EuROpA

Operability Engineering for the Europa Clipper Mission: Formulation Phase Results and Lessons

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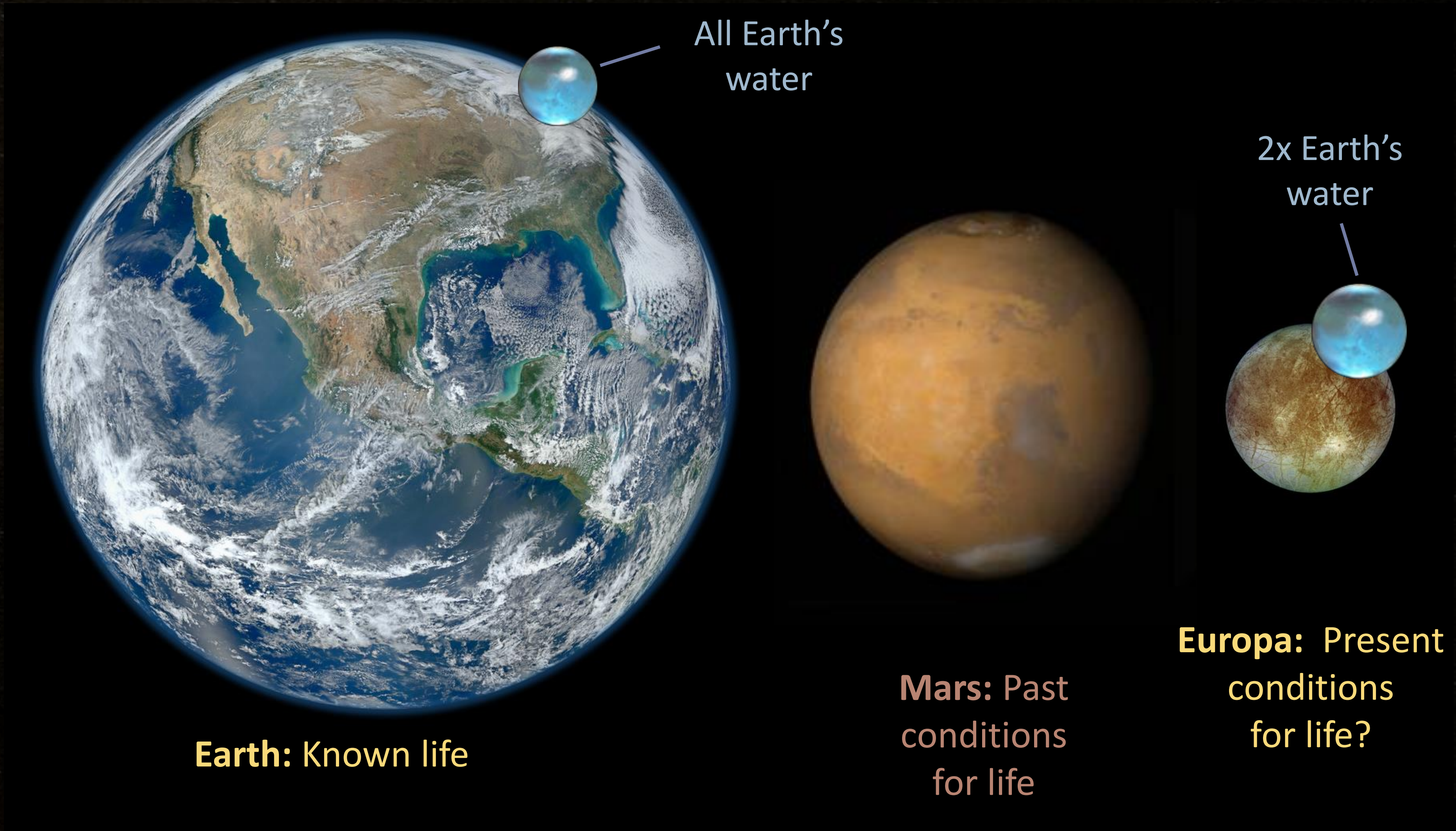
5/31/18

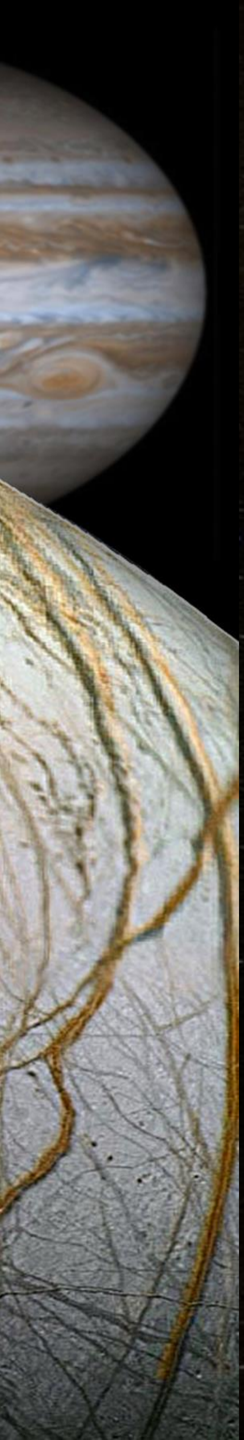
Outline

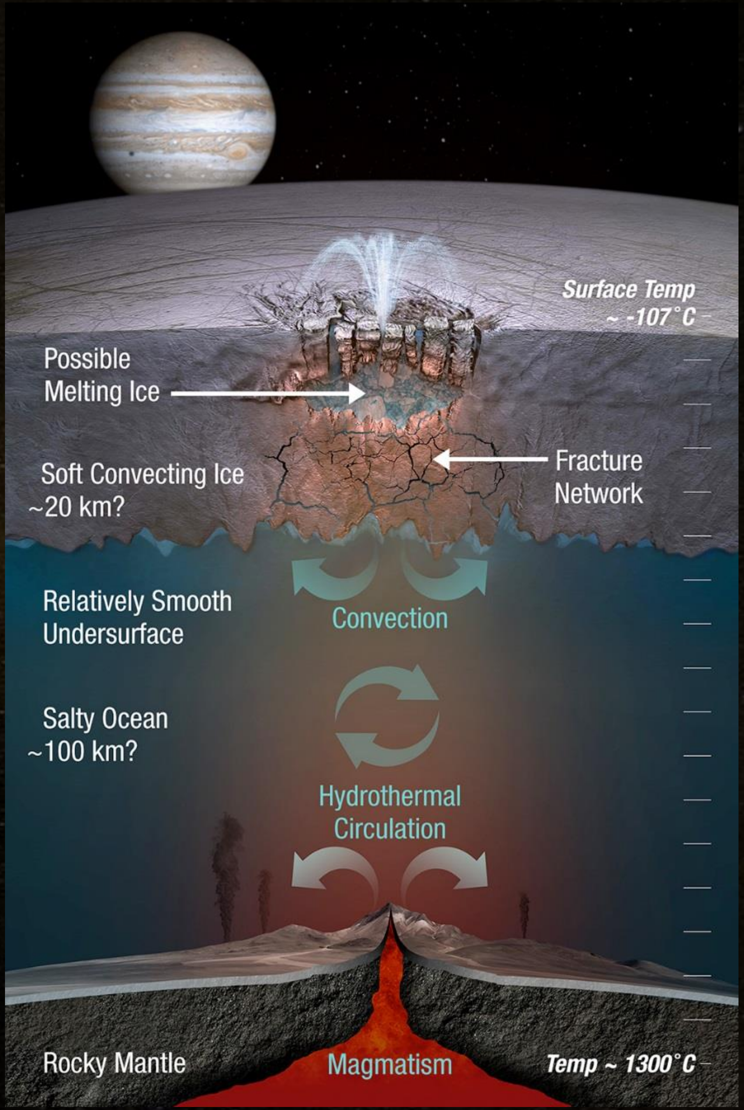
- Mission and Flight System Overview
- What is Operability?
- Operability on Europa Clipper
  - mission characteristics that drive need for operability
  - management-directed focus
  - aspects of operability
  - operability requirements
  - involvement in trades, design decisions, scenarios
  - operability assessment
- Lessons Learned

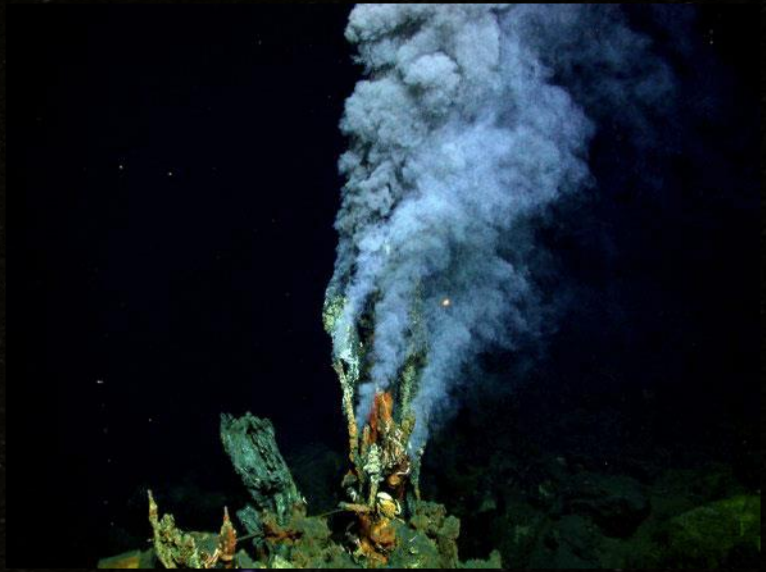
Europa—Water World



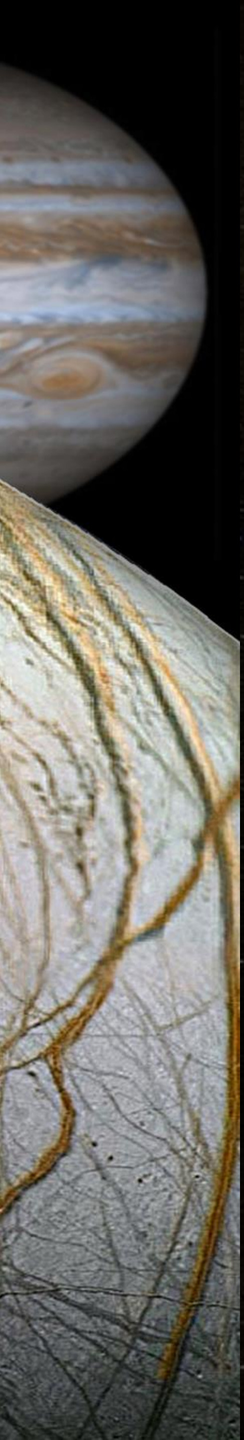
Habitability: Ingredients for Life







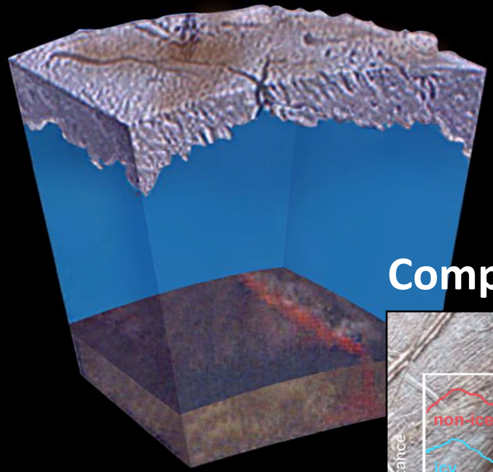
National Oceanic and Atmospheric Administration



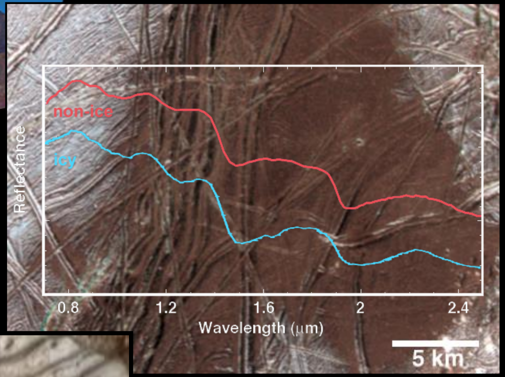
Europa Mission Science

Goal: Explore Europa to investigate its habitability

Ocean & Ice Shell

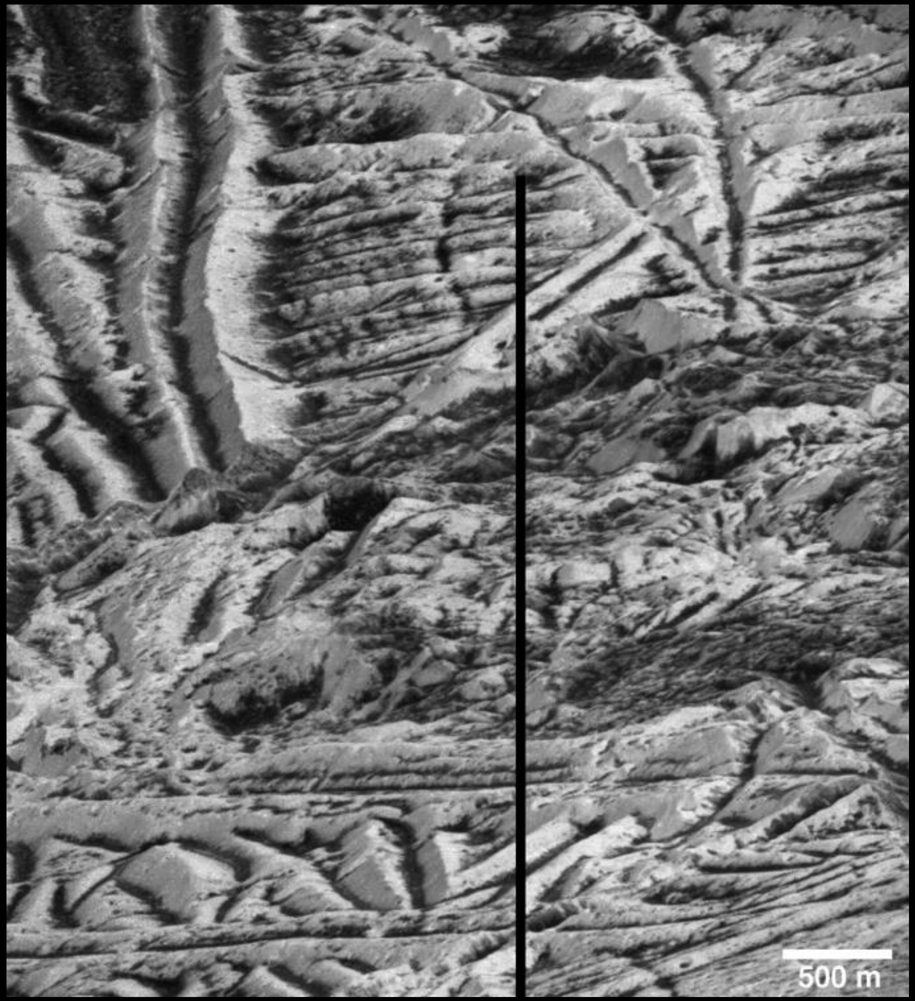


Composition



Geology

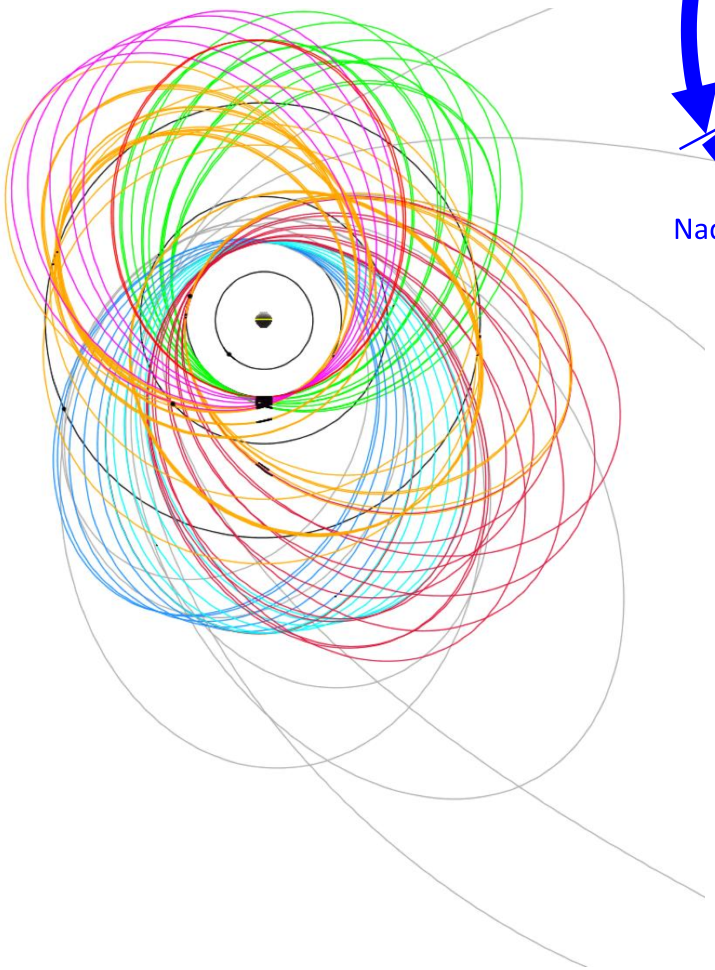
Reconnaissance

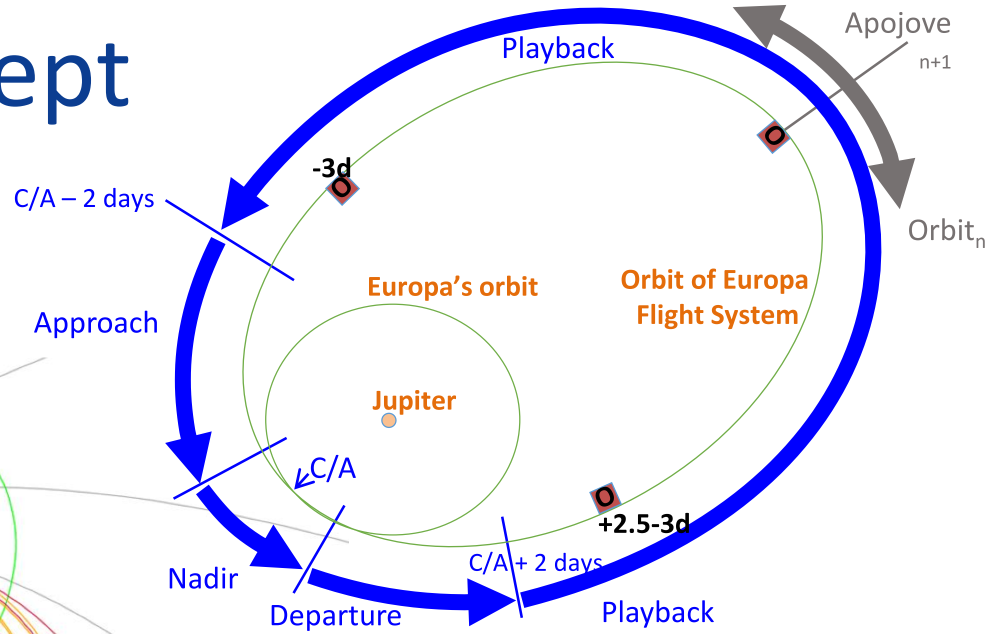


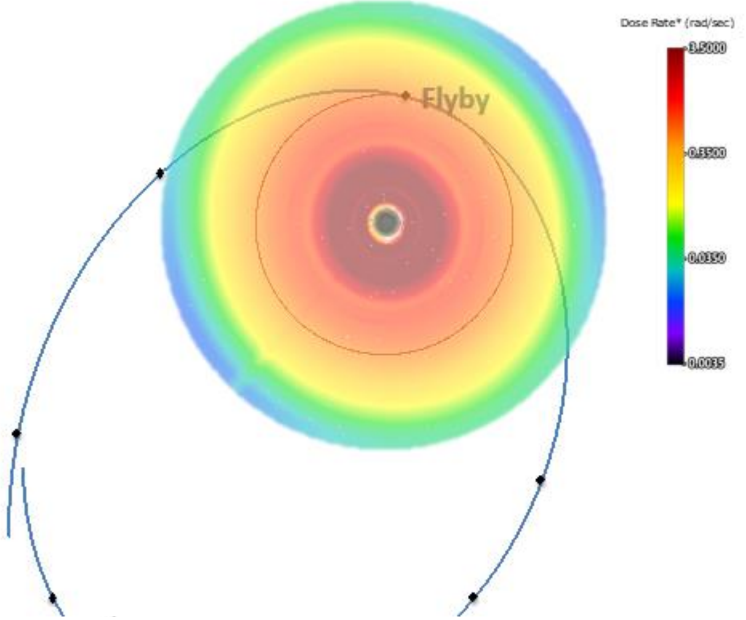
Multiple Flyby Mission Concept

Baseline Mission	
Launch vehicle	SLS Block 1B
Launch Window Opens	June 2022
Time of Flight (direct trajectory)	2.5 years
Jupiter Arrival	Dec 2024
Tour Duration	3.7 years
Number of Jupiter orbits	70
Number of Flybys:	
Europa	46
Ganymede	4
Callisto	9
Mean Time between Europa Flybys	~14 days
Closest Europa approach	25 km
Total Ionizing Dose** (TID)	2.5 Mrad
Primary Mission End	Dec 2028 (Ganymede Impact)

**Si behind 100 mil Al, spherical shell (GIRE2)

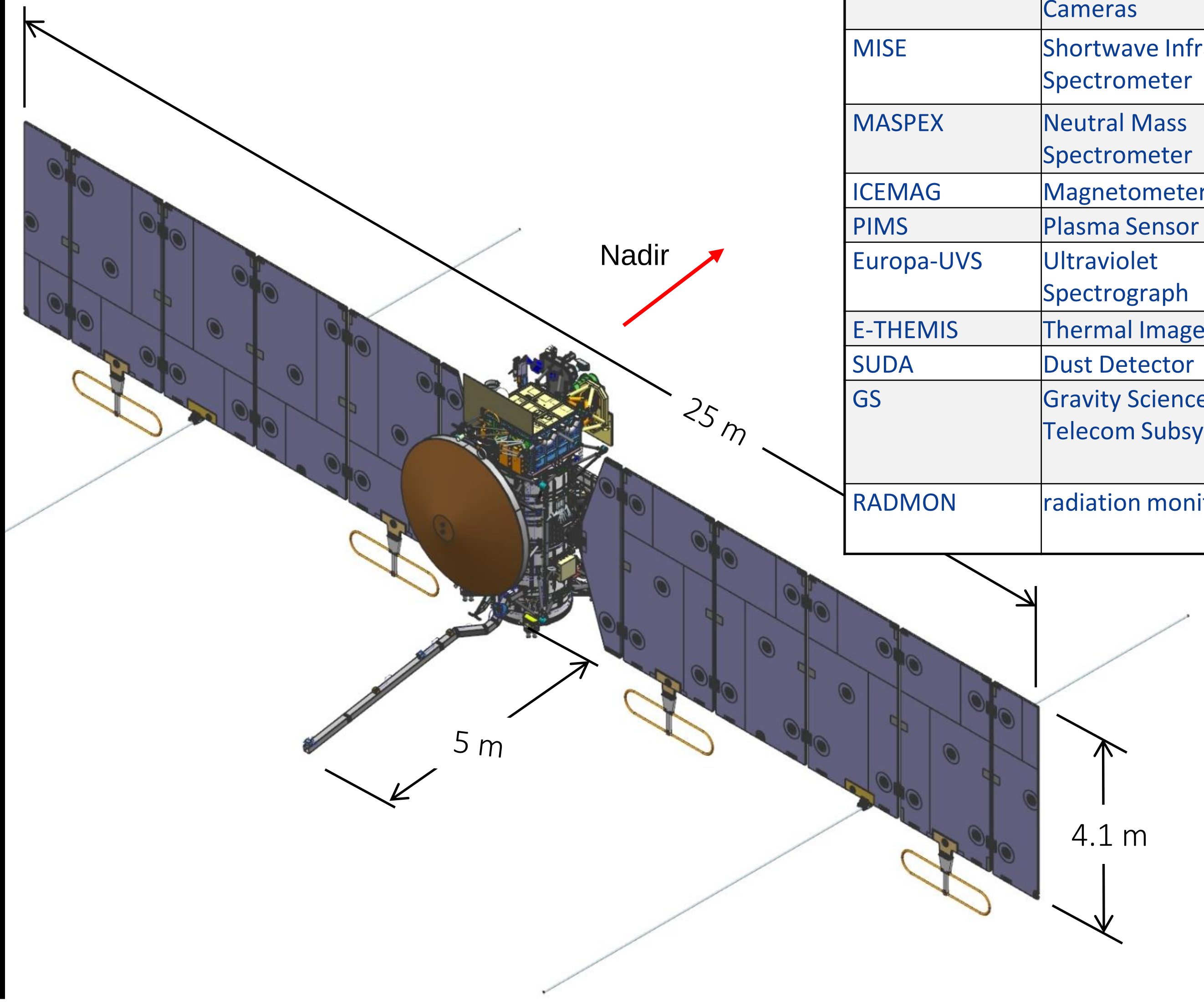






Flight System Overview

Power	• ~86 m^2 Solar Array generating 700 W (EOM) • 339 Ah (EOM) Battery • Single axis gimbaled arrays
Propulsion	• Bipropellant MMH/NTO (MON-3) propulsion subsystem • 1,726 m/s delta-V, 2,750 kg propellant (1,046 kg fuel, 1,704 kg oxidizer) • Twenty-four 25-N engines
Avionics	• RAD750 flight computer and 512 Gibits data storage
Telecom	• X-band: Uplink & 20W Downlink • Ka-band: 35 W Downlink • 3-m HGA, MGA, fan beam (3) and LGA (2)
GNC	• 3-axis: Reaction wheels(4), RCS engines • Star trackers(2), IMU(2), sun sensors(4)
Thermal	• Active thermal pump loop, MLI, heaters, radiator with louvers • Avionics heat reclamation – minimizes electrical heaters
Mechanical	• 5.27 m ICEMAG Boom • Vault significantly reduces total dose to electronics



Instrument	Instrument Type
REASON	Dual band Ice Penetrating Radar
EIS-WAC EIS-NAC	Narrow Angle & Wide Angle Cameras
MISE	Shortwave Infrared Spectrometer
MASPEX	Neutral Mass Spectrometer
ICEMAG	Magnetometer
PIMS	Plasma Sensor
Europa-UVS	Ultraviolet Spectrograph
E-THEMIS	Thermal Imager
SUDA	Dust Detector
GS	Gravity Science via Telecom Subsystem
RADMON	radiation monitor

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What is Operability?

- Recognition that there might be a better way to design, build, test, and operate flight systems.
  - consider how decisions made early in the design phase will impact mission operations
  - aim to make the system to be easy, intuitive, safe, and efficient to operate
  - design with the human user in mind
  - incorporate lessons learned from past missions and the ops community
- In simplest terms, “operability” describes how easy a system is to operate.
  - “Operability is a feature of the end-to-end system (including flight and ground segments) that enables the ground segment (comprising hardware, software, personnel, and procedures), to operate the space segment during the complete mission lifetime, using a minimum of resources, while maximizing the quality, quantity, and availability (or timeliness of delivery) of mission products, without compromising spacecraft safety.” --ISO Standard 14950 (Europa Project modified).
- Operability is a key factor in enabling a “small” operations team to effectively and safely operate the flight and ground systems, thus potentially lowering costs.
- Operability is more than just human factors engineering.
- “Operability for operability sake” is *not* the goal.
  - Operability should be traded off with cost, schedule, risk, etc.

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Mission Characteristics that Drive Need for Operability

- Repetitive passes through a high radiation environment
  - may induce temporary onboard faults, resulting in science data loss
- Deep-space solar powered mission
  - power dependent on attitude, distance, geometry; power availability linked to downlink bandwidth; array affects s/c dynamics; not all flight system components can be powered on concurrently, nor operated continuously
- Long-duration, high-frequency flyby mission
  - multiple, overlapping operations activities required for each encounter (e.g., 3 orbit trim maneuvers, sequence development, ephemeris updates, engineering activities, instrument calibrations, control and coordination of downlink prioritization); potential for ops team fatigue/ burn-out
- Nine independent science instruments collecting collaborative science data
  - varying flight system interfaces, control approaches for commanding, operations concepts, and operating constraints

Operability on Europa Clipper

- Early in project formulation, operability was established as policy by the Europa Clipper Project Manager:
  - "During formulation and development phases, the Europa Clipper Project team will make every attempt to consider operability in all design decisions."
- Operability expressed as a stakeholder "concern" on Europa Clipper
  - "The robotic space mission operations community has put together many reports and papers addressing lessons learned from legacy missions, along with recommendations for future mission operations, *particularly in the area of operability*. There is a concern that these recommendations do not get reviewed, thought about, and addressed, thus *not mitigating the possibility of needlessly repeating errors or inefficiencies from the past*."
- To address and implement the Project Manager's policy on operability, the Operability Working Group (OPRWG) was formed
  - represent the operations team early in development (Pre-Phase-A), with the goal of ensuring that operations impacts and concerns are considered in the system design
  - define operability for the Europa Clipper system
  - develop system requirements that address operability
  - lead and participate in project working groups, trade studies, and operational scenario development
  - assess requirements and Engineering Change Requests (ECRs) for operability impacts
  - improve the operability of the selected design
  - provide an on-going assessment of Europa Clipper operability throughout its lifecycle

Aspects of Operability

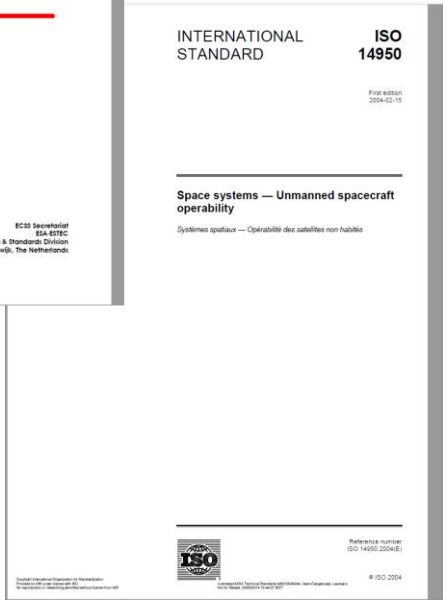
- The OPRWG defined nine "aspects of operability" as an attempt to describe the characteristics of an operable system.

Aspect of Operability	Shorthand Description
Visibility / Observability	The extent to which the system provides the operations team with usable information about the configuration, status, and performance of the system.
Commandability / Controllability	The extent to which the operations team can place the flight system in the desired state (e.g., attitude, configuration), and produce the desired outcome via commanding.
Predictability	The extent to which the operations team is able to predict, with some certainty, the outcome of the execution of a planned event.
Flexibility	The extent to which the operations team can reconfigure components to maximize or optimize component utilization, to circumvent anomalous components, provide options, to increase robustness.
Robustness	The extent to which the system maintains performance under perturbations, and prevents and contains errors.
Autonomy (aka, automation)	The extent to which the system manages nominal or contingency operations without ground intervention.
Efficiency	The extent to which the operations team can optimize the use of time and resources
Testability	The extent to which the operations team can verify and validate system components and test assets.
Tractability	The extent to which the operations team is freed from the need to pay attention to, or “care and feed” the system.

Operability Requirements on Europa Clipper

- The OPRWG was charged with developing operability requirements for the mission, beginning in early formulation phase.
- The OPRWG drew on a wealth of operations community lessons learned and best practices
  - Operability industry standards:
    - Unmanned Spacecraft Operability, ISO 14950
    - European Cooperation for Space Standardization, Space Segment Operability, ECSS-E-70-11A
  - Experience and lessons learned
    - unpublished lessons learned documents and studies
    - conference papers
    - NASA lessons learned database
    - discussion with members of the Europa Operability Working Group
    - discussions with members of operations teams on other missions (Cassini, Juno, Messenger, Dawn, etc.).
  - Institutional best practices:
    - JPL Design Principles
    - Flight Project Practices


ECSS-E-70-11A
5 August 2005
EUROPEAN COOPERATION
ECSS
FOR SPACE STANDARDIZATION
Space engineering
Space segment operability
ECSS Secretariat
ESA-ESTEC
Requirements & Standards Division
Noordwijk, The Netherlands


INTERNATIONAL STANDARD
ISO 14950
First edition
2004-02-15
Space systems — Unmanned spacecraft operability
Systèmes spatiaux — Opérabilité des satellites non habités
Reference number
ISO 14950:2004(E)
© ISO 2004

Operability Requirements on Europa Clipper

- ~450 candidate requirements were vetted by the OPRWG, and resulted in 151 operability requirements.
  - requirements (125)
  - policies (23)
  - receivables / deliverables (3)
- Requirements address topics across the entire system, including both the ground and flight systems.
  - e.g., spacecraft subsystems; instruments; flight and ground software; testbeds; command and telemetry dictionaries; data transfer and storage; command sequencing; fault management; models; telemetry content and visualization; data access
- Each requirement includes a rationale, linked to which aspects of operability the requirement seeks to enhance.

Operability Requirements on Europa Clipper

- Operability requirements are not necessarily anything new or earth-shattering
  - many currently exist as requirements on other projects
  - gives operability-related requirements a “home” and a rationale to exist as a whole
  - gives the project another “perspective” from which to view system requirements development
  - provides an operability focus—brings attention to an area that might have been traditionally forgotten, neglected, or only an after thought
  - requirements source is the *operators*, as opposed to the *developers*

Example Operability Requirements (1 of 3)

OPR.149	**Automated end-to-end downlink data product accountability.** “The Project System shall provide the capability for automated flight to ground downlink data product accountability, including a verification that requested downlink data products have been successfully downlinked by the Flight System, and have been successfully received by the Ground System."
Rationale / Aspect of Operability	**efficiency**: Provides an automated process to ensure flight system products have been successfully downlinked to the interplanetary network and received by the GDS. On some flight projects, this has been a tedious, manual, or semi-automated process. Helps maximize the effectiveness of the operations team by allowing them to focus on tasks that actually require their attention, as opposed to doing routine, repetitive, or manual tasks.
OPR.277	**Auto-generation of antenna configuration.** "The MOS shall develop the capability to automatically generate flight system control programs or commands (on the ground) to select and configure the optimal antenna based on planned upcoming flight system activities and attitude."
	efficiency: Provides an automated tool to replace a potentially tedious, manual process. Helps maximize the effectiveness of the operations team by allowing them to focus on tasks that actually require their attention, as opposed to doing routine, repetitive, or manual tasks. This capability needs to be integrated into the planning and sequencing process, as opposed to just an off-line tool, thereby preventing it from becoming a laborious and inefficient iterative process.
OPR.156	**Data Product Downlink Prioritization.** “The flight system shall have the capability to assign downlink priority to data products stored on the on-board data storage based on assignments made by the MOS.”
	visibility: Provides the flight team with the ability to decide which data products are most important to them at a given time during the mission, and delivering it to them more expeditiously. **flexibility**: Provides the flight team with the ability to change downlink priorities during the course of the mission (e.g., based on mission phase or need).

Example Operability Requirements (2 of 3)

OPR.320	**Testbed initialization time.** “The hardware and software testbeds shall be able to be initialized by the operator to a defined set of user-defined states in under 1 hour.”
Rationale / Aspect of Operability	**efficiency**: Initializing the testbed on the Dawn mission takes approximately 4 hours and is not a robust process. The MRO testbed can take up to 6 hours to initialize. And if an anomaly occurs 4 hours into the process, a whole workday can be “blown” without having accomplished the test. Having a 1 hour initialization enables a reasonable sized test to be performed in a work day. This 1 hour initialization will be available for a limited set of user-defined cases (e.g., before a flyby begins, after launch vehicle tip-off, before an OTM), and for major state initializations (e.g., spacecraft attitude, spacecraft mode, RWA / momentum state, tables and FSW parameters, FSW version, etc.).
OPR.126	**Epoch-based sequencing.** "The flight system shall have the capability to execute control programs and commands based on an updateable epoch."
	efficiency: Provides operations team the ability to build sequences based on an epoch (e.g., time of closest approach). Would just then need to update the epoch when the ephemeris changes, as opposed to having to delete, update, and then re-load affected sequences. Also provides the ability to potentially re-use or templatized sequences.
OPR.272	**Health-based telemetry prioritization.** "The flight system shall have the capability to prioritize health and status telemetry based on the health of the subsystem / instrument.”
	efficiency: Provides the ops team with the ability to place higher priority on anomalous subsystem/ payload health and status telemetry, allowing them to downlink those data first. Helps the ops team to more quickly assess anomalies. **visibility:** Provides the operations team with situational awareness. Enables them to efficiently assess the health and status of the flight system. Provides ability to detect anomalous behavior and trends, thus enhancing their ability to take prompt corrective action.

Example Operability Requirements (3 of 3)

OPR.401	**Data latency modeling.** “The MOS shall model when specific data will be downlinked to within a single downlink pass accuracy.”
Rationale / Aspect of Operability	**predictability**: Enables the MOS to predict, with some certainty, when a particular data product will be downlinked. Such predictability is important, for example, for instrument teams, who may need to alter their plans / sequencing for subsequent flybys, based on an expected downlink product (i.e., feed-forward data). This may be a time-sensitive process. **efficiency:** Enables the ops team to efficiently answer the question “When is my data product coming down?” An automated tool helps avoid the time required to manually estimate and juggle such variables as the upcoming DSN pass schedule, the desired data product’s priority, the amount of data in the downlink queue with higher priority, etc. This process could be made even more efficient if all ops teams (including instrument ops) have access to the tool and could run it for themselves.
OPR.370	**Flight System command nomenclature.** "Flight system commands (including instrument commands) shall reflect command intent in a human readable manner, implying the use/ function of the command, activity, or behavior being commanded.”
	robustness: Helps minimize human-generated errors by making commands and uplink products more intuitive and human readable.
OPR.201 (Policy)	**Full and partial flight software updates.** "Flight software shall provide the capability to perform both full and partial (modular) updates."
	efficiency: Allows the operations team to update/ replace only the portion of flight software of interest, as opposed to being required to do a complete/ full flight software update. This could be implemented by structuring the code in a modular fashion, or updating via table loads. For example on the Dawn mission, you could just update and replace the ACS “task” without needing to update anything else.

Involvement in Trades, Design Decisions, Scenarios (1 of 2)

- The OPRWG represents the operations perspective on Europa Clipper issues and designs early in project development, with the goal of increasing system operability.
- Active participation in trade studies, requirements development and flowdown, engineering change proposal review, working groups, and operations scenario development allow operations concerns to be identified and addressed.
- Operability has seldom been the discriminating factor in Europa Clipper trade studies. Operability is only one of many rating factors considered in evaluating trade studies. Trade decisions can and have been made that decrease operability of the system.
- But there is value in identifying and capturing these impacts early in development:
  - provides awareness to project management of potential impact to future operations (e.g., cost, schedule, personnel)
  - provides the opportunity to mitigate the effects of design choices to improve operability
  - helps maintain focus on items that impact operability.

Trades, Design Decisions, Scenarios Examples (2 of 2)

Trade	Operability Issues Identified	Mitigations
Power Source Trade (solar versus RTG variants)	- power output becomes a function of attitude, solar distance, radiation degradation, etc. - power availability limits downlink bandwidth - reduced power generated during eclipses and safing scenarios - imposes off-sun attitude constraints - adds mission-critical solar panel deployment - larger inertial properties leading to increased slew rates, settling times	new requirements: - high-fidelity power/energy balance prediction tools and supporting on-board telemetry - solar array articulation and constraint avoidance software processes: - run full-orbit sequencing + power balance simulations - modify downlink plan to account for decreased downlink availability - higher level of scrutiny and analysis by the operations team ROM cost: ~$2M (ops labor and software development)
Bulk Data Store Design Changes	- science data collectively stored in interleaved “BDS storage units” - no conventional file system for science data storage - no end-to-end observation accountability - on-board preparation for downlink preludes other activities	new requirements: - allow for binning & prioritization of data - add an “accountability ID” to each observation /data product - ground tools to reassemble data products - BDS state prediction tools processes: - define and assign priorities for instrument data return - BDS state modeling - data packet tracking / accountability - data reconstruction on ground - plan and command filtering activities ROM cost: ~$5M

Operability Assessment of Europa Clipper (1 of 3)

- The OPRWG provides an on-going assessment of the operability of Europa Clipper throughout its lifecycle.
- A baseline operability assessment was made prior to flight system Preliminary Design Review in October 2017.
- The assessment will be updated prior to future gate reviews, and be used as a mechanism to track the evolving operability of the system, and to influence and improve the operability of the selected design.

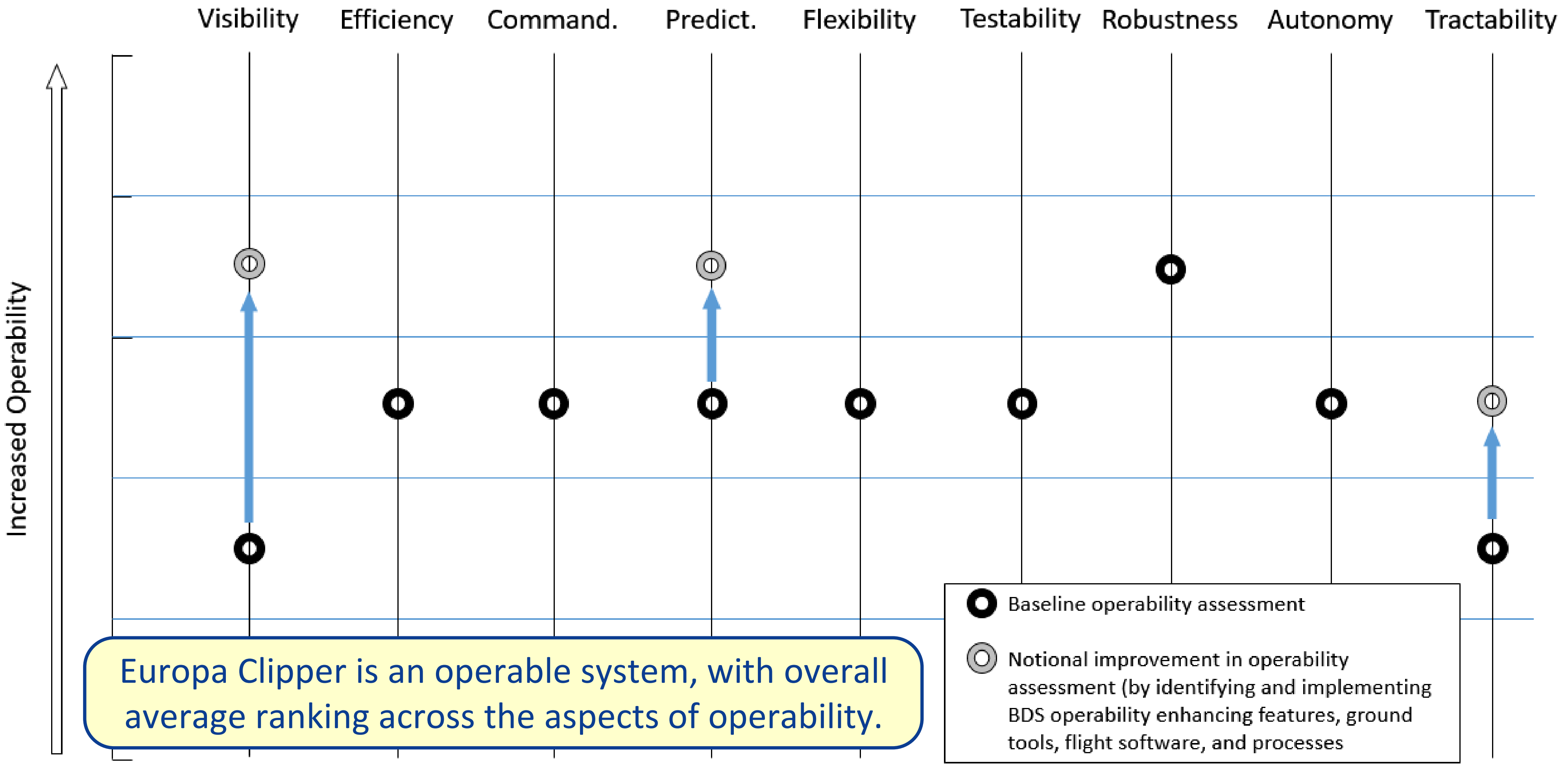
Operability Assessment of Europa Clipper (2 of 3)

- The OPRWG identified "enhancers" and "detractors" to operability, as well as which aspects of operability were most affected by the enhancer or detractor.

		visibility	efficiency	command-ability	predict-ability	flexibility	testability	robustness	autonomy	tractability
Programmatic Detractors and Enhancers										
+++	early Project-level focus on Operability	X	X	X	X	X	X	X	X	X
+++	Joint APL-JPL institutional experience	X	X	X	X	X	X	X	X	X
+++	nadir pointed mission with minimal off-nadir obs.		X		X			X		X
++	early system-level modeling effort				X			X		
- - -	concurrent requirements development	X	X	X	X	X	X	X	X	X
- -	delayed start to end-to-end information system effort	X	X		X					
Design Detractors and Enhancers										
+++	downlink and uplink accountability (CFDP)		X					X		
+++	activity restart timeline (ART)		X					X	X	
++	"data rich" H&S data (e.g., reports, logs, EVRs, etc.)	X	X							
++	auto prioritization of H&S data (based on state)	X	X							
+	effort to decouple / make the payloads non-interactive		X	X	X			X		X
- - -	solar powered mission		X		X	X	X	X		X
- - -	BDS architecture and maintenance	X	X	X	X	X	X	X		X
- - -	telecom link margin (use of tones in certain scenarios)	X	X	X	X	X	X	X		
- - -	validation of activity restart timeline (ART)		X		X		X			X
- -	variability in the control methods of the instruments		X	X	X		X			

Operability Assessment of Europa Clipper (3 of 3)

- The OPRWG weighed the enhancers and detractors associated with each aspect of operability and determined a relative baseline operability ranking for that aspect of operability.



Europa Clipper is an operable system, with overall average ranking across the aspects of operability.

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Lessons Learned

- **Get early project support for operability**.
  - Early, official endorsement helped set the tone, and laid out the expectation that operability would be considered in design decisions.
- **Infuse operability early into project development processes.**
  - Early consideration of operability and operations concerns by the project has significantly increased the likelihood of yielding an operable Europa Clipper system.
  - On Europa Clipper operability has been infused into the system design via requirements and policies.
  - Impacts to operations of design decisions have been captured trade studies, operations scenarios, and engineering change request evaluations.
  - Socialization of operability impacts has been made via participation in numerous project working groups.
- **Socialize payload operability at the earliest opportunity**.
  - The operability of the spacecraft's payload (instruments) is a large contributor to the operability of the entire system. Having the ability to influence the operability of the payload very early in the mission is highly desirable.
- **Employ integrated system modeling tools in operability evaluations.**
  - Europa Clipper's early use of system modeling tools and analyses have been invaluable in supporting trade studies, engineering change request evaluations, requirements verification etc.
- **Track operability trade-by-trade and cumulatively**.
  - Operability has seldom been the discriminating factor in Europa Clipper trade studies.
  - But there is value in identifying and tracking these impacts. The project will have a better sense of the cumulative effect of all trade decisions on operating the mission.
  - The operations implications of an individual decision, choice, or trade may be small. But, in the aggregate, these decisions could lead to an unacceptable or costly operations burden. The project needs to be cognizant of "death by 1,000 cuts."
- **Authority and responsibility for operability should be delegated in an end-to-end, cross-cutting manner**.
  - It is beneficial for the disciplines (e.g., spacecraft subsystems) to take stewardship of the lower-level operability requirements within their own discipline.
  - It provides them with a sense of ownership of these requirements, as opposed to the appearance of having them "imposed from above."

Conclusions

- Operability has been endorsed by and assimilated into the culture of the Europa Clipper project.
- We've designed and developed a practical definition of, and process to, evaluate and influence the operability of Europa Clipper.
- Operability is an extensive effort that has not been implemented this fully on prior JPL/APL missions. But steady, useful progress has been made, and has had a positive impact on the design and function of Europa Clipper.
- We encourage planned and existing missions to fully implement operability efforts.

Backups

Jet Propulsion Laboratory
California Institute of Technology