National Aeronautics and Space Administration

Mission Operations Planning for Increasingly Autonomous Spacecraft

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Program: FY21 R&TD Strategic Initiative **Strategic Focus Area: Operations for Autonomous Spacecraft**

Objectives

In this R&TD research we focus on developing ground system capabilities for operating and commanding autonomous spacecrafts, specifically for the **uplink process**. The objectives of this research are the following:

- **Objective 1**: to develop a modeling technology to facilitate the iterative design process of science intents in ground operations, including capturing intents and constructing plans with those intents;
- **Objective 2**: to develop techniques for outcome/execution prediction, visualization, explanation, and advisory techniques, to facilitate the operators learning process while helping them reassure that the spacecraft will achieve the target intents and complete the plan successfully.

In addition to delivering prototype system capabilities, our approach will make recommendations for autonomy, flight software, and ground system development to support operability and trust. It will also make recommendations on training an autonomy-aware operations team.

Mission Scenario & Campaign	Scenario	
Monitoring (Campaign 1)	S1.1	Magnetospheric Variability Detection; data compression
	S1.2a	Magnetospheric Reconnection Event Detection, resource-neutral
	S1.2b	Magnetospheric Reconnection Event Detection, replan resource use
Mapping and Event Detection (Campaigns 2 and 4)	S2.1a	Mapping Triton and Plume Detection, missed the event
	S2.1b	Mapping Triton and Plume Detection, event interrupts mapping
	S2.1c	Mapping Triton and Plume Detection, event and mapping coexist
	S2.2	Off-nominal: FDIR during mapping
	S2.3a	Mapping Neptune and Storm Detection, missed the event
	S2.3b	Mapping Neptune and Storm Detection, event interrupts mapping
	S2.3c	Mapping Neptune and Storm Detection, event and mapping coexist
Mission Scenario 3: Targeted Observation and Event Detection (Campaigns 3 and 5)	S3.1	Target selection
	S3.2	FDIR affects science plan during critical engineering event
	S3.3a	Instrument tweaks capture parameters autonomously, resource-neutral
	S3.3b	Instrument tweaks capture parameters autonomously, replan resource use

Figure 1. Reference autonomy-enabled mission scenarios identified in the effort.

Background

Future spaceflight missions will employ advanced onboard autonomy capabilities, including autonomous fault management, planning, and execution, selection of scientific targets, and data summarization and compression. Such autonomy technologies hold promise to i) enable missions that cannot be operated through a regular ground-in-the-loop operations cycle due to communication bandwidth and latency constraints and limited lifetime, (e.g. flybys of outer planets, surface operations in adverse environments) and to ii) increase science returns, improve spacecraft reliability, and reduce operation costs. For example, autonomy has already significantly increased the capabilities of Mars rover missions, enabling them to perform autonomous long-distance navigation and autonomous data collection on new science targets. However, the challenge of operating such onboard autonomous capabilities and integrating them in ground operations has never been studied to a level of detail sufficient for consideration in mission concepts. To enable scientists and engineers to operate autonomous spacecraft, new operations tools and workflows must be developed. This effort focuses on developing such tools and workflows to assist the **uplink team** in a) communicating science and engineering intent to onboard autonomy software, and b) assessing the expected impact of such intent on the spacecraft state and performance.

Approach and Results

In **Objective 1**, the approach is to develop modeling techniques to construct spacecraft plans by defining science campaigns as the means to encode intent. We propose an intent-oriented hierarchical plan specification, from strategic to tactical, which largely aligns with current mission practices at JPL. Building on previous JPL work (e.g. Rosetta planning [1], 3x Systems Autonomy task networks), we will develop software technology where intent will be specified as: a set of goals, a range of input states, execution variability, key performance indicators, and relationships between goals.

In **Objective 2**, the approach is to develop techniques for a) prediction of expected outcomes and possible executions, b) visualization and inspection of outcomes, c) explanation of possible executions/outcomes, and d) advising plans modifications to address undesirable outcomes. Leveraging existing JPL work We will use simulations [2-4] we will use simulations. and formal methods to construct a set of execution traces for the given intent and world (environment and spacecraft) conditions. The operators will iterate with the system, adjusting inputs such that the execution meet target intent and performance.

This R&TD research is on track with respect to milestones and meeting initiative's long-term objectives. The main FY21 accomplishments are:

- **Identification and development of science scenarios and their concept of operations for the Ice Giant tour mission**. We successfully identified and developed 14 science scenarios, across 5 campaigns, for the Ice Giant tour mission (Figure 1) in collaboration with the sibling (Downlink) task in the initiative, as well scientists, operators, and autonomy providers to inform the developments in this research.
- **Uplink operations workflow and supporting tools.** We analyzed the current uplink workflows and gathered requirements for uplink operations with autonomous spacecraft. We designed an uplink workflow prototype and a set of user interfaces to support intent capture (e.g. Figure 2) and outcome prediction processes (e.g. Figure 3). We also designed and implemented the prediction engine that will support Monte Carlo simulations and the understanding of possible outcomes and expected spacecraft performance.
- **Spacecraft simulator**. We developed, in collaboration with the Downlink task, an efficient and expressive ROS-based simulation framework (Figure 4) that is well-suited to help both the development and the evaluation of the proposed approaches.
- **Engagement of the science and operations communities**. In collaboration with the Downlink task, we conducted a detailed user study involving JPL scientists and operators to assess the performance of the designed tools/concepts and inform future development. Results of the user study will be published in an IEEE AERO paper in 2022.

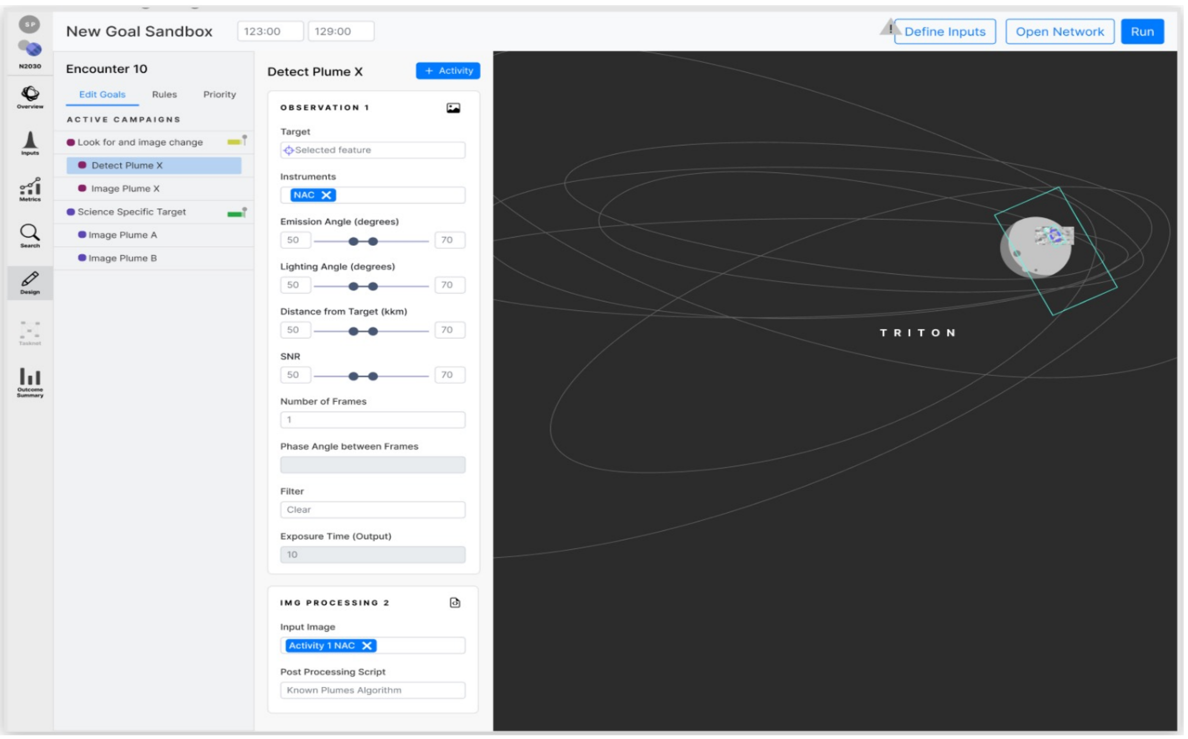

Figure 2. User interface design for capturing intent as campaigns.

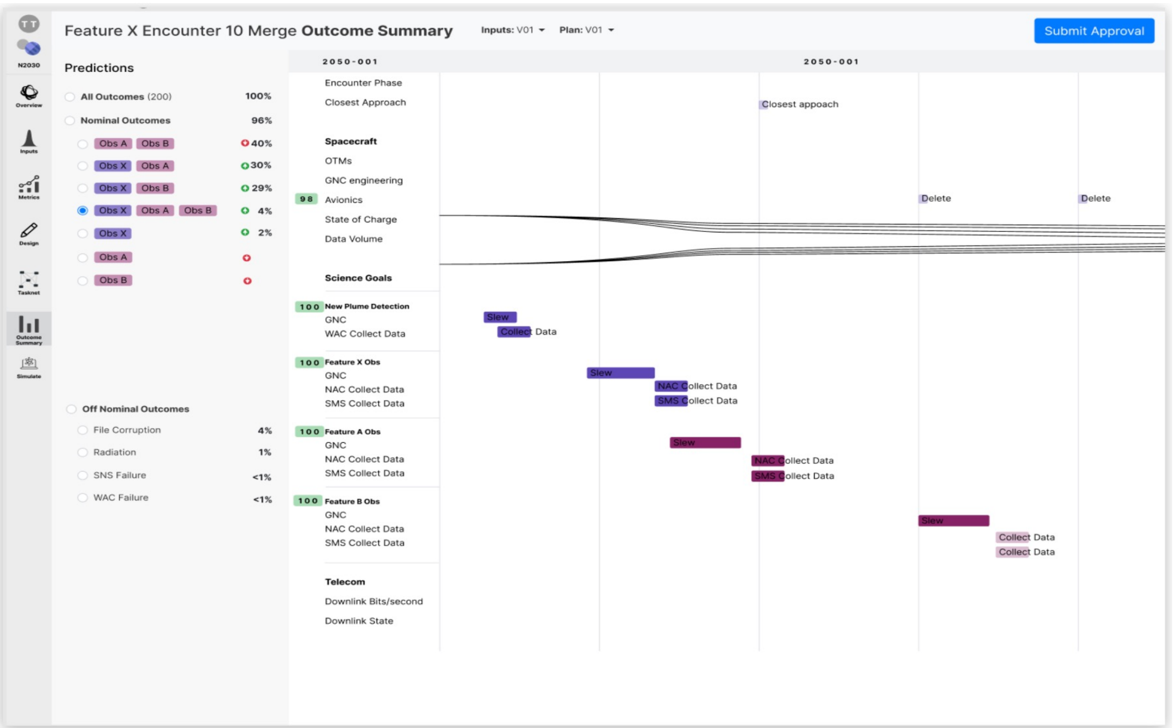

Figure 3. User interface design for analyzing the prediction of outcomes.

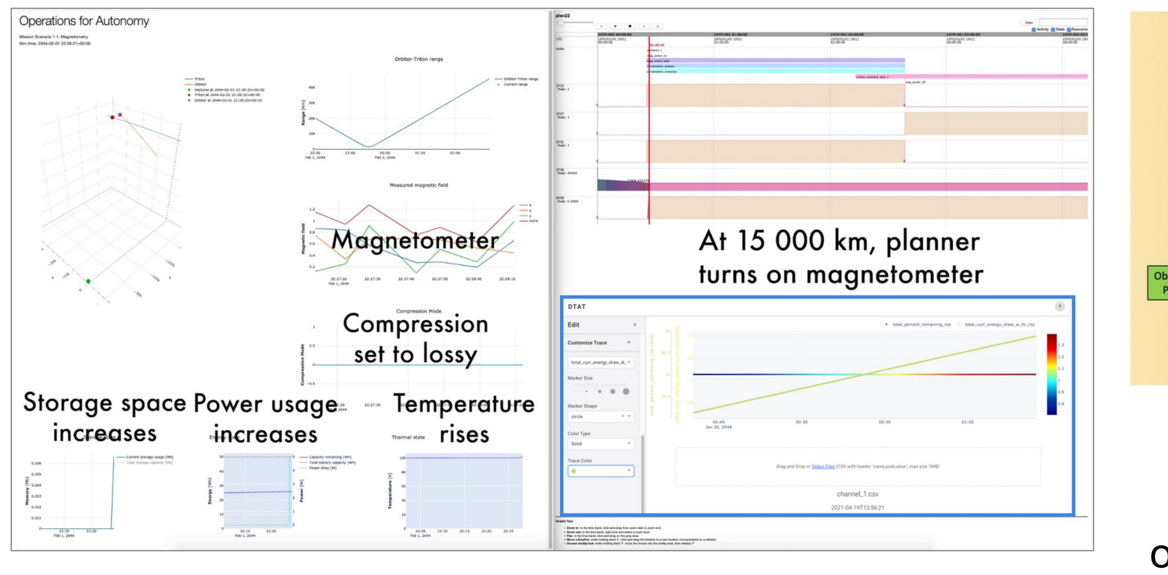

Figure 4. Simulation environment developed as a joint effort between the tasks in the initiative.

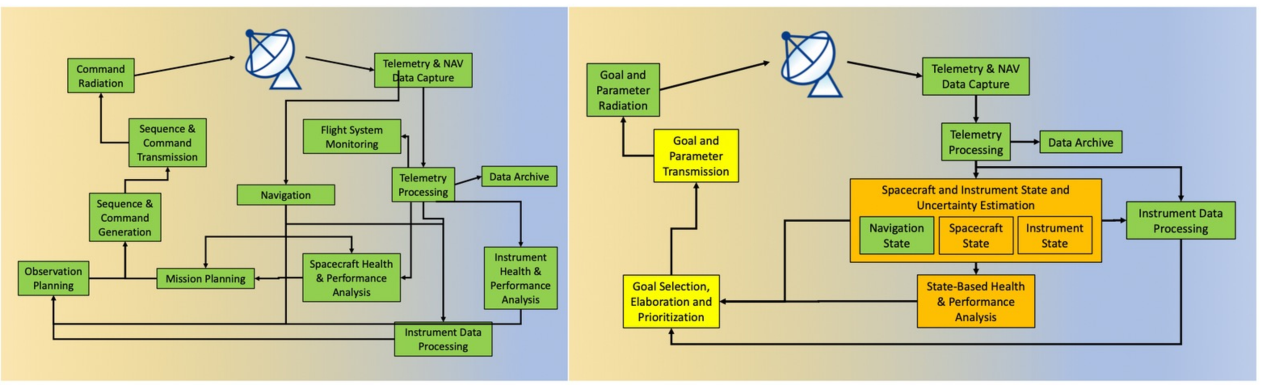

Figure 5. Mission operations flowcharts. The current structure (left) and the simplified structure (right) enabled by a mission operations system using the proposed tools. Yellow boxes refer to this research effort, orange to the companion (downlink) task.

Significance/Benefits to JPL and NASA

This R&TD effort directly addresses the two primary findings from the JPL Operations for Autonomy workshop, October 2017: impacts of onboard autonomy to the uplink process and gaining operator/scientist trust in the onboard autonomy capability. The effort will incorporate findings from the FY20 Study "Operating Autonomous Spacecraft" and the FY20 Multi-mission Ground Systems and Services (MGSS) study on the anticipated impacts of onboard autonomy to the Advanced Multi-mission Operations System (AMMOS). The team has refined the concepts with feedback from a steering committee and has been working closely with the MGSS Office to develop capabilities that will be compatible with future plans for AMMOS and to feed the successful outcome of this research Into MGSS Office. Figure 5 shows the current task flow of mission operations from the AMMOS perspective and the elements that will be affected by a fully autonomous spacecraft. The techniques developed by this effort has been demonstrated for an Ice Giant tour mission scenario, but could directly feed into future missions that rely on autonomy, across a variety of mission classes, including surface missions, small body exploration, and farther out concepts examined by the JPL NEXT program and Planetary Science Decadal Survey.

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Publications

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Clearance Number: CL#21-4764
RPC/JPL Task Number: R21003