The Reference Activity Plan: Collaborative, Agile Planning for NASA's Europa Clipper Mission

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Abstract— **Activity planning efforts on planetary exploration missions must effectively translate high-level scientific objectives into command products that execute onboard the spacecraft. In prior flagship-class orbiter missions, this process has been implemented using two approaches: activity plans are either systematically created from scratch for each orbit via a linear planning process, or future orbit plans are developed far in advance and carefully iterated upon to ensure maximum science return. These approaches have been effective, particularly for projects whose science observation strategies vary over the course of the mission, but require a number of operational constraints. Large team sizes, difficulty in relating detailed plans to qualitative science objectives, and the fragile nature of pre-planned activity sets allow limited opportunity for flexibility and optimization of plans during development.**

The baseline trajectory design for the Europa Clipper mission uses a suite of 45 low-altitude, short-period flybys of Europa at varying geometries to globally map the surface of the moon. In order to effectively integrate the activities of the spacecraft and its ten science instruments into a valid plan on the cadence necessitated by the trajectory design, mission operations engineers have developed a collaborative, agile uplink planning architecture. The foundational product of this planning architecture is the Reference Activity Plan (RAP), a full-mission activity plan that leverages the project's largely repeatable science observation patterns to create a template for planning at both strategic and tactical levels. Activities in the RAP are codified using a common schema and can be placed in the plan using constraint-based scheduling software that is driven by objective and quantifiable science measurement requirements. This approach enables dynamic modification of the whole mission plan in large or small segments, which allows planners to react to new science information or incorporate flight system performance characteristics into future orbit activities. The RAP also allows planners to understand the impact of their activity changes on the rest of the plan; since each subject matter expert has visibility into the entire set of planned activities, and the impact of their proposed changes upon the full plan is simulated, they can more effectively collaborate with the rest of the operations team to develop a conflict-free plan with less iteration. This paper examines unique operations considerations that drove the design of the Reference Activity Plan, the composition and proposed implementation of the RAP, and how the use of a single authoritative activity plan allows collaborative, flexible planning during uplink plan development.

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1. INTRODUCTION

Strategic and tactical activity planning is a critical component of operations for planetary exploration missions. Due to mission objectives that require complex science observation strategies and lengthy one-way light times between spacecraft and Earth, operations teams must invest significant time planning and creating commands for each desired instrument and spacecraft behavior up to several months before execution. Past projects have used various approaches to effectively evolve strategic mission objectives into executable activity plans, but significant pain points exist with each heritage process. NASA's Europa Clipper mission's unique operations concept and restrictive activity planning time drivers have necessitated the development of a novel, agile planning approach that allows operations staff to plan at both strategic and tactical levels while reducing historic uplink planning pain points.

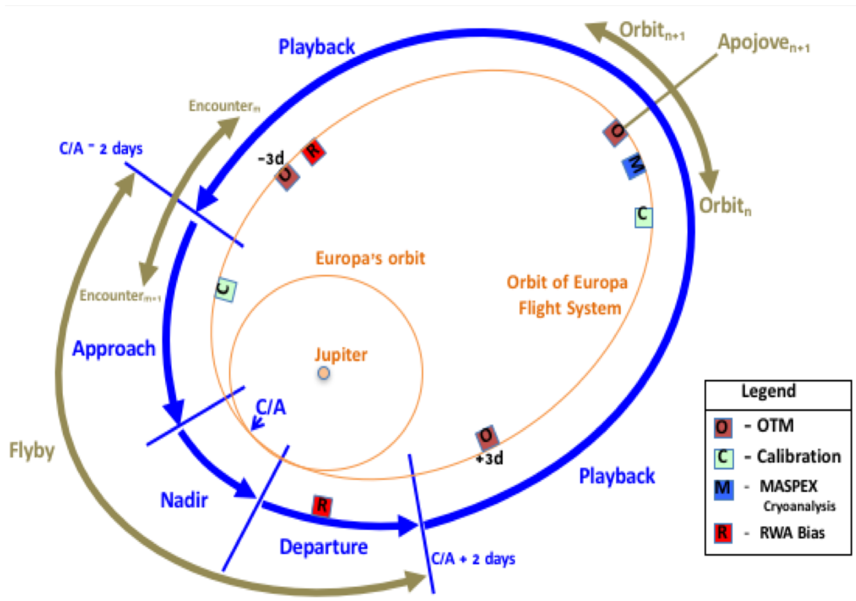

Fig. 1. Europa Clipper's orbit phases relative to Europa Closest Approach (C/A)

2. Europa Clipper Mission Overview

The Europa Clipper mission seeks to assess the habitability of Europa by characterizing four areas of scientific interest: properties and heterogeneity of the moon's ice shell and subsurface liquid water ocean, chemistry and composition of water, surface features and geologic motion within the ice shell, and any dynamic processes, like plumes or thermal anomalies, occurring on the moon. In order to effectively observe the desired properties of the moon, particularly those that evolve over time, it is necessary to collect multiple concurrent science data sets with the entire suite of onboard instrumentation [1].

Quantifying the effectiveness of the current trajectory, and subsequent refinements, is accomplished through evaluation of science measurement requirements. These requirements relate a specific measurement data type to a set of composite products which provide the necessary information to characterize each of the four primary science objectives. By tracking the collection of each data type over the course of the mission, the operations team can project when sufficiently robust measurement sets exist to meet mission objectives. Additional details on the formulation of measurement requirements are outlined in [2].

Europa Clipper's operations concept achieves the desired global coverage of the moon by executing approximately forty-five flybys, or encounters, of Europa as the Clipper spacecraft orbits Jupiter during the tour phase of the mission. These flybys have been designed using Jovian satellite gravity assists to rotate the spacecraft's orbit around Europa while limiting spacecraft exposure to Jupiter's powerful radiation environment [3]-[5]. Each encounter is divided into four functional phases: approach, which begins two days prior to closest approach of Europa; the nadir phase, during which the spacecraft is pointed in a nadir orientation for the entirety of the closest approach period; departure, which spans the two days following closest approach; and the playback phase, during which data from the preceding closest approach is downlinked to the ground (Fig. 1). The set of approach, nadir, and departure phases is also known as the flyby phase.

With the exception of calibration activities and in-situ measurements, the majority of science data collection occurs during the flyby. All science instruments will be on and collecting data simultaneously during the nadir phase of each encounter. Due to the consistency in the spacecraft pointing profile around closest approach of each flyby, a templatized set of science observations have been developed to ensure comparable data sets are collected during each encounter.

The flight system, which comprises the spacecraft and ten scientific instruments, has been engineered to withstand the inhospitable Jovian environment and support simple, repeatable science operations. Spacecraft and instrument designs are captured in detail in [6]-[9].

3. Mission Operations Overview

The Europa Clipper Mission Operations System (MOS) is composed of the flight operations teams, operations processes, services, hardware, software, facilities and network infrastructure responsible for maintaining successful operations of the flight system throughout the mission. This includes primary functions such as: planning spacecraft and instrument activities; developing and transmitting commands to the spacecraft; monitoring and assessing flight system health and performance; identifying, investigating and

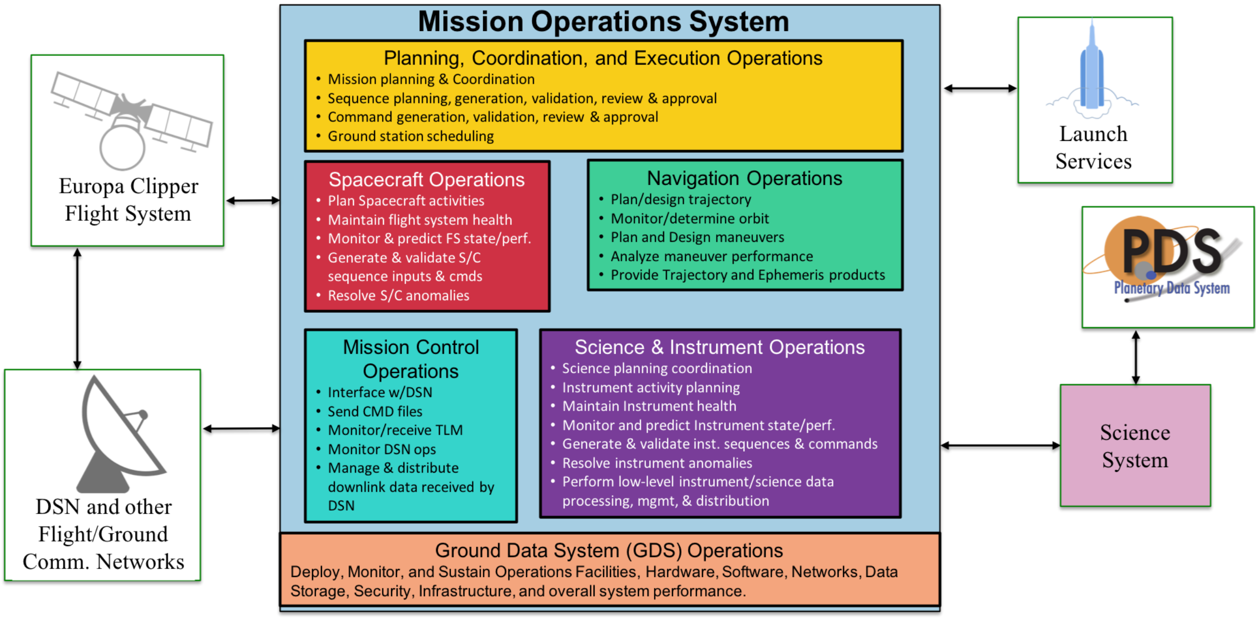

Fig. 2. The Europa Clipper Mission Operations System is composed of six discipline oriented subsystem areas

responding to spacecraft anomalies or discoveries; and storing and disseminating collected science and engineering data. The MOS is composed of a core set of discipline-oriented subsystems that are designed to work together as a closed-loop system to operate the flight system (Fig. 2). Members of the MOS are physically distributed, with operations personnel in California, Maryland, Colorado, Texas, and Arizona.

The Ground Data System (GDS) is part of the MOS, and is composed of the underlying hardware, software, networks, facilities, and infrastructure responsible for collecting, processing, archiving and disseminating command products, telemetry, radiometric data, science and engineering data transmitted to/from the Flight System, and for deploying and sustaining these components and systems throughout the mission.

4. Heritage Uplink Planning Architectures

Planning the detailed science and engineering activities for robotic space missions is a complex and laborious process, particularly for missions in deep space. Planning systems, also referred to as uplink systems, are the portion of an overall mission operations system that is responsible for defining and creating the specific activities and commands that will be uplinked and carried out by flight hardware and software. Designers and implementers of planning systems contend with factors such as spacecraft and payloads that are highly individualistic or unique, highly constrained budgets, and the difficulty of incorporating operator concerns into flight hardware and software designs. These planning systems tend to share a number of concerns in common:

- The need to integrate a diverse set of plan inputs from payload and spacecraft operators into a single plan that meets both operator intent and all of the resource, geometric, scheduling, and other constraints imposed by the flight hardware and software, stakeholder needs (e.g., science results), physics, and the space environment.
- The use of sequences, tables, and other constructs that are uplinked to the spacecraft to control its behavior.
- The need for methods to resolve conflicting operator desires or constraint violations within a specific operational timeline.
- A planning approach that proceeds from the strategic, long-term view, to the more tactical, short-term view, as well as the need to ensure the impact of short-term planning changes on overall, more strategic mission plans and goals.
- The need to keep any command-related errors to a practical minimum, which affects duration and iteration in planning processes, configuration management, and automated verification and validation, among other system characteristics.

In trying to fulfill these and other needs within their cost and schedule constraints, there are two competing tensions in uplink system development:

1. A desire for reuse; utilizing applicable parts (software, interfaces, designs, processes) of previous systems.

2. A desire for improvement; updating or replacing systems in part or whole, in order to address operational pain points or inefficiencies.

In general, uplink planning systems have evolved in an incremental fashion, with piecewise improvements being made (or not) on the basis of whether reuse or improvement was perceived as "better" from a standpoint of cost, risk, schedule and other mission constraints. This approach tends to leave out certain fundamental, architectural issues that recur across multiple missions as discussed in [10]-[11]. In developing Europa Clipper's planning system, we considered some of the following aspects of legacy systems as areas where changes could potentially yield overall improvement in cost and efficiency across the mission lifecycle:

- The use of separate software tools and resource or constraint models for activity planning vs. sequence generation
- The fact that activities identified in early planning are only implicitly related to final, uplinkable sequence products.
- The degree to which manual, implicit efforts are needed to "close the loop" and ensure accurate predictions of initial conditions for each sequence start.
- The amount of time-consuming, iterative negotiations to resolve competing priorities between activities (such as science observations) or to resolve violations of resources or other constraints.
- Predominance of software characterized by pipe-and-filter tools, necessitating the creation of many dozens of files and processes to identify and use authoritative versions of those files.
- Use of "glue ware" or informal scripts to fill gaps in planning software functionality and to provide automation.
- Large degree of variability in resource modeling tools and their interfaces with planning systems, making planning system integration difficult.
- Lack of explicit relationships between mission objectives and planned science activities, making assessment of various plan alternatives (e.g., trajectories, priorities between observations, etc.) a highly subjective, often laborious exercise.

The Clipper planning system's response to each of these items is discussed in Section 6.

5. Operational Drivers for Europa Clipper's Uplink Planning Architecture

The nature and complexity of the Europa Clipper Science Mission, coupled with key aspects of the Flight System and Mission Design, drives the MOS towards the use of a collaborative and integrative planning and sequencing approach. Those drivers include, but are certainly not limited to: collaborative science collection by 10 science instruments; varying instrument software and command architectures; repeatable nature of observations on each flyby; shared resource limitations; short encounter durations; and the number of navigation maneuvers required on each encounter to implement the complex trajectory.

Science planning on this mission is highly collaborative at both the strategic and tactical levels. Europa Clipper's ten science instruments tie together closely with collaborative science goals and collaborative data acquisition plans. This requires an integrated plan to meet overall goals, as opposed to individual science opportunities and plans for each instrument. Data product transparency and availability to all participants is key. Europa Clipper instrument command products for the various science / instrument investigations will vary in form and command methodology. Some instrument control programs reside/execute within the instrument, while some are stored onboard within instrument storage, and can be activated by spacecraft sequenced commands, and yet others are executed out of spacecraft sequence engines as spacecraft commands directly to the instruments. The Mission Operations System needs a planning and sequencing approach that can translate, model, and simulate the behavior of all instrument and spacecraft commanding in order to provide visibility into the impacts on shared resources.

The mission concept relies on a repeatable pattern of observations that is performed during each encounter - the mission plan generally includes the same type of activities during the approach phase, nadir, and departure phases of each Europa encounter, with minor variations depending on flyby altitude and lighting conditions. Such a mission concept lends itself to beneficial use of re-usable, ground-developed, parameterized activities that can be scheduled in software.

Due to the collaborative nature of the nadir-focused flyby, spacecraft attitude and pointing are critical shared resources and constraints on collaborative planning. An integrated spacecraft pointing plan should be a product of strategic planning and subject to relatively few changes during tactical planning. Pointing is controlled at the spacecraft level, with the exception of those instruments with internal mechanisms for pointing. Additionally, data volume is a critical shared resource. While data storage onboard the spacecraft is not particularly mission-limiting, the downlink data volume per encounter is. The instruments are able to collect far more data than they can downlink during a given encounter. This drives the need to manage and track the collected and downlinked data volume for each instrument at a system level. Since Europa Clipper is a solar-powered mission traveling at large solar distances, energy production and power management at Jupiter, particularly towards end of life, have tight margins. Due to this, operational power management by the MOS is a key task, and will drive the need to model and simulate the energy usage and the state of the power system for each encounter prior to uplink.

The short duration between Europa targeted flybys (typically 14-days) combined with the cadence of maneuvers (3 per orbit), equates to a hefty potential operations workload. To accommodate this, the operations processes are designed with as little overlap as possible. The team plans to build a set of sequences that encompass ~28 days in duration (2 encounters), in less than 28 days. This means the flight team must complete the detailed sequence planning, generation, validation, and uplink of 28 days-worth of sequences/command products in less than 28 calendar days (i.e. < ~20 work days), including margin and allowing for multiple uplink opportunities.

The size of the mission and number of instrument teams, along with the distributed nature of operations across the country drives the need for good communication and collaboration. Common access to planning tools, behavior models, and simulation/validation capabilities will allow for the necessary collaboration for mission success.

6. Overview of Clipper Planning Architecture & Key Differences from Heritage

In architecting and designing the Clipper planning system, the MOS have chosen to focus on a number of key system capabilities that address some of the pain points described above. This section describes those capabilities and how they are expected to address such issues.

Most previous missions deal with the difference between earlier planning ("activity planning"), most frequently accomplished at the level of activities for each payload or spacecraft subsystem, and creation of uplinkable command products ("sequence generation") by using separate software applications. Clipper will use a single set of software applications for both activity planning and sequence generation. This decision drives a number of the other characteristics (described and discussed below) that improve system efficiency, but a primary advantage of such as architecture is that users will not need to learn both an activity planning tool and a sequence generation tool, each with unique user interfaces and unique procedural features. Instead, when working on or developing the integrated plan the mission, whether in strategic, long-term planning, or more immediate, tactical changes, users will interact with a single interface.

A key capability that enables such a single interface is the automated generation of commands from activities. Planning at the activity level is a necessary abstraction from the highly-detailed, long list of individual commands that are necessary to direct the behavior of many spacecraft instruments and subsystems. But command generation itself may be a complex, tedious task. Systems using separate tools for activity planning and sequence generation have generally accepted that commands are generated only after activity planning is complete. This also leads to difficulty in understanding the relationship between activities and the sequenced commands that implement them. Workarounds to make the relationship explicit, such as naming conventions or use of metadata, have their own costs. By building activities such that commands may be generated directly from them in software, a labor intensive and error prone activity can be automated, and the relationship between activities and associated commands is defined and made explicit.

A second characteristic of systems with separate activity planning and sequence generation tools is that each tool tends to require its own models for estimating resources and checking of constraints. For example, some JPL missions have used the Activity Plan Generator (APGen) application for activity planning, and SEQGEN for sequence generation. Each tool commonly contains its own models for such items as power modeling or onboard data storage and downlink. Each is coded separately and must be maintained and updated by different software developers. The existence of two separate models represents both cost in updating and validating software, as well as risk should the model results differ in any substantive way. Clipper's use of a single set of applications for both planning and sequencing eliminates both undesirable qualities.

Negotiation and other efforts to resolve contention over resource usage, such as pointing, downlink bandwidth, onboard data storage, or other constraints is a significant aspect of any planning process for operations. For the Clipper architecture the MOS takes a software-assisted scheduling approach, in which activities (and thus, their associated commanding) are scheduled using constraint-based scheduling, along with a set of prioritization rules that are determined in collaboration with the Clipper science team. Such automated scheduling has been used on the Rosetta mission and is an established part of the Deep Space Network's (DSN) process for scheduling mission use of DSN assets [12]-[13]. The Clipper uplink planning process is built to accommodate the likelihood that not every single activity will be scheduled appropriately in software; however, if 80%-90% of activities can be laid out in a timeline in a manner acceptable to instrument operators and the science team, while meeting operational constraints, this will yield a significant savings in time and effort over the course of Clipper's four year tour of Europa.

The concept of a unified set of processes for activity planning and sequence generation is further supported by Clipper's decision to adopt a Reference Activity Plan (RAP) as the authoritative source of activity plans throughout operations. This key aspect of Clipper planning is discussed in more detail in Section 7. In particular, the utility of the RAP is that it replaces the need for multiple file-based inputs that must be

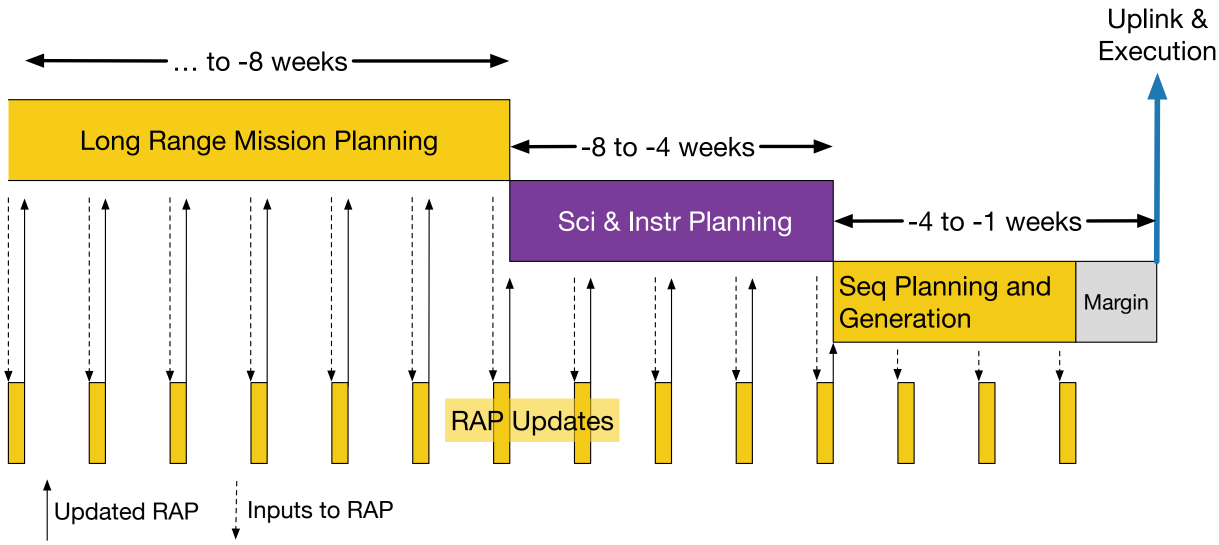

Fig. 3. Schematic representation of Clippers uplink planning flow. Long Range Mission Planning is responsible for updates to overall plans up to eight weeks prior to the beginning of execution for a four-week (two-encounter) sequence. Science and Instrument Planning makes tactical updates between eight and four weeks prior. Sequence Planning and Generation makes final adjustments. During each process and throughout Tour, the RAP Update Process provides a weekly, integrated update to the RAP, factoring in changes from all other processes.

integrated into a single authoritative file. Instead, users work with a branch or version of the RAP in a "sandbox" environment. Their inputs (and changes thereof) are maintained within the planning software and are implemented into the single, authoritative RAP only after they have been verified and validated as part of the planning process itself.

The final key capability is represented in Fig. 3 and Fig. 4. Fig. 3 depicts the four main processes that constitute Clipper's uplink planning. Long Range Mission Planning is the strategic planning process that will be used to plan the science campaign of Europa prior to arrival at the Jovian system and will maintain the overall activity plan during operations at Jupiter. Science and Instrument Planning represents the primary tactical planning phase, in which any changes to strategic plans affecting instrument operations are made. In Sequence Planning and Generation, final tweaks to the sequence for a particular pair of encounters are made, final products are generated and validated for uplink, and then products are sent to the spacecraft for execution. The MOS has currently baselined a two-encounter planning cadence, which best balances planning's ability to respond to science discoveries and operational workforce needs. The fourth process shown is the RAP Update, which serves as the integrator of any and all changes to the Reference Activity Plan. Its relationship to the other processes is depicted in Fig. 4. The RAP Update thus functions to ensure that the RAP and the initial conditions for any given sequence period (reflected in the Initial Encounter Plan (IEP)) provided to Sequence Planning and Generation are as up to date and correct as possible.

7. Key Uplink Planning Concepts: The Reference Activity Plan, Plan Inputs, Activities, and Scheduling

Reference Activity Plan Overview

The Reference Activity Plan is an information object containing the baseline integrated set of planned flight and ground system activities for the Clipper mission. It serves as the central planning product throughout operations and provides a single authoritative source for planning information so all members of the operations team know where to go to get the latest, official information. The RAP provides a means to predict the spacecraft state to which downlink telemetry can be compared to verify completion of activities and monitor health, safety, and performance. At a minimum, the RAP will contain all planned spacecraft, payload, and ground station activities (DSN configurations, etc.). The state of the spacecraft over time is predicted through simulation based on activity timing and how each activity interacts with the system (the activity's "behavior"). The description of an activity's behavior is encoded into activity definitions that are configuration managed within an activity dictionary.

Activities exist in the RAP for the current encounter planning period (e.g. E9-10) all the way through the end of the mission. As plans are executed, as-flown data will be used to seed the RAP so that the predicted state for the current encounter planning period going forward is more accurate. In addition, as-flown information combined with the predicted set of activities will provide a means to check how well the mission is performing against science objectives and ensure that the

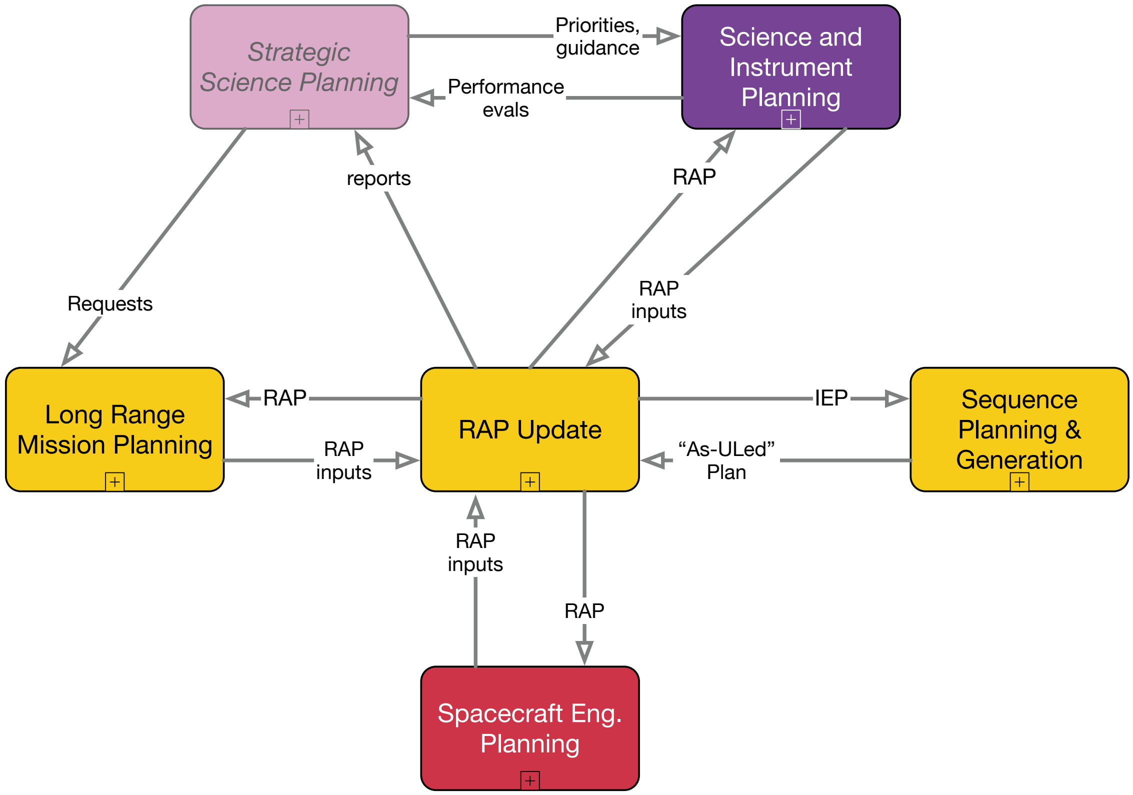

Fig. 4 Relationships between the various processes involved in Clipper uplink planning. In addition to those shown in Fig. 3, Strategic Science Planning (responsible for all science-related strategy and staffed by project Science personnel) and Spacecraft Engineering Planning (for all spacecraft maintenance and other activities) are shown. The diagram focuses on the RAP update and the information it receives from and provides to other processes.

spacecraft has sufficient resources (data storage space, energy, fuel, etc.) to complete the mission. This feature of the RAP will allow the operations team to assess mission success criteria and critical mission resources at any time during planning.

With the RAP spanning to the end of the mission, operations engineers can work strategic planning problems early and record solutions for them via the RAP. Initially, activities in the RAP far out from execution may only be representative activities since detailed planning for that time period has yet to occur. However, as that time period get closer to execution, the activities within the RAP will evolve so that they fully meet science and engineering intent by the end of the final planning iteration.

Activities within the RAP will contain sufficient detail such that they can be automatically expanded into associated spacecraft and/or instrument internal commands. In other words, an algorithm in software should exist that maps activities into the commands that cause the behavior described by that activity. Planning at the activity level with automated command expansion should dramatically increase efficiency during the typically onerous sequence generation process while decreasing the likelihood of human errors.

RAP Inputs

A new or updated RAP is generated via a scheduling and simulation process driven by configurable inputs as shown in Fig. 5. Planners adjust these inputs in order to modify activities within the RAP instead of modifying those activities directly. As a given encounter planning process gets closer to execution, there may be a time when modifying activities directly in the RAP becomes more efficient than modifying RAP inputs. The timing of this transition is a topic of on-going work on the project. A brief description of each of the RAP inputs is provided below; more detailed information on activity definitions and scheduling logic are provided in the following sections.

- Trajectory, Navigation, and Planetary Ephemerides – Current knowledge of where the spacecraft and planetary bodies of interest are and where they will be in the future. The navigation team will also provide a measure of the spacecraft orbit determination uncertainty, which may be factored into decisions on how much data instruments need to collect.

- Activity Definitions – A quantitative description of how an activity of a particular type behaves (how it affects spacecraft resources, etc.), constraints on when in the plan that activity can be considered valid, and a connection to the algorithm that describes how that activity expands into commands.

- Scheduling Logic – Algorithms and/or additional constraints that define when and where an activity or group of activities gets scheduled into the plan.

- Global Constraints – Constraints and operational restrictions that apply to all activities that must be adhered to in order for the plan to be considered valid. Many of these constraints, such as flight rules, are already in the process of being captured and will eventually get integrated into the planning system that manages the RAP.

- Models – Algorithms that describe the behavior of an aspect of the spacecraft such as power, propulsion, or attitude. These models are initialized based on spacecraft telemetry and respond to external inputs driven by activities. Many of the models have interdependencies and thus work together as one to predict the future state of the spacecraft over time.

Activities

Activities are one of the primary methods for storing and transferring planning information and are the foundation of the RAP. The most basic definition for an activity is, "a collection of mutually related behaviors, typically associated with some intent". While activities are a basic unit for planning on the ground, they are not uplinked to the spacecraft. The commands that can be expanded from activities, however, do get packaged together and sent to the spacecraft after being validated.

Many activities in a plan have very similar if not identical behavior. Activity definitions provide a means to create a "blueprint" or "template" from which individual activities, known as activity instances, are created. Activity instances inherit the majority of the behavior described in the activity definition, but have the flexibility to be modified based on additional knowledge of an activity instance's context (e.g. where in the plan the instance was scheduled). For those familiar with object-oriented programming, activity definitions and instances have the same relationship as classes and objects. An activity dictionary contains the set of all activity definitions.

The major components of an activity definition are:

- Name and Documentation – unique name and documentation that describes in words the activity's purpose and behavior

- Behavior Description – algorithmic description of how the activity interacts with the system (i.e. activity "effects"). Much of the behavior of the system itself will be described in subsystem models (e.g. power, attitude), so the activity's behavioral description must define how the activity affects those models. For example, an activity may turn on/off a piece of hardware, which in turn will change the overall system power load. The behavior description should capture the activity's effect on critical spacecraft resources like power, data, and pointing so that these resources can predicted from an activity plan.

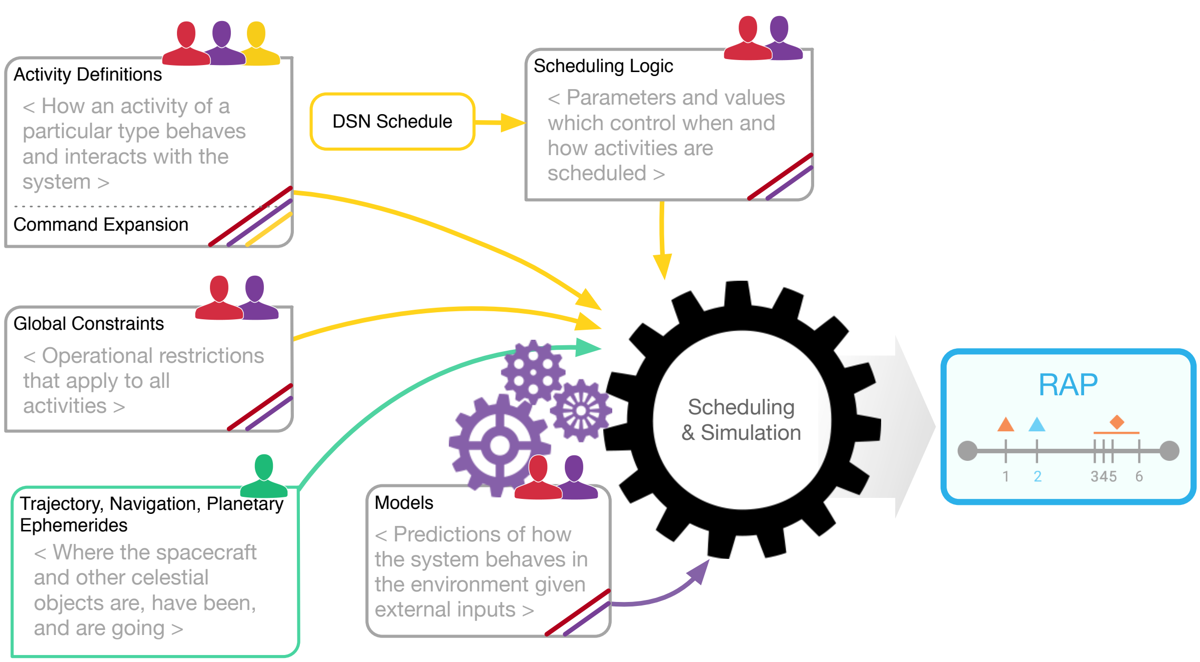

Fig. 5. Inputs used for RAP Generation. The colored figures above each input box represent the mission operations subsystem responsible for generating each input.

- Parameters – knobs that can tune activity behavior (including command expansion). The algorithms used to define an activity's behavior and command expansion can use the parameter values as variables to tweak how the activity behaves. This allows planners to develop more generic activity definitions, which results in less activity definitions for the operations team to manage.

- Constraints – list of restrictions that describe when an activity can/cannot be scheduled. Common constraints include those involving geometry (lighting, altitude, etc.) and relationships to other activities (e.g. activity 1 must occur prior to activity 2).

- Command Expansion – link to algorithmic description for how commands are used to implement the activity on-board the spacecraft. The behavioral description of the activity is essentially describing the result of using these commands.

Activity definitions serve many purposes by providing the means to track shared system resources, assess the achievement of science objectives, and produce uplinkable command products. One of the challenges operators will face is how to develop clear and concise activity definitions that can fulfill all of these purposes. A useful tool available to activity definition developers is "composition", where more complex activities can be built by combining together simpler activities that represent a more well-defined behavior. For example, complex calibrations can be pieced together with a series of turn, scan, and instrument observation activities.

An activity should capture behavior at a sufficient level of detail so that planning software can recognize and resolve conflicts during scheduling and validate the plan without additional work. Although increasing the level of detail at which activities are modeled potentially leads to more complexity, up front development work, and downstream maintenance, it provides a more accurate representation of actual behavior during execution and allows teams to catch potential problems and interactions sooner (proactive rather than reactive).

Scheduling and Associated Logic

Sophisticated planning software will assist planners in scheduling activity instances into the RAP. The scheduling software will gather all of the constraints on the plan to determine the timing and parameter values for each activity instance in the RAP. These constraints explicitly describe the intent of the plan so that operators know why the plan looks the way it does. Instead of having manage activity instances separately, planners can manage the constraints and let the scheduler do the work of managing each instance. This allows the plan to automatically adjust when there are changes to inputs like periodic trajectory updates or additional uncontrollable constraints due to spacecraft anomalies.

While many of the constraints on the plan will reside in activity definitions, constraints that change over the course of the mission are more appropriately defined outside of activity definitions. These constraints are the primary "knobs" that planners can dynamically tune during operations to modify the plan; in contrast, activity definitions are more static entities that will require a more rigorous process to create and update. Scheduling constraints outside of activity definitions that apply to all activities are called global constraints while those that apply to only a subset of activities are called scheduling logic.

Scheduling logic provides a means to describe rules for scheduling instances of activities that may change over time without having to modify activity definitions. For example, activities with the same definition may have different priorities or parameter values during different Europa flybys. Other examples where scheduling logic is more appropriate than constraints embedded in activity definitions include:

- Scheduling policies that define how often or how many times an activity or set of activities should be scheduled (e.g. at least 3 stellar occultations and 4 scans per flyby)

- Instrument and/or system-wide resource allocations, which will likely change per encounter

- Data downlink prioritization, which will likely change per encounter

Planners may highly constrain the timing of specific activities if necessary, so that the scheduling of those activities is predictable. Certain activities in the RAP will also be fixed in time due to other tools and processes (e.g. DSN schedule, trajectory maneuvers); interfaces will be developed so that these activities can be easily pulled into the RAP. However, if too many activities are highly-constrained, the scheduler could become over-constrained and find no viable solution. In cases of over-constrained scheduling, reevaluation of user-defined constraints will be necessary, and the scheduling algorithm design will accommodate adjustment of constraints in order to ensure that viable activity plan solutions can be found.

8. Operational Use of the Reference Activity Plan and Expected Benefits

The set of activity instances, planning constraints, scheduling logic, and system behavior models that form the Reference Activity Plan create a temporally extendable representation of the entire tour phase. Since each encounter follows the same notional pattern of science observations, spacecraft behaviors, and ground station activities, operations planners can create a generalized encounter activity plan template that reflects the entire set of onboard actions that occur during each encounter and their dependencies. The initial Reference Activity Plan will be created from this encounter activity template, which will be developed by science and spacecraft planning teams to ensure that it contains an accurate representation of the common, repeated activities that occur during each flyby. Once these teams identify their patterned activities and codify them as a template in the operations planning software, this template can then be applied to each encounter, creating a seamless representative plan of all activities that occur during the tour phase.

With a templatized estimate of the activities that will occur during each encounter in the mission, the initial RAP becomes the central product for Europa Clipper's uplink planning processes. All planning processes interact with the RAP, but focus on refining different portions of the plan (Fig. 4): strategic planning processes (like Long Range Mission Planning) update activities that occur several encounters in the future, while tactically oriented processes (like Science & Instrument Planning, Sequence Planning & Generation, and Spacecraft Engineering Planning) focus on refining plans for nearing encounters and generating command products from the finalized RAP activities.

Strategic Planning Operations Approach

The Reference Activity Plan's use in strategic planning operations is focused on implementation of plan changes that may have long-term impacts on spacecraft resources and consumables, achievement of mission science objectives, or how operators can use the spacecraft. Potential sources of strategic-level plan alterations include modification of the baseline mission trajectory that alters the geometry of many encounters, constriction or relaxation of allowable resource use limits, extension of the prime mission, alteration of high-level science objectives, or significant change to spacecraft performance that alters basic system functionality. These updates effectively change the inputs of the entire Reference Activity Plan, and will cause ripple effects to most, if not all, activities downstream of the implemented change. During the strategic planning processes, long-term operations planners develop solutions to these observed ripple effects and implement them within the Reference Activity Plan.

Strategic Planning Benefits

The Reference Activity Plan's utility in strategic planning operations lies in its representation of the behaviors of each instrument and spacecraft subsystem over the entire tour phase. Since the RAP spans all future encounters, planners can model system resources and measurement requirement compliance far in advance of the flight system executing the plan. This situational awareness allows operations planners to make strategic decisions in the context of the entire plan and understand their impacts downstream. The use of scheduling for plan generation also enables rapid updates to a set, or all, of the activities in the RAP. This capability eliminates the fragility of full-mission activity plans from past missions by transitioning the time-intensive manual process of updating each activity instance in an existing plan to software-based replanning.

Science Measurement Requirements Compliance and Assessment of Requirements Resilience—The Reference Activity Plan contains science observation activities for each encounter with Europa, providing a natural method for projecting when each instrument data set will contribute to the achievement of the mission's science objectives. Using project-developed analysis software described in [1], strategic planners can determine what data is produced by each science observation in the RAP, and quantitatively determine when each measurement requirement is satisfied during the tour phase. These profiles of measurement requirement completion allow scientists to understand when they'll have the most comprehensive data sets for studying certain aspects of Europa. Measurement requirement fulfillment analysis also enables strategic planners to understand the fragility of certain measurement requirements. By determining which encounters contribute to the achievement of a measurement requirements, strategic planners can deduce which science activities are critical for meeting mission objectives, and which late-tour observations provide measurement requirement margin. From this information, planners can better understand the science implications of altering or removing observation activities at different points in the tour phase.

Accurate Projection of Lifetime Resources and Constraint Adherence—Each activity contains references to behavior models, like onboard power and energy use, data collection and storage, and component duty cycles. By calculating the effect of each activity on consumable resources over the course of the mission, strategic planners can use the RAP to determine if the current activity plan violates resource usage limits throughout tour. These modeled behaviors can also be used to measure plan adherence to mission planning constraints, like those discussed in [1], and identify flight rule violations and hardware lifetime limitations. The ability to accurately forecast the characteristics of the RAP for the entire tour helps long-term focused planners identify potential issues far in advance of the start of tactical planning.

Responsiveness to Mission Replanning, Trajectory Updates, and Science Direction Changes—In heritage uplink planning processes, a major alteration to the input of an activity plan would require time-intensive identification of which activities in the plan are impacted by the change and subsequent manual updates of each affected activity. However, Europa Clipper's activity paradigm uses scheduling logic, planning constraints, and activity nesting to create relationships between multiple activities and to capture the optimal placement of each activity instance within the plan. Since these relationships, logic, and constraints are built into the Reference Activity Plan and are used to schedule each activity instance within the full-tour plan, operations planners can simply enter new inputs into the planning software and run the software-based scheduler. The scheduler uses the sum of its logic set, planning constraints, activity relationships, and plan inputs to rapidly determine potential activity instance layouts; since human interaction is no longer required to identify and resolve issues that arise from altering one of activity plan's fundamental inputs, the Europa Clipper operations team can agilely respond to large-scope updates to the mission operations concept.

Tactical Planning Operations Approach

Tactical planning operations focus on refining two encounter portions of the RAP to ensure that each upcoming flyby contains the desired science and spacecraft behaviors. This process begins eight weeks before the start of execution of the activities for a set of two encounters. During tactical planning, science and spacecraft operations planners refine the timing, parameterization, constraints, and scheduling logics associated with their respective sets of activity instances to ensure that the desired science data is collected and required spacecraft behaviors execute as expected. Planners are also free to add and remove activities from this plan portion.

Updates to the activities within the two-encounter portion of the RAP notionally occur for the first five weeks of tactical planning. It is expected that changes to activities in the plan will decrease in scope as the tactical planning period progresses, and the plan will be finalized at the conclusion of the fifth planning week. The last three weeks of the tactical planning processes are reserved for (1) changes needed to maintain basic integrity of the plan, (2) final validation of activities, and (3) a week of design margin as a hedge against performance issues. Uplinkable command products are also generated using the command expansion information codified in the finalized two-encounter portion of the RAP.

Tactical Planning Benefits

Tactical planners must be able to create detailed, valid activity plans that accommodate the necessary science and engineering activities. These plans are the basis for generating command products to uplink to the flight system. The Reference Activity Plan allows seamless integration between the planned activities that are refined during the tactical process, the long-term expected activities, and the uplink products used to command the flight system.

Rapid Iteration of Activities via Integrated Modeling—Since the essential building block of the RAP is the activity, and activities functionally represent a specific behavior and its resultant impacts on instrument and spacecraft state, the RAP can be used to model the effects of each activity. This capability allows tactical planners to calculate the state of the spacecraft at a moment in time during any given encounter and enables the impacts of a single activity change to be computed at any point in the plan. Since planners can view the near-term impacts of proposed activity changes, they can use this model-based feedback to rapidly iterate on their activities until their intended effects are realized.

Collaborative Planning in Context—A key challenge on past missions was the siloed nature of activity planning. Due to the lack of supporting technology and distributed teams, science and spacecraft planners would create individualized activity plans for their instrument or subsystem, then identify conflicts when attempting to merge their plans with the rest of an orbit's activities. The RAP resolves this issue by capturing both science and spacecraft activities in a single plan. Since operations planners directly interact with the activities in the RAP during tactical planning, they have visibility into the changes proposed by other planners. This enhanced planning context provides two improvements to the tactical process: 1) conflicting activities are identified earlier, reducing the amount of rework needed to create a valid plan, and 2) planners are able to more effectively collaborate on mutually beneficial activity updates.

Visibility into Impact of Short-Term Changes on Long-Term Objectives—The same model-based benefits that allow planners to understand their changes' impacts on the focused two-encounter plan can be extended for the full tour RAP. If the impacts of a proposed activity change are calculated for the remained of the tour phase, a planner can understand the potential long-term ramifications of implementing that change. This is especially powerful in the case where altering planned activities during a tactical period may impede the mission's progress towards meeting science objectives or create undesirable behavior trends long-term; increased visibility into downstream effects of a change can improve informed planning during the short-term tactical processes.

Automated Command Expansion—Since command expansions are included in each activity definition, the finalized activity plan developed during the first four weeks of tactical planning contains the necessary information to generate uplink products. Europa Clipper's integrated planning software can automatically expand the finalized two-encounter activity plan down to individual commands. This automated capability provides significant time savings during command product generation over traditional uplink product build methods. The activity-command expansion relationship is pre-validated, which limits command product validation that must take place during each planning cycle, and also provides a direct link from the RAP to each command product, enabling traceability between planned activities and commanded behaviors.

9. Summary and Future Development Efforts

Strategic and tactical activity planning efforts are complex, time-intensive endeavors in heritage planetary orbiter mission operations. In order to develop activity plans that represent mission objectives, past projects have relied upon highly iterative planning approaches that often lack linkages between planned behaviors and the command products that execute onboard the flight system. The Reference Activity Planning paradigm enables flexible, context-rich activity planning and command generation functions that span strategic and tactical planning, accurately model shared resource profiles over the entire tour duration, reduce workload on operations personnel via software-assisted plan scheduling, and directly tie activities to auto-generated command products. Through successful implementation of the RAP and supporting infrastructure, the Europa Clipper operations team seeks to streamline planning functions and efficiently support the mission's repeatable operations paradigm.

Future work to mature the Reference Activity Plan architecture includes detailed use case development for scheduling logic, conceptual design for a "reconstructed" RAP that documents each activity as it occurred onboard the flight system, and configuration management process creation for each planning concept element.

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BIOGRAPHY

Kaley Pinover *is a Mission Planning Operations Engineer for the Europa Clipper Mission at NASA's Jet Propulsion Laboratory, where she leads operations design for the Reference Activity Plan. Before joining JPL in 2017 to design mission operations and ground software architectures, Kaley received a B.S. in Aerospace Engineering Sciences and a M.S. in Aerospace Engineering Sciences with a certificate in Astrodynamics and Satellite Navigation from the University of Colorado, Boulder. Her past experience includes ground systems operation on the Juno Mission and scheduling software development for NASA's space communication networks.*

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Kathy Schimmels *is a member of JPL's Mission System Engineering & Architecture Group and is currently the MOS Engineering Lead for the Europa Clipper Mission. Kathy served as the MOS Engineering Lead for the Dawn Mission to Vesta and Ceres, and for the NuSTAR Xray Telescope Mission. She has over 7 years of flight ops experience in science operations and leadership during both prime and extended mission operations on the Galileo Mission, and an additional 16 years in development of flight projects at JPL. Additionally, Kathy was the lead systems engineer in the development of a multi-mission operations system model as the basis for future mission development. She received her B.S. and M.S. degrees in Aerospace Engineering Sciences from the University of Colorado, Boulder with a minor in Astrophysical, Planetary, and Atmospheric sciences.*