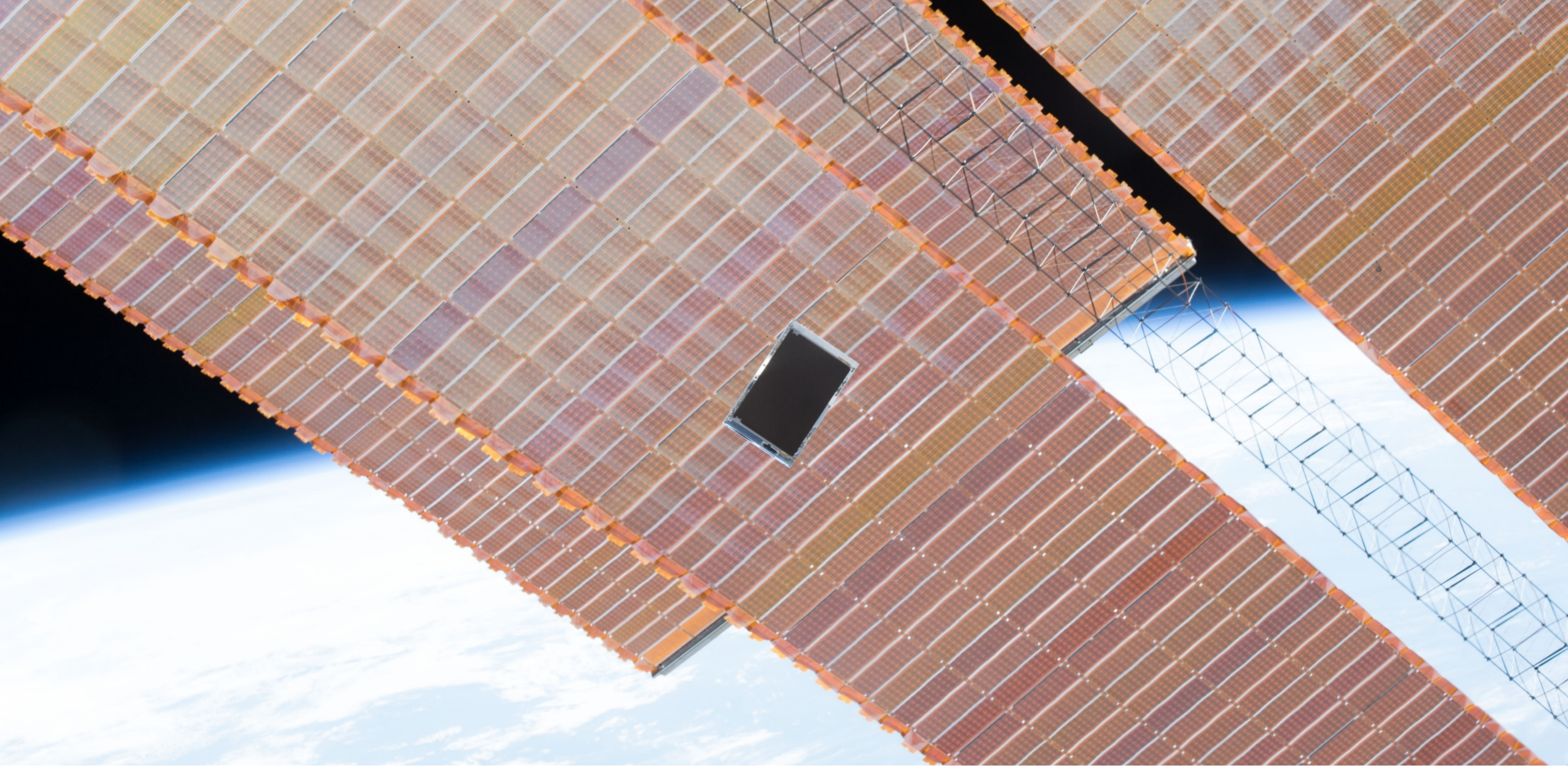

Jet Propulsion Laboratory
California Institute of Technology

ASTERIA

Lessons Learned: Small Satellite Reliability Initiative (SSRI) Technical Interchange Meeting-4 (TIM-4)

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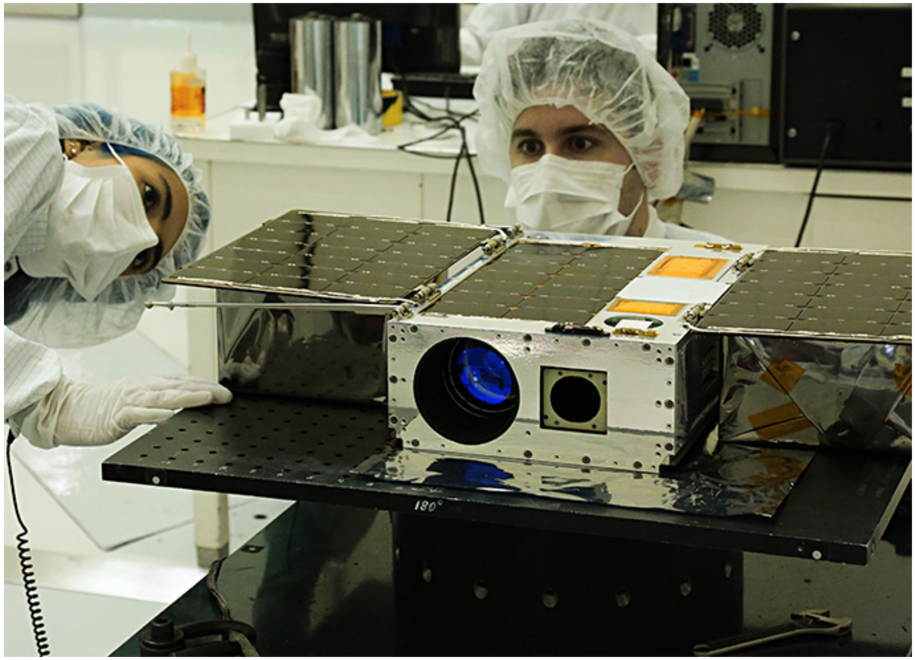
ASTERIA

Arcsecond Space Telescope Enabling Research In Astrophysics

Overview

- 6U CubeSat (approx. 10.2 kg, 11 x 24 x 37 cm^3)
- JPL and MIT collaboration
  - Sara Seager, PI
  - Built, tested, operated at JPL
- Funded through JPL's Phaeton Program for early career training plus MIT contributions to ops
- Launched to ISS in August 2017 on SpaceX CRS-12, deployed into orbit 3 months later by NanoRacks
- 300+ days of operation in space



Prime Mission Achievements

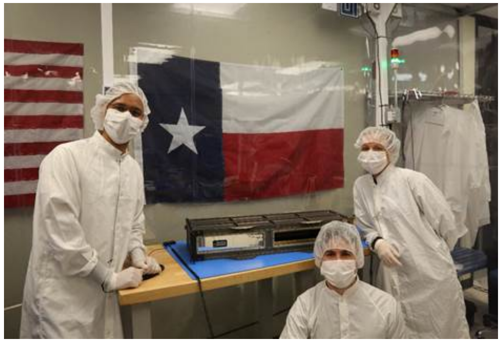
- Demonstrated **pointing stability of <0.5 arcseconds RMS** over 20 minutes
- Demonstrated **pointing repeatability of 1 milliarcsecond RMS** from orbit to orbit
- Demonstrated **focal plane thermal stability of ±0.01 K** over 20 minutes

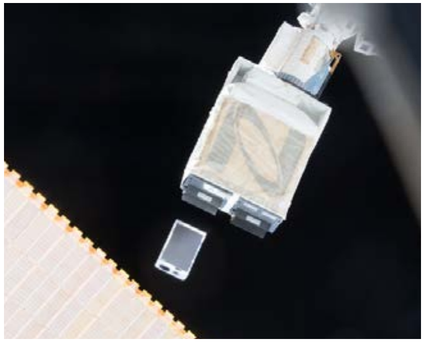
ASTERIA

Arcsecond Space Telescope Enabling Research In Astrophysics

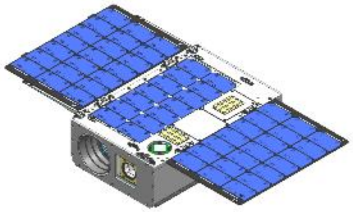
Extended Missions Status

- ***First CubeSat to detect an exoplanet:*** known super-Earth 55 Cancri e
- Continued observations of primary target star system, HD219134
- Continuing observations of secondary target star system, Alpha Centauri
- Demonstrating LEO orbit determination without GPS by imaging satellites in the geostationary belt
- Further characterizing reaction wheel jitter and its contribution to imaging performance
- Developing task networks to increase spacecraft autonomy and reduce ground-in-the-loop operations

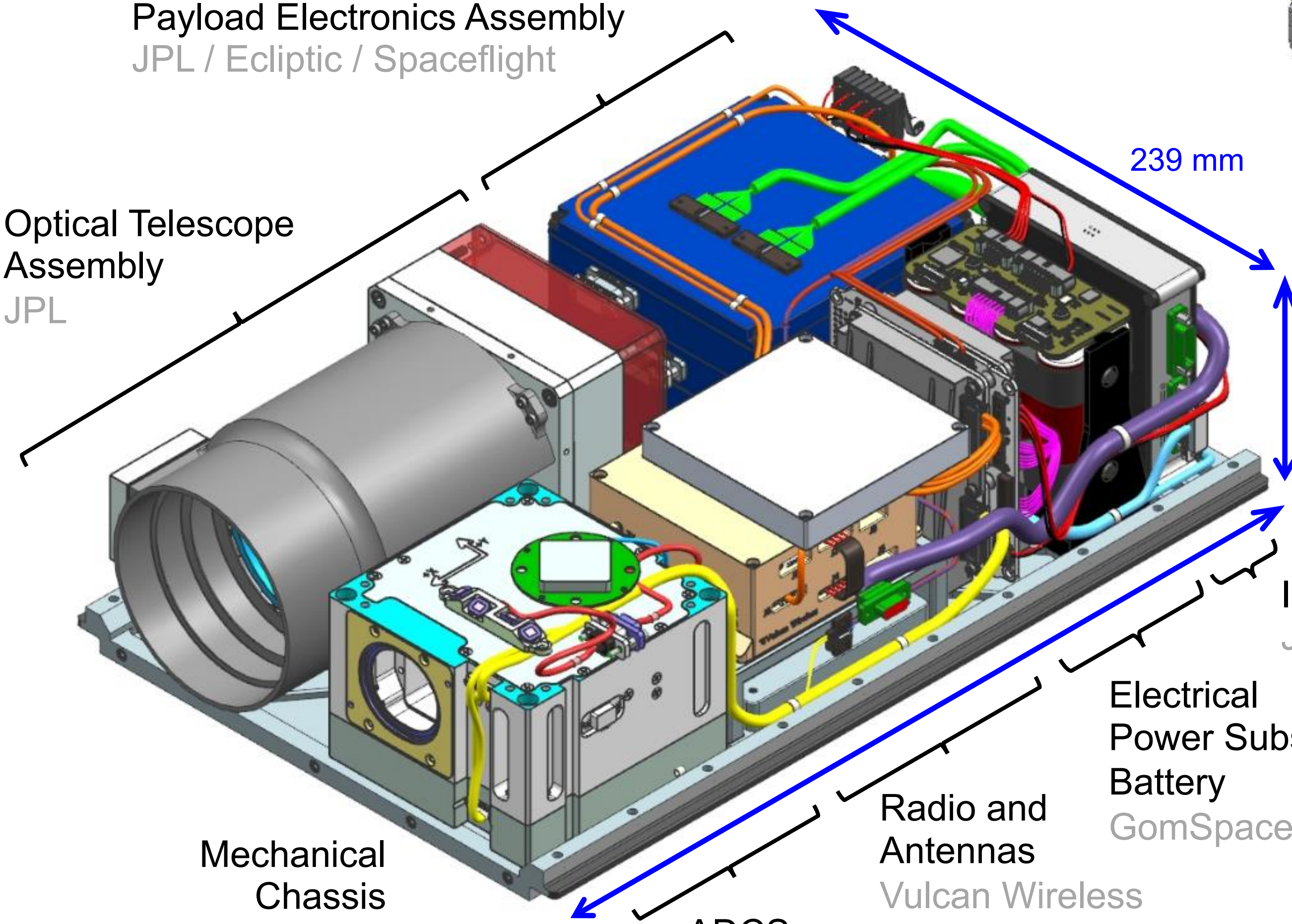





ASTERIA Spacecraft Overview



Solar Array
MMA Design



Payload Electronics Assembly
JPL / Ecliptic / Spaceflight

Optical Telescope Assembly
JPL

Interface Board
JPL

Electrical Power Subsystem / Battery
GomSpace

Radio and Antennas
Vulcan Wireless

ADCS
Blue Canyon Technologies

Mechanical Chassis
JPL

Flight Software
JPL (F Prime)

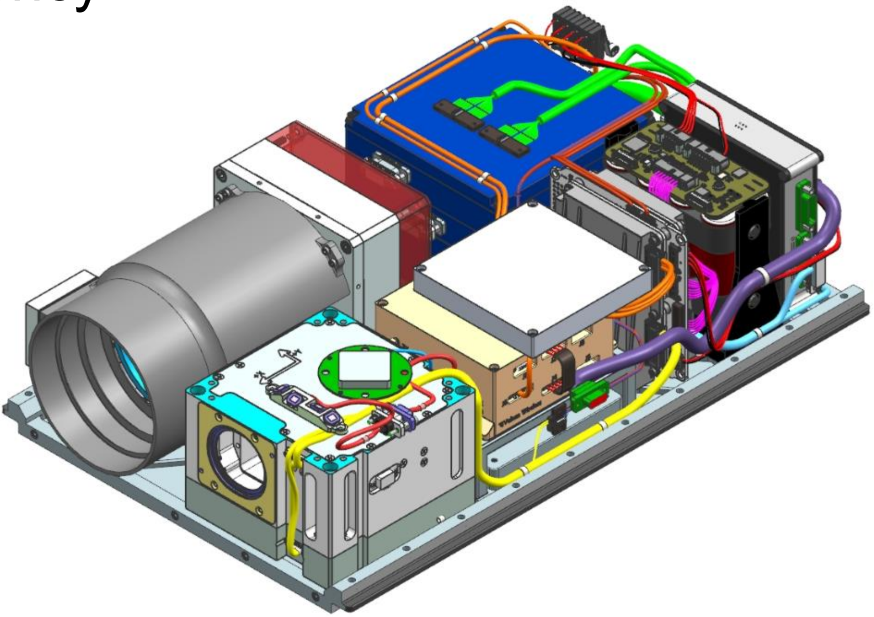
PCS Software
JPL

MOS Software
JPL / Alethium

ASTERIA: Lessons Learned

General Categories

- **Vendor interactions:** contracts vs. results
- **Design decisions:** cost vs. risk
- **Mission assurance:** independence vs. insight
- **Integration and test:** schedule vs. completeness
- **Operations:** rigor vs. efficiency



Vendor Interactions

Lessons Learned

- Background: ASTERIA supplier overview
    - Most suppliers (especially of COTS components) were specific to the CubeSat industry, and had not been previously used by JPL
    - Many CubeSat suppliers are small start-ups and do not have a certified Quality Management System (QMS)
    - A majority of suppliers used to fabricate JPL designs (e.g., PWB fabrication) did have a QMS and history with JPL
- Detail requirements and expectations in procurement documents (PO, statement of work), even for “COTS” hardware
    - Example: flight computer vendor data sheet described features that were not implemented in the product (e.g. SPI interface).
- Verify system behaviors of delivered products via testing
    - Example: Radio "auto mode" (speak only when spoken to) was not documented, which prohibited a beacon mode.
    - Example: Behavior of EPS timers governing power sequencing was nuanced, and finally fully characterized in system testing.

Hardware Design Decisions

Lessons Learned

- Thermal model accuracy was critical
  - Example: EPS board-level thermal analysis revealed high junction temperatures, and a custom mount was designed to move heat away from the EPS
- Staking and conformal coating
  - All electronic boards included staking of large components
  - Access to conformal coating facilities and technicians was a challenge at JPL (oriented toward large, Class B missions)
    - Availability of a “cheap” and “fast” conformal coating capability would have removed schedule bottlenecks
    - Primary drivers for conformal coating were general protection against FOD, etc. and potential mitigation against tin whiskers (some pure tin parts used, but leaded solder used throughout)
- Latchup prevention
  - Known sensitive parts were avoided as much as possible, and/or protected with overcurrent protection circuitry

System Design Decisions

Lessons Learned

- Value in designing flexibility and extensibility into the system with an eye toward operations.
  - Example: Fault protection updates via parameter table updates have allowed response to idiosyncracies not identified during limited system testing time.
  - Example: Flight software update capability has allowed team to address corner cases or space environment-related
  - Testing the flexibility features (e.g. FSW update) is essential
- To achieve positive power margin in worst case scenarios, a radio duty cycle was required
- FSW is a significant driver of system cost and complexity
  - F-prime FSW architecture developed on ASTERIA helped manage complexity but caused additional development work (ASTERIA was one of the first adopters of F-prime)
  - System engineering involvement in FSW design early is critical: decisions such as hard-coded parameters and different forms of parameters in each component were challenging
  - Clearly defined change control process for FSW (e.g., in JIRA) extremely useful

Mission Assurance

Lessons Learned

- Limited funding on CubeSat mission requires:

A: Insight > Independence
One full-time individual acting as MAM also fills multiple other roles, ideally all related to risk mitigation.

or

B: Independence > Insight
One individual fills MAM role and maintains independence, but is not funded beyond a low-level of support.

- Solution A worked well on ASTERIA (with MAM also specifically filling the role of fault protection engineer, and ultimately MOAM in operations)
  - Incorporation of independent reviews of mission assurance and fault protection approaches were key to mitigating a potential conflict of interest

CubeSat Fault Protection:

- Identify simple ***"catch-all" fault monitors*** and test them thoroughly
- Do not hesitate to implement a ***"hard-hammer" power-cycling response***
- Allow for ***in-flight fault protection updates*** without a FSW update

Mission Assurance

Tailored approach on ASTERIA

- **Hardware Quality Assurance (HQA):**
  - Inspections start at board assembly level (not part level)
  - Flow quality assurance requirements to vendors (e.g., require tin-lead, not pure tin, solder)
  - Conduct reviews for subsystems prior to system integration
  - Oversight during assembly and testing of flight system

- **Environments Assurance:**
  - Vibration test (per NanoRacks requirements) of flight system
  - Thermal vacuum test of flight system (with qual batteries)
  - Minimize effects due to electromagnetic interference and electrostatic discharge

- **Reliability Assurance:** focus on derating of electronic parts for JPL-designed boards

- **Electronic Parts Assurance:** minimize radiation-induced single event effects

- **System Safety:**
  - NanoRacks safety requirements compliance evaluation
  - Conduct safety surveys of lab areas

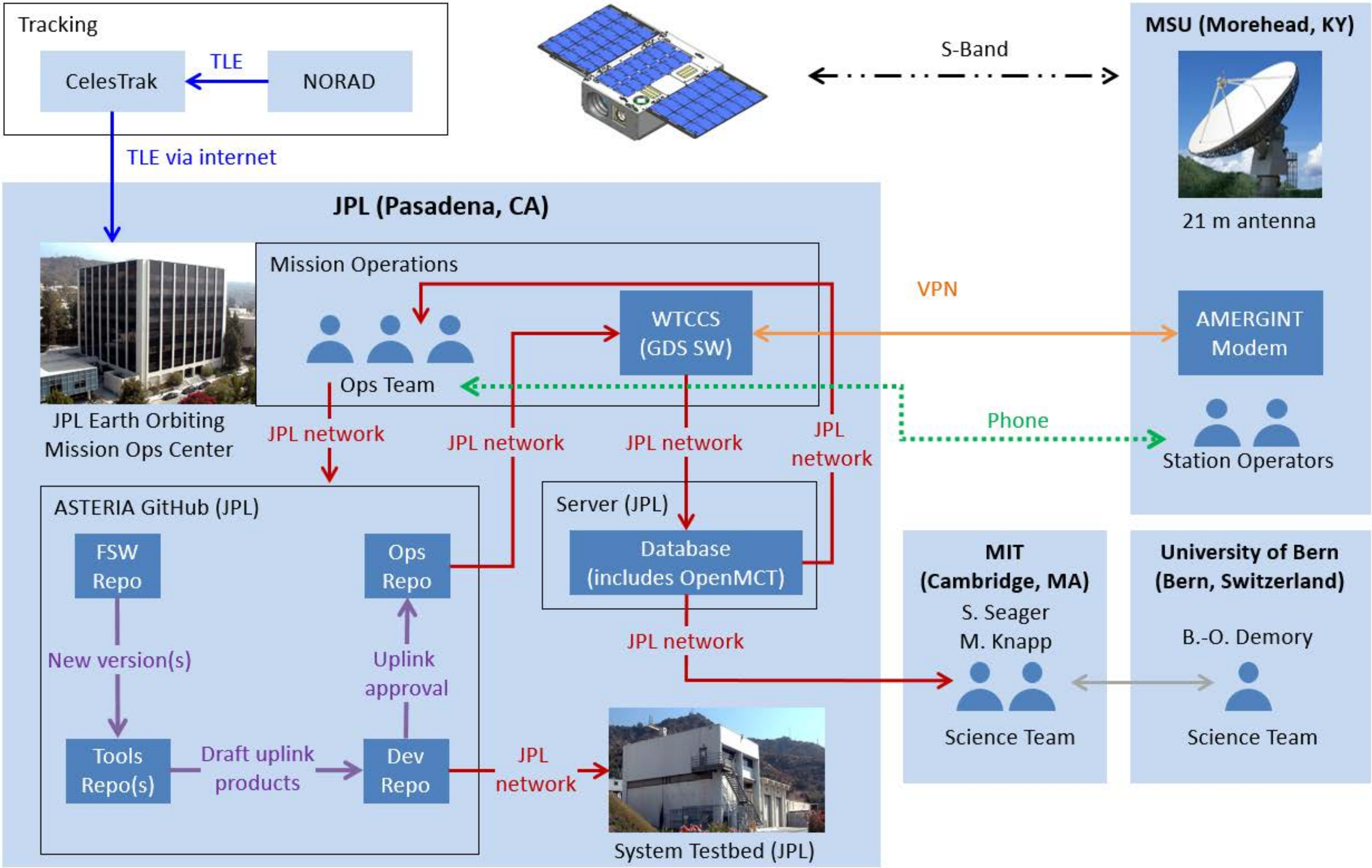
- **Software Quality Assurance (SQA):**
  - Review initial flight software development plan
  - Support reviews of launch delivery software and in-flight software updates
  - Assisted with software static analysis shortly before delivery (earlier may have been helpful)

Integration and Test

Lessons Learned

- Mission Scenario Tests (MSTs) are critical to understanding system behavior and identifying idiosyncracies:
  - MSTs run included: nominal deploy/detumble, off-nominal deploy/detumble, nominal day-in-the-life, off-nominal day-in-the-life (interjection of multiple faults), observation sequence
- Long duration system testing was also critical
  - On ASTERIA, ran tests in parallel on flight system and on testbed to “shake out” long-term issues in FSW, for example, before fully verifying on flight system
- Overlap Cog-E and technician roles
  - Train Cog-E’s in crimping, conformal coating, etc., to minimize wait time for technicians
- Make multiple testbeds available to FSW team
  - The ideal, not always realized, is to have a testbed for the exclusive use of the FSW team that includes the flight-equivalent CDH hardware

ASTERIA Operations Overview



Operations

Lessons Learned

- Operational Readiness Tests (ORTs) were helpful
  - Exercised and refined operations processes in the flight venue using the testbed as a proxy for the spacecraft
  - Especially valuable for this team, which for the most part was new to operations
  - Occurred after delivery but before deployment
  - Real operations exposed issues that were not identified in the ORTs (low data rates, spacecraft rotation, fault recovery)
- End-to-end information system (EEIS) testing was essential
  - Performed several EEIS “thread tests” to validate the end-to-end data flow from RF at the station to the GDS server
  - No single thread test covered the entire chain; needed to combine multiple tests to achieve full coverage due to equipment constraints (e.g. ground station modem was at JPL for the first ORT but shipped to Morehead in the weeks prior to deployment)

Operations

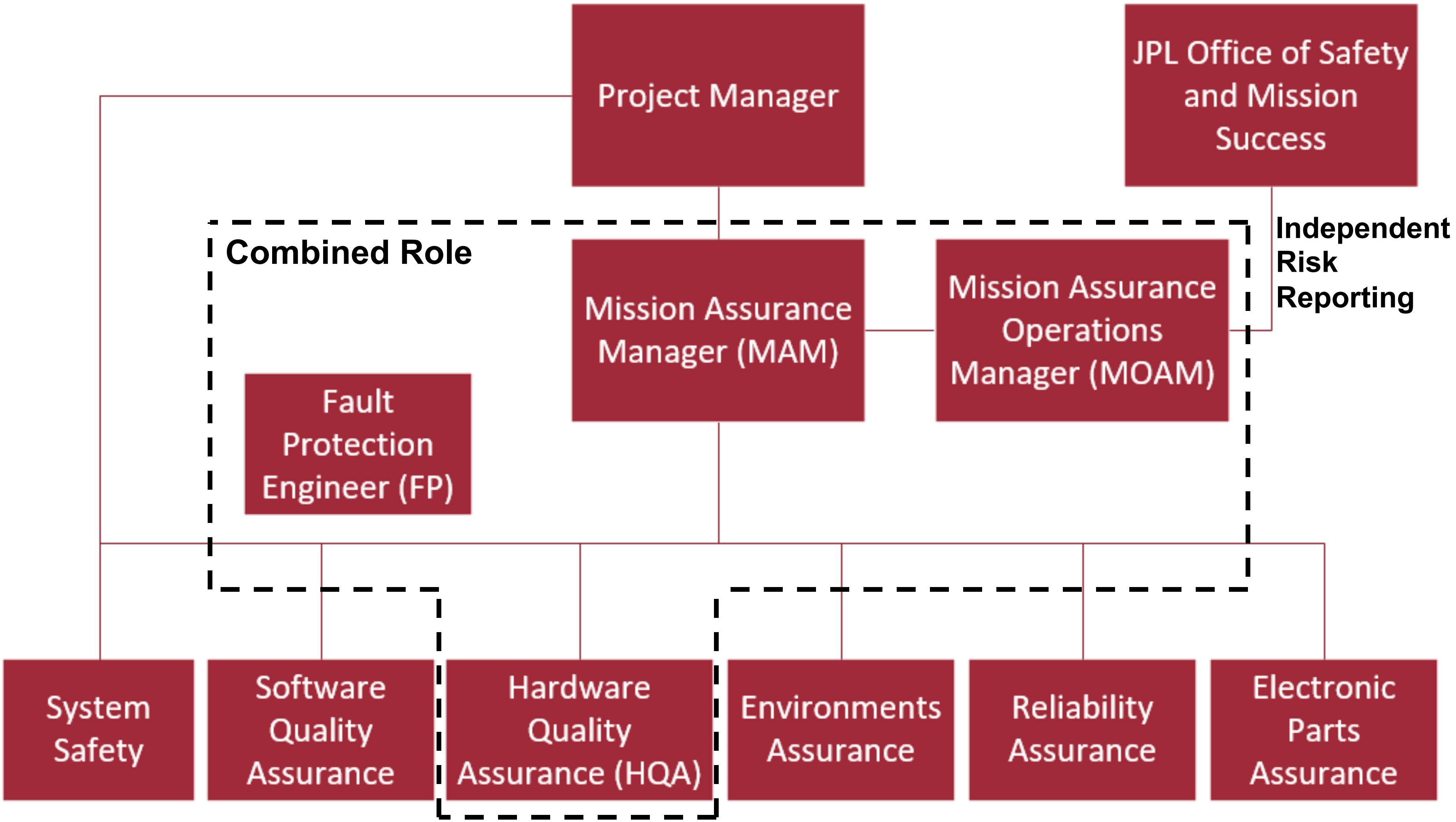
Lessons Learned

- Value of full system testbed (combines flight spare and EM hardware, and ground system hardware for “front door” testing)
  - “Front door” testing (through the flight GDS interface) allows end-to-end testing of new commands, which was especially valuable in validating a new FSW update process using a FSW patch
  - “Back door” testing used primarily for testing new sequences and testing new FSW versions
- Single ground station
  - Pros: responsive and flexible
  - Cons: no backup in the event of a failure, weather, etc.
- Access to shell commanding on the spacecraft CDH through Linux OS has been beneficial (allows access to low-level payload commands and access to system logs)
- GitHub-based uplink approval process works well

Questions?

Safety and Mission Assurance (SMA) Approach

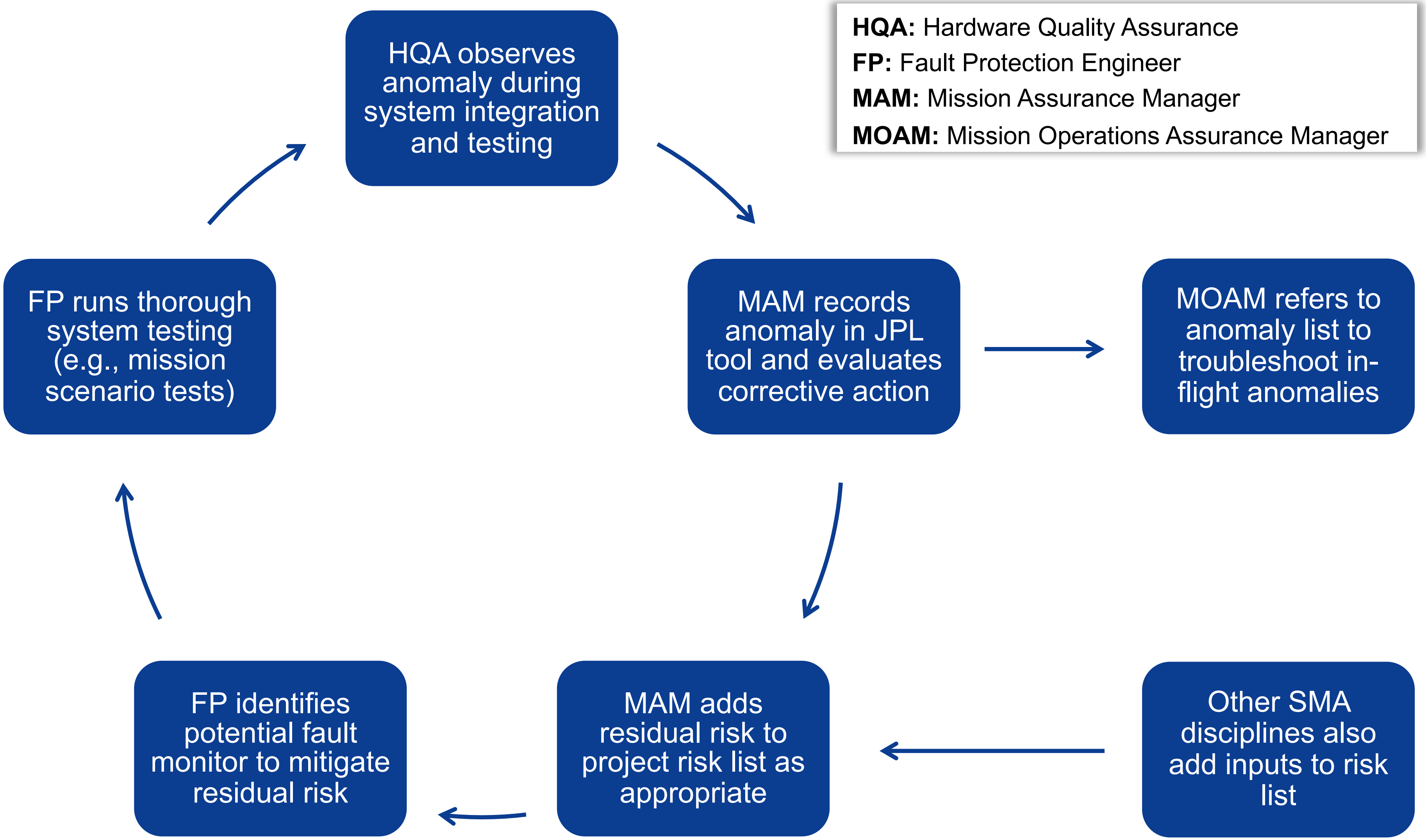
ASTERIA: Combined Roles to Scale for Small Team



Combined Roles on ASTERIA

Risk Management Example

HQA: Hardware Quality Assurance
FP: Fault Protection Engineer
MAM: Mission Assurance Manager
MOAM: Mission Operations Assurance Manager



HQA observes anomaly during system integration and testing

MAM records anomaly in JPL tool and evaluates corrective action

MOAM refers to anomaly list to troubleshoot in-flight anomalies

MAM adds residual risk to project risk list as appropriate

Other SMA disciplines also add inputs to risk list

FP identifies potential fault monitor to mitigate residual risk

FP runs thorough system testing (e.g., mission scenario tests)

Fault Protection Design

Monitors catch system-wide safety issues

Examples:
Low battery voltage*
ACS off-sun
Command loss
Sequence failure

Responses assert safe state

“Soft hammer” safe mode response powers off payload and commands ACS to point at sun

“Hard hammer” reset response power cycles all subsystems except EPS

EPS watchdog

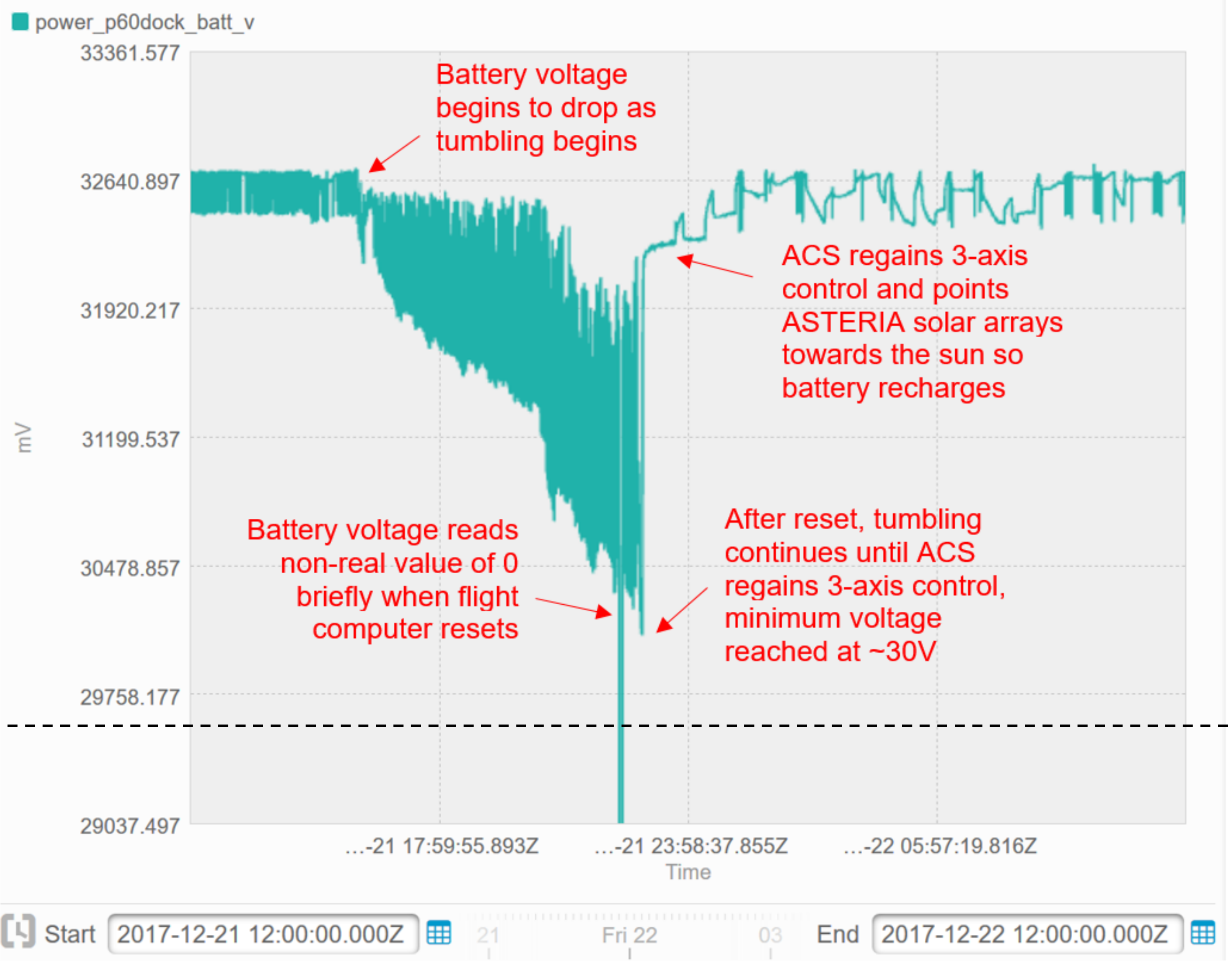
If FSW does not respond to health pings, EPS power cycles flight computer, which boots into Safe Mode

*At launch the response to this fault was the safe mode response, as testing and analysis had not identified a credible scenario where power cycling the ACS unit would provide greater benefit than risk…

Tumbling Anomaly and Commanded Reset

Motivation for Fault Protection Updates

Battery Voltage vs. Time (Analysis Tool: OpenMCT)



Battery voltage begins to drop as tumbling begins

ACS regains 3-axis control and points ASTERIA solar arrays towards the sun so battery recharges

Battery voltage reads non-real value of 0 briefly when flight computer resets

After reset, tumbling continues until ACS regains 3-axis control, minimum voltage reached at ~30V

Under-voltage threshold was not reached before reset was commanded

Fault Protection In-Flight Changes

Immediate Changes: No FSW Update

Before ACS Anomaly

Low battery voltage fault monitor called “soft-hammer” safe mode response

→

After ACS Anomaly

Low battery voltage fault monitor calls “hard-hammer” reset response

Later changes via FSW update

Before ACS Anomaly

Mode manager did not include a power cycle of ACS unit at safe mode entry

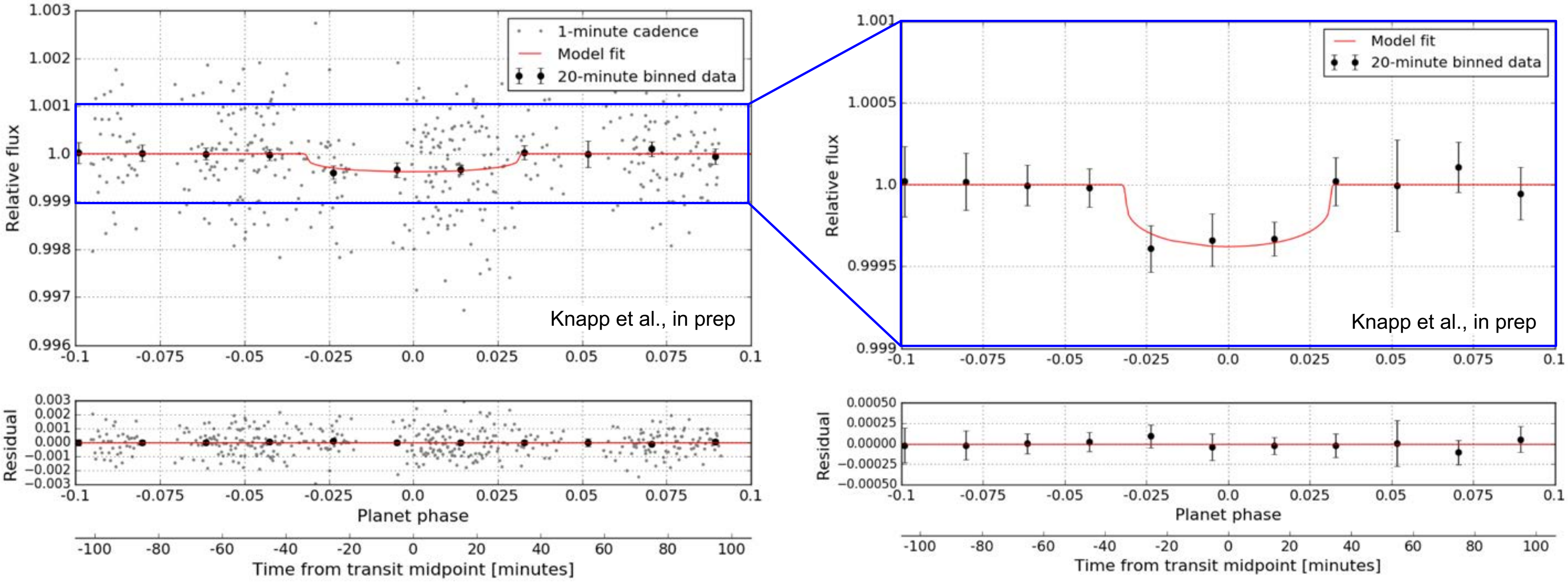
→

After ACS Anomaly

Updated mode manager to include power cycle of ACS unit upon safe mode entry

All changes were tested on the testbed per ASTERIA operations procedures

55 Cancri e Detection



Knapp et al., in prep

Knapp et al., in prep

- 410 ppm transit observed at SNR=3
- $2R_E$ exoplanet around a V=5.95 Sun-like star
- The above plots contain 526 minutes of cumulative observation time, phase folded
- Photometric precision is 730 to 1140 ppm/min at V=5.95