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EVOLUTION OF TRAJECTORY DESIGN REQUIREMENTS ON NASA'S PLANNED EUROPA CLIPPER MISSION

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Abstract

Europa is one of the most scientifically intriguing targets in planetary science due to its potential suitability for extant life. As such, NASA has funded the California Institute of Technology Jet Propulsion Laboratory and the Johns Hopkins University Applied Physics Laboratory to jointly develop the planned Europa Clipper mission—a multiple Europa flyby mission architecture aimed to thoroughly investigate the habitability of Europa and provide reconnaissance data to determine a landing site that maximizes the probability of both a safe landing and high scientific value for a potential future Europa lander. The trajectory design—*a major enabling component for this Europa Clipper mission concept*—was developed to maximize science from a set of eight model payload instruments determined by a NASA-appointed Europa Science Definition Team (SDT) between 2011-2015. On May 26, 2015, NASA officially selected 10 instruments from 6 different U.S. research facilities and universities. With the selection of instruments have come the development of new science measurement requirements, as well as a rich set of requirements stemming from project policies, planetary protection, and the evolved capability and characteristics of the flight system and mission operations system. This paper will focus on the evolution of requirements levied on the trajectory design, discuss strategies and solutions to the multidimensional optimization problem of designing high fidelity end-to-end trajectories that maximize Europa science while mitigating mission risk, complexity and cost, and last, verification of candidate trajectories to meet the requirements on the trajectory design.

Keywords: Mission design, trajectory design, gravity assist, Europa, habitability, optimization

Nomenclature

V_∞	Hyperbolic excess velocity
ΔV	"delta-V" (i.e., change in velocity)
R_J	Jupiter equatorial radius (71,492 km)
TOF	Time-of-flight
LST	Local solar time

Acronyms/Abbreviations

JPL	Jet Propulsion Laboratory
APL	Applied Physics Laboratory
SDT	Science Definition Team
PSD	NASA's Planetary Science Division
AO	Announcement of Opportunity
IPR	Ice-penetrating radar
TI	Topographic imager
SWIRS	Short wave infrared spectrometer
(I)NMS	(Ion) Neutral mass spectrometer
MAG	Magnetometer (x2)
LP	Langmuir probe (x2)
RC	Reconnaissance camera
ThI	Thermal imager
EIS	Europa Imaging System
E-THEMIS	Europa Thermal Emission Imaging System
Europa-UVS	Europa Ultraviolet Spectrograph
ICEMAG	Interior Characterization of Europa using Magnetometry
MASPEX	MAss Spectrometer for Planetary Exploration / Europa
MISE	Mapping Imaging Spectrometer for Europa
PIMS	Plasma Instrument for Magnetic Sounding
REASON	Radar for Europa Assessment and Sounding: Ocean to Near-Surface
SUDA	SUrface Dust Mass Analyzer
JOI	Jupiter orbit insertion
PRM	Periapsis raise maneuver
DSM	Deep space maneuver
DSN	Deep space network
(E)VEEGA	(Earth) Venus-Earth-Earth gravity assist trajectory
SLS	Space Launch System
NRC	National Research Council
PDR	Preliminary Design Review
COT	Crank-over-the-top sequence
SNR	Signal-to-noise ratio
FY	Fiscal year
ELV	Expendable launch vehicle
TID	Total ionizing dose (Si behind a 100 mil Al, spherical shell)

1. Introduction

Data returned by NASA's Galileo spacecraft in the mid-1990's indicated the strong likelihood of a global liquid water ocean beneath Europa's relatively thin ice shell [1-5]. While diminutive in sized compared to Earth, Europa—slightly smaller than our moon—is believed to contain 2–3 times more liquid water than Earth [6,7]. This presumed global ocean, is kept in a liquid state by the perpetual tidal flexing and heating associated with Europa's eccentric orbit around Jupiter, is believed to be in direct contact with a rocky mantle (potentially creating reductants via hydrothermal activity [8]), and is believed to have existed for the better part of the age of our solar system [2,9]. Furthermore, due to the harsh radiation environment Europa resides in, Europa's surface is continuously irradiated, a phenomenon known to create oxidants [10,11]. These postulates, coupled with a geodynamically active ice shell (as is evident from Europa's chaotic terrain void of many craters), could make Europa's ocean a rich source of chemical energy. Thus, planetary scientist's current understanding of Europa points to it potentially possessing the three components (when simultaneously existing in a single environment) that define the necessary, but not sufficient, conditions required for life as we know it to exist: 1) a sustained liquid water environment, 2) a suite of biogenic elements (C, H, N, O, P, S), and, 3) energy sources that could be utilized by life. As such, Europa is one of the most astrobiologically intriguing destinations in our Solar System, and has been the focus of many mission concepts since the end of the Galileo mission [12,13].

Many different mission architectures have been considered for further exploration of Europa, including impactors, flyby missions, sample return, orbiters with and without simple lander combinations, and sophisticated lander-only missions [14-19]. While the vast majority of these mission studies have focused on the latter two architectures—under the premise that these platforms would be the most conducive to performing the key Europa observations and measurements necessary to significantly advance our knowledge of Europa—the Europa Clipper Mission, a multiple flyby mission concept, has been developed jointly by the Jet Propulsion Laboratory (JPL) and the Applied Physics Laboratory (APL), and has been shown to offer many advantages in cost, risk, and science value and volume over the other aforementioned architectures [20, 21].

The Europa Clipper mission concept is predicated on the developed capability [22-25] to obtain global-regional coverage of Europa (i.e., data sets at the regional scale, distributed across Europa globally) via a complex network of flybys while in Jupiter orbit. The mission concept focuses *strictly on investigating Europa*; hence, the spacecraft would either be taking Europa data, downlinking Europa data, calibrating instruments to maintain/improve Europa data quality, or executing tasks to setup the next Europa flyby.

2. Science and Reconnaissance Objectives

The overarching goal of the Europa Clipper mission concept is to investigate the habitability of Europa. Per NASA's Astrobiological Roadmap, a habitable environment "must provide extended regions of liquid water, conditions favorable for the assembly of complex organic molecules, and energy sources to sustain metabolism" [26]. From 2011-2014, a NASA-appointed Europa Science Definition Team (SDT) derived a set of scientific objectives that include confirming the existence of an ocean, characterizing any water within and beneath Europa's ice shell, investigating the chemistry of the surface and ocean, and evaluating geological processes that might permit Europa's ocean to possess the chemical energy necessary for life. These SDT derived science objectives were consistent with Europa-specific objectives recommended by the 2011 Decadal Survey [27], and can be categorized in priority order as:

1. ***Ice Shell and Ocean**:* Characterize the ice shell and any subsurface water, including their heterogeneity, ocean properties, and the nature of surface-ice-ocean exchange.
2. ***Composition***: Understand the habitability of Europa's ocean through composition and chemistry.
3. ***Geology***: Understand the formation of surface features, including sites of recent or current activity, and characterize high science interest localities.

The Europa SDT emphasized the need for obtaining simultaneous complementary data sets at Europa in order to best address these driving goals and objectives, and the need to obtain global-regional data sets. Both requests drive the mission design, with the latter levying the requirement to accomplish regional-scale remote sensing measurements (with sufficient coverage and resolution) in at least 11 of the 14 roughly equal-area "panels" distributed across Europa's surface (Fig. 1).

In addition to performing high caliber science investigations at Europa, NASA also strongly desires that the next Europa mission enable a future lander mission. This desire stems from the likelihood of a landed mission being the next step in exploring Europa, and current data does not provide sufficient information to identify landing site hazards (in order to design a lander to maximize the probability of a safe landing), nor the ability to discern location(s) of the highest scientific value. Therefore, in consultation with the Europa Clipper study team and NASA, the Europa SDT developed two reconnaissance objectives emphasizing engineering and science, respectively:

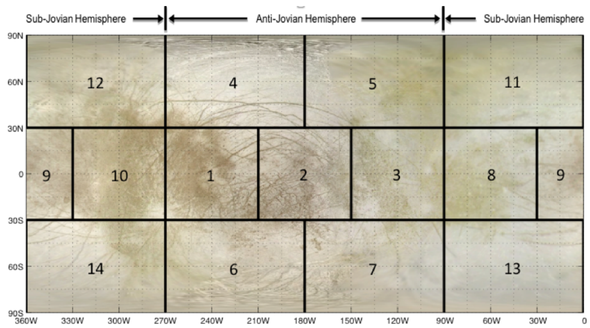

Figure 1: *Cylindrical projection map of Europa, centered on the satellite's anti-Jupiter point. Europa is tidally locked, resulting in the same hemisphere always face toward Jupiter (sub-Jovian) or away from Jupiter (anti-Jovian). The 14 numbered panels are utilized to assess "global-regional" coverage.*

1. ***Site Characterization***: Assess the distribution of surface hazards, the load-bearing capacity of the surface, the structure of the subsurface, and the regolith thickness.

2. ***Scientific Value***: Assess the composition of surface materials, the geologic context of the surface, the potential for geologic activity, the proximity of near-surface water, and the potential for active upwelling of ocean material.

3. Model Instrument Payload

The SDT-derived model payload was chosen as a best attempt to maximize the capability to efficiently achieve high quality science and reconnaissance from a multiple flyby mission architecture. Furthermore, the model payload was necessary to quantify and analyze all engineering aspects of the mission concept including the trajectory design, spacecraft design, and scenarios associated with operating the spacecraft in the intense radiation environment near Europa.

The Europa Clipper model payload consists of eight instruments, plus a gravity science investigation that would utilize the spacecraft's telecommunications hardware. Specifically, the model payload includes: Ice-Penetrating Radar (IPR), Short Wave Infrared Spectrometer (SWIRS), Topographical Imager (TI), Neutral Mass Spectrometer (NMS), two magnetometers (MAG), two Langmuir probes (LP), Reconnaissance Camera (RC), and Thermal Imager (ThI).

3.1 Model Payload Measurement Requirements

A total of 111 science measurement* requirements were developed by the SDT. Figure 2 summarizes the model payload instrument-specific breakdown both in terms of total requirements and requirements specific to trajectory design or the mission plan. Table 1 summarizes the 71 science requirements (64% of total science requirements) levied on the trajectory design from the model payload in terms of geometric constraints and cumulative coverage, which were used to guide the design (and subsequent evaluation) of a number of multiple Europa tour designs. Iteration between the Mission Design Team and the SDT culminated with the 13F7 trajectory [24], the trajectory released with the Europa instrument Announcement of Opportunity in July 2014 [28].

For a complete mapping of the scientific objectives to the model payload, please refer to the science and reconnaissance traceability matrices [29], and Buffington 2014 [24] for a comprehensive description of the 13F7 trajectory.

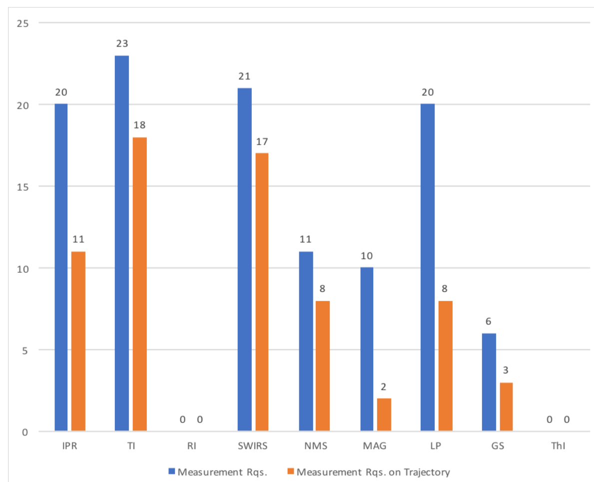

Figure 2: *A per instrument breakdown of the 111 model payload measurement requirements and the 71 measurement requirements specific to the mission design.*

4. NASA Selected Instrument Payload

On May 26, 2015, NASA officially selected 10 instruments from 6 different U.S. research facilities and universities [30]. The NASA selected instrument suite is aimed to not only meets the original set of SDT-derived Europa science objectives, but to exceed them. Specifically, the selected instrument payload contains two addition instruments not included in the model payload (i.e., a dust analyser and UV spectrograph), and in conjunction with other enhanced capabilities of the selected payload (when compared to their model payload counterpart), significantly enhances the capability to actively search for plumes emanating from the surface of Europa. Evidence of Europa plumes was first published in 2014 (after the Europa SDT had been disbanded) by

*A measurement requirements is defined as a requirement that quantitatively specifies observations needed to support a given Level-2 science requirement.

Table 1. *SDT derived science requirements on the trajectory design.*

	Instrument		Velocity (km/s)	Altitude (km)	Viewing Geometry	Coverage
Floor	IPR	Deep	< 6	≤ 1000	Groundtrack lengths ≥ 1600 km	Distributed in 11 of 14 panels with ≥ 3 groundtracks in each anti-Jupiter panel and ≥ 2 groundtracks in each sub-Jupiter panel. Each groundtrack must intersect another below 1000 km (intersection may lie outside panel of interest)
		Shallow		≤ 400	Groundtrack lengths ≥ 800 km	
	SWIRS		< 6	≤ 66,000	Local solar time between 9:00 and 15:00	≥ 70% of Europa at better than 10 km/pixel ~100 representative landforms at better than 300 m/pixel distributed across 11 of 14 panels All reconnaissance sites at better than 300 m/pixel
	Topographical Imager			≤ 4000	Required: Incidence angles in the range of 20° to 80° and solar phase angle ≤135° Desired: Incidence angles in the range of 45° to 70° and solar phase angle ≤135°	Stereo imaging spanning radar ground tracks ≥ 70% of Europa at better than 1 km/pixel ≥ 25% of Europa at better than 250 m/pixel
	NMS		< 7	≤ 200 (lower is better)	Within 10° of spacecraft ram direction when below 200km.	Global distribution
Baseline	Magnetometer			< 1561	N/A	Flybys distributed across a range of orbital phases and System III longitudes (better than each 45° of longitude)
	Langmuir Probe			< 1561	N/A	Same as MAG
	Gravity Science			≤ 100	Highest value: Repeat equatorial flybys along the Jupiter-Earth line. Spacecraft must not be occulted ± 18 Europa radii from closest approach. Avoid flybys near solar conjunction.	Flybys distributed across a range of orbital phases, especially near Europa's periapsis and apoapsis
Recon.	Reconnaissance Camera			≤ 50	Required: Incidence angles in the range of 20 to 80° Desired: Incidence angles in the range of 45° to 70°	Required: At least 15 2x10 km images at better than 0.5 m/pixel Desired: At least 15 5x10 km images at at better than 0.5 m/pixel
	Thermal Imager			≤ 1000	10:00 to 15:00 local solar time	All reconnaissance sites at better than 250 km/pixel
				≤ 60,000	3:00 to 6:00 and 10:00 to 15:00 local solar time	Selected reconnaissance sites at better than 15 km/pixel

Roth *et al.* utilizing Hubble Space Telescope (HST) Space Telescope Imaging Spectrogrpah (STIS) observations [31], and has been supported by subsequent HST observations [32-34].

Figure 3 shows the mapping from the model payload instruments to the selected instruments, and Figure 4 shows the selected instrument locations on the spacecraft [35]. The selected instruments are described in detail in the following sub-sections [35].

4.1: Europa Imaging System (EIS)

EIS is a dual-system camera, consisting of a wide-angle camera (WAC) and a narrow-angle camera (NAC). The EIS science objectives include the investigation of geologic structures and processes, correlation of surface features with subsurface structure and possible water, studying the ice shell thickness and ocean interface, and identifying scientifically-compelling landing sites, as well as producing digital terrain models for use in decluttering REASON data. The measurement requirements consist of imaging the moon in the visible spectral range, including near-global coverage at 50-m resolution or better for 95% of the surface.

The WAC has a field of view (FOV) of 48º cross-track and 24º along-track, and a 210 μrad iFOV (which corresponds to a resolution of 10.5 m/pixel at a 50 km altitude), can operate in either a monoscopic mode or a pushbroom stereo mode, and has 6 filters for color imaging.

The NAC has a FOV of 2.3º by 1.2º, and is mounted on a 2-axis gimbal with a 60º range of motion in each axis. The gimbaled design enables significantly more coverage of Europa without changing the orientation of the spacecraft (that would otherwise adversely affect other instruments observations). The NAC has a 10 μrad iFOV, and hence has the ability to produce 0.5 m/pixel stereo imagery at an altitude of 50 km.

4.2 Europa Thermal Emission Imaging System (E-THEMIS)

E-THEMIS will detect and characterize thermal anomalies on the surface that may indicate recent active venting or resurfacing on Europa. It will also determine the regolith particle size, block abundance, and sub-surface layering for landing site assessment and surface process studies, and it would identify active plumes.

The E-THEMIS FOV is 5.7º cross-track by 4.3º along-track. E-THEMIS can image the Europa's surface at a resolution of 5 x 22 m (including spacecraft motion) from a 25-km altitude, has a precision of 0.2 K for 90 K surfaces and 0.1 K at 220 K, and with an accuracy of 1-2.2 K from 220-90 K. The instrument will obtain images with up to 360 cross-track pixels with a 10.1-km wide image swath from 100 km.

4.3 Europa Ultraviolet Spectrograph (Europa-UVS)

Europa-UVS will investigate the composition and chemistry of Europa's atmosphere and surface, and study how energy and mass flow around the moon and its environment. In addition, the Europa-UVS instrument has the capability to actively hunts for, and uniquely characterizes, plumes erupting from Europa's surface.

The instrument is a sensitive imaging spectrograph that can observe in a spectral range of 55 nm to 210 nm

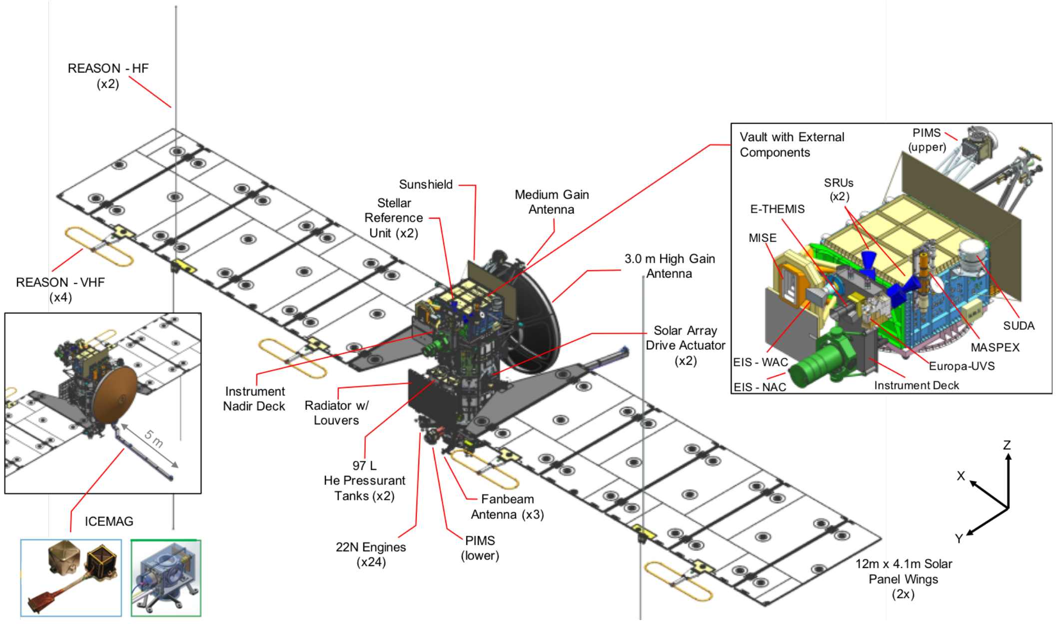

Figure 4: *The spacecraft configuration (A7) with* selected *payload accommodated.*

and can achieve a spectral resolution of <0.6 nm full width at half maximum for a point source and a spatial resolution of 0.16º through its airglow port and 0.06º through its high spatial resolution port (both ports are co-boresighted). Europa-UVS also has a separate solar port (off-set 40º from the other ports to be utilized for solar occultations. The instrument does not contain a scan mirror, so the spacecraft must provide the pointing capability necessary to obtain complete spatial images of Europa.

4.4 Interior Characterization of Europa using Magnetometry (ICEMAG)

ICEMAG is a four-sensor magnetometer composed of 2 flux gate (FG) sensors and 2 scalar-vector helium (SVH) sensors. The sensors are mounted along a 5-m long boom extending from the spacecraft (Fig. 4). ICEMAG will measure the magnetic field near Europa, which is induced by Europa's movement through Jupiter's strong rotating magnetic field. Measuring the induced B-field of Europa over multiple frequencies will constrains the ocean and ice shell thickness to ±2 km, and ocean conductivity to less than ±0.5 S/m. ICEMAG measures the magnetic field with an accuracy better than 1.5 nT in all three axes.

ICEMAG's data will be used in conjunction with the Plasma Instrument for Magnetic Sounding (PIMS) measurements to better isolate the induced magnetic field from other field components caused by plasma in the Europa ionosphere.

4.5 MAss Spectrometer for Planetary Exploration/ Europa (MASPEX)

MASPEX is a neutral mass-spectrometer that will determine the chemical composition, distribution and density variations of major volatiles and key organic compounds of the Europa atmosphere and exosphere. The instrument contains a multi-bounce time-of-flight mass spectrometer with a closed ion source, pulsers, a detector, and associated electronics. MASPEX will be able to classify particles of masses in the range 2 – 1,000 Daltons at a mass resolution (which varies with integration time) of 7,000 to 24,000.

4.6 Mapping Imaging Spectrometer for Europa (MISE)

MISE acquires data for spectral analysis of the composition of the surface of Europa, including the presence of organic compounds, acid hydrates, salts, and other materials germane to assessing the habitability of the Europan ocean. MISE will also investigate the geologic history of Europa and characterization of currently-active geologic processes. The instrument has an iFOV of 250 μrad (full angle), corresponding to images with better than 25 m/pixel resolution at an altitude of 50 km.

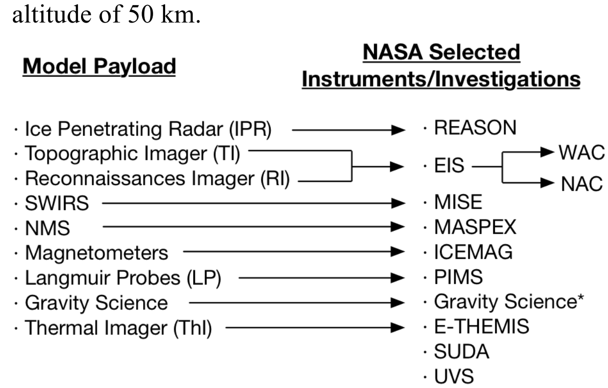

Figure 3: *Mapping from SDT-derived model payload to the NASA-selected instruments. (*Note: Gravity Science was not selected at the same as the rest of the payload).*

MISE has a spectral range of from 800 to 5,000 nanometers with a spectral resolution of 10 nm. It has a FOV of 4.3º in cross-track, and from 0.75º to 4º (one pixel) in along-track. It also has a ±30◦ along-track scan mirror. Lastly, to maintain the detector at the necessary cryogenic temperatures, the instrument must use a cryocooler.

4.7 Plasma Instrument for Magnetic Sounding (PIMS)

PIMS will measure the density, flow and energy of ions and electrons during the spacecraft's entire orbit around Jupiter, with the highest value science being near Europa. This instrument works in conjunction with ICEMAG and is key to determining Europa's ice shell thickness, ocean depth, and ocean salinity by correcting the magnetic induction signal for plasma currents around Europa, thereby enabling precise magnetic sounding of Europa's subsurface ocean.

PIMS is composed of two sensor heads, each hosting two Faraday cups (FCs), each with a 90-degree FOV, measuring the 1.5-dimensional velocity distribution function (VDF; a 1-D reduced distribution function plus vector flow angles as a function of energy/charge) of ions and electrons.

PIMS has two data acquisition modes; magnetospheric and ionospheric. The former allows the measurement of electrons with energies of 10 eV – 2 keV and ion energies in the range 20 eV – 7 keV. In the latter mode, detection of electrons and ions in the energy range 1 – 50 eV is possible. It has an energy resolution of 10% ΔE/E, and a sensitivity of 0.5 pA/cm^2 – 105 pA/cm^2.

4.8 Radar for Europa Assessment and Sounding: Ocean to Near-Surface (REASON)

REASON's science objectives are to characterize the distribution of shallow subsurface water and structure of the ice shell; search for an ice-ocean interface; and correlate surface features, subsurface structures, and geological processes. REASON is a dual-frequency sounder with a 60-MHz band with 10-MHz bandwidth for shallow sounding, and a 9-MHz band with 1-MHz bandwidth for deep sounding. REASON's 60-MHz band is divided into two receiving channels for interferometry to remove clutter along the off-nadir portions of the swath. This technique reduces or removes the need for supporting cross-track topography imaging. Projected REASON performance capabilities include 10-m vertical resolution depth sounding from 300 m to 4.5 km, and 100-m vertical resolution from 1 to 30 km.

4.9 SUrface Dust Mass Analyzer (SUDA)

SUDA detects and characterizes small particles in the atmosphere around Europa, allowing an analysis of the composition of the particles ejected from the surface of the moon. SUDA can capture up to 40 particles per second at closest approach. The instrument measures not only the density and composition of particles, but also the velocity, allowing backtracking to the originating surface position of materials, and thus to a mapping of the surface composition.

4.10 Gravity Science

The objective of the gravity science investigation is to determine the amplitude and phase of Europa's gravitational tides in order to confirm the presence (or absence) of a global subsurface ocean beneath Europa's ice crust. The Gravity Science experiment requires maintaining a 2-way link (at X-Band) with Earth during Europa flybys. While geometric constraints preclude the co-boresighted high gain antenna (HGA) and medium gain antennas (MGAs) from maintaining a continuous link to Earth while the instrument deck remains nadir pointed during Europa flybys, three fanbeam antenprovidnas have been strategically placed on the spacecraft (two of the three antennas were already needed for inner-cruise communications) to provide wide angle coverage in the spacecraft Y-Z plane for the Europa flybys that provide the most advantageous geometry for gravity science [36].

4.11 Selected Payload Measurement Requirements

As previously stated, the selected payload is a much more capable suite of instruments than the model payload, both in terms of total number of instruments (8 vs. 10), and in performance capability when compared to their model payload counterpart (Fig. 3). This increased capability has resulted in an increase in the number of science datasets per instrument, and not surprisingly, has corresponded to an increased number of science measurement requirements. Figure 5 gives a per investigation breakdown of the 378 baseline science requirements. Of the 378 total science requirements, 211 are levied on the mission design (i.e., trajectory design and mission plan) (Fig. 6). The remaining measurement requirements are, self-derived requirements on their own instrument performance (i.e., sensor SNR, sample rate capabilities, sensor wavelength range, etc.), the Flight System (i.e., magnetic cleanliness, pointing stability, outgassing, etc.), the Project System (prioritization of data, in-flight alignment characterization, etc.) and a handful of other project elements.

From Figure 6, it's very clear the majority of the science requirements are levied on the mission design, and represent a 3-fold increase in science requirements when compared to the model payload. Hence, while the simpler and lower total number of model payload requirements could be distilled into Table 1, a different construct was needed to understand how measurement requirements related to one another in order to effectively inform future trajectory designs (i.e., maximize the number of measurements met) and validate science

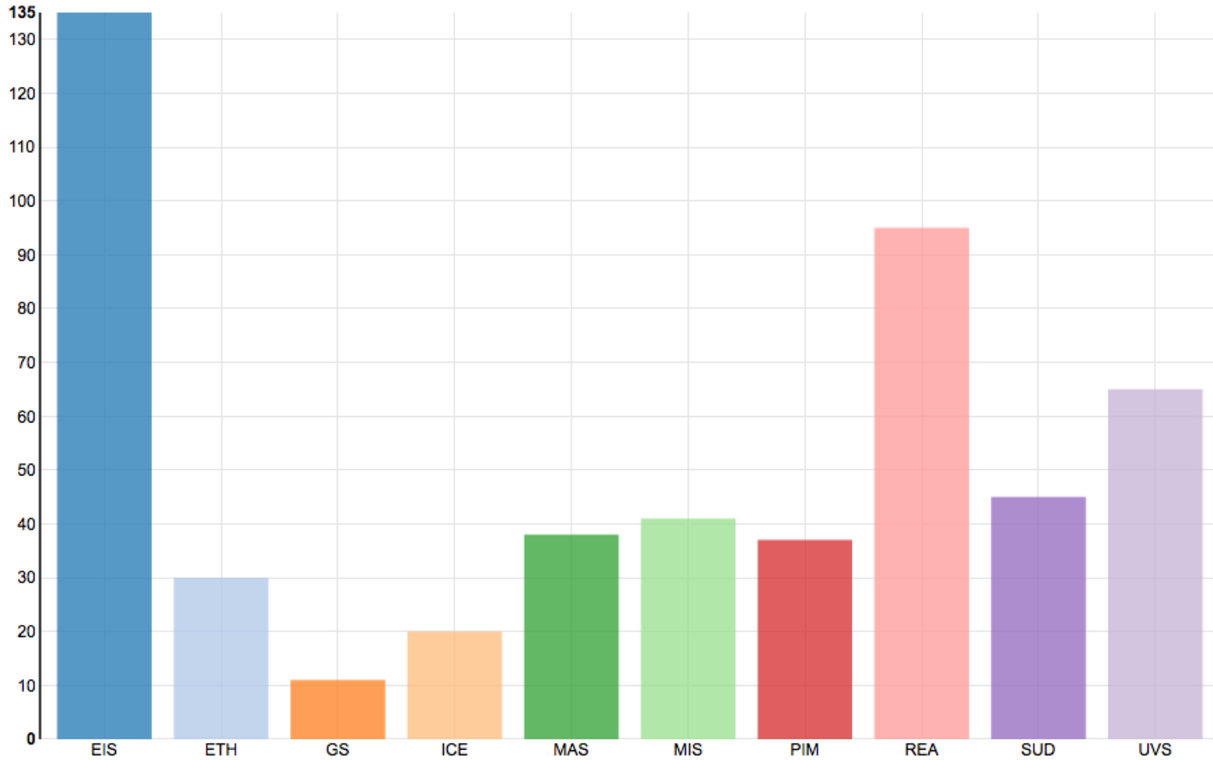

Figure 5: *Science measurement requirements broken down by investigation.*

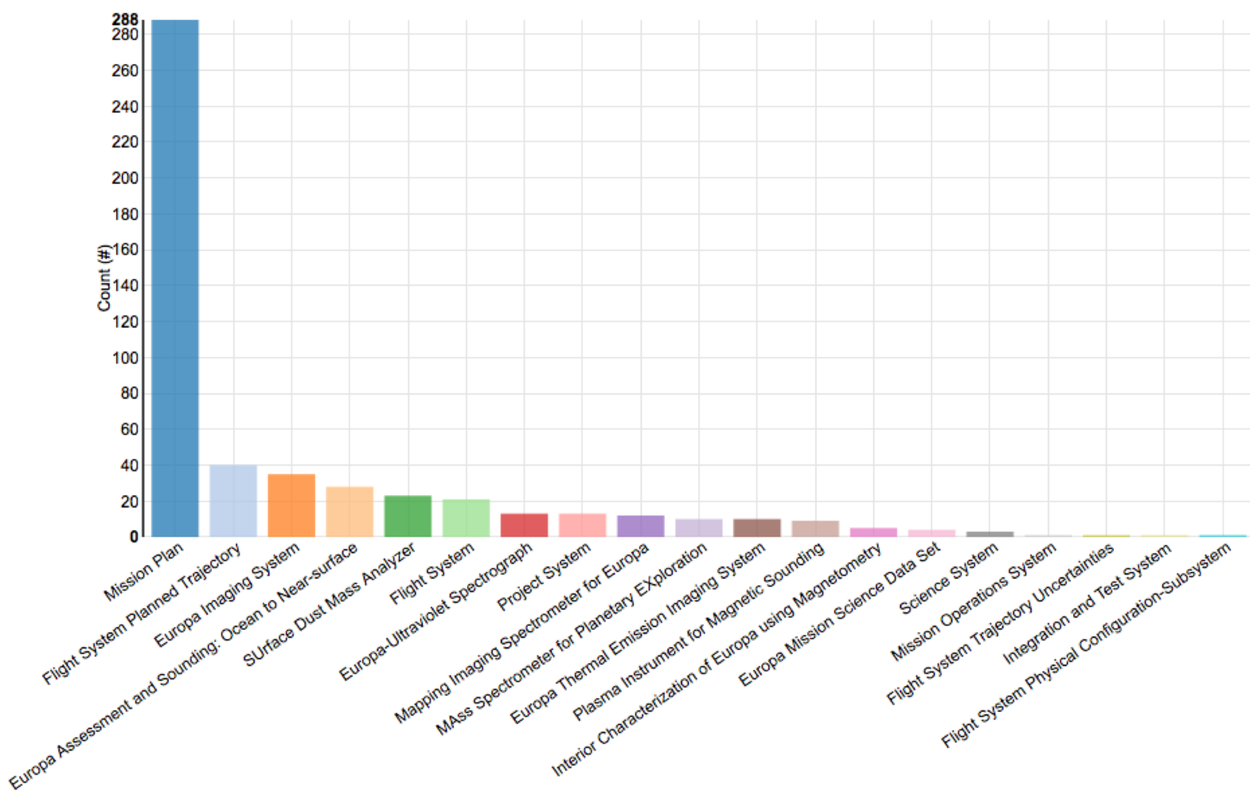

Figure 6: *Science measurement requirements broken down by specified element.*

requirement compliance for a given candidate reference trajectory.

In a completely separate task spearheaded by two Europa Clipper payload instrument engineers (Sara Susca and Laura Jones-Wilson), a framework for writing and linking related measurement requirements on the Europa Clipper Project began development in 2015 [37]. This novel approach, referred to as measurement-domain science traceability and alignment framework (or, M-STAF), provided a common construct that was used to ensure consistency across all instruments, completeness in the coverage of the requirements, and traceability of the engineering work to the Level-2 science objectives. The output of this extensive exercise (beyond a complete set of measurement requirements that *fully specifies* the measurements needed to fulfill each instrument dataset) was a set of instrument-specific M-STAF matrices. These matrices serve as a compact way of conveying the complete set of measurement requirement where each cell is a shorthand version of a single requirement and each row represents a different observation that contributes to a given science dataset [37]. Figure 7 exhibits the M-STAF for MISE.

Leveraging off the M-STAF matrices, a set of mission design-centric visualizations for each instrument have been created. These visualizations capture the requirements that are needed to develop new or modify existing trajectory design strategies, and clearly convey which datasets share common conditions describing the configuration of the spacecraft and planetary bodies when observations will be collected. Armed with the complete set of these visualizations, a mission designer can now easily gauge complexity of each instrument's datasets, compare between different instruments, and utilize them as maps to develop trajectories that best accomplish the cumulative set of science requirements—something not easily done with a list consisting of 211 prose science measurement requirements. Lastly, these visualizations serve as pseudo-code for the requirement verification and validation (V&V) process.

To complement the MISE M-STAF (Fig. 7), the MISE trajectory-centric science measurement visualization is shown in Figure 8. The remaining instrument trajectory-centric science measurement visualizations can be found in Appendix A.

4.11 Non-Measurement Requirements on Mission Design

The overarching goal when designing trajectories for any NASA Science Mission Directorate (SMD) funded mission is to maximize the number of high-quality scientific observations and measurements derived from the mission-specific science requirements. However, in order to mitigate mission cost and risk, the cost function of trajectory design optimization must also include minimizing propellant expenditure and adhering to operational, spacecraft, and environmental constraints [38]. These constraints are manifested on the trajectory as requirements as the capability and limitations of the spacecraft, payload, ground system and mission operations system designs evolve. These requirements, are summarized in Table 2.

5. Trajectory

5.1 Trajectory Design Strategy

Europa orbits Jupiter in a region of intense radiation, the result of Jupiter's strong magnetosphere collecting and accelerating charged particles. As such, spacecraft near Europa will be bombarded by radiation, a detriment to on-board electronics and instrumentation. To counter this harsh environment, shielding—in the form of aluminum, titanium, tantalum or other metals—are needed to surround sensitive electronics.

The key design strategy of the Europa Clipper mission concept is, while in orbit *around Jupiter*:

1. Quickly dip into the harsh radiation environment to collect a large volume of Europa data (remote sensing observations and *in situ* measurements)

2. Escape the intense radiation environment such that the majority of the transfer time to the next Europa flyby will be available to downlink data sans radiation dose accumulation

3. Repeat steps 1 and 2 to systematically build-up a network of Europa flybys to obtain global-regional coverage of Europa.

This "store and forward" approach (i.e., collect, store, and eventually downlink data) offers many advantages of over previously conceived Europa orbiter mission architecture, including, a higher total data return, the utilization of higher powered instruments (the spacecraft does not have to simultaneously operate instruments and a high-power telecom system), simpler mission operations, and a mission timeline more immune to spacecraft anomalies and capable of reacting to potential discoveries.

5.2 Baseline Trajectory for PDR: 17F12_V2

The current baseline trajectory for the Europa Clipper mission concept that will be used for all sub-system and project Preliminary Design Reviews (PDRs) is 17F12_V2 [39]. The 17F12_V2 trajectory has very similar attributes to previous Europa Clipper trajectories. The trajectory sub-phase can be seen graphically in Fig. 9 and summarized as follows:

Pump-down: Utilization of four outbound Ganymede flybys to reach the correct Europa flyby conditions (specifically, the relative velocity and illumination of the

MISE																	
Science Dataset				Science Observation					Measurement Requirements								
				Conditions									Measurement Quality				
Science Theme		Meas. Class	Technique	Altitude @ Meas	Range to Target	S/C Ground Speed @ CA	Local Solar Time	Sun-Target-S/C Angle	Spatial Coverage and Distribution	Temporal Coverage and Distribution	Diversity and Special Case	Internal Correlations	Pixel Scale @ Altitude	Spectral Range and Resolution	Spectral Contrast	Cube Size	Pixel Scale Over Dwell Time
Global-Scale Compositional Surface Mapping		Infrared Imaging Spectroscopy	Scanning	Altitude between TBR [1200] km and TBR [40,000] km (MIS.013)		<TBR [5] km/sec (MIS.007)	TBR [9:00] to TBR [15:00] (MIS.006)		>=TBR [70]% of surface (MIS.009)		>= TBR [90]% within a circle of TBR [15] deg radius centered at 270 degree E (MIS.011) >=TBR [90]% within a circle of TBR [15] deg radius centered at 90 degree E (MIS.012)		<=10 km @ TBR [40,000] km (MIS.010)	0.8 to 5.0 um (MIS.001) Sampling <= 10 nm from 0.8 microns to 2.6 microns. (MIS.004) Sampling <=16 nm from 2.6 microns to 5 microns. (MIS.005)	1% of the continuum from 0.8 microns to 2.6 microns (MIS.002) 2.5% of the continuum at greater than from 3.2 microns to 5.0 microns (MIS.003)		+/- 0.5 pixel scale (3 sigma) over the dwell time between TBR [125] km and TBR [40,000] km (MIS.008)
Landform Composition		Infrared Imaging Spectroscopy	Scanning	Altitude between TBR [125] km and TBR [1,200] km (MIS.023)		<TBR [5] km/sec (MIS.007)	TBR [9:00] to TBR [15:00] (MIS.006)		>=50 cubes (MIS.017)		Center point of >=1 cube within a circle of TBR [15] deg radius centered at 270 degree E (MIS.019) Center point of >=1 cube within a circle of TBR [15] deg radius centered at 90 degree E (MIS.020) Center point of >=1 cube above TBR [70] deg N or S (MIS.021)		<=300 m @ TBR [1,200] km (MIS.018)	0.8 to 5.0 um (MIS.001) Sampling <= 10 nm from 0.8 microns to 2.6 microns. (MIS.004) Sampling <=16 nm from 2.6 microns to 5 microns. (MIS.005)	1% of the continuum from 0.8 microns to 2.6 microns (MIS.002) 2.5% of the continuum at greater than from 3.2 microns to 5.0 microns (MIS.003)	>TBR [85] km along by >TBR [85] km cross @ 1200 km (MIS.022)	+/- 0.5 pixel scale (3 sigma) over the dwell time between TBR [125] km and TBR [40,000] km (MIS.008)
Landform Composition	Local-Scale Surface Properties	Infrared Imaging Spectroscopy	Scanning	Altitude <= TBR [125] km (MIS.028)		<TBR [5] km/sec (MIS.007)	TBR [9:00] to TBR [15:00] (MIS.006)		>= TBR [30] features (MIS.024)		>=1 landform above TBR [70] deg N or S (MIS.027)		<=50 m @ TBR [125] km (MIS.025)	0.8 to 5.0 um (MIS.001) Sampling <= 10 nm from 0.8 microns to 2.6 microns. (MIS.004) Sampling <=16 nm from 2.6 microns to 5 microns. (MIS.005)		>TBR [1.5] km along by >TBR [7] km cross @100 km (MIS.026)	
Surface Thermal Anomaly Search		Infrared Imaging Spectroscopy	Scanning	Altitude <TBR [40,000] km (MIS.016)		<TBR [5] km/sec (MIS.007)	18:00 to 6:00 (MIS.015)		>= TBR [22] cubes (MIS.014)				<= 10 km @ TBR [40,000] km (MIS.016)	0.8 to 5.0 um (MIS.001) Sampling <= 10 nm from 0.8 microns to 2.6 microns. (MIS.004) Sampling <=16 nm from 2.6 microns to 5 microns. (MIS.005)			+/- 0.5 pixel scale (3 sigma) over the dwell time between TBR [125] km and TBR [40,000] km (MIS.008)
Inferred Plume Evidence		Infrared Imaging Spectroscopy	Scanning		<=4,000 km range to target (MIS.032)			between 160 deg and TBR [175] deg (MIS.030)					<1km @ range-to-target 4,000 km (MIS.029)	0.8 to 5.0 um (MIS.001) Sampling <= 10 nm from 0.8 microns to 2.6 microns. (MIS.004) Sampling <=16 nm from 2.6 microns to 5 microns. (MIS.005)			

Figure 7: *MISE M-STAF [37].*

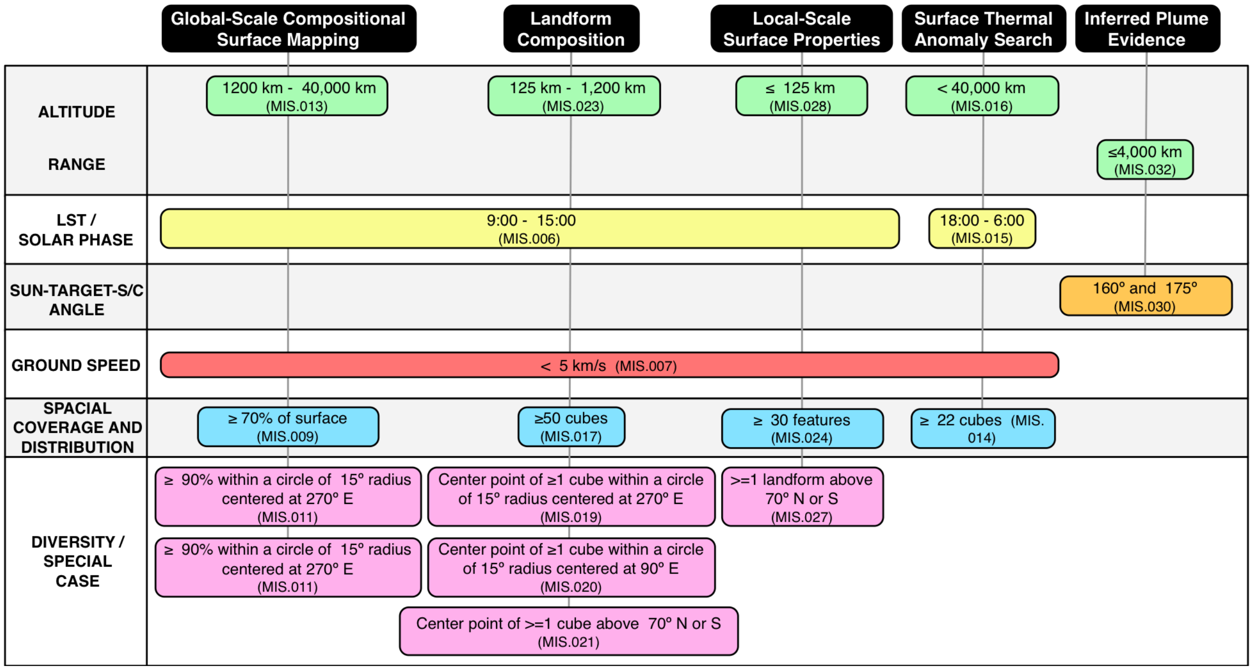

Figure 8: *MISE science requirements on trajectory design.*

anti-Jupiter hemisphere of Europa) to begin Europa Campaign 1.

COT-1 and COT-2: A series of 13 low altitude Europa flybys that cover the illuminated anti-Jovian hemisphere over a wide range of latitudes, with a high number of groundtrack crossings below 1000 km, and two flybys over Thera and Thrace.

Petal Rotation: A sequence of alternating non-resonant Europa-to-Europa transfers designed to obtain three sets of repeat equatorial groundtracks over panel 1 and 3 (Fig. 1) at different true anomalies (highest value for gravity science). This sequence of flybys also rotates the Europa flyby location CCW, moving the sub-solar point close to Europa's trailing hemisphere.

Switch-Flip: A series of Europa and Callisto transfers to move the Europa flybys to the opposite side of Jupiter, rendering the sub-Jupiter hemisphere of Europa illuminated.

COT-3 and COT-4: A series 12 low altitude Europa flybys that cover the illuminated sub-Jovian hemisphere over a wide range of latitudes, with a high number of groundtrack crossings below 1000 km.

COT-5: A series of 5 Europa flybys the cover the now night side of Europa to obtain coverage of the same terrain both lit and unlit for E-THEMIS (see Fig. A.1).

There are a number of key differences between 17F12_V2 previously published tours [22, 24-25].

1. A pump-down sequence that is robust to JOI over-/under-burn of up 50 m/s has been built in [40]
2. During the switch-flip setup, the Europa flyby closest approaches were placed in the in southern hemisphere in order to maximize the probability of encountering potential plumes detected by HST [31-34].
3. A fifth crank-over-the-top sequence (COT) consisting of Europa night-side closest approaches.
4. An adjusted number of 25 km Europa flybys to strike balance between remote sensing and in-situ requirements

Table 3 summarizes the key statistics of the 17F12_V2 trajectory. For much more detail on the 17F12_V2 trajectory, please stay tuned for a future paper to be written and published in early 2018 by Lam et al. [41].

Table 2: *All requirements on the trajectory design, excluding science measurement requirements.*

	Requirement Subject	Required/Constrained Value	Where Documented
Project	Launch Year	2022-2025 Prime Opportunity: 2022 Backup Opportunity: 2023	DRM Guidebook [39] RQ102.107 RQ104.453
	Launch Vehicle	SLS Block 1B Delta IV Heavy	RQ102.142 RQ104.459
	Mission Lifetime	Flight System: 11.1 years Spacecraft: 11.3 years	RQ100.040 RQ102.100
	Mission ΔV	≤1726 m/s	RQ100.025 RQ102.102
	Chemical Propulsion	Utilize chemical propulsion for all propulsive ΔV	RQ102.134
	Communication During Key Events - Mission Activities	SEP angle >3°, Earth in view	RQ102.129
	Solar Conjunction Activity	No maneuvers or targeted flybys when SEP angle < 5°	RQ105.440
Launch and Interplanetary Trajectory	Interplanetary Trajectory	Earth-Jupiter Direct EVEEGA	RQ102.139 RQ104.457
	Launch Period Duration	≥21 days	RQ107.245
	Launch Window	>30 minutes per day	RQ105.437
	TCM-1 Timing for ΔV Computation	ΔV necessary for TCM-1 at Launch + 30 days	RQ103.374
	Earth Occultations During Interplanetary Cruise	Permitted	RQ103.338
	Solar Eclipses During Interplanetary Cruise	Permitted	RQ103.340
	Probability of Mars impact by Flight System	≤1x10^-2 (for 50 years post-launch)	RQ102.207
	Planetary Flyby Approach TCM Timing	≥3 days	RQ105.438
	Planetary Flyby Departure TCM Timing	≥5 days	RQ105.439
	Minimum Earth Flyby Altitude	300 km	RQ102.966
	MicroMeteroids/Orbital Debris (MMOD) Impact Risk	≤ 0.01 probability when within 40,000 km of Earth (objects ≥10 cm in diameter)	RQ104.478
	Minimum Venus Flyby Altitude	1500 km	RQ102.124
	Minimum Perihelion	0.65 AU	RQ102.131
	Maximum Aphelion	5.6 AU (during TEC1) 5.46 AU (at end of prime mission)	RQ102.125 DRM Guidebook [39]
Jupiter Orbit Capture and Pump-down	Minimum Jupiter Distance	6 R_J (no Io gravity assist)	RQ102.097
	JOI-Assisting Jupiter Moon Flybys	≤ 2 prior to JOI	RQ103.342
	Earth Occultations During JOI-Related Jupiter Moon Flybys	Permitted	RQ103.343
	Solar Eclipses During JOI-Related Jupiter Moon Flybys	Not permitted prior to JOI completion	RQ103.339
	Maximum JOI ΔV	950 m/s	RQ104.549
	Jupiter Capture Orbit Period	≤260 days	RQ103.381
	JOI Sun-Earth-Probe (SEP) Angle	>3° for [-15 days, +12 days] centered at JOI	RQ105.435
	Pump Down Resilience to JOI Variations	Europa-1 (E1) maintained for JOI +/-50 m/s	RQ105.442
	Earth-Jupiter Direct Trajectory Arrival Date Variation – Tour Compatibility	≤5 months, E1 arrival conditions maintained	RQ103.382
Tour	Maximum TID	3.0 Mrad(Si) behind spherical shell of 100 mils Al	RQ102.034 RQ102.104
	Communication During Flybys & Maneuvers	SEP >3° for +/-4 days from targeted flybys and maneuvers	RQ104.449
	Minimum Jovian Moon Flyby Altitude	≥20 km (99% confidence)	RQ102.220
	Probability of Callisto Impact	≤1x10^-3 (during the prime mission)	RQ106.785
	Probability of Ganymede Impact	≤1x10^-3 (during the prime mission)	RQ106.786
	Probability of Europa Impact at Europa Closest Approach Minus 5 Days	<10^-6	RQ102.118
	Pre-Flyby OTM Timing	≥3 days (from closest approach)	RQ102.224
	Post-Flyby OTM Timing	≥2 days (from closest approach)	RQ102.221
	Minimum Europa-Europa Transfer Duration	10 days	RQ105.448
	Minimum Galilean Satellite to Galilean Satellite Transfer Duration	5 days	RQ105.449
	Maximum Eclipse Duration	9.2 hrs. (prior to EC2) 3.25 hrs. (After TEC2)	RQ102.038 RQ102.140
	# Europa Encounters	60	DRM Guidebook [39]
	# Galilean Satellite Encounters	73	DRM Guidebook [39]
Disposal	Disposal Impact Target	Io, Ganymede, or Callisto	RQ102.130
	Flight System Disposal Duration	≥30 days, ≤60 days; (with SEP>3°), post last Europa flyby	RQ102.089

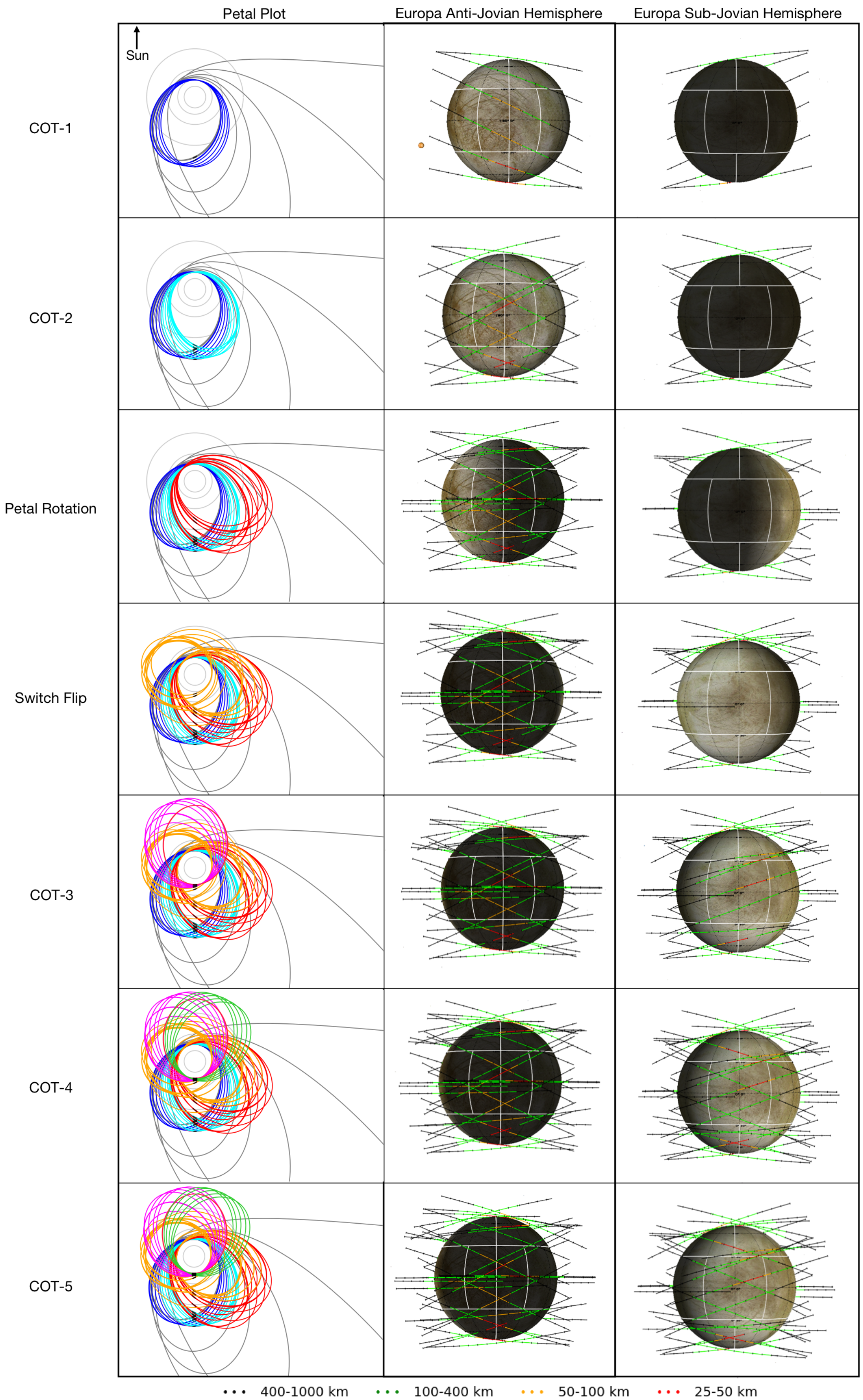

Figure 9: *Europa global-regional coverage build-up for the 17F12_V2 trajectory. Europa-centered trajectories are color contoured by altitude (see legend).*

Table 3: *17F12_V2 tour statistics.*

Tour	17F12_V2
Launch Date	6/4/22
Arrival Date	12/23/24
Tour Duration (years)[1]	3.7
Number of Flybys[2]	
Europa	46
Ganymede	4
Callisto	9
No. of Jupiter Orbits[1]	70
Time between Flybys (days)	
Maximum	229
Minimum	5.4
Minimum (Europa-to-Europa)	10.1
Deterministic ΔV, post-PRM (m/s)	182
Total Deterministic ΔV (m/s)	1,305
Maximum Inclination (deg.)	18.9
No. of Jupiter Eclipses	47
Maximum Eclipse Duration (hours)	9.15
Total Ionized Dose (Mrad)[3]	2.5

(1) From **G0** to EOM (last Europa flyby)
(2) Includes last Europa flyby necessary to set-up Callisto impact
(3) Calculated using **GIRE-2p** model from **G0** to the end of the Prime Mission (last Europa flyby); **Si** behind 100 mil **Al**; spherical shell

6 Requirements Verification

The requirements summarized in Table 2 can be verified by inspection or with simple one-off scripts, however, verification of the cumulative set of science measurement requirements—often involving the verification of a number of separate requirements before compliance (or non-compliance) can be ultimately be determined—required the development of an entirely new tool.

6.1 Measurement Requirement Verification Tool

VERITaS (Verification of Europa Requirements Integrating Tour and Science) is a tool that has been developed specifically to assess compliance with science measurement requirements for the Europa Clipper mission. VERITaS also has the capability to estimate the margin with which each requirement is, or is not, met, using a timeline of activities from APGen (Activity Plan Generator). APGen uses activity-scheduling rules applied to a specific trajectory to produce a timeline of activities that represents the project's best understanding of the planned operations profile (.csv file). More generally, VERITaS can take input from any tool that is able to generate a simple instrument timeline, making it robust to potential planning software changes or additions in the future.

VERITaS is built in MATLAB to perform the analysis of each measurement using the M-STAF matrices. As discussed earlier, the M-STAF connects the measurement requirements together and maps them to specific science themes (e.g., ocean properties). A custom-built sensor coverage tool, also built in MATLAB, is utilized to determine the coverage achieved by remote sensing instruments using the APGen-generated timeline to determine valid observation times and technique types (e.g., framing image or pushbroom). JPL's SPICE toolkit is used natively throughout VERITaS and the coverage tool, providing confidence in the necessary frame transformations and geometric calculations. Its use also enables a single set of data files describing the trajectory, frames, solar system ephemeris, and spacecraft attitude to be easily used and shared with other teams within the project.

The integration of VERITaS into the mission planning workflow has allowed for rapid turn-around times for assessing requirement compliance in the face of changing flight system behaviors, hardware capabilities (e.g., agility), and new trajectories. The tool has dramatically increased the quality of communication between mission planning, trajectory design, and the instrument teams, leading to refinements of science measurement requirements, instrument behaviors, and tweaks to trajectories. Additionally, VERITaS has been key to evaluating trades on the science return impact of different flight system fault-response implementations. The ability to ingest fault timelines [42] for any instrument is built into the foundation of VERITaS, as depicted in Fig. 10.

6.2 Measurement Requirement Verification - 17F12_V2

A a summary of the current state of science measurement requirements compliance is shown in Fig. 11. As can be seen in Fig. 11, approximately 71% of the science measurement requirements have been checked, and of those, 81% are met by the 17F12_V2 trajectory. The majority of the requirements that have not be check yet do have enough information to be check, the code has simply not written yet. Only a minor number or requirements (8 reqs., 4.6%) do not currently have enough information to evaluation. These requirements stem from yet to be determine terms such as "sites," landforms," and or spacecraft operations concept not yet approved (i.e., Europa-UVS solar occultations). Lastly, the 23 requirements that currently aren't being met are (as well as any future requirements assessed to be non-compliant) are being investigated to understand if a modification(s) to a future trajectory design can afford enough opportunities to meet the requirement, the concept of operations needs to be modified to fully take advantage of opportunities already present in the trajectory to meet the requirement, or that the requirement is simply over constraining and needs to be modified.

Lastly, Fig. 12 shows an example graphical output that is part of a 155-page (and counting) report provide to the project to fully understand how and when each measurement requirement is/is not being met.

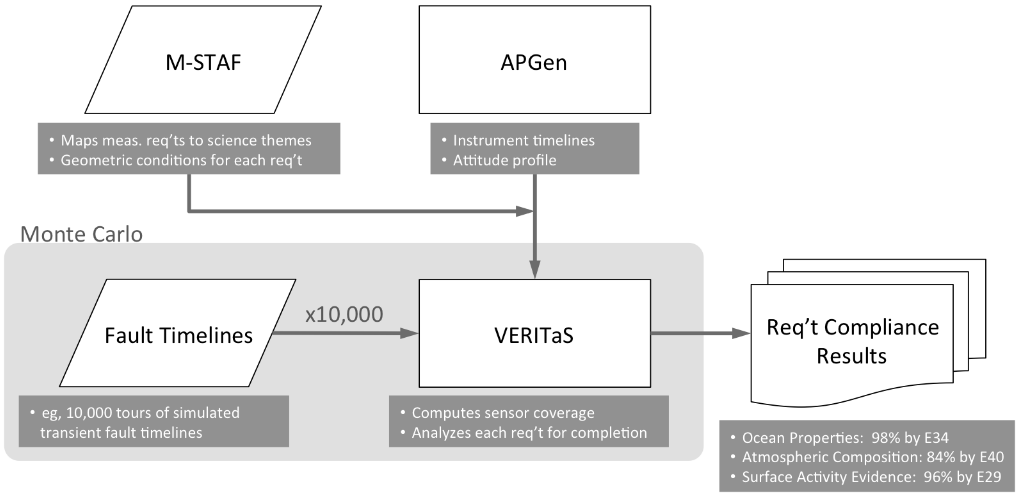

Figure 10: *Flowchart depicting inputs and outputs of VERITaS. Highlights the use of the tool with the injection of simulated fault timelines to assess margin and robustness on requirements.*

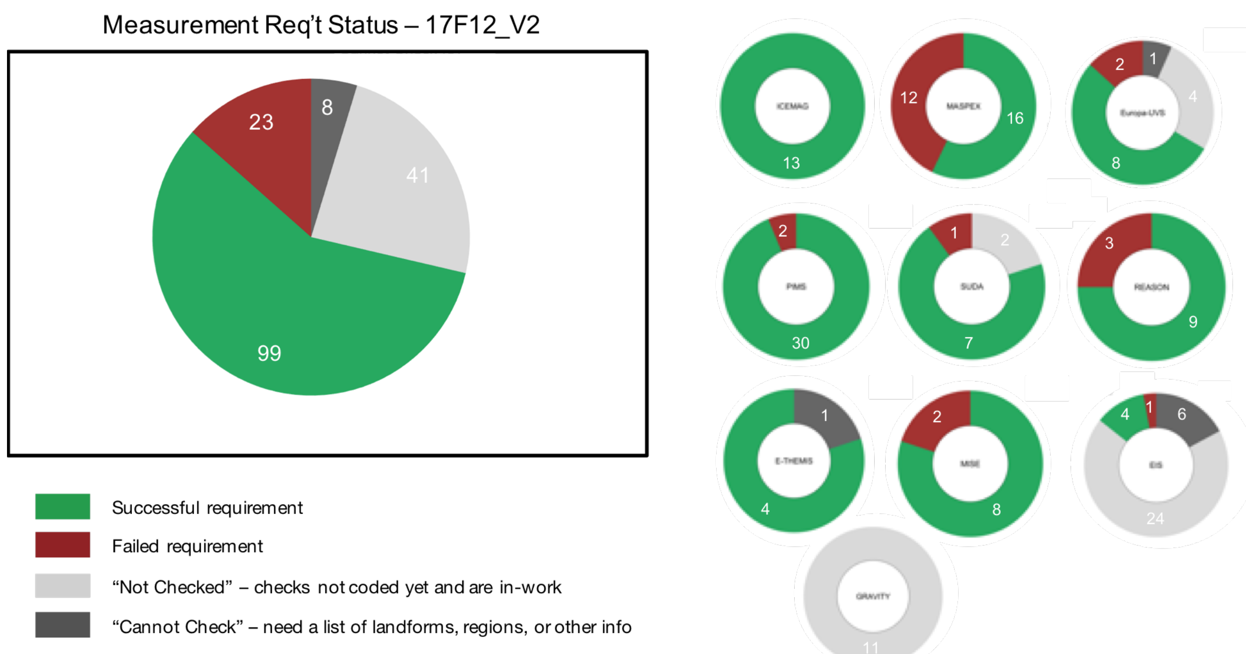

Figure 11: *VERITaS requirements status for the 17F12_V2 trajectory as of 29-Aug-2017.*

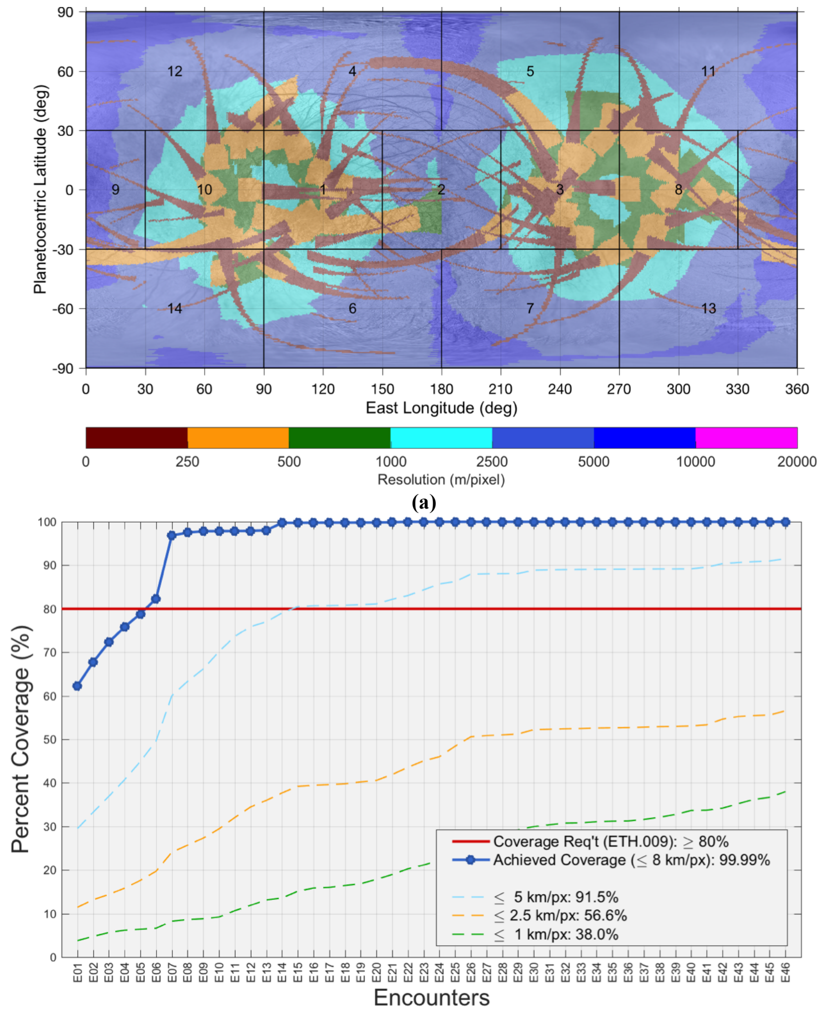

Figure 12: (a) *Achieved coverage resolution contour plot, and, (b) accumulations plot of ETHEMIS observations over the course of the mission. Local Solar time and emission angle geometry conditions were placed on coverage assessment (ETH.009).*

8. Conclusions

The planned Europa Clipper mission continues to progress through formulation. On May 26, 2015, NASA HQ selected the science instrument payload that consisted of both a higher number of instruments (8 vs. 10), and increased performance capability when compared to their model payload counterpart. This, coupled with a better and more in-depth understanding of the science investigations, and the evolved design of the flight system and mission system, have led to a 3x increase in requirements on the trajectory design. In response, a set of highly useful visualizations have been developed that allow mission designers to easily parse and digest the large set of science measurements requirements. Armed with the complete set of these visualizations, a mission designer can now easily gauge complexity of each instrument's datasets, compare between different instruments, and utilize to develop trajectories that best accomplish the cumulative set of science requirements.

In addition, the VERITaS tool has been developed specifically to assess compliance with science measurement requirements for the Europa Clipper mission, and has been used to exhibit the 17F12_V2 trajectory meets a high number science measurement requirements that have been assessed to date. Once all measurement requirements have been assessed in VERITaS, the requirements that aren't met will be investigated to understand if a modification(s) to a future trajectory design can afford enough opportunities to meet the requirement, the concept of operations needs to be modified to fully take advantage of opportunities already present in the trajectory to meet the requirement, or that the requirement is simply over constraining and needs to be modified. This complete requirements assessment should lead to a strong showing at the Project PDR in August of 2018.

Acknowledgements

The authors would like to acknowledge and extend their gratitude to Alek Kezhner for the development of an online interactive tool that enables users to easily view, manipulate, synthesize and export project requirements stemming from the Europa Clipper system model (i.e., the single source of truth with the most current information). This tool has, and continues to be, instrumental in efficiently querying requirements, and visualizing their associated statistics (see Figs. 5 and 6), to better understand requirement relationships and relative importance. The authors would also like to thank Sara Susca and Laura Jones-Wilson for developing a new path for mapping L1 and L2 science requirements to a *complete* set of science measurement requirements. The products of this novel approach, the instrument specific M-STAF matrices, were an enabling component to the development of the trajectory-centric science measurement requirement visualizations and serve as the input data source for VERITaS.

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

Appendix A: Science Requirements on Trajectory Visualisations
(Note: Black squares represent science datasets)

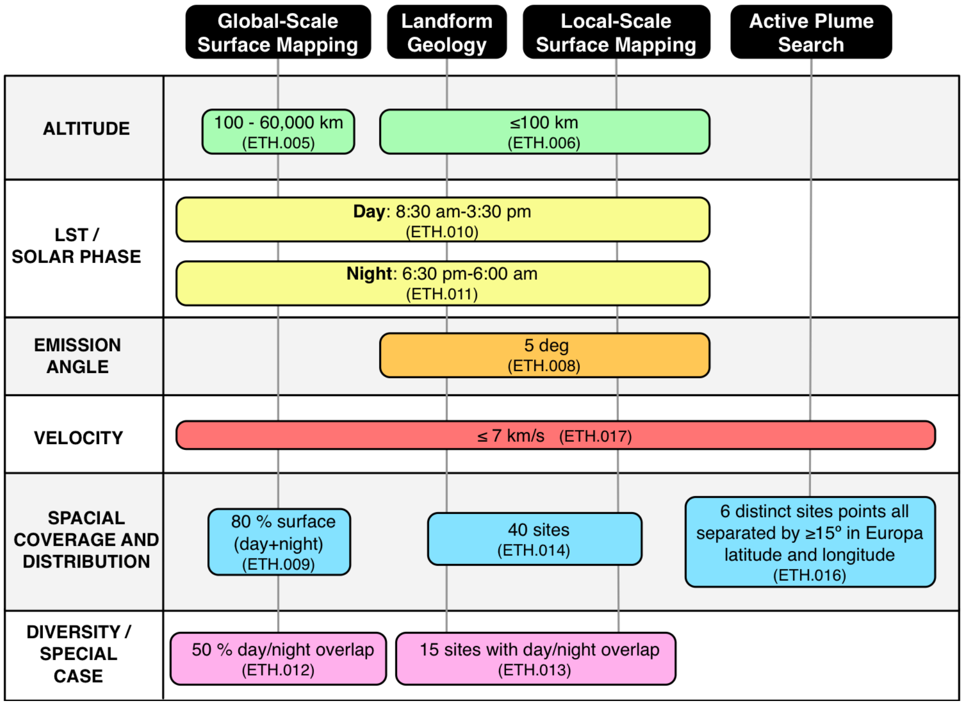

Figure A.1: *ETHEMIS science requirements on trajectory design.*

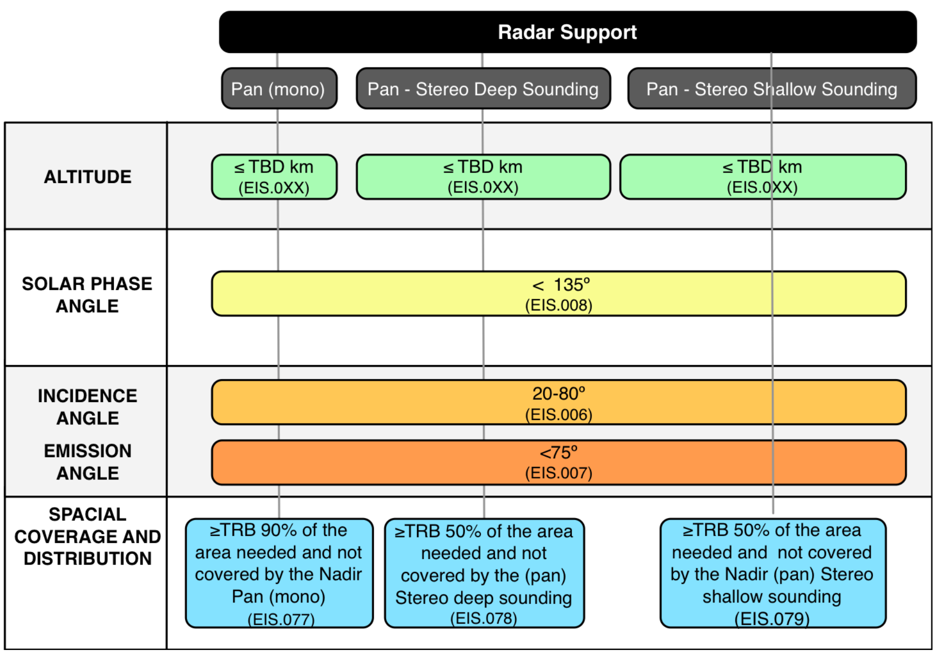

Figure A.2: *EIS (for REASON) science requirements on trajectory design.*

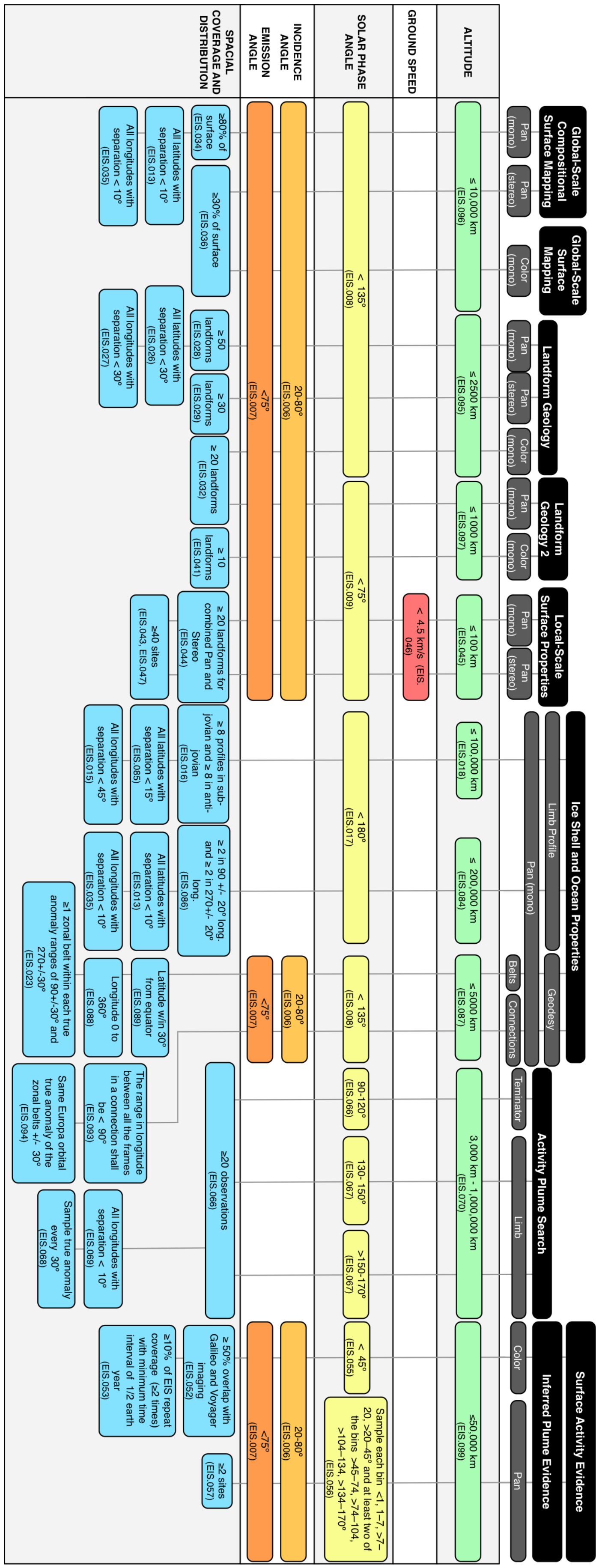

Figure A.3: *EIS science requirements on trajectory design.*

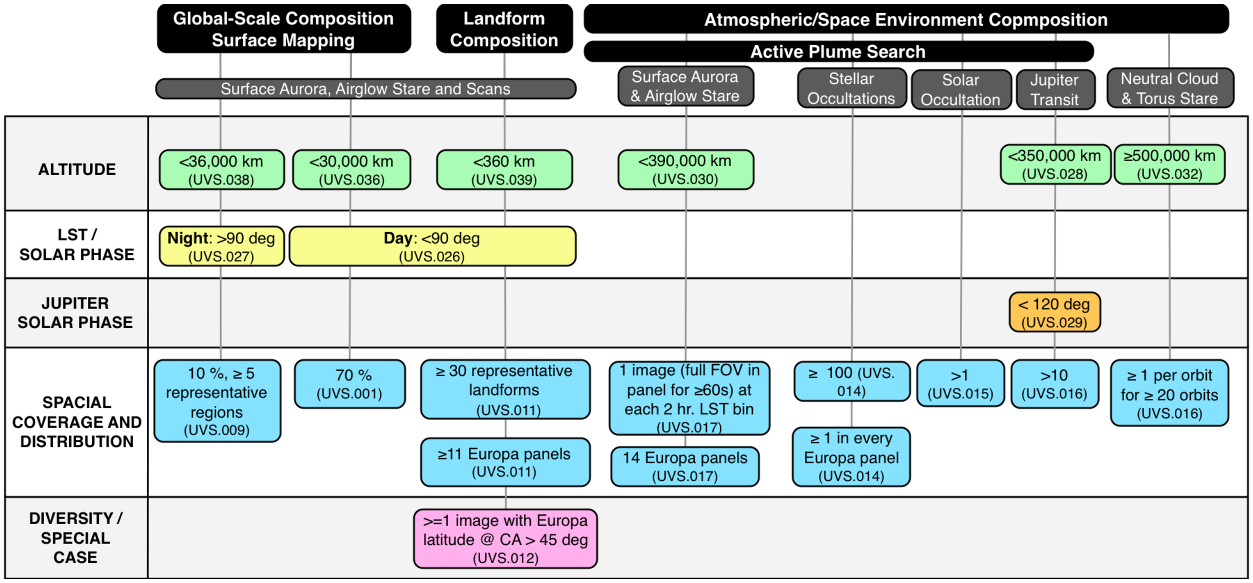

Figure A.4: *Europa-UVS science requirements on trajectory design.*

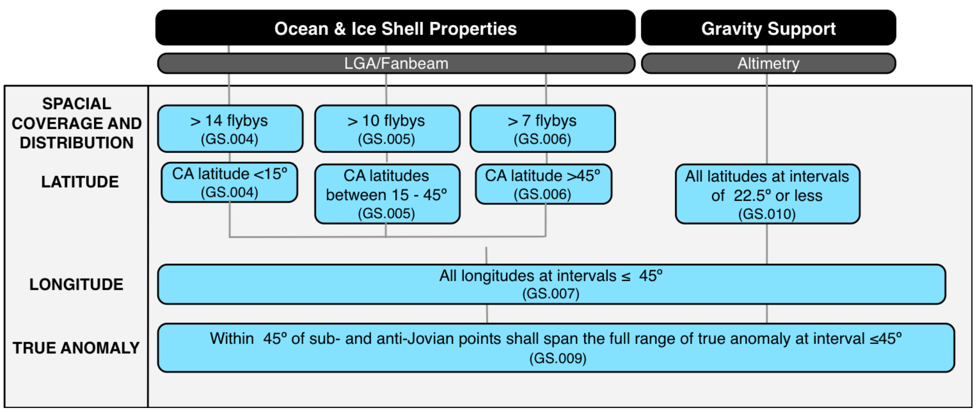

Figure A.5: *Gravity Science science requirements on trajectory design.*

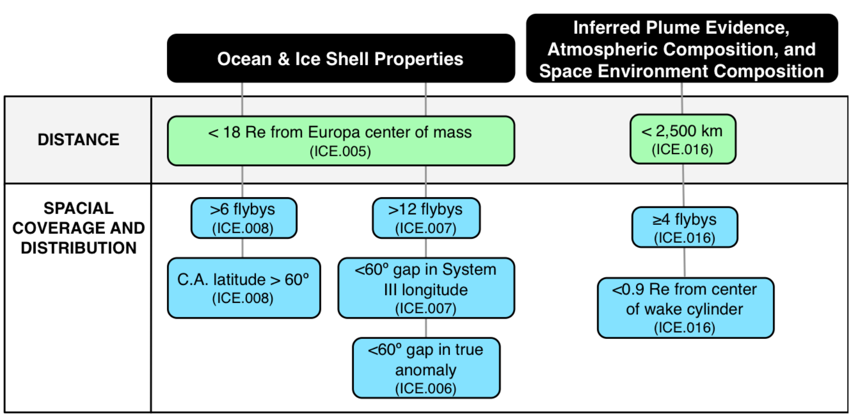

Figure A.6: *Magnetometry science requirements on trajectory design.*

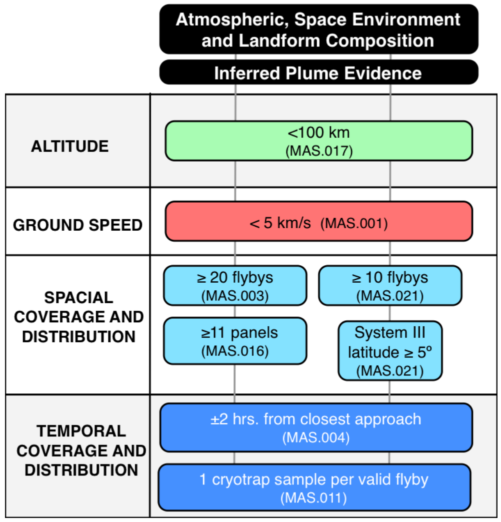

Figure A.7: *MASPEX science requirements on trajectory design.*

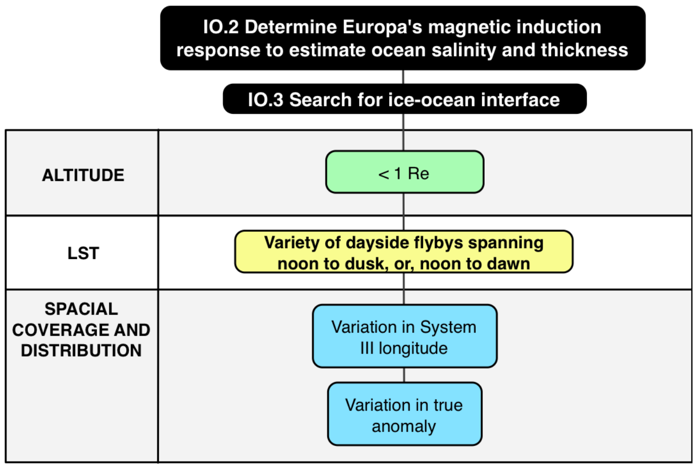

Figure A.8: *PIMS science requirements on trajectory design.*

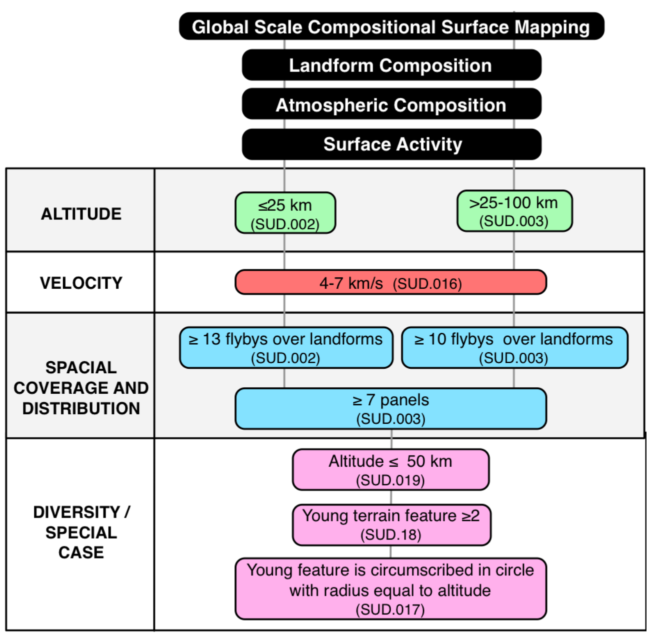

Figure A.9: *SUDA science requirements on trajectory design.*

s

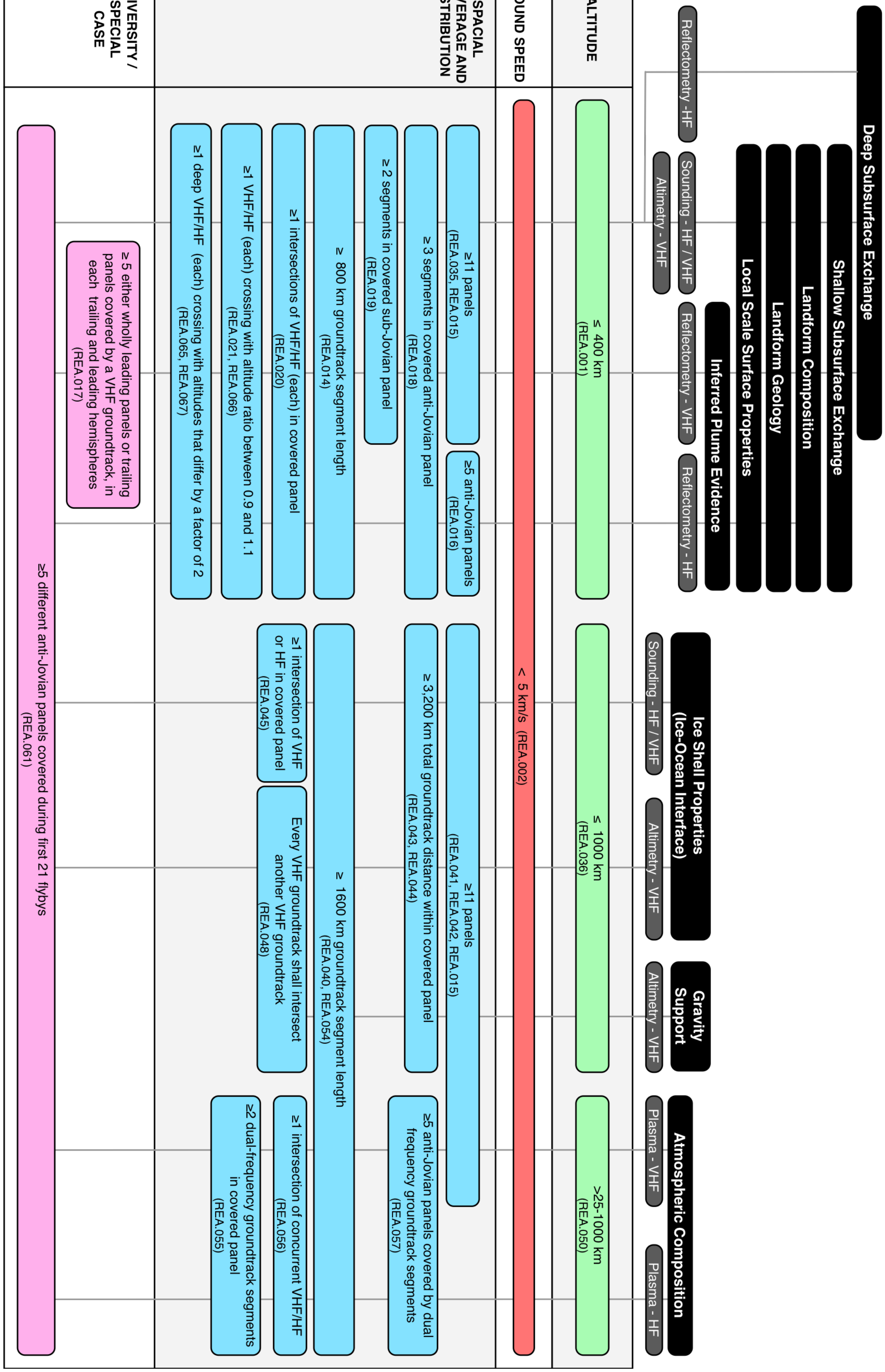

Figure A.10: *REASON science requirements on trajectory design.*

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