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Operating Deep Space Autonomous Spacecraft: Ground Processes and Tools for Operability and Trust

Rebecca Castano*, Federico Rossi, Tiago Stegun Vaquero, Vandi Verma, Dan Allard, Rashied Amini, Anthony Barrett, Mathieu Choukroun, Scott Davidoff, Nihal Dhamani, Raymond Francis, Mark Hofstadter, Bennett Huffmann, Michel Ingham, Ashkan Jasour, Marijke Jorritsma, Ellen Van Wyk, Gregg Rabideau†

† Jet Propulsion Laboratory, California Institute of Technology
Pasadena, California, 91109, United States

* Corresponding Author

Abstract

Future deep-space robotic explorers will use advanced onboard autonomy to address high-priority science questions, e.g., observing fast-changing phenomena and adapting to dynamic environmental circumstances. Onboard autonomy technologies such as planning and scheduling, identification of scientific targets, and content-based data summarization will lead to exciting new deep space science missions. However, traditional operations practices, skills, and processes were not designed for spacecraft with such onboard autonomous capabilities. This paper summarizes the results of a two-year investigation conducted at JPL to explore how ground operations processes, practices, and tools will need to adapt to support effective use of onboard autonomy. In particular, we identify areas where current workflows and tools will need to be enhanced to accommodate commanding and analysis onboard planning and scheduling software for deep space exploration. Our focus is on onboard planning and scheduling: we identify the required changes necessary to enable operators and scientists to convey their desired intent to future autonomous spacecraft's planning and execution systems via goals and priorities rather than sequences of commands, and to be able to reconstruct and explain the decisions made onboard and the state of the spacecraft - providing a practical path to users trusting the autonomy, which is one of the most significant barriers to full adoption. Collectively, these results form key steps toward adoption of onboard spacecraft autonomy, which will enable new, bolder exploration of the outer solar system, small bodies, and the surface of ocean worlds.

Keywords: autonomy, operations, planning and scheduling, downlink analysis

1 Introduction

Onboard autonomy technologies such as planning and scheduling, identification of scientific targets, and content-based data summarization are likely to unlock the answers to hitherto-unexplored, high-priority science questions and yield exciting new deep space science missions, providing the ability to adapt to fast-changing phenomena; observe fleeting targets; and optimize use of scarce onboard resources such as power and downlink bandwidth.

However, to fully realize this vision, ground operations will also have to adapt to allow scientists and operators to interact with such onboard autonomy capabilities. In this paper, we report on a two-year investigation conducted at JPL exploring ground operations processes, practices, and tools that will be needed for effective use of onboard autonomy.

Onboard autonomy, in effect, transfers aspects of command authority from the ground to the spacecraft. The two key areas impacted are commanding and analysis, which intuitively correspond to current uplink and downlink processes. Commanding will evolve from sending prescribed sequences of commands to an onboard open-loop executive to conveying user intent, expressed as goals, to an onboard planner. Correspondingly, to

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provide situational awareness, the analysis process will expand beyond confirming execution of the command sequence to understanding what was executed onboard and why the onboard autonomy made the decisions it did, in addition to the traditional assessment of state. Both of these properties are aspects of operability, and facilitate operator and scientist trust in the autonomy capability.

Our contribution is threefold. First, we provide a brief survey of existing tools for ground-based planning and analysis in Section 2. Next, in Section 3, we identify key design drivers that are uniquely required by operations of autonomous spacecraft, and are not satisfied by existing tools. We then turn our attention to the design of workflows and tools to satisfy these design requirements in Sections 4 and 5 respectively. Finally, we draw our conclusions and identify directions for future work in Section 6.

2 Existing Tools for Ground-based Planning and Analysis

In this section, we provide a high-level description of tools that have been used on various NASA spaceflight missions, and provide an overview of their functionality. Many of these tools are available to all NASA missions through the Advanced Multi-Mission Operations System (AMMOS) while some of the tools are JPL internal. Our spaceflight examples focus on missions implemented by JPL for NASA. We remark that each mission has customized the planning and analysis processes and tools to meet their specific needs. Historically, the **uplink planning** and **downlink analysis** teams have each developed their own tools, with no tight coordination. NASA's current M2020 mission and the upcoming Europa Clipper mission, for example, have put in considerable effort to change this paradigm and have a tighter link between what is commanded and the analysis of telemetry returned from the spacecraft, a process often referred to as "closing the U" [1] 1.

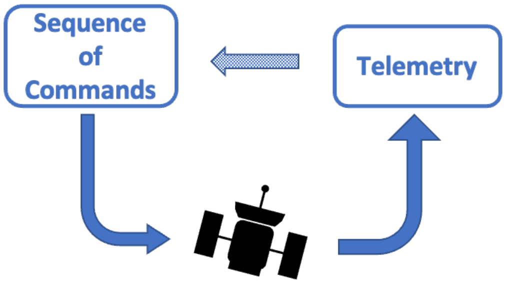


Figure 1: "Closing the U" consists of relating downlinked telemetry such as key spacecraft state values and event records (EVRs) back to commands in the prior sequence.

2.1 Uplink Planning

Missions generally have at least two planning phases, long-term, or "strategic" planning, and nearer-term, or "tactical" planning. The timeframe for each of these phases depends on the mission and its characteristics. For example, on the Mars Science Lab (MSL) rover, the strategic planning process addresses science campaigns and management of rover resources on a timescale of weeks to months, while the tactical planning process reacts to fresh data received from Mars to plan the activities of the rover for the next one to three Martian sols [2].

In contrast, orbiters and touring spacecraft tend to plan most science observation opportunities years in advance. For instance, the Cassini mission to Saturn planned the spacecraft trajectory 10 years before the prime mission, and developed a draft sequence of commands 2 years before prime mission. The near-term cycle began around 20 weeks before execution, when the command sequence was updated and refined based on new discoveries, science data analysis, spacecraft/instrument performance changes, and any changes to the original trajectory [3].

Uplink planning can be further divided into *science planning* and *sequencing.* Science planning begins with a reference activity plan. The reference activity plan is initially prepared in the long-range planning stage, but generally is iteratively updated over time based on new information before it is input to the near-term planning. In near-term science planning, this reference activity plan is fleshed out and refined until it meets science objectives and constraints. Missions generally employ a science planning tool to support the science planning process by determining observation opportunities and targets for instrument observations. Examples of science planning tools include: the Science Opportunity Analyzer (SOA) used on Cassini, Europa Clipper, and Psyche [4, 5]; CLASP adapted for THEMIS [6], used for Europa Clipper planning [7] and used on a number of Earth science missions [8, 9, 10]; and ASTTRO used on Mars 2020 [1].

Once science activities have been selected, activity planning tools are used to place activities on a timeline along with other required activities (e.g. engineering activities). The activity planning tools typically model activity constraints and flight rules, and aid the user in checking the proposed plan for compliance. A number of activity planning tools have been developed and used in spaceflight, including APGen, the mission planning activity plan generator and scheduling engine [11]; Blackbird (AERIE) [12]; Cocpit and Copilot [13]; MSlice [14]; Merlin [15]; ASPEN [16].

A number of Activity Plan Visualization Tools are also used to visualize activities, events, modes, flight rule violations, and resources states. These include the SPICE-enhanced version of Cosmographia [17], an interactive tool used to produce 3D visualizations of planet ephemerides, sizes and shapes; spacecraft trajectories and orientations; and instrument fields-of-view and footprints; Copilot and Crosscheck to explore auto-generated sequences [18] and the Resource and Activities Visualization Engine (RAVEN) tool created by NASA's Multimission Ground System and Services (MGSS) program to view and interact with timeline data via a web browser.

The activity plan is then turned into a sequence of commands. In the process of sequencing (done for example using SeqGen, Falcon), flight rules are checked, and the sequence is verified and validated. After the sequencing step, the sequence of commands is ready for upload to the spacecraft where it is executed.

2.2 Downlink Analysis

Data received by the mission team from the spacecraft includes channelized data (time-series measurements of key spacecraft state values), event notifications, or EVRs (event-driven logs produced by flight software), and other binary engineering and science data products. Using this information, downlink operators must confirm that the command sequence was executed correctly, assess compliance with flight rules, and assess the state and health of the spacecraft. State and health information is a critical input to the next planning cycle, in particular for rover missions. The combination of long round-trip light times, typically with highly constrained downlink pipelines, makes it challenging to conduct a thorough evaluation of spacecraft health and safety and an overall assessment of the state of the spacecraft - challenges that are exacerbated for missions to the outer Solar System. To support these activities, a number of tools have been developed, including time-series and tabular telemetry visualizations; 3D visualizations combining the spacecraft's pose and key relevant telemetry; tools for automated analysis and verification of flight rules; and backends to support data storage and advanced queries.

2D visualization of telemetry channels and EVRs The Advanced Multimission Operations System data Processing and Control System (AMPCS) [19] is an Advanced Multimission Operations System (AMMOS) [20] suite of tools that make up the core Ground Data System (GDS) for a number of missions. AMPCS provides telemetry data processing, real time downlink data visualization, telemetry data storage and query, and built-in support for test venues. AMPCS supports telemetry data types such as channel values, EVRs, data products, and also processing information such as downlink frame and packet meta-data.

Visualization for Telemetry Analysis (VISTA) [21] is a web-based telemetry data visualization tool (an adaptation of the more general Open Mission Control Technologies (Open MMCT) framework [22]) slated for use on Europa Clipper. VISTA is designed as a configurable dashboard that users and projects can adapt to specific use cases, and includes several built-in views for channelized telemetry, EVRs, and tabular listings of the types supported by AMPCS. VISTA also supports a user-configurable 'rule based checking' feature, which can be valuable for more complex analysis use cases.

3D visualizations of spacecraft state *Spacecraft*: Tball is a tool developed across several JPL missions including Mars Exploration Rover (MER), Dawn, and Juno, that combines telemetry data such as channels with a 3D rendering of the spacecraft, providing users the ability to interactively scroll through time and visualize the spacecraft geometrically, in the context of associated telemetry in view.

Surface Navigation Caspian is a 3D web tool developed for analysis of Perseverance auto-navigation behavior. It provides visualizations of several types of information related to auto-nav, including computed paths, terrain height maps, and dangerous terrain locations.

Telemetry Analysis and Exploration JPL's "Engineering Analysis Subsystem (EAS) Tools" provides tools for 'Data to Information' software. A key new tool is called Rounds, which performs advanced rule-based analysis of telemetry data, based on user-defined rules that can be specified via an editor. Rounds supports all channel alarm types, but also EVR rule checks as well as state machine checks based on channel and EVR values. Rounds is closely integrated with companion tools Channel Viewer (time series visualization), EVR Viewer (integrated EVR Visualization) and Epoch Viewer (relative time data visualization). The EAS tools have supported Mars 2020 operations through cruise and surface operations, and have since been adapted for Psyche and Europa Clipper.

Data Storage and Query Support Europa Clipper's Flight System Performance Analysis (FSPA) Tools have been developed to support the Europa Clipper operations concept, which requires the ability to compare a large number of predicted data types against telemetry actuals to support a "Close the U" data architecture. Within this architecture, predicted and actual states are combined within the same schema, which is also capable of tracking relationships between data types and groups across types, providing a complete 'state dictionary' for analysis of downlink.

3 Design Drivers for Onboard Autonomy

As planning and scheduling moves onboard spacecraft, a number of new capabilities will be required of ground-based tools. In this section, we briefly list the key drivers of change that will require development of new tools to support operators.

3.1 Uplink Planning Design Drivers

The key drivers for new tools and workflows in uplink planning refer to: 1) the need for specifying goals (e.g. high-level activities or desirable state) as opposed to timed sequence of activities of commands - the decision on planning and scheduling the activities would be made onboard; 2) the need for understanding the possible outcomes and spacecraft performance with such goals given that activity planning is done onboard and there is potentially large uncertainty in the environment in which the resulting plan will be executed, and 3) the need for assessing the impact of such goals and expected outcomes with respect to mission progress towards Level 1 requirements (to be accomplished for mission success). In what follows, we enumerate additional drivers that provide specific needs within the three aforementioned key drivers:

- Provide a way for scientists to understand the science models of their system in context of the trajectory, existing plan, and system geometry so that they can ensure they collect and receive the science data they need.
- Support iterative development of goals and resolution of potential conflicts between goals. Allow scientists to enter intent for autonomy and see the impact it has on the plan, including priority and logic.
- Operators need to be able to see how plans are progressing towards their mission objectives, to identify areas to improve the plan, make decisions about what to prioritize, and identify whether a proposed change is having the desired impact. Also, a change to the plan may have ripple effects to other parts of the plan, so "regression testing" is needed.
- As the mission evolves, operators need to not just understand whether they are on track to complete the objectives as originally intended, but they need to be able to consider alternative ways to achieve success.

- Changes to the plan can have unexpected impacts on the overall success of the mission. These impacts vary depending on the possible outcomes, and are useful in the context of the baseline plan.

3.2 Downlink Analysis Design Drivers

The key design driver for new tools and workflows in downlink analysis is the change in the notion of what "nominal" operations entail. In non-autonomous spacecraft, the nominal execution of an uplinked sequence is relatively straightforward to predict. The sequence specifies what tasks should be performed, and when. This information (together with high-quality models of the spacecraft) can be used to predict the state of the vehicle to a high degree of accuracy. If downlinked measurements match the prediction, operators can have a high degree of confidence that execution of the sequence was nominal.

In contrast, with autonomous operations, the set of activities that is executed onboard is not known in advance. The onboard planner schedules activities in response to the state of the spacecraft and of its environment. This has the effect that relatively small changes in the state of the spacecraft, or of its surroundings, can result in drastically different execution paths that are nevertheless "nominal", in that they correctly translate the operators' intent into actions. On the other hand, onboard autonomy can hide underperformance of spacecraft subsystems by planning around them, e.g., rescheduling tasks in response to diminished resources: accordingly, operators need to inspect the spacecraft's state closely to spot such anomalies.

These considerations point to a need for tools to help operators reconstruct what tasks were scheduled onboard, and assess the state of the spacecraft's resources; and, critically, tools to compare the as-executed plan with the ensemble of possible nominal and off-nominal execution paths simulated during planning, in order to assess whether execution satisfied the operators' intent and expectations. To assess this, operators will need to "peek into" decisions of onboard autonomy, understanding not only what tasks were scheduled and executed, but why they were scheduled and executed at a given juncture. User interfaces and algorithms are required to provide operators with the contextual information required to evaluate and reconstruct the as-executed plan; identify what key states informed the plan and motivated scheduling decisions; and assess the spacecraft's state.

In addition, the presence of onboard planning and scheduling will affect other subsystems, e.g., the thermal, power, and data storage subsystems, whose performance directly depends on the tasks scheduled by autonomy. Operators of these subsystems will also need access to an accurate reconstruction of the decisions performed by the onboard planner, and the ability to filter simulations performed during planning in order to assess whether the subsystem's performance is in line with ground models, given the onboard planner's decisions. This motivates the design of user interfaces and data management tools to provide subsystem operators situational awareness into the onboard planner's decisions, and to filter the potentially large number of simulations performed during planning to only show data relevant to the actual execution.

4 Workflows for Onboard Autonomy

The design drivers outlined above motivate a rethinking of the workflow for spacecraft operations. To this end, we designed an iterative workflow for intent capture and refinement in the planning phase; and performance evaluation and explanation in the analysis phase. The proposed workflow is shown in Figure 2.

The workflow for commanding, or communicating intent, to an autonomous spacecraft is an iterative process. First, intent is formally captured; then, possible outcomes arising from this intent are explored; and finally, suggestions are made to the users (scientists, spacecraft engineers and operators) to adjust the formal specification of intent. With the predicted outcomes and the suggested updates, users can refine their specification of goals and iterate through the process. This workflow requires new tools to capture and express the user intent in a way that is meaningful to both the users and the spacecraft's onboard planner; such tools are presented in Section 5.

The workflow for downlink analysis, in turn, is designed to enable the operators to infer what tasks and goals were executed onboard, why those (and not other) tasks were executed at a given time, and assess the state of the spacecraft and the environment. Data from the spacecraft, including telemetry and science data, is combined with the specified goals and priorities in an "inference engine" to reconstruct a

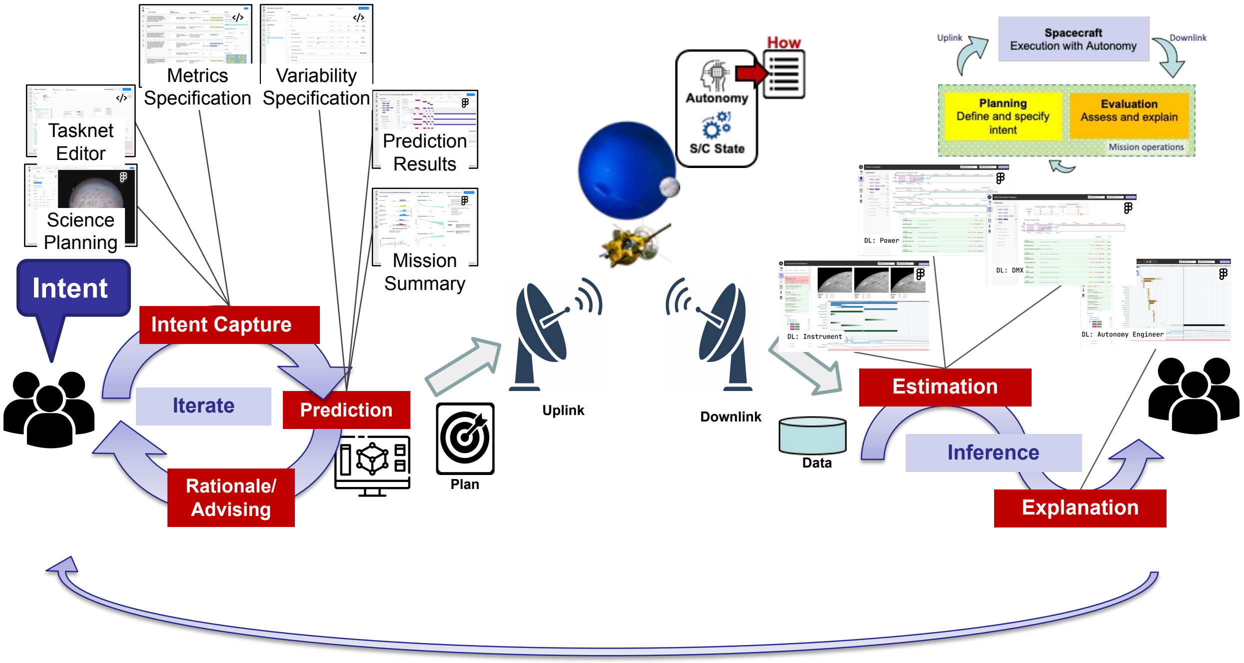


Figure 2: Proposed workflow and tools for operations of future autonomous spacecraft

distribution of likely execution paths and corresponding states. The activity has similarities to current efforts in "Closing the U" of spacecraft operations; however, the process of reconstructing the spacecraft's decisions is significantly more complex with onboard autonomy. On the one hand, the presence of autonomy strives to ensure that spacecraft states will remain within prescribed limits, which simplifies the state estimation process; on the other hand, reconstructing what happened onboard is more complex compared to operations of non-autonomous spacecraft, where a command sequence either executes nominally, or exits early due to a fault. Indeed, in presence of onboard autonomy, the distinction between "nominal" and "off-nominal" is less well-defined, since the spacecraft may make unexpected decisions that are not an indication of a fault (e.g., replacing a task with another one in response to an observation) and may reallocate resources so as to recover from anomalies with minimal impact to the overall goals.

For both uplink planning and downlink analysis, early user studies indicated that a new role, that of an *autonomy engineer*, greatly facilitated operations. The autonomy engineer should be familiar with both traditional operations, and the onboard autonomy capability, and thus be able to adjust expectations and translate the behavior of the onboard autonomy into an operations paradigm familiar to scientists and operators more used to traditional spacecraft operations.

5 Tools for Onboard Autonomy

While many tools in current use for spacecraft operations will remain relevant, a set of new tools will be required to support commanding and analysis workflows. For uplink planning and commanding, tools enabling scientists and engineers to understand and identify observation opportunities similar to current observation planning tools such as JPL's SOA will remain critical to the workflow. However, several novel tools will be needed to capture a set of goals and their relationships and priorities (rather than specifying a sequence of commands, as current tools do); specify key performance indicators that can be used to measure progress against the goals (a process that is currently largely informal and not explicit on most missions); predict the possible outcomes of a given set of goals through simulations (with orders-of-magnitude more variability compared to current simulations of non-autonomous spacecraft); explore the outcomes of the simulations, keeping in mind that multiple, very different outcomes may be "nominal", depending on the spacecraft's state and observations; and assess the (probabilistic) progress against campaign objectives based on the performance indicators provided by users.

For downlink analysis, existing tools for exploration of downlinked data will have to be extended to aid users in reconstructing the decisions of onboard autonomy and assess the spacecraft state at the time of the decisions, with the goal of helping operators understand why autonomy made certain decisions. The process of explanation will be aided by comparisons with simulations produced during the commanding process; this process will require updated user interfaces and data-storage backends to store many simulation outcomes, query them efficiently, and display them to users in an easy-to-interpret manner. In order to reconstruct the spacecraft state and the autonomy's decisions, new data products will also be downlinked to support interpretation of the autonomy's decisions (e.g., compact snapshots of the planner state); and state estimation algorithms will be critical to help the user interpret downlinked data and reconcile it with the commanded intent and with spacecraft models.

We designed and prototyped user interface and software tools to support this workflow. The tools are shown in the context of the proposed operations workflow in Figure 2. In this paper, we provide a high-level description of the tools; a detailed description is available in [23].

5.1 Uplink Planning Tools

5.1.1 Science Planning tool

We envision a tool (Figure 3) that supports adding and updating science goals in the plan. It gives scientists visibility into which science goals are active during a selected time period, and where along the trajectory a requested observation (whether through metrics or manually added activities) is possible and what its conflicts with other goals are. It allows scientists to view and update priority between science goals, view and update logic for which goals are conditionally executed, and view a limited preview of what outcomes may happen as a result of the modifications to the plan. It provides a 2D or 3D graphical preview of the field of view of the instruments to create a very familiar visualization for scientists.

5.1.2 Metric Specification tool

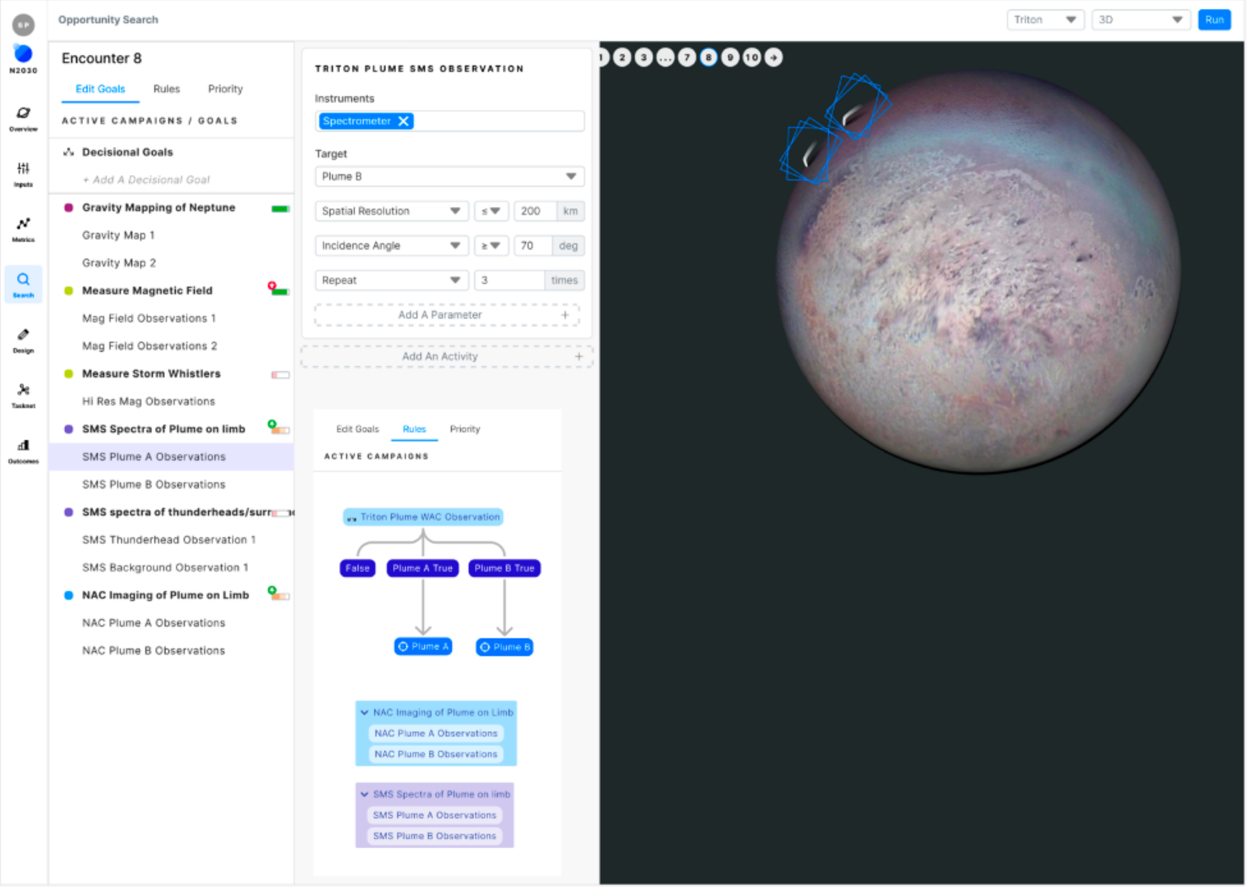
This tool (Figure 4) captures the traceability of mission objectives all the way from high level objectives (science questions the mission is required to answer) down to metrics (operational requirements). Metrics define the quantity and quality of science or engineering data that needs to be collected in order to answer a science/engineering question, and is associated with a campaign or set of goals. The tool includes logic where different combinations of approaches can answer the same mission objectives. The metrics data is integrated into other tools for analysis including tracking of the mission progress, projection in outcome prediction, and making trade-offs between different approaches.

5.1.3 Task Network tool

The task network editor/tool (Figure 5) is designed for creating and visualizing goals in the form of task networks. Engineers may create, update, delete, and validate tasks from scratch or by templates, and preview limited simulation outputs running the task network. The tool provides visibility into the plan for each planning cycle, captures the constraints and impacts applied to spacecraft state, and surfaces errors and constraint violations. The tool aids decision making by including explanations for unexpected outcomes, and captures the evolution of tasks and the task network over time. It also provides a high level view of campaigns, and lets users inspect subtasks. The task network is coupled with input from the Variability tool, selected by the user, to preview and troubleshoot how the task network might execute in a simulated environment.

5.1.4 Variability Specification tool

This tool (Figure 6) feeds all the variation that creates the range of Monte Carlo simulation outcomes. It includes engineering and science variability, where engineering model how spacecraft performance (task duration, power draw, data size etc) and science/environment (how many of a feature, feature lifespan and



TRITON PLUME SMS OBSERVATION

Instruments: Spectrometer

Target: Plume B

Spatial Resolution ≤ 200 km

Incidence Angle ≥ 70 deg

Repeat 3 times

Figure 3: Science Planning tool captures intent from scientist and instruments teams while allowing them to explore and query observation opportunities.

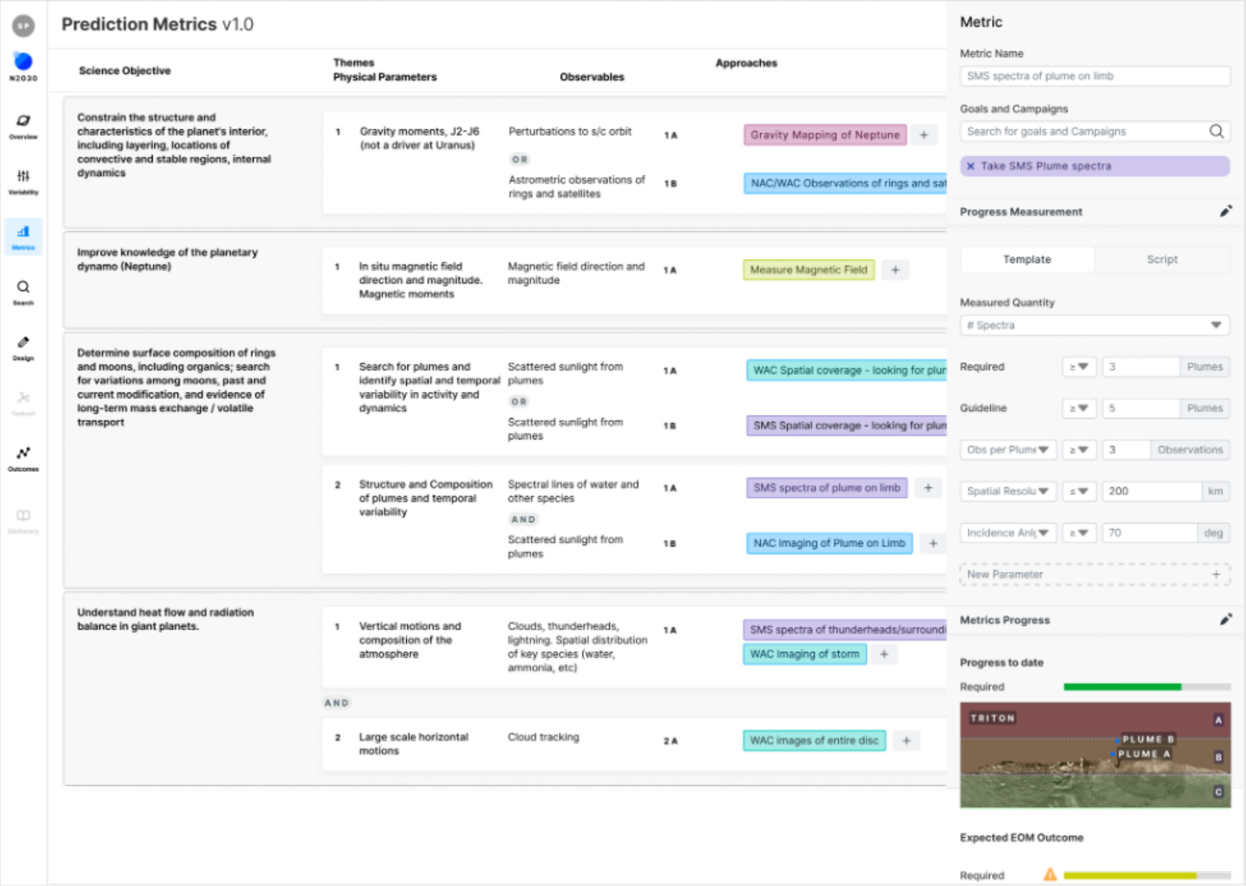
size, start and end of a feature) might vary due to uncertainty. The variability can be a constant value, a normal distribution, or other types of probabilistic distribution. Using variability in this way in Monte Carlo simulations can help operators identify edge cases and unfavorable outcomes, as well as try to maximize favorable outcomes.

5.1.5 Outcome Prediction tool

The Prediction Outcomes tool (Figure 7) supports visualization of the wide range of plans that come from Monte Carlo simulations. It resembles Mars 2020's copilot system [18] in that it allows operators to see at a high level the distribution of goals, tasks, modes, and key resources generated by the simulator. Operators can inspect the performance of plans, understand the conditions that led to them, and maximize positive outcomes while minimizing poor ones. The tool calls out differences between a baseline plan and new iterations to help operators identify improvements and unintended consequences of making a change. Plans can be clustered based on goals executed, and also on anomalies. The corresponding percent likelihood for each cluster may help scientists identify whether they might achieve the science they need.

5.1.6 Mission Summary tool

This tool (Figure 8) shows the results of many outcomes for the duration of the mission. It highlights the difference between a new plan and the baseline in key trends, campaign success rate, and likely types of outcomes. This tool helps users identify whether a change had unintended impacts, or if it supports the campaign progress the way they expect.



Prediction Metrics v1.0

Science Objective		Themes Physical Parameters	Observables		Approaches
Constrain the structure and characteristics of the planet's interior, including layering, locations of convective and stable regions, internal dynamics	1	Gravity moments, J2-J6 (not a driver at Uranus)	Perturbations to s/c orbit	1A	Gravity Mapping of Neptune +
			OR		
			Astrometric observations of rings and satellites	1B	NAC/WAC Observations of rings and sat
Improve knowledge of the planetary dynamo (Neptune)	1	In situ magnetic field direction and magnitude. Magnetic moments	Magnetic field direction and magnitude	1A	Measure Magnetic Field +
Determine surface composition of rings and moons, including organics; search for variations among moons, past and current modification, and evidence of long-term mass exchange / volatile transport	1	Search for plumes and identify spatial and temporal variability in activity and dynamics	Scattered sunlight from plumes	1A	WAC Spatial coverage - looking for plur
			OR		
			Scattered sunlight from plumes	1B	SMS Spatial coverage - looking for plun
	2	Structure and Composition of plumes and temporal variability	Spectral lines of water and other species	1A	SMS spectra of plume on limb +
			AND		
			Scattered sunlight from plumes	1B	NAC Imaging of Plume on Limb +
Understand heat flow and radiation balance in giant planets.	1	Vertical motions and composition of the atmosphere	Clouds, thunderheads, lightning. Spatial distribution of key species (water, ammonia, etc)	1A	SMS spectra of thunderheads/surroundi WAC Imaging of storm +
	AND				
	2	Large scale horizontal motions	Cloud tracking	2A	WAC images of entire disc +

Metric

Metric Name: SMS spectra of plume on limb

Goals and Campaigns: Search for goals and Campaigns

× Take SMS Plume spectra

Progress Measurement

Template | Script

Measured Quantity: # Spectra

Required ≥ 3 Plumes

Guideline ≥ 5 Plumes

Obs per Plum ≥ 3 Observations

Spatial Resolu ≤ 200 km

Incidence Anl ≥ 70 deg

New Parameter +

Metrics Progress

Progress to date

Required

Expected EOM Outcome

Required

Figure 4: The Metric Specification tool captures key performance indicator and methods to measure them during mission with respect to science objectives and campaigns.

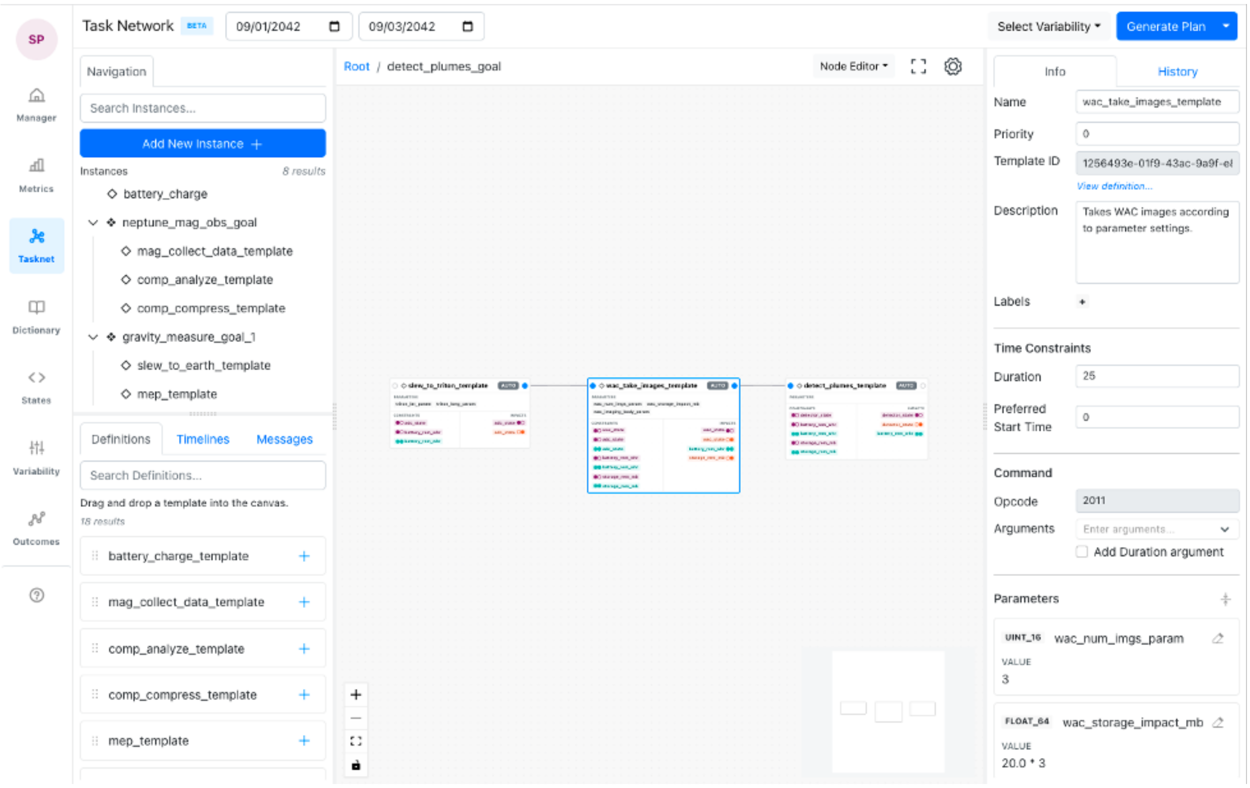
5.2 *Downlink Analysis Tools*

5.2.1 *Plan Reconstruction tool*

We envision that a new tool, the *Plan Reconstruction* tool (Figure 10), will support the autonomy engineer's analysis of the planner's performance. The plan reconstruction tool provides operators with a view of the activities scheduled by the onboard planner, and their execution status. It also allows operators to compare predictions of spacecraft states used by the onboard planner with the spacecraft's actual reconstructed state, helping identify potential mismatches between models and reality. Critically, the plan reconstruction tool also allows the operator to filter simulations executed during the analysis phase to only select simulations representative of the actual executed plan, and to overlay the tasks and states predicted by the simulations on the actual plan: this helps the operator assess whether the executed plan was in line with uplink expectations, or whether additional analysis is warranted. Interactive tools also allow operators to assess EVRs and to examine the spacecraft's state in detail; finally, the tool can display the output of ground-based state estimation algorithms to "fill in" sparse or missing channelized data.

5.2.2 *Power, Thermal, and Data Management Tools*

User interfaces for power, thermal, and data management engineers will also require updates to provide situational awareness into the plan executed onboard, and allow operators to assess whether their subsystems' performance is in line with the executed plan. Critically, the tools will allow operators to compare the subsystem's performance with the simulated performance in similar scenarios, a capability that will require efficient querying and identification of such scenarios among the many simulations performed in uplink.



09/01/2042
09/03/2042

Name: wac_take_images_template
Priority: 0
Template ID: 1256493e-01f9-43ac-9a9f-el
Description: Takes WAC images according to parameter settings.
Duration: 25
Preferred Start Time: 0
Opcode: 2011
Arguments: Enter arguments...

UINT_16 wac_num_imgs_param
VALUE
3

FLOAT_64 wac_storage_impact_mb
VALUE
20.0 * 3

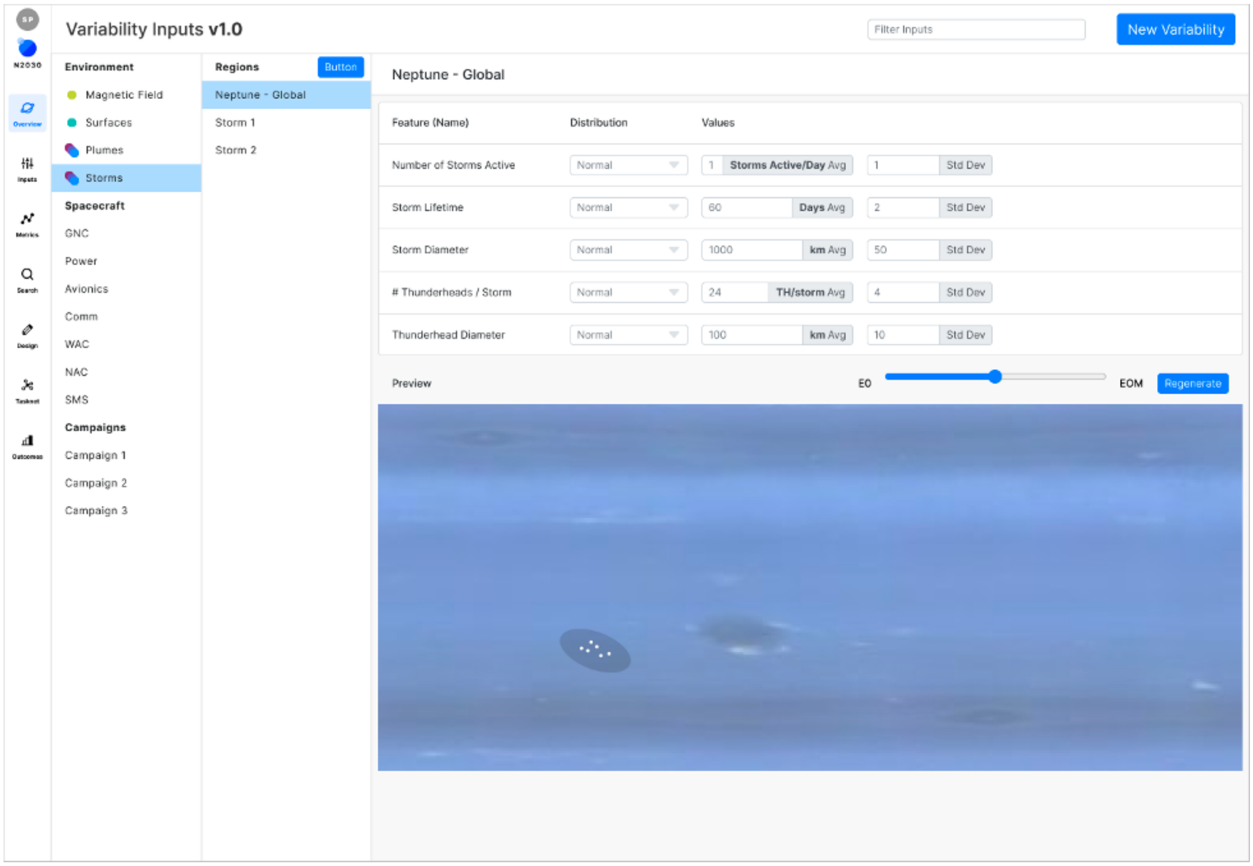
Figure 5: The Task/Goal Network tool supports the modeling of goals in the form of high level (hierarchical) tasks.

5.3 *Assessment of the Workflow and Tools*

We evaluated the proposed roles, processes, and tools through a multi-day design simulation [24] of downlink and uplink operations with spacecraft operators, who analyzed and managed the behavior of an autonomous spacecraft performing a Neptune-Triton tour across multiple flybys. This use case has a number of mission characteristics that make onboard autonomy beneficial to increased mission science return, including significant light-speed latency, low available bandwidth, short duration of flybys, and dynamic scientific phenomena. Mockups of the tools were used to understand the effectiveness of the processes and tools in enabling a shared framework of understanding, and the ability of the operators and scientists to effectively achieve mission science objectives. A detailed description of the design simulation is provided in [23]. The results of the design simulation largely validated the proposed workflow and tools, showing that operators could effectively command an autonomous spacecraft and confidently interpret the autonomy's decisions.

6 Conclusions and Future Work

In this work, we identify how uplink planning and downlink analysis operations will have to evolve to support onboard planning and scheduling on future autonomous spacecraft. We survey existing operations tools used by NASA; identify key changes to operations workflows, and gaps in existing operations tools; and propose a suite of tools designed to fill these gaps, enabling operations of future autonomous spacecraft. A number of directions for future work are of interest. First, while the design of the tools proposed in this work is relatively mature, their implementation and integration into mission systems is ongoing; investments will be required for maturation and integration of the tools and development of training aids for future operators. Second, the focus of this work has been on onboard planning and scheduling. Additional tools will be required to support operations of specific autonomous behaviors (e.g., event detection and event-triggered observations); operations of failure detection, identification, and recovery (FDIR); and autonomous data



Feature (Name)	Distribution	Values	
Number of Storms Active	Normal	1 Storms Active/Day Avg	1 Std Dev
Storm Lifetime	Normal	60 Days Avg	2 Std Dev
Storm Diameter	Normal	1000 km Avg	50 Std Dev
# Thunderheads / Storm	Normal	24 TH/storm Avg	4 Std Dev
Thunderhead Diameter	Normal	100 km Avg	10 Std Dev

Figure 6: The Variability Specification tool supports the specification of science and engineering parameters that can vary, and a corresponding model (e.g. stochastic) for that variability.

compression and curation. Finally, integration of the proposed tools into future missions (starting with ground-based verification and validation activities) will be key to raising the technology readiness level of the proposed tools and workflows. Overall, our work identifies the required upgrades to workflows and tools necessary to enable operators and scientists to convey their desired intent to future autonomous spacecraft, and to be able to reconstruct and explain the decisions made onboard and the state of the spacecraft; key steps toward adoption of onboard spacecraft autonomy, which will enable new, bolder exploration of the outer solar system, small bodies, and the surface of ocean worlds.

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High Fidelity

Sims: 10,000

Metrics: V01

Inputs: V01

Plan: NewFeatureX

Orbit 8

● Most Likely Plans

○ num_storms_observed plume_A_observed plume_B_observed triton_lossless_magnetometer	71%
○ gravity_at_CA plume_A_observed plume_B_observed	11%
○ num_storms_observed plume_A_observed triton_lossless_magnetometer	8%
○ num_storms_observed plume_B_observed triton_lossless_magnetometer	6%
○ gravity_at_CA plume_A_observed plume_B_observed triton_lossless_magnetometer	2%
○ gravity_at_CA plume_B_observed triton_lossless_magnetometer	1%
○ num_storms_observed triton_lossless_magnetometer	1%
○ gravity_at_CA plume_A_observed	1%

○ Underperforming Clusters

○ gravity_at_CA	85%
○ num_storms_observed	15%
○ triton_lossless_magnetometer	12%
○ plume_B_observed	10%
○ plume_A_observed	8%

○ Mismatched Clusters

○ num_storms_observed	1%

Figure 7: The Outcome Prediction tool supports the analysis of Monte Carlo simulation results by showing the distribution of outcomes with respect to goals achievement and off-nominal scenarios.

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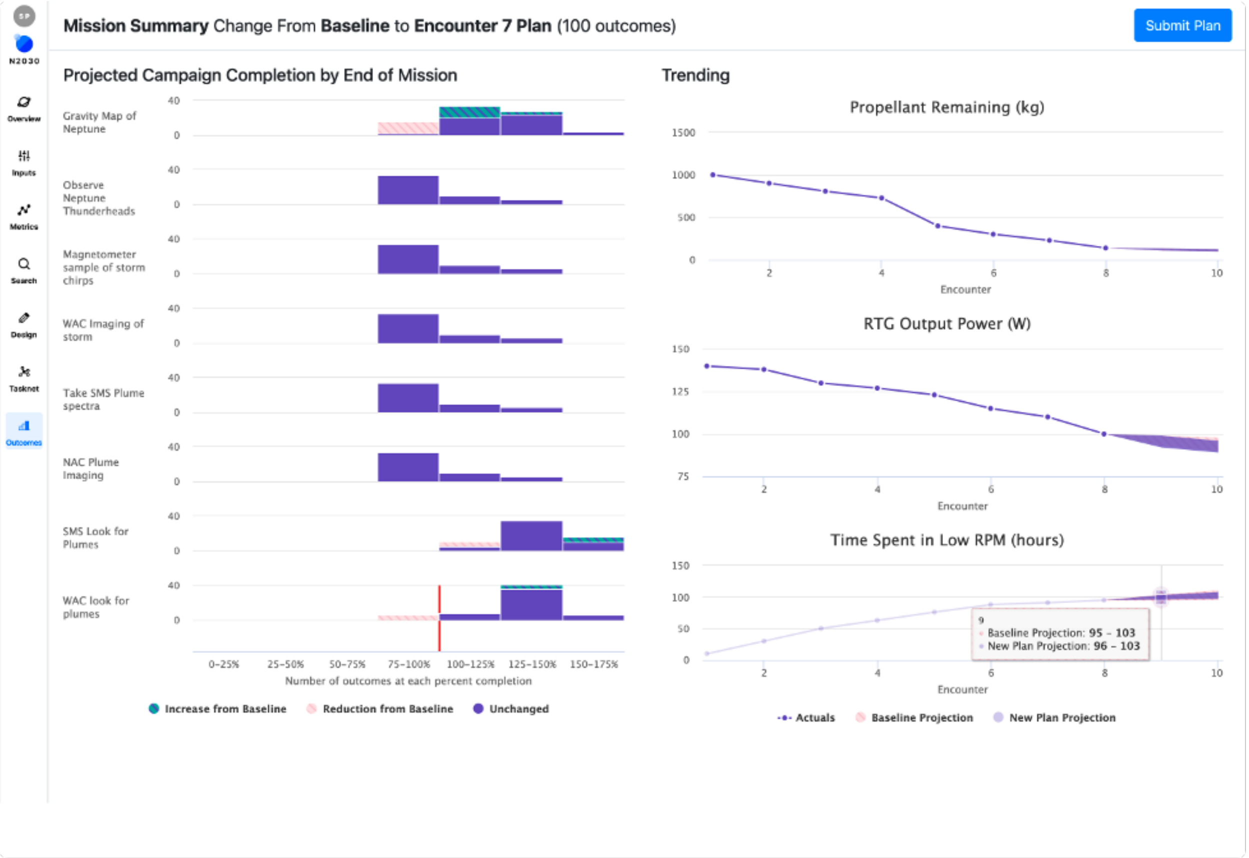

Figure 8: The Mission Summary tool supports the analysis of the overall impact and progress for the new plan in contrast with the baseline.

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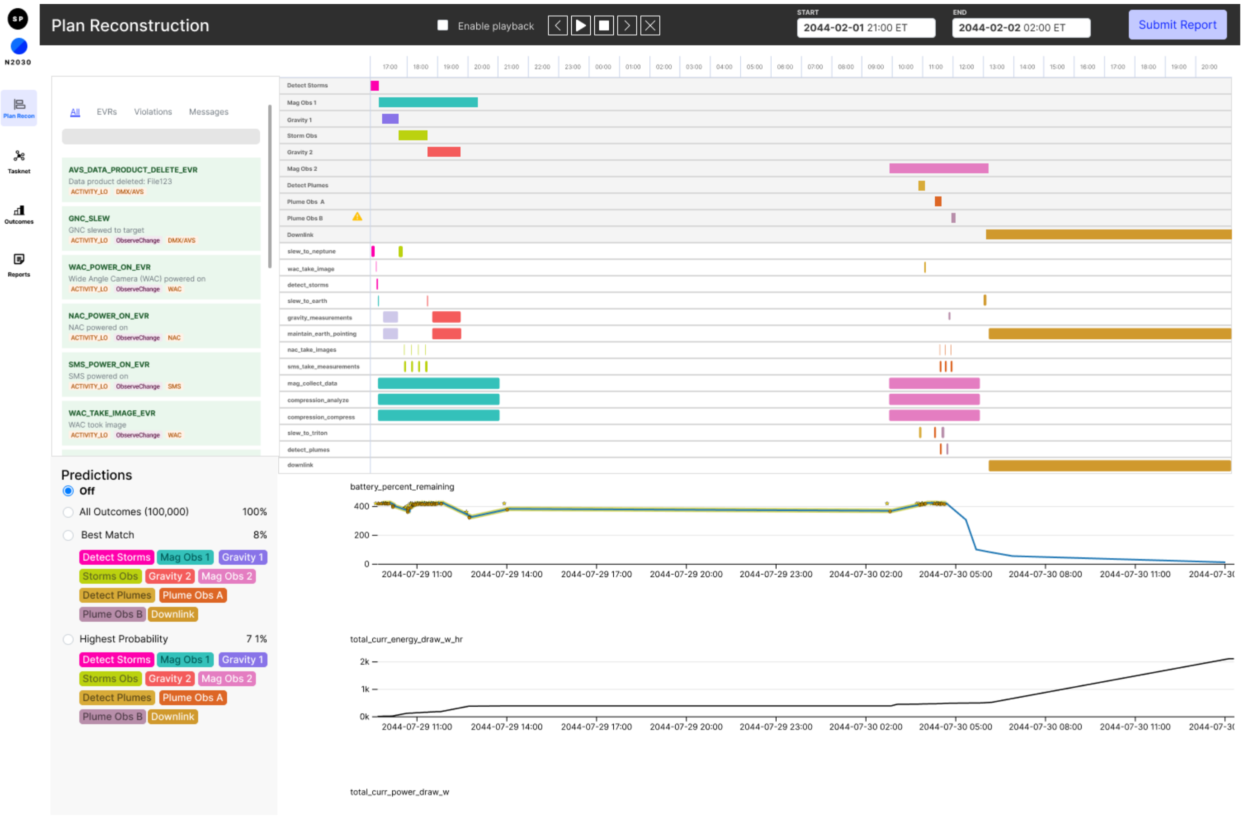

AVS_DATA_PRODUCT_DELETE_EVR
Data product deleted: File123
ACTIVITY_LO DMX/AVS

GNC_SLEW
GNC slewed to target
ACTIVITY_LO ObserveChange DMX/AVS

WAC_POWER_ON_EVR
Wide Angle Camera (WAC) powered on
ACTIVITY_LO ObserveChange WAC

NAC_POWER_ON_EVR
NAC powered on
ACTIVITY_LO ObserveChange NAC

SMS_POWER_ON_EVR
SMS powered on
ACTIVITY_LO ObserveChange SMS

WAC_TAKE_IMAGE_EVR
WAC took image
ACTIVITY_LO ObserveChange WAC

Predictions
● **Off**
○ All Outcomes (100,000) 100%
○ Best Match 8%
Detect Storms, Mag Obs 1, Gravity 1, Storms Obs, Gravity 2, Mag Obs 2, Detect Plumes, Plume Obs A, Plume Obs B, Downlink
○ Highest Probability 7 1%
Detect Storms, Mag Obs 1, Gravity 1, Storms Obs, Gravity 2, Mag Obs 2, Detect Plumes, Plume Obs A, Plume Obs B, Downlink

Figure 9: The Plan Reconstruction tool supports the autonomy engineer's analysis of the onboard planner's decisions, and of their impacts on the system. An interactive, browser-based prototype of the tool has been developed and is undergoing testing.

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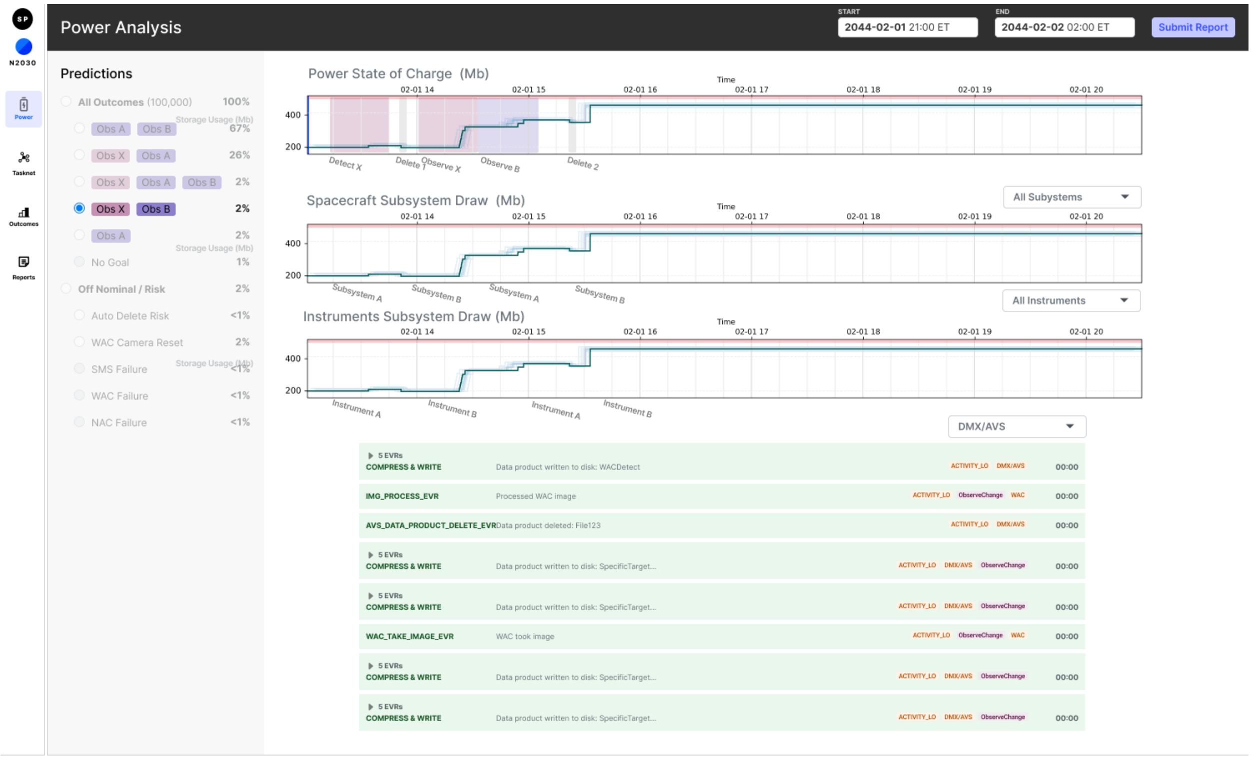

Predictions

○ All Outcomes (100,000) 100%
- ○ Obs A Obs B 67%
- ○ Obs X Obs A 26%
- ○ Obs X Obs A Obs B 2%
- ● Obs X Obs B 2%
- ○ Obs A 2%
- ○ No Goal 1%

○ Off Nominal / Risk 2%
- ○ Auto Delete Risk <1%
- ○ WAC Camera Reset 2%
- ○ SMS Failure <1%
- ○ WAC Failure <1%
- ○ NAC Failure <1%

▶ 5 EVRs COMPRESS & WRITE	Data product written to disk: WACDetect	ACTIVITY_LO DMX/AVS	00:00
IMG_PROCESS_EVR	Processed WAC image	ACTIVITY_LO ObserveChange WAC	00:00
AVS_DATA_PRODUCT_DELETE_EVR	Data product deleted: File123	ACTIVITY_LO DMX/AVS	00:00
▶ 5 EVRs COMPRESS & WRITE	Data product written to disk: SpecificTarget...	ACTIVITY_LO DMX/AVS ObserveChange	00:00
▶ 5 EVRs COMPRESS & WRITE	Data product written to disk: SpecificTarget...	ACTIVITY_LO DMX/AVS ObserveChange	00:00
WAC_TAKE_IMAGE_EVR	WAC took image	ACTIVITY_LO ObserveChange WAC	00:00
▶ 5 EVRs COMPRESS & WRITE	Data product written to disk: SpecificTarget...	ACTIVITY_LO DMX/AVS ObserveChange	00:00
▶ 5 EVRs COMPRESS & WRITE	Data product written to disk: SpecificTarget...	ACTIVITY_LO DMX/AVS ObserveChange	00:00

Figure 10: The Power Analysis tool helps the power engineer assess the performance of the power subsystem by correlating the spacecraft state with the as-executed plans, displaying simulations of the scenarios closest to the executed plan, and relevant EVRs. Similar tools will be required for thermal and data management engineers.