of the electronics vault from the imaging platform that contains the NAC.

Located within the vault, the heat re-distribution system is powered by a six bladed impellor driven pump. This pump operates continuously and pushes fluid throughout the vault and propulsion module to balance the head load throughout the flight system. Driven at approximately 190 Hz the forces and torques introduced to the system are lower magnitude than the cryocoolers, but still of concern for the NAC observations.

The last disturbance source that partially straddles the low-frequency high-frequency boundary is the SADA, which produces significant disturbance when the stepper motor moves the large arrays. This disturbance is quite large and overwhelms the NAC requirements, though this is the only operation that we have been able to de-conflict with NAC observations. SADA stepping has been restricted to a specific potions of the flyby phase to effectively remove this disturbance source.

EVOLUTION OF THE JITTER ASSESSMENT METHODOLOGY

It is appropriate to outline some of the path that has led to the current jitter assessment methodology and issues that arose along the way that influenced the current state. This section is intended to help the reader understand some of the rationale for our current methods, as well as outline pitfalls that were encountered. Initial assessment of the requirements assumed that the jitter requirement could be met with a decoupled analysis of each element, with their results combined to assess the worst case. With the 10 μrad requirement falling below the stringent requirement of a space telescope, but tight enough to take seriously, this seemed like a good approach.

Early on, one area that caused uncertainty was a lack of a consistent Model Uncertainty Factor (MUF) policy. Early results were presented with no MUF, which led to optimistic results early in the development process. Concern about proper conservativism led to application of MUF's, although a lack of a clear MUF policy led to inconsistent application and stacking of MUF's resulting in over conservativism. This was exposed at the GNC PDR where results were shown with MUF's that compounded, producing results that were so far exceeding requirements, that mitigation options did not seem practical. A focused team was organized to pull the contributing parties together and propose a unified MUF policy, that was appropriately conservative. This tiger team developed a consistent policy, backed by industry examples, that received stakeholder agreement.

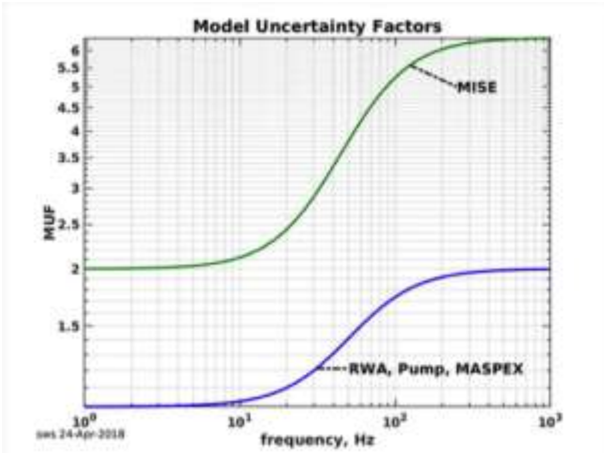
A second area that showed to be insufficient was the use of decoupled Finite Element Model (FEM) assessments. Both questions about integration of the FEM with various assemblies, and fidelity of the FEM, resulted in some changes in direction. Because the spacecraft is hosting many instruments which are being developed by different institutions the plan had been to simplify the modeling and get assessments at the interfaces. For example the spacecraft team would provide an environment at the NAC mounting interface based on spacecraft disturbances and the NAC team would provide an assessment of the camera system itself, then the baseplate motion and the camera motion assessments would be combined. This method overlooked interaction between the structures and also could end up combining results in a non-realistic way. Overtime it became evident that the requirements could not be adequately assessed without higher fidelity modeling. If significant margin was available the initial method may have sufficed, but it was determined that we needed to do assessments with an integrated FEM of all the components in the load path between the disturbance and the LOS.

CURRENT ASSESSMENT METHODOLOGIES

There are three parts to incorporate conservativism in the jitter assessment results, Model Uncertainty Factor (MUF) which account for amplitude uncertainty in disturbance transmissibility, frequency sweeps which account for frequency uncertainty in modeled modes, and the analysis metric either max or max-median result.[4] All three must be thought of together when determining the conservativeness of the analysis results. The objective of all of these components was to have a policy that was conservative enough to give confidence that performance would ultimately be met, yet also not so conservative that it resulted excessive mitigations. This policy for jitter assessments required significant negotiation to get all stakeholders in agreement.

The MUF policy that has been adopted by the Clipper project is dependent on the disturbance source characteristics. There are two main categories; the max-median which assumes the disturbance can be adjusted to reduce jitter impacts, and the max-value method which assumes the worst case result must be accommodated. Disturbance sources which have the ability to tune the drive frequency in flight were given a higher MUF. The max-median metric allows credit for the ability to de-tune a disturbance, by not being driven by the worst case result. However a larger uncertainty is carried in this case to account for larger uncertainty in the underlying backbone of the transfer-function. The MISE instrument cryocooler fits in this category. Disturbances that were unable to be tuned for jitter reduction used a lower MUF, but the reported assessment is the max value of the frequency sweep. This method accounts for the possibility of having resonant modes couple and not having the ability to de-tuned in flight. The HRS pump, MASPEX cryocooler, and RWA's all fell in this second category. The MUF for the project preliminary design review can be seen in **Error! Reference source not found.**. Since the modeling accuracy is expected to be better at lower frequencies the MUF is a frequency dependent, ranging from 2-6.4 for the tunable disturbance, and 1-2 for the non-tunable disturbances. These MUF values can be reduced as the model design matures and component level testing validates the finite element models used for analysis.

To ensure that the analysis results are not overly optimistic by assessing only at the designed drive frequency, the disturbance frequency is varied by applying a sweep. This ensures that the results are not performed in a spot where the transmissibility of the model is at a local minimum. Shifting the frequency could be done by modifying the transfer-function or by shifting the harmonics on the disturbance source. Shifting the input disturbance source is significantly easier in this case and is the method that has been applied. The disturbance harmonics are shifted ±10% in 0.1 Hz (TBD) increments, computing the LOS jitter for each, and finding the appropriate Max or Median result.



General MUF Equation, $k_1 \rightarrow k_2, 60Hz$

$$MUF = \frac{k_2(s^2 + 2\omega_1 s + \omega_1^2)}{s^2 + 2\omega_2 s + \omega_2^2}$$

$$\omega_2 = 2\pi 60, \omega_1 = \omega_2 \sqrt{k_1/k_2}$$

Figure 5 Model Uncertainty Factor (MUF)

The implementation for these processes can be seen in Figure 6. The source force and torque disturbance data is applied through the transfer-function from the integrated FEM, which has been inflated by the frequency dependent MUF. A high pass filter is applied based on the observation exposure time prior to incorporating the optical sensitivity matrix. This optical sensitivity matrix incorporates the effects of the relative motion of the optics on the line-of-sight motion. This data is then integrated across the frequency range, and then the max of either the tip or tilt axis is reported as the 1-σ result which is multiplied by 2. At this point the results are re-computed with a 0.1 Hz shift in the input harmonic frequencies. After completing the ±10% the frequency scan either the median (MISE), or max value across that scan is reported as the 2-σ jitter estimate.

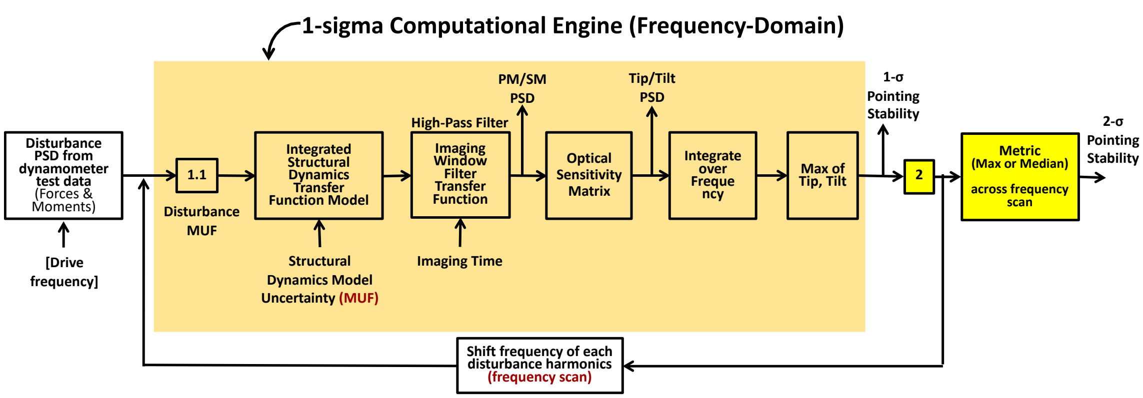


Figure 6 Jitter Analysis Assessment (MISE, MASPEX, HRS Pump)

P95

Reaction wheel disturbances are handled slightly differently than the more steady disturbance sources of the coolers and pumps. Disturbance from the reaction wheels are analyzed over the full range of wheel speeds, however providing an result based on the worst case of 4 wheels all spinning at the same speed was deemed too conservative. A probabilistic metric for the reaction wheel disturbance was chosen to provide a conservative result without designing to a condition that may never happen in flight. The selected metric was to report the jitter estimate as the 2-σ value that covers 95% of all expected wheel speeds (P95). This computation relies on a Monte Carlo analysis that can be seen in Figure 7.

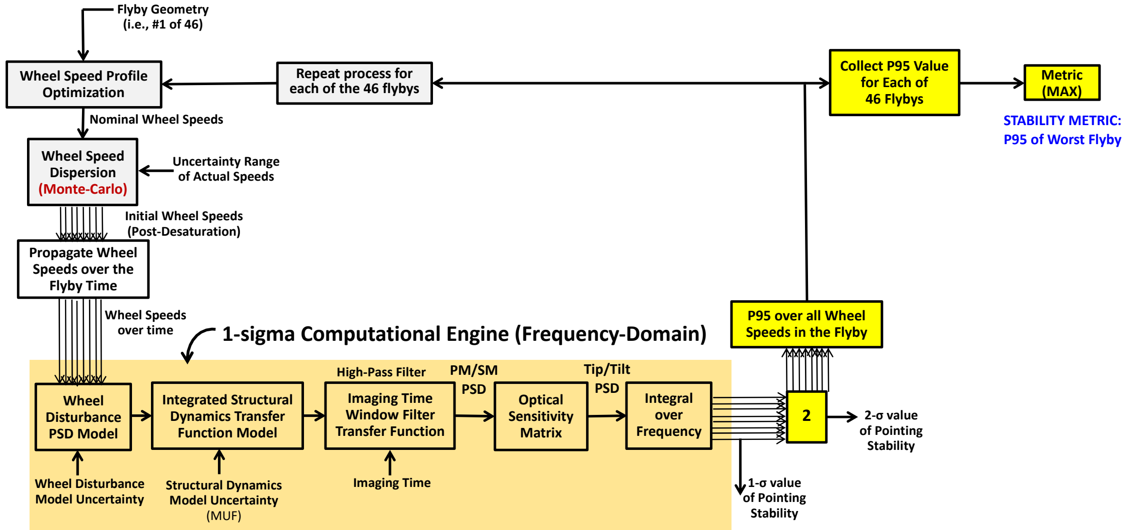


Figure 7 RWA P95 Jitter Metric

The process starts with a nominal spacecraft attitude time history which is used to fine an optimized wheel speed profile. The profile is optimized to keep wheel speeds in a desirable range over the flyby, not necessarily to minimize jitter. The initial wheel speed target is then dispersed to account for uncertainty in achieving the desired target wheel speed. Each of the dispersed initial wheel speeds is propagated through the spacecraft attitude profile for the given science flyby producing a set of wheel speed time histories for all 3 wheels. At this point the frequency domain analysis for the prescribed combinations of wheel speeds is computed, for each time point during the flyby profile and for each profile of the distribution. This process produces a 2-σ estimate for every time step of each profile the 95 percentile (P95) of that data is found for that profile. This Monte Carlo process is repeated for each of the 45 flybys in the science tour and the max P95 value is used to represent the max jitter disturbance expected in flight.

DESIGN CONSIDERATIONS / MITIGATIONS

Aside from improving jitter assessment methodologies there have been a number of design changes implemented to help mitigate the jitter effects. One of the biggest impacts on the jitter was the decision to hold the solar arrays in fixed position for all observation that require medium to tight pointing stability requirements. The large mass of the arrays driven by a stepper motor induced very large disturbances to pointing.

The reaction wheels are one of the larger sources of jitter disturbance affecting the NAC, in addition the reaction wheel also faced challenges from the launch shock environment. For these two reasons an isolation system was incorporated between the reaction wheels and their mounting interface. This isolation was designed to reduce the shock load on the wheels, but also to reduce the disturbance from the higher frequency harmonics that were propagating to the NAC boresight. The preliminary results show significant improvement of jitter from the higher harmonics terms, though wheel imbalance based disturbances in the area of the isolator comer frequency still need to be monitored as they have the potential to interact with the NAC gimbal modes.

Although not currently implementing isolation the coolers and pumps have been considering design changes to reduce the jitter disturbance they produce. The MISE instrument early on accepted the capability to tune the cryocooler drive frequency in flight. There has also been work on the instrument structural design with considerations for transferring the exported forces and torques to the spacecraft interface. The HRS pump is implementing a new impeller design with more blades to help performance, including reducing the exported disturbances. MASPEX has included a re-design of it electronic controller for the cryocooler with expectations of reduced vibration. MASPEX is also considering the cooldown power profile to avoid specific structural interactions.

CONCLUSION

The imaging requirements for the Europa Clipper mission result in jitter requirements that are challenging to meet in concert with other instrument requirements. Preliminary design reviews resulted in focused effort to improve the details of Line-of-Sight jitter assessments. This paper discussed the unique aspects of collecting science observations on the Europa Clipper spacecraft and the challenges in meeting the driving line-of-sight jitter requirements. Our current assessment methodologies were described, outlining the different approaches for in-flight tunable and non-tunable disturbances, as well as the more complex assessment for reaction wheel. We believe that we have reached a process with prudent conservativism that is a good compromise of managing uncertainty while not forcing extraordinary measures. A quick overview of the results from this process was presented in conjunction with some of the mitigation steps that have been taken to ensure that we will meet the required jitter performance. Developing and understanding a new spacecraft destined for Jupiter system, with challenging pointing needs, has required significant negotiation and compromise. Overall we believe that we have developed a process that will help ensure success and guide us in building a system that will meet the science needs.

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