Jet Propulsion Laboratory
California Institute of Technology

Extended Mission Technology Demonstrations Using the ASTERIA Spacecraft

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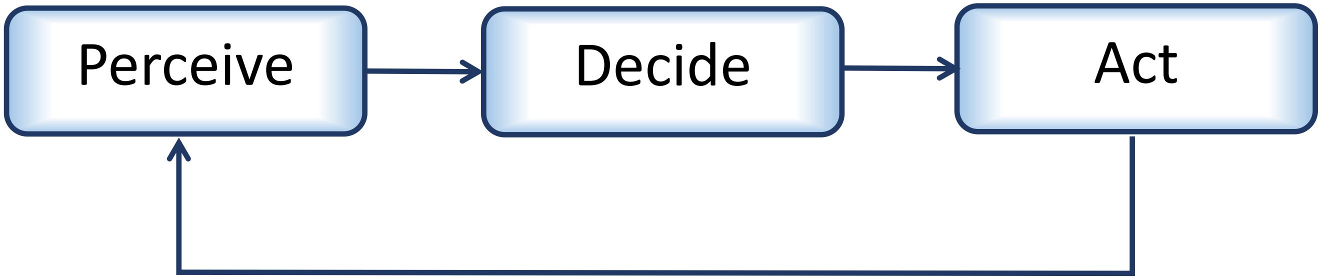
IEEE Aerospace Conference, Big Sky, MT

March 6, 2019

What is Autonomy?



Autonomy: *To make decisions and take actions, in the presence of uncertainty, to execute the mission and respond to internal and external changes without human intervention.*

Hardware
- *Sensing and perception*
- *Computing*
- *System architecture*

Software
- *Autonomy algorithms*
- *Autonomy architecture and infrastructure*

Systems Engineering
- *System design*
- *Verification and validation*
- *Operations*

Autonomy Taxonomy

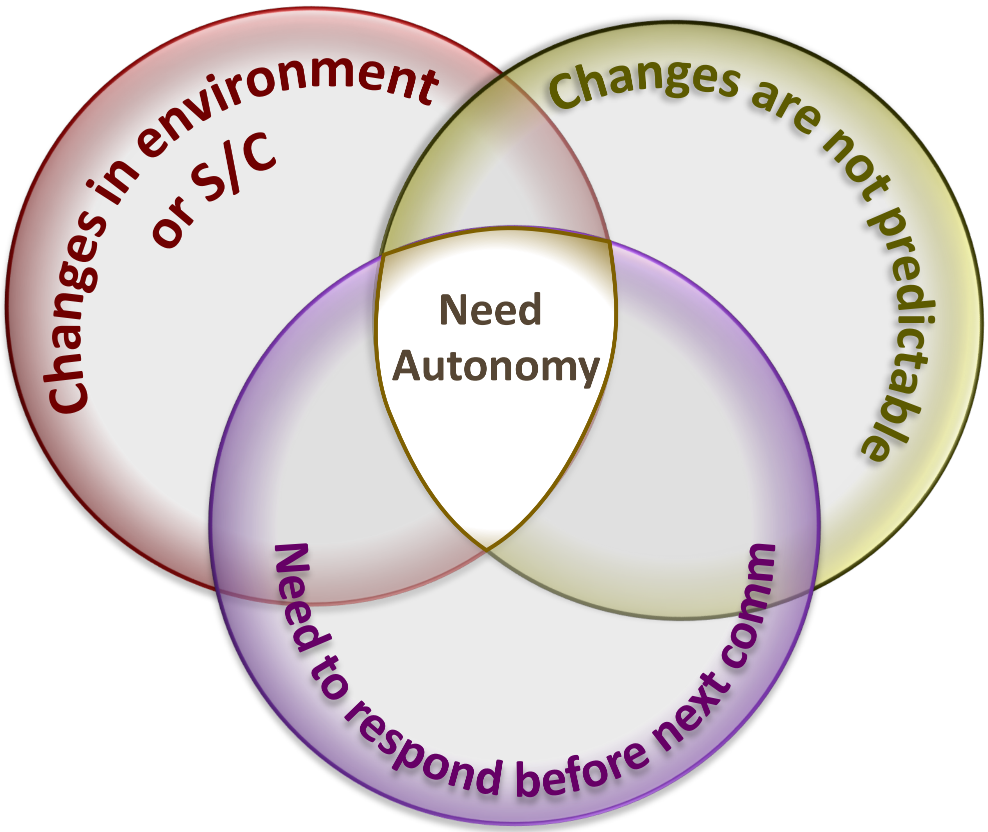
Autonomy viewed as a spectrum:

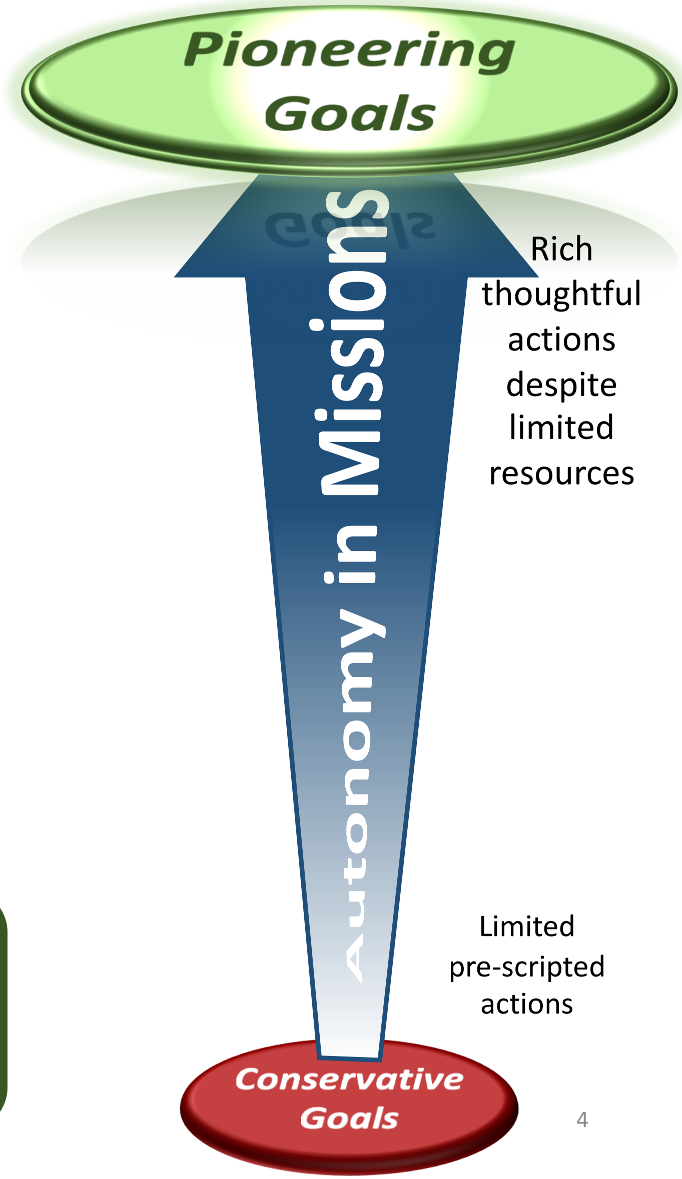
Less Autonomy → *More Autonomy*

Less Autonomy	More Autonomy
Limited to a few functions	*All functions are autonomous*
Functions are optional	*Function are critical*
Limited decision options	*Wide decision space*
Environment well-characterized and understood	*Unknown/unpredictable environment*
Models manually updated	*Learns and adapts*
Operators closely supervise execution	*Lights out operations*

- Time-based sequences
- Unplanned situations halts execution and require human input
- Conditional decision-making
- Onboard state awareness of system and environment
- Onboard activity planning
- Reasoning in large decision space
- Responds to unplanned situations without human input
- Learns from past experience

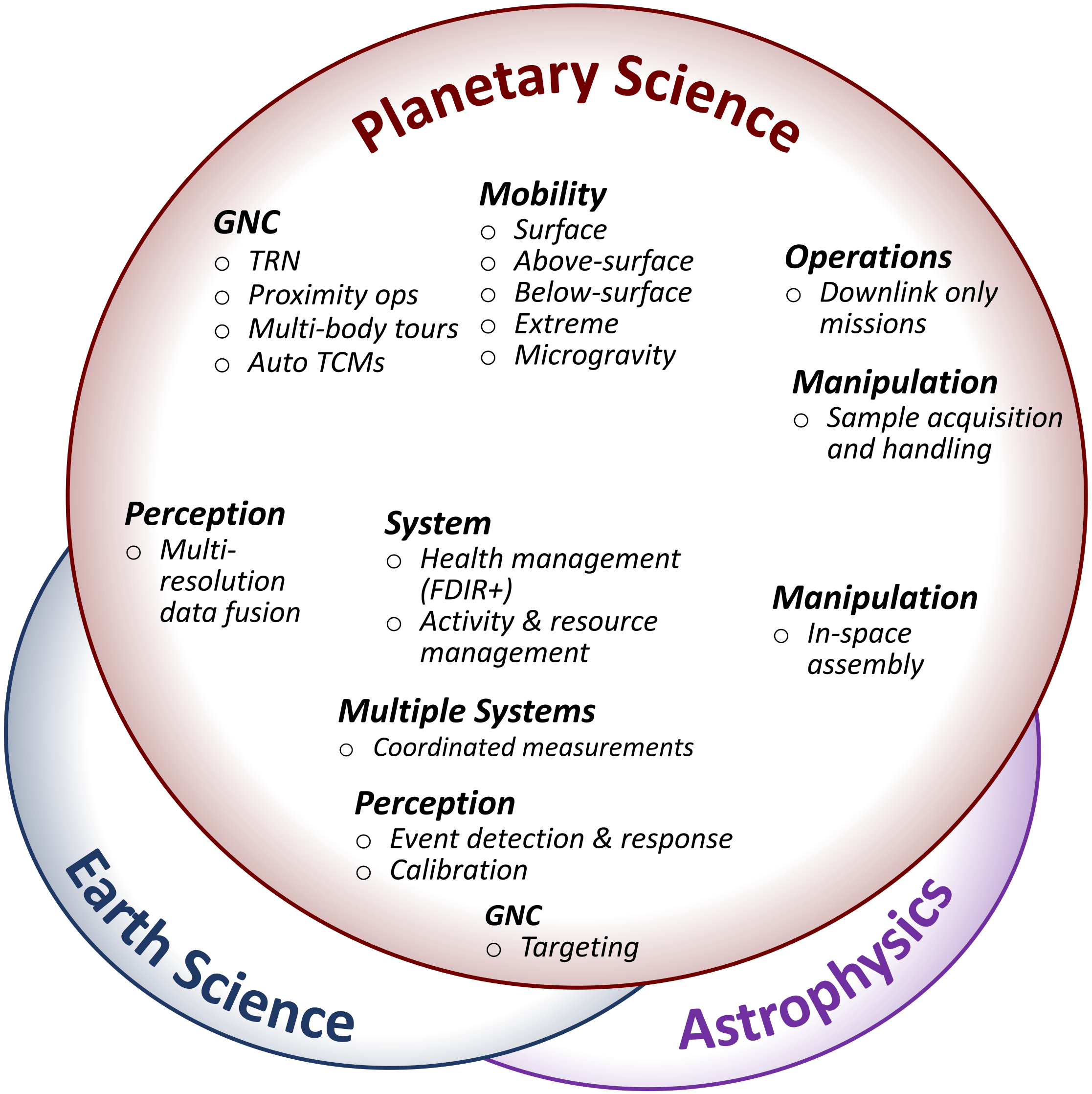
The Need for Autonomy in Spacecraft





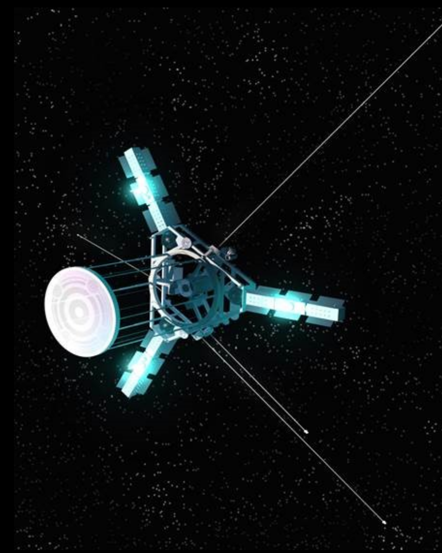
Autonomy enables pioneering missions:
- Explore new destinations and increase science yield, robustness, operability

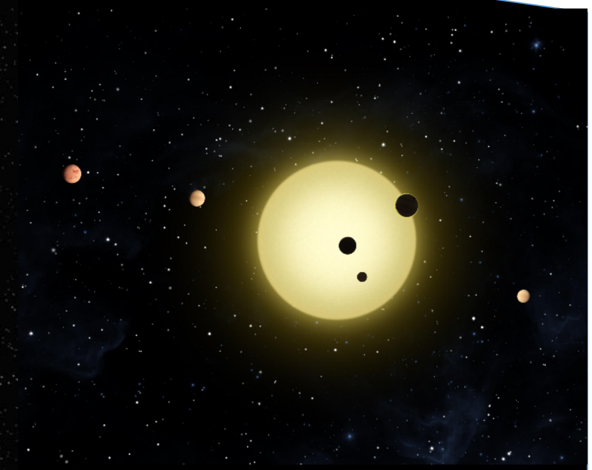
Autonomy is Integral to All JPL Missions



Vision: In situ Exploration of Nearby Exo-planetary System

No Uplink Mission





- In situ exploration of nearest exo-planetary system **will require autonomy**
- Speed of light will prohibit “interactive” science and spacecraft operations
- Requires major advances in autonomy together with power, propulsion, etc.
- Could be a very long duration mission [e.g. ~100 years]

Benefit to JPL Missions

New Science — *Exploration*

- **New observations:** see
- **New destinations:** get to, survive and explore


Enceladus geyser sampler

More Science — *Productivity*

- **Increase science yield** (diversity, quality and quantity)
- **Identify and access science targets**


Astrophysics missions

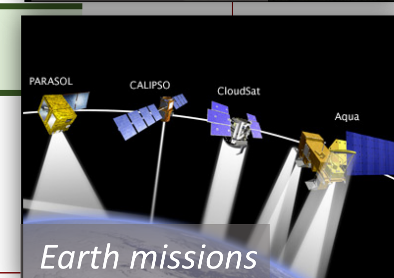
Guaranteed Science — *Robustness*

- **Increase flight-system reliability**
- **Decrease mission risk**


Europa Clipper

Cost-effective Science — *Operability*

- **Simplify spacecraft operations**
- **Reduce operations costs**



Earth missions

Design for Autonomy

Advanced avionics

- Orders of magnitude improvement in compute capability; process large, high volume, high data rate instruments and sensors; reliable, diagnosable computing and buses

Smart Sensing

- Filter out noise; compensate for errors; reliable, self-calibration, self-testing, self-diagnosis, power-efficient, high-throughput, diverse, small and abundant engineering sensors

Function-level Autonomy

- Algorithms that make certain functions autonomous such as autonomous cruise, proximity ops, EDL, mobility, manipulation, image recognition and science decision making

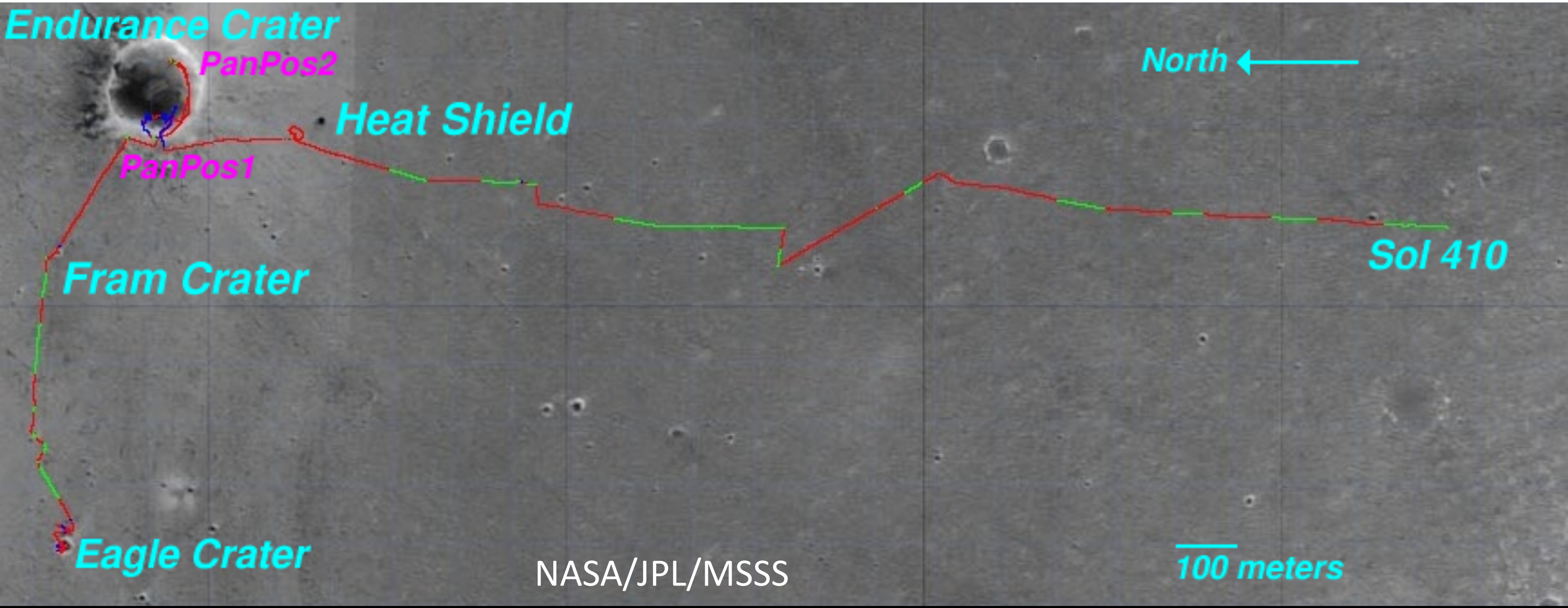
System-level Autonomy

- System infrastructure and architecture for health, activity, and resource management

Systems Engineering / Operations

- Systems engineering, V&V, and operations training

Opportunity Traverse (through Sol 410)



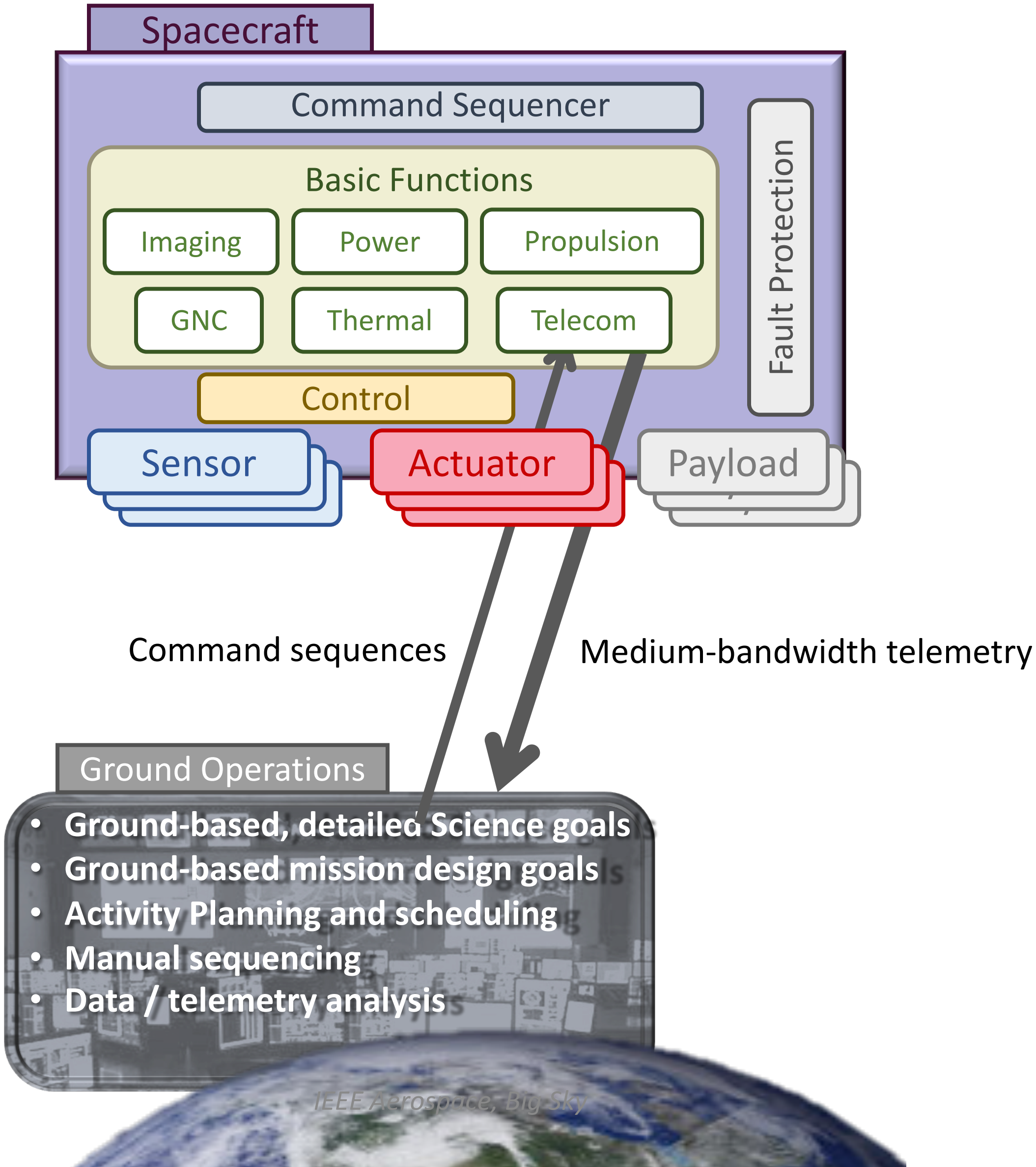
Adapted from a Slide by M. Maimone

Driving Modes:

- **Blind Drive** (planned by ground)
- **Autonomous path planning** (uses on-board perception and terrain analysis)

From Today to Tomorrow's Autonomy

Today



From Today to Tomorrow's Autonomy

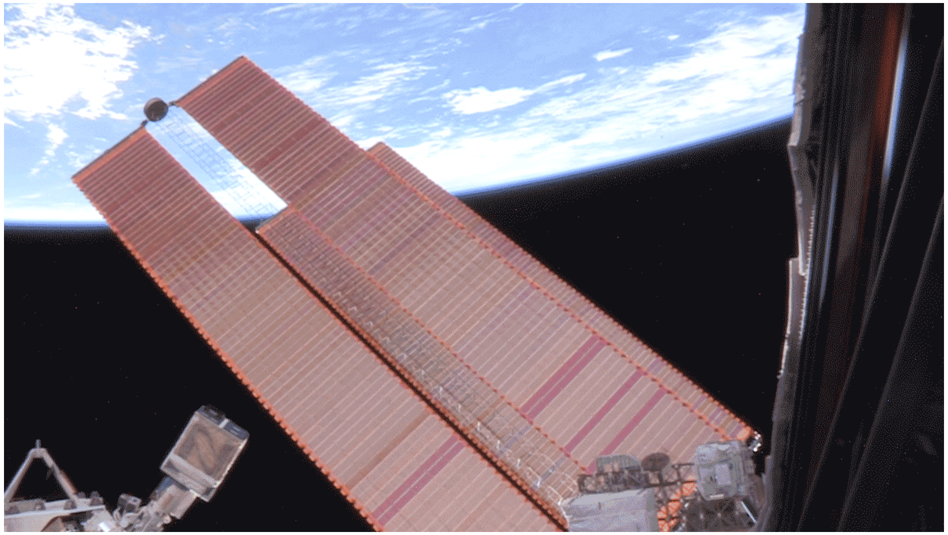
2035

- Substantial migration of ground operation to on-board (increase in autonomous onboard behaviors)
- Working with goals, not canned sequences
- Integrated control, health, activity and resource management

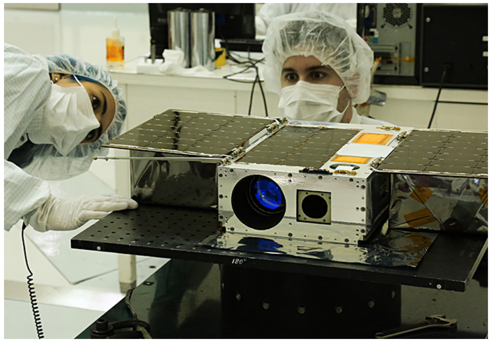
Using the ASTERIA* Cubesat to demonstrate In-Space Autonomy

*Arcsecond Space Telescope Enabling Research In Astrophysics

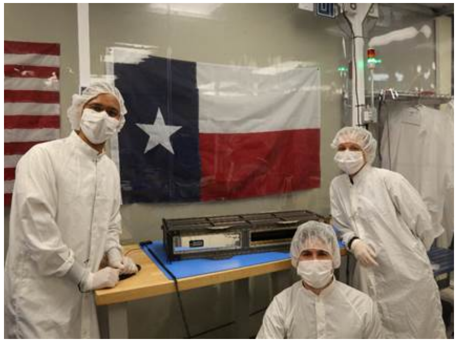
- 6U CubeSat built, tested, operated by JPL
- Collaboration with MIT's Sara Seager, PI
- Demonstrated **pointing stability of <0.5 arcseconds RMS** over 20 minutes
- Demonstrated **pointing repeatability of 1 milliarcsecond RMS** from orbit to orbit
- Demonstrated focal plane **thermal stability of ±0.01 K** over 20 minutes



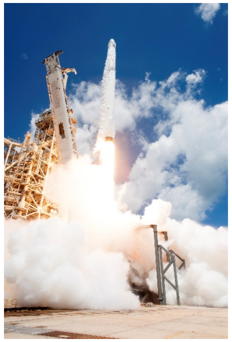
Deployed from International Space Station



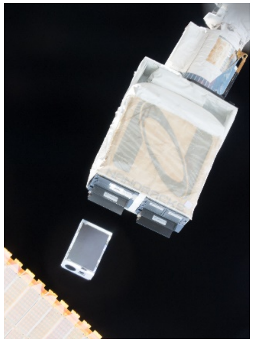
Development
Dec 2014 through Jun 2017



Delivery
1 Jun 2017



Launch
14 Aug 2017

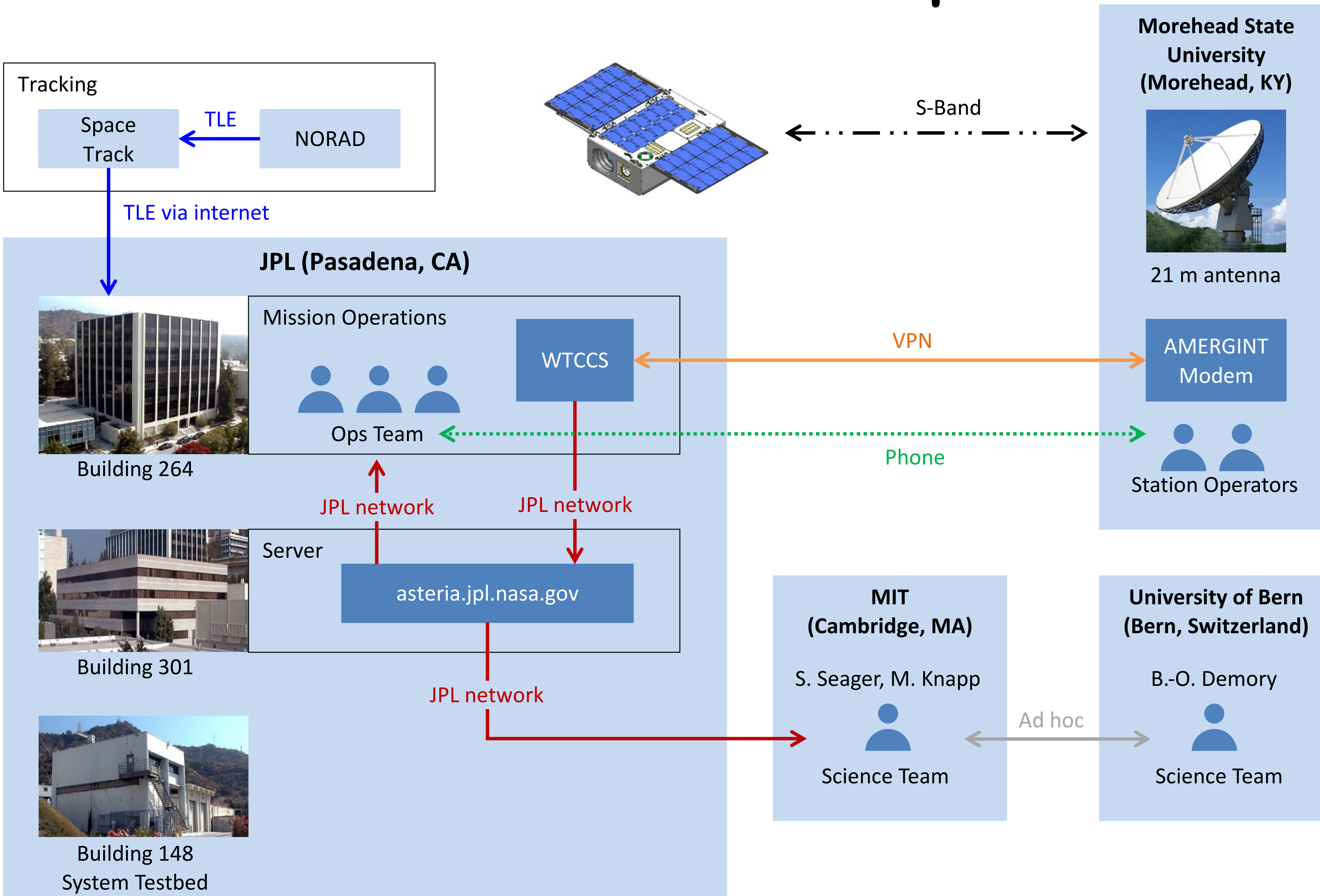


Deployment
20 Nov 2017

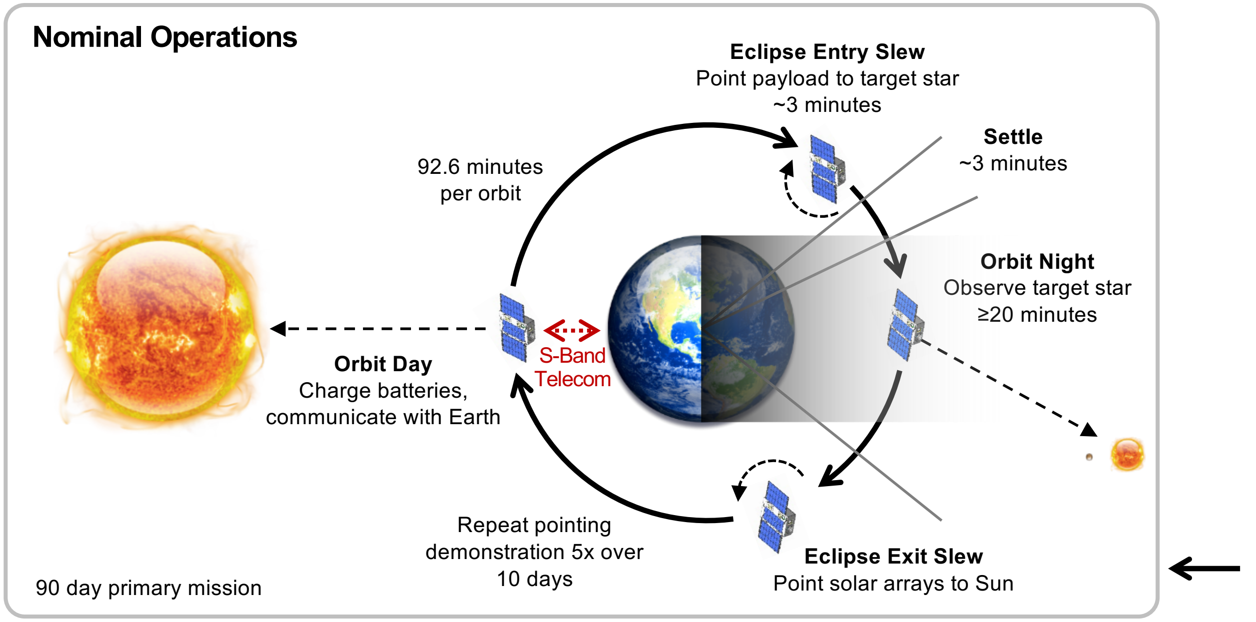
Operations
Into FY2019

First CubeSat to detect an exoplanet: Known super-Earth 55 Cancri e

ASTERIA Mission Operations

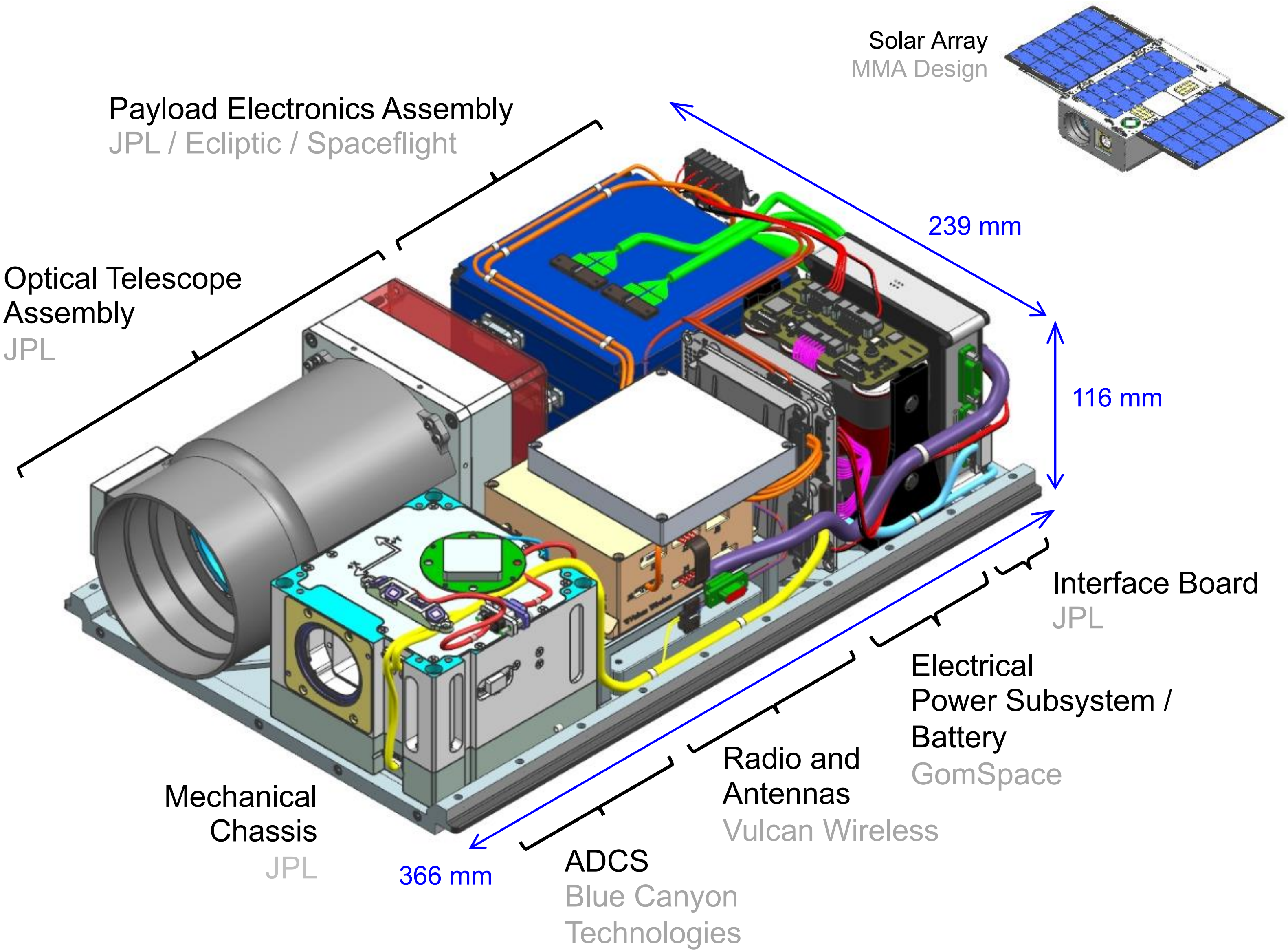


Concept of Operations



ASTERIA won SmallSat of the Year award in 2018:
https://www.jpl.nasa.gov/news/news.php?feature=7213

ASTERIA Spacecraft Overview



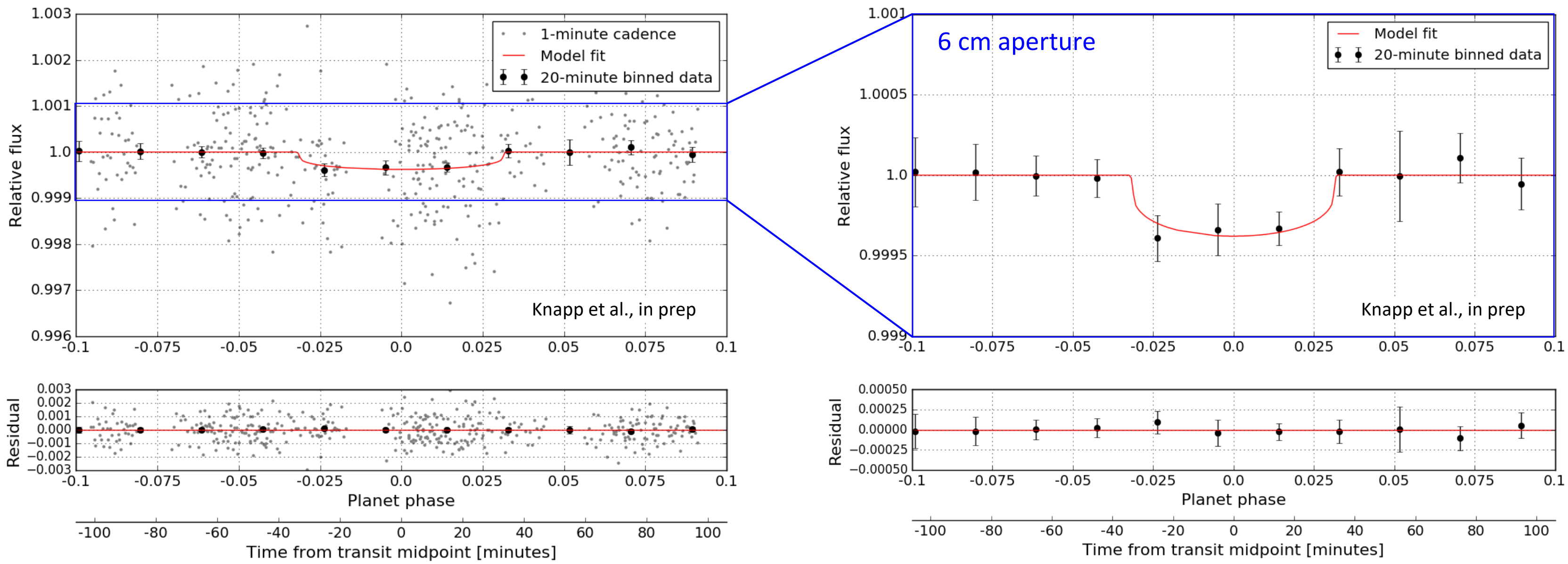
Flight Software
JPL (F Prime)

PCS Software
JPL

MOS Software
JPL / Alethium

Exoplanet Transit Detection

Observed the known transit of super-Earth exoplanet 55 Cancri e

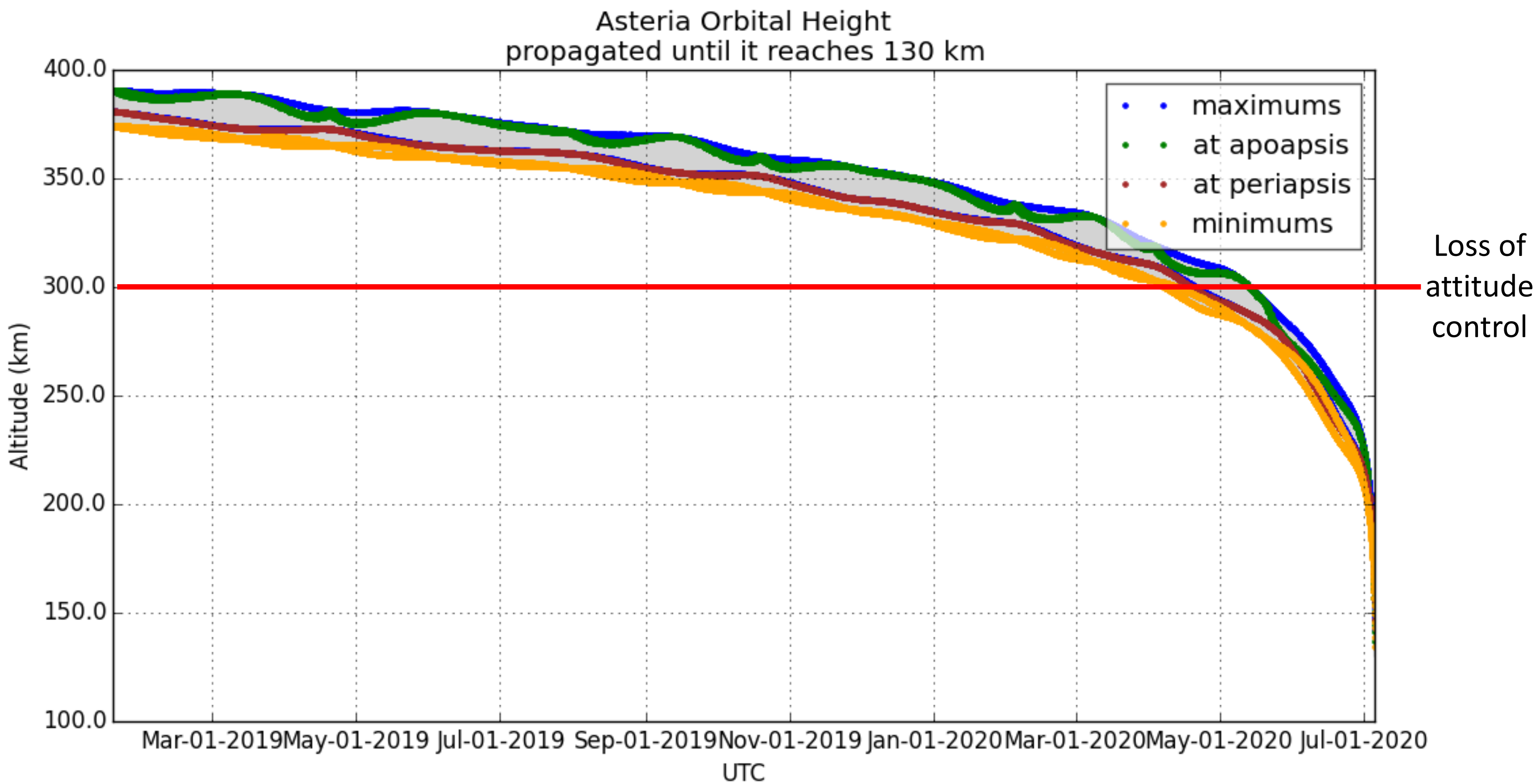


410 ppm transit observed at SNR=3, super-Earth exoplanet ($2R_E$) around a V=5.95 Sun-like star.

Photometric precision is 730 to 1140 ppm/min.

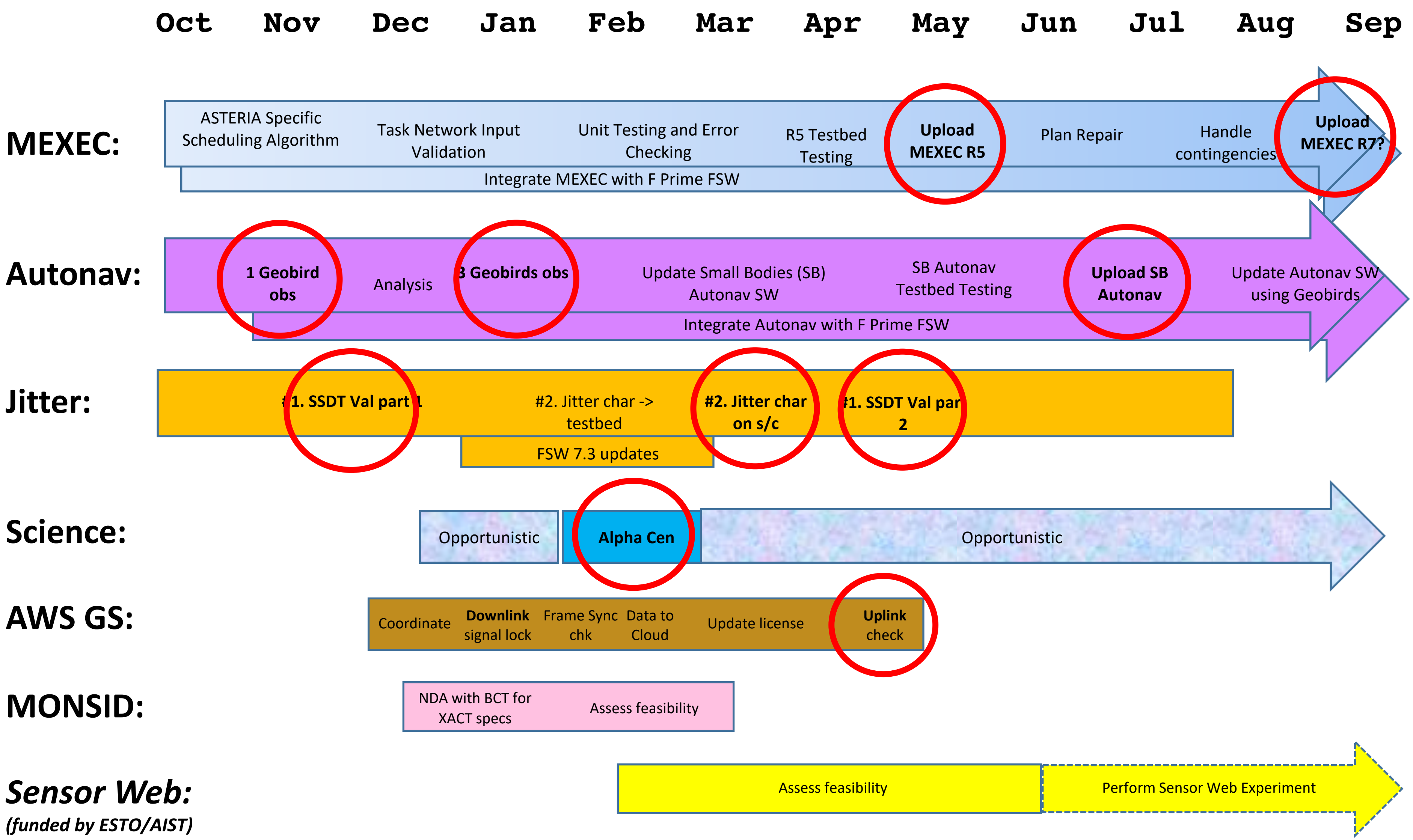
ASTERIA Lifetime Prediction: April 2020

21-day fit propagated using the GGM02 gravity field truncated to 100x100 and the DTM atmospheric model with current solar/geomagnetic values. It reaches 270 km on 26 MAY 2020 and 130 km on 05 JUL 2020.



Apoapsis happens close to the minimum latitude, periapsis close to the maximum latitude, minimum heights closer to the equator due to Earth's flattening

ASTERIA III Schedule Snapshot



= Major milestone

Background on Commanding Spacecraft

Command sequencer

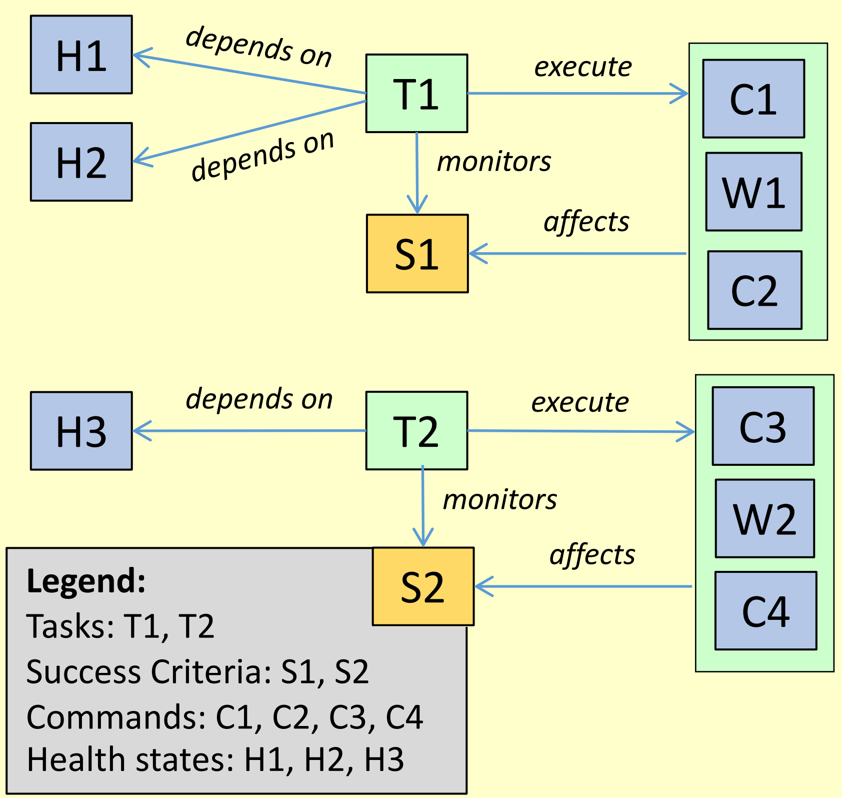
Start of sequence

- Issue command C1
- Wait W1 seconds
- Issue command C2
- Issue command C3
- Wait W2 seconds
- Issue command C4

End of sequence

- Sequence success/failure unknown until telemetry analyzed on Ground
- Works well for predictable, fault-free scenarios
- If fault occurs, sequencer does not know what activities are affected

Task Sequencer



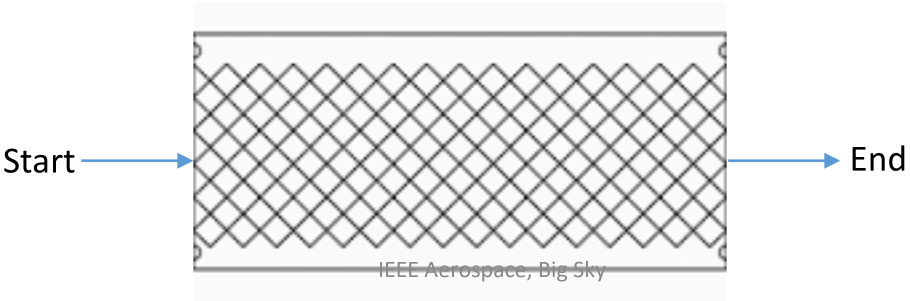
- Task = commands + pre- and post-conditions
- Task success/failure monitored onboard
- Fault recovery more localized because dependencies known onboard
- Unaffected tasks continue to run

ASTERIA Experiment #1. Multi-mission EXECutive (MEXEC) Closed-Loop Task Execution

Shift the paradigm to operate spacecraft from open-loop sequence commanding to closed-loop task execution.

- Sequences provide one execution path and do not provide flexibility to respond to current conditions. Unexpected events stop the sequence.
- Task-level commanding enables the space asset to determine order and timing of activities based on current conditions – traversing a net to achieve successful path

- ASTERIA Goal: Demonstrate effectiveness of “task networks” (tasknets) to increase the efficiency and robustness of future space missions.
- Tasknets check preconditions and postconditions of tasks and enable simpler commanding and more robust on-board execution.
- MEXEC code to be flight-certified, integrated into ASTERIA flight software, validated on testbed and uplinked in Spring 2019.



ASTERIA Experiment #1. Multi-mission EXECutive (MEXEC) Closed-Loop Task Execution

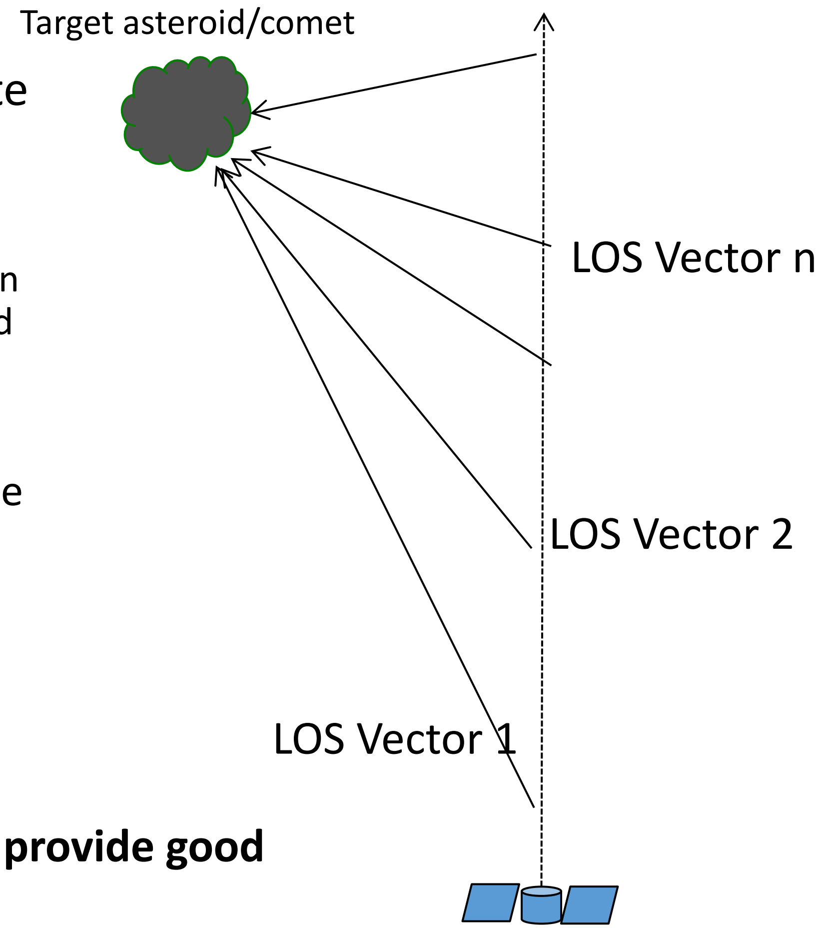
Shift the paradigm to operate spacecraft from open-loop sequence commanding to closed-loop task execution.

- Goal: Demonstrate effectiveness of “task networks” (tasknets) and applicability of this approach for increasing the efficiency and robustness of future space mission commanding and execution.
- Tasknets will enable simpler commanding and more robust on-board execution.
- Tasknets check preconditions and postconditions of tasks
- MEXEC code is being flight-certified, integrated into ASTERIA FSW, validated on testbed and uplinked in Spring 2019.

ASTERIA will perform scientific observations using tasknets

Background: Optical Navigation

- Optical images of objects are used to estimate spacecraft position, velocity, and attitude
- For distant, resolved objects
  - Center-of-figure found using various cross-correlation or limb-finding methods, or centroiding if unresolved
  - Background stars provide inertial reference frame
- Centroid location provides line-of-sight vector to that body in the star-based inertial reference frame (angular measurement)
- Time series of LOS vectors can be input to a least-squares filter to estimate spacecraft position and velocity



For solar system navigation, Main belt asteroids provide good beacon sources

- Ephemerides are reasonably well known
- Lots of asteroids to chose from

Adapted from a slide by S. Bhaskaran

Autonomous Navigation (AutoNav) Overview

- All ground-based OpNav techniques transferred to spacecraft and automated
- Involves 3 steps – (1) image processing, (2) orbit determination, and (3) maneuver planning and execution
  - Image processing automatically identifies stars and body in camera FOV and performs center-finding
  - OD filter combines images and other s/c ancillary information (such as thrusting, attitude knowledge, etc.) to get complete s/c state
  - Maneuvers computed at pre-specified times to retarget s/c to reference trajectory

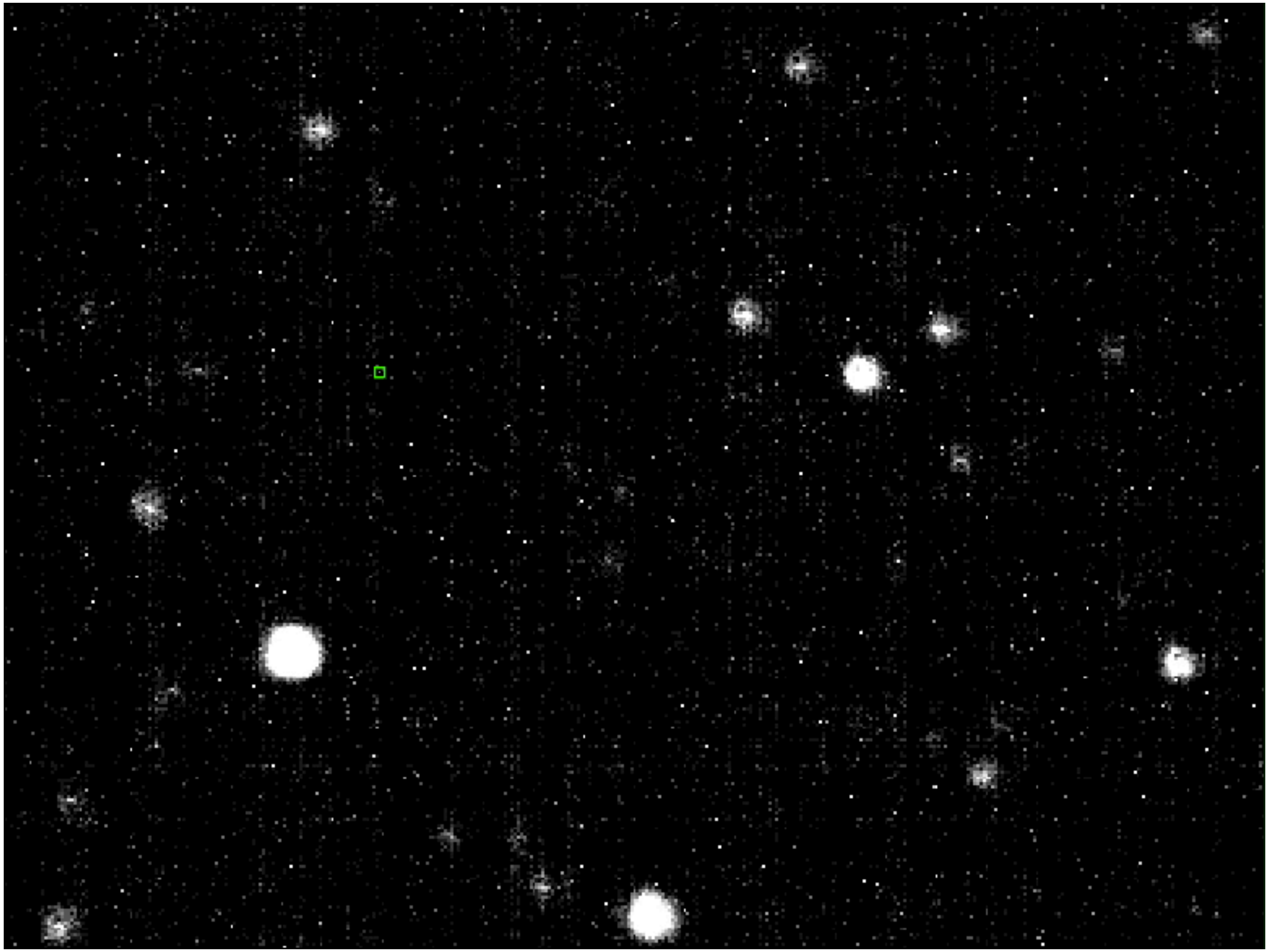
Adapted from a slide by S. Bhaskaran

ASTERIA Experiment #2. Autonav

Demonstrate onboard orbit determination in Low Earth Orbit (LEO) using autonomous navigation (Autonav) without GPS.

- Demonstrate a fully independent means of spacecraft orbit determination for Earth orbiters with only passive imaging using ASTERIA camera.
- Enable future missions to navigate in GPS-denied environments and with a more robust sensor suite.
- Approach:
  - ✓ Image a small body to confirm camera quality
  - ✓ Image geo-stationary spacecraft to assess feasibility
  - ✓ Run Autonav software on testbed for metrics
  - o Integrate Autonav into ASTERIA FSW, test and upload.
- JPL's Autonav software is being integrated into ASTERIA FSW, validated on testbed and uplinked in Summer 2019.

Geobird Observations – 4 images



Geostationary spacecraft have been observed using ASTERIA's camera for use by Autonav software

#3 Jitter Experiments

Two jitter experiments will improve pointing performance for ASTERIA and for future missions with similar integrated attitude control systems.

1. JPL's Small Satellite Dynamics Testbed (SSDT) Validation: Flight-validate the SSDT simulation models for the ASTERIA ACS system (Sternberg)
   - Obtain additional insights into the contribution of XACT jitter to the ASTERIA photometry
   - Inform the feasibility of other small satellite missions for which jitter control is an enabling technology.
2. Characterize ASTERIA's jitter (Ardila)
   - Characterize the spacecraft pointing jitter (XACT+Piezo Stage+Piezo Offloading) as a function of target brightness and reaction wheel speed.
   - This experiment will require changes to ASTERIA FSW. These changes are minor and may be useful in the future; the changes will be included in ASTERIA's main FSW.

Jitter characterization will benefit all future smallsat missions and is crucial to future astrophysics smallsat missions (e.g., SPARCS)

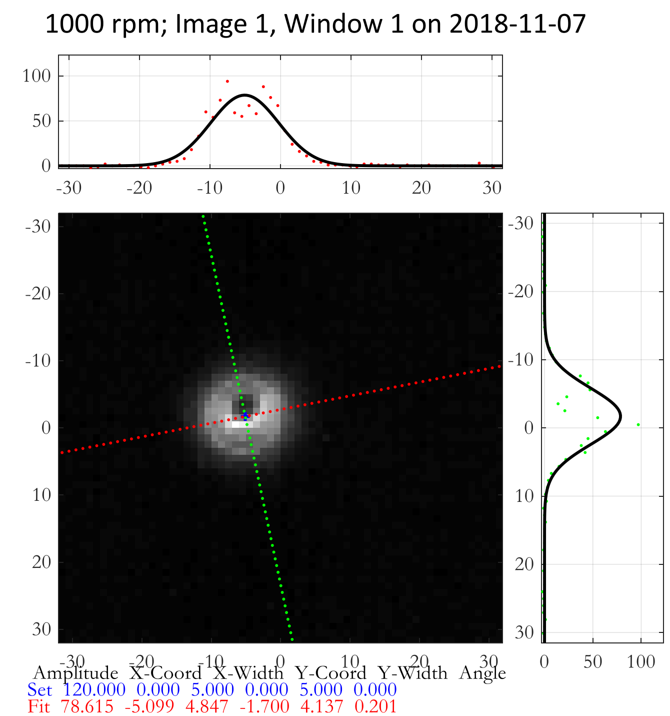
Jitter Characterization Accomplishments & Plans

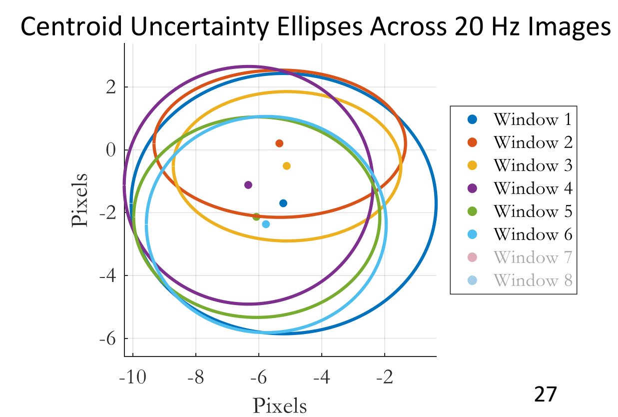
Accomplishments

- SSDT Validation
  - Refine set of observation allocations for the jitter experiments based on spacecraft capabilities
  - Write the sequence for the first observation and successfully pass CAM
  - Perform the first observation and downlink its image data
  - Complete the coding of a basic set of data analysis tools
- Jitter analysis
  - Identified stars and observations. Creating sequences.
  - Software updates completed to perform characterization experiments

Next Month's Plans

- SSDT Validation
  - Identify observation times to complete at least half of the required jitter observations
  - Conduct and analyze the image data from the first half of the required observations
- Jitter Characterization
  - Begin data analysis tool development





#4. Science Observations

Perform new ASTERIA observations to extend mission science.

- ASTERIA has demonstrated unprecedented photometric precision for a CubeSat mission.
- Current science goals will shift from follow-up of previously detected planets to discovery of as-yet unknown additional planets. The spacecraft is uniquely suited to perform long-term monitoring of stars such as alpha Centauri for small transiting planets.
- The discovery of a transiting Earth-sized planet around alpha Cen A and/or B would be of the highest scientific value as such a planet would be our closest exoplanetary neighbor orbiting a Sun-like star.

Science Accomplishments & Plans

Accomplishments

- Paper covering observations of 55 Cancri e transit submitted to Astronomical Journal. Referree report has been received and revisions are in progress.
- Brice Demory at University of Bern completed HD219134 analysis and concluded known b and c transits were observed, but no f and d transits were observed
  - Likely indicated f and d do not transit
  - Further analysis in progress
  - Paper to be written
- Month-long series of Alpha Cen observations per Science Team's (Brice and Mary) request has been initiated.

The first planet that ASTERIA observed is featured in NASA's Exoplanet Travel Bureau!

55 Cancri e: Skies Sparkle Above a Never-Ending Ocean of Lava

#5. Amazon Web Services Ground Station Experiment

Rough Schedule for AWS Adaptation

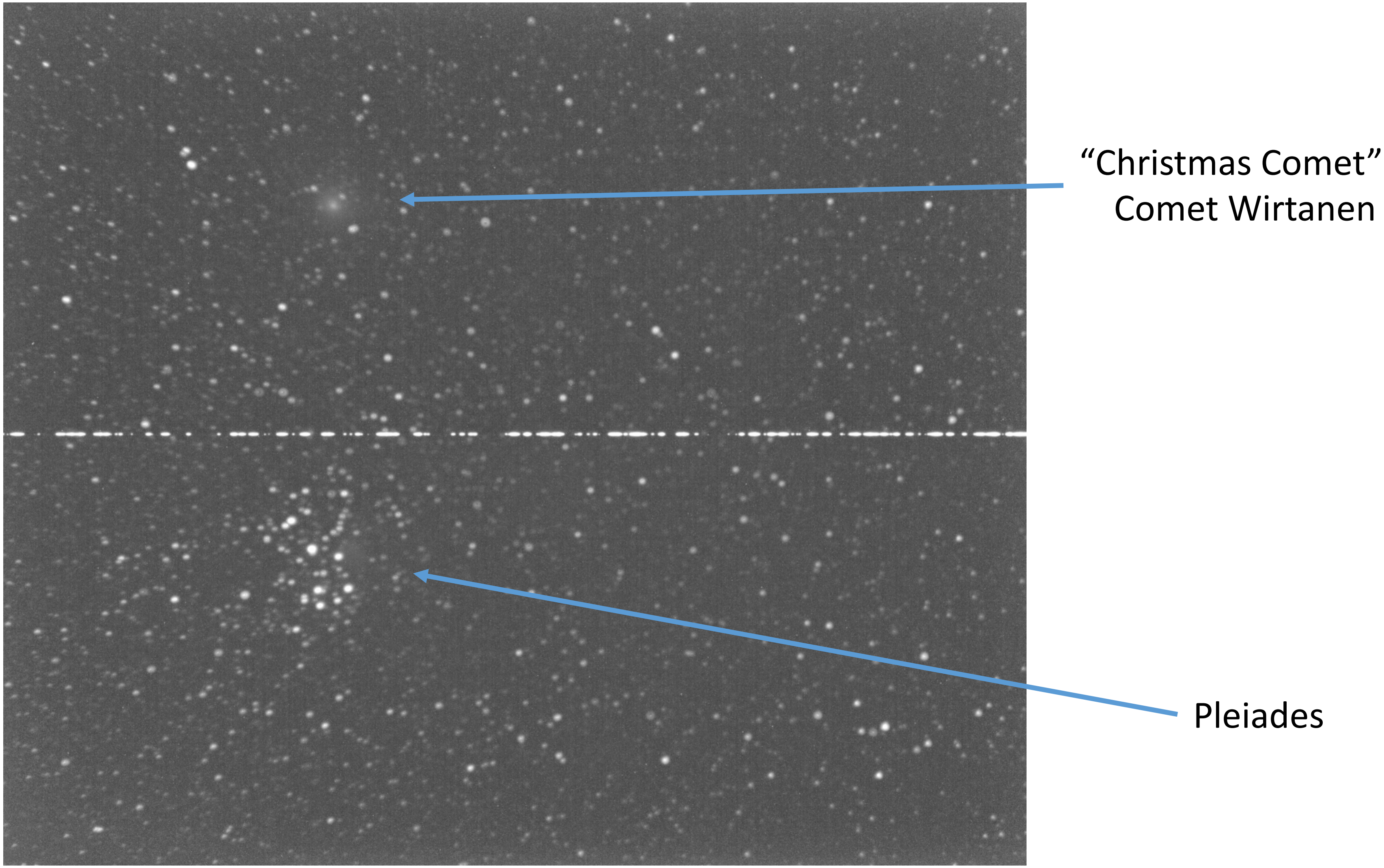
1. Signal lock to AWS GS (done)
2. Frame sync with AWS GS (Soon)
3. Telemetry Processing and Verification of Downlink (Soon)
4. 1-3 in real-time delivered to ASTERIA AWS account. (Primary GS Preview downlink path)
    1. Set up Cloud-based GDS Downlink in AWS (1-2 weeks)
    2. After licensing demonstrate full-cloud operations with AWS GS (3-6 months)
5. 1-3 in real-time delivered to JPL MOC via hosted FEP (primary preview uplink path, future general service for downlink)
    1. Demonstrate traditional MOC downlink with AWS GS (3-6 months)
    2. After licensing demonstrate full-operations with AWS GS and traditional MOC (3-6 months)
6. Integrate other AWS ground stations into mission operations and regular scheduling and contacts into procedures (3-6 months)

Separately:

1. Complete Licensing with NTIA for uplink via AWS GS, enabling 4b, 5b, and 6. (3-6 months)
2. Transition from GS Preview to Operations (Spring 2019)
3. Transition to Govcloud implementation of GS (TBD but in the pipe)
4. Document the AWS GDS design, identify steps that would need to be completed for a new project adaptation that weren't for ASTERIA.

This experiment will benefit future cubesats, confirming that AWS GS can provide downlink services

Operations Accomplishments



Summary

- NASA’s vision of future human and robotic exploration is exciting, yet challenging
- Each mission type has different needs, but autonomy is viewed by all as an enabler
- Elements of autonomy are being developed and infused
  - Task-level execution
  - Autonav
  - Model-based health management
- There is still much work to be done – come join us!


Europa Lander


Mars Ascent Vehicle


Titan submarine

Acknowledgements

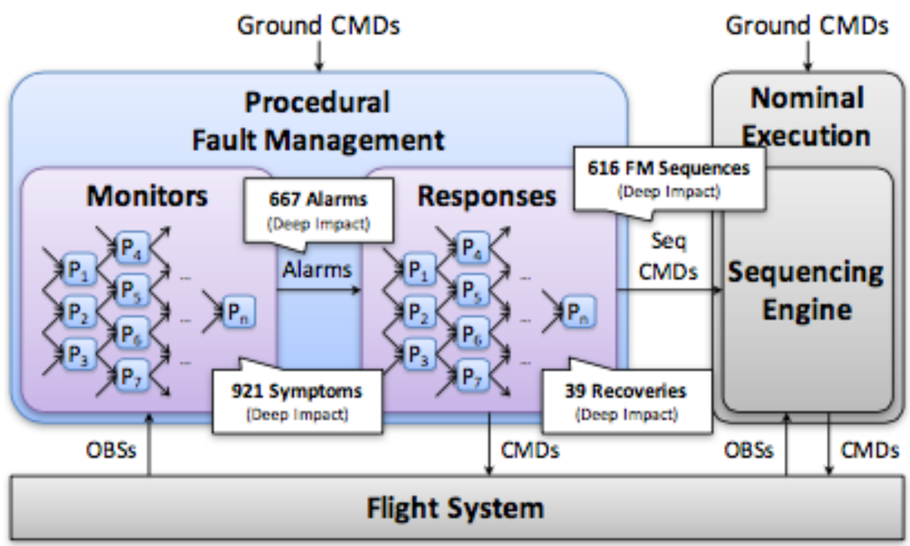
- Co-authors:
  - JPL: Patricia Beauchamp, Amanda Donner, Rob Bocchino, Brian Kennedy, Faiz Mirza, Swati Mohan, David Sternberg, Matthew W. Smith, Martina Troesch
  - MIT Haystack Observatory: Mary Knapp
- We thank the ASTERIA Principal Investigator Sara Seager for supporting our efforts to use the spacecraft for these technology demonstrations while continuing to perform exoplanet exploration science; Jose Carlos Abesmis, Brian Barker, Brian Campuzano, Peter DiPasquale, Kyle Hughes, and Ansel Rothstein-Dowden who continue to keep the spacecraft healthy and operational; Chris Pong, Shyam Bhaskaran, Patrick Doran, and Carolyn Maynard who are supporting development of the technology demonstrations; Bryce Demory from the University of Bern for science data analysis, and Ben Malphrus and his team from Morehead State University for continued ground station support.

Jet Propulsion Laboratory
California Institute of Technology

Background: Spacecraft Fault Protection

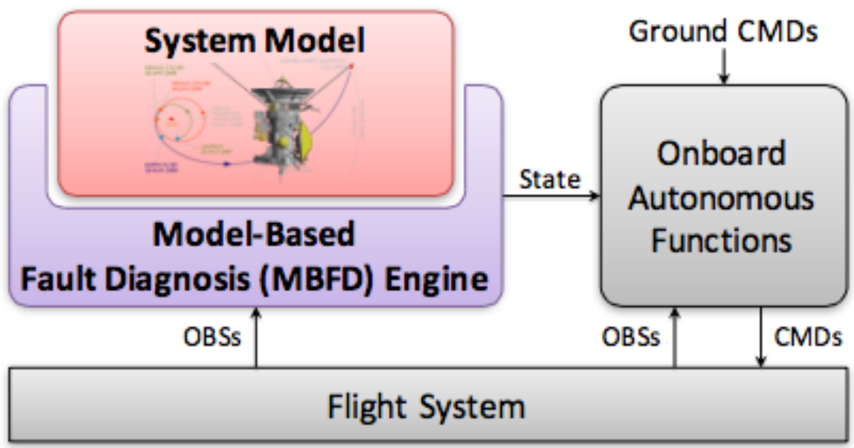
Traditional monitor-response approach to Fault Protection:

- Engineers write monitors to detect symptoms and recovery response procedures.
- Sufficient for simple systems
- As system become more complicated, suffers from scalability issues (e.g., MSL has over 1000 monitors), resists formal and systematic V&V approaches, is difficult to maintain, and inflexible to reusability.

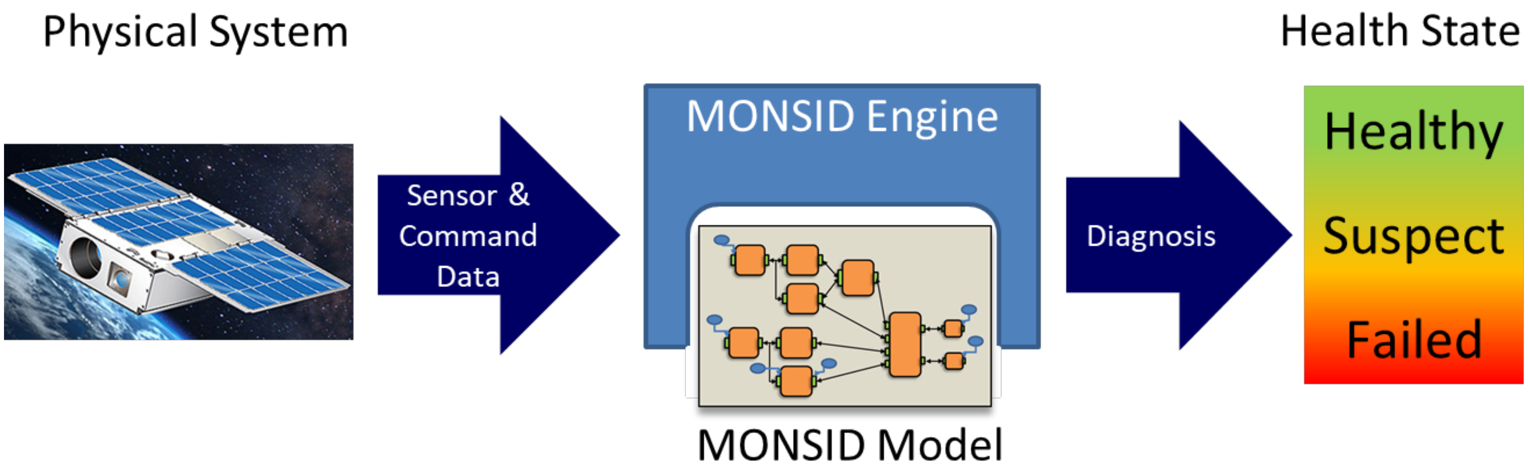


New Approach: Model-Based Fault Diagnosis

- Model-Based Fault Diagnosis uses multiple sources of information including onboard sensor, command, expected behavior of components, and relationships between components to assess system health.
- Engineers model the system; software "engine" uses the model to perform diagnosis and possibly recovery.



ASTERIA Experiment #3: Model-Based Health Assessment



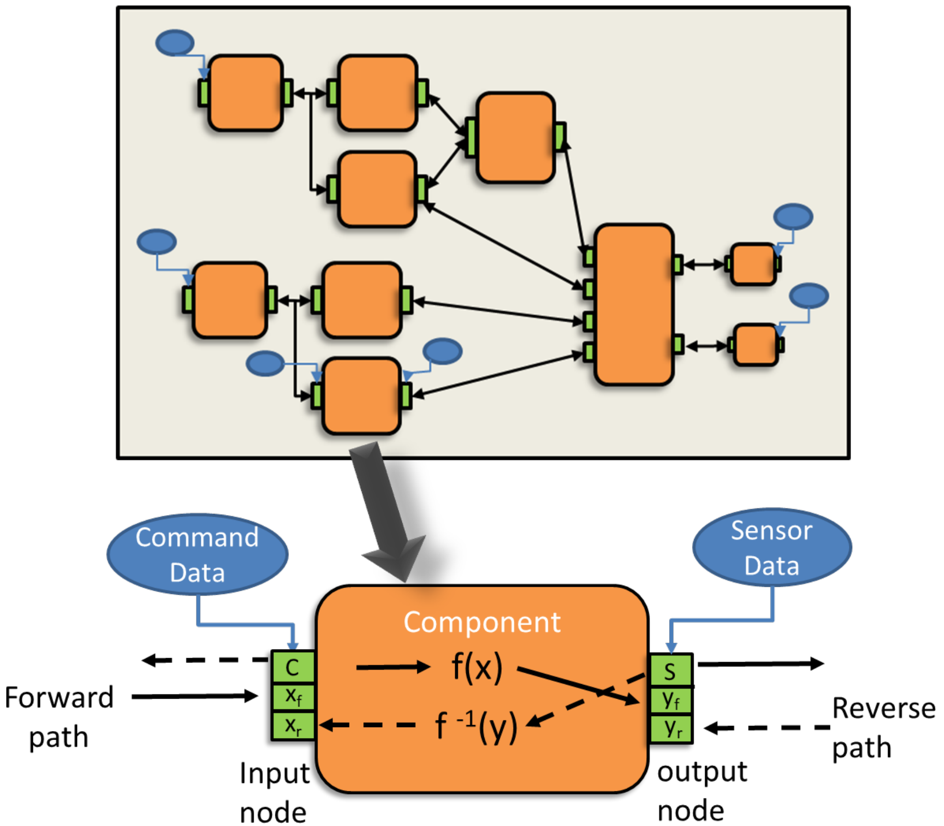
Model-based **O**ff-**N**ominal **S**tate **I**dentification and **D**etection

- The MONSID* Health Assessment system has two main parts
  - Diagnostic Engine based on constraint suspension technique
  - Model capturing nominal system behavior
- Sensor and Command data are inputs to MONSID Model
  - Inputs are propagated through model
- MONSID outputs healthy/failed state of hardware components

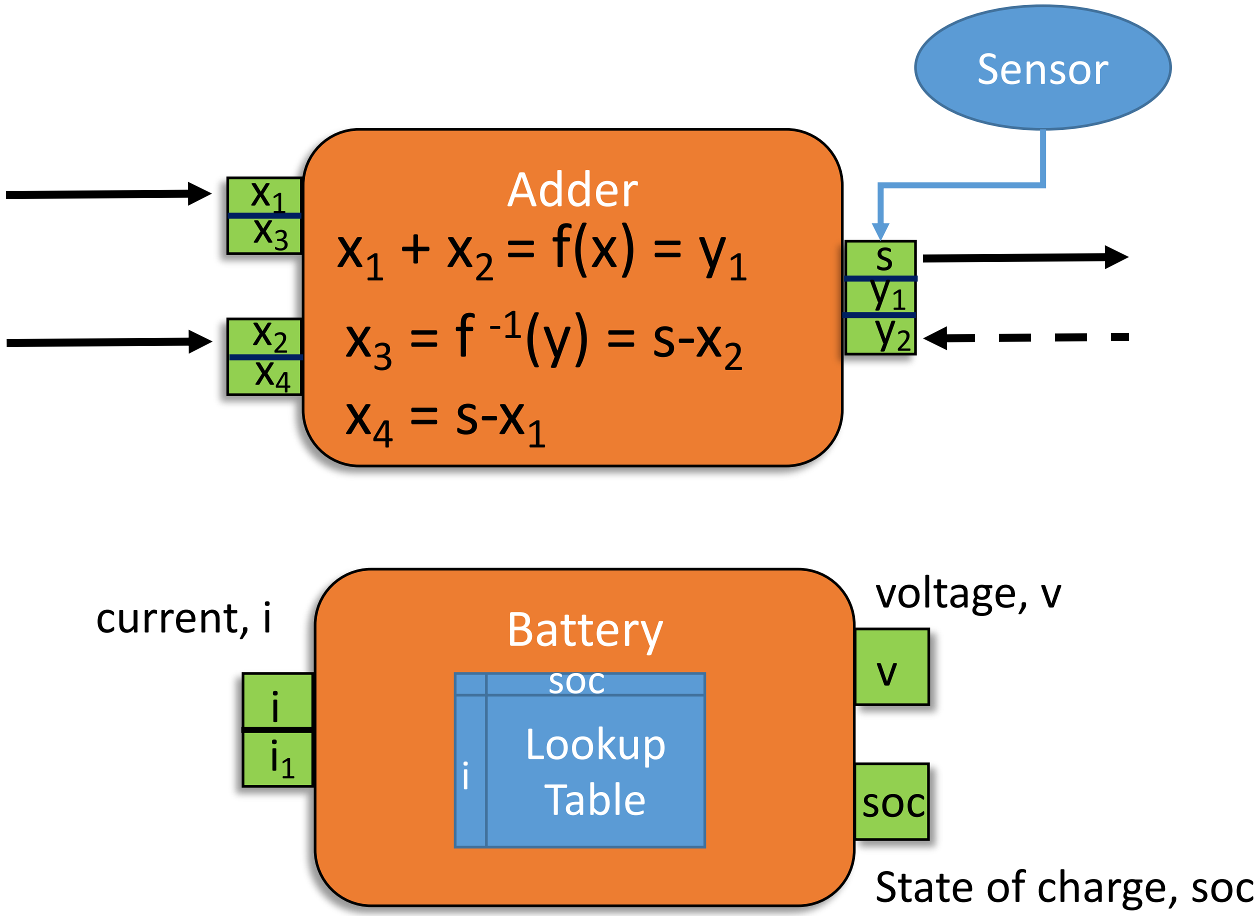
*MONSID is developed by Okean Solutions, Inc.

MONSID Models

- Sensor and model data propagated via
  - Forward constraints (input to output)
  - Reverse constraints (output to input)
  - No restrictions on constraint format
- Component nodes hold sensor and model data for consistency checks



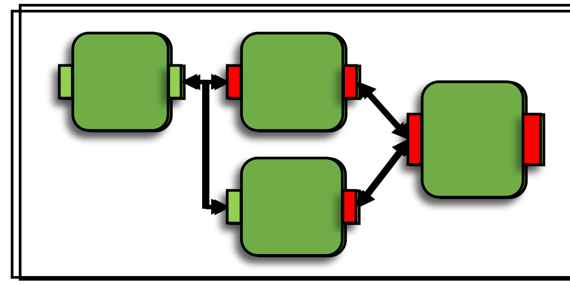
Constraint Examples



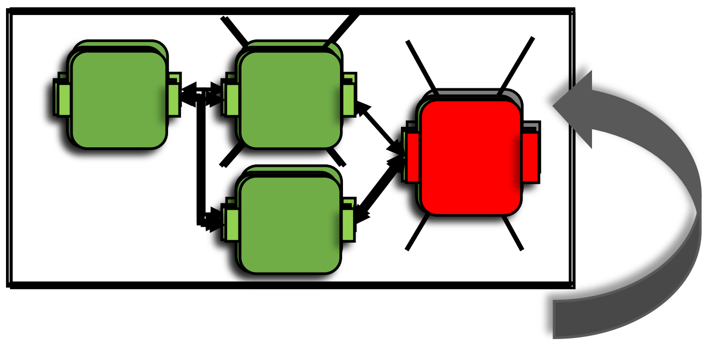
How the MONSID Engine Works

Constraint Propagation

Sensor and command data



Fault Detected! / Node Violations!



Node Violations!

Component Isolated!

- Verifies nominal behavior
  - Checks consistency at nodes
  - Node consistency checks fail
- Fault Detection
- Fault Isolation
  - Iteratively suspend components
  - Suspend a component and check nodes

Collaborating with Prof. Soon-Jo Chung and his student Sorina Lupu to integrate MONSID into the spacecraft simulators.

Getting more science via better sequencer

conventional

Command sequencer

- Commands issued at absolute and relative times
- Works well for predictable, fault-free scenarios
- No built-in checks to see if commands succeeded or failed ("flying blind")
- When a fault occurs, no way for sequencer to know what activities are affected
- Safing events lose precious time
- Result: science time lost during Earth-in-the-loop recovery

proposed

Task Sequencer

- Acts like a command sequencer in degenerate case
- Task = command + success criterion
- Task tree preserves what-depends-on-what
- Task tree can hold pre-planned fault recovery options for when a task does not succeed
- Unaffected tasks continue running
- Safing is recovery of last resort
- Result: more science accomplished while Earth diagnoses task failure

AutoNav Overview (cont.)

- Orbit determination
  - Numerical integration of dynamic equations of motion/ force modeling
    - Ground navigation uses very high fidelity models of forces acting on spacecraft since radiometric data is very accurate, and processing speed not an issue
    - Onboard computers not as fast, and rapid turnaround is important, so force models not as detailed
      - Include central and 3rd body point mass gravitational accelerations, simple solar pressure model, impulsive Delta-V. Onboard thruster activity accumulated by IMUs also included in integration
      - Low-thrust (e.g., ion propulsion system) modeled as linear polynomials
  - Least-squares estimation
    - Difference observed values of data against predicted values (based on predicted spacecraft trajectory) to get residuals
    - Perform least squares fit - adjust parameters of trajectory to minimize the residuals until only random noise remains
    - Result is reconstruction of past spacecraft trajectory, which can also be propagated into future to get predicted path

Adapted from a slide by S. Bhaskaran