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

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Operability is an important factor in both success and cost of space missions, but is difficult to quantify, and can suffer if not considered as part of early formulation and design. The Europa Clipper mission has taken a deliberate approach to infusing operability into the concepts and designs since early in the formulation phase. This paper reports on that approach to operability and the results thus far, as the Europa Clipper mission approaches its Preliminary Design Review. Definitions for operability and its various aspects are presented along with a description of the engineering and organizational approach taken to infusing operability into designs. A number of examples of operability requirements are shown, and key examples of trade studies and design decisions are described, along with influence on outcomes motivated by operability considerations. We find that support from management, empowerment of a cross-discipline Operability Working Group, consistent tracking of operability aspects over time, and broad infusion and participation in operability considerations are all significant factors in implementing operability. In particular, thoughtful and deliberate consideration of operability criteria has led to design decisions that include proper consideration of concerns related to the mission operations phase, and seem likely to provide better science results and mission outcomes.

I. Introduction

The operability of spacecraft and their payloads (or flight systems) is a key factor in the cost of operations, the risk assumed by operators, and the likelihood of mission success. A highly operable flight system manages routine tasks autonomously, or provides interfaces and behaviors that enable ground automation. It demands fewer on-ground human resources to operate, and tends to relegate routine, repetitive, and tedious tasks to software. Such characteristics also decrease the risks associated with human error and enable human effort to be focused on achieving or enhancing mission success.

The Europa Clipper Mission has adopted a formal approach to infusing operability into the design of the flight system, ground system, and overall mission. This paper presents that approach and its application during the formulation phase, provides the mission context for operability efforts, and discusses the definition of operability characteristics and how they have informed some of the key decisions made during early system development. We find that project system and project-level endorsement and support for an Operability Engineer and an Operability Working Group was significant in socializing and obtaining buy-in from the engineering team as to the utility of operability concepts. By providing practical definitions of operability characteristics and their application, it is possible to both communicate operability concerns broadly and to assess their influence on flight and project system design.

Operability influence on design is variable; cost, schedule, budget, heritage, and other technical concerns may outweigh operability concerns in any given example. However, the Europa Clipper mission experience to date demonstrates that this approach to operability results in more thorough, balanced consideration of the effect of early design trades and decisions on the operations phase of a mission than seen in many previous missions, and provides operations development insight into prioritizing work to go.

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II. What is Operability?

A. Operability Defined

The space operations community recognizes that there may be better ways to design, build, test, and operate flight systems. If the system is designed from the beginning of its development to be easy, intuitive, safe, and efficient for the human operator, then there is increased potential that the mission could be operated with lower risk, increased science return, and reduction in required resources (e.g., personnel).

But how can the "goodness" of the human-system interaction be described or quantified? The term "operability" has been used to describe this relationship. In simplest terms, operability describes how easy a system is to operate. The dictionary defines operability as the ability to keep equipment, a system, or a whole industrial installation in a safe and reliable, functioning condition, according to pre-defined operational requirements. For mission operations of a spacecraft, safe, reliable, and functional only scratch part of the itch. Flexibility, robustness, and affordability are also areas of consideration. Thus the Europa Clipper project uses a modified version of the ISO 14950 definition of operability [1]:

> 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.

Central to achieving operability is to consider how decisions made early in the design phase of a mission may eventually impact mission operations. Space operations community corporate knowledge and lessons learned are good sources of how design decisions may impact mission operations.

In cost-constrained environments, operability is seen as one way to enable smaller operations teams to effectively and safely operate the flight and ground systems, thus potentially lowering mission operations costs. For cost-capped, long-duration missions (e.g., Europa Clipper), this could be a significant reduction in overall mission cost.

Operability is *more* than just "human factors engineering," or the quality of the human-machine interface. In some cases, autonomy or automation, enablers of operability, may be used to actually *replace* humans in control loops, thus minimizing the human-machine interface. For example, autonomy / automation may be used to perform routine, repetitive tasks, or when control loops are too rapid to allow for human interaction. Also, the application of margins (e.g., propellant, power, slew time, etc.) may be sufficient so as to minimize the operations team need to interact with the flight system.

However, "operability for operability sake" is not necessarily the goal. Operability is one of a number of factors, including cost, schedule, performance, and risk, that project management may take into consideration when allocating project resources. Defining operability and providing a taxonomy makes it easier for it to be incorporated into those decisions.

B. An Historic Example of How Design Decisions Affected Operability

One example of how a decision made in the project development phase led to an effect on mission operations can be seen in the Cassini mission to Saturn [2]. Cassini was originally designed such that the remote sensing instruments were placed on a scan platform while the in-situ instruments were placed on a turntable. This configuration allowed the decoupling of instrument pointing from spacecraft pointing. This configuration would have enabled the instruments to largely point independent of spacecraft attitude, and potentially enable data acquisition to happen simultaneously with data downlink via the high gain antenna. But as a cost savings measure, the scan platform and turntables were removed from the design, and the instruments were body-fixed, and co-bore sighted where complementary. As a result, the entire spacecraft had to be reoriented during flight to point the instruments at their intended targets during observations, and to point the high gain antenna at Earth for communications passes and gravity science experiments.

Cassini's 12 science instrument teams now had to vie for "control" of the spacecraft pointing during key observation times. As a result, pointing control was treated as a resource. One instrument at a time was allocated control of where the spacecraft was pointed. Instruments were assigned a prime or ride-along status for events such as Titan flybys. The prime instrument dictated spacecraft pointing while the other instruments "took what they could get" based on the prime instrument pointing. Multiple science working groups had to be instantiated to negotiate and de-conflict the pointing requests from the instrument and make allocations among them.

Science data acquisition, storage, and playback would now need to be more scrutinized and overseen by the flight operations team due to the fact that simultaneous data acquisition and downlink could no longer be performed.

So, instead of instrument pointing and data acquisition being somewhat independent of each other, it now became a highly coupled and complex task. The sequence development process for prime mission took approximately 22 weeks to in order to develop a 4 week sequence of on-board activities.

As a result of the decision to remove the scan platform and turntable, which saved the project several million dollars, the resulting increased complexity to Phase-E operations (personnel, tools, processes, etc.) was multiples of this, though the exact cost has never been calculated. It should be pointed, however, out that the decision to remove the scan platform and turntable, though negatively impacting operability, saved enough money in development to prevent the project from being canceled entirely. It is possible that had an operability impact assessment of the removal of the scan platform and turntable been performed at that time, potential opportunities could have been identified (e.g., priorities for automation) to help mitigate the large operations cost increase.

III. Operability on the Europa Clipper Mission

The Operability approach used on the Europa Clipper Project represents the first formalized JPL/APL effort to: 1) define what is meant by an operable system; 2) influence design choices and trades; 3) improve the operability of the selected design; and 4) provide an on-going assessment of the operability of the system throughout its lifecycle.

A. Mission Overview

The Europa Clipper Mission's exploration objectives are intimately tied to understanding the three "ingredients" for life: liquid water, chemistry, and energy. The Europa Clipper mission will investigate these ingredients by comprehensively exploring Europa's ice shell, liquid ocean interface, surface geology and surface composition in to gather insight into the inner workings of this unique moon of Jupiter. Additional goals of the mission are to characterize the radiation environment near Europa and investigate scientifically compelling landing sites for hazards to inform a potential future landed mission.

The Europa Clipper mission is planned for launch from Kennedy Space Center (KSC), Cape Canaveral, Florida, on a NASA supplied launch vehicle, no earlier than 2022. The mission is formulated, implemented, and operated by a joint Jet Propulsion Laboratory (JPL) and Johns Hopkins Applied Physics Laboratory (APL) project team.

The team will send a solar-powered flight system, consisting of a spacecraft equipped with a payload of nine NASA-selected scientific instruments, to execute numerous flybys of Europa. A key challenge is that the flight system must survive and operate in the intense Jovian radiation environment, which is especially harsh at Europa's orbital distance. The innovative design of this multiple-flyby tour is an enabling feature of this mission: by minimizing the time spent in the harshest radiation environment, the spacecraft complexity and cost has been significantly reduced compared to previous mission concepts.

The tour portion of the mission contains the science campaign, which consists of approximately 45 close flybys of Europa, with many as low as 25 km above the surface. Each encounter is divided into four subphases (shown graphically in Fig. 1): the approach subphase, beginning approximately two days prior to closest approach; the nadir subphase, when the spacecraft is closest to Europa and in a nadir-pointed attitude for science data collection; the departure subphase, extending from the end of the nadir subphase until about two days after closest approach; and a playback subphase, where the data recorded during the flybys are transmitted to the ground.

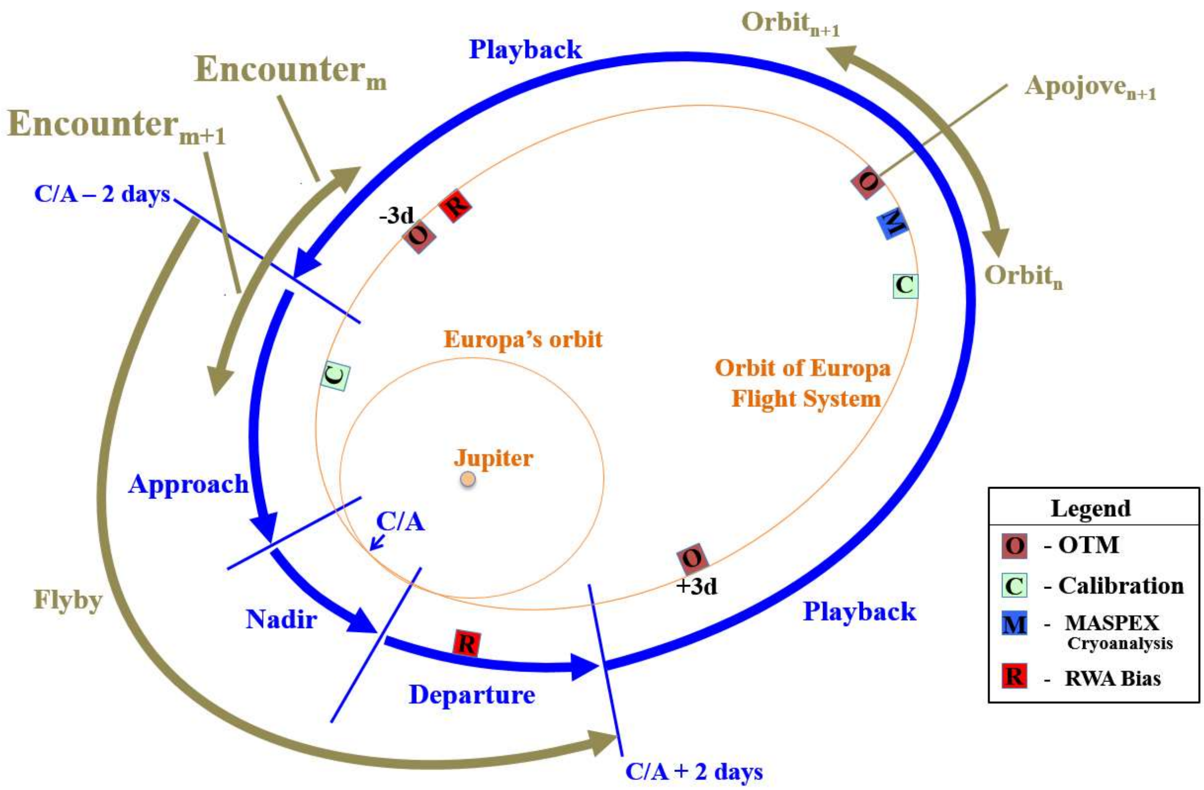

Fig. 1 Nomenclature for Europa Clipper Encounter with Europa

Almost all of the of the science data collection occurs in the approach, nadir, and departure subphases, with the exception of some in-situ data collection and occasional instrument calibrations during the playback phase. The encounter plan follows a reusable template that enables the integrated set of science measurement requirements to be met over the course of the mission.

Due to downlink data volume limitations and high science data volumes collected on each encounter (approximately 100 Gbits), there may be latencies of up to several weeks before all the science data is returned to the ground from a given encounter, so carry over into the playback phases of subsequent encounters will occur. The operations teams will enable prioritized data return based on science-driven priorities in order to receive decisional data in a timely manner early in the playback phase that is "fed forward" to use in design of observation plans that require optimization or information from a prior encounter.

In addition to the primary activity of data downlink, three orbit trim maneuvers (OTMs) are executed during the playback phase to maintain and optimize the flight system's planned trajectory and the flyby altitude. Following the final approach maneuver three days prior to the flyby, the operations teams will have a short time (on the order of a day) to update related parameters in the sequence plans to adjust for the latest timing and pointing for the upcoming flyby.

B. Characteristics of the Mission that Drive Need for Increased Operability

In addition to the unique nature of the mission driving flight system design choices and mission design choices, the mission operations design on Europa Clipper must also respond to several unique challenges.

- **Long duration mapping mission accomplished by multiple flybys, with repeatable data collection strategies**. At least six years of planned operations drives the need for an operations system design that is adaptable to change over time, with simplicity and workflow automation in operations processes to alleviate workload and staff fatigue/burn-out over the long mission duration.
- **Repetitive passes through a high radiation environment**. Passing through the high Jovian radiation environment during each Europa flyby may cause temporary faults onboard the flight system. Fault management must be robust, and ground contingency responses must be well planned, tested, and allow rapid

recovery to prevent loss of science. This drives the need to consider robustness in operations system and flight system designs for restarting science acquisition quickly in the case of a fault, and to consider operations margin to allow for anomaly response by the operations team while not risking future operations task success.

- **Rapid cadence of targeted science flybys.** An average spacing between flybys of Europa of 14 days drives the need for numerous, high-frequency overlapping activities to support science data collection and spacecraft health and performance: 3 orbit trim maneuvers, sequence development and verification processes for all 9 instruments, updates to final flyby ephemeris, engineering activities, instrument calibrations, and control and coordination of downlink prioritization. Use of automation and simplification of ground processes to limit sequence development-to-execution ratio to 1:1 or better can help reduce the overlap of operations tasks during each encounter.
- **Nine independent science instruments collecting collaborative Europa science data.** Each instrument has varying flight system interfaces, control approaches for commanding, operations concepts, and operating constraints contributes its own set of drivers on operations. The mission will provide a collaborative science investigation approach with data product transparency and availability to all teams; accommodation of parameter/ command updates between flybys; use of common resource models during planning and sequence generation for consistency from plan through uplink product implementation; and a distributed operations architecture to allow for science & instrument operations from Principle Investigator home institutions.
- **Long one-way light time and orbital geometry**. Large earth-probe distances and geometry of the trajectory make communications challenging. The mission requires the ability to have flexible methods to communicate state of the flight system under less-than optimal telecom link conditions. Long one-way light time also makes communications and control challenging, driving the need for long-running sequences that can do the mission without the ground in the loop on a daily basis.
- **Solar power restrictions on spacecraft and instrument activities**. Not all flight system components can be powered on concurrently, nor operated continuously. This drives the need to model power usage versus energy available to a high fidelity and to manage component usage to stay within power available. Power availability is also linked to downlink bandwidth—the transmitter cannot be powered consistently, so downlink passes must have spacing between them during portions of the mission. A challenge for operations is to balance the carry-over of data from one encounter to the next due to the limited bandwidth with the need for downlink of decisional data following an encounter.

Given these attributes, application of operability principles early in the design of both the flight and ground systems is required to help increase the visibility, commandability, and flexibility available to the mission operations team as it interacts with the flight system over the course of the mission.

C. Europa Clipper Management-Directed Focus on Operability

The Europa Mission System Manager (MSM) played a vital role in establishing operability on the Europa Clipper mission during the pre-project phase. Among the contributions were: socializing operability with the project and Laboratory management; laying the groundwork to having operability established as project policy; contributing to the initial literature search on past operability efforts; obtaining buy-in on staffing operations positions early in the mission, with the intent of ultimately reducing operations costs; and staffing the Operability Engineer position.

Early in the project formulation, operability was established as a project policy by the Europa Project Manager [3]: “During formulation and development phases, the Europa Clipper Project team will make every attempt to consider operability in all design decisions.”

Operability should be considered a general “stakeholder concern” for any project. On Europa Clipper, this concern is expressed as: “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*.”

D. Implementing Operability on Europa Clipper

To address and implement the Project Manager’s policy on operability, the Operability Working Group (OPRWG) was formed. The OPRWG membership was designed to be cross-Center (Jet Propulsion Laboratory and Johns Hopkins Applied Physics Laboratory), and cross-discipline (e.g., personnel from mission operations system, science system engineering, ground data system, flight system (avionics, fault management, flight software, behaviors, information system, etc.), modeling, mission planning, sequencing, etc.)). OPRWG membership currently consists of a core team of 20, supplemented by 25 other subject matter experts as issues arise.

The OPRWG is responsible for: 1) representing the flight operations team early in development (Pre-Phase-A), with the goal of ensuring that operations impacts and concerns are considered in the system design; 2) defining operability for the Europa Clipper system; 3) developing system requirements that address operability; 4) leading and participating in project working groups, trade studies, and operational scenario development; 5) assessing requirements and Engineering Change Requests (ECRs) for operability impacts; 6) improving the operability of the selected design; and 7) providing an on-going assessment of Europa Clipper operability throughout its lifecycle.

E. Aspects of Operability

A challenging issue with operability is how to quantify or describe the operability of a system. The Operability Working Group defined nine "aspects of operability" as an attempt to describe the characteristics of an operable system. These were derived from the "categories of operability" noted in the ECSS Space Segment Operability document.[4] By maximizing these aspects, the operability of the system should generally increase. Additional aspects of operability could have been selected (e.g., simplicity, intuitiveness), but the OPRWG felt these nine were adequate for its purposes. It should be noted that some aspects of operability may counter each other. For example, increased flexibility may actually lead to reduced robustness.

The nine aspects of operability used by Europa Clipper are described below.

1. Visibility / Observability

Visibility (aka observability) is the extent to which the system provides the operations team with usable information about the configuration, status, and performance of the system.

Visibility:

- Enhances situational awareness, and the ability to efficiently assess the health and status of the flight system.
- Enhances the ability to detect anomalous behavior and trends, thus increasing the operations team's ability to take promptly diagnose and take corrective action.
- Enhances the operations team's ability to track/ trend, and allocate resources (e.g., thrusters pulses, component on/off cycles, percentage of consumable remaining, etc.)

2. Commandability / Controllability

Commandability (aka controllability) is 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.

Commandability:

- Enhances the operations team's ability to perform science acquisition and vehicle maintenance activities (i.e., do the mission).
- Quantifies the extent to which the system is available to receive and execute commanding.
- Enhances the ability of the operations team to configure the flight system to the desired state.
- Encompasses the ease at which "intent" is translated into "effect"

3. Predictability

Predictability is the extent to which the operations team is able to predict, with some certainty, the outcome of the execution of a planned event.

Predictability:

- Enhances the confidence that planned events will have the desired, predicted results.
- Helps minimizes uncertainty, thus requiring less scrutiny by the operations team (e.g., time, manpower), less use of margin (e.g., slew time, propellant), and less use of resources (e.g., power).
- Helps minimizes the need for replanning events due to unexpected outcomes.
- Helps provide more "deterministic behavior," thus reducing uncertainty and ambiguity.

4. Flexibility

Flexibility is 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.

Flexibility:

- Helps increase the number of options to complete a function. In the case of degraded or failed components, this ability to reconfigure adds robustness to the mission, and enhances the chances for mission success.

- Enhances the ability of the operations team to get the *same* functionality by using different components and/or processes, and get *different* functionality out of components by enabling or disabling features /functions.
- Helps increase the number of options available to the operations team through the use of margins.

But flexibility needs to be traded against the risk of potentially making a system more complicated, more difficult to analyze, more difficult to predict, less robust.

5. Robustness

Robustness is the extent to which the system maintains performance under perturbations, and prevents and contains errors.

Robustness:

- Enhances the ability of the system to autonomously protect itself from mission-degrading or fatal errors.
- Helps minimize human-induced anomalies from affecting the system, and any resulting anomaly resolution efforts.
- Enhances the ability of the system to contain errors (either human-generated or system internally generated) from propagating to other system elements.
- Helps avoid anomalous or detrimental situations by providing enough margin (e.g., power, turn duration, data volume) to avoid tripping a protective response from the system.
- Enhances the ability of the operations team to maintain visibility and control of the system through anomalous events.

6. Autonomy

Autonomy is the extent to which the system manages nominal or contingency operations without ground intervention.

Autonomy:

- Enhances the ability of the flight system to respond to situations that would be impossible or impractical for the operations team to respond to (e.g., because of one way light time, time criticality of anomaly, control loop are too fast to allow for human intervention).

(Note: Automation used to replace manual processes is considered under the efficiency aspect of operability)

7. Efficiency

Efficiency is the extent to which the operations team can optimize the use of time and resources.

Efficiency:

- Enhances the ability of the operations team to focus on tasks that actually require their attention, as opposed to doing routine, repetitive, or manual tasks.
- Enhances the ability of the operations team to optimize available time and resources.

8. Testability

Testability is the extent to which the operations team can verify and validate system components and test assets.

Testability:

- Enhances the ability of the operations team to easily assess the health or functionality of components (includes both hardware and software).
- Helps increase the ability to easily configure for a test, perform the test, expeditiously obtain and analyze the results. This includes tests performed on both the flight system and ground testbeds.
- Helps increase the ability to test a component, function, or sequence.

9. Tractability

Tractability is the extent to which the operations team is freed from the need to pay attention to, or "care and feed" the sytem.

Tractability:

- Helps relieves the operations team of having to worry about the details of how components, sequences, etc. may interact with each other, allowing them to focus on issues that really require their attention and limited resources.
- Helps minimizes system "annoyance" features (e.g., spurious errors and warnings the system issues), that may distract the operations team or mask legitimate issues.

- Helps minimize the amount of interaction that is be required from the system (e.g., the frequency at which an ephemeris file must be uplinked to the flight system, or momentum management must be commanded from the ground).

Closing the Mission Operations Control Loop

One important function the operations team needs to perform is "closing" the mission operations control loop. The operations team needs to be able to plan and execute activities on the fight system, and then verify that the desired outcome was achieved. The predictability, commandability, and visibility aspect of operability aid in this function (Fig. 2).

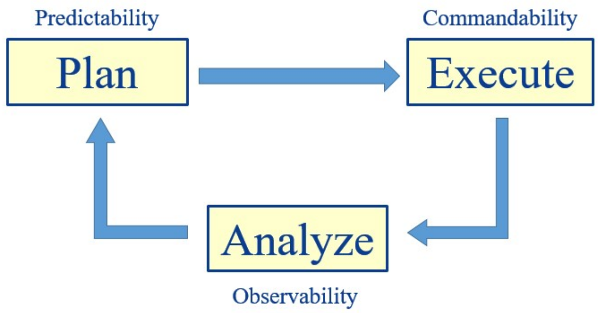

Fig. 2 Closing the mission operations control loop.

Aspects of Operability and Perspectives

Depending on a stakeholder's particular perspective, they may have interest in certain aspects of operability as over others (Table 1). For example, if a stakeholder is interested in how the operations team might be subject to fatigue or burnout, their prime focus might be on how robust, autonomous, efficient, testable, and tractable the system is. Or, if the stakeholder is interested in closing the mission operations control loop, they would be primarily concerned with the observability, commandability, and predictability of the system. If a stakeholder desire was to enable a small operations team to effectively operate the system, all aspects of operability would be of concern.

	Closing the Loop	Human Factors	Mission Assurance	Sequencing	Small Ops Team
Observability / Visibility	X				X
Commandability / Controllability	X			X	X
Predictability	X		X	X	X
Flexibility					X
Robustness		X	X		X
Autonomy		X			X
Efficiency		X		X	X
Testability		X		X	X
Tractability		X			X

Table 1 Aspects of operability and sample perspectives

F. Operability Requirements Development

The Mission System charged the Operability Working Group with developing operability requirements for the Europa Clipper mission, beginning in early formulation phase (Pre-Phase A). Early involvement of this operations-focused group was considered essential in laying the foundation for an operable system design.

The OPRWG drew on a wealth of operations community lessons learned and best practices in developing operability requirements. This corporate knowledge is captured in a variety of sources and covers many classes and varieties of missions, from multiple institutions. The OPRWG applied this corporate knowledge and experience and infused it into the Europa Clipper system design via the operability requirements.

Sources for Europa Clipper's operability requirements included:

1) Operability industry standards:

- Unmanned Spacecraft Operability, ISO 14950 [1]
- European Cooperation for Space Standardization, Space Segment Operability, ECSS-E-70-11A [4]

2) 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.).

3) Institutional best practices:

- JPL Design Principles [5]
- Flight Project Practices [6]

These sources were used as starting points and adapted for the specific attributes of the Europa mission, and the way JPL and ALP perform mission operations. Approximately 450 candidate requirements were vetted by the OPRWG, and resulted in 160 operability requirements (as of the Preliminary Design Review) [7].

Europa Clipper operability requirements address topics across the entire system, including components of both the ground and flight systems. Some of these topic areas include: spacecraft subsystems, payload / instruments; flight and ground software; hardware and software testbeds; command and telemetry dictionaries; data storage and transfer; telemetry content; sequencing; commanding; fault management; simulation and support equipment; models; telemetry content and visualization; data access. Each requirement includes a rationale to justify the need for the requirement. The rationale references which aspects of operability the requirement seeks to enhance.

The initial expression of operability concerns from the OPRWG consisted of three types: 1) traditional requirements; 2) policies and guidelines (for items that are important, valid operability concerns that need to be captured and enforced but cannot be easily validated and verified because of their general, subjective nature); and 3) contractual receivables / deliverables from the payload teams (e.g., instrument data production models).

1. Example Operability Requirements

Europa Clipper implemented a deliberate approach to operability, as opposed to previous missions more informal or implicit approach. This improves the degree to which operators concerns are infused into the requirements process. Operability-related requirements in and of themselves are not necessarily anything new nor unique for space missions. Previous missions may have in fact had such requirements, though not with the moniker of operability. Developing operations-focused requirements under the umbrella of operability: 1) gives operability-related requirements a home and a rationale to exist as a whole; 2) gives projects another perspective from which to view system requirements development; 3) brings attention to an area that might have been traditionally forgotten, neglected, or only addressed as an afterthought; and 4) provides an *operator's* perspective on requirements, as opposed to a *developer's* perspective.

Table 2 presents example Europa Clipper operability requirements and policies. These examples are meant to demonstrate the breadth (e.g., spacecraft, instruments, ground system, testbeds, etc.) of the operability requirements/ policies set, as well as provide examples across the nine aspects of operability. Each example includes which aspect(s) of operability the requirement/policy seeks to enhance, as well as the source of the requirement or policy.

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.
Sources	ECSS 5.8.9.12, DP 4.1.7.1. Historic operations community lessons learned and experience.
OPR.374	**Off-nadir instrument pointing**. “Instruments which require off-nadir pointing during nadir pointing periods shall provide their own independent, non-interfering pointing mechanism.”
Rationale / Aspect of Operability	**efficiency**: Enables the operations team to perform flyby planning and execution more efficiently by simplifying the coordination and planning needed for each flyby. Instruments that require off-nadir pointing will be able to control their own pointing through their non-interfering articulation mechanism. Accommodating “one off” pointing requests can become burdensome for a small ops team. Decoupling one off instrument pointing from the rest of the instruments avoids the complexities experienced by the Cassini mission in trying to integrate and juggle the numerous instrument pointing requests.
Source	Historic operations community experience and lessons learned.
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."
Rationale / Aspect of Operability	**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.
Source	Historic operations community experience and lessons learned.
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.”
Rationale / Aspect of Operability	**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).
Sources	ECSS 5.8.9.6
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.).
Source	Historic ops community experience and lessons learned.
OPR.026	**Off-line testability of redundant components.**

	"The flight system shall provide the capability for the MOS to assess the health and functionality of backup electronic components, without interrupting the prime component's functionality."
Rationale / Aspect of Operability	**testability:** The operations team needs to be able to easily test the health, status, and performance of redundant components (both software and some hardware) without disturbing the prime components, or making the redundant component prime. **visibility:** Provides the operations team with the health, status, and performance of redundant components (both software and some hardware) without disturbing the prime components.
Sources	ISO TMDES-1060, TEST-0030, PRSO-1030; ECSS 4.7.2, 5.3.1.14, 5.3.1.15, 5.9.1.5; DP 4.1.3.4 and DP 9.3.7.

OPR.126	**Epoch-based sequencing.** "The flight system shall have the capability to execute control programs and commands based on an updateable epoch."
Rationale / Aspect of Operability	**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.
Sources	ECSS 5.8.5.6. Historic ops community lessons learned and experience.

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."
Rationale / Aspect of Operability	**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.
Source	Historic ops community lessons learned and experience.

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.
Source	Historic operations community experience and lessons learned.

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."
Rationale / Aspect of Operability	**robustness:** Helps minimize human-generated errors by making commands and uplink products more intuitive and human readable.
Sources	Historic operations community experience and lessons learned.

OPR.326	**Ground display of telemetry.** "Upon receipt of the data, the GDS shall display telemetry, state histories and summaries, error logs, notification of on-board activities, and command history logs, in a time-sequenced human readable format."
Rationale / Aspect of Operability	**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. This is the 3rd component of "closing the loop." Tools that display flight system logs in a human readable format (not hex or op codes) will give immediate visibility and insight into executed commands, faults, and other logs that are received from the spacecraft. **efficiency**: Provides tools to help the operations team operate efficiently. 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. These data will help the ops team quickly assess the status of the flight and aid in anomaly resolution. This display helps enable a small flight team to quickly assess outcome of flight system activities.
Sources	APL RBSP Ground System Requirements Document (APL 7417-9040); historic operations community experience and lessons learned.
OPR.416	**Control Program Development Timeline.** "The MOS shall generate, model, validate, and uplink Control Programs on a 1:1 or better time ratio with real-time execution, including margin."
Rationale / Aspect of Operability	**efficiency:** This constrains the ratio of the time to develop, validate, and uplink control programs (e.g., a background sequence) to the actual time to execute on the flight system to be 1-to-1 or better. Provides the potential for a smaller operations team. This would simplify the control program development, validation, and uplink cycle, enabling a single team to do these functions without the need to have concurrent, overlapping teams performing these functions for subsequent encounters. The Cassini ops team required five months to do these functions to produce a one month background sequence (a 5:1 ratio), resulting in 5 concurrent, overlapping teams to support Tour background sequence development. Increases ease of planning and tracking—no overlapping development team schedules. Avoids having to schedule and keep track of two or more overlapping development teams. **flexibility**: With a development to execution ratio of 1-to-1 or better, the ops team could (if needed) wait longer before initiating sequence development, thereby more easily accommodating late-breaking update requests (e.g., late DSN schedule changes, added activities, etc.).
Source	Historic operations community experience and lessons learned.
OPR.201 (Policy)	**Full and partial flight software updates.** "Flight software shall provide the capability to perform both full and partial (modular) updates."
Rationale / Aspect of Operability	**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.
Sources	ECSS PRSO-1040; DP 9.2.1. Historic operations community experience and lessons learned.

Table 2 Example Operability requirements

G. Involvement in Trade Studies, Design Decisions, Scenarios

One of the roles of the Operability Working Group has been to represent the operability 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. Four examples of this involvement are described below.

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. Nevertheless, there is value in identifying and capturing these impacts early in development: 1) provides awareness to project management of potential impact to future operations (e.g., cost, schedule, personnel); 2) provides the opportunity to mitigate the effects of design choices to improve operability; and 3) helps maintain focus on items that impact operability.

1. Trade Study Participation—Power Source Trade Study Example

A power source trade was initiated by the project in Phase-A, to determine the most suitable power source for the mission. The baseline Europa Clipper concept consisted of five multi-mission radioisotope thermoelectric generators (MMRTG). In addition to MMRTGs, the power source trade considerd: enhanced MMRTG (eMMRTG); advanced Stirling radioisotope generator (ASRG); photovoltaic cells (i.e., solar panels); and RTG/solar panel combination hybrids. (The ASRG option was soon eliminated due to program cancellation).

Trade criteria were divided into five evaluation categories, and each category was assigned a weighting factor: technical (30%); cost (20%); schedule (20%); risk (20%); and reliability (10%). Operability was evaluated in two subcategories: *operations complexity* under technical; and *operations cost related to power source* under cost.

The OPRWG identified operability issues and operations complexities associated with operating a flight system with a solar power source. Some of these included: an added mission-critical solar panel deployment; variable power output as a function of attitude, solar distance, solar cell radiation degradation, etc.; larger inertial properties leading to increased turn slew rates, settling times, and potential for dynamic structural interactions; added inner cruise (Venus flyby) thermal constraints on array; significant solar panel configuration coupling with other subsystems (e.g., the REASON radar instrument); potential for added off-sun attitude constraints; reduced power generated during eclipses and fault (safing) scenarios; and need to articulate array for optimal power production.

To mitigate these impacts, the operations team would: 1) need to develop, run, and maintain high-fidelity solar power models and incorporate them into a full-orbit simulation to ensure sufficient power was available to support planned flight system activities; 2) need to perform pre-launch and in-flight solar array performance characterizations; 3) increase margins (power, timing, etc.) in sequence design; 4) develop and maintain solar panel articulation and constraint avoidance software; 5) develop contingency plans for the increased potential for power-related fault recoveries; 6) potentially require a higher-level scrutiny and analysis by the operations team. A rough order of magnitude cost estimate for performing these activities was $2.0M.[**]

Overall, it was determined the use of a solar power source could introduce significant impacts to mission operations and operability.

The OPRWG also identified operability issues and operations complexities associated with operating a flight system with a radioisotope power system (RPS). These were fewer than with a solar powered system, and included the need to plan and implement "sufficiently high orbit" measures for launch, and Earth avoidance measures for flybys. As with the solar powered option, the operations team would need to develop, run, and maintain power models and incorporate them into a full-orbit simulation to ensure sufficient power was available to support planned flight system activities. But these models and simulations would not require the complexity of the solar powered analogs. A rough order of magnitude cost estimate for performing these activities was $1.5M. It was determined the use of an RPS would introduce relatively minor impacts to mission operations.

The solar option was evaluated by the OPRWG as the *least* desirable choice from an *operability* perspective. But the operability impacts were outweighed by other evaluation categories. Ultimately a solar-based power was chosen by the project over RPS partly due to: the cost differential between solar and RPS (on the order of tens of millions of dollars for solar versus low hundreds of millions for MMRTGs); shorter development and procurement lead time with solar; long lead time with nuclear due to plutonium production; shorter solar qualification schedule; and ease of scaling with solar. Solar became the project baseline in August 2014.

One of the roles of the OPRWG is to propose requirements to help mitigate the negative effects on operability of decisions made in the design process. Table 3 presents two new operability requirements developed to address changes in the system's characteristics when going to a solar power source.

[**] The cost information contained in this document is of a budgetary and planning nature and is intended for informational purposes only. It does not constitute a commitment on the part of JPL and/or Caltech.

OPR.300	**High-fidelity power balance prediction capability.** "The MOS shall predict via modeling that the flight system can provide sufficient power/ energy to complete the planned flight system activities and science data collection."
Rationale / Aspect of Operability	**predictability**: Power output is a function of many factors (e.g., distance from sun, solar incidence angle, attitude, temperature, eclipsing/ shadowing, propulsion contaminants, radiation, etc.). The operations team must be able to predict if upcoming flight system activities will be supportable by the power subsystem, without violating any requirements/ constraints (e.g., state of charge before a flyby, state of charge before a Ka-band downlink can begin, etc.), and can do so with acceptable margin. A high-fidelity power balance prediction capability which will enable the planning and sequencing team to verify sequences (including background, OTMs, flybys, downlinks, science calibrations, etc.), planned for a TBD period, fit within the available power profile, including margin. **efficiency:** Required for operations team to fly this power-limited, highly coupled (attitude, thermal, power, etc.) spacecraft. This is especially true if the ops team is small (our goal). **robustness:** Helps ensure safety of the flight system by helping to prevent "over-subscribing" available power resources (i.e., this increases the fidelity of predicted power margins).
Source	**Source**: Historic operations community experience and lessons learned, based on chosen spacecraft design implementation (results of the power source trade).

OPR.220	**Battery state of charge telemetry.** "The flight system shall provide the MOS with telemetry necessary to be able to determine battery state of charge, throughout the mission, accurate to within ±15% of the actual value."
Rationale / Aspect of Operability	**visibility**: Ensures that telemetry necessary to determine the state of charge of the spacecraft battery is made available to the operations team. **predictability**: Provides input to the high-fidelity, integrated power/ thermal/ sequence model. The operations team must be able to predict if upcoming flight system activities will be supportable by the power subsystem, without violating any requirements/ constraints (e.g., state of charge before a flyby, state of charge before a Ka-band downlink can begin, etc.), and can do so with acceptable margin.
Source	**Source**: Historic operations community experience and lessons learned, based on chosen spacecraft design implementation (results of the power source trade)

Table 3 Example Operability requirements resulting from trade study decisions

2. Design Decisions— Response to Onboard Storage Design Changes

Operability concerns significantly shaped design decisions regarding the Europa Clipper's onboard science data storage. A key aspect of the Clipper's mission is the collection of a large fraction of its science data during the few hours around each closest approach to Europa. The presence of multiple imaging instruments and sounding radar requires the data system to handle very high rates of data transfer from the instruments (most of which do not buffer data internally). Data are streamed from the instrument into the bulk data storage (BDS) subsystem to await downlink.

During early formulation phase, the flight and operations members of the OPRWG were asserting that the Europa Clipper hardware design would support onboard storage of instrument-created files, enabling the operations team to make straightforward selections of files for downlink during the data return (or playback) portion of each encounter. Due to mass, power, and other constraints, it was found that the BDS would be unable to sort the multiple high-rate input data streams in real time and create individual files for each instrument. Once this was understood, the spacecraft design team began a series of discussions with key stakeholders, including the OPRWG, instrument teams, and MOS designers to re-establish with how data were to be stored onboard and selected for downlink.

Initial discussions included the possibility of treating the BDS like a tape recorder—a first in, first out (FIFO) device. This was untenable, failing to meet both science and MOS needs. In discussion, the acknowledgement of science needs (e.g., to selectively return data), and of operability concerns (e.g., operational efficiency) helped to guide the process of assessing potential solutions. The interdisciplinary team working this issue was able to identify the following key operability and science concerns:

- Selective replay of data. Some instruments are able to significantly increase science return by early analysis of part of their data for a given flyby, then selective return of remaining portions.
- Prioritized data return scheme. Some instruments need to return data within a certain period in order to support operational decisions. The MASPEX instrument is a particularly driving case. MASPEX must receive and analyze a portion of data collected near Europa within a few days after the flyby in order to support onboard processing of cold-trap samples (performed at apojove, in order to minimize radiation interference to measurements).
- Creation of accountable data products (ADP). While instrument-created files are not supported by the BDS design, the addition of metadata to the instrument data packets could be used to create logical "files" (groups of packets) that could then be the basis for both planning (of data production and data return) and for post-data-return accountability.
- Efficiency of science data return. Designs that support the above three concerns can range from those requiring frequent, detailed input from instrument operators to update downlink priorities during a post-flyby period, to those that facilitate up-front planning and prioritization of data return, and tend to minimize the need to update that data return plan.

In considering solutions, the nine aspects of operability were not considered formally. Time limitations and the interactive, iterative nature of the design process (necessitated by spacecraft development schedules) required a lightweight approach to reaching design decisions. However, the involvement of the OPRWG and other experienced MOS personnel meant that such criteria were part of any solutions that were acceptable. In effect, the participation of engineers experienced in the consideration of operability criteria resulted in more operable solutions than might have been considered otherwise. In addition, the development of key step-by-step operations scenarios significantly improved common understanding by the design team while helping to reinforce the value of incorporating operability concerns. The first was for the onboard production and processing of science data, from an information transfer perspective. The second was from an operator's perspective, looking at the planning of science activities through the selection of data for return, transmission of data to the ground, and delivery to end-user science teams.

The result of design discussions yielded a BDS system design that relies on post-flyby sorting of recorded science data, placing it in logical "bins" according to instrument and priority for downlink. Data are most easily selected for downlink on the basis of instrument and priority number. Stored data can also be selected for downlink on the basis of a time range (related to instrument data packet creation) or the name of the fixed-length files that make up the smallest addressable unit of data within the BDS. The set of methods for data selection enables a highly operations-efficient scheme for most of the data return (based on a simple set of priorities that would change little from one encounter to the next). Further, it retains the flexibility needed to modify priorities as data is received. This is accomplished by modifying downlink instructions to return data according to time range.

The net result of this design negotiation was largely successful in terms of operability. While the design constraints imposed by the harsh Jovian environment, budget, and schedule constraints prevented the desired use of a conventional file system onboard, careful prioritization and minimalist application of operability concerns resulted in an achievable design that meets operator's most important needs.

3. Scenario Development—Safemode Recovery Timeline Example

To accommodate power and mass limitations on the spacecraft, the telecom subsystem was designed to be as efficient as possible for nominal operations. This is reflected in the use of a low-mass Mars Science Laboratory (MSL) heritage medium gain antenna (MGA), and a 20W TWTA. However, this results in hardware that does not provide as much signal strength for off-nominal operations scenarios, particularly spacecraft safemode events, as is generally available for deep-space missions. For certain spacecraft distances and geometries, special tactics will be required to restore communications after a safemode event, whereas typically, low-rate telemetry data (e.g. 10-40 bps) would be continuously transmitted to the ground.

These tactics include "clocking" (moving the antenna boresight around the estimated sun position), as well as a "rotisserie" roll (rotating the spacecraft Y-axis about the sun-line). Clocking and rotisserie modes require ground involvement to monitor and stop the rotation at a position that is optimal for restoring communications, which allows diagnosis of the fault that resulted in the safemode execution. Due to the complex nature of the interaction required, and the long one-way light times, these ground activities could take as long as 22 hours to execute.

From an operability point of view, this design results in compromised visibility into the state of the flight system, particularly for the critical period immediately following a significant spacecraft anomaly. In addition, tractability is reduced by the need to add more operational steps and decisions before basic information is received.

These impacts to operability were identified, and the Flight Systems Engineering team was engaged to perform a trade study to determine if it was reasonable to make changes to the baseline spacecraft design to improve its operability. Several options were identified that could mitigate these impacts to operability, in particular a higher-power TWTA, as well as a larger, more capable MGA. However, due to the significant negative mass and power impacts these measures would incur, the decision was to retain the baseline design.

While this trade was not decided in operations favor, the flight system did make an effort to reduce the impact and risk to operations. One step taken was to re-examine the time required for the spacecraft to restore communications after a worst-case fault, which provides operations more time to perform the steps described above. Another step was to carefully analyze the potential fault scenarios, to ensure that only very low likelihood, non-exempted faults would result in the spacecraft being placed in sun-relative attitude determination modes, thereby reducing the probability that these complex operational activities would need to be executed.

4. Trade Study Participation—Autonomous Recovery During Flybys

The intense Jovian radiation environment poses a significant challenge to spacecraft like Europa Clipper that must operate within it. The Clipper mission's strategy of repeated flybys (as opposed to orbiting Europa) is driven by radiation issues as much as by the delta-V and propellant mass requirements for achieving a Europa orbit. All spacecraft that have flown through into the high-radiation environment of the Io plasma torus have experienced at least some anomalous events related to radiation-induced charging or radiation-induced component damage (temporary or permanent) [8]. Although Clipper's hardware design (which includes a shielded vault for avionics and data storage) is intended to protect the mission from radiation effects, there remains the potential for design escapes or unforeseen vulnerabilities.

Using the Europa Clipper mission's simulation capabilities, engineers have found that repeated anomalies within a few days of Europa closest approach would significantly impact overall science return if they resulted in spacecraft safing and required ground-in-the-loop recovery. This led the project to initiate a trade study into ways to best perform autonomous recovery of the spacecraft, at least for subset of potential fault cases.

The trade study examined three control architecture options to support rapid recovery:

- Option 1: A ground-sequenced approach, similar to that taken by the New Horizon's mission, in which a recoverable fault that interrupted the nominal sequence would be dealt with by restarting the sequence and rolling forward in time to the next restart time point [9]. In this approach, the sequence would consist of self-contained segments, one for each restart time point. All commands necessary to establish the proper initial conditions and spacecraft states for the execution of subsequent spacecraft and instrument activities would be included at the beginning of each segment.
- Option 2: A contingency state-matching sequence approach. In this option, a contingency sequence is developed to perform the state-matching task after a recoverable fault. Once the avionics have recovered basic spacecraft functions, the contingency sequence would execute to take the necessary actions to match spacecraft states to those needed to support a restart of the nominal sequence at time a few minutes after the recovery began.
- Option 3: A declarative command approach. This approach relies on flight software to keep track of ground-commanded states and to have the capability to autonomously replan and retry in the event of recoverable anomalies. This option would have responded to a recoverable fault with onboard knowledge of the current state of the spacecraft and instruments, and the ability to recover some observations as well as to return to the nominal plan shortly after the fault

As part of the evaluation of the trade space, the following subjective criteria were considered.

- flexibility*
- testability*
- robustness*
- predictability*
- expressivity*
- reusability
- development risk
- operations risk

The first five of these (denoted by *) are aspects of operability. The first four are, as defined in the study, identical to their counterparts in the nine aspects of operability described earlier. Expressivity is the ease of communicating planned intent, and is a subset of tractability. Reusability is the extent to which a capability developed for Clipper might be reusable by another, later mission. In addition to the familiar consideration of risk, estimates of the cost were also included as criteria.

The inclusion of specific operability criteria in the trade space evaluation significantly improved the degree to which operations concerns were able to productively influence the discussion and improve the depth and breadth of potential issues with any given option. For example, Option 1 was very predictable, and likely to be quite robust, since it was a straightforward method. It also was the most straightforward method to test. But it suffered considerably in terms of flexibility, because of the need to specifically constrain restart points to a finite number of times during a flyby when spacecraft states could be guaranteed. It also appeared to be quite labor-intensive (by analogy to the New Horizons Pluto Flyby sequence), and thus costly during operations at Jupiter.

Option 3 scored well in terms of flexibility and expressivity, and was perceived as being highly robust. However, there were concerns about how testable such a scheme would be, both in pre-flight testing and in ground validation of any declarative-type command sequences and all the accompanying fault cases. It was unclear how well the operations team would have been able to predict the behavior of the spacecraft, or even to reconstruct it after the fact, under Option 3. Ultimately, it appeared to also include significant risk and cost to develop.

Option 2 was evaluated as being intermediate in terms of the five aspects of operability. It was a much more flexible solution than Option 1, but still had limitations that Option 3 didn't. In particular, predictability weighed heavily in the comparison by the operations personnel between Options 2 and 3. Option 2 was seen as much more likely to be predictable before execution, and more likely to be able to be reconstructed after the fact, an important consideration in dealing with any situation in which the recovery capability did not perform as expected. It was also seen as being somewhat intermediate in cost and risk, both in development and operations.

From the standpoint of operability, which option was chosen (it was Option 2) is not particularly important. What is important is that the explicit consideration of operability criteria facilitated a broader, more comprehensive technical discussion of the pros and cons of each option than might have occurred without them. By elevating operations concerns to being included in a trade space helps to ensure that discussion includes such items as the operations scenarios for each option, which helped surface specific issues such as the needs of operators to validate command sequences on the ground prior to uplink.

5. Use of integrated system modeling tools and analyses.

Europa Clipper's early system modeling tools and analyses have been invaluable to the OPRWG in their evaluation of project trade studies, engineering change requests, operational scenarios, and requirements verification [10]. These high-fidelity, mission-level simulations model the spacecraft, ground, and environment from launch to end-of-mission, and allow the user to better understand how design changes (e.g., mechanical configuration, component selection), impact the system (e.g., data volume generation and latency, power/ energy demands and generation; telecom link margin). The results of these analyses allow for realistic determination of the impacts to the operability of the system of a given change. This modeling capability played an indispensable role in the evaluations cited above (III.G.1-4).

H. Ongoing Assessment of Europa Clipper Operability

One of the roles of the OPRWG is to provide an on-going assessment of the operability of Europa Clipper throughout its lifecycle. The OPRWG established a baseline operability assessment prior to flight system Preliminary Design Review in October 2017. The OPRWG will update this assessment prior to future gate reviews, and use the assessment as a mechanism to track the evolving operability of the system, and to influence and improve the operability of the selected design.

As part of the baseline operability assessment, the OPRWG identified "enhancers" and "detractors" to operability. Enhancers (or pros, pluses) are attributes that improve system operability, while detractors (or cons, minuses) are attributes that reduce system operability. Enhancers and detractors (for a flagship class mission) were quantified as follows (Table 4):

	Qualitative Definition	Cost Impact	Personnel Impact
Enhancers			
+++	high, significant, considerable positive impact on operability	>$3M	> 10 WY
++	medium, meaningful positive impact on operability	≤ $1M	≤ 3 WY
+	low, small, minor positive impact on operability	≤ $300K	≤ 1 WY
Detractors			
- - -	high, significant, considerable negative impact on operability	>$3M	> 10 WY
- -	high, significant, considerable negative impact on operability	≤ $1M	≤ 3 WY
-	low, small, minor negative impact on operability	≤ $300K	≤ 1 WY

Table 4 Definitions of operability enhancers and detractors

Enhancers or detractors were either *programmatic* or *design* in nature. Programmatic factors are those that result from the basic nature, architecture, or structure of the mission, and are not associated with any design decisions made. Design factors are those that result from design and implementation decisions made to implement the mission.

Table 5 shows a sample of some of the enhancers and detractors identified by the OPRWG 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			

Table 5 Sample operability enhancers and detractors

Members of the OPRWG then weighed the enhancers and detractors associated with each aspect of operability and determined a relative baseline operability ranking for that aspect of operability (Fig. 3). At the time of this assessment (flight system PDR), Europa Clipper was deemed an operable system, with overall average ranking across the aspects of operability.

The largest contributor a reduced visibility ranking was the result of the bulk data storage (BDS) implementation selected by the project (Section III.G.2). The largest contributor a positive robustness ranking comes from the project's decision to use CFDP protocol for assured uplink and downlink, as well as the implementation of the activity restart timeline (ART) architecture (see Section III.G.4). The largest contributor to a reduced tractability ranking was the projects selection of a solar array as the flight system's power source (Section III.G.1).

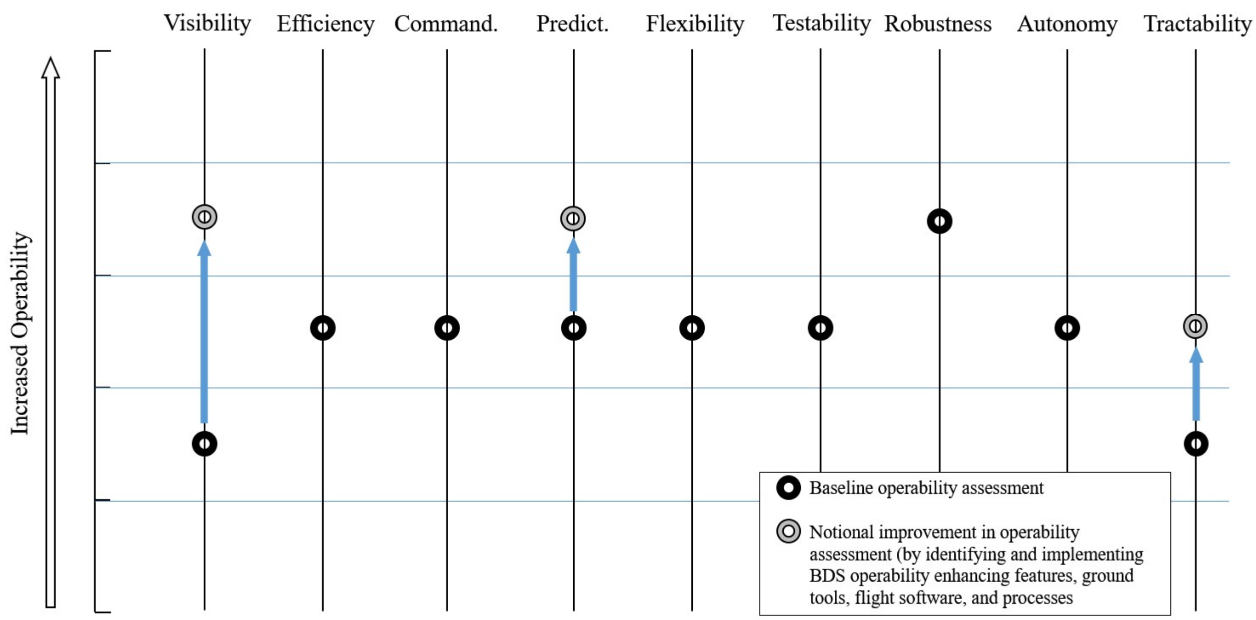

Fig. 3 Notional baseline Europa Clipper operability assessment

One of the utilities of this evaluation is to help influence and improve the operability of selected designs. For example, if measures were taken by Europa Clipper to identify and implement bulk data store operability-enhancing features, ground tools, flight software, and processes, it is expected to have a beneficial impact on several aspects of the operability assessment (Fig. 3).

As this operability assessment is repeated throughout the project lifecycle, and operability-improving enhancements are implemented, it is expected that the evaluation will indicate an increase in the system operability score. A future task of the OPRWG will be to perform similar assessments on past and current space missions. This will serve as a useful comparison tool to help assess 1) how Europa Clipper operability compares to similar missions; and 2) will help the space operations community track the evolving progress of operability.

IV. Lessons Learned

After implementing operability on Europa Clipper beginning in Pre-Phase-A, the OPRWG has captured a few lesson learned that may be beneficial to the space operations community:

1) **Get early project support for operability**. Early project management endorsement of operability was instrumental in establishing operability as a tenet of Europa Clipper. This official endorsement helped set the tone, and laid out the expectation that operability would be considered in design decisions.

2) **Infuse operability early into project development processes.** Early consideration (Pre-Phase-A) 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 (ECR) evaluations. Socialization of operability impacts has been made via participation in numerous project working groups.

3) **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. (This was not attempted on Europa Clipper mission). Future projects should socialize instrument operability via the instrument announcement of opportunity (AO) (a NASA Headquarters generated document), and the proposal information package (PIP) (project generated).

4) **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.

5) **Track operability trade-by-trade and cumulatively**. Operability has seldom been the discriminating factor in Europa Clipper trade studies. Operability is only one of many evaluation factors considered (e.g., cost, schedule). Many decisions have been made that have decreased operability (e.g., the bulk data store design). But nonetheless, 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. Going into operations prepared to deal with impacts of design decisions is preferable to being blindsided. 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."

6) **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. Ideally, they would define for themselves, based on their operations experience, what operability means within their discipline, and establish their own set of operability requirements and policies for that discipline. It would provide them with a sense of ownership of these requirements, as opposed to the appearance of having them "imposed from above."

V. Next Steps

The early phases of project formulation focus on requirements development, architecture concepts, concepts of operation, and trade studies. The focus of the operability effort during these early phases of a project supports these same efforts. Requirements on flight and ground system designs to enhance the aspects of operability are derived and flowed down. The architecture characteristics should be developed with operability attributes in mind. The concept of operations should look for ways to reduce operator load and team size, automate where possible both in onboard functionality and in the ground software, and take steps to reduce operations cost and risk by employing choices to invoke aspects of operability. Finally, trade studies and design decisions should consider operability as a trade criteria, and the Operability Engineer should impact and participate in such trades.

During the preliminary design phase, the Operability Engineer continues to assess design choices against the operability requirements to ensure intent is being met, providing input to trade studies and communicating the "soft" impacts that tie to aspects of operability that are not as easily quantifiable. The Operability Engineer participates in project change control processes, providing official impact assessments applicable to requirements or design changes under change control. Functional Design Document (FDD) development and table top reviews of flight and ground system designs involve the Operability Engineer, and the delivered baseline FDDs have an operations/operability as signatories. As the System Integration & Test plan and testbed / simulation venue development begins to mature, the Operability Engineer will begin to focus on testability aspects, working alongside the verification and validation (V&V) engineers.

As the project matures into the implementation phase, operability efforts move towards inclusion of the Operability Engineer in development of integrated system test plans, training and staffing development, and operational readiness testing. Areas of focus in this phase of the mission development include human factors, workflow and ground process automation, staffing strategies (e.g. multi-shift arrangements, backups and cross training approaches), and general workforce-loading studies. The Operability Engineer is also an excellent candidate for performing cross-cutting systems coordination tasks, such as coordinating an end-to-end set of phase-specific operations through planning, testing, and execution. The assessment of the system against operability characteristics continues throughout this phase as well, gauging "how the project is doing" as hardware and software actually come into being.

The Operability Engineer's job doesn't end when the system design is complete. They will capture and enable the lessons learned during testing and training and funnel those lessons back into the system, and into the institution. The Operability Engineer's role should continue into Phase E early operations to capture all early operations lessons learned to benefit future missions.

VI. 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.

Nomenclature

ACS	attitude control system
ADP	accountable data products
AO	announcement of opportunity
APL	Johns Hopkins Applied Physics Laboratory
ART	activity restart timeline
ASRG	advanced Stirling radioisotope generator
BDS	bulk data store
BPS	bits per second
C/A	closest approach
Caltech	California Institute of Technology
CFDP	CCSDS File Delivery Protocol
DP	(JPL) Design Principles
DSN	Deep Space Network
ECR	Engineering Change Request
ECSS	European Cooperation for Space Standardization
FDD	Functional Design Document
FIFO	first in, first out
FSW	flight software
GDS	ground data system
ISO	International Organization for Standardization
JPL	Jet Propulsion Laboratory
KSC	Kennedy Space Center
MMRTG	multi-mission radioisotope thermoelectric generator
MSL	Mars Science Laboratory
MSM	Mission System Manager
MOS	mission operation system
OPRWG	operability working group
OTM	orbit trim maneuver
PDR	Preliminary Design Review
PIP	proposal information package
RBSP	Radiation Belt Storm Probes (APL)
RPS	radioisotope power system
RWA	reaction wheel assembly
TWTA	travelling wave tube assembly
V&V	verification and validation
WY	work year

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