National Aeronautics and Space Administration

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


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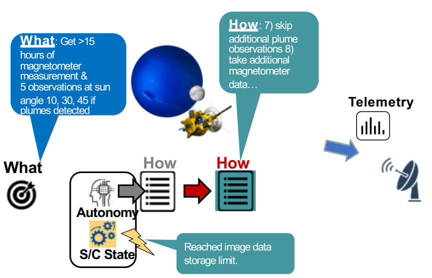
## Goal and Objective

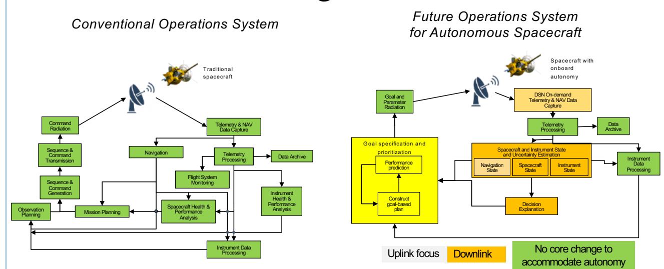



- What is the spacecraft state?
- What happened onboard?
- Why did the autonomy make the decisions it did?

**Objective:** Enable operators of future autonomous spacecraft to:

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

## Background




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

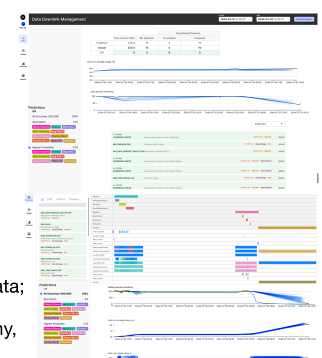
## Approach

### *User Interfaces*

**Objective:** provide *situational awareness* of spacecraft state by

- *Reconstructing* as-executed autonomy plan;
- Allowing operators to intuitively *explore* telemetry and see *correlations* between states, activities, EVRs;
- Comparing telemetry with uplink *predictions;*
- Augmenting telemetry with *state estimates* for missing or sparse data;

**Results**: designed and successfully tested in design sim UIs for autonomy, DMX, power, instrument engineers.



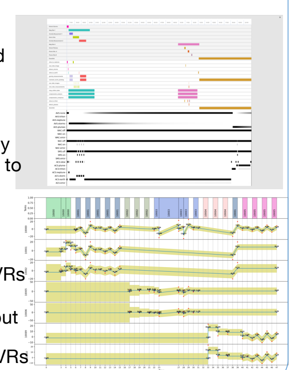
### *State Estimation and Inference*

**Objective:** *reconstruct* as-executed *plan* and spacecraft *state* (with its uncertainty) by

- exploiting channelized data, EVRs, and spacecraft models.
- Reusing existing models used by autonomy
- Making modeling easier through new tools to reduce adoption cost

**Results**

- *Continuous states:* implemented a Kalman filter that exploits the *same model* used by the on-board planner, channel data and EVRs
- *Discrete states:* designed an intuitive, composable language to model input-output Hidden Markov Model, and algorithms to perform inference using the models and EVRs

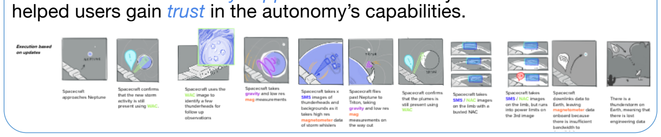


## Design Simulation

We assessed the performance of the proposed tools through a high-fidelity *design simulation*.

- Eight JPL scientists and operators
- Two simulated Triton flybys of a notional Ice Giants orbiter
- Two full downlink sessions
- Competing goals, conflicting instruments result in non-intuitive scheduling decisions
- Multiple on-board anomalies to investigate

**Results**: tools *successfully supported* the necessary downlink tasks and helped users gain *trust* in the autonomy's capabilities.



## 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*

- **Interfaces:** *implement* UI prototypes, *integrate* with existing backends
- **Inference:** provide intuitive *explanation* of scheduling decisions
- **State estimation:** characterize tradeoff between *uncertainty* and *data volume* for representative mission scenarios
- **Infusion**: infuse in ***CADRE*** operational readiness tests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## Publications:


[A] R. Castano, T. Stegun Vaquero, F. Rossi, *et al.*, *"Operations for Autonomous Spacecraft,"* in *IEEE Aerospace Conference*, Big Sky, MT, 2022. (In Press)

[B] T. Stegun Vaquero, F. Rossi, R. Castano, A. Jasour, E. van Wyk, N. Dhamani, B. Huffman, and M. Jorritsma, *"A Knowledge Engineering Framework for Mission Operations of Increasingly Autonomous Spacecraft,"* in *Workshop on Knowledge Engineering for Planning and Scheduling (KEPS)*, Singapore, 2022. (In Press)

[C] Castano, R.; Vaquero, T.; Rossi, F.; Verma, V.; Choukroun, M.; Allard, D.; Amini, R.; Barrett, A.; Castillo-Rogez, J.; Dhamani, N.; Francis, R.; Hofstadter, M.; Ingham, M.; Jasour, A.; Jorritsma, M.; Wyk, E. V.; and Chien, S. *Operations For Autonomous Spacecraft: Workflows And Tools For A Neptune Tour Case Study*. In *Lunar and Planetary Science Conference (LPSC)*, March 2022.


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