ICON
Ionospheric Connection Explorer

Spacecraft Anomalies and Failures Workshop

ICON Satellite Failure Investigation

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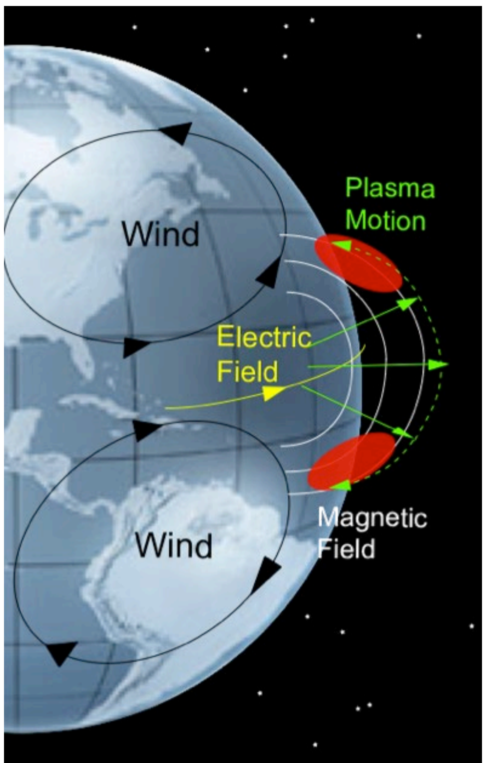
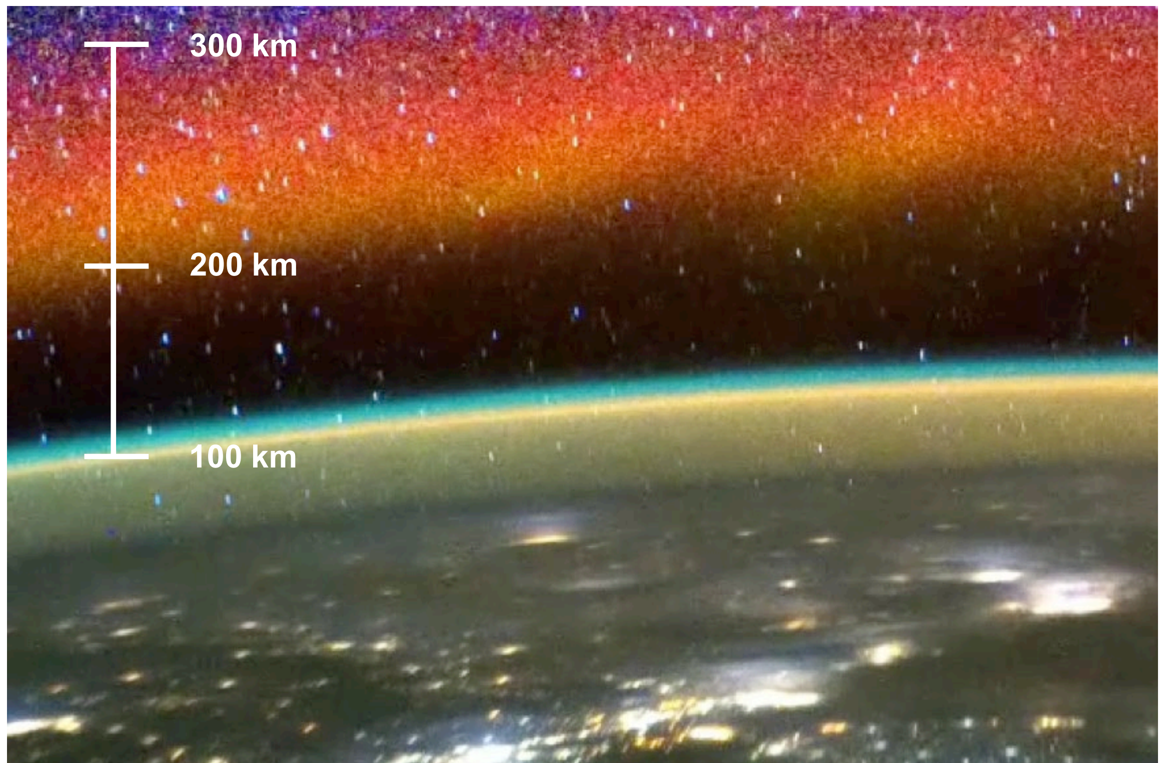
Concept of Operations – Science Objectives

Science Objectives

- Measure altitude profiles of airglow near the Earth limb at visible and UV wavelengths via remote sensing, and measure in-situ ion densities and flows near the local magnetic field line to determine the connection between terrestrial weather and space weather.

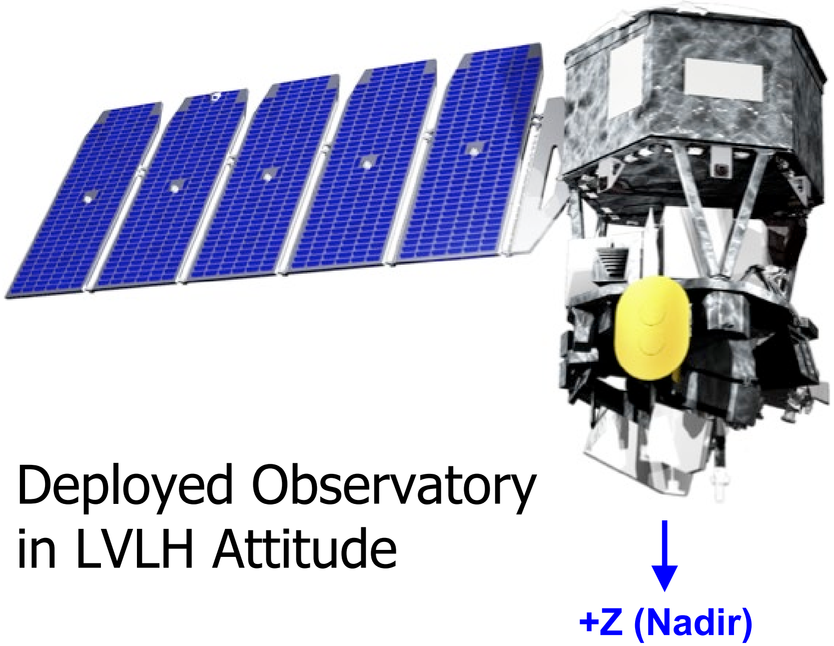




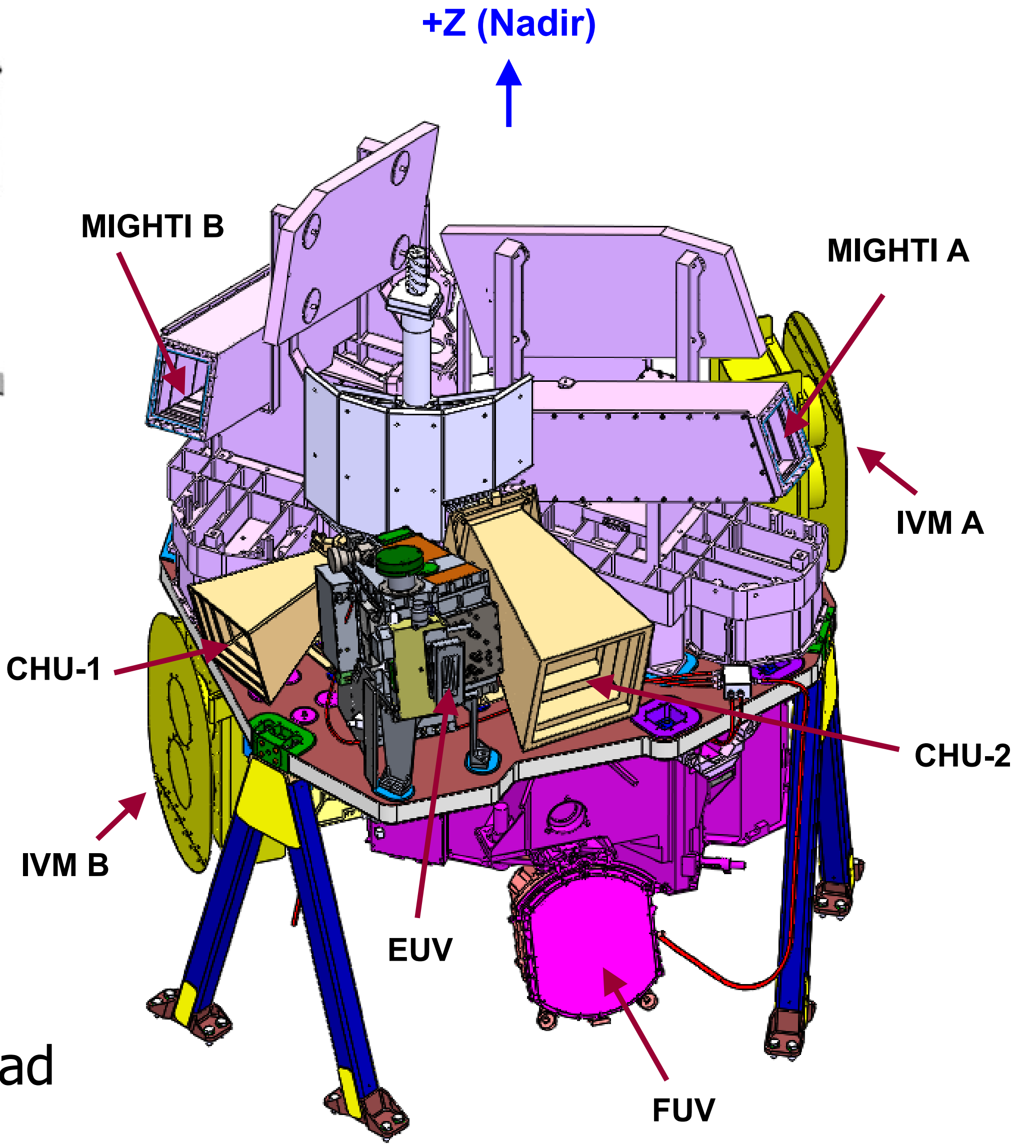
Concept of Operations – Implementation

- Implementation
  - Observatory platform: 3-axis stabilized **Northrop Grumman LEOStar-2 bus**
    - Articulated solar array, 30-Ah Li-ion battery, RAD processor, 128-MB SDRAM
    - ADCS: Star tracker (2 CHUs), RWA (4 wheels), IMU, GPS receiver
    - S-band transponder
  - Instrument suite: Remote sensing and in-situ measurements (6 sensors)
  - Operations mode: Nominal LVLH attitude
    - Various attitude maneuver scenarios to collect science data and to perform instrument calibrations
  - Mission orbit: 601 km x 575 km at 27 deg inclination
    - Launch: October 10, 2019 on Pegasus XL from Reagan Test Site
  - Networks: S-band communications via BGS, NEN, and SN
  - Operations centers: MOC and SOC co-located at UCB/SSL
  - Mission phases:
    - Launch and on-orbit commissioning (1 month)
    - Prime mission science operations (2 years)

Integrated Payload & Observatory Configuration

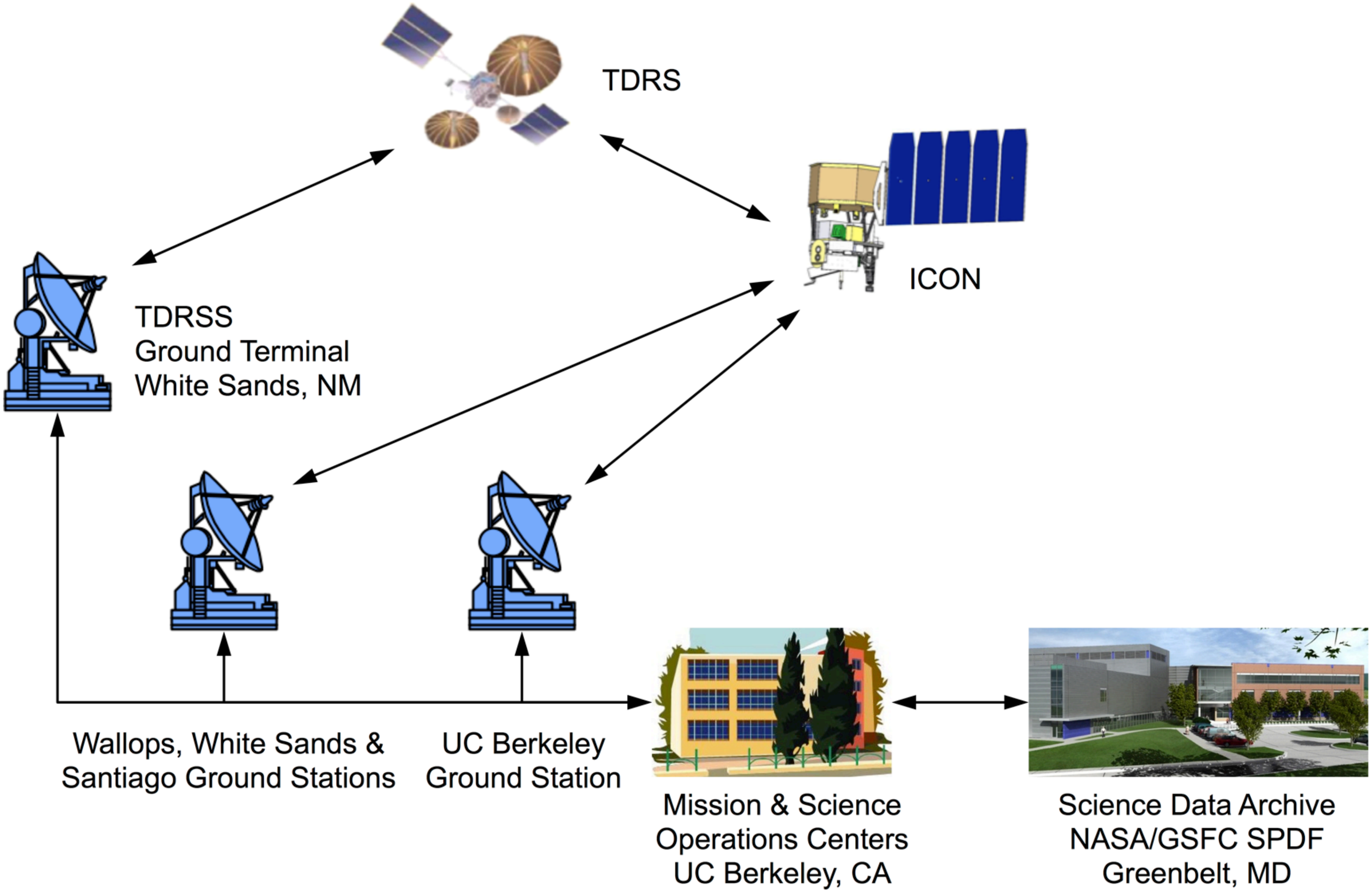


Deployed Observatory
in LVLH Attitude



Integrated Payload

Mission Operations System Overview



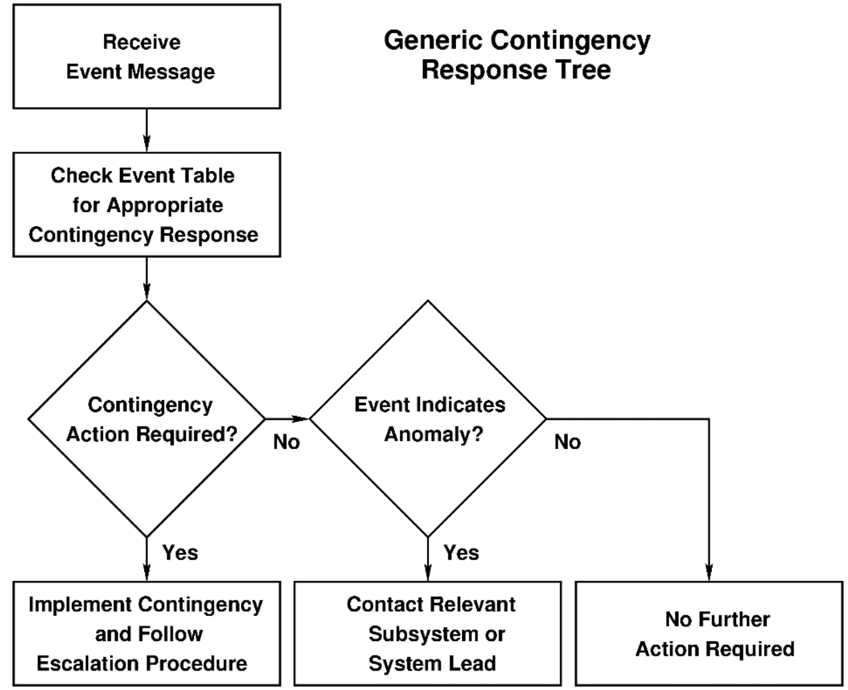
Anomaly Detection

- Spacecraft, MOC and Remote Stations Will Be Capable of Two-way Communications
  - All passes with BGS, NEN and SN will be scheduled with two-way links
- An Anomaly May Be Detected by Ops team or anomaly automation software on the ground
  - Ops team monitors real-time passes and trend data
- Software Monitors Every Pass and All Back Orbit Data
  - Pages ops team on detection of limit violation
  - Paging is persistent with anomaly information included in SMS
  - Additional information available via multiple MOC online tools
  - Paging is persistent until acknowledged (via iPhone/email/web)
- SatConstat also monitors real-time contacts and will page ops team members on limit violations

Anomaly and Contingency Response

❑ Anomaly and Contingency Response

- Flight controllers are trained to handle spacecraft safing operations.
- Paging systems are in place to alert flight controllers and operations management during off-hours.
- Anomalies are assessed in consultation with cognizant systems and subsystems engineers.



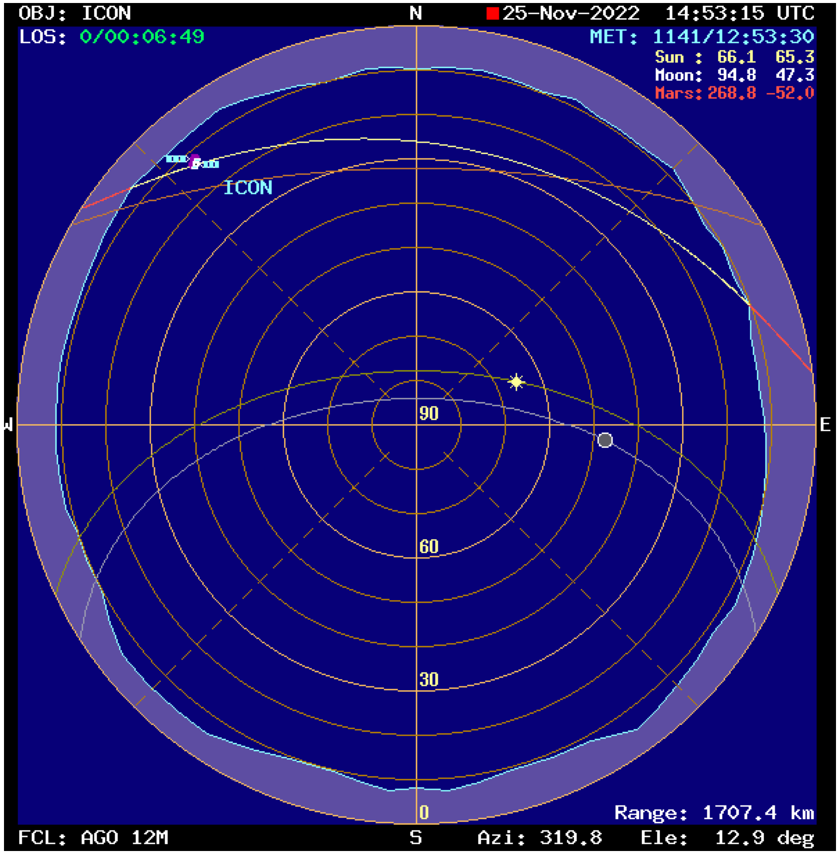
❑ Operations Team Expertise

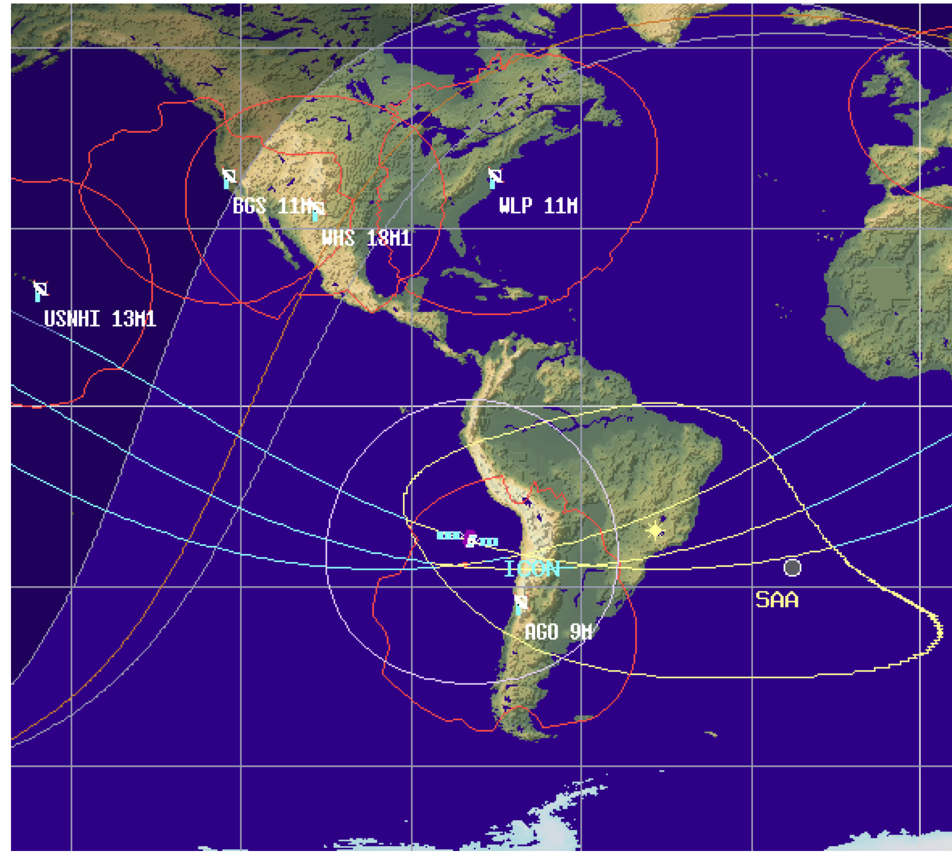
- Flight controllers are trained to act as first responders in case an anomaly is detected.
- Anomaly resolution involves operations management and all stakeholders, as required.

Anomaly timeline

- 2022-**329**-15:00 UTC last Telemetry seen from ICON during a Santiago contact with transponder commands controlled out of the on-board command sequence (Absolute Time Sequence-ATS)
- This ATS contained transmitter, as well as instrument commanding, through 2022-**338**-23:59:59 UTC
- Later analysis of ICON's ballistic coefficient showed an <u>apparent attitude change </u>sometime between 329-15:00 and day 331 (shown on later chart)

2022-329-15:00 UTC AGO pass geometry





View from the station

- The solar activity had been on the rise since the start of the current solar cycle in 2019, but the end of November 2022 was no outlier here.

ICON inside the SAA during the entire pass and 2 subsequent orbits

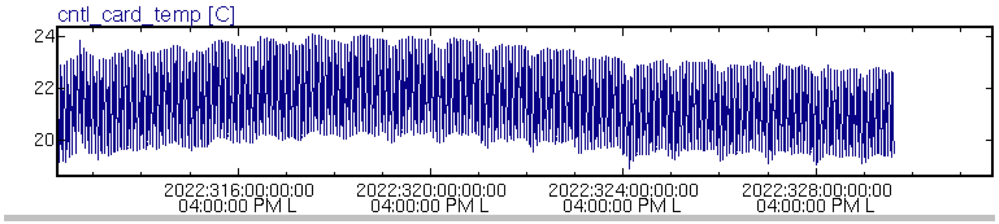
Last good pass Santiago 2022-329-15:00 UTC

- Normal high-rate pass controlled from the ATS
- Inside the South Atlantic Anomaly (SAA)
- Last command verified at 2022-14:53:15 UTC
- The ATS was running and had commands sequenced up to 2022-338-23:59:59 UTC
- 8 day master command timeout SHOULD have begun counting down: runs a full box power cycle once expired (that might clear most SEU faults)
  - 2022-337-14:53:15 (after last verified command)
  - 2022-339-04:37:18 (after last unconfirmed command sent)

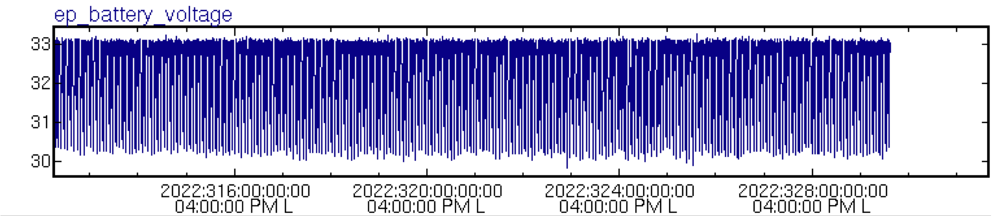
Telemetry leading up to the outage

❑ Before the outage there was no indication of any problem

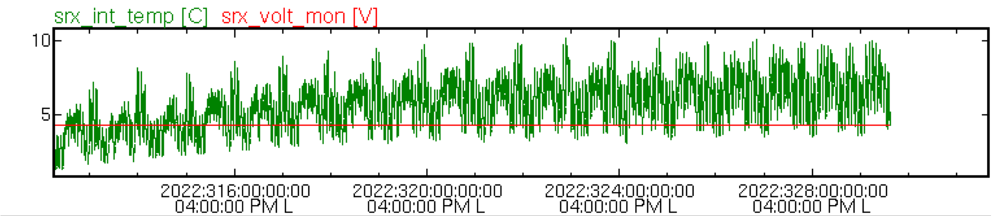
- Control Card Temp



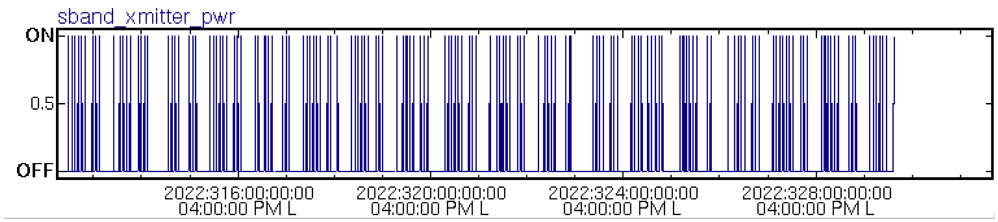
- Battery Voltage



- Transmitter Temp and voltage



- Transmitter ops



- 15 days

Summary of commanding

- Blind acquisition commanding sent multiple times starting 2022-330-06:00
  - Normal high-rate blind acquisition command sequences sent through the Berkeley ground station, Wallops and Santiago
  - Low rate blind acquisition commands sent via TDRS 12, 10, 7 and 6
- 2022 days 331-339 Hardware commands sent
  - Uplink and downlink interfaces reset on the controller card
  - Warm and cold reset commands to the CPU and all cards
  - Hardware commands to power cycle the entire system
  - Commands repeated after waiting for an 8 days uplink timer to expire
- 2023-006-19:00 commands sent to rotate the solar array 87 degrees
  - No change observed in the ballistic coefficient
- 2022-348 – until Loss of Spacecraft
  - Sending blind acquisition commands (both hardware and software versions) during every ground station contact, **more than ~4000 sequences**

Passes leading up to the attempted recovery

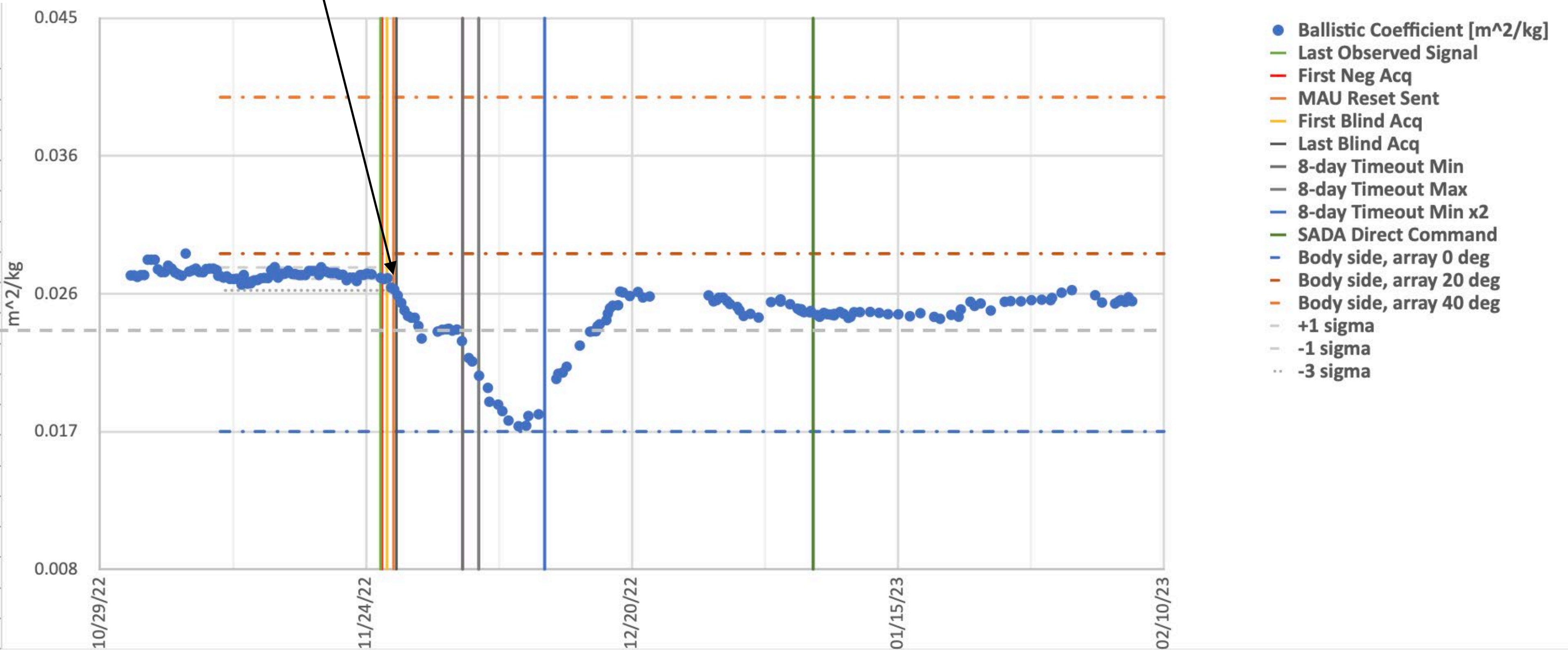
AGO	2022/329 14:51:52 - 15:00:00	Nominal pass 329-14:53:15 command verified
AGO	2022/329 16:34:08 - 16:42:20	Station not configured for the support
AGO	2022/329 18:16:28 - 18:24:24	No RF detected
WLP	2022/330 01:13:16 - 01:20:00	No RF, 4.9 degree elevation
BGS	2022/330 04:26:52 - 04:31:48	

Commanding after the start of the anomaly

BGS	2022/330 06:06:24 - 06:15:36	6x high-rate blind acq. sequences
TDRS 10	2022/330 07:25:03 - 07:37:03	7x low-rate blind acq. sequences
BGS	2022/330 07:47:44 - 07:57:48	5x high-rate blind acq. sequences
BGS	2022/330 09:29:56 - 09:39:04	9x high-rate blind acq. sequences
AGO	2022/330 18:21:56 - 18:29:16	6x high-rate blind acq. sequences **HW cmds to reset the UL and DL interfaces**
TDRS 11	2022/330 19:33:00 - 19:47:00	6x low-rate blind acq. sequences **HW cmds to reset the UL and DL interfaces**
TDRS 6	2022/330 20:12:00 - 20:24:30	3x low-rate blind acq. sequences **SW and HW cmds to reset the UL and DL interfaces**
TDRS 7	2022/330 20:50:00 - 21:02:00	3x low-rate blind acq. sequences **SW and HW cmds to reset the MAU**
TDRS 10	2022/330 21:20:00 - 21:32:00	2x **HW cmds to power cycle of the avionics** 3x low-rate blind acq. sequences
TDRS 12	2022/330 21:42:00 - 22:02:00	2x **HW cmds to power cycle of the avionics** 6x low-rate blind acq. sequences
BGS	2022/331 04:30:52 - 04:38:00	1x **HW cmds to power cycle of the avionics** 5x high-rate blind acq. sequences

ICON's ballistic coefficient

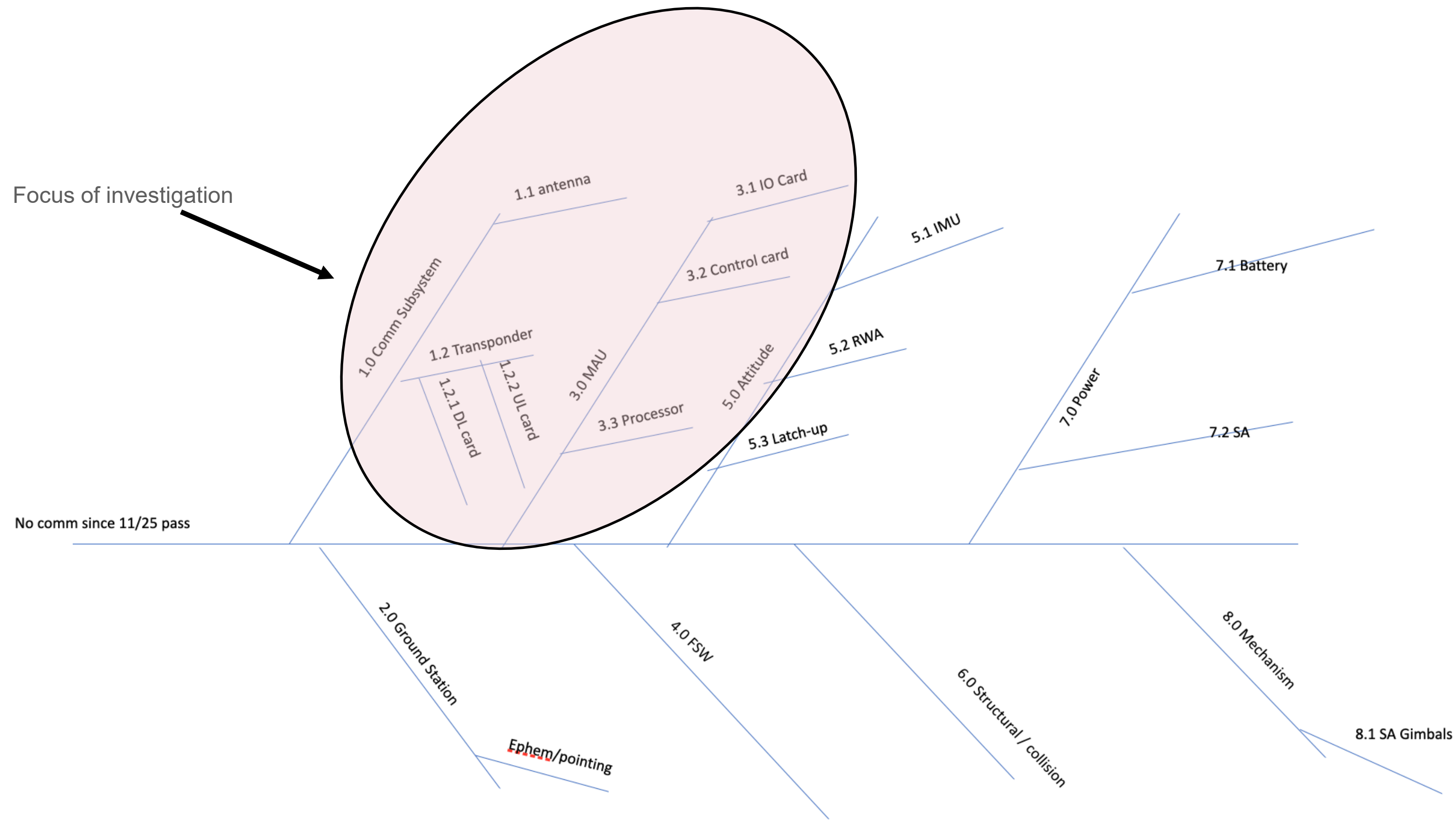
Analysis showed an apparent (unexpected) change of attitude around the time of loss of contact



Unlikely or exonerated faults

- **Transceiver unit failure**
  - Would not lead to an attitude change seen on the scale observed
- **Ground System Failure**
  - Many stations used (BGS, Wallops, Santiago, Whitesands, TDRS)
- **Unwanted commanding**
  - Nothing seen, in command logs or spacecraft telemetry leading up to the anomaly would indicate malicious or inadvertent commanding
- **Spacecraft collision**
  - Headcount conducted on November 26, day 330, did not indicate a breakup event
- **I/O card failure**
  - The transmitter should still have been under control of the ATS
- **Attitude**
  - Failure by any single component of the attitude control system would not prevent the transmitter from being controlled out of the ATS in the short term

Initial Fishbone Created by Mission Ops



SSL

Possible causes of failure

What could have put us in this state

- ❑Failure of one of a few cards within the spacecraft's master avionics unit (~15K orbits/thermal & Rad cycles)
- ❑Some power bus fault
- ❑Indeterminant low probability design or part failure OR MMOD strike to MAU or Power bus parts

Recommendations

- Black box feature for the last telemetry: Spacecraft that are single string for communications or C&DH should be required to have a "black box" feature that would use some separate standalone electronics to record the last several orbits of spacecraft bus housekeeping and transmit this repeatedly at low bandwidth should a heartbeat from the communications or C&DH elements fail. An additional chip in the narrow-band transmitter could accomplish this by listening to the serial bus. This function would allow the causes of failures like ICON's to be known so that future systems could benefit.
- Comm System Redundancy: If one redundancy can be added to a spacecraft, it should be in the comm system (receiver, transmitter).