Jet Propulsion Laboratory
California Institute of Technology

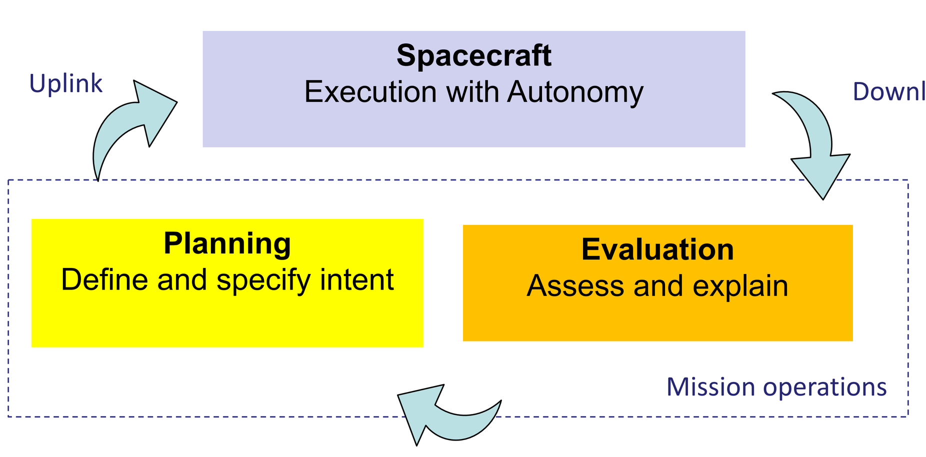
# Operations for Autonomous Spacecraft: A Neptune Tour Case Study

**R. Castano, T. Vaquero, V. Verma, F. Rossi, D. Allard, R. Amini, A. Barrett, J. Castillo-Rogez, M. Choukroun, A. Dadaian, N. Dhamani, R. Francis, R. Hewitt, M. Hofstadter, M. Ingham, C. Sorice, E. Van Wyk, S. Chien**

## Motivation

Onboard autonomy capabilities such as autonomous resource and fault management, planning, scheduling, and execution, onboard detection of scientific targets, and data summarization, hold promise to enable and enhance missions by augmenting traditional ground-in-the-loop operations cycles. Potential benefits include increased science returns, improved spacecraft reliability, and reduced operation costs. As a compelling 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.

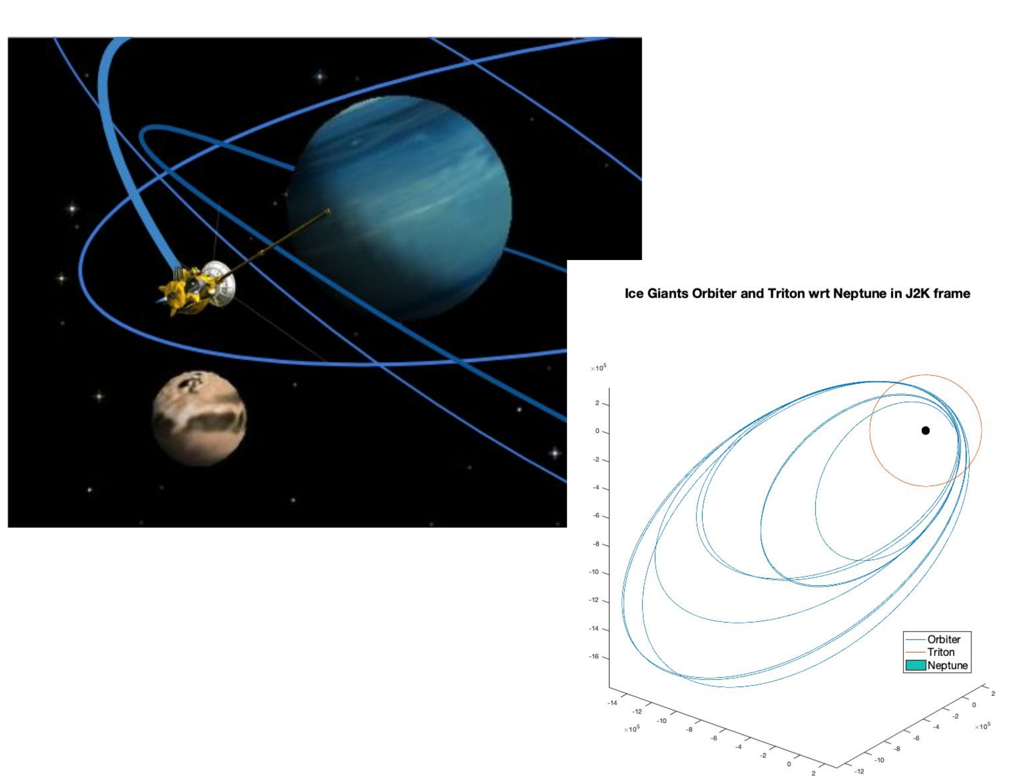
The impact of such onboard autonomous capabilities on ground operations and the challenge of operating such capabilities is rarely addressed to a level of detail sufficient for consideration in mission concepts. Scientists and engineers must not only understand the behavior of the autonomy capabilities, that is communicate intents and understand what and why happened, they must trust the overall process. Through the use of a Neptune-Triton tour mission case study, we are developing new operations tools and workflows, for both uplink and downlink teams, to enable a shared understanding of algorithm behavior between humans and the autonomous system, in order to achieve mission goals for a spacecraft with onboard autonomy.



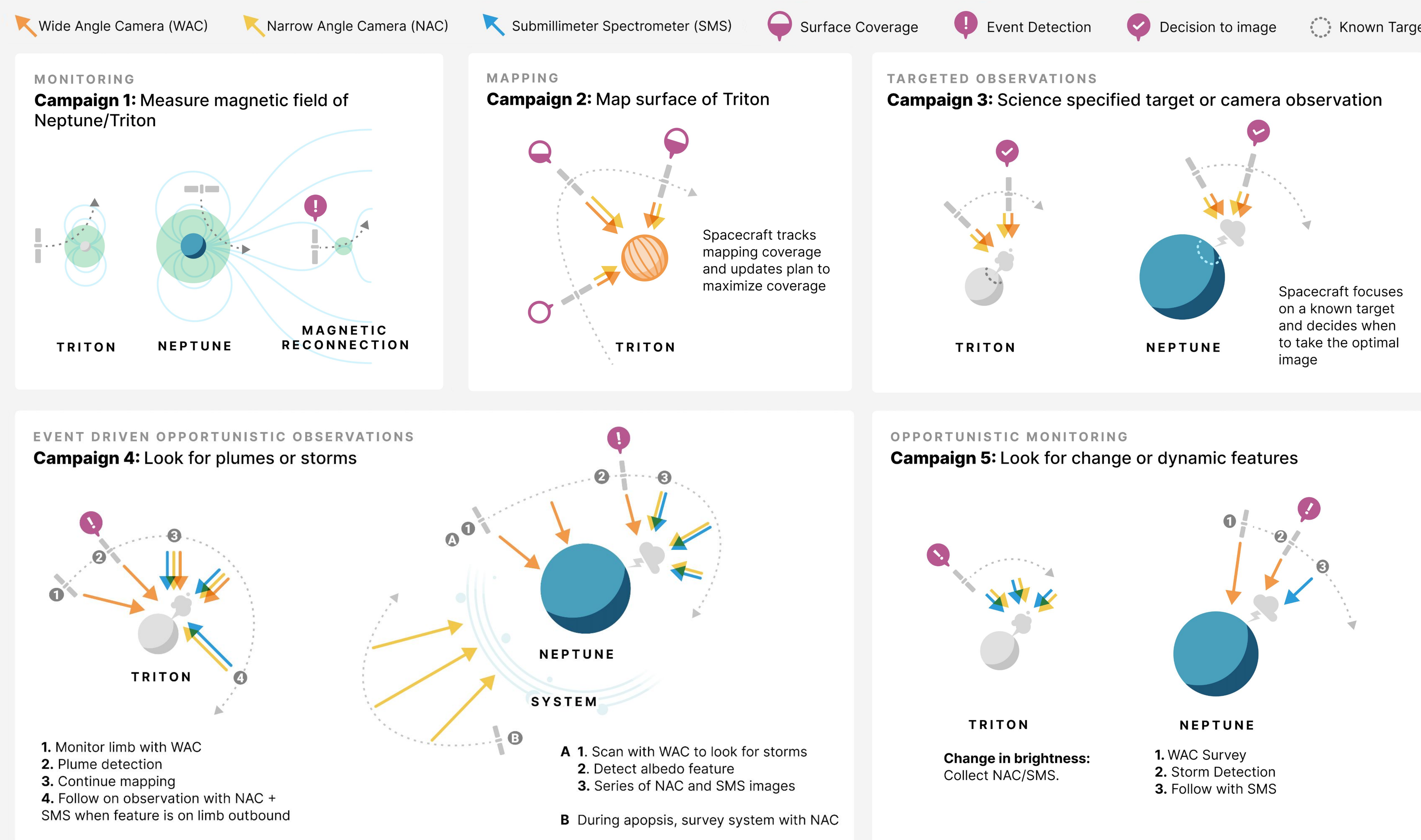

## Mission Case Study

Leveraging several prior mission concepts including the Neptune Odyssey mission concept [1], Trident Mission concept [2] and Ice Giants Study [3], a subset of representative instruments and tour orbits were selected. Five classes of science campaigns that could involve varying autonomy capabilities were selected: monitoring, mapping, targeted observations, event-driven opportunistic observations, opportunistic monitoring.

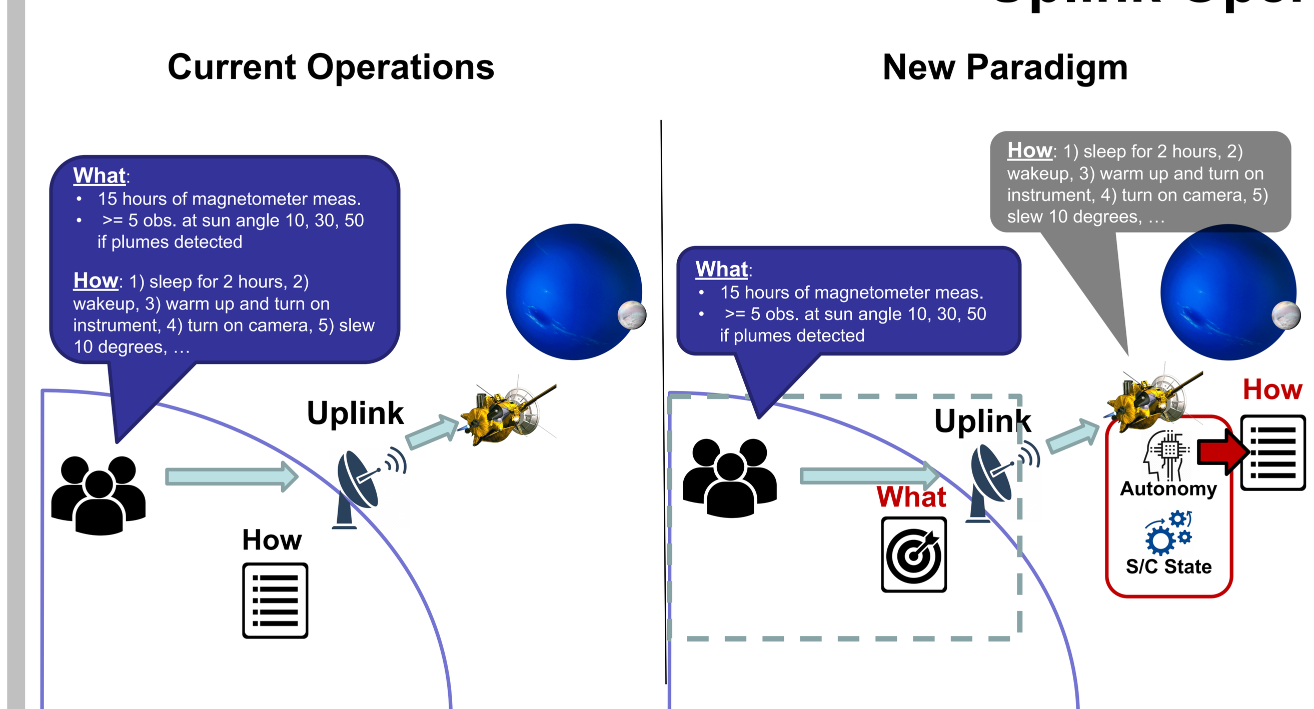
Using these campaigns, 14 more specific scenarios exercising the instrument suite and variability in the perceived state of the environment, instruments, and spacecraft were defined. Examples of variable scientific events impacting observation time, power, and data volume include detecting plumes on the limb of Triton, magnetospheric variability, and storm detection at Neptune. Scenarios with anomalous instrument or spacecraft behavior were also included. For this exercise, we assumed that the trajectory is fixed and can only be adjusted by ground operations, although this could be changed in the future.

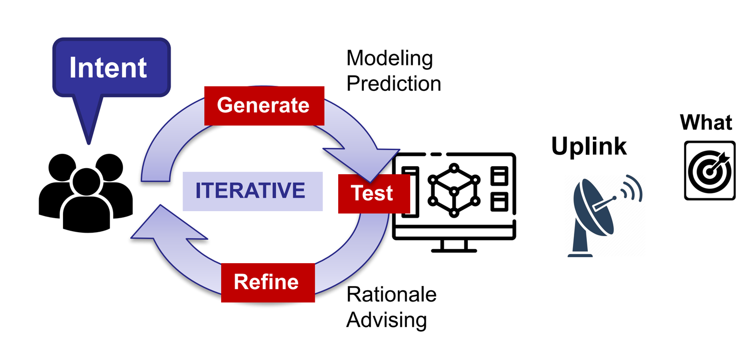



## Science Campaigns and Scenarios




## Uplink Operations

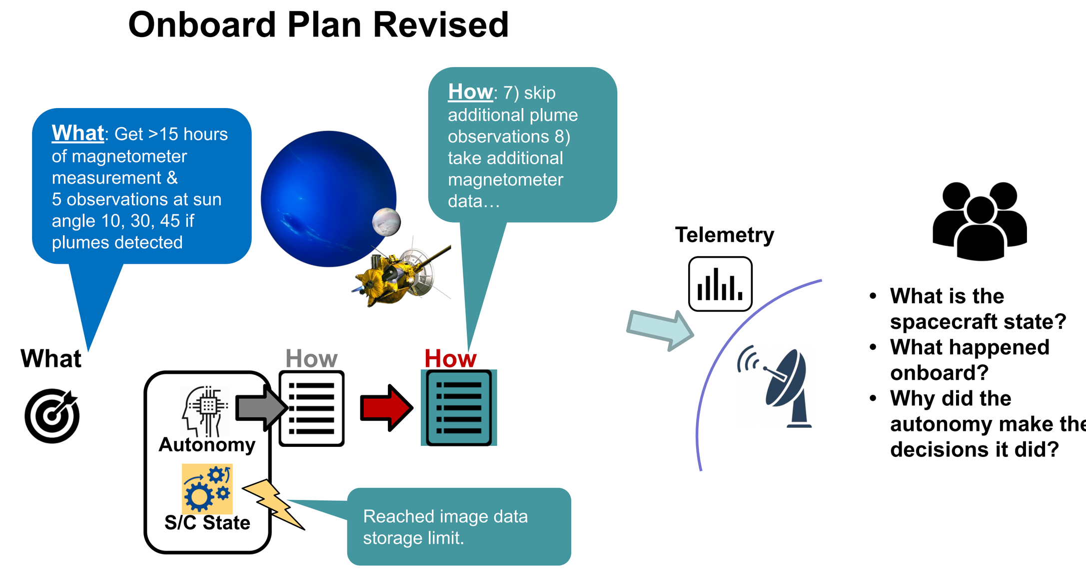


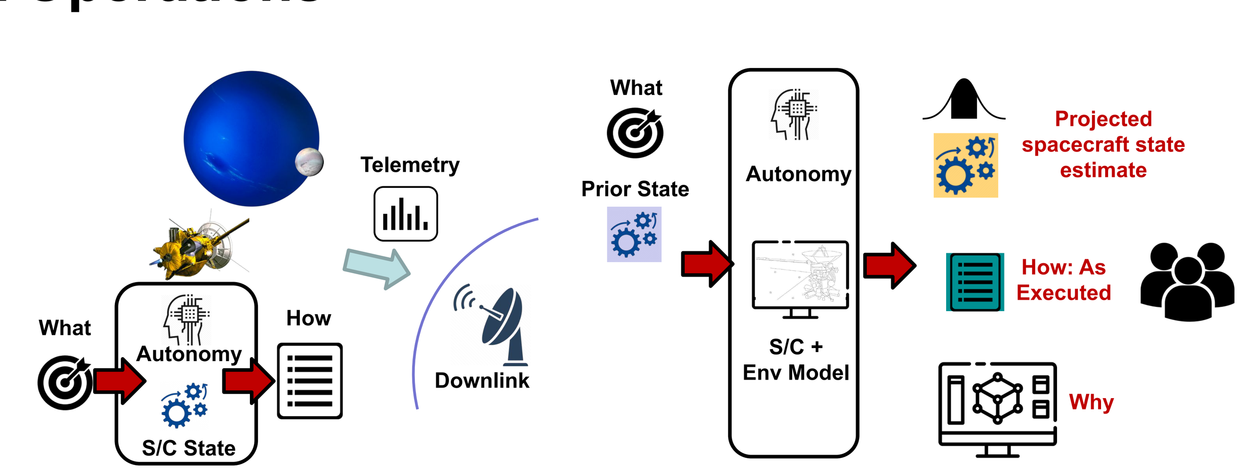




**Objective**: Develop technology to allowing operators to model plans based on intents (goals) to uplink to the spacecraft and to validate plans by understanding the range of potential outcomes from execution.

1. Enable construction of plans that capture intent
   Develop a modeling technology (leveraging previous JPL work on this area) to facilitate the construction of plans with science intent and the iterative design process.
2. Provide operator feedback and instill trust
   Develop techniques for outcome/execution prediction, visualization, explanation, as well as advisory techniques (e.g., to fix undesirable behavior, add/change this constraint), to facilitate the operators learning process while helping them reassure that the spacecraft will complete the plan successfully.

## Downlink Operations




**Objective**: 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.

1. Explain what executed and why
   Provide an operator-understandable explanation of the decision-making of the autonomy system, from post-execution telemetry, such that the operator gets the equivalent explanation as from a team of experts analyzing the data and helping the operator.
2. Estimate and project spacecraft state
   Predict state range of the spacecraft at the beginning of autonomy plan execution and during execution accounting for uncertainty introduced by on-going onboard autonomous execution.

## Conclusion

Lessons learned, along with the tools and workflows developed under this effort, will directly inform future science and exploration missions across a variety of mission classes, including surface missions (e.g., Europa and other Icy World Lander, Mars surface missions, and Venus Lander), small body exploration (e.g., fast flybys, Centaur rendezvous), and farther out concepts.

## References

[1] Rymer, A., et al. Neptune Odyssey (2020) PSJ.
[2] Prockter, L., et al. (2019) *LPS* 50, 3188.
[3] Ice Giants Study (NASA 2017)

**National Aeronautics and Space Administration**

**Jet Propulsion Laboratory**
California Institute of Technology
Pasadena, California
**jpl.nasa.gov**

CL#21-3992



**Acknowledgments**
The research was carried out at the Jet Propulsion Laboratory, California Institute of Technology, under a contract with the National Aeronautics and Space Administration