NASA's STEREO Mission: Living Past Your Warranty

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Outline

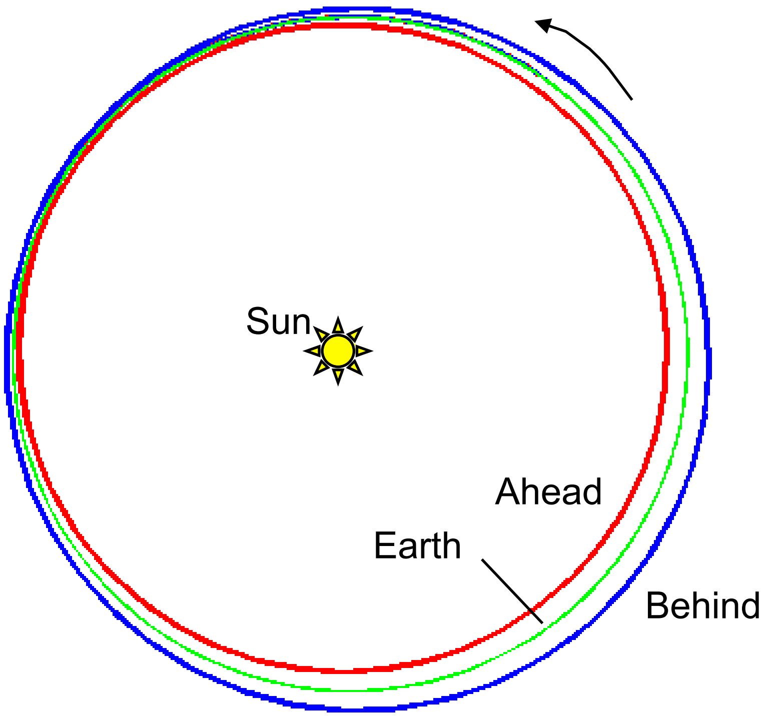
- Mission and spacecraft overview
  - Theme: “selective redundancy”
- IMUs, IMUs, IMUs
- Solar conjunction challenges
- STEREO AHEAD Status
- STEREO-B loss of communications anomaly
- Post-mortem
- Lessons Learned

STEREO Mission Overview

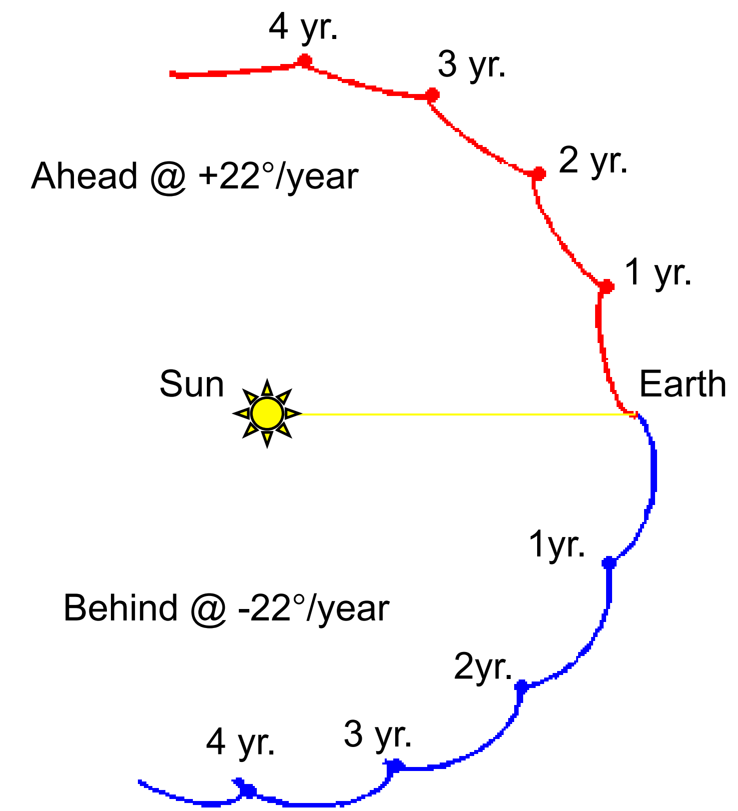
- Science Objectives
  - Understand coronal mass ejections (CMEs)
  - Characterize propagation of CMEs through the heliosphere
  - Discover mechanisms and sites of energetic particle acceleration in the low corona and interplanetary medium
  - Improve understanding of the solar wind
- Mission design:
  - Image the Sun in 3-D
  - 2 spacecraft in heliocentric orbit at approximately 1 AU

STEREO Orbital Drift

Mission Design: 2 years heliocentric orbit required, 5 years goal

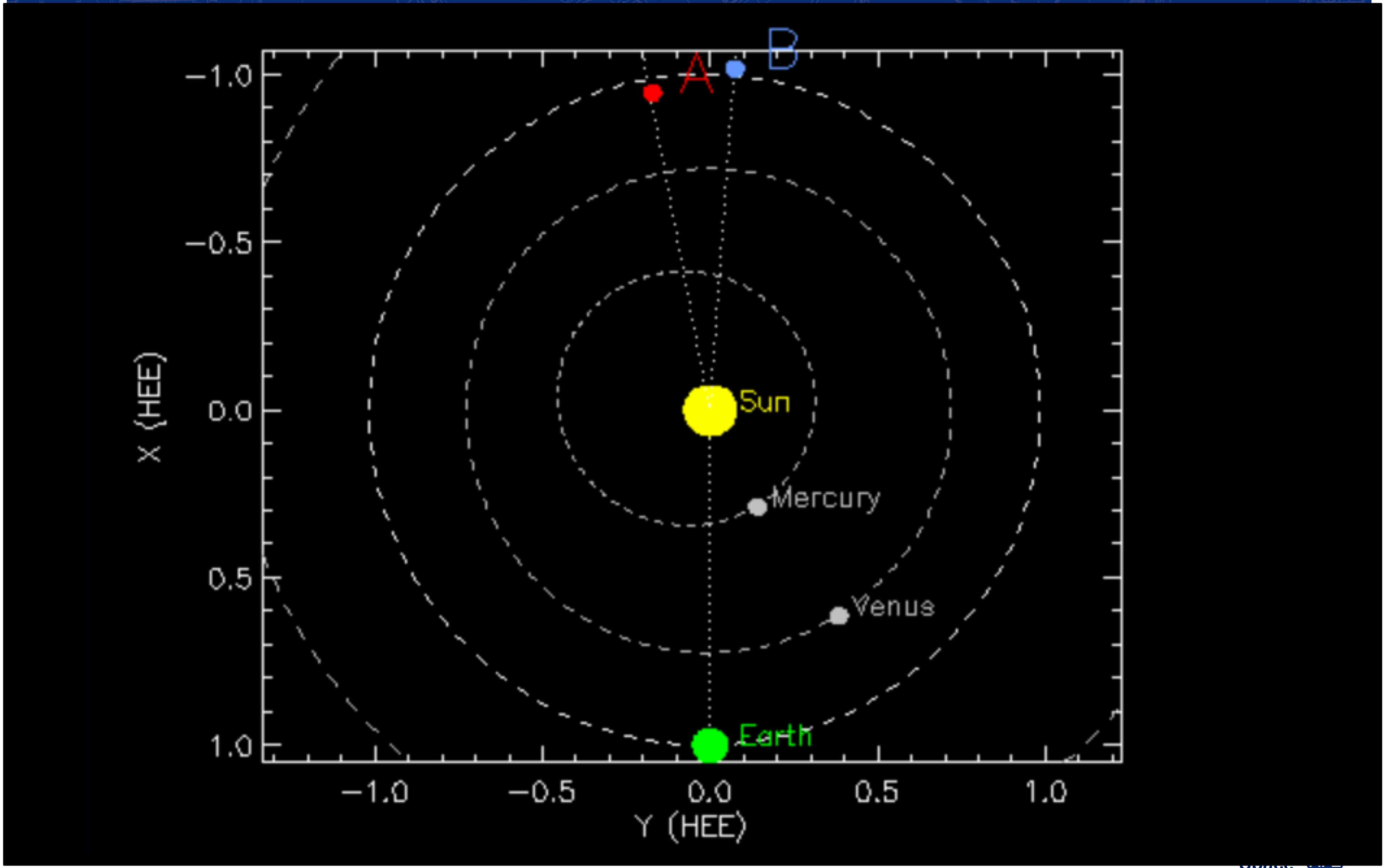


Heliocentric Inertial Coordinates
(Ecliptic Plane Projection)



Geocentric Solar Ecliptic Coordinates
Fixed Earth-Sun Line
(Ecliptic Plane Projection)

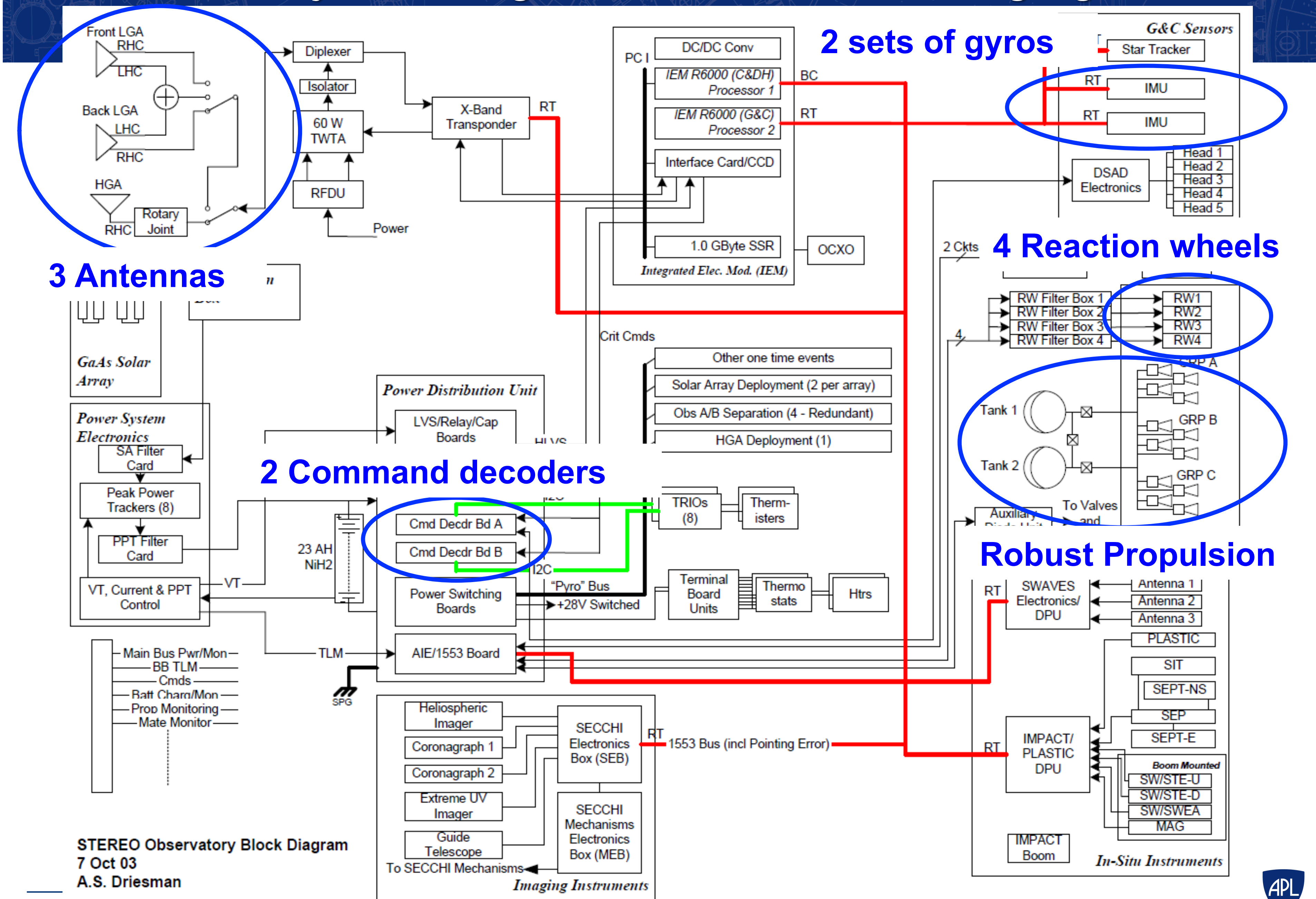
Where are STEREO-A and -B today (Oct. 6, 2015)? – 4 years past mission goal



STEREO Spacecraft Design Approach

- Requirement: survive for **2** years in heliocentric orbit
- Design goal: survive for **5** years if possible within cost
- Strategy: Meet the goal by employing "selective" redundancy
  - Save money by using redundancy only for critical, high risk components
  - Having two spacecraft provides some redundancy

Observatory Block Diagram – with redundancies highlighted

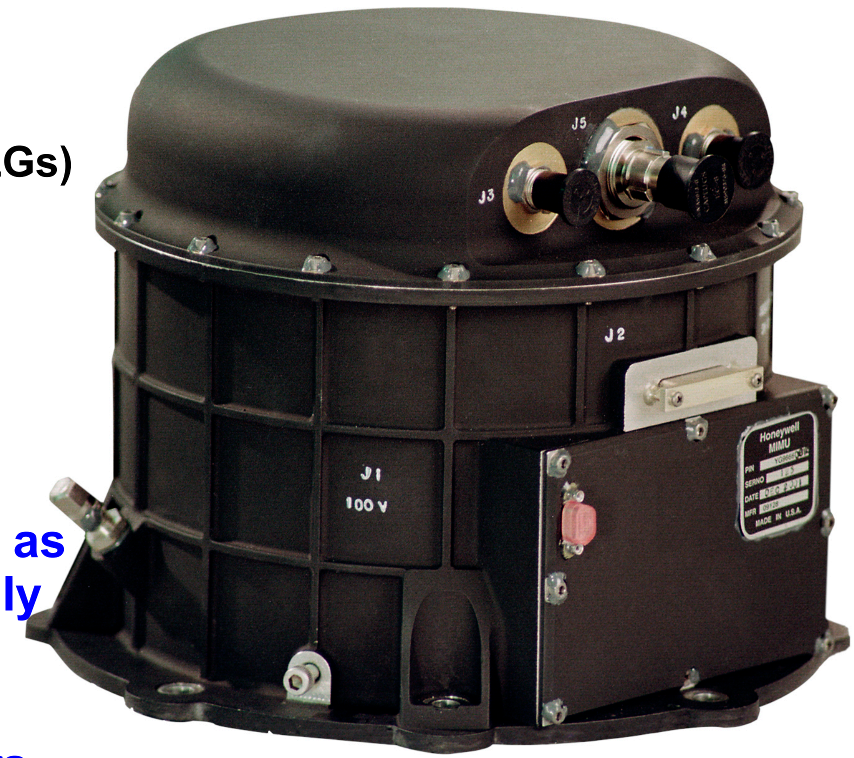


STEREO Observatory Block Diagram
7 Oct 03
A.S. Driesman

Inertial Measurement Units (IMUs)

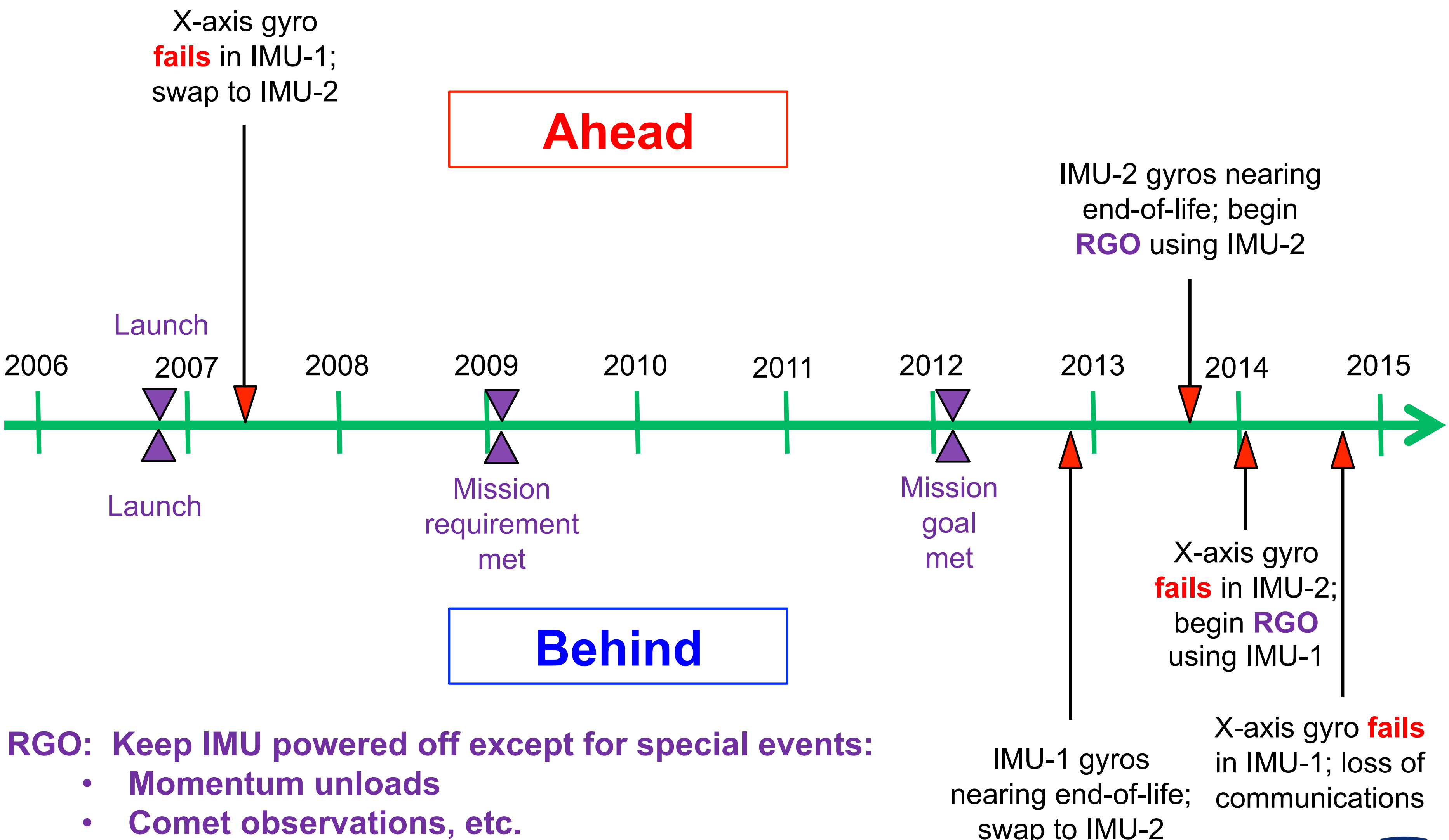
- Each STEREO spacecraft carries a pair of Honeywell MIMUs (Miniature Inertial Measurement Units)
- Each MIMU contains:
  - 3 orthogonal ring laser gyroscopes (RLGs)
  - 3 orthogonal accelerometers

- One MIMU designated as primary, the other as a cold-spare
- RLGs have a known life-limiting mechanism. Laser intensity decreases as operating hours increase, and eventually the gyro fails.
- Honeywell has made dramatic improvements in RLG life over the years. The STEREO units were predicted to last about <u>5</u> years <u>each</u> – more than enough to ensure that the 5-year goal was met.



~4.7 Kg, 23 Watts

STEREO's Actual IMU History Forces a Change to a New ConOps: "Reduced Gyro Operations" (RGO)



RGO: Keep IMU powered off except for special events:

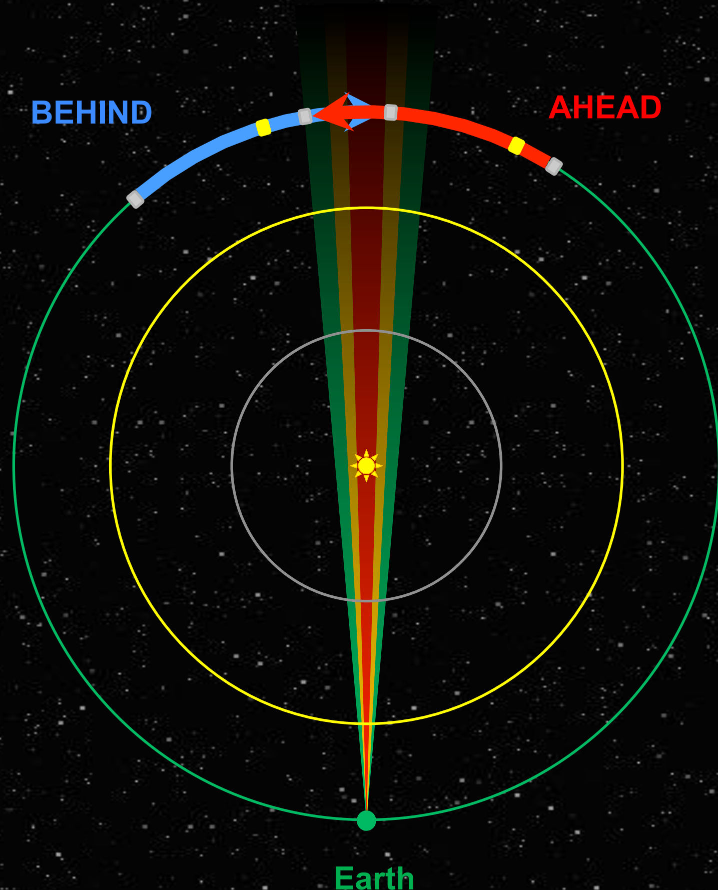
- **Momentum unloads**
- **Comet observations, etc.**

Superior Solar Conjunction

Spacecraft pass each other in 2015

- AHEAD: 24-Mar-15 → 7-July-15
- BEHIND: 22-Jan-15 → 23-Mar-15

- Mission designed for routine daily ground-contacts
- 72.3-hour Hardware Command Loss Timer
  – unavoidable spacecraft resets
- Avionics aging: down to one IMU each; each w/ limited remaining life
- Earth is at the skirt of the LGA patterns, where there is very little antenna gain



From Earth they both seem to cross in back of the Sun

Solar Conjunction Challenge

- Spacecraft pass behind the Sun, as viewed from Earth
- Communications impossible for months
- Command-Loss Timer reboots spacecraft every 3 days

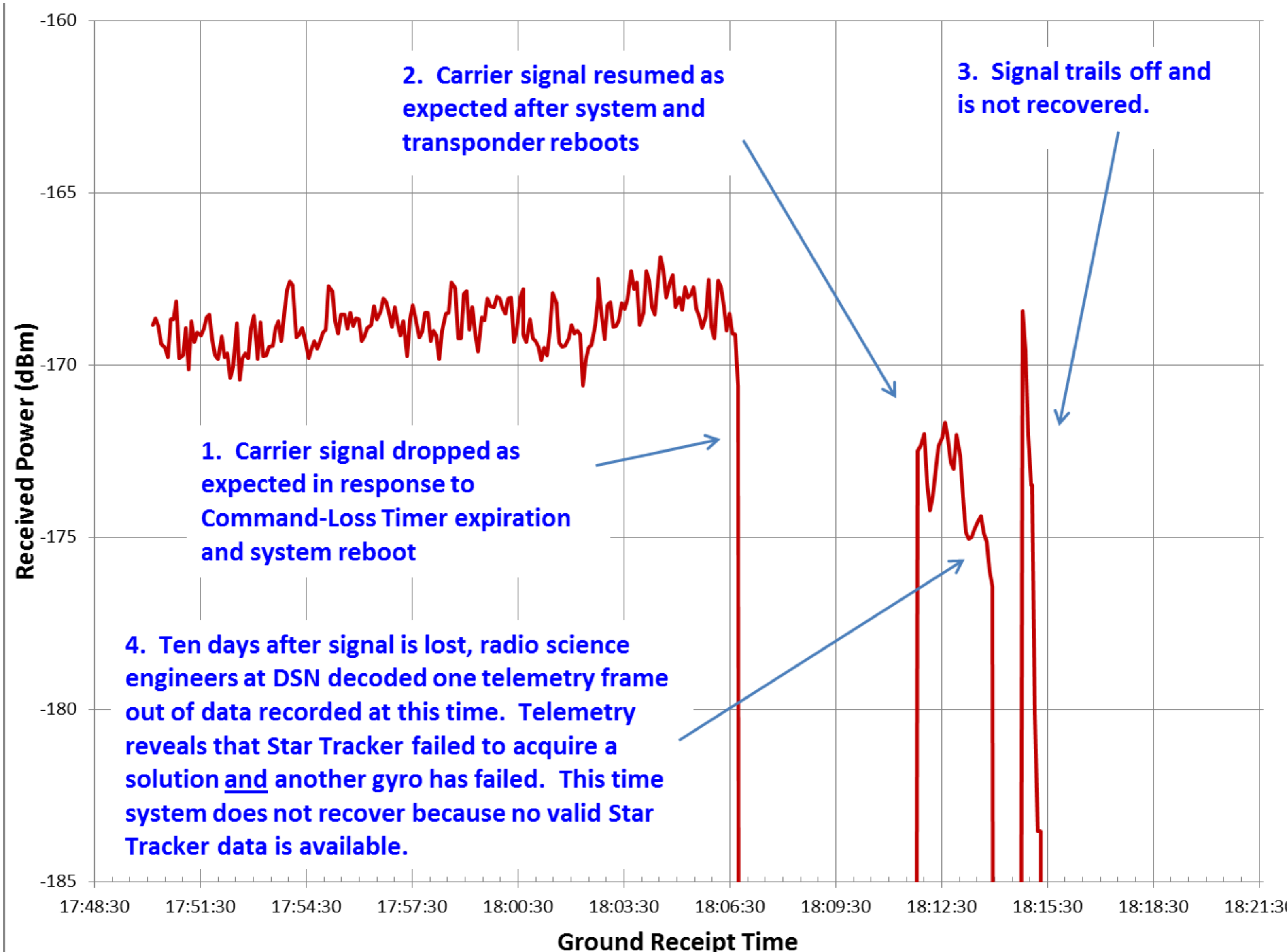
STEREO was not designed for this!!!

- Numerous configuration changes needed prior to conjunction
- We felt compelled to test the changes prior to conjunction
- Tested STEREO-A successfully in July 2014
- Tested STEREO-B in late September 2014
  - At the end of the test (October 1, 2014), we lost communications
  - Multiple attempts to re-establish communications have been unsuccessful
  - Still trying

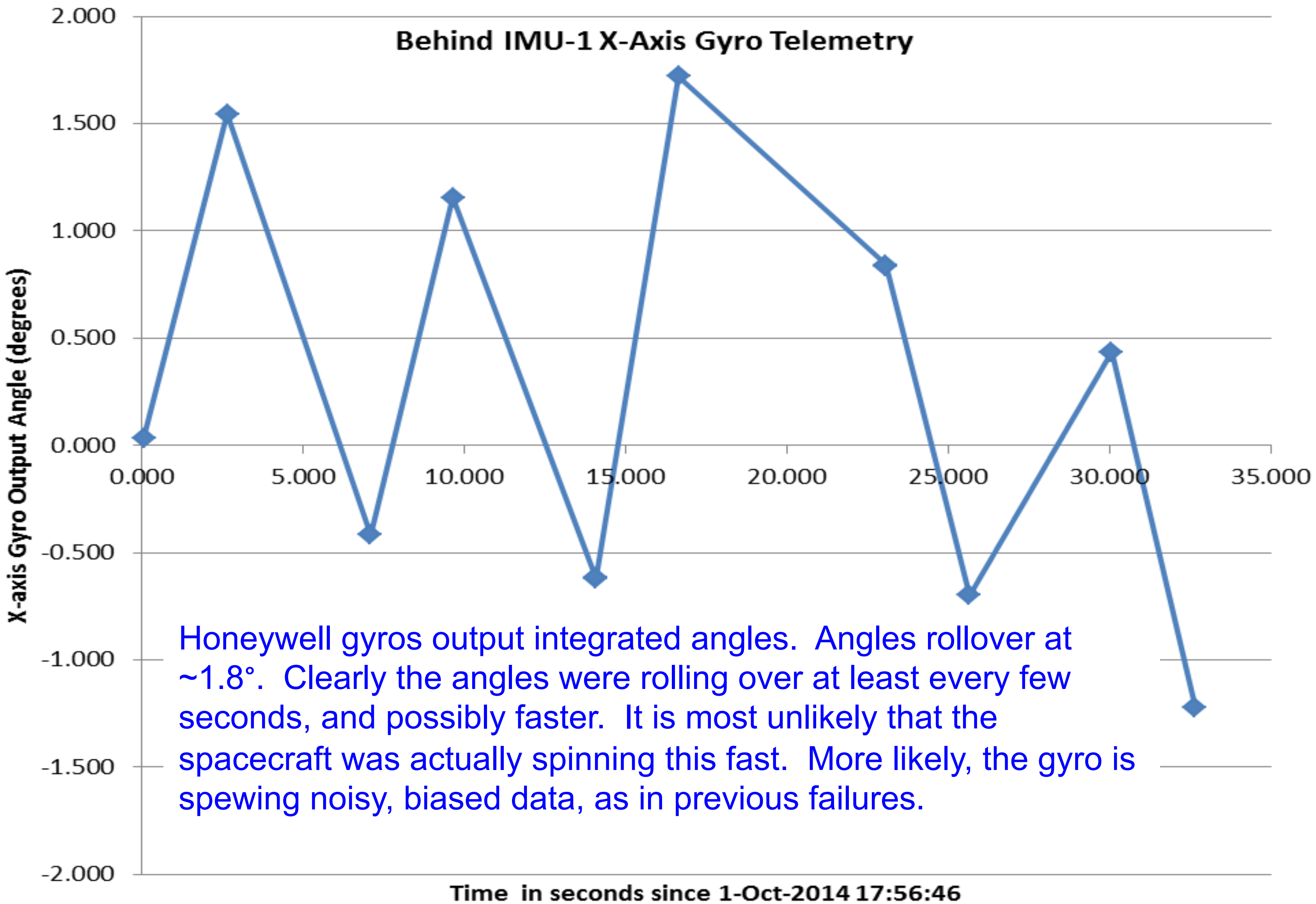
STEREO AHEAD Status

- Safely exited a 3-month long superior solar conjunction in July
- Conducting limited daily real-time science data return during HGA 1st side lobe operations through mid-November
  - HGA off-pointed for 15 months to protect feed assembly from overheating
    - 1st and 2nd side lobes provided very stable RF performance
  - Recording in-situ space weather data at 1 packet/minute for 15 month duration
  - Real-time space weather available only through DSN/ESA stations
    - Average daily availability = 38%
- Return to nominal daily science return in mid-November
  - NOAA Antenna Partners can close the RF link on space weather broadcast on November 10th
  - HGA rides along 1 degree offpoint through December
  - Allows substantial data rate improvement
    - Downlink = from 10 kbps to 360 kbps (720 kbps by January)
    - Uplink = from 500 bps to 2000 bps

Loss of Communications with STEREO-B

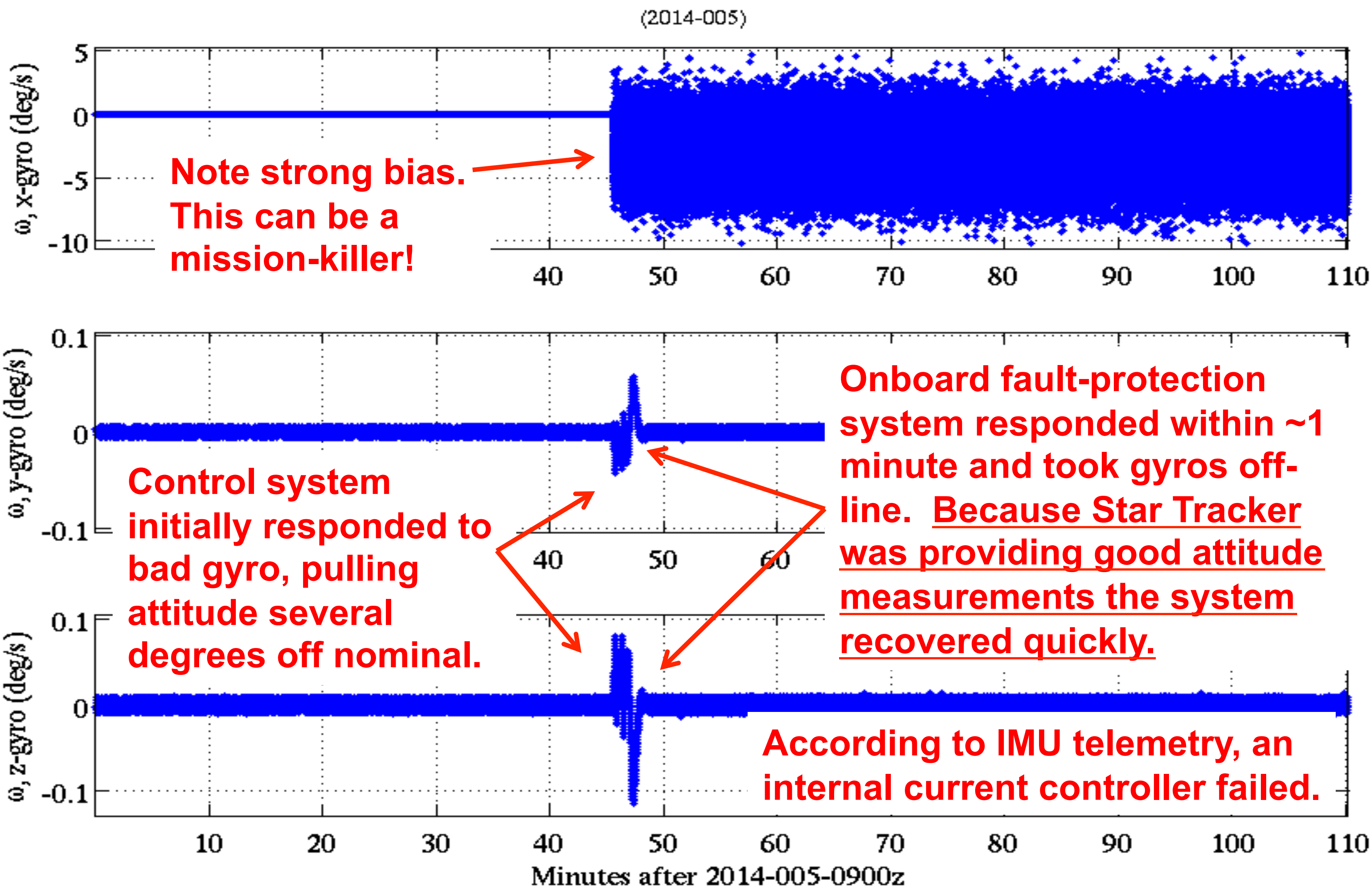


12 Telemetry Samples from X-axis Gyro After Last Reboot Show Multiple Path Length Correction (PLC) Resets and Wild Angles



Honeywell gyros output integrated angles. Angles rollover at ~1.8°. Clearly the angles were rolling over at least every few seconds, and possibly faster. It is most unlikely that the spacecraft was actually spinning this fast. More likely, the gyro is spewing noisy, biased data, as in previous failures.

High Rate Data During Previous Failure of X-axis Gyro on Behind's IMU-2 (January 5, 2014)



October 1, 2014: Most Likely Sequence of Events (based on simulation and NASA's Failure Review Board)

1. System resets, as planned, due to command-loss timeout.
2. Star Tracker is power-cycled by the stored reset command sequence. Tracker was unable to acquire a solution, causing onboard autonomous fault protection to power up the IMU.
3. IMU fails within a few seconds of power-up, and starts spewing noisy, biased data. Only other sensors available are coarse sun sensors, which do not provide rate measurements.
4. Attitude software tries to null the reported angular rate by spinning up the wheels, but the perceived rate persists no matter how fast the wheels spins.
5. Eventually, one or more wheels spins up to the saturation point, and the onboard software starts firing thrusters to shed momentum and bring the wheel speeds down.
6. During the attempted momentum dump, the software still sees the biased rate to be nulled, and so fires the thrusters to null it, thus adding momentum to the system. The momentum dump times out after 7 minutes, leaving the spacecraft in a high rate of spin.
7. The spacecraft axis of maximum moment-of-inertia is ~the solar panel axis. So the long-term, minimum-energy rotation with no attitude control will be about the S/C Y-axis. This points the solar panels edge-on to the Sun, thus draining the battery within a few hours.
8. Spacecraft freezes – propellant first, and eventually the batteries.

Gyro failing at a time when no Star Tracker solution was available led to loss of communications.

This was a double failure, or even a triple failure, if you count the previous (January) IMU failure.

Lessons Learned from STEREO

Positive lessons

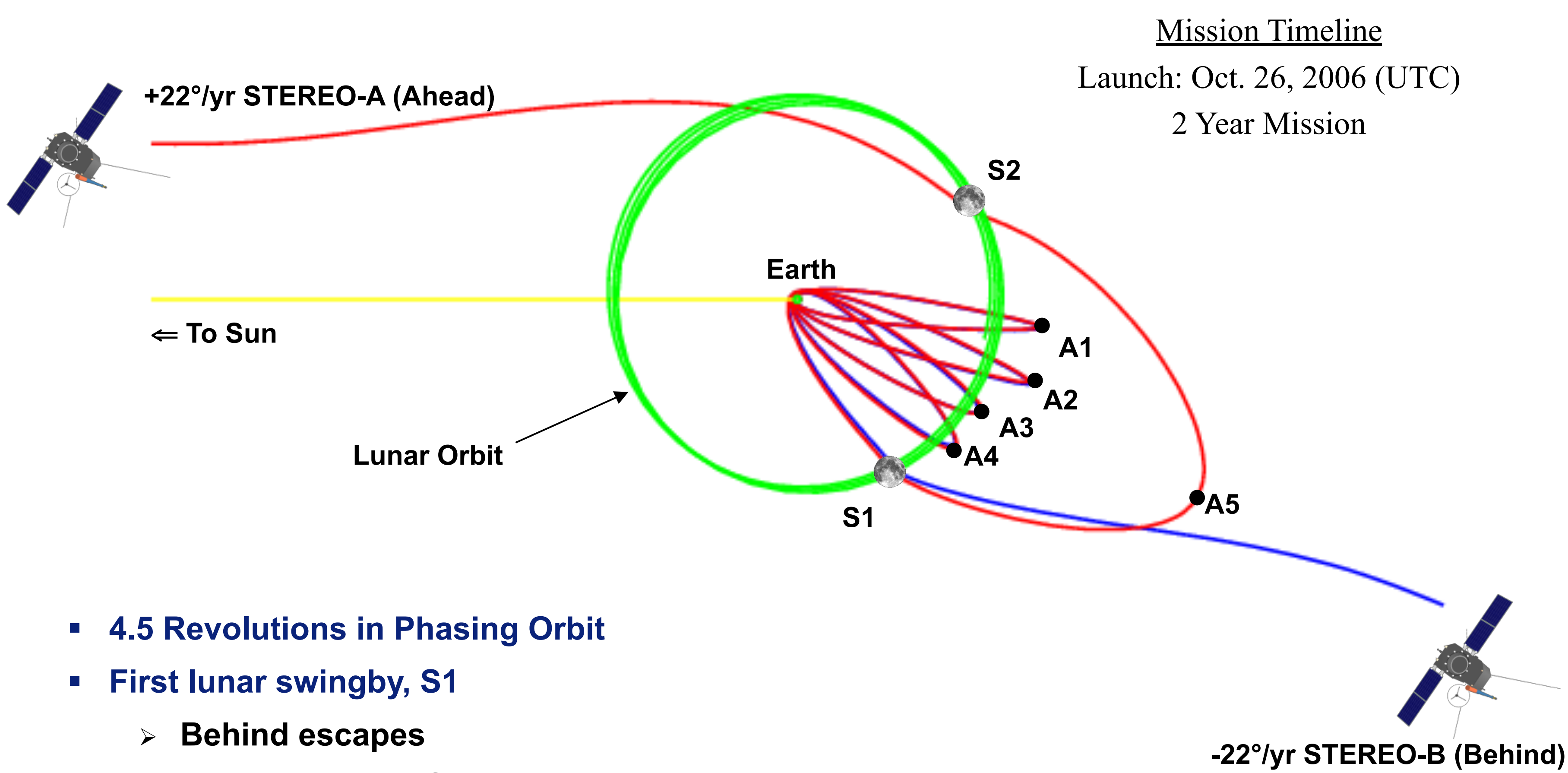
1. Redundancy was allocated correctly during the design phase
   - Two sets of RLGs were sufficient to meet the 5-year mission goal
2. Detailed reporting in telemetry of errors aids diagnosis
   - Error reports include first 6 words of IMU message
3. A software design that can compute rates from all available sensors aids longevity
   - Gyros, Star Trackers, sun sensors, etc.

Negative lessons

1. Employ value-based requirements to ensure safety and survivability of the observatories for significant orbital milestones such as solar conjunction.
2. Provide a way to disable or modify the Command-Loss Timer and its response. System resets and component power-cycles unduly stress the system.
3. Design should respond immediately if any Built-In-Test (BIT) flag is set in the IMU data. Response should be to ignore the data to prevent biased data from driving the attitude control unstable.
4. Don't align the IMU axes with the spacecraft axes or other sensors' boresights.
5. Decline in laser intensity may be tracked by monitoring telemetry, permitting prediction of remaining life. But other sources of failure are possible and are not predictable.
6. Counting on RLGs for very long missions is risky; include option to operate on an intermittent basis.
7. Operate Star Tracker as cold as possible to accelerate reacquisitions.

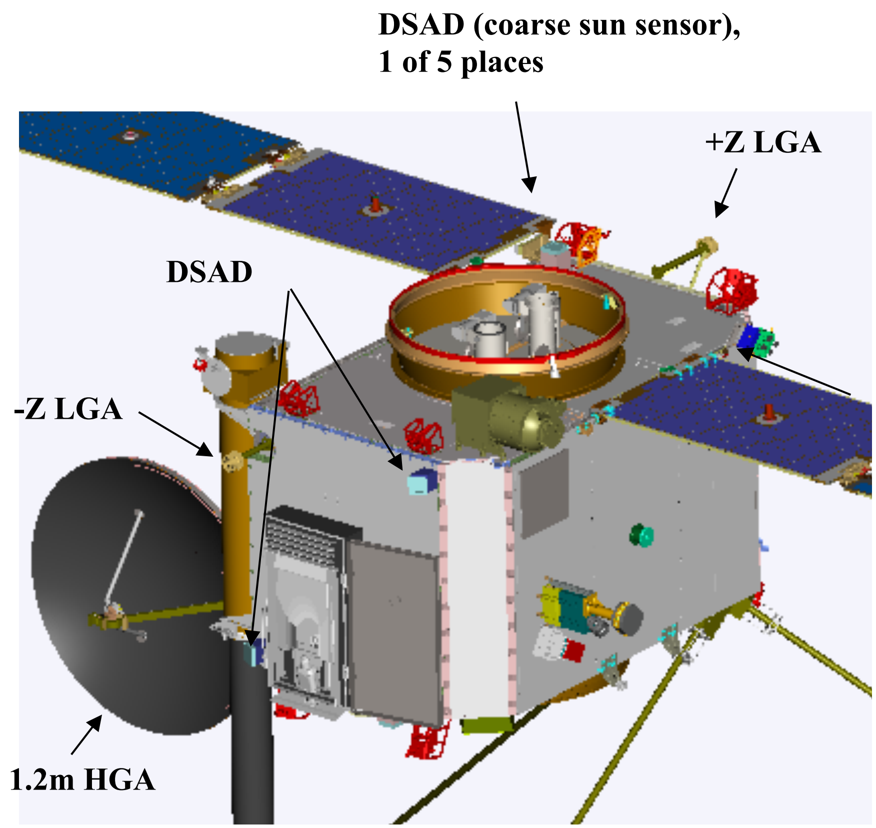
Backup Material

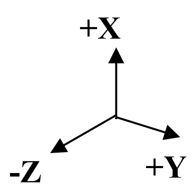
One rocket + Small Separation + Moon = Two Orbits

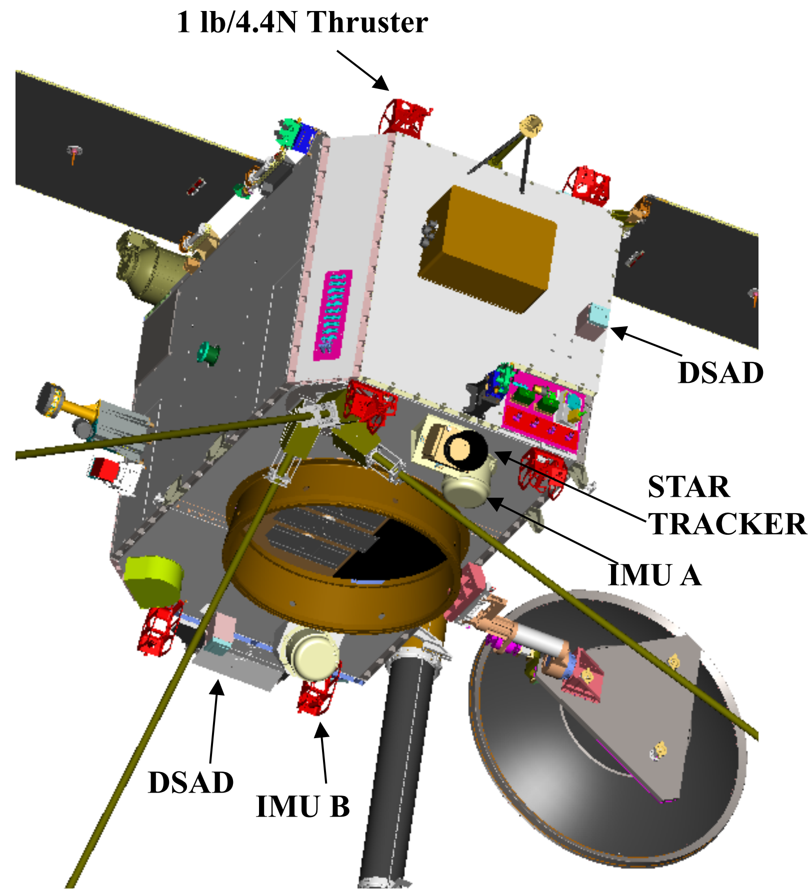


- 4.5 Revolutions in Phasing Orbit
- First lunar swingby, S1
  - Behind escapes
  - Ahead spacecraft enters 1 month 'outer loop'
- Second lunar swingby, S2
  - Ahead escapes

Antenna and Sensor Locations



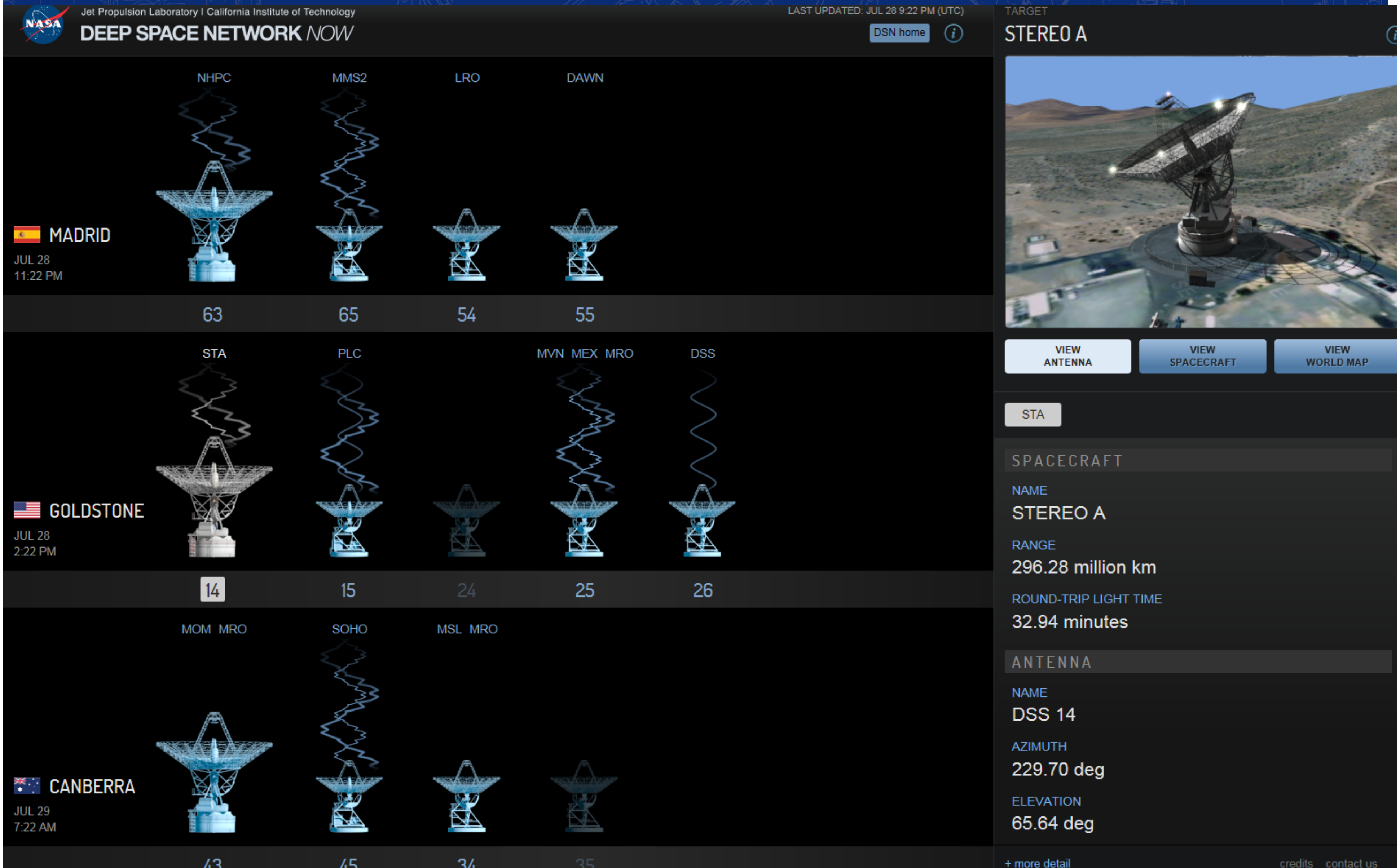




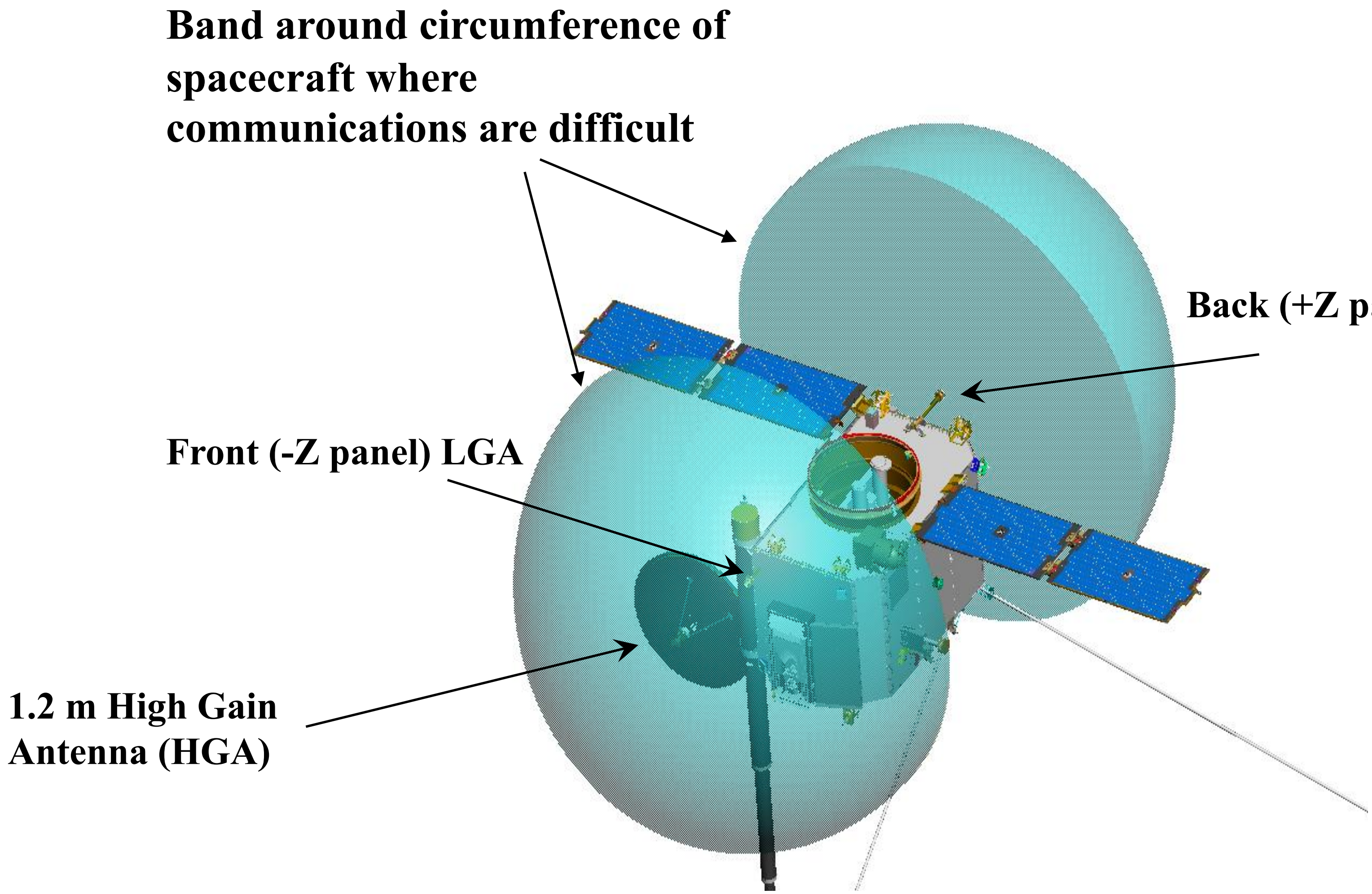
X-Z plane contains Sun and Earth ⇒ HGA rotates about Y-axis ±90°

BEHIND OBSERVATORY SHOWN

Communications: Daily Contacts (3-8 hours, typical)

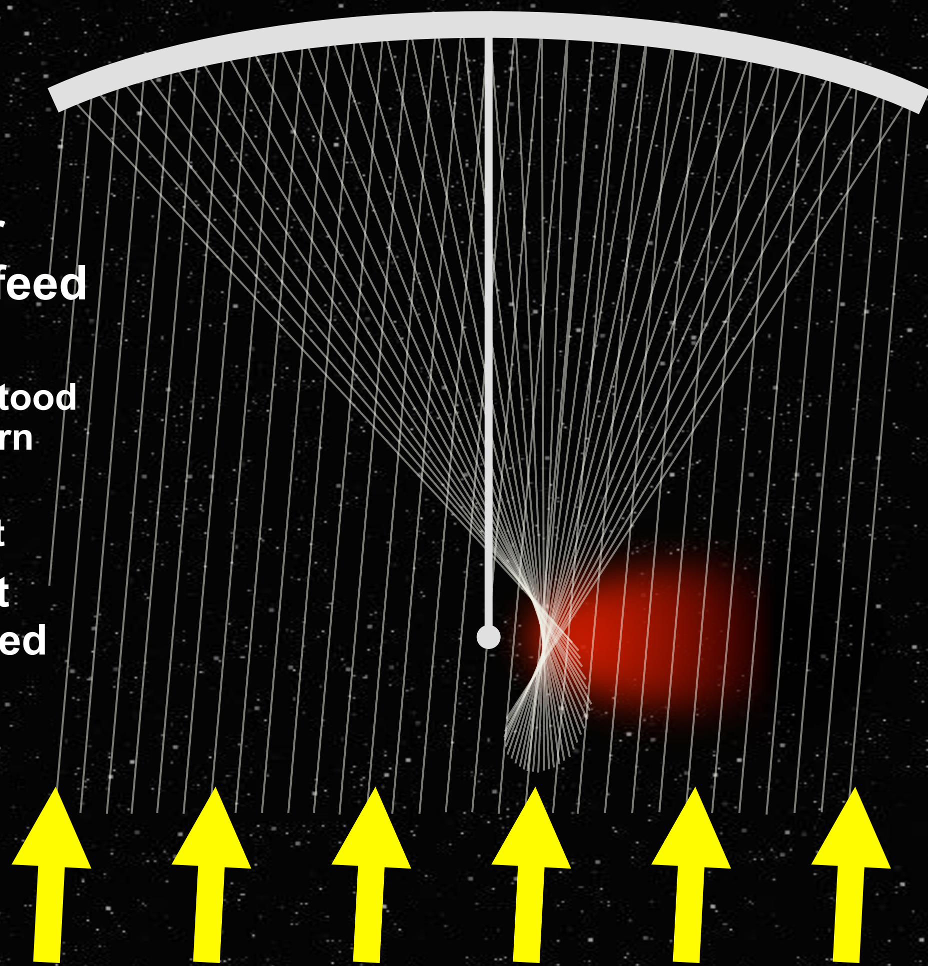


Fields of View for +Z and -Z Low Gain Antennas (LGAs)



HGA/one LGA/both LGAs may be coupled to 60 W transponder via RF switches

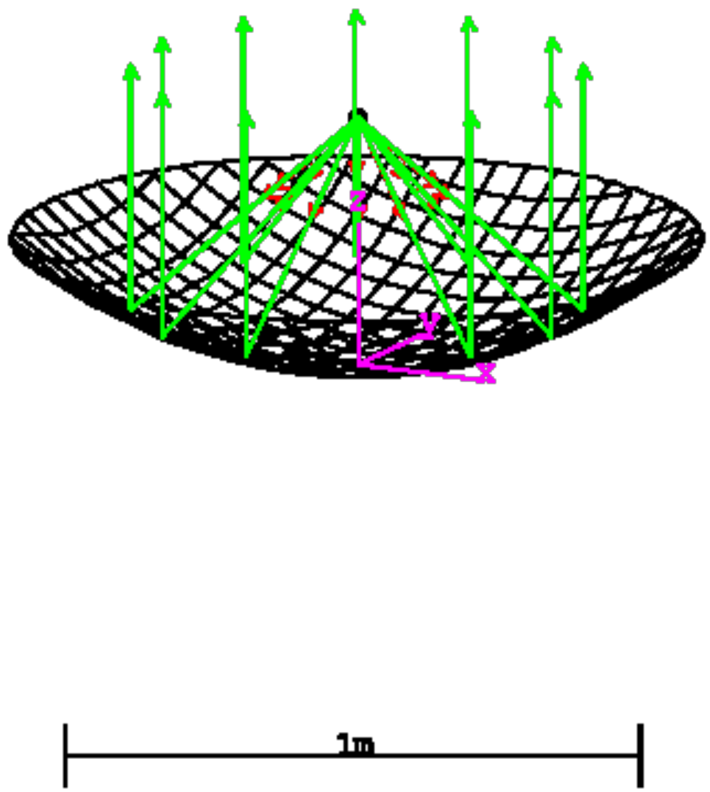
- Parabolic dish concentrating solar energy at the HGA feed point
  - Originally understood not to be a concern
  - Has become the driving constraint
- No thermal model that can reliably predict feed temperature

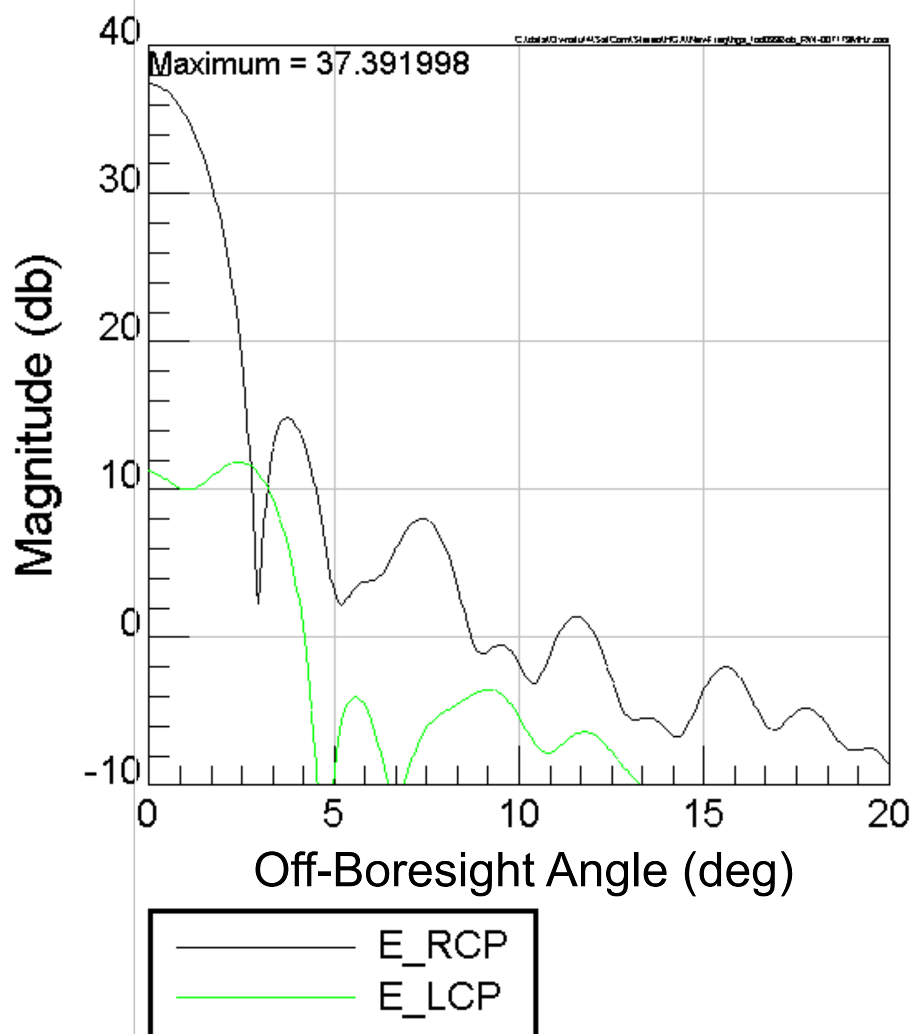


High Gain Antenna (HGA) Directivity

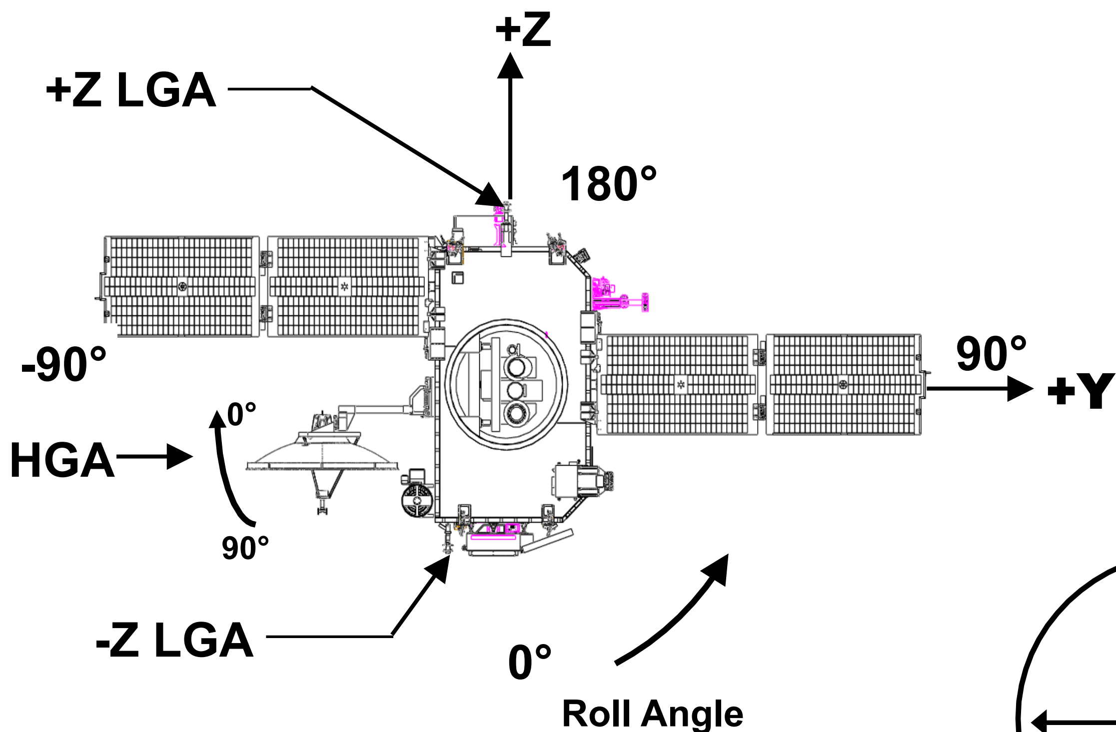
Calculation Parameters:

Prime Focus Reflector
F/D: 0.33
Diameter: 1.2 meters
Feed: 1.07" Choke Ring Horn
Blockage for Feed Horn Structure



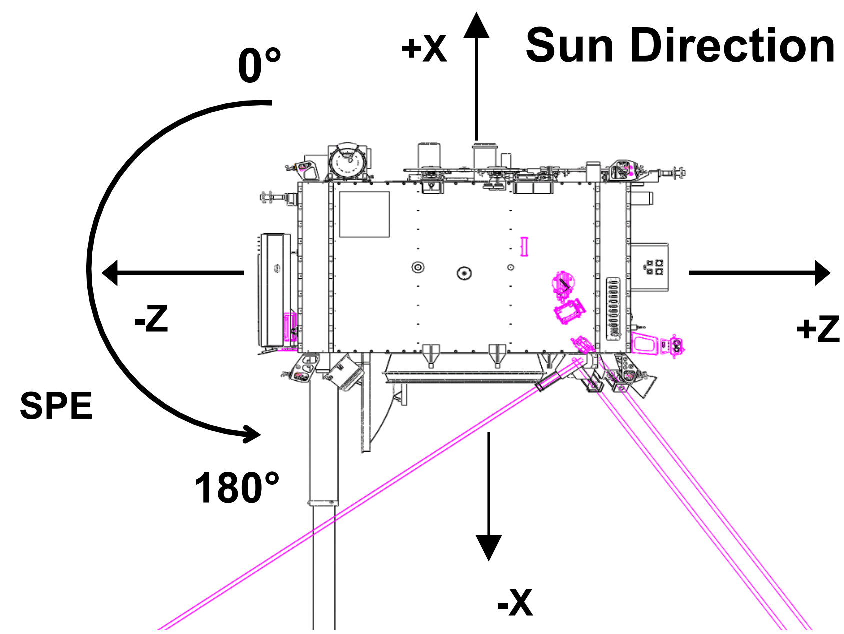


RF Telecommunications Subsystem
High and Low Gain Antenna Orientations



Definition of Roll Angle

Definition of
Sun-Probe-Earth (SPE) Angle



Note: for normal operation, Earth is in X-Z plane (on the -Z side), and the Sun is on the +X axis

Anomaly Reporting

When STEREO Flight Software detects an interesting event or anomaly, it creates a 20-byte telemetry report consisting of:

- **2-byte unique numeric event/anomaly code**
- **5-byte time of occurrence**
- **2-bit type code:**
  - **0 = event**
  - **1 = start of a persistent anomaly**
  - **2 = end of a persistent anomaly**
  - **3 = single occurrence of an anomaly**
- **12-bytes of data specific to this event/anomaly code**