End of Prime Mission Review STEREO Spacecraft

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End of Prime Mission Review

Spacecraft Agenda

- **Mission Milestone Overview**
- **Current Spacecraft Status**
- **Spacecraft Risks**
- **Spacecraft Engineering/Requirements Review**
- **Lessons Learned**
- **Summary**

Mission Milestone Overview

Start of Phase E Operations	Jan. 22nd 2007
Program Handover to SSMO	Jan. 23rd 2007
Lunar Transit on "B" Obs.	Feb. 25th 2007
1st SECCHI Campaign	May 1-14, 2007
Min Science Req for 2 Obs.	July 20th, 2007
Leonid Shower (S/C A)	Oct 28th, 2007
2nd SECCHI Campaign	Jan 7-20, 2008
480 Kbps data rate on S/C A/B	Fall 2008
End of Prime Mission (Spacecraft)	January 21, 2009
360 Kbps data rate on S/C A/B	Summer 2009
Extended Mission	Feb 2009 – Sept 2010

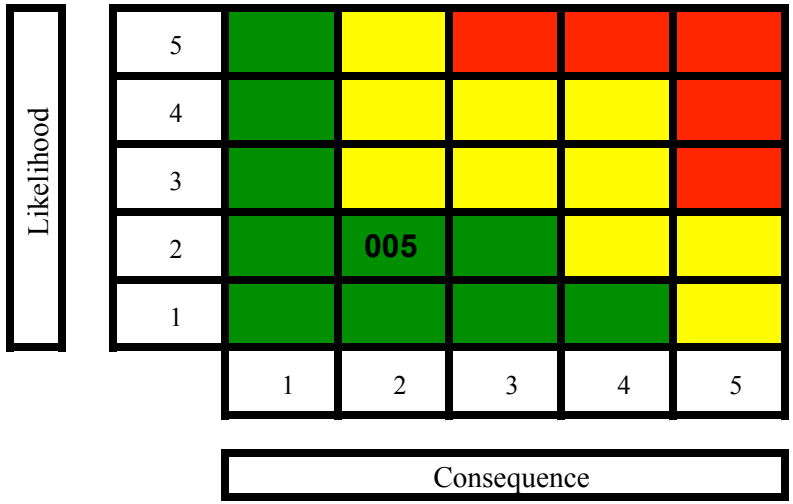
STEREO Status

- **Operations**
  - Began automated unattended tracks April 30,2007
  - Operations team reduced from 8 to 6 on September 1, 2008
  - Mission operations center collecting, on average, 7 Gbits per day in support of the prime science mission.
  - Observatories approximately 120 degrees apart.
- **Special Observatory Events**
  - 60+ instrument calibration events
  - 18 High Gain Antenna Calibrations
  - 44 Momentum Dumps (~every 6 weeks)
  - 2 SECCHI Campaigns
  - Observation of L4 and L5

IMU1 X-Gyro Failure

STR-PL-005

- Risk: If remaining IMU fails on S/C A then there is a potential for loss of navigation accuracy and loss of prime science data
- Status: Closed
- Risk Level : Green
- Likelihood: Low
- Consequence: Minimal



Mitigation：

- Spacecraft performance has been verified (on-orbit) using solely ST rates.
- Performance requirements (operating with the GT) as stated in the MRD were met, though performance was not nearly as good as with the IMU.
- G&C 3.2.6 loaded to the spacecraft this summer, allows for the rate information from either IMU to be melded with the information from the GT and/or the ST. The spacecraft can replace the loss of one more gyros with rate information from either the GT and/or the ST.

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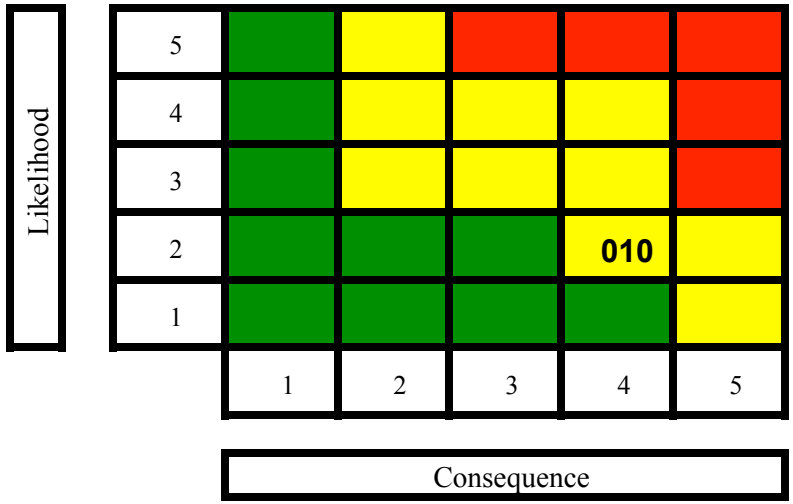
Star Tracker Anomaly

STR-PL-010

- Risk:
  - *If Star Tracker fails then there is potential for loss of HGA pointing knowledge resulting in a loss of science data.*
- Status:
  - *Closed out regular discussions with Galileo.*
  - *Investigation inconclusive:*
    - No conclusion possible on cause of reset
    - Least unlikely cause of failure to acquire attitude is passing through a dense, small-particle debris field (Low confidence conclusion)
- Risk Level : Yellow
- Likelihood: 2 (Low)
- Consequence: 4 (Major – Potential loss of level 1 science data)



Mitigation strategies:

- *Improved gyro bias drift estimation to extend time to loss of HGA lock - Done*
- *Developing algorithm to determine roll angle w/o ST*
- *Developed operational macro to perform Earth search with HGA - Done*
- *Developing algorithm to "cue" ST and bypass coarse acquisition – On SCA and evaluating performance*

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End of Prime Mission Review: Spacecraft Engineering

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Review Intent

- **Review Goal:**
  - **"perform a systematic review of performance *vs.* specifications at the spacecraft and Mission Operations Center subsystem level for the technical engineering assessment"**
  - **"These subsystem and product assessments should be summarized and related to Level 1 requirements, to provide a quantitative assessment of how well the Level 1 requirements have been met."**
- **A systematic assessment is provided in the backup slides.**
- **Key requirements and STEREO's compliance are in the main body**

STEREO Requirements Structure

- STEREO Level 1 Requirements from NASA/GSFC levied on JHU/ APL are captured in:
  - 460-RQMT-0001 Revision D, Solar Terrestrial Probes (STP) Program Code 460 STEREO Mission Requirements Document.
  - Dated February 2003
- Document levies requirements against all phases of the program.

- This presentation addresses:
  - All requirements, regardless of phase.
  - Only sections that include spacecraft requirements.

- JHU/APL has no requirement for formal verification post launch.

Compliance Overview

Section Number	Name	Compliance
4.1.1	Nominal Mission	Fully Compliant
4.1.2	Extended Mission	Fully Compliant
4.2.2	Orbital Drift Rate	Fully Compliant
4.3	Orbital Debris	Fully Compliant
4.4	Data Recovery	Fully Compliant
4.5.2.2	Launch Window	Fully Compliant
4.5.3	Launch Facility	Fully Compliant
4.6.1.1	Nominal Mission	Fully Compliant
4.6.2	Attitude Control	Fully Compliant
4.6.2.1.2	Spacecraft ACS Pointing	Fully Compliant

Compliance Overview (cont.)

Section Number	Name	Compliance
4.6.2.1.3	Fine Pointing	Fully Compliant
4.6.2.1.5	Roll Attitude	Fully Compliant
4.6.2.1.6	Pointing Requirements	Fully Compliant
4.6.2.4	Pointing Constraints	Fully Compliant
4.6.2.5.1	Rolling about Observatory-Sun Line	Fully Compliant
4.6.2.5.2	SECCHI Calibrations	Fully Compliant
4.6.2.6	Spacecraft Attitude Knowledge	Fully Compliant
4.6.3	Fields of View	Fully Compliant
4.6.5.1	Simultaneous Forward and Return Links	Fully Compliant
4.6.5.2	Command Distribution	Fully Compliant

Compliance Overview (cont.)

Section Number	Name	Compliance
4.6.5.3	On-Board Storage	Fully Compliant
4.6.5.5.1	Real Time and Stored Commands	Fully Compliant
4.6.5.5.2	CCSDS Format	Fully Compliant
4.6.5.5.3	Stored Command Buffer	Fully Compliant
4.6.5.6	Time Distribution	Fully Compliant
4.6.5.7.1	Overall Data Rates and Volumes	Fully Compliant
4.6.5.7.2	Instrument Telemetry Format	Fully Compliant
4.6.5.7.3	Multiple Instrument Data Rates	Fully Compliant
4.6.5.7.4	Real-time, Space Weather and Recorded Packets Processing	Fully Compliant
4.6.5.8	Space Message Status	Fully Compliant

Compliance Overview (cont.)

Section Number	Name	Compliance
4.6.6	Power	Fully Compliant
4.6.7	Autonomous Operations	Fully Compliant
4.6.8	Removal of Instrument Power	Fully Compliant
4.6.9.1.1	Total Dose	Fully Compliant
4.6.9.1.2	Single Event Upsets	Fully Compliant
4.6.9.3	Electrostatic Cleanliness	Fully Compliant
4.6.9.4	Electromagnetic Interference	Fully Compliant
4.6.9.5	Contamination Control	Fully Compliant
4.6.10.1	Thermistors Provided	Fully Compliant
4.6.10.2	Thermistor Monitoring	Fully Compliant

Compliance Overview (cont.)

Section Number	Name	Compliance
5.1	Integration and Test	Fully Compliant
5.2	Spacecraft Emulators	Fully Compliant
5.3.1	Verification	Fully Compliant
5.3.2	Mission Assurance	Fully Compliant
5.4	Instrument IGSE Failure Safe	Fully Compliant
6.1.1	Flight Operations	Fully Compliant
6.1.2	Level Zero Files	Fully Compliant
6.1.3	Software Maintenance	Fully Compliant
6.3.1	Navigation accuracy	Fully Compliant
6.3.2	Coordinate Frames	Fully Compliant

Compliance Overview (cont.)

Section Number	Name	Compliance
6.3.3	Navigation Accuracy During Fly-bys	Fully Compliant
6.4.1	MOC Uploads	Fully Compliant
6.4.2	Command Volume	Fully Compliant
6.4.3	Instrument Commands	Fully Compliant
6.4.6.3	Command Validation Reports	Fully Compliant
6.4.7	Real Time Commanding	Fully Compliant
6.5.1	Level Zero Files	Fully Compliant
6.5.3	Real Time Telemetry	Fully Compliant
6.7.1	Space Weather Beacon Capability	Fully Compliant

Section 4.1 Mission Duration Requirements

- 4.1.1 Nominal Mission
- Requirement:
  - The mission requires an uninterrupted view of the Sun for an extended period of time to observe significant solar phenomena (CMEs in particular). The Science Definition Team concluded that 2 years of observation is the minimum required observing time to collect a meaningful sample of the CMEs and related in-situ measurements. The period of two years of observation begins after both observatories have reached heliocentric orbit.
- Compliance: FULLY COMPLIANT
  - Second spacecraft entered heliocentric orbit on 21 Jan 2007. Two year requirement was met on 21 Jan 2009.

Section 4.1 Mission Duration Requirements

- 4.1.2 Extended Mission
- Requirement:
  - The observatories shall be designed with sufficient fuel for a 5 year mission.
- Compliance: FULLY COMPLIANT
  - As of the last momentum dumps:
    - Spacecraft A: 42.89 +/- 0.43 kg of usable propellant remaining.
      - Equates to ~220 years of momentum dumps.
    - Spacecraft B: 43.29 +/- 0.42 kg of usable propellant remaining
      - Equates to ~290 years of momentum dumps.

Section 4.2 Orbit Definition Requirements

- 4.2.2 Drift Rate
- Requirement
  - The orbit shall be designed such that both observatories slowly drift away from the Earth. One observatory shall drift ahead of Earth at the rate of 22 ± 2 degrees/year while the other shall drift behind Earth by 22 ± 2 degrees/year.
- Compliance: FULLY COMPLIANT
  - Spacecraft A drift rate is: 21.58 degrees per year
  - Spacecraft B drift rate is: -21.95 degrees per year
  - Due to thruster location, the Delta-v imparted by momentum dumps is negligible.

Section 4.4 Data Recovery Requirements

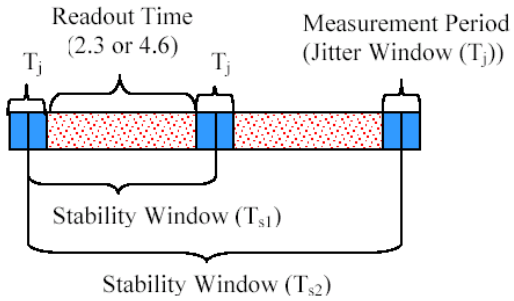
- **4.4 End to End Data Recovery**
- **Requirement:**
  - **The spacecraft and ground system shall be designed to deliver an average of at least 5 Gbits of science data per 24-hour day per spacecraft to the instrument POCs. This requirement starts for each spacecraft after it has achieved heliocentric orbit. The averaging period shall be twelve months. In order to meet this requirement the spacecraft will downlink a larger volume of data per day (the actual size of this distribution to be agreed with the instrument PIs), and accept data loss on a pass or daily basis, provided that the average science data capture is at least 5Gbit.**
  - **Compliance: FULLY COMPLIANT**
    - **Spacecraft A returned an average of 7.32 Gbits per day for Year 1**
    - **Spacecraft A returned an average of 7.72 Gbits per day for Year 2**
    - **Spacecraft B returned an average of 7.32 Gbits per day for Year 1**
    - **Spacecraft B returned an average of 7.45 Gbits per day for Year 2**
  - **Total Return over two year prime mission.**
    - **Spacecraft A: ~5.28 Tbits**
    - **Spacecraft B: ~5.34 Tbits**

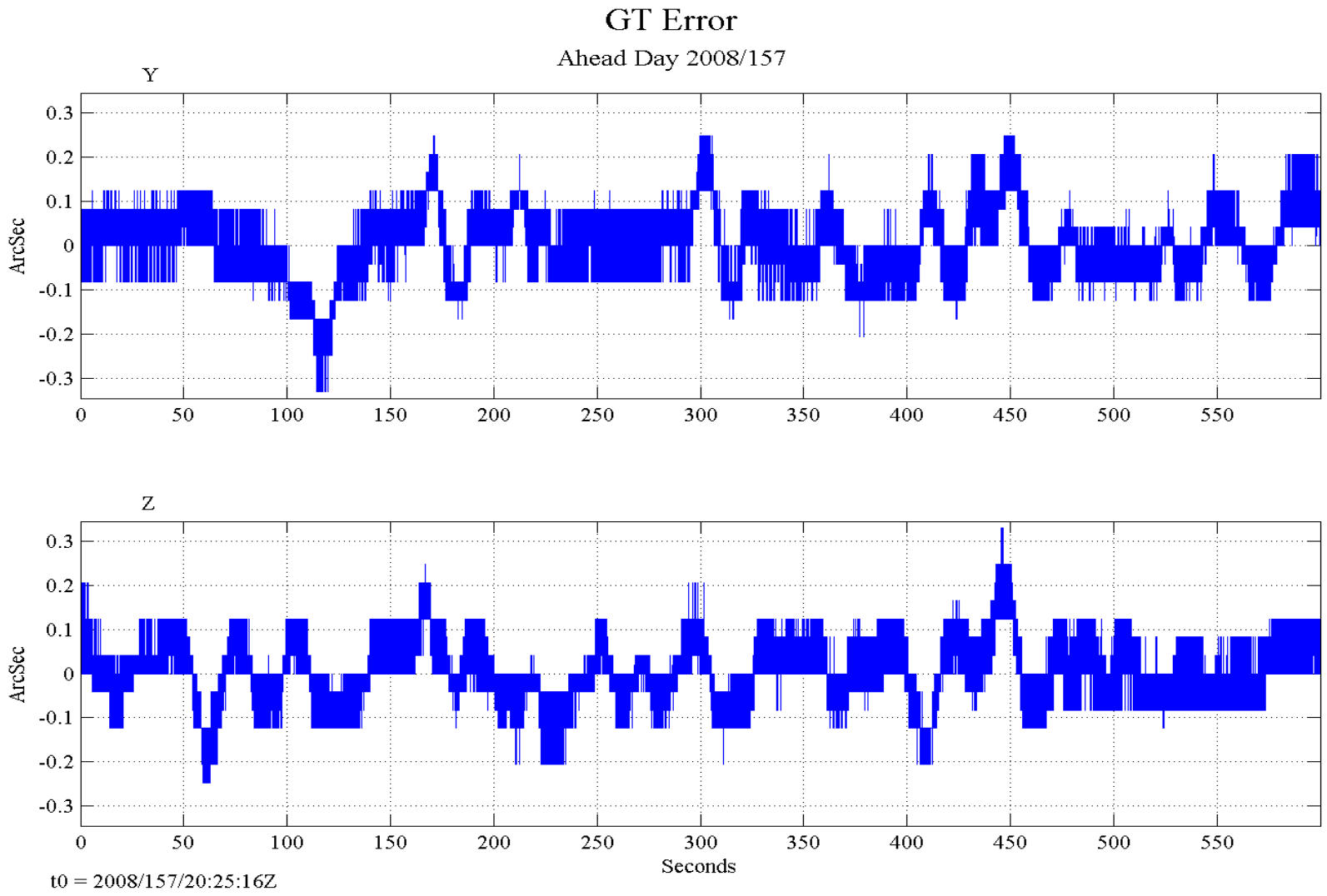
Section 4.6 Observatory Requirements

- 4.6.1.1 Nominal Mission
- Requirement:
  - Each spacecraft and the ground segment shall be designed to support a minimum daily data volume of 5 Gigabits per observatory. During designated periods early in the heliocentric orbit period, up to 9.2 Gbits (TBC) of SECCHI data will be downloaded per 24-hour day.
- Compliance: FULLY COMPLIANT
  - See data capture slide showing 5 Gbit requirement being met
  - 9.2 Gbit statement was to allow for SECCHI Campaign mode.
    - APL had requirements to support two campaigns, they ran from:
      - May 3rd thru May 17th, 2007, SECCHI Data return was 8.44 Gbits, Total Return was 10.44 Gbits.
      - Jan 7th thru Jan 20th, 2008, SECCHI Data return was 8.98 Gbits, Total Return was 10.92 Gbits.

STEREO Pointing Requirements

	Pitch and Yaw Performance Each Axis (arcsec)	Roll Performance (arcmin)	Window Times (seconds)
Accuracy	$3\sigma a \leq 7.25$	$3\sigma a \leq 35$	----
Jitter	$\sigma j \leq 1.53$	$\sigma j \leq 3.4$	Tj = 15 (30 as a goal)
Windowed Stability	$\sigma sw \leq 1.90$	$\sigma sw \leq 6.70$	$0.1 \leq Tj \leq 1.0$ $T_{S1} = Tj + 2.3 \quad T_{S2} = 2T_{S1}$ $T_{S3} = Tj + 4.6 \quad T_{S4} = 2T_{S3}$
	$\sigma sw \leq 3.75$	$\sigma sw \leq 6.70$	$1.0 \leq Tj \leq 8.0$ $T_{S1} = Tj + 2.3 \quad T_{S2} = 2T_{S1}$ $T_{S3} = Tj + 4.6 \quad T_{S4} = 2T_{S3}$



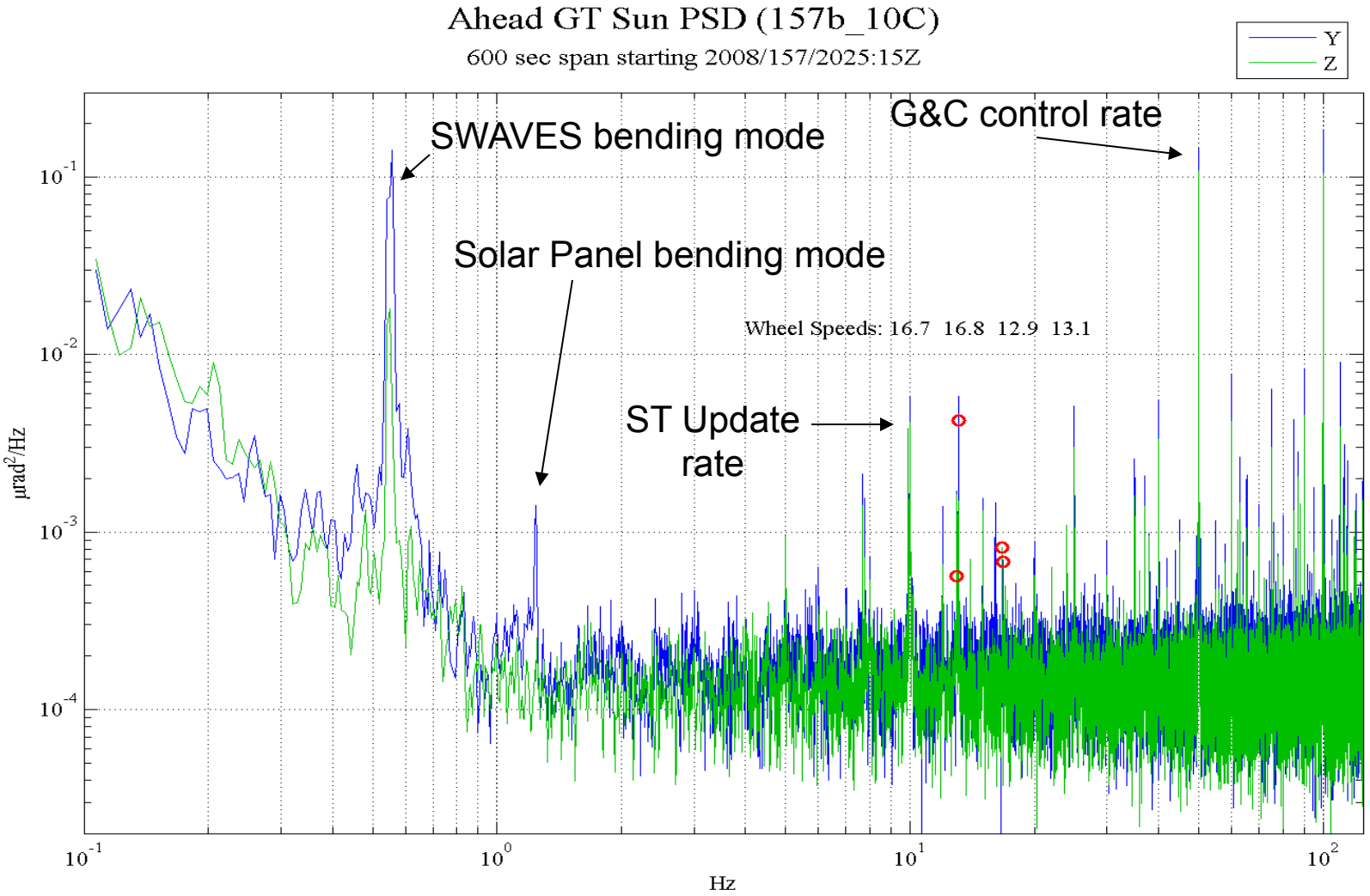


“Nominal” Performance example.

Directly measured from 250 Hz GT data.

Behind data during good periods is similar.

Frequency domain follows…



"Nominal" Performance example.

Wheels not dominant disturbance.

Metrics (arcseconds, 1 σ):

	Accuracy	Stability-2	Jitter	Stability-1
Y	0.077	0.055	0.097	0.113
Z	0.070	0.051	0.090	0.104
Limits:	2.42	1.53	1.90	3.75

STEREO End of Prime Mission Review Lessons Learned

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Value Based Data Return

- **Specifying a data return percentage would have driven flow down requirements to add complexity to the flight software and ground system and increase DSN usage.**
- **Requirement – The S/C and ground system shall be designed to deliver an annual average of 5 Gbits/day per observatory.**
  - **Leap of faith for all PIs – return more data than required.**
- **Each S/C averaged over 7.3 Gbits/day for the prime science mission.**
- **STEREO is a continuous data pipeline for two deep space observatories.**
- **Only one opportunity (DSN track) each day per S/C to downlink the SSR.**
- **While data continuity is not required, more often than not the data is continuous.**
- **Ground segment teams (DSN, MOps, Schedulers) always try to maximize data return.**
- **Allows for a manageable, unattended track operations implementation with reduced MOps staff.**
- **Allows STEREO project flexibility in responding to DSN schedule changes.**

Post Launch Anomalies

- **Multiple S/C missions result in more thoroughly tested S/C at launch with fewer post launch anomalies than single S/C missions.**
  - **S/C are nearly identical**
  - **Higher level of characterization and operational knowledge of S/C at launch**
  - **Reduces mission risk**

Decoupled Instrument Operations

- Instrument teams are responsible for their own instrument commanding and instrument health assessment.
  - Requires prelaunch allocation of shared resources, i.e., power, thermal, pointing, bus bandwidth, SSR storage, etc.
  - Reduces MOC complexity
  - Minimizes MOps staff

Summary

- Observatories are operating better than expected and collecting more than 7 Gbits/day
- Autonomous operations are going very smoothly.
- Flight software and autonomy is working as expected with few patches with only one G&C flight load (none during the prime mission).
- The spacecraft are in Heliocentric orbits and about 120 degrees apart with large margins on both propellant and power.
- All instrument teams are very excited about the data being returned but are getting tired of the quiet sun.

STEREO is an unqualified success

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Back up Slides

Section 4.3 Orbital Debris Requirements

- 4.3 Serviceability, Retrieval, Disposal and Debris
- Requirement:
  - On-orbit servicing, retrieval, and disposal are not required. An orbital debris assessment shall be performed in accordance with NSS 1740.14.
- Compliance: FULLY COMPLIANT
  - Orbital assessment was performed and approved by NASA/HQ prior to launch.

Section 4.5 Launch Requirements

- 4.5.2.2 Launch Window per Month
- Requirement:
  - Flexible launch windows shall be planned as follows: at least one per day with a 14-day window around each chosen date.
- Compliance: FULLY COMPLIANT
  - Launch window ran from 26 Oct 2006 (UTC) through 8 Nov 2006.
  - Two launch windows per day, one two minutes long followed by a second one 15 minutes long.

- 4.5.3 Launch Facility
- Requirement:
  - The Cape Canaveral Air Force Station/ Kennedy Space Center launch facility shall be used.
- Compliance: FULLY COMPLIANT

Section 4.6 Observatory Requirements

- 4.6.2 Attitude Control Performance
- Requirement:
  - The observatories shall be three-axis stabilized, fixed in attitude with respect to the Sun.
- Compliance: FULLY COMPLIANT

Section 4.6 Observatory Requirements

- **4.6.2.1.2 Spacecraft ACS Pointing**
- **Requirement:**
  - **The observatory's attitude control system shall provide the capability to point the Sun Centered Imaging Package (SCIP) boresite to within 15 arc-minutes, ½ cone angle, 3σ of Sun-center.**
  - **Compliance: FULLY COMPLIANT**

Section 4.6 Observatory Requirements

- **4.6.2.1.3 Fine Pointing**
- **Requirement:**
  - **Once within this target window, the spacecraft attitude control system shall utilize the pitch and yaw error signals from the SCIP to point the GT boresite to Sun-Center within the limits defined in Table 1.**
  - **Compliance: FULLY COMPLIANT**

- **4.6.2.1.5 Roll Attitude**
- **Requirement:**
  - **The spacecraft roll requirements are defined in Table 1.**
  - **Compliance: FULLY COMPLIANT**

- **4.6.2.1.6 Pointing Requirements**
- **Requirement:**
  - **The spacecraft shall meet the pointing accuracy, jitter, and windowed stability requirements about Pitch (Z-axis rotation), Yaw (Y-axis rotation), and Roll (X-axis rotation) as indicated in Table 1. The requirement shall be met for each of the four stability times T^{s1}, T^{s2}, T^{s3}, and T^{s4} over the range of T^{j} indicated.**
  - **Compliance: FULLY COMPLIANT**

Section 4.6 Observatory Requirements

- **4.6.2.4 Pointing Constraints – Earth/Moon/Sun Avoidance**
- **Requirement:**
  - There are no Earth or Moon avoidance requirements. There are no sun exclusion constraints. Pointing at the sun for an extended period can damage the SIT & SEPT instruments. The spacecraft design shall maintain a rotation rate of >180° in 12 minutes through the SIT & SEPT field of view when the doors is open. SIT & SEPT shall not open their doors until all the maneuvers in the phasing orbits are complete.
  - **Compliance: FULLY COMPLIANT**
  - **Formally verified prior to launch.**

Section 4.6 Observatory Requirements

- 4.6.2.5.1 Rolling about the Observatory-Sun Line
- Requirement:
  - The spacecraft shall be capable of rolling about the observatory – Sun line to support IMPACT magnetometer and SECCHI calibrations. After commissioning, these calibrations will occur not more frequently than every six months.
  - Compliance: FULLY COMPLIANT
- 4.6.2.5.2 SECCHI Calibrations
- Requirement
  - The spacecraft shall execute a 360-degree roll in steps of not smaller than 15 degrees. At each dwell position, the spacecraft shall be in fine-sun pointing for a minimum of 10 minutes. Fine-Sun pointing is not required while the observatory is rolling to the desired step positions. Pitch and yaw off point maneuvers will be required to calibrate the SECCHI guide telescope. The pitch and yaw maneuvers will be up to 1 °. The frequency will be approximately once every two to three months for a duration of less than 1 hour.
  - Compliance: FULLY COMPLIANT
  - SECCHI Calibration rolls have been completed four times per year for each spacecraft, at Aphelion, at Perihelion and at the two mid points

Section 4.6 Observatory Requirements

- **4.6.2.5.1 Rolling about the Observatory-Sun Line**
- **Requirement:**
  - **To allow calibration of the magnetometer, the spacecraft shall be capable of completing a smooth roll about the observatory-sun line. The roll rate shall be limited by the capability of the reaction wheels.**
  - **Compliance: FULLY COMPLIANT**
  - **A single smooth roll was executed on each spacecraft during the phasing orbits. There have been no additional requests for calibration rolls.**
- **4.6.2.6 Spacecraft Attitude Knowledge**
- **Requirement:**
  - The spacecraft shall telemeter sufficient star tracker telemetry to provide post-processed knowledge of spacecraft star tracker attitude to 5 arc-min (3σ) in pitch, roll and yaw in an agreed upon reference frame. As a goal, star tracker attitude to 1-2 arc-min (3σ) in pitch and yaw shall telemetered in the ground.
  - **Compliance: FULLY COMPLIANT**
  - **See attitude charts.**

Section 4.6 Observatory Requirements

- **4.6.3 Fields of View**
- **Requirement:**

STEREO Science Instrument	Field-Of-View (FOV)	Component Orientation
1.0 SECCHI		
1.1 SCIP	8 Degree Cone (w/180 Degree Clear FOV)	Sun Pointing
1.2 HI*	85 Degree Cone (w/183 Degree Clear FOV Tilted 1.5 Degrees Along -Z Axis)	90 Degrees to Sun-Earth Line
2.0 IMPACT		
2.1 SWEA	130 X 360 Degree Annular Shape	Boom Mounted - Anti-Sun
2.2 STE	80 X 80 Degree Fan Shape into Ecliptic (East & West)	Boom Mounted - Anti-Sun
2.3 MAG	N/A	Boom Mounted - Anti-Sun
2.4 SEP		
2.4.1 LET		
2.4.1.1 Earth Behind Observatory	100 X 30 Degree Fan shape into Ecliptic (East & West) 130 X 30 Degree Fan Shape into Ecliptic (East & West) goal	50 Degrees to Sun-Spacecraft Line
2.4.1.2 Earth Ahead Observatory	100 X 30 Degree Fan shape into Ecliptic (East & West) 130 X 30 Degree Fan Shape into Ecliptic (East & West) goal	50 Degrees to Sun-Spacecraft Line
2.4.2 HET		
2.4.2.1 Earth Behind Observatory	50 Degree full Cone into ecliptic (east & west) 60 Degree full Cone into Ecliptic (East & West)goal	45 Degrees to Sun-Spacecraft Line
2.4.2.2 Earth Ahead Observatory	50 Degree full Cone into ecliptic (east & west) 60 Degree Cone into Ecliptic (East & West)goal	45 Degrees to Sun-Spacecraft Line
2.4.3 SEPT -E		
2.4.3.1 Earth Behind Observatory	45 Degree full cone in Ecliptic (East & West) 52 Degree Cone into Ecliptic (East & West)goal	45 Degrees to Sun-Spacecraft Line
2.4.3.2 Earth Ahead Observatory	45 Degree full cone in Ecliptic (East & West) 52 Degree Cone into Ecliptic (East & West)goal	45 Degrees to Sun-Spacecraft Line
2.4.4 SEPT -NS		
2.4.4.1 Earth Behind Observatory	52 Degree Cone perpendicular to Ecliptic (North & South)	90 Degrees to Sun-Spacecraft Line
2.4.4.2 Earth Ahead Observatory	52Degree Cone perpendicular to Ecliptic (North & South)	90 Degrees to Sun-Spacecraft Line
2.4.5 SIT		
2.4.5.1 Earth Behind Observatory	44 X 17 Degree rectangular Shape into Ecliptic (West)	45 Degrees to Sun-Spacecraft Line
2.4.5.2 Earth Ahead Observatory	44 X 17 Degree rectangular Shape into	45 Degrees to Sun-Spacecraft Line

STEREO Science Instrument	Field-Of-View (FOV)	Component Orientation
	Ecliptic (West)	
3.0 PLASTIC		
3.1 Solar Wind Sector Main	55 X ±20 Degree Fan Shape (clear FOV)	Sun Pointing
3.2 Solar Wind Sector Proton	55 X ±20 Degree Fan Shape	Sun Pointing
3.3 Wide Angle Partition	250 X ±7 Degree Fan Shape	In Ecliptic non-sunward
4.0 SWAVES	3 Mutually Orthogonal Antenna Elements	Anti-Sun

* - **SWAVES antenna impingement present in clear FOV**

Section 4.6 Observatory Requirements

- **4.6.3 Fields of View**
- **Compliance: FULLY COMPLIANT**
  - **Compliance was verified at the pre-ship review. All FOV requirements were met.**

- **4.6.5.1 Simultaneous forward and return links**
- **Requirement:**
  - **The spacecraft design shall include the capability of receiving command loads while simultaneously transmitting over the downlink.**
  - **Compliance: FULLY COMPLIANT**
  - **Capability was formally verified prior to launch and is demonstrated during every contact.**

- **4.6.5.2 Command distribution**
- **Requirement**
  - The spacecraft shall distribute commands and collect telemetry from all the instruments' data processing units (IDPUs).
  - **Compliance: FULLY COMPLIANT**
  - **Capability was formally verified prior to launch and is demonstrated during every contact and throughout the day.**

Section 4.6 Observatory Requirements

- **4.6.5.3 On-board Storage**
- **Requirement:**
  - **The spacecraft shall provide data storage on the flight recorder to hold as a minimum the data volume generated in one 24-hour day (5 Gbits) plus appropriate margin for a total of at least 7.5 Gbits.**
  - **Compliance: FULLY COMPLIANT**
  - **The Solid State Recorder on each is 1 Gbyte or 8.59 Gbit is size.**

- **4.6.5.5.1 Real time and stored commands**
- **Requirement:**
  - The spacecraft shall support real time commands, as well as stored command loads. Real time commands shall be bent-piped to the individual instruments and be processed by the instrument data processing units. The spacecraft shall support storage of command packets for distribution to the IDPUs at a later time. Stored command packets shall be individually time tagged.
  - **Compliance: FULLY COMPLIANT**
  - **Capability was formally verified prior to launch and is demonstrated during every contact and throughout the day.**

Section 4.6 Observatory Requirements

- 4.6.5.5.2 CCSDS format
- Requirement:
  - All commands (except critical commands) to the spacecraft bus and IDPUs shall be formatted as CCSDS command packets.
  - Compliance: FULLY COMPLIANT
  - Capability was formally verified prior to launch and is demonstrated during every contact.

- 4.6.5.5.3 Stored command buffer
- Requirement:
  - The size of the stored command buffer allocated to the instruments shall be at least 20 kbytes.
  - Software uploads to the instruments shall be performed through the normal commanding channels using CCSDS telecommand packets.
  - Compliance: FULLY COMPLIANT
  - Capability was formally verified prior to launch and is demonstrated during every contact. Each instrument has successfully uploaded software to their CPU.

Section 4.6 Observatory Requirements

- **4.6.5.6 Time Distribution**
- **Requirement:**
  - The command and data handling system shall be responsible for providing the timing signal to each Instrument Data Processing Unit (IDPU). Ground correlated UTC time shall be provided to the IDPUs by the spacecraft over the 1553 bus once a second. The format of the time message will be in the form of seconds from a start epoch. The time code format will be an unsegmented time code and fully defined in the spacecraft to instrument ICD.
  - **Compliance: FULLY COMPLIANT**
  - **Capability was formally verified prior to launch and is demonstrated during every contact.**

Section 4.6 Observatory Requirements

- **4.6.5.7.1 Overall Data Rates and Volumes**
- **Requirement:**
  - The command/ telemetry bus shall be capable of handling the instrument data rates defined in the STEREO Resource Allocation document (460-TBdRQMT-0034), table below is provided for information only.
  - **Compliance: FULLY COMPLIANT**
  - **Capability was formally verified prior to launch and is enforced on board. Note that these numbers were for the primary mission. As Earth-Probe distances increase, the overall system telemetry rate drops. Individual rates drop accordingly.**

Table 5. Observatory Data Rate and Daily Data Volume

	Data Rate (kbps) Average[2] (including space weather data, packet primary & secondary header overhead)	Daily Data Volume (Mbit) Average[3]
SECCHI	45.812	3958
IMPACT	3.237	279.7
SWAVES	2.037	176.0
PLASTIC	3.237	279.7
Space Weather Data	0.0	0
Spacecraft Housekeeping	3.000	259.2
Total with overhead	57	4954

Section 4.6 Observatory Requirements

- **4.6.5.7.2 Instrument Telemetry Format**
- **Requirement:**
  - **The spacecraft bus shall accept telemetry formatted as CCSDS telemetry packets from the different IDPUs and process them for transmission to the ground.**
  - **Compliance: FULLY COMPLIANT**
  - **Capability was formally verified prior to launch and is constantly demonstrated.**

- **4.6.5.7.3 Multiple Instrument Data Rates**
- **Requirement:**
  - **The spacecraft shall provide the flexibility to support multiple fixed data rates from the IDPUs. It is anticipated that during Integration and Test (I&T) and Launch and Early Orbit (L&EO) the particle and waves instruments will generate data at a higher rate than during normal science operations.**
  - **Compliance: FULLY COMPLIANT**
  - **Capability was formally verified prior to launch and is when even downlink rates are changed**

Section 4.6 Observatory Requirements

- **4.6.5.7.4 Real-time, space weather and recorded packets processing**
- **Requirement:**
  - The spacecraft shall provide a mechanism for determining whether to process instrument science packets as real-time, space weather, or recorded playback data packets.
  - **Compliance: FULLY COMPLIANT**
  - **Capability was formally verified prior to launch and is constantly daily when the spacecraft provides these data packets. Different ApIDs are assigned to the different data designations.**

- **4.6.5.8 Spacecraft Status Messages**
- **Requirement:**
  - The spacecraft shall provide a status message to the IDPU's via the 1553 bus. As a minimum, this message shall contain the following status and warning parameters: Time, Sun Keep-In violation, Thruster Firing, Instrument Power Off, Spacecraft Housekeeping data defined in ICDs, HGA Movement.
  - **Compliance: FULLY COMPLIANT**
  - **Capability was formally verified prior to launch. All have been re-verified during normal operations**

Section 4.6 Observatory Requirements

- **4.6.6 Power**
- **Requirement:**
  - The spacecraft shall provide each of the instruments with unregulated 28V nominal (22 to 35 V) DC input power. A separate unregulated 28Vdc power bus shall provide input power to support the instruments' survival heaters.
  - **Compliance: FULLY COMPLIANT**
  - **Capability was formally verified prior to launch and has been demonstrated during normal operations. Survival heater operation was demonstrated during G&C Software upload on both spacecraft.**

- **4.6.7 Anomalous Operations**
- **Requirement:**
  - Under detection of an anomalous condition, the spacecraft shall be capable of autonomously switching attitude control to an independent source other than the spacecraft processor used to maintain normal attitude for normal mission mode. This safehold mode shall place the spacecraft in a stable, power positive condition that shall ensure the health and safety of the spacecraft for an indefinite period of time until it can be returned to normal operations. Science operations will be suspended during this mode.
  - **Compliance: FULLY COMPLIANT**
  - **Capability was formally verified prior to launch and re-verified during our EA (safe) mode test on spacecraft A and the transition to EA mode to activate new G&C Flight code on both spacecraft after the primary mission ended.**

Section 4.6 Observatory Requirements

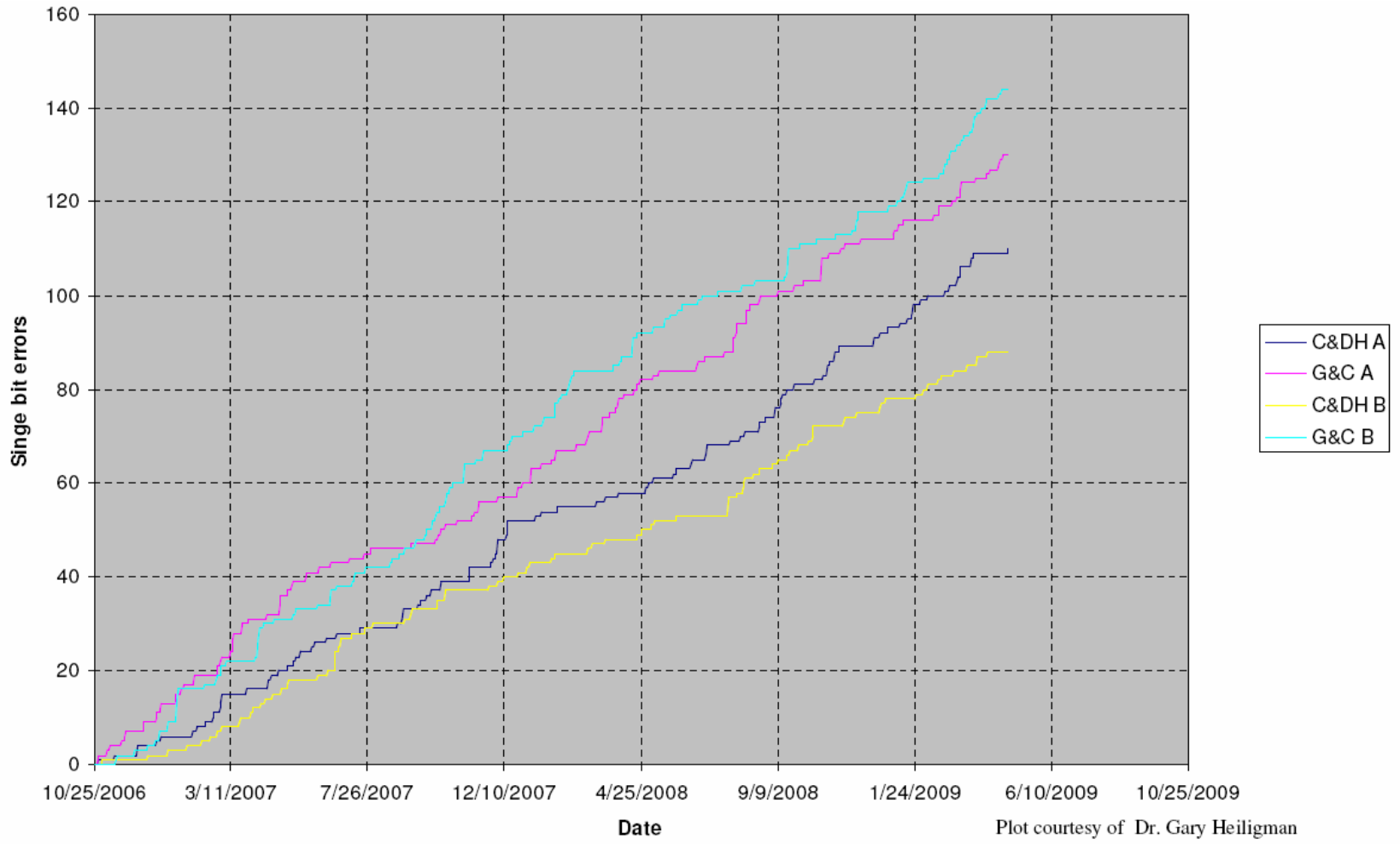
- **4.6.8 Removal of Instrument Power**
- **Requirement:**
  - The spacecraft shall provide the IDPUs sufficient warning time, when possible, before removal of power to allow for proper instrument safing/shutdown. In addition, the instruments shall be designed to withstand an instantaneous removal of power, without a warning message from the spacecraft.
  - **Compliance: FULLY COMPLIANT**
  - **Capability was formally verified prior to launch and has been demonstrated during our EA mode transitions.**

- **4.6.9.1.1 Total Dose**
- **Requirement:**
  - The Observatory shall survive the total radiation dose estimated for the space environment . The current estimate is 8 Krads for the nominal mission.
  - **Compliance: FULLY COMPLIANT**
  - **Capability was formally verified prior to launch. Spacecraft have fully survived the during the nominal mission. There is no way of assessing the spacecraft's actual dose.**

Section 4.6 Observatory Requirements

- **4.6.9.1.2 Single Event Upsets**
- **Requirement:**
  - Single Event Upsets shall not cause permanent damage, e.g. all devices must be immune to catastrophic latch up. The observatories shall be protected by appropriate part selection, latch-up detection and recovery circuitry, and error correction software. Should the launch date change, the mission office shall recalculate the radiation levels.
  - **Compliance: FULLY COMPLIANT**
  - **Capability was formally verified prior to launch. System has received numerous upsets since launch and has flown through them as designed.**

Section 4.6.9.1.2 Single Event Upsets



Plot courtesy of Dr. Gary Heiligman

Section 4.6 Observatory Requirements

- **4.6.9.3 Electrostatic Cleanliness**
- **Requirement:**

At a maximum, 0.2% of the total exposed surfaces of the observatory may be non-conductive, all apertures from instruments and components included. The allowed non-conductive surfaces (Instrument and star tracker viewing apertures excluded), shall be well distributed, especially if they are located on areas that are not exposed to light. Exceptions, beyond 0.2% of the exposed surfaces, will be considered in a case-by-case basis. The solar cell cover glasses shall be exempt from the electrostatic requirement.

All other exposed surfaces of the observatory shall be electrically conductive and connected to a single spacecraft electrical ground. The maximum variation in surface potential between any two points on the external surface of the spacecraft shall not exceed 1Volt. Therefore, the resistivity of the surface material shall not exceed 10^8 Ohms/square. The design of the spacecraft and instruments shall be consistent with the guidelines in the document “Producing Magnetically, Electromagnetically, and Electrostatically Clean Spacecraft”.

- **Compliance: FULLY COMPLIANT**
- **Capability was formally verified prior to launch and has been demonstrated during science operations**

Section 4.6 Observatory Requirements

- **4.6.9.4 Electromagnetic Interference (EMI)**
- **Requirement:**
  - A comprehensive EMI program shall be implemented to minimize degradation of the SWAVES science due to interference from the spacecraft or other instruments. This program shall be reviewed and approved by the STEREO Project Office. An EMI/EMC Plan shall be developed in accordance with the guidelines in the document "Producing Magnetically, Elecromagnetically, and Electrostatically Clean Spacecraft".
  - **Compliance: FULLY COMPLIANT**
  - **Capability was formally verified prior to launch. EMI Plan developed, approved and implemented prior to launch. Compliance demonstrated prior to launch.**

- **4.6.9.5 Contamination Control**
- **Requirement:**
  - A comprehensive contamination program shall be implemented to minimize degradation to the instruments due to exposure to contaminants. The STEREO instruments are extremely sensitive to contamination by dust or particulates and by hydrocarbon vapors and liquids. This program shall be reviewed and approved by the STEREO Project Office
  - **Compliance: FULLY COMPLIANT**
  - **Contamination Control plan developed, approved and implemented prior to launch. Compliance verified prior to launch.**

Section 4.6 Observatory Requirements

- **4.6.10.1 Thermistors Provided**
- **Requirement:**
  - The spacecraft shall monitor two (TBC) thermistors to each instrument. The thermistors shall be provided to the instrumenters by APL, the instrumenters shall be responsible for mounting the thermistors at critical points within their instruments and providing wires to the instruments external interface.
  - **Compliance: FULLY COMPLIANT**
  - **Formally verified prior to launch.**

- **4.6.10.2 Thermistor Monitoring**
- **Requirement:**
  - The spacecraft shall provide the capability to monitor the temperature of these critical thermistors at all times when the spacecraft is powered, including those times when the instruments are unpowered.
  - **Compliance: FULLY COMPLIANT**
  - **Capability verified prior to launch and demonstrated post launch.**

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Section 5.0 Integration and Test

- **5.1.1 GSE**

Ground Support Equipment (GSE) shall be provided by the spacecraft developer to support observatory integration, testing, launch operations, and early orbit checkout. This excludes GSE required to test, lift, calibrate, send commands to, receive telemetry from or display/reduce data for specific instruments.

- **5.1.2 I&T**

The I&T Mission Operations Center (MOC), shall distribute all housekeeping and science telemetry during observatory integration and testing.

- **5.1.3 EMI Requirements on GSE**

The detailed requirements for the electrical GSE electromagnetic compatibility will be derived from the observatory requirements and the required EMI and SWAVES tests to be performed during I&T.

- **5.1.4 Calibration**

All test equipment shall be within calibration date at all times when used with the spacecraft(s).

- **Compliance: FULLY COMPLIANT**
- **All requirements were verified prior to and during integration and test.**

Section 5.0 Integration and Test

- **5.1.5 Horizontal and Vertical Support**

Certain instrument tests and alignments are required to be performed horizontally (spacecraft X-axis horizontal), consequently the observatory mechanical GSE shall allow for horizontal and vertical support.

- **5.2 Spacecraft Emulators**

Spacecraft emulators shall be provided and supported by the spacecraft developer to ensure appropriate interface testing by the instruments during integration. The emulators shall provide the means for checking electrical (except relay actuated signals and power) and data interface functions between the spacecraft and the instruments that couldn't otherwise be performed until the instruments are delivered. Two or more spacecraft emulators shall be provided for each instrument data processing unit. The number and distribution of the emulators are defined in the JHU/APL statement of work.

- **5.3.1 Verification**

GEVS-SE (see Applicable Documents) shall be used as a baseline, but the STEREO Project Office will consider deviations on a case-by-case basis.

- **Compliance: FULLY COMPLIANT**
- **All requirements were verified prior to and during integration and test.**

Section 5.0 Integration and Test

- **5.3.2 Mission Assurance Requirements**

The spacecraft mission assurance requirements are defined in the JHU/APL statement of work. The instruments shall comply with the IMAR (STEREO Instrument Mission Assurance Requirements document.

- **5.4 Instrument IGSE Failure Safe**

The spacecraft GSE shall have the capability to safe an instrument, in the event of an inadvertent failure or malfunction of the instruments' own ground support equipment.
Office will consider deviations on a case-by-case basis.

- **Compliance: FULLY COMPLIANT**
- **All requirements were verified prior to and during integration and test.**

Section 6.0 Flight Operations

- **6.1.1 Flight Operations**
  - **Requirement:**
  - The STEREO ground systems shall support mission and science operations for the observatory testing, launch and early orbit support, checkout period and the nominal science operations.
  - **Compliance: FULLY COMPLIANT**
  - **STEREO Ground Systems have supported the mission fully through the phases stated above. Evidenced by more than meeting the data capture requirements.**
- **6.1.2 Level Zero Files**
  - A DSMS track is complete when all data relayed to the DSMS ground station from the STEREO spacecraft is received by the MOC. Therefore, the DSMS track is not finished until the MOC receives the real-time telemetry via a socket and SSR dump file. After the MOC receives from DSMS all data associated with a track, the MOC shall ingest the data into the short term archive and shall keep the data in the archive for at least thirty days. The MOC shall generate level 0 data files for each POC within 24 hours of the completion of the track. The level 0 files and the MOC short term archive shall be available electronically to the POCs and the SSC.
- **Compliance: FULLY COMPLIANT**
- **MOC automatically generates level zero files and provides them within 24 hours. Files are updated if necessary with new data off the SSR. Files are held for 30 days.**

Section 6.0 Flight Operations

- **6.1.3 Software Maintenance**
  - **Requirement:**
  - The ground systems shall support flight software maintenance for the spacecraft bus. The ground systems shall be capable of providing high fidelity ground testing of new spacecraft flight software loads, patches, tables, etc., prior to actual changes made to the current in-flight spacecraft software version.
  - **Compliance: FULLY COMPLIANT**
  - **STEREO Ground Systems are available to support FSW maintenance including stand-alone test facilities and the HILs. FSW changes are verified using pre-existing processes which include unit, integration and regression testing prior to upload.**
- **6.3.1 Navigation Accuracy**
  - The STEREO ground systems shall be capable of knowing the position of each observatory to within 7500 Km on the radial, latitudinal and longitudinal directions once the heliocentric mission starts.
  - **Compliance: FULLY COMPLIANT**
  - **FDF INPUT NEEDED**

Section 6.0 Flight Operations

- **6.3.2 Coordinate Frames**
  - **Requirement:**
    - The coordinate system to be used for navigation references shall be agreed upon by the spacecraft provider and the instrumenters during the phase B period.
  - **Compliance: FULLY COMPLIANT**
  - **Coordinate frames are called out in the Instrument ICDs and the Spacecraft Requirements Document**
- **6.3.3 Navigation Accuracy during flybys**
  - Navigation requirements for the lunar swingbys shall be derived during phase B.
  - **Compliance: FULLY COMPLIANT**
  - **Evidenced by successful lunar flybys.**
- **6.4.1 MOC Uploads**
  - **Requirements**
    - The STEREO MOC, located at the JHU/APL, shall be responsible for accepting instrument command loads and uploading them to the respective spacecraft
  - **Compliance: FULLY COMPLIANT**
  - **Formally verified prior to launch. Demonstrated during every contact after launch.**

Section 6.0 Flight Operations

- **6.4.2 Command Volume**
  - **Requirement:**
    - The typical daily command volume is yet to be determined. The total spacecraft-plus-instrument command load shall not exceed that capable of being uplinked during a nominal contact.
  - **Compliance: FULLY COMPLIANT**
  - **Largest command load was the load of G&C FSW which was completed during a single pass.**
- **6.4.3 Instrument Commands**
  - Instrument command loads will be generated by the instrument teams and transferred to the MOC via the open internet as defined the MOC-POC-SSC ICD.
  - **Compliance: FULLY COMPLIANT**
  - **Formally verified prior to launch.**
- **6.4.6.3 Command Validation Reports**
  - **Requirements**

The MOC shall provide a command validation report, which shall be transmitted back to the originator.

  - **Compliance: FULLY COMPLIANT**
  - **DAN TO COMFIRM**

Section 6.0 Flight Operations

- **6.4.7 Real Time Commanding**
  - **Requirement:**

Near-real time commanding shall be available during the commissioning period and during instrument contingency operations. During these periods, the ground system will impose a latency of no more than 10 minutes (TBR) from the time the command load is transferred from the originator to the MOC, through transmission from the DSN antenna.

  - **Compliance: FULLY COMPLIANT**
  - **Formally verified prior to launch. Demonstrated during commissioning.**
- **6.5.1 Level Zero Files**
  - **Requirement:**

The MOC shall generate level-zero data files. The definition of “Level zero” data is that it has been spacecraft sorted, time sorted, with merged data sets, and duplicates removed. The generation of level-zero files begins after all data within a designated time has been received. If retransmission of data is planned, then the level-zero data set will not be generated until this function is completed.

  - **Compliance: FULLY COMPLIANT**
  - **Formally verified prior to launch. Demonstrated daily.**

Section 6.0 Flight Operations

- **6.5.3 Real Time Telemetry**
  - **Requirement:**

The MOC shall provide the data products to the SSC and instrument Payload Operations Centers (POC) as defined in the subsections below:

- **6.5.3 Real Time Telemetry**
  - **Compliance: FULLY Compliant.**
  - **Formally verified prior to launch. Demonstrated daily.**
- **6.5.4 Archived Telemetry**
  - **Compliance: FULLY Compliant.**
  - **Formally verified prior to launch. Demonstrated daily.**
- **6.6.1 Navigation Data**
  - **Compliance: FULLY Compliant. Position and velocity data provided.**
  - **Formally verified prior to launch. Demonstrated daily.**
- **6.6.2 Attitude Data**
  - **Compliance: FULLY Compliant.**
  - **Formally verified prior to launch. Demonstrated daily.**

Section 6.0 Flight Operations

- **6.5.3 Real Time Telemetry**
  - **Requirement:**

The MOC shall provide the data products to the SSC and instrument Payload Operations Centers (POC) as defined in the subsections below:

- **6.6.3 Event History Logs**
  - **Compliance: FULLY Compliant. Event History is posted daily on the STEREO Data Server**
  - **Formally verified prior to launch. Demonstrated daily.**
- **6.6.4 DSN Schedules**
  - **Compliance: FULLY Compliant. DSN Schedules are posted on the STEREO Data Server.**
  - **Formally verified prior to launch. Demonstrated daily.**
- **6.6.5 Daily Status Reports**
  - **Compliance: FULLY Compliant. Status reports are posted on the STEREO Data Server**
  - **Formally verified prior to launch. Demonstrated daily.**
- **6.6.6 Spacecraft Bus Engineering Values**
  - **Compliance: FULLY Compliant. A subset of the engineering data is posted on the STEREO Data Server.**
  - **Formally verified prior to launch. Demonstrated daily.**

Section 6.0 Flight Operations

- **6.7.1 Space Weather Beacon Capability**
  - **Requirement:**

The STEREO observatories shall provide the means to support continuous real-time transmission of space weather beacon data, which consists of highly compressed relevant images and measurements from each instrument.

  - **Compliance: FULLY COMPLIANT**
  - **Each STEREO Spacecraft broadcasts as subset of the science data at 632 bps between DSN passes**