2023 Ground Software Architecture Workshop (GSAW)

Autonomy & Automation in Deep Space Mission Operations

March 27, 20223

Seung H. Chung,
Planning & Execution Systems Section Manager

Jet Propulsion Laboratory
California Institute of Technology

Launch: 2023.10.10

Target: 16 Psyche

Type: Orbiter

Arrival: 2029.08

Instruments

Multispectral Imager

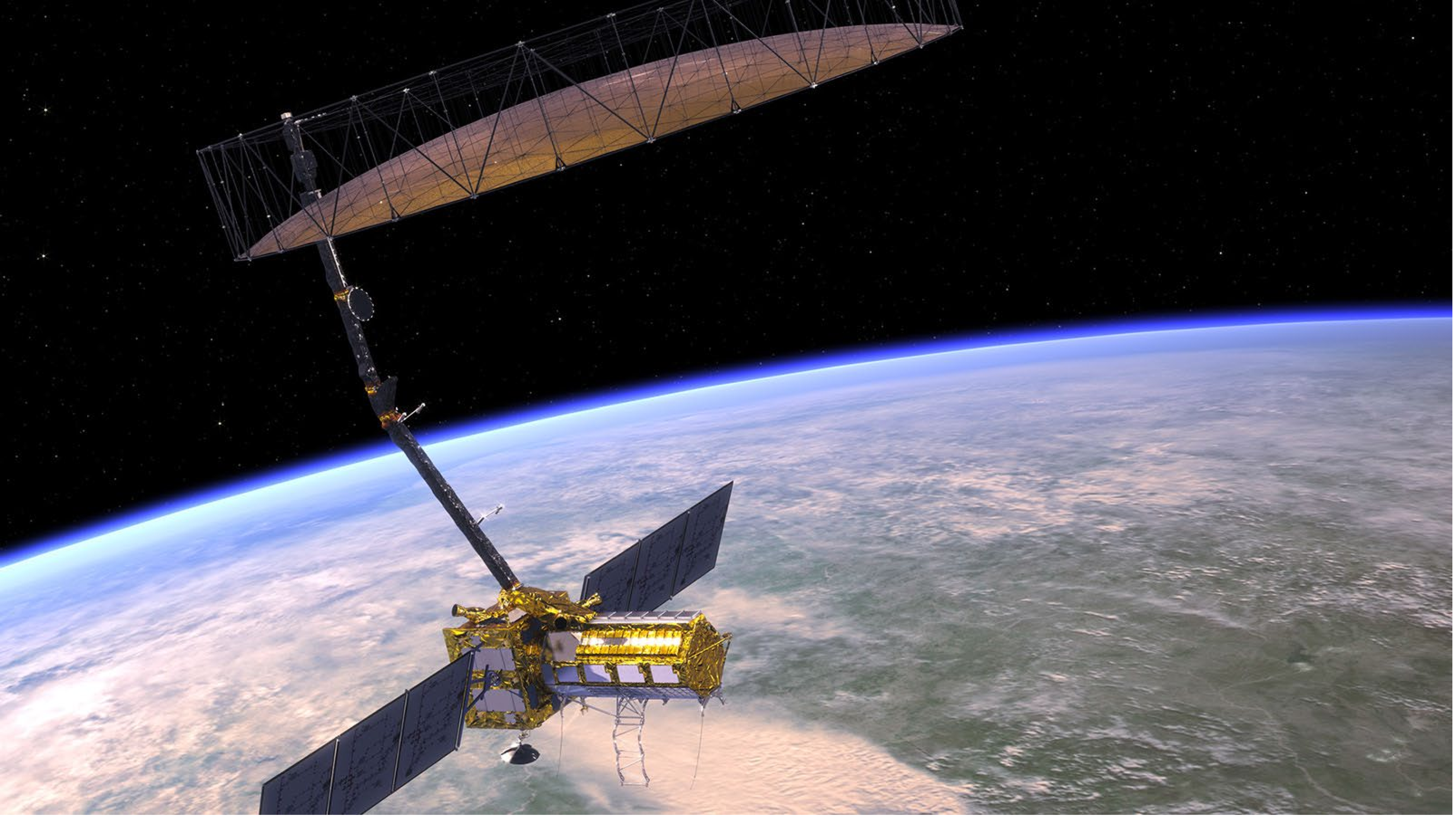
Gamma Ray and Neutron Spectrometer

Magnetometer

X-band Gravity Science Investigation

Deep Space Optical Communication (DSOC)

Psyche



Launch: 2024

Target: Earth

Type: Orbiter

Instruments

L-band (24-cm wavelength) Polarimetric Synthetic Aperture Radar

S-band (12-cm wavelength) Polarimetric Synthetic Aperture Radar

NISAR - NASA-ISRO Synthetic Aperature Radar

Launch: 2024.10.06

Target: Europa, Jupiter

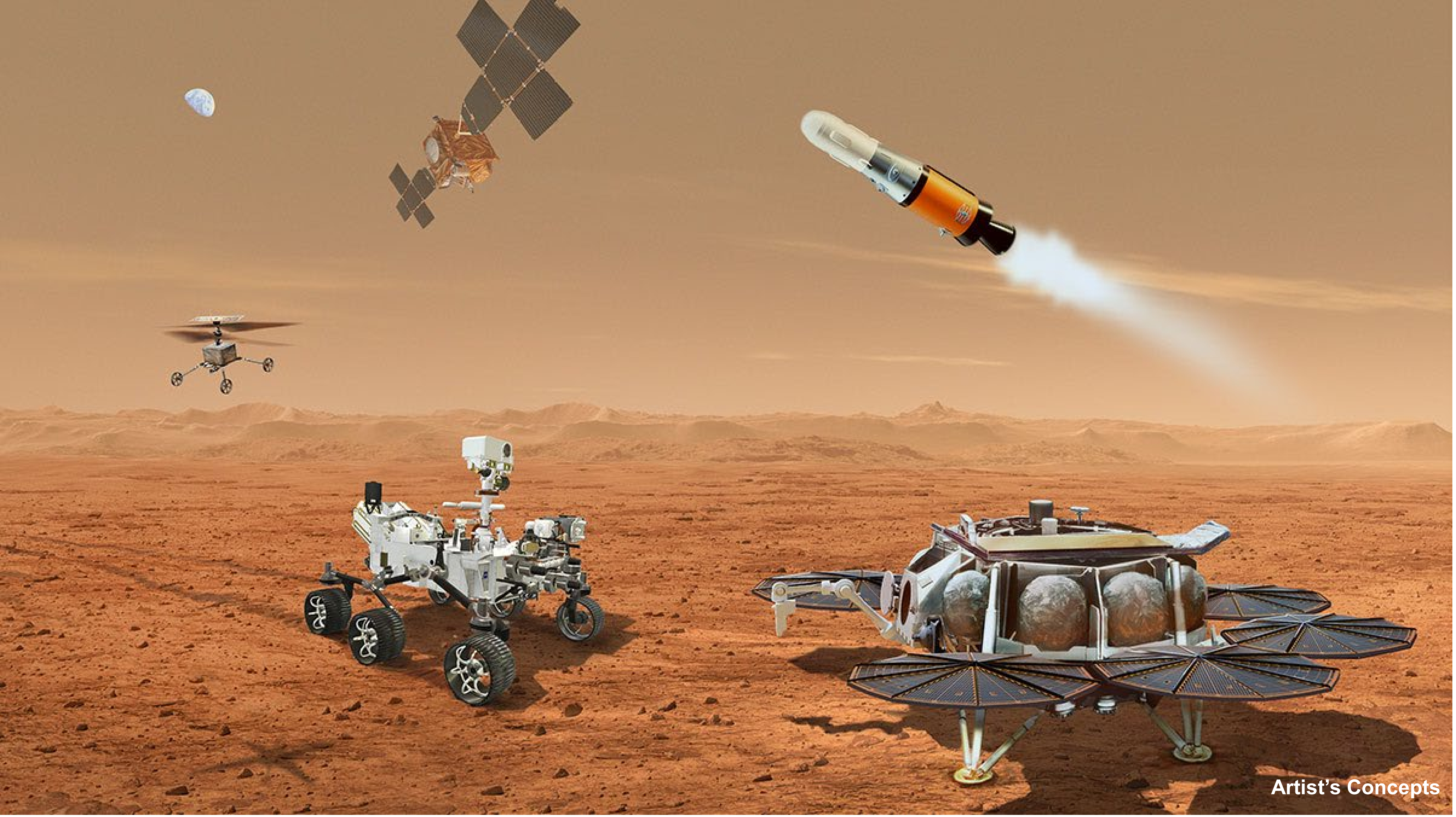
Type: Orbiter

JOI: 2030.04.11

Instruments

- Plasma Instrument for Magnetic Sounding (PIMS)
- Europa Clipper Magnetometer
- Mapping Imaging Spectrometer for Europa (MISE)
- Europa Imaging System (EIS)
- Radar for Europa Assessment and Sounding: Ocean to Near-surface (REASON)
- Europa THermal Emission Imaging System (E-THEMIS)
- MAss SPectrometer for Planetary EXploration/Europa (MASPEX)
- Europa Ultraviolet Spectrograph
- SUrface Dust Mass Analyzer (SUDA)

Europa Clipper



Launch: 2027 – 2028 Planned

Target: Mars

Type: Orbiter, Lander, Helicopter/Rover, Launcher

Pre-Decisional Information – For Planning and Discussion Purposes Only

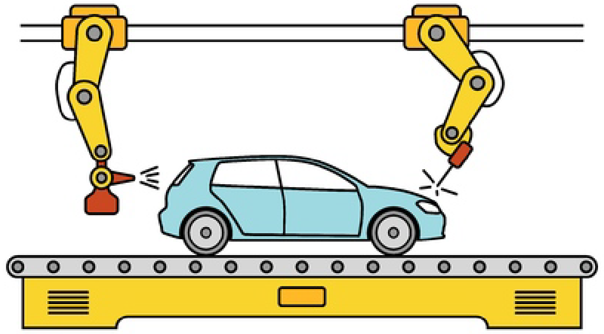
Mars Sample Return

Automation and Autonomous Around Us

With various degree of automation and autonomy



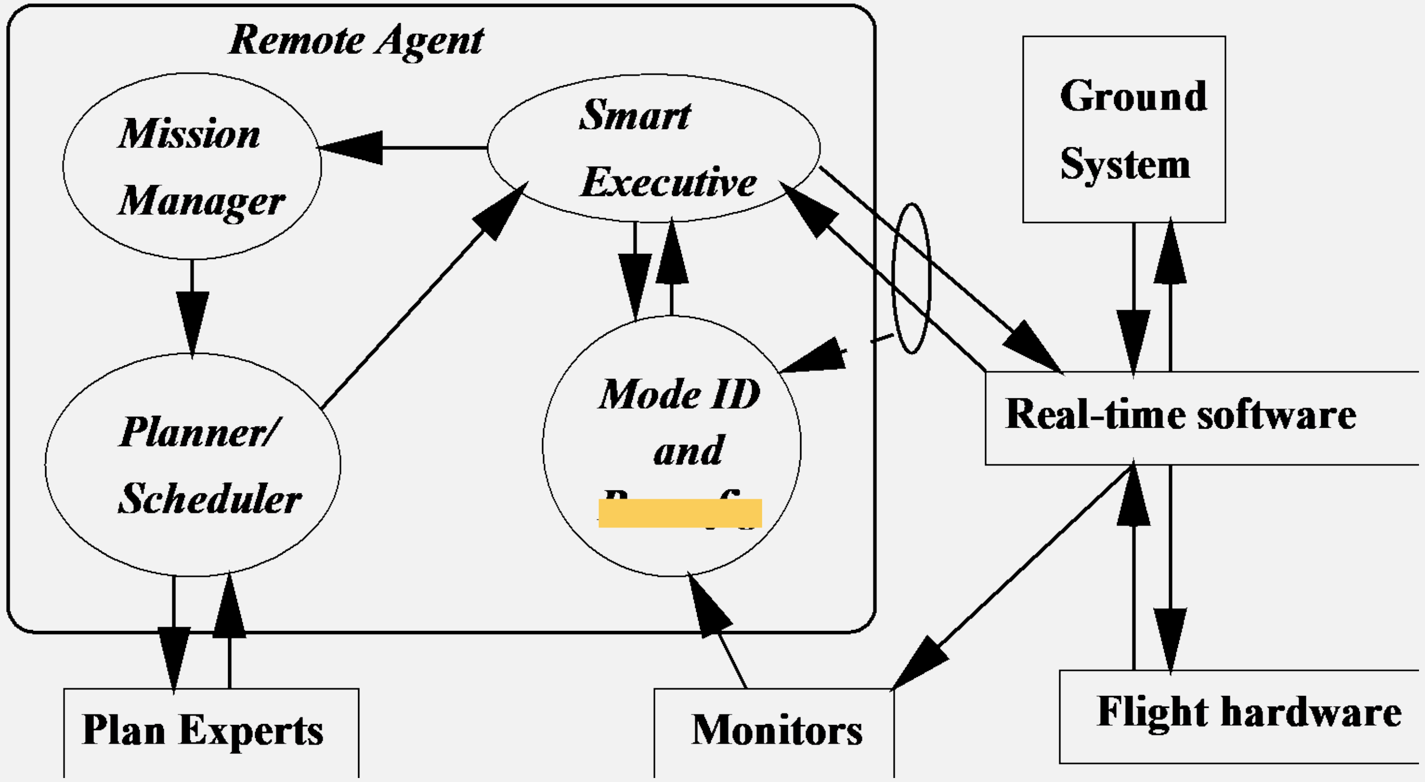


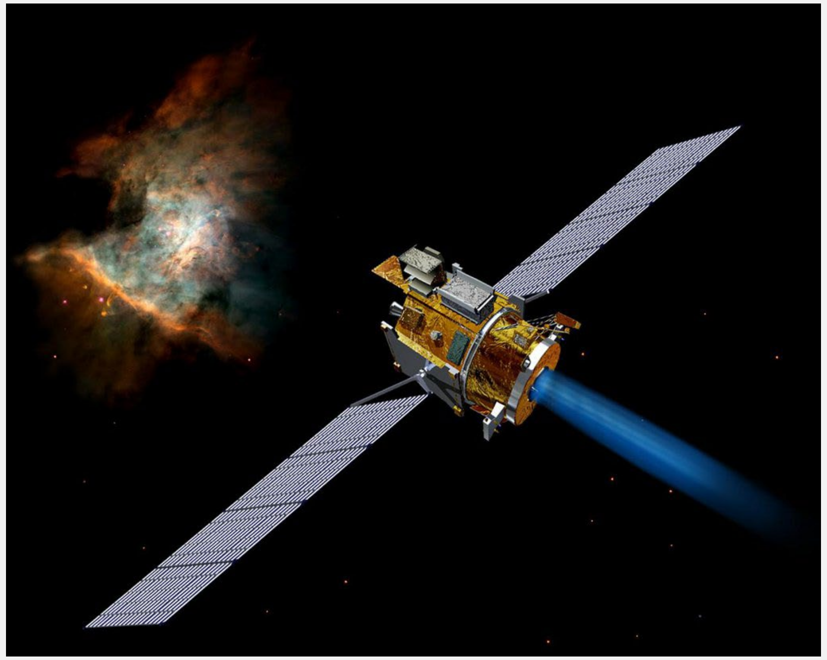



- Automatic Train Operation
- Airliner Autopilot, Autoland, Auto Takeoff?
- Autonomous Vehicle
- Autonomous Power Plant
- Autonomous Chemical Plant
- Automotive Manufacturing Automation and Robots
- Autonomous Warehouse
- …

Autonomy & Automation Technologies in the Flight System

DS1 Remote Agent Experiment





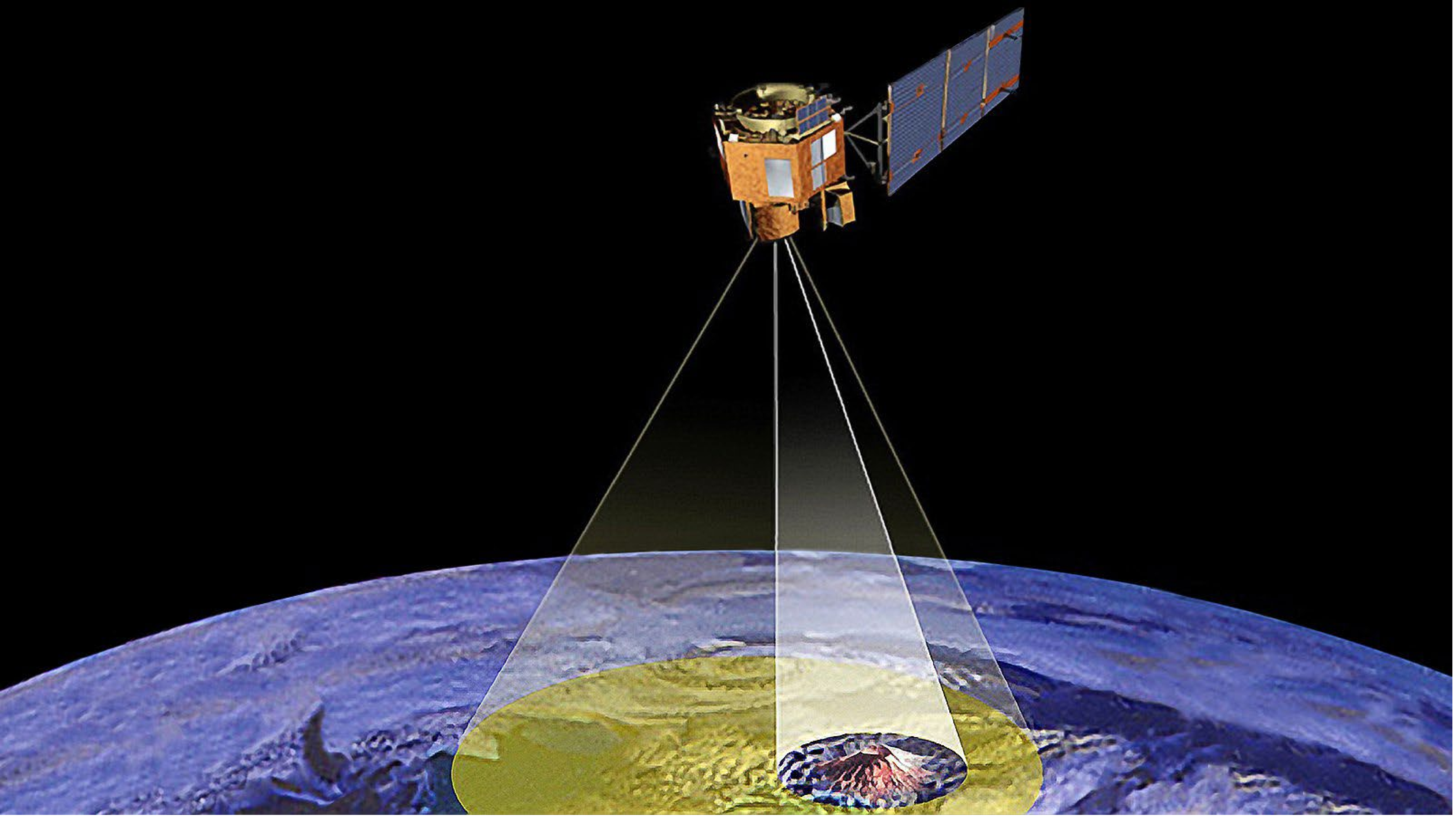
Rajan et al., Remote Agent: An Autonomous Control System for the New Millennium. ECAI 2000, Proceedings of the 14th European Conference on Artificial Intelligence, Berlin, Germany, August 20-25, 2000

Technology

- PS - Automated Planning and Scheduling
- EXEC - Automated plan execution and monitoring
- MIR – Model-based diagnosis and reconfiguration

Mission Heritage

- DS1



https://ai.jpl.nasa.gov/public/projects/ase/

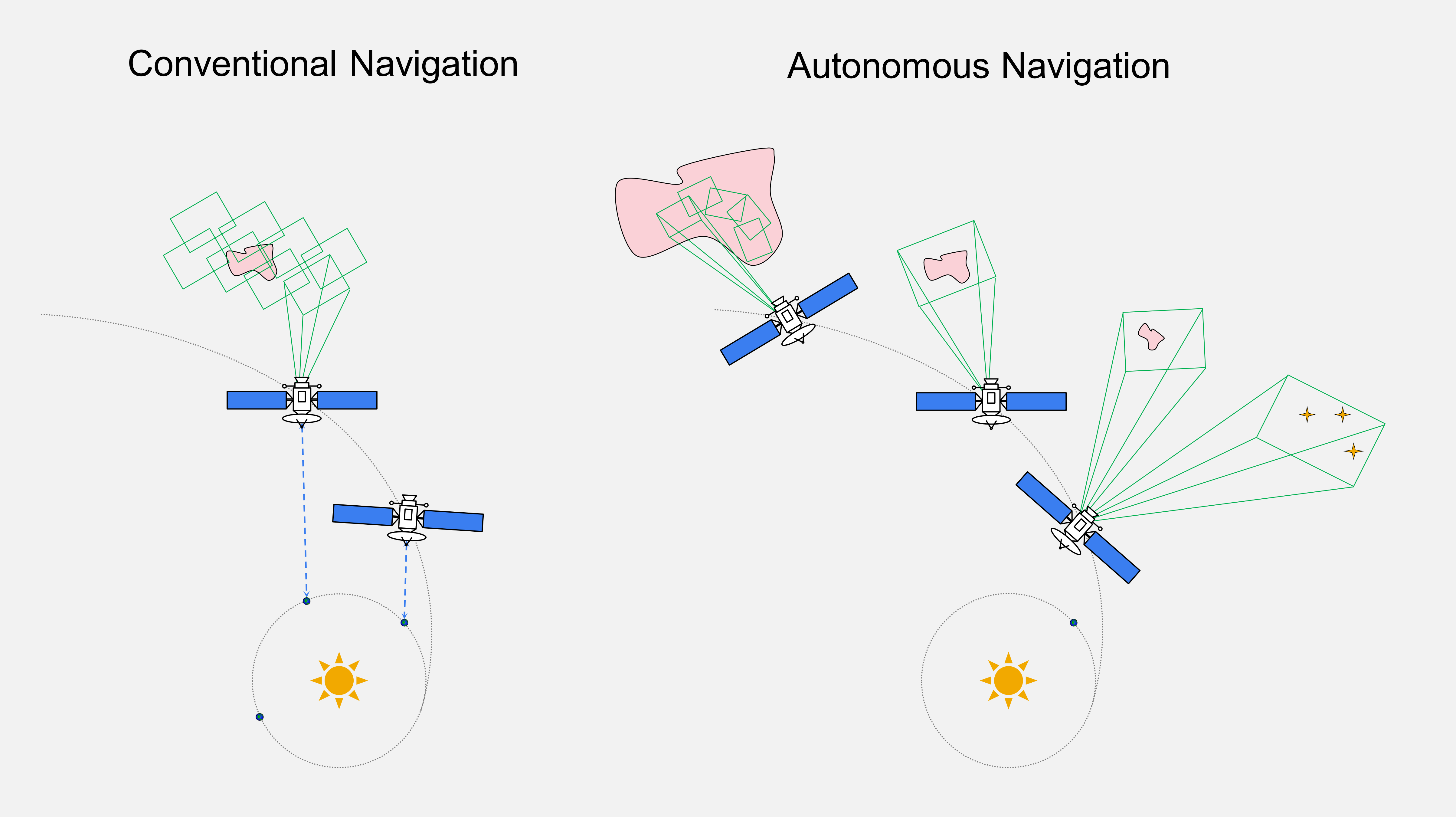
ASE (Autonomous Science Experiment)

Technology

- Onboard Science – Feature detection
- CASPER – Automated planning and scheduling
- SCL – Plan execution and fault protection

Mission Heritage

- EO-1



https://www.jpl.nasa.gov/nmp/ds1/tech/autonav.html

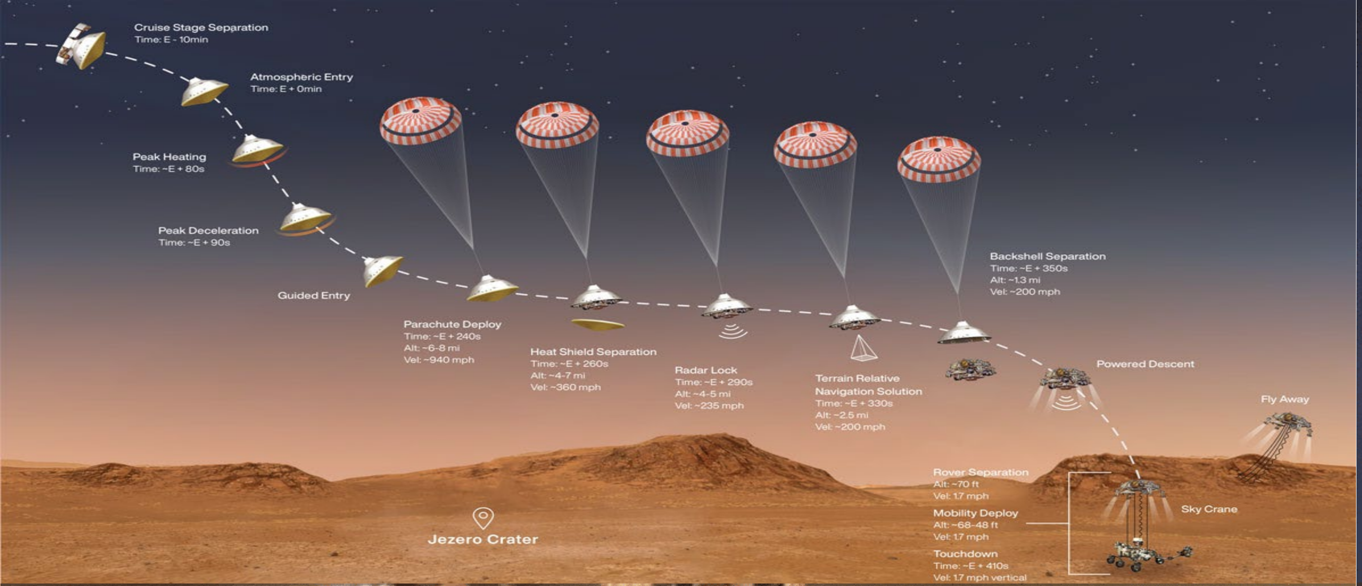
Technology

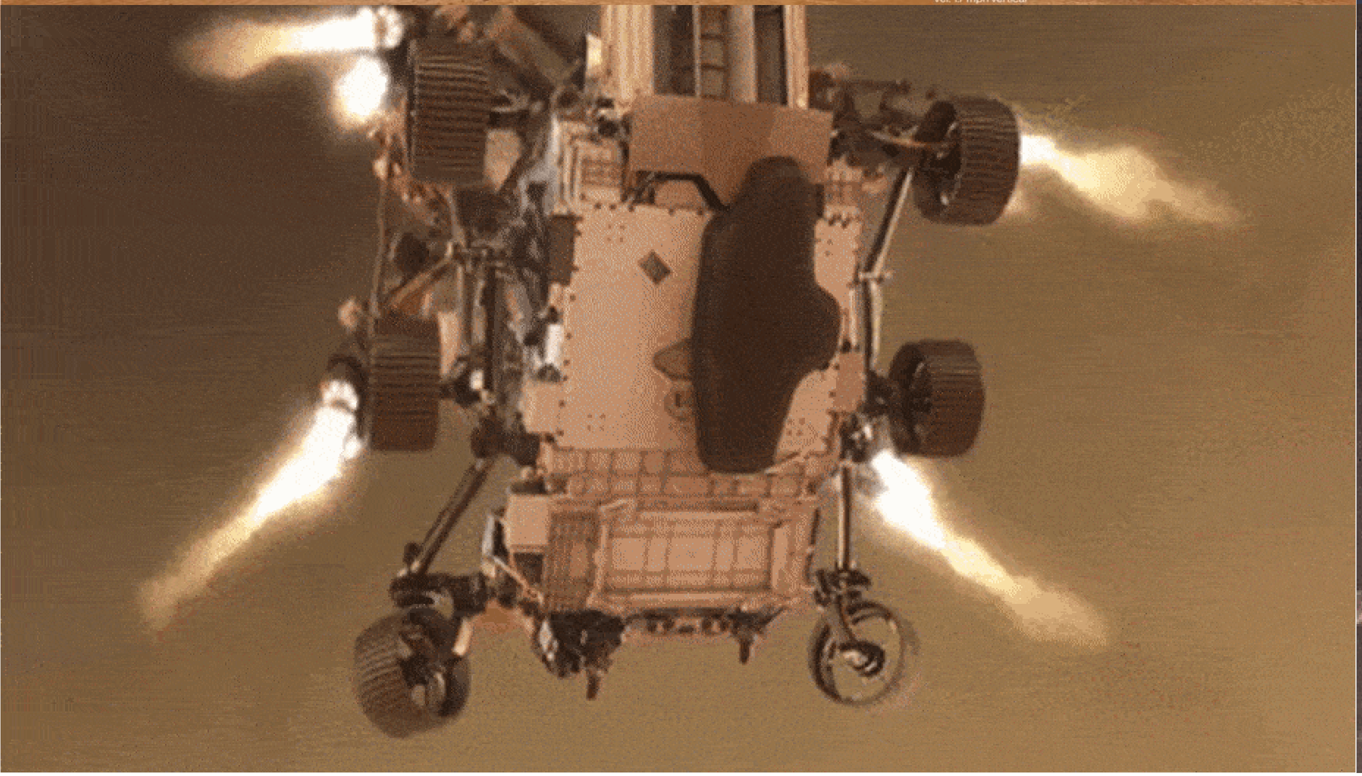
- Image processing
- Orbit determination
- Maneuver planning and execution

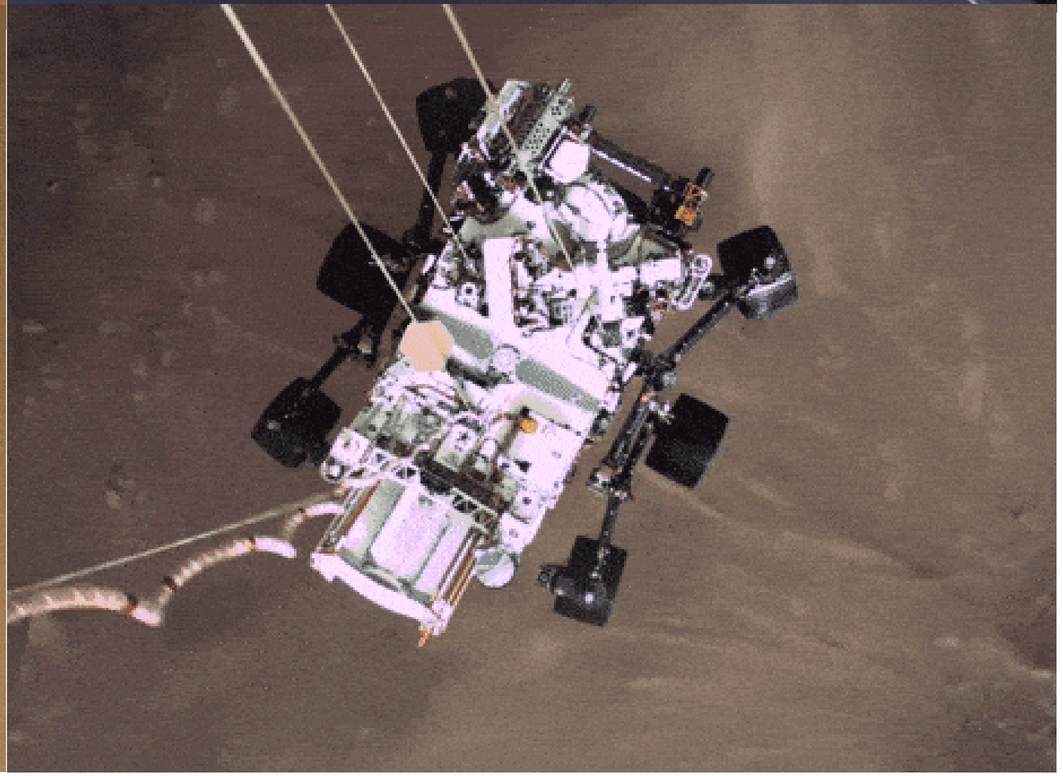
Mission Heritage

- DS1
- Stardust
- Deep Impact / EPOXI
- ASTERIA

Deep Space AutoNav (Autonomous Navigation)







Technology

- Guided entry
- Parachute descent
- Powered descent
- Sky Crane and Flyaway

Mission Heritage

- MSL
- M2020

https://mars.nasa.gov/mars2020/timeline/landing/entry-descent-landing/

Mars EDL (Entry Descent and Landing)

https://robotics.jpl.nasa.gov/what-we-do/flight-projects/mars-2020-rover/terrain-relative-navigation/

TRN (Terrain Relative Navigation)

Technology

- Lander Vision System Localization
- Safe Target Selection

Mission Heritage

M2020

https://www-robotics.jpl.nasa.gov/what-we-do/flight-projects/mars-2020-rover/m2020mobility/

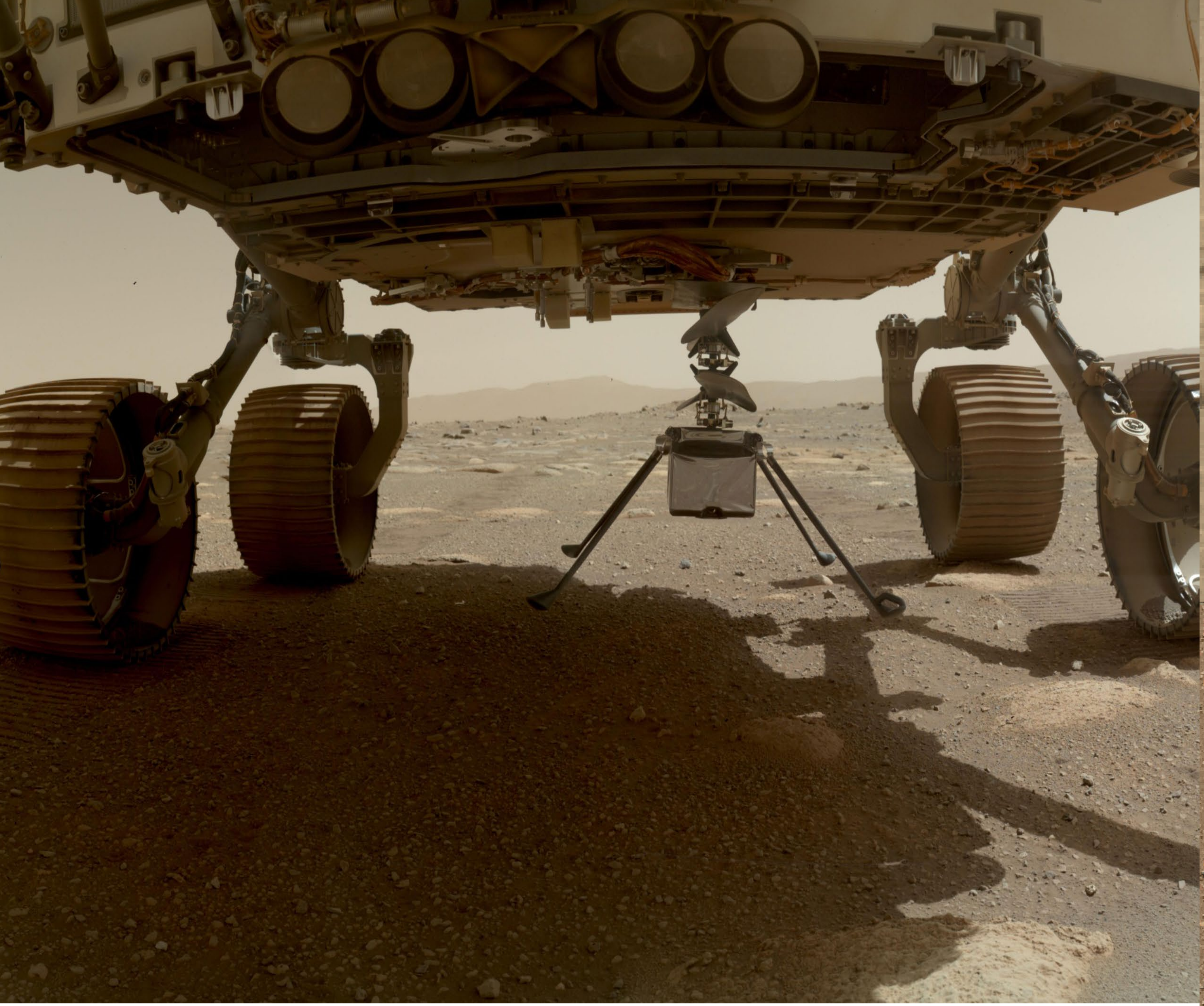
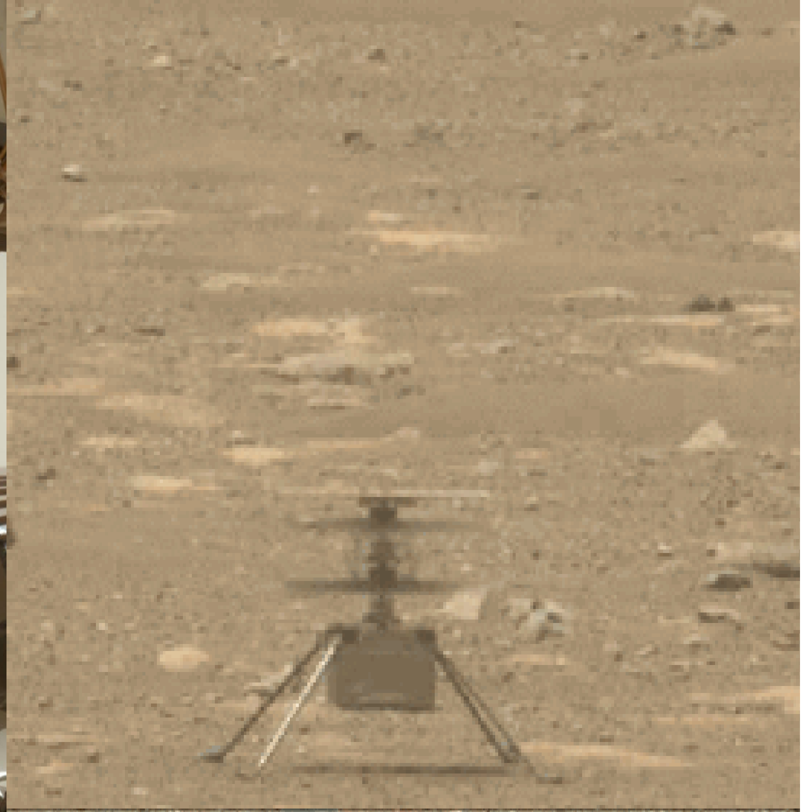
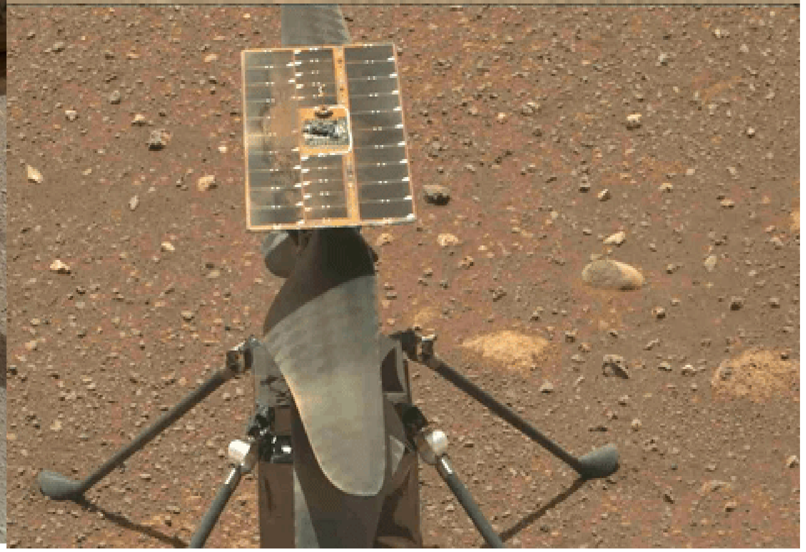
Rover AutoNav (Autonomous Navigation)

Technology

- Stereo vision
- Visual odometry
- Hazard assessment
- Path planning

Mission Heritage

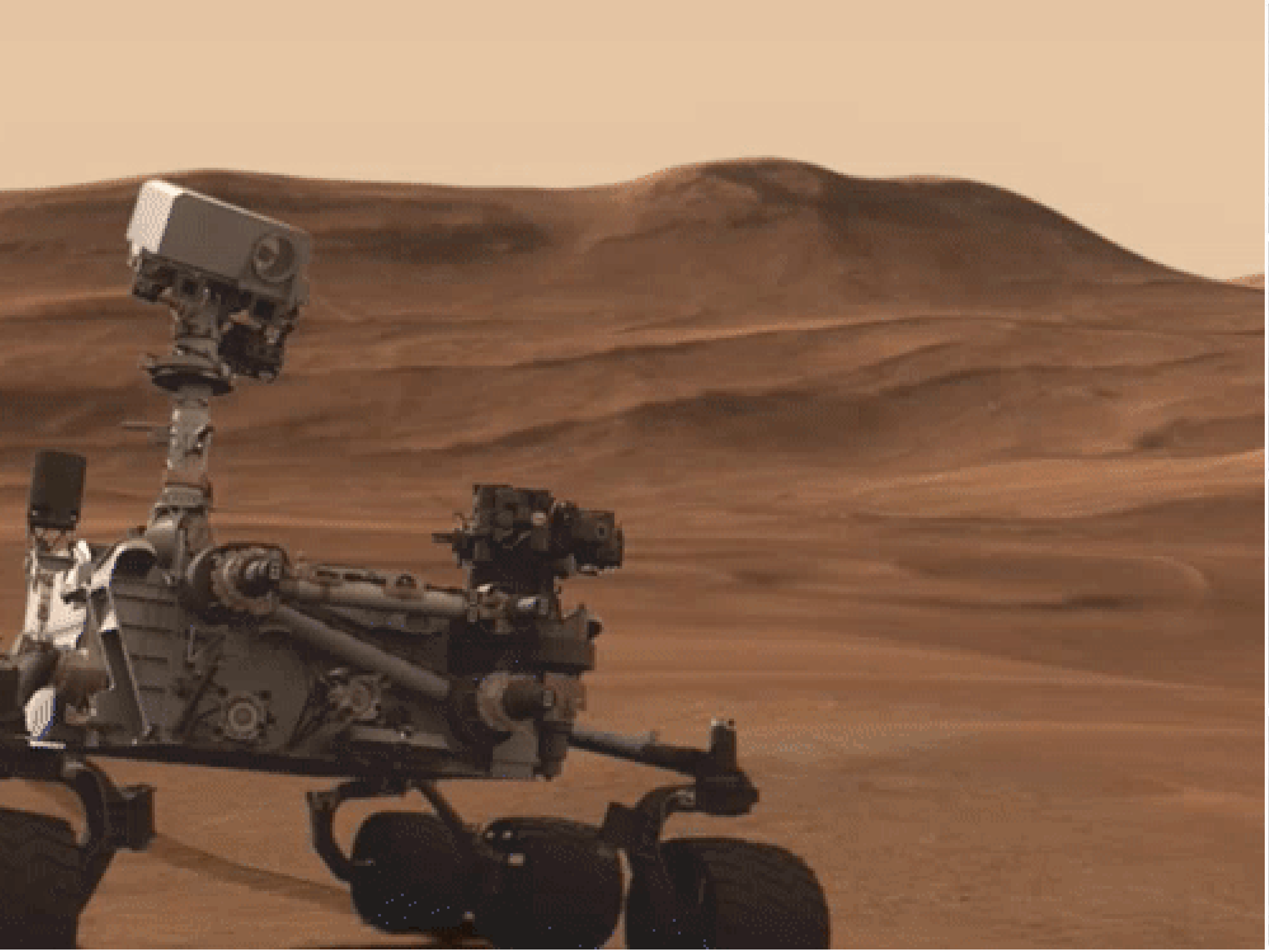
- MER
- MSL
- M2020

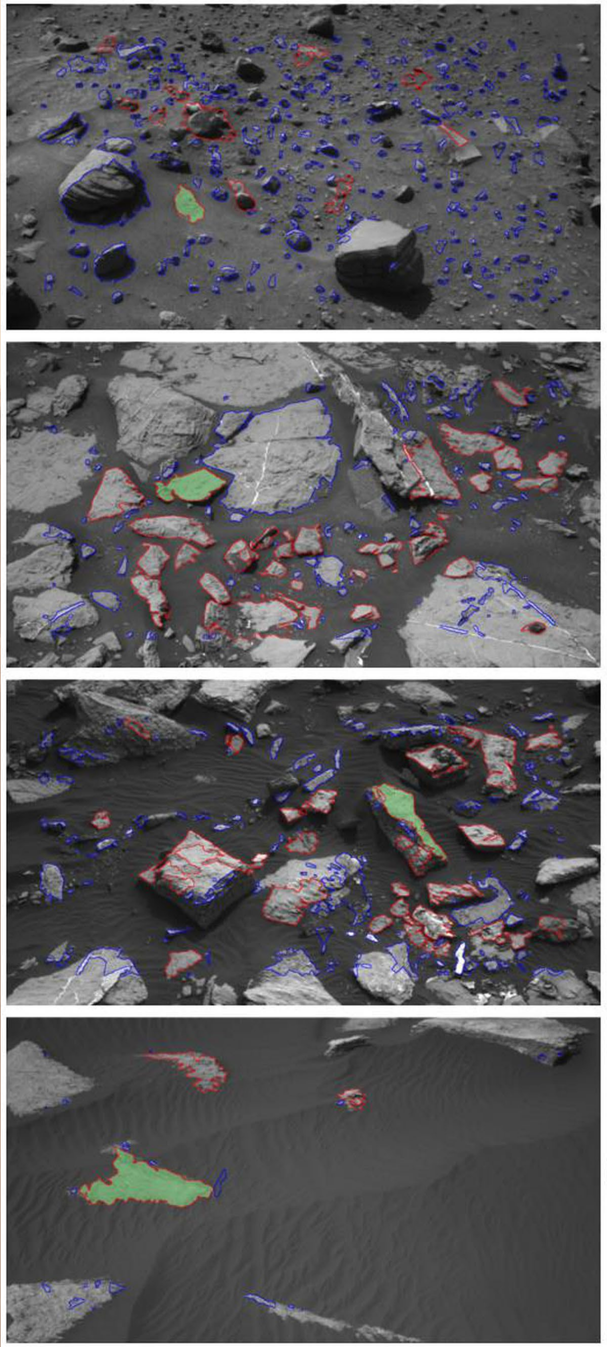




Launch: 2020.07.30
Target: Mars
Type: Helicopter
First Flight: 2021.04.19

https://mars.nasa.gov/technology/helicopter/

Ingenuity Mars Helicopter





Francis, Raymond et al. "AEGIS autonomous targeting for ChemCam on Mars Science Laboratory: Deployment and results of initial science team use." Science Robotics 2 (2017).

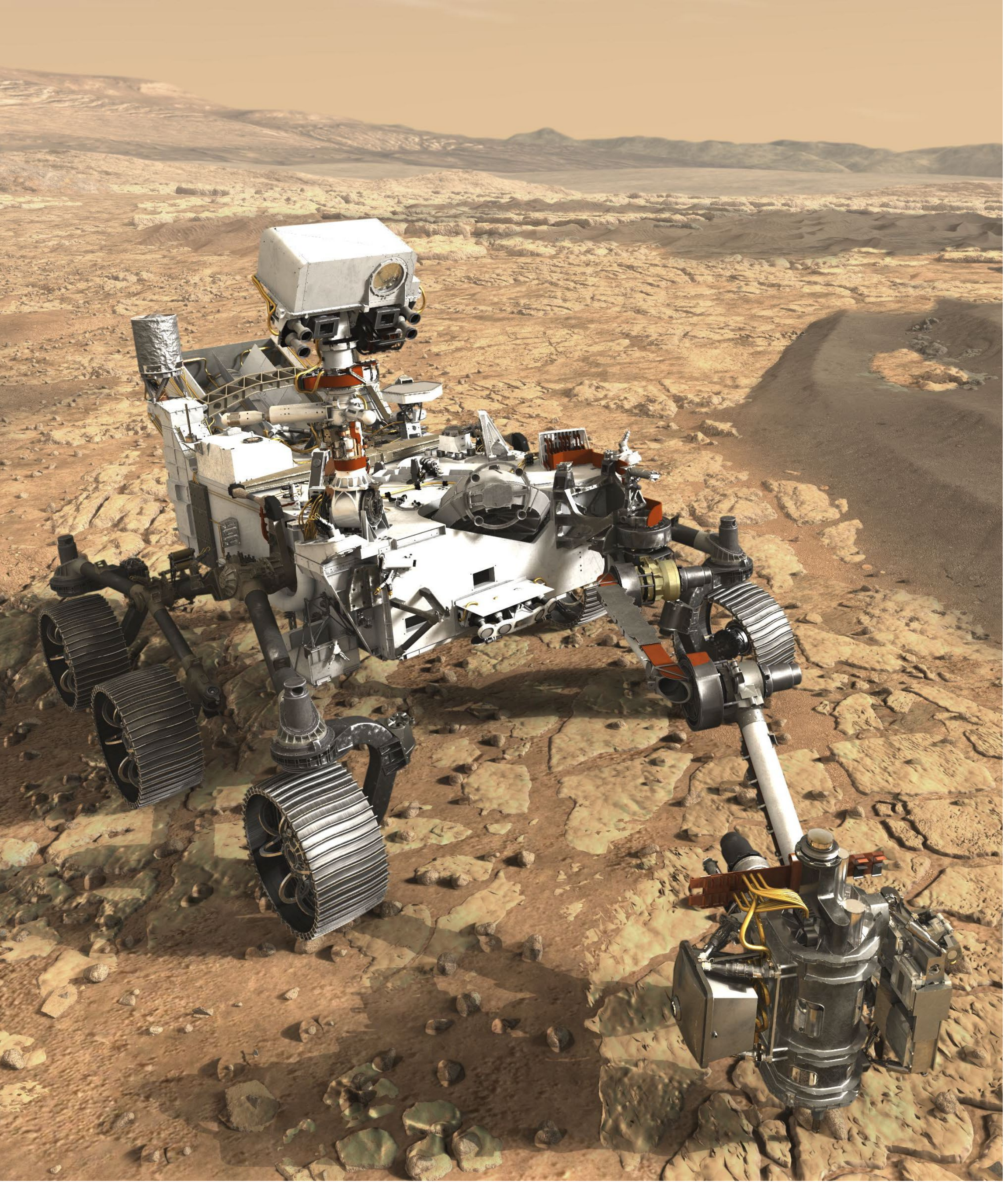
AEGIS (Autonomous Exploration for Gathering Increased Science)

Technology

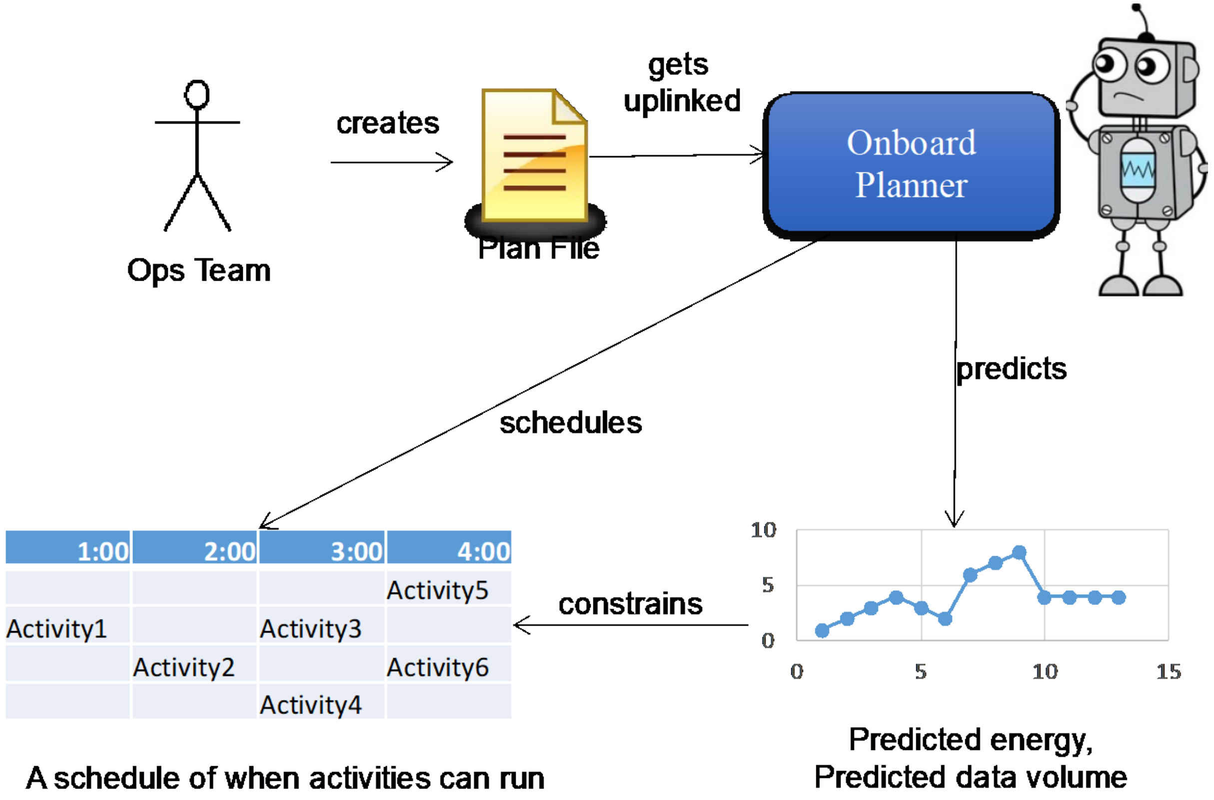
- Target Feature detection
- Target prioritization
- Target pointing determination

Mission Heritage

- MER
- MSL
- M2020



https://ai.jpl.nasa.gov/public/projects/m2020-scheduler/



Technology

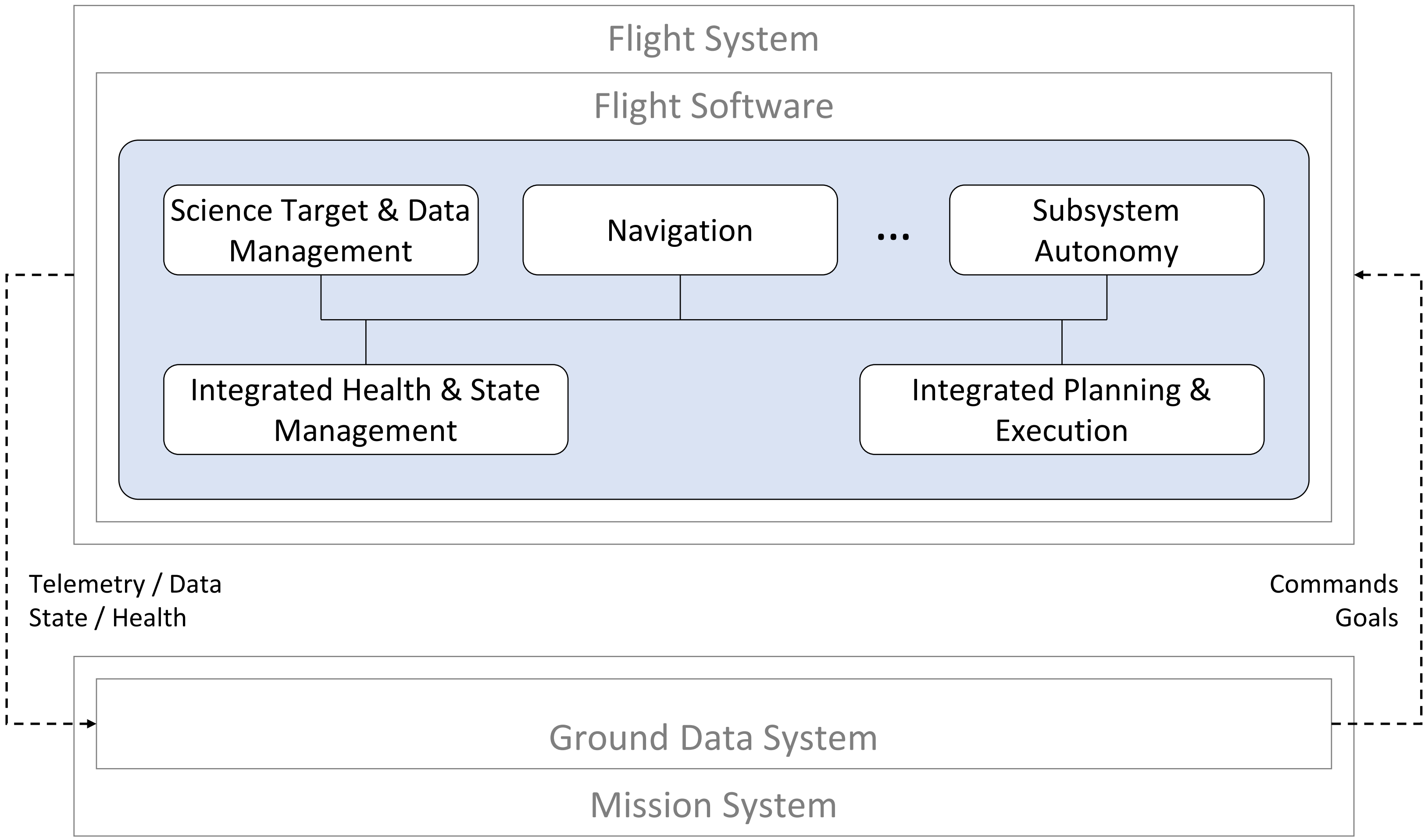
- Automated planning and scheduling
- Automated plan executive

Mission Heritage

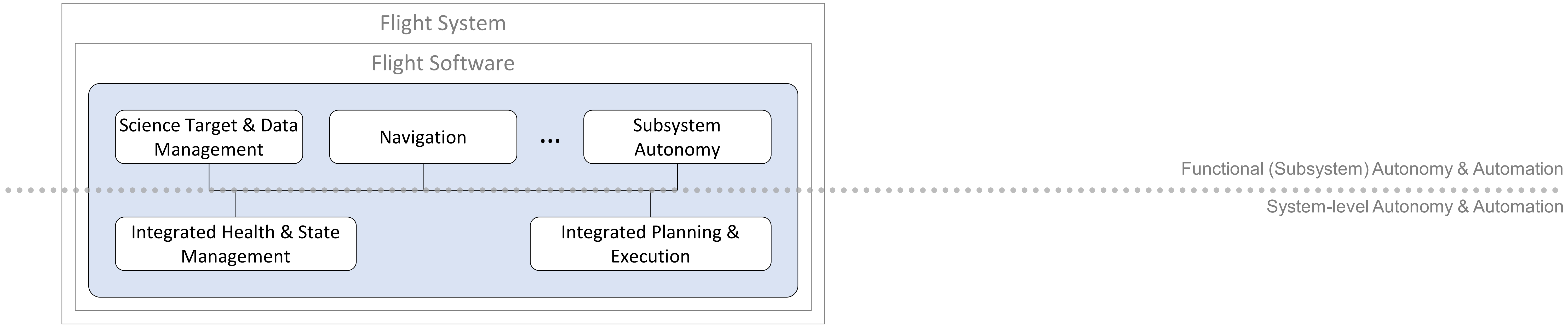
- M2020 (not yet deployed)

M2020 On-Board Planner

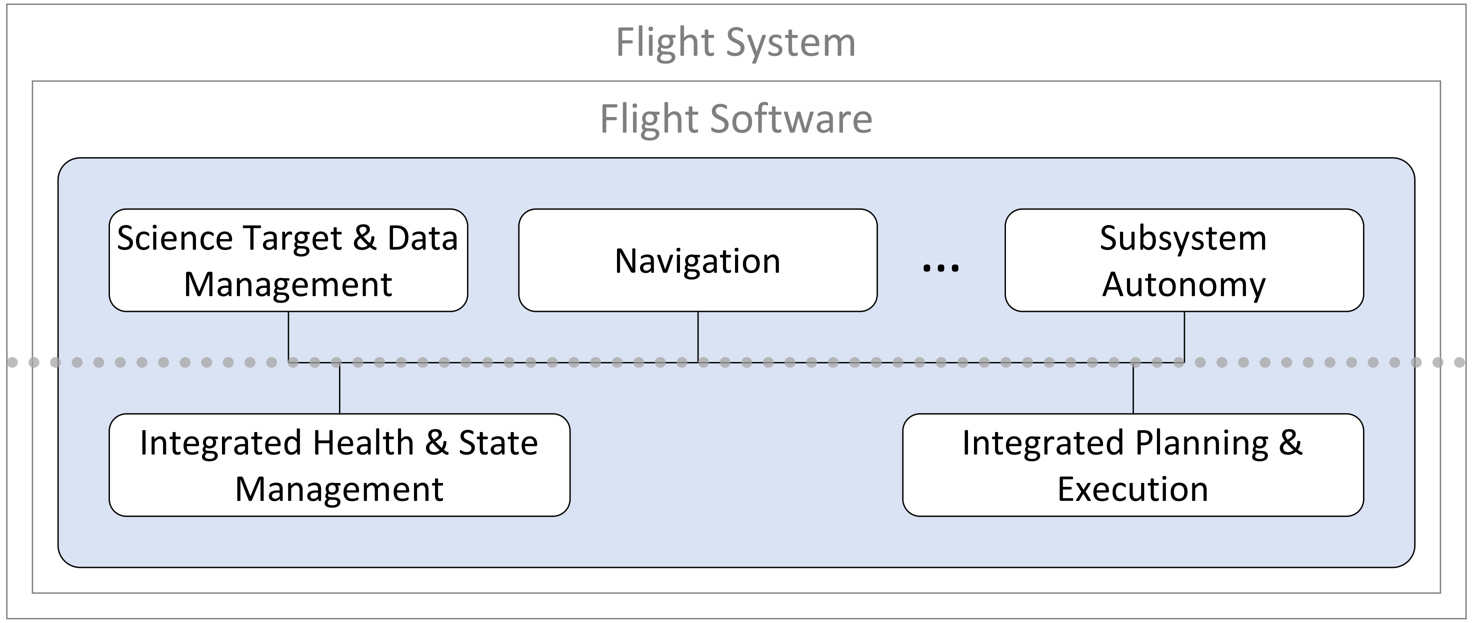
Flight System Automation & Autonomy – Notional



Functional vs. System-Level Automation & Autonomy



Functional vs. System-Level Automation & Autonomy



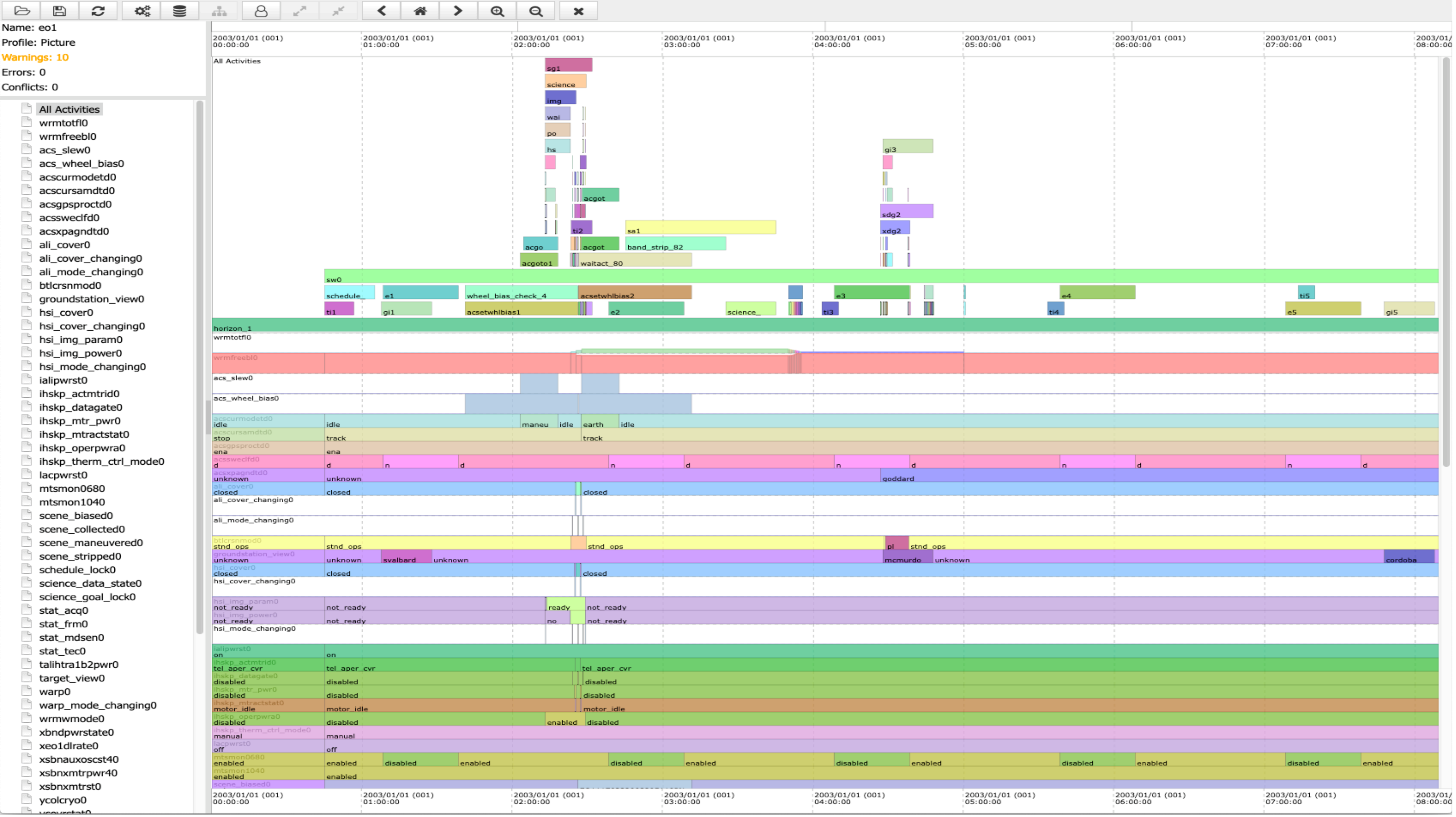
- Deep Space AutoNav
- Mars EDL (Entry Descent and Landing)
- TRN (Terrain Relative Navigation)
- Rover AutoNav
- Ingenuity Mars Helicopter
- AEGIS (Autonomous Exploration for Gathering Increased Science)

Functional (Subsystem) Autonomy & Automation

System-level Autonomy & Automation

- DS1 RAX (Remote Agent Experiment)
- ASE (Autonomous Science Experiment)
- M2020 On-Board Planner

Autonomy & Automation Technologies in the Ground System



https://ai.jpl.nasa.gov/public/projects/aspen/

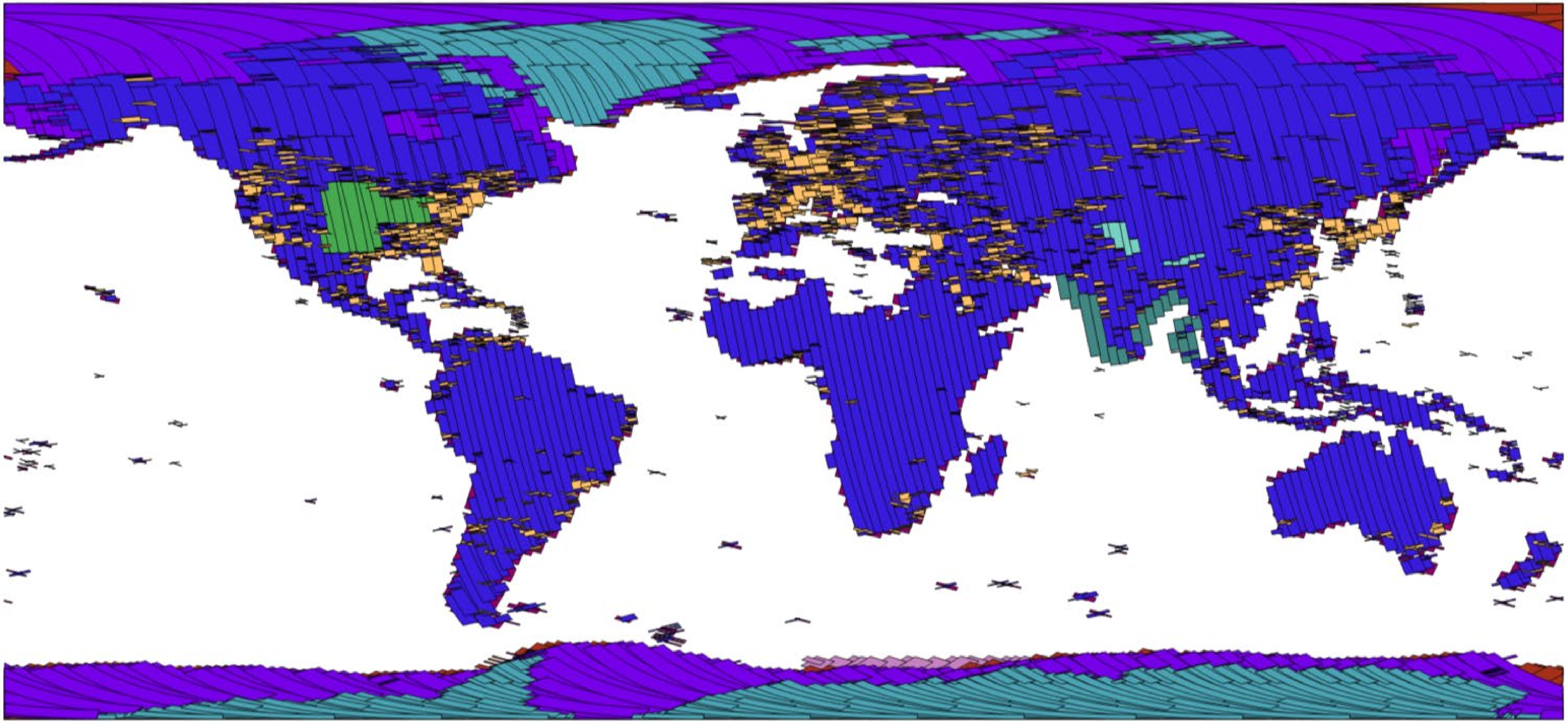
Technology

- Automated activity planning and scheduling

Mission Heritage

- EO-1
- Rosetta

ASPEN (Automated Scheduling and Planning ENvironment)



https://ai.jpl.nasa.gov/public/projects/clasp/

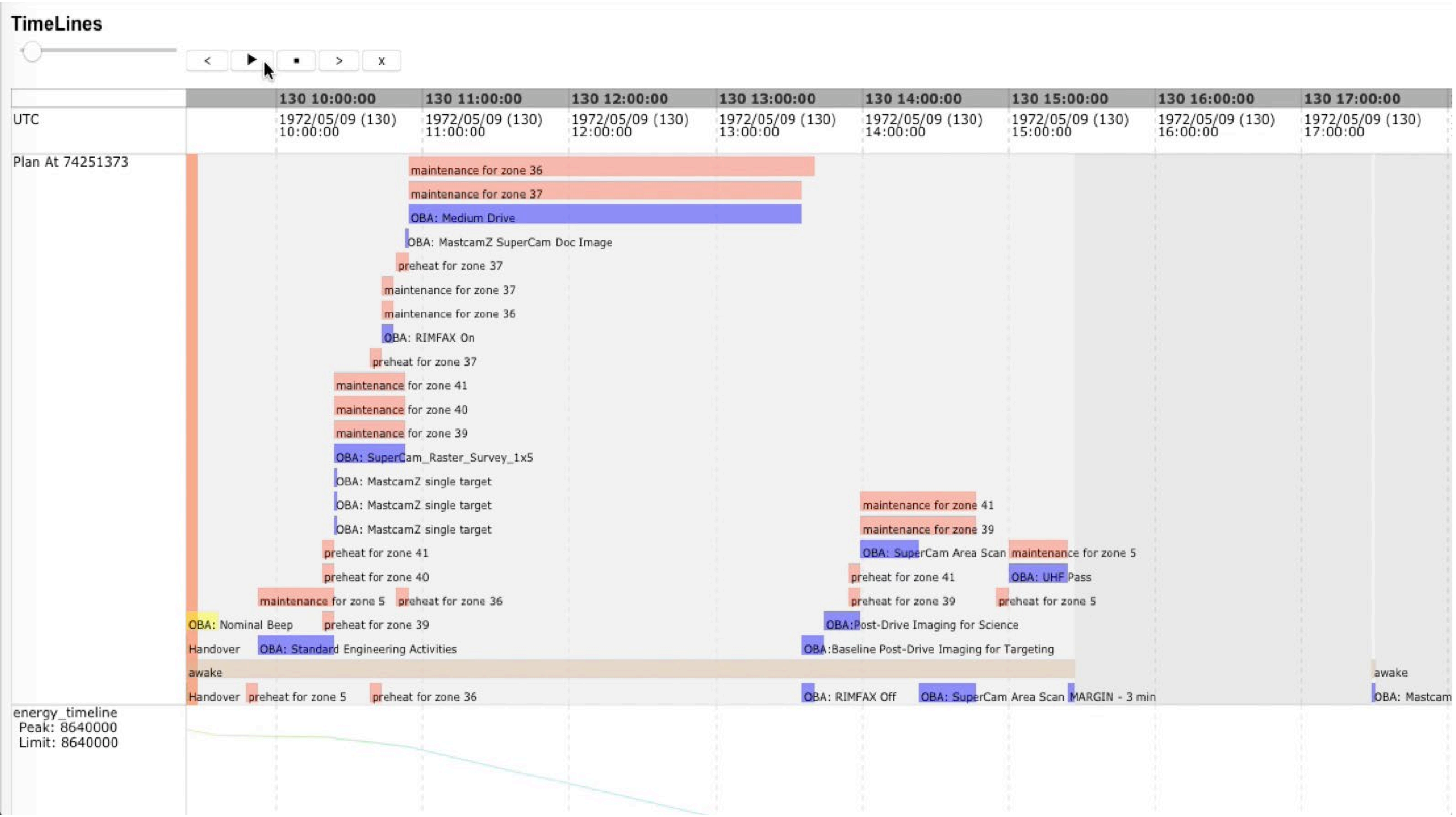
Technology

- Automated observation planning and scheduling

Mission Heritage

- NISAR
- ECOSTRESS
- EMIT
- OCO-3

CLASP (Compressed Large-scale Activity Scheduling and Planning)



https://ai.jpl.nasa.gov/public/projects/m2020-scheduler/

M2020 Copilot

Technology

- Stochastic plan analysis
- Activity prioritization for robust planning

Mission Heritage

- M2020 (not yet deployed)

Automating Deep Space Mission Operations

Reasons for Automation & Autonomy

Many argue that automation and autonomy…

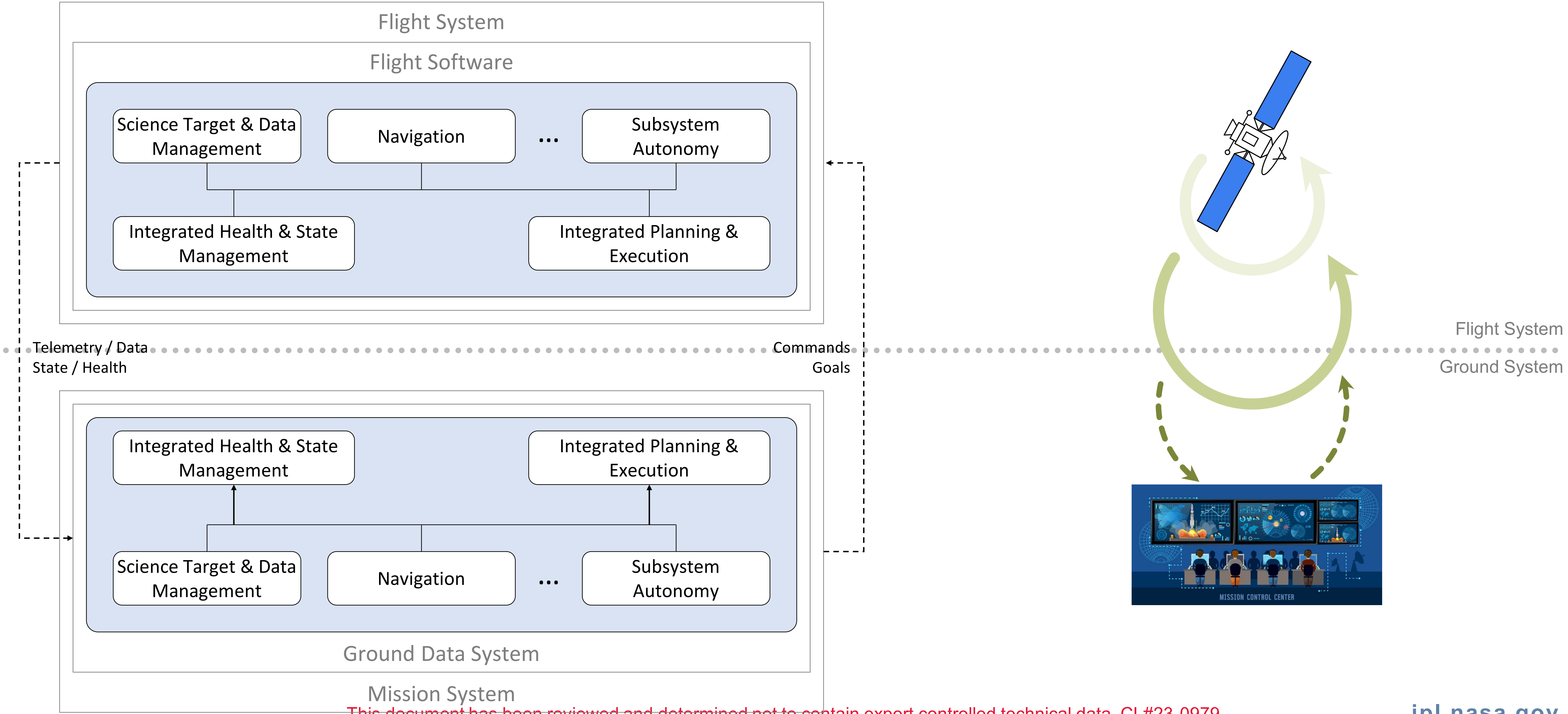
- Enables missions otherwise not possible
- Reduces operations cost

Operations Cost of Deep Space Missions

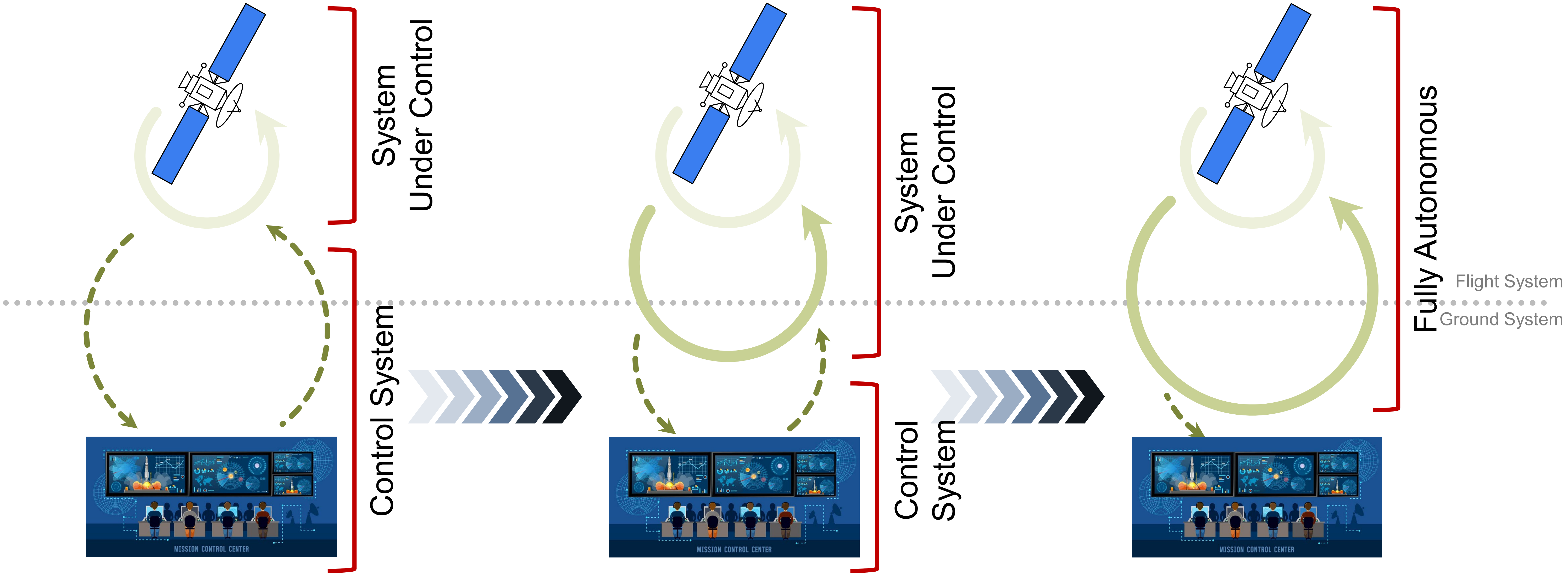
Operations cost growth concerns

- B. Barley et al., Life Cycle Cost Growth Study for the Discovery and New Frontiers Program Office, February 2010.
- R. Bitten et al., Phase E Cost Analysis for NASA Science Missions, AIAA Space 2012 Conference & Exposition, Pasadena, CA, September 2012.
- J. F. McNeill et al., Understanding Cost Growth During Operations of Planetary Missions: An Explanation of Changes. IEEE Aerospace Conference, Big Sky, Montana. March 2013.
- **New Frontier 5 Phase E operations cost capped at $300M in FY22$**

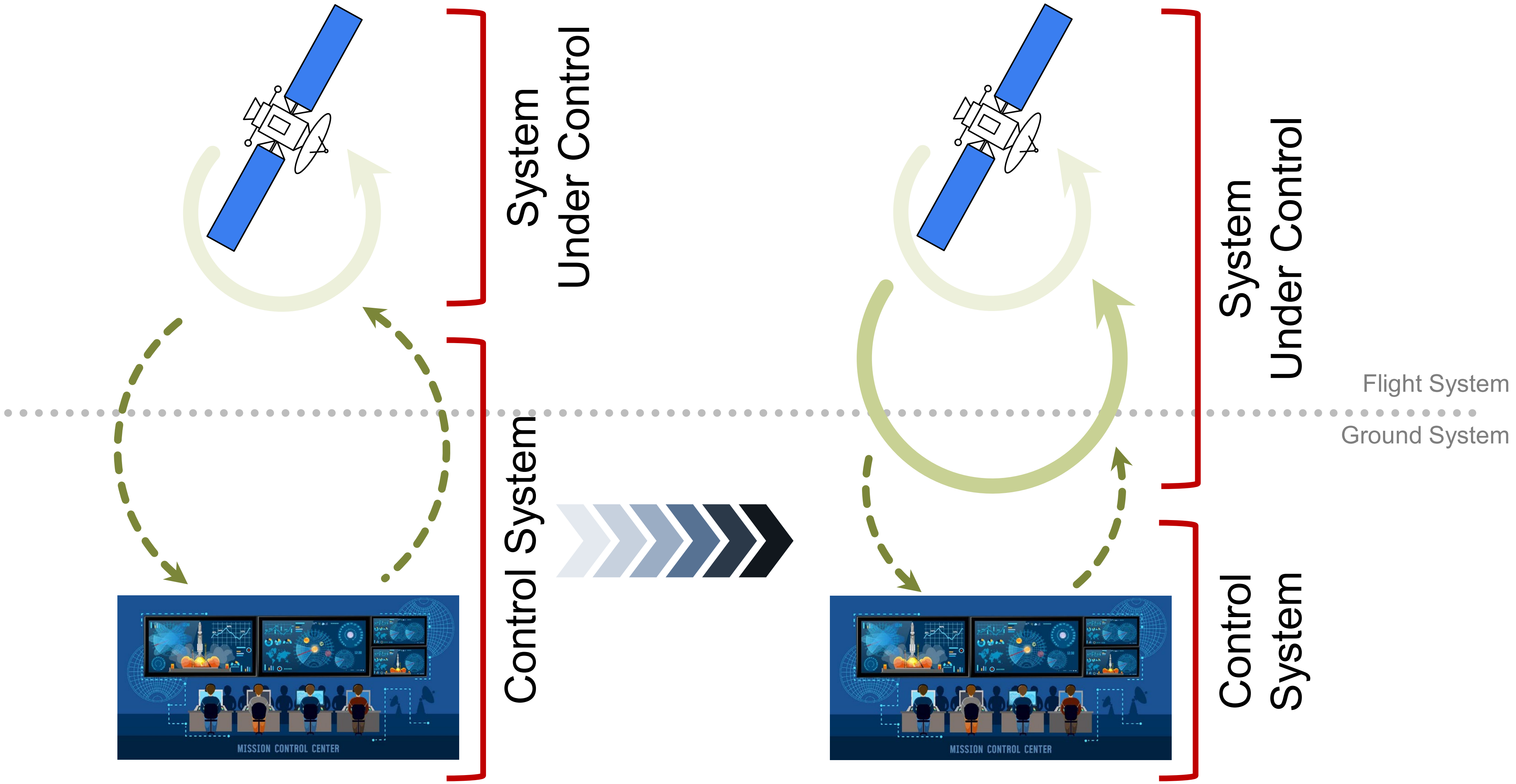
Flight and Ground Automation & Autonomy



Range of Automated Ground System



Cost of Greater Ground Automation & Autonomy

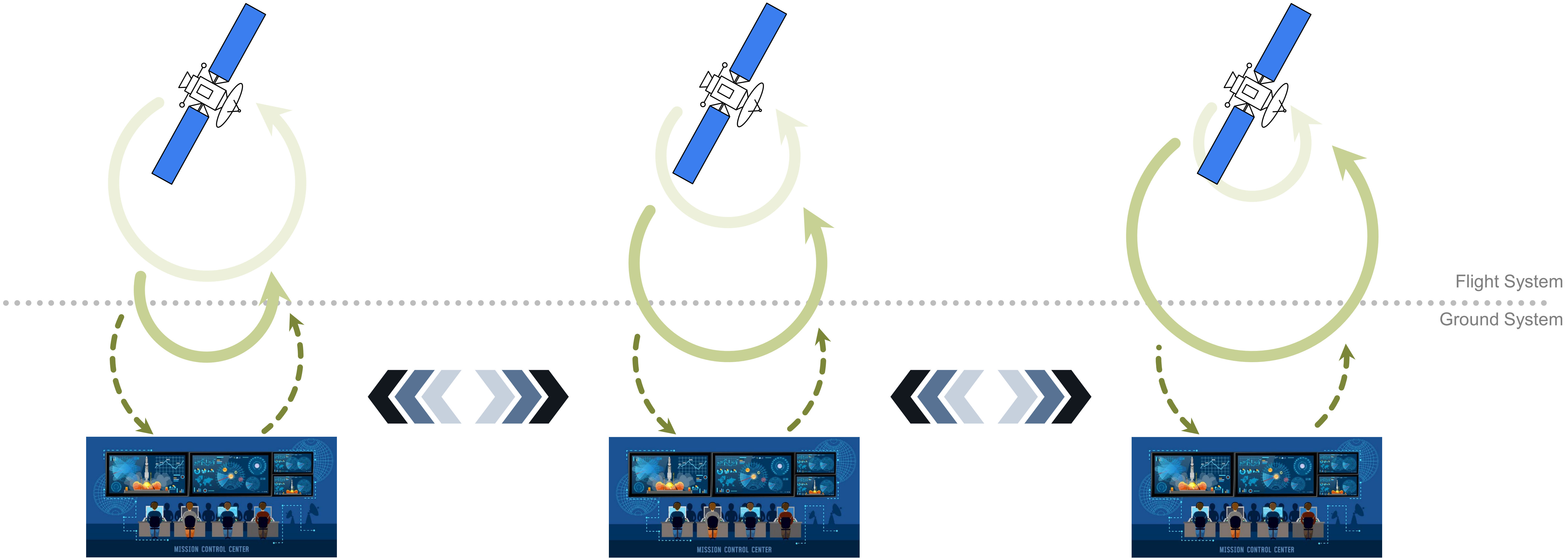


Cost of developing and maintaining the system under control

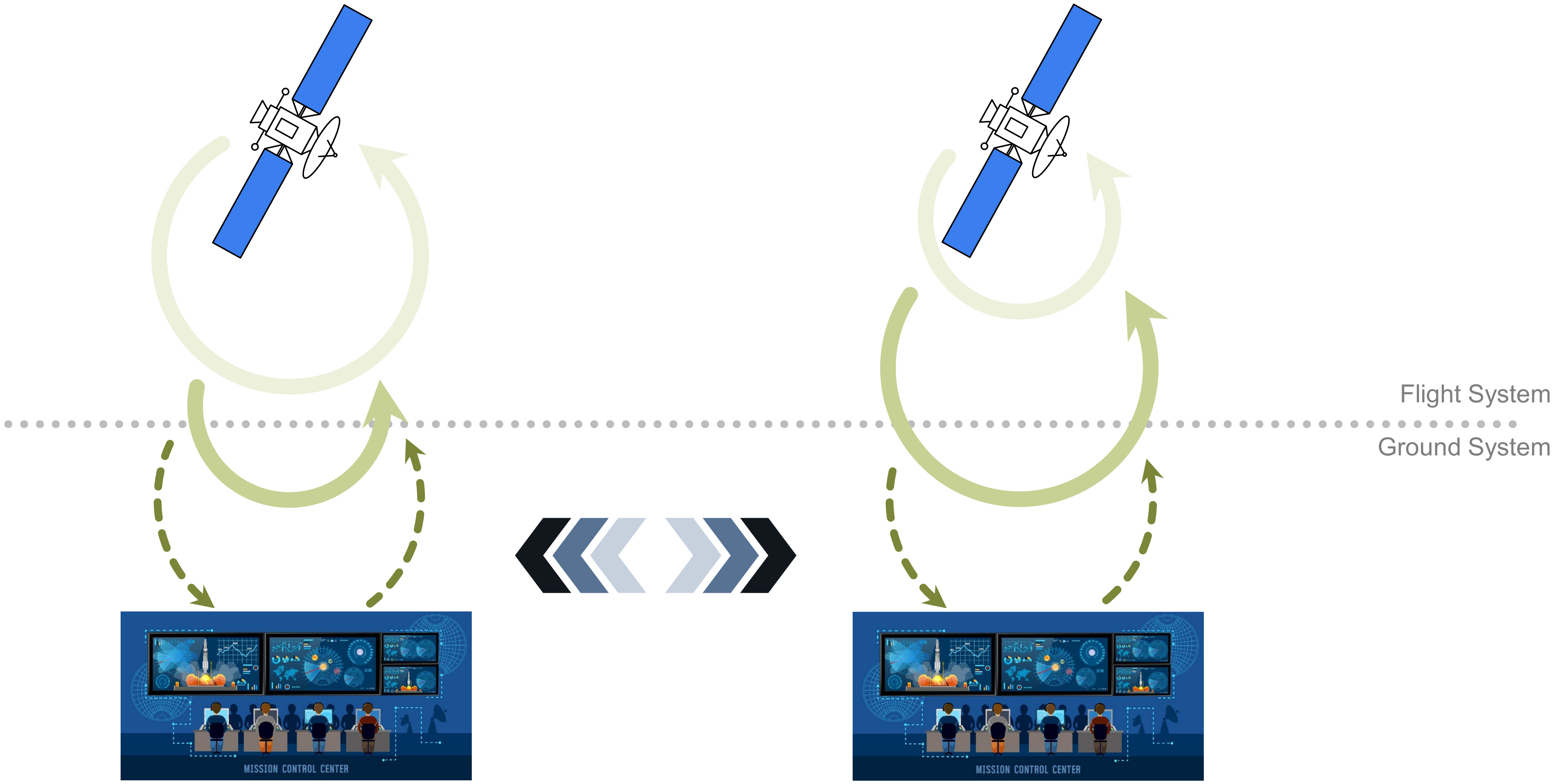
vs.

Cost of developing and maintaining the control system

Tradeoff between Flight/Ground Automation & Autonomy



Tradeoff between Flight/Ground Automation & Autonomy



- Latency
- Observability
- Controllability
- Reliability
- Maintainability
- Computing Capability
- Cost
- …

Challenges with Automated Operations

Sample of common concerns…

- Safety of the flight system
- Depletion of resources
- Allocation and management of HW lifetime
- Handling anomalies
- Operating degraded or faulty flight system
- Knowledge of flight system state and behavior when manual override is required
- Quality of mission outcomes
- …

Challenges with Automated Operations

Anomaly Handling / Trust / Return on Investment

Anomaly Detection and Recovery

- Operator complacency and skill atrophy
- Operator's inability to understand and manipulate autonomous system behavior and state

Trust

- Mission success… autonomous action/inaction that may lead to mission failure
- Quality of science return given the nature of scientific "exploration" of deep space… the unknown

Return on Investment… Is it worth the trouble?

- Reusability of automation and autonomy across missions, given heterogeneous robotic spacecraft and instruments

Challenges with Automated Operations

How about ***explainability***?

- Explain about an automated system…
  - How it works
  - When it works or doesn't work
  - Why it works or doesn't work
- Examples to consider…
  - Users' understanding of PID controllers and Kalman filters
  - Drivers' understand adaptive cruise control system
  - …

Success Criteria for Automated Operations

Addressing **Anomaly Detection & Recovery** and **Return on Investment**

- Standard automation and autonomy behavior
- Standard interface to flight system across missions… standardizing the telemetry and command for common flight system behavior
- Multi-mission operators and operations infrastructure
- Infrastructure to train operators and aid in retaining the skill and knowledge

Success Criteria for Automated Operations

Addressing **Trust**

- “Bounded” autonomy behavior for safety and risk assessment
  - Uncertainty assumption and characterization
  - Convergence or stability criteria
  - Soundness guarantees of the behavior
- Fault protection for automation and autonomy behavior… i.e. monitoring deviation from the designed boundary of autonomy behavior
- Operations experience with gradual increase in automated operations
- Scientists in the loop operations

Automation and Autonomy Techniques

Generalized high-level classification of the techniques

- Procedural
- Data-driven
  - System identification
  - Feature recognition / Classification
- Model-based
  - Estimators
  - Controllers
  - Activity planning and scheduling†
  - Path/Motion planning†

† Traditionally model-based techniques have been used, but more data-driven and hybrid approaches are being adopted

Challenges for Automation and Autonomy Techniques

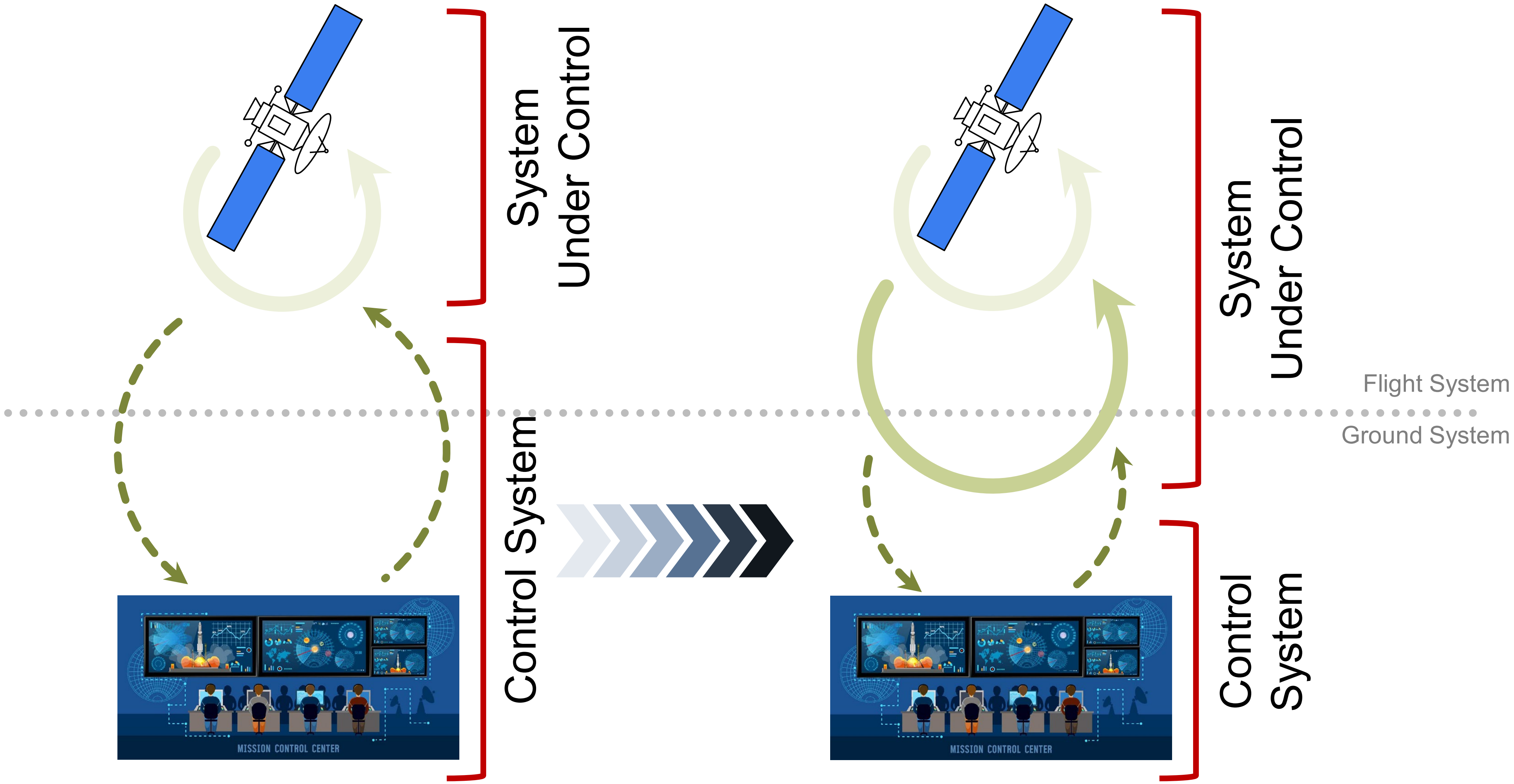
How do we bound the automated behavior given the challenges?

- Procedural
  - Robustness
- Data-driven
  - Data availability
  - Data coverage
- Model-based
  - Model structure and complexity
  - Model creation †
  - Model verification †

† Data-driven approach commonly used

What should be next?

Continue developing automation & autonomy!



Continue developing automation & autonomy to enable missions and reduce operations cost!

But be sure to…

- Bound the behavior
- Grow from functional to system-level
- Assess overall benefits, risks, and cost

Jet Propulsion Laboratory
California Institute of Technology

jpl.nasa.gov