National Aeronautics and Space Administration

Operations for Autonomy: Spacecraft State Estimation to Support Execution and Understanding of Onboard Decisions

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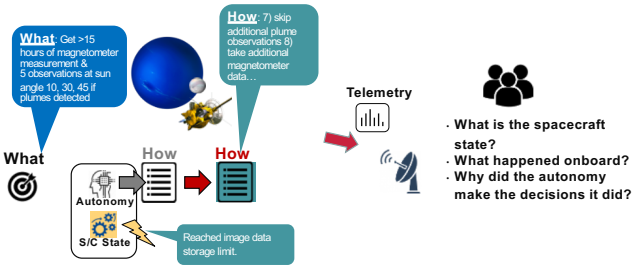
Program: FY21 R&TD Strategic Initiative **Strategic Focus Area: Operations for Autonomous Spacecraft**

Goal and Objective



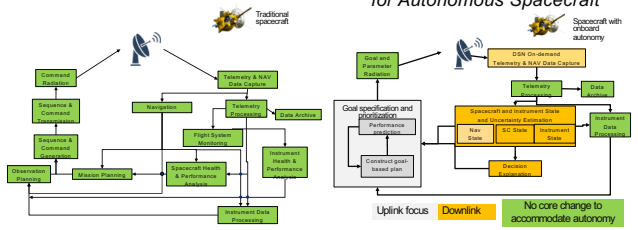
Goal: Develop technology to enable operations to

- understand *what* onboard decisions were made and *why*, enabling reconstruction of what the spacecraft executed
- predict the *state* of the spacecraft to inform specification of future science and engineering *goals*

Background

Conventional Operations System

Future Operations System for Autonomous Spacecraft



On-board autonomy *enables* missions such as outer planets **flybys** and **surface operations** in adverse environments when ground-in-the-loop operations are not feasible due to to *bandwidth, latency,* limited *lifetime*

New **tools** and **workflows** needed to: (i) *explain* autonomy decisions, (ii) infer future spacecraft *state* with autonomy in the loop, and (iii) identify *anomalies* that may be hidden by autonomy

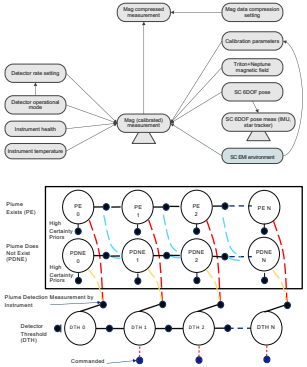
Approach

Inference

Objective: based on *information* downlinked from the spacecraft, infer *state* of spacecraft (including autonomy and any faults) and *explain* autonomy decisions

Modeling

- Build a representative model that captures interactions between spacecraft components and environment, *including autonomy*
- Modeling tool: **Bayes Networks** informed by **state effect diagrams**
  - Capture *relations* between states
  - Amenable to *inference*



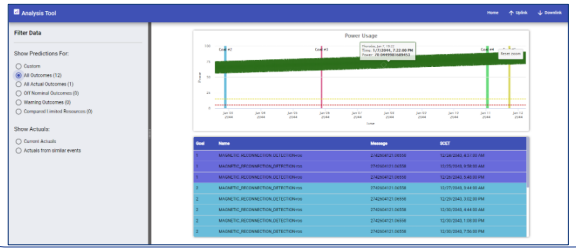
Algorithms

- Identify, extend, and develop algorithms to *infer* spacecraft state based on *models* (spacecraft, environment, autonomy) and downlinked *measurements*
- Inference tool: **MH-iSAM2** factor graph optimization library

UX tools

Objective: provide *situational awareness* of spacecraft state by

- Showing *correlations* in telemetry received by the spacecraft
- Comparing telemetry with uplink *predictions*
- Providing *explanations* and *state estimates* provided by inference



User Studies

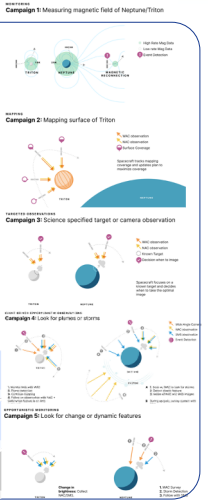
Developed 14 **scenarios** for a notional Ice Giants multi-flyby mission exercising

- on board *planning and scheduling*
- event *detection*
- *FDIR*

Developed a detailed **simulation environment**

- Integrates autonomy
- Provides telemetry to UX and inference tools

Assessed the performance of the proposed tools through **user studies** with JPL scientists and operators



Significance and Next Steps

Impact

- Addresses findings of October 2017 JPL Ops for Autonomy workshop
- Working closely with **MGSS** towards future integration with AMMOS
- Close collaboration with **Europa Lander Autonomy Project**
- Ongoing discussions with autonomy projects and mission concepts at JPL including *CADRE, DARE, SYNOPSIS*

Going Forward

- **Inference:** *extend* prototype inference tool and *integrate* with UX tools
- **State estimation:** capture state *uncertainty* and probabilistic state estimates through particle filters and importance sampling
- **UX:** detailed *design simulations* with operators and scientists

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Publications

[A] Rebecca Castano, Tiago Vaquero, Vandi Verma, Federico Rossi, Dan Allard, Rashied Amini, Anthony Barrett, Julie Castillo-Rogez, Mathieu Choukroun, Al Dadaian, Nihal Dhamani, Raymond Francis, Rob Hewitt, Mark Hofstadter, Mitch Ingham, Cristina Sorice, Ellen Van Wyk, and Steve Chien, "Operations for Autonomous Spacecraft: A Neptune Tour Case Study," Poster presented at Outer Planets Assessment Group (OPAG) 2021.

[B] Rebecca Castano, Tiago Vaquero, Vandi Verma, Federico Rossi, Dan Allard, Rashied Amini, Anthony Barrett, Julie Castillo-Rogez, Mathieu Choukroun, Al Dadaian, Nihal Dhamani, Raymond Francis, Rob Hewitt, Mark Hofstadter, Mitch Ingham, Cristina Sorice, Ellen Van Wyk and Steve Chien, "Operations for Autonomous Spacecraft", in preparation for the 2022 IEEE AERO conference.

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