

Journey 'Round the Sun: STEREO Science and Spacecraft Performance Results

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Abstract— The Solar TERrestrial RELations Observatory (STEREO) was originally designed as a two to five year heliocentric orbit mission to study coronal mass ejections (CMEs), solar energetic particles (SEPs), and the solar wind. After over ten years of continuous science data collection, the twin NASA STEREO observatories have significantly advanced the understanding of Heliophysics. This mission was the first to image CMEs all the way from the Sun to Earth and to observe the entire sphere of the Sun at one time. STEREO has demonstrated the importance of a point of view beyond the Sun-Earth line to significantly improve CME arrival time estimates and in understanding CME structure and trajectories and the longitudinal distribution of SEPs. STEREO was also the first to use one launch vehicle to insert two spacecraft into opposing heliocentric orbits, undergo a 3.5 month long superior solar conjunction, implement unattended daily science operations on two deep space observatories, maintain 7 arcsec continuous pointing without gyros, and detect and attempt to recover a spacecraft after a 22-month long communications anomaly at a range of 2 AU. This paper discusses the significant performance results after the first ten years of operations of the STEREO mission from its journey around the Sun.

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1. INTRODUCTION

The STEREO mission consists of two nearly identical spacecraft orbiting the Sun, combining both in situ and remote sensing instrumentation to expand our understanding of the sun and solar wind beyond what can be gleaned from a single vantage point. This mission has produced unique scientific contributions and also unique challenges. Here we describe some of the scientific highlights of the mission and also some of the significant engineering challenges confronted during mission operations and lessons learned.

2. MISSION OVERVIEW

STEREO (Solar-TERrestrial RELations Observatory) [1] is the third mission in the Solar Terrestrial Probes program of the National Aeronautics and Space Administration (NASA) Science Mission Directorate Sun-Earth Connection theme. The mission consists of two nearly identical spacecraft in heliocentric orbits designed to investigate the three-dimensional structure of the Sun's corona, the origin of coronal mass ejections (CME's), and the dynamic coupling between CME's and the Earth's environment. This Heliophysics mission is managed by NASA Goddard Space Flight Center (GSFC).

The two spacecraft were designed, integrated, and operated by Johns Hopkins University/Applied Physics Laboratory (JHU/APL) with instrument packages provided by the Naval Research Laboratory, University of California Berkeley, University of New Hampshire, the Observatoire de Paris and their partners. The instrumentation includes a mix of remote sensing in visible, extreme ultraviolet and radio wavelengths and in-situ detection of conditions at the spacecraft.

- Sun-Earth Connection Coronal and Heliospheric Investigation (SECCHI) – imaging suite including five telescopes that, combined, image from the Sun to Earth orbit.
- In situ Measurements of Particles and CME Transients (IMPACT) – instrument suite including

in situ measurements of the solar wind, including magnetic field, and energetic particles.

- Plasma and Suprathermal Ion Composition (PLASTIC) – characteristics of the in situ solar wind, including low energy ions.
- STEREO WAVES (SWAVES) – radio waves and in situ electric fields.

3. INSERTING OBSERVATORIES IN OPPOSING HELIOCENTRIC ORBITS USING ONE LAUNCH VEHICLE

The twin STEREO observatories were successfully launched stacked, with the Behind observatory on the bottom, on a single Boeing Delta II 7925-10L rocket on 26 October 2006 Coordinated Universal Time (UTC) from the Kennedy Space Center in Florida. The complex first orbit operations during the 10 days following launch, including two 0.2 m/s engineering test maneuvers and an 11.7 m/s apogee maneuver to raise perigee, preventing atmospheric reentry, were described in a previous paper [2]. The highly accurate launch inserted the two spacecraft into highly elliptical Earth orbits with apogee beyond lunar orbit. Phasing orbits were employed allowing periodic maneuvers needed over a two-month period to target the lunar swingbys to accomplish the mission objectives thereby placing the observatories into heliocentric orbits; with STEREO Ahead's orbit slightly inside Earth's (and therefore slightly faster than Earth), and with STEREO Behind's orbit slightly outside Earth's (and therefore slightly slower than Earth), see Figure 1.

vehicle, into very different (in this case, oppositely-directed) orbits. Maneuvers that were performed extremely accurately, combined with an accurate launch, has left the STEREO spacecraft with a generous supply of propellant sufficient to manage momentum for over a 100 years.

The resulting orbits cause the two satellites to move away from the Earth at a rate of 22° per year, as required by the mission. See Figure 2 below. Noting the direction of the Earth's revolution about the Sun, the positions of STEREO Ahead and STEREO Behind relative to the Earth gives rise to the nicknames "Ahead" and "Behind," respectively, for the two spacecraft.

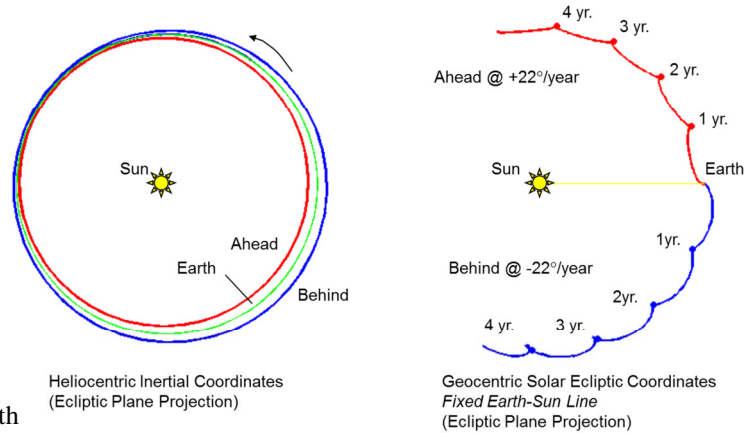


Figure 2: STEREO Orbits

4. STEREO SCIENCE

STEREO mission data have been utilized for over 1,300 studies in the refereed literature. It would not be possible to do justice to all the varied research that the mission has enabled. Here we provide just an overview of some of the important science produced by the mission.

The scientific goals of the STEREO mission are centered around solar activity. In particular, the mission is focused on coronal mass ejections (CMEs), large magnetic disturbances that erupt off the sun and into the solar system, and solar energetic particles (SEPs), atomic particles that are accelerated to relativistic speeds by solar activity. Both of these phenomena form part of what is referred to as space weather, which can have

significant effects on human technologies, including spacecraft, communications, and power systems. STEREO also studies the solar wind, the Sun's magnetized atmosphere that expands outward from the sun and into the solar system. The solar wind varies, exhibiting relatively low speed flows from regions in the Sun's atmosphere with a closed magnetic topology and

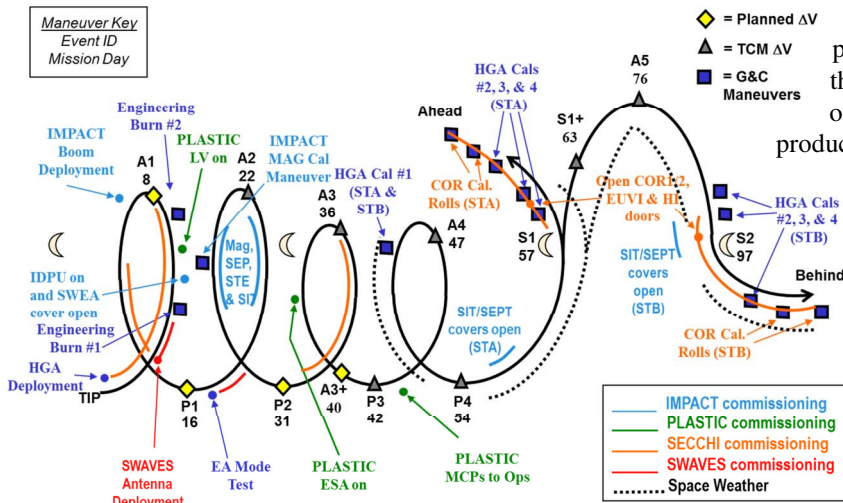


Figure 1: Schematic of STEREO's Phasing Orbits showing key events

The two-month phasing orbits also provided the opportunity to check out the spacecraft subsystems and instruments and calibrate several instruments before the prime science mission began. STEREO was the first mission to use lunar swingbys to place two spacecraft, launched on one launch

higher speed flow emanating from coronal holes, regions in which the Sun's magnetic field opens out into the solar system. These high-speed streams can, like CMEs, create disturbances in Earth's magnetic field. Furthermore, the solar wind affects the propagation of CMEs, altering both their speed and trajectory.

Coronal Mass Ejections

Coronal mass ejections are giant magnetized clouds of plasma that erupt off the sun at hundreds of kilometers per second, expanding to solar-system wide scales. They are difficult to observe from the ground and were first discovered using space based coronagraphs, telescopes with occulting disks that cover the bright sun, making its much fainter outer atmosphere, the corona, visible. CMEs are associated with other eruptive phenomena, including solar flares, intense brightenings that occur low in the solar atmosphere. These are all due to releases of energy from the sun's complex magnetic fields. Like flares and sunspots the number of CMEs changes over the course of the sun's approximately eleven-year activity cycle, with about one every other day at solar minimum and 2-3 a day at solar maximum [3]. CMEs usually take 1-4 days after eruption to arrive at Earth orbit, although occasional highly energetic ones can arrive in less than 24 hours. If oriented correctly the magnetic field of the CME can couple with Earth's magnetic field resulting in geomagnetic activity, including major aurora displays around Earth's magnetic poles. Geomagnetic disturbances can also result in problems with communications, navigation, spacecraft, and power systems. Thus, understanding CMEs, including their structure and how they propagate through the solar system is highly important in being able to better predict space weather.

STEREO's multiple points of view have greatly enhanced our understanding of CME structure and trajectories. In one of the first major results of the mission, STEREO data allowed us to confirm that CMEs conform to the general shape of a magnetic flux rope – consisting of helical field lines bending back towards the sun at both ends (see Figure 3). Before STEREO it was not clear if there were CMEs with different types of topology or if we were seeing the same basic structure from different points of view.

STEREO's suite of 5 imaging telescopes (Figure 4) has allowed us to image CMEs and other structures in the solar wind all the way from the sun to Earth orbit and combine these images with in-situ and radio data from the STEREO and other spacecraft. This has allowed us to bring together information concerning large-scale structures detected by remote sensing with local characteristics observed with in situ instrumentation.

STEREO has demonstrated the utility of a view to the side of the Earth-sun line to improve predictions of CME arrival times, an important goal in space weather forecasting. Multiple points of view are highly useful in determining the speed and trajectory of the CME. Even so simple a thing as determining if a CME is headed towards or away from the

Earth can be difficult with only one point of view. There has been extensive research into methods for CME forecasting using STEREO data and studies have shown that predictions incorporating STEREO data can lead to improvements of up to half a day as compared to predictions based on a single view-point on the Earth-sun line [6]. This has led to efforts to provide space weather monitoring missions to the Earth-sun L5 and/or L4 points.

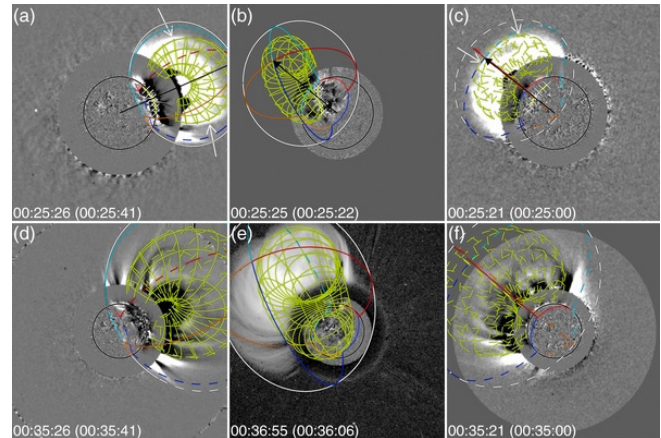


Figure 3. 3D reconstruction of CME with a flux rope model [4] superimposed on coronagraph images from two different times on March 7, 2012 from STEREO-A (left), SOHO (center) and STEREO-B (right). The model flux rope is shown in green. [5]. STEREO's additional points of view have made it possible to probe the three-dimensional structure of these solar storms. ©AAS. Reproduced with permission.

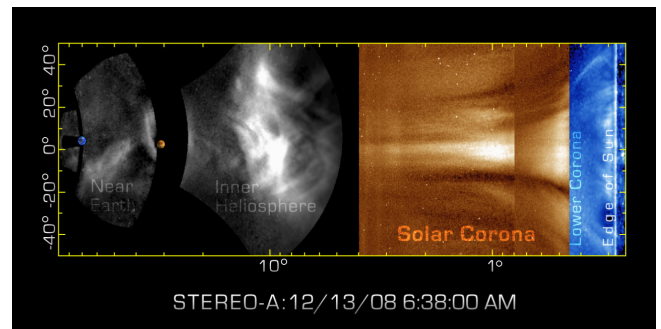


Figure 4. Each STEREO spacecraft contains five telescopes that make it possible to track CMEs all the way from the sun to Earth orbit. These images from STEREO-A show a CME moving out from the sun (in blue on the right) passed Venus and Earth (represented by the brown and blue dots respectively on the left). Credit: NASA/GSFC/SwRI/STEREO.

Multiple points of view have allowed researchers to carefully map the three-dimensional trajectories of CMEs as they move through the solar system. This has allowed us to understand CME-solar wind interactions, for instance that the solar wind acts as a drag on CMEs, causing them to speed up or slow down to match the solar wind speed. Also, CMEs can be redirected by structures in the solar wind such

as coronal holes, causing CMEs that are initially directed out of the ecliptic to trend back down to where they are more likely to impact Earth.

Solar Energetic Particles

The heliosphere is bathed in energetic particles that span energies from keV in the solar wind to GeV in Galactic cosmic rays. The processes that energize and transport them throughout the heliosphere are not completely understood. Solar energetic particles (SEPs) are particles (electrons, protons, and heavier ions) with energies between 10's of keV to several GeV, that originate from processes at the Sun. Not only do SEPs provide insight into the fundamental processes of acceleration and transport but are important in predicting space weather effects that jeopardize ground-based instrumentation, space hardware, and astronauts. Generally, SEPs with narrower latitudinal distributions (generally less than 30 deg) and shorter more impulsive time profiles (a few hours) are thought to have been accelerated by solar flares in the sun's atmosphere, whereas ones with greater spatial distribution and more gradual, multi-day time profiles are thought to have been accelerated in shock fronts ahead of CMEs [7]. Multi-point observations from STEREO A/B have transformed our understanding of how these particles are accelerated and transported.

It is thought that such high velocity charged particles should move outward from the sun along magnetic field lines shaped into a spiral (known as the Parker spiral) by solar rotation and the expansion of the solar wind (see Figure 5). It should be possible to determine the acceleration sites of SEPs by tracing along the Parker Spiral from the observation site. However, STEREO's multi-point measurements have confirmed early observation from the *Helios* mission that SEP's are often spread over much greater latitudes than expected from particle transport along the Parker spiral. Small ³He-rich SEP events are accelerated near active regions and have been thought to be associated with magnetic reconnection near jets. Despite the association with compact active regions, STEREO A/B was able to register these small impulsive SEPs at extraordinarily wide longitudes, typically > 60 degrees but sometimes as large as 140 degrees [9]. Figure 5 shows a case in which spacecraft located at a wide range of longitudes registered SEPs within a narrow time range that is difficult to explain by simple particle diffusion. The wide spread in longitudinal distributions has been attributed to extended CME-driven shocks [10], cross-field diffusion, and turbulent field-line meandering [11].

STEREO's in-situ instrumentation has allowed us to study the longitudinal distribution, composition, energies, and anisotropies of SEPs, along with their source regions, resulting in a more complete understanding of how SEPs are accelerated and transported through the solar system.

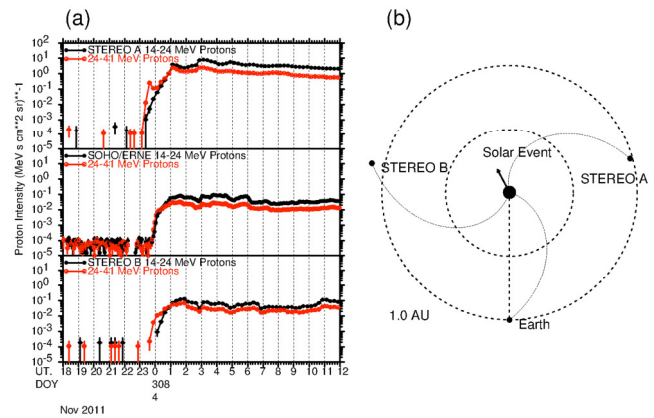


Figure 5. Solar energetic particle (SEP) event of 2011 November 3 observed across a broad range of longitudes [8]. The diagram shows the locations of STEREO-A and B and SOHO (near Earth) and the spiral lines show the expected magnetic connections of the spacecraft to locations in the solar surface and in the solar wind. The arrow shows the direction of the CME. STEREO-A, the best connected of the spacecraft, showed the strongest SEP fluxes, but all three measured SEPs soon after the eruption. Figure courtesy I. Richardson [8].

STEREO's radio instrumentation has also been important for studying these particles. Type II radio bursts are formed at the shock fronts that accelerate gradual SEPs, while type III bursts are produced by relativistic electrons streaming along magnetic field lines in the solar wind, see Figure 6. The direction finding capability of STEREO/WAVES experiment has been extremely important in understanding the dynamics of shocks and electron beams. Using this technique, [12] demonstrated that the type II emission (generally associated with shocks) was emanating from the flanks for the 2013 November 29 CME (rather than the nose).

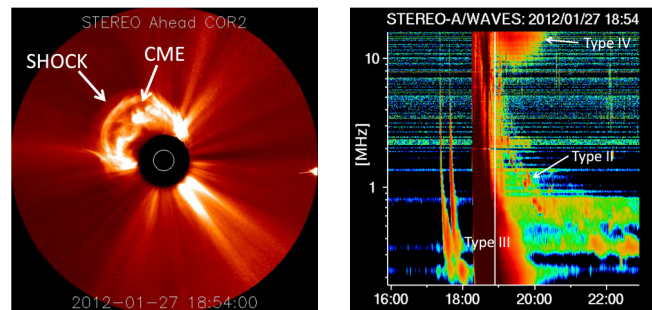


Figure 6. Left: CME with preceding shock wave imaged by a coronagraph on STEREO-A. Right: Radio bursts observed by STEREO-A/WAVES, including Type II burst produced by the shock. The plot also shows Type III bursts that trace electron beams as they move along magnetic field lines and Type IV bursts emitted by trapped particles in loops in the corona. Figure courtesy N. Gopalswamy, NASA/GSFC.

STEREO has led to a more complete picture of space weather by providing us information concerning solar activity beyond just the Earth-sun line. Prior to STEREO our main sources of space weather information were relatively close to Earth, either in Earth orbit or at the Earth-sun L1 point. As the STEREO spacecraft moved towards the far side of the Sun, STEREO was able to provide information concerning space weather through an entire 360 degrees around the Sun, see Figure 7.

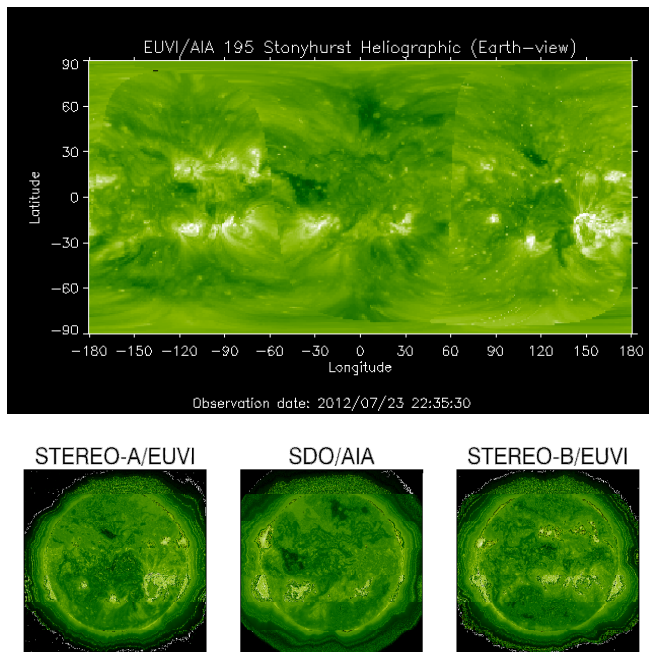


Figure 7. Top: The entire solar corona at 195 Å as observed from three points of view by STEREO-A, Solar Dynamics Observatory (SDO), and STEREO-B on July 23, 2012, shown in the bottom row. At the time, the three spacecraft were approximately 120 degrees apart.

Starting in 2011 images from STEREO combined with those from SDO in Earth orbit allowed us to image the entire solar disk. The sun takes approximately 27 days to rotate on its axis. During this time active regions on the sun, the source of the most intense solar activity, can evolve significantly. Imaging and in-situ measurements on the far side of the Sun can thus provide advanced warning of new or intensified active regions or coronal holes before they rotate onto the Earth facing side of the Sun and affect space weather near Earth.

STEREO's presence on the far side of the sun provided us with a much more complete understanding of solar activity from all parts of the sun. This is important both for protecting NASA assets throughout the solar system and also for obtaining a more complete picture of the totality of space weather events. For instance, in July 2012 STEREO-A was buffeted by one of the most energetic CMEs of the space age (see Figure 8). Multi-point observations from

STEREO-A and B and SOHO revealed that this CME was the culmination of a string of CMEs, and showed some of the highest velocities on record accompanied with intense SEPs [13]. Studies of the event indicate that an earlier CME preconditioned the solar wind so that the later CME experienced relatively limited deceleration between the sun and 1 AU [14].

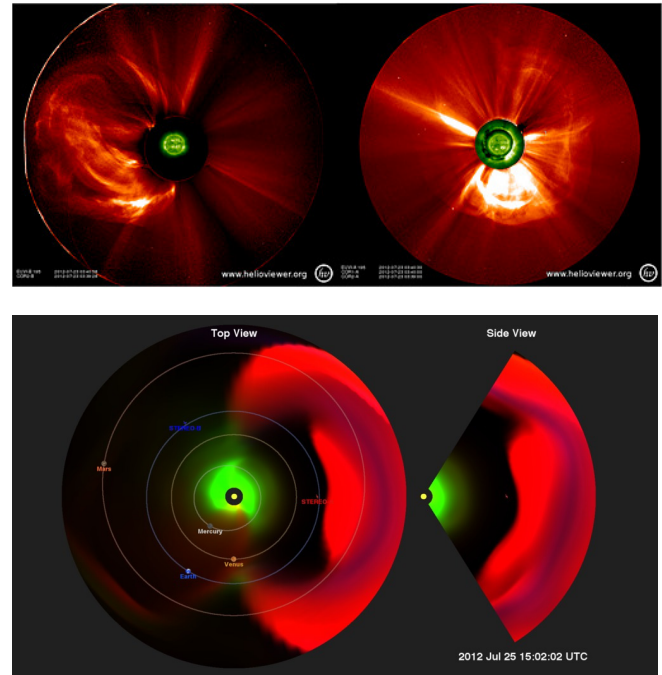


Figure 8. Top: Images of the CME erupting on the July 23, 2012 as observed STEREO-A (left) and STEREO-B (right) [15]. This CME, one of the fastest on record, was directed away from Earth and we would have little understanding of its magnitude without data from STEREO-A, which was directly in its path. **Bottom:** Simulation of the CME based on STEREO and SOHO data. To the left is a view of the ecliptic plane seen from the north. To the right is the view in the ecliptic of the CME passing STEREO-A. The green shows the density variations and red the temperature variation associated with the CME. Credit: NASA GSFC SVS.

STEREO provided the opportunity to analyze in depth this event, and gives us greater insight into the frequency of such extreme weather events, which could have substantial affects when directed at Earth [15].

Observations of the far side of the sun have also allowed us to research in more depth the origins of CMEs. For example, CMEs are usually associated with solar activity that can be seen by imaging the sun directly, including solar flares, coronal dimmings, and prominence eruptions. However, there have been reports of “stealth” CMEs that do not seem to be accompanied by signatures in the low corona. With only one point of view it can be difficult to determine if such a CME is headed towards or away from the observer, making it impossible to determine if the CME

truly has no signature low in the corona, or is simply erupting on the far side of the sun. STEREO data have made feasible studies of this topic, which has ramifications for space weather prediction as well as for our general understanding of CME initiation. Recent research using STEREO data has shown that even CMEs previously reported as stealth CMEs do show some sort of signature in the low corona, although sometimes it is quite faint. The CMEs which show minimal signatures tend to be relatively slow moving, and it has been suggested that they are initiated from much higher in the corona than usual, resulting in low acceleration [16].

5. CONTINUOUS FINE POINTING WITHOUT GYROS

The longevity design requirement for STEREO was just two years, with a design goal of five years. Thus, both STEREO spacecraft have greatly exceeded expectations. Most hardware has shown no aging effects at all. However, the gyroscopes in the Inertial Measurement Units (IMU) and the Star Tracker (ST) have some issues. Each spacecraft is equipped with a pair of IMUs, with each IMU containing three orthogonal ring laser gyroscopes (RLGs) and three orthogonal accelerometers. The original operational concept was to fly with one IMU on at all times to provide 100 Hz rate data for maintaining continuous pointing requirements of ≤ 7.25 arcsec, listed in Table 1.

Table 1. STEREO Pointing Performance 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	$\sigma_j \leq 1.53$	$\sigma_j \leq 3.4$	$T_j = 15$ (30 as a goal)
Windowed Stability	$\sigma_{sw} \leq 1.90$	$\sigma_{sw} \leq 6.70$	$T_s = 10.2$ $T_j = 0.1$
	$\sigma_{sw} \leq 3.75$	$\sigma_{sw} \leq 6.70$	$T_s = 25.2$ $T_j = 1.0$

The second IMU unit was to be kept powered off as a cold spare. In the event of an IMU fault, rule based fault protection autonomously swaps to the backup IMU.

As gyros aged (and failed) the mission was forced to change to a new concept of operations called Reduced Gyro Operations (RGO), see Figure 9. In RGO, the spacecraft “flies” using the ST, sun sensors, and the Guide Telescope (essentially, a high-precision sun sensor), with both IMUs turned off. As the primary IMU had failed or the remaining lifetime was being conserved, the backup IMU was turned

on only for monthly thruster-firing for momentum management and periodic instrument calibration rolls. This changed the IMU duty cycle from 100% to less than 3%, thus prolonging the remaining life of the backup IMUs.

The change was implemented without uploading new guidance and control (G&C) flight software or patches. Only some adjustment of parameter values in the G&C software, as well as new onboard autonomy policies to maintain spacecraft health were necessary. For example, if the ST were to suddenly lose lock on stars, the system would need to autonomously power-up its only remaining fully-functional IMU.

STEREO Ahead switched to RGO in September 2013 and STEREO Behind in February 2014. There was some observed degradation in pointing performance without gyro measurements, but the system was still able to meet or exceed its pointing requirements. From this point forward, both spacecraft were operating with one failed IMU, and one seriously aged IMU, using RGO to preserve the life of the remaining functional IMU.

Each spacecraft is equipped with a single ST which provides rate data at 10 Hz. With the IMUs in a precarious state, the ST is relied upon much more than during the early years of the mission. By and large, the ST has performed extremely well. There have been a handful of cases, however, where the ST “dropped lock,” i.e., failed to provide attitude solutions for extended periods of time (hours). In most cases, no root cause for the outages has been determined. In each case, eventually, the ST resumed normal operations. This phenomenon was dubbed the “lazy ST.”

There is a known aging issue with this ST: its charge-coupled device (CCD) can accumulate radiation damage after years in space. The vendor had advised that lowering the CCD temperature can mitigate this problem. The ST is equipped with a Thermal Electric Cooler (TEC) to keep the ST at or below room temperature. The set point for the TEC was lowered on the Ahead observatory from 10 deg C to -10 deg C in Electrically Erasable Programmable Read-Only Memory (EEPROM) in December 2014.

To preserve the remaining IMU lifetime on the Ahead observatory, no-gyro operations (NGO) were implemented in December 2015. Under NGO, the IMUs remain off unless needed by fault protection for safing events and for high value science opportunities, e.g., comet observations, as deemed necessary by the project scientist. Monthly momentum management and periodic instrument calibration rolls are all executed without IMU usage.

In summary, the Ahead observatory has been maintaining continuous fine pointing performance requirements for over the last 4 years using only ST, GT, and coarse sun sensors to do so.

6. UNATTENDED OPERATIONS OF TWO DEEP SPACE OBSERVATORIES

The STEREO mission operations center (MOC) uses track automation for unattended control operations. This operations concept was implemented six months after launch. The STEREO mission operates as two continuously recording solar data pipelines with daily Deep Space Network (DSN) and/or European Space Agency (ESA) tracks for science data return. The mission also employs a decoupled instrument operations concept where each instrument team operates their respective instruments and routinely sends commands on a daily basis. Each observatory uses rule based logic for on board fault protection as the first line of defense. For these reasons, an unattended control operations concept was developed which resulted in minimizing the phase E staffing level by eliminating the control team.

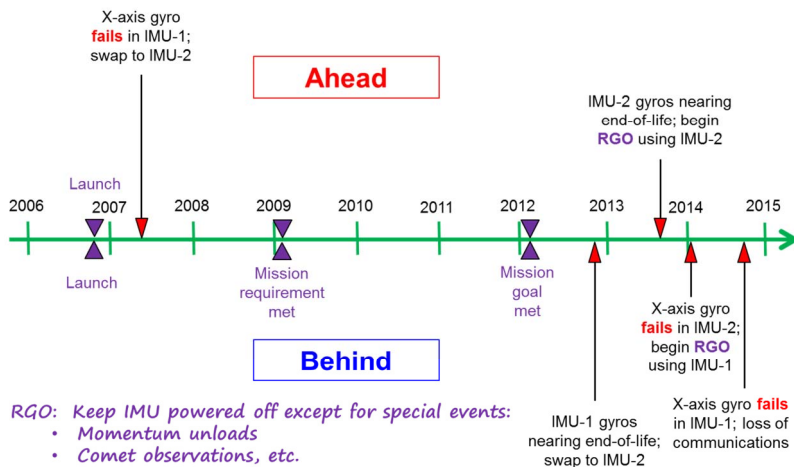


Figure 9. Actual IMU history forcing Reduced Gyro Operations concept

The DSN and ESA deep space antennas are used for tracking, and operate behind a firewall on a secure network. There is a separate, but less secure network that allows for remote notification, which is also used for planning and assessment but cannot send commands. Control information is relayed from the secure to the less secure network in real-time. The two networks meant that the STEREO track automation system would need to be split into two sections. First would be the Master Control Procedure (MCP) to perform the mechanics of configuring to the correct DSN or ESA station and sending commands would be on the secure network. A separate paging system known as Tron performs state of health checks on the spacecraft on the less secure network. Telemetry is used to communicate between the two systems through database global variables. These are essentially null values in the telemetry database that can be set by the ground.

Given this baseline hardware and software configuration, a low-tech implementation using Satellite Test Operations Language (STOL) was used for track automation. STOL is an interpreted language similar to Basic and was familiar to

members of the mission operations team. This allowed for ease of use and maintainability by the missions operations team (MOT) over the course of the mission as events warrant. Specially developed software applications generally require software staff to maintain them, using STOL reduced software maintenance. The primary driver of the track automation software is the DSN 7-day Schedule, which also contains ESA tracks. The mission planning software creates a command procedure that sets database global variables on track information for the next 21 days.

The MCP supports limited failure recovery actions for which the MOT is notified via text and or email messages. Most of the MCP failure recovery actions deal with problems establishing a command link.

While the MCP executes in a linear fashion, the Tron program does not. Tron was therefore implemented as a scanning program. Every 30 seconds it performs a complete scan of the MCP status, network status, as well as spacecraft status. If it identified that a track was in progress it would perform real-time checks. Tron implements a core set of checks that are performed continuously during a track, and a set of extended checks that are performed at the start of the track and hourly thereafter. Core checks are limited to the following:

- Fault autonomy rule firing
- Spacecraft not in the operational mode
- Battery state of charge less than 95%
- High Gain Antenna (HGA) pointing is disabled
- No command acknowledgment for any command
- No telemetry received for any 20 minute period
- Unresponsive networks
- Unresponsive MCP

The extended checks grew from the health and safety checking procedure used at launch and checks over 2000 telemetry points. A failure in any check could be responded to by either an email or a text message.

Responsibility for monitoring the automation system and responding to pages rotates through the team on a weekly basis. Once paged, team members can log in from their remote location and monitor spacecraft telemetry. Once the problem is determined, the rest of the team is advised with the status/resolution of the problem via email. Typical issues are failures with the command or telemetry links at the station. The team typically receives two pages every week.

7. SURVIVING A 3.5 MONTH LONG SOLAR CONJUNCTION

The solar conjunction mission phase for STEREO was not initially required by NASA. Nevertheless, after 8 years post launch and multiple mission extensions, it became necessary to safely conduct superior solar conjunction and to continue science return post conjunction. A detailed understanding of the STEREO superior solar conjunction operations can be found in a previous paper [17].

As suggested by Figure 2, the two spacecraft pass behind the Sun (superior solar conjunction). X-band communications are significantly degraded when the Sun-Probe-Earth (SPE) angle approaches 3° due to solar scintillation effects. It took Ahead about 3.5 months to pass through this blackout region, and about 2 months for Behind due to the required slow mean drift rate for science.

These unprecedented months-long solar conjunctions presented two significant problems: how to ensure spacecraft safety when it is designed for daily communications and how to prevent damaging the parabolic HGA as it cannot be used for communications within several degrees of Sun.

Command-Loss Timer

STEREO is equipped with both a software command-loss timer (SCLT) and a hardware command-loss timer (HCLT). Both the timeout value and the corresponding action taken for the SCLT may be changed by mission operators. The SCLT may be disabled, however, the HCLT is implemented in hardware/firmware and it cannot be disabled. Neither the HCLT timeout value nor the action taken can be changed after launch.

The STEREO HCLT expires if no command is received from the ground within three days (72.332 hours, to be precise). This value was chosen based on the requirements for the immediate post-launch mission phase, where orbital maneuvers might be required every few days in order to avoid Earth impact and to achieve eventual heliocentric orbit. The value is also consistent with the STEREO mission concept of operations, which calls for daily station contacts.

Among the many actions taken in response to an HCLT timeout, are:

- Shutdown of all four scientific instrument suites
- Avionics reset, including rebooting of the flight processors
- Reboot the transponder in the communications subsystem
- Power off the Star Tracker (ST)
- Adjust heaters for low-power consumption

As can be seen, collectively, these are drastic actions to take, and not without risk to spacecraft health. Therefore, an HCLT timeout is something to be avoided. In fact, in the almost 8 years of operation prior to initiation of solar conjunction planning, no HCLT resets occurred on either spacecraft.

The STEREO HCLT design, while necessary and appropriate for early operations, presents a serious problem for surviving the solar conjunction. The Ahead spacecraft, for example, experienced 35 HCLT timeouts during its long 3.5 month communications blackout.

Antenna Thermal Issue

STEREO uses a 1.2 m parabolic dish as its High Gain Antenna (HGA). This is the spacecraft's primary means of communication. By rotating the HGA gimbal, the flight software maintains the HGA boresight on the Earth as the spacecraft proceeds on its path around the Sun.

As the spacecraft approached superior solar conjunction, sunlight fell more directly into the parabolic dish and was concentrated at the focus. Despite the dish's flat black surface, this effect drove the antenna feed temperature to the point where damage is possible, see Figure 10. Specifically, after analyzing the materials on the antenna feed, it was concluded that degradation would start around 150°C , and actual damage would occur around 170°C . Projections indicated that if the HGA was allowed to point at the Earth through the solar conjunction, the temperature would greatly exceed the damage point.



Figure 10. STEREO High Gain Antenna 1.2m parabolic dish

This thermal issue was not analyzed during the design phase because the goal for mission life was set at five years, and the issue did not arise until mission year eight. While it may seem short-sighted to stop the analysis at five years, it must be remembered that development managers are typically hard pressed to justify costs incurred when

attempting to significantly exceed agreed upon mission requirements.

The antenna thermal issue presented one of the biggest challenges for operating STEREO through the solar conjunction period. In fact, the issue presented a problem for many months before the actual conjunction and continued for many months after the conjunction. Altogether, the “hot zone” for HGA operations spans up to 15 months (447 days) on Ahead, and 13 months (397 days) on Behind.

Side Lobe Operations and Radio Frequency (RF) Communications

After data analysis and testing on each spacecraft it was shown that moving the HGA boresight away from the Sun by just a few degrees had a dramatic beneficial effect on the feed temperature. By using the HGA side lobes, a level of radio frequency (RF) communication could be maintained with the spacecraft and reduce thermal effects. Testing revealed that both the command and telemetry links could be maintained by switching from the main lobe of the HGA antenna pattern to either the first or second side lobes, located about $\sim 3^\circ$ and $\sim 6^\circ$, off the boresight, as shown in Figure 11. The big drawback to using the side lobes is that the signal strength drops by 1 to 3 orders of magnitude. This forced the implementation of significantly reduced data rates and requires the use of DSN 70 meter ground stations for daily contacts.

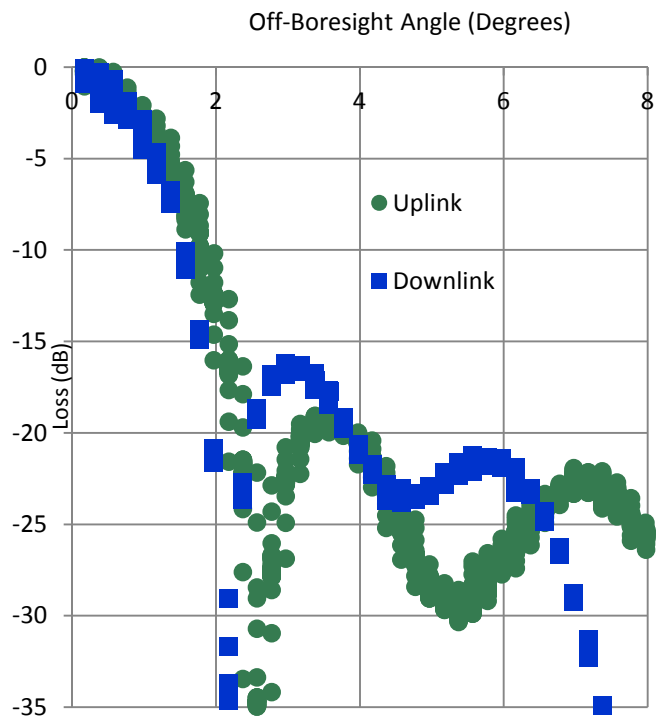


Figure 11. STEREO Ahead High Gain Antenna (HGA) pattern, showing side lobes

Solar Conjunction Plan and Implementation

The solar conjunction mission phase consisted of three periods of operations; two side lobe operations periods, before and after solar conjunction, and the actual superior solar conjunction blackout period. Side lobe operations are required for several months before and after solar conjunction to maintain the HGA feed assembly temperature to within measureable limits while maintaining some level of ground-communications. Table 2 lists the approximate duration of each period. A timeline depicting the significant events the Ahead observatory during the solar conjunction mission phase is shown in Figure 12.

Table 2. Solar Conjunction Mission Phase Durations

	Pre-Solar Conjunction (days)	Superior Solar Conjunction ($\pm 2^\circ$) (days)	Post-Solar Conjunction (days)
Ahead Observatory	216	105	126
Behind Observatory	52	60	285

The entry and exit into the solar conjunction was at the 2° SPE angle to ensure communication and verify the required observatory configuration. System momentum was set to 8 Nms to minimize the need for autonomous momentum dumps during the solar conjunction blackout period. Upon entry into the superior solar conjunction, each observatory was commanded, via an absolute time command in the on-board startup sequence, to rotate the spacecraft about the Sun-line at 5 degrees/minute to distribute system momentum so as to better manage buildup along all three axes. As the 72.332 hour HCLT cannot be changed, each observatory undergoes a system reset every three days, thereby reinitializing the state of the observatory. As the SWAVES instrument uses minimal power and its default power-on configuration provides routine science, it remained on and was power-cycled with each three day HCLT system reset to continue to record science data at 1 packet per minute. The other instruments were turned off during the conjunction period.

On June 26, 2015, the first telemetry was received from STEREO Ahead post superior solar conjunction after the 31st HCLT initiated system reset at a 1.5° SPE angle. The DSN received a strong downlink signal and telemetry using the Goldstone 70 meter station. The observatory was operating nominally continuing to rotate slowly while communicating on the 2nd HGA side lobe as planned. The HGA feed temperature was within the predicted range at 113° C. System momentum was at the anticipated level of 8.0 Nms. As occurred during solar conjunction entry, after the 31st HCLT reset, the star tracker was again “lazy” to re-acquire a solution causing IMU2 to power on for two hours. One additional anomaly occurred, namely reaction wheel #3

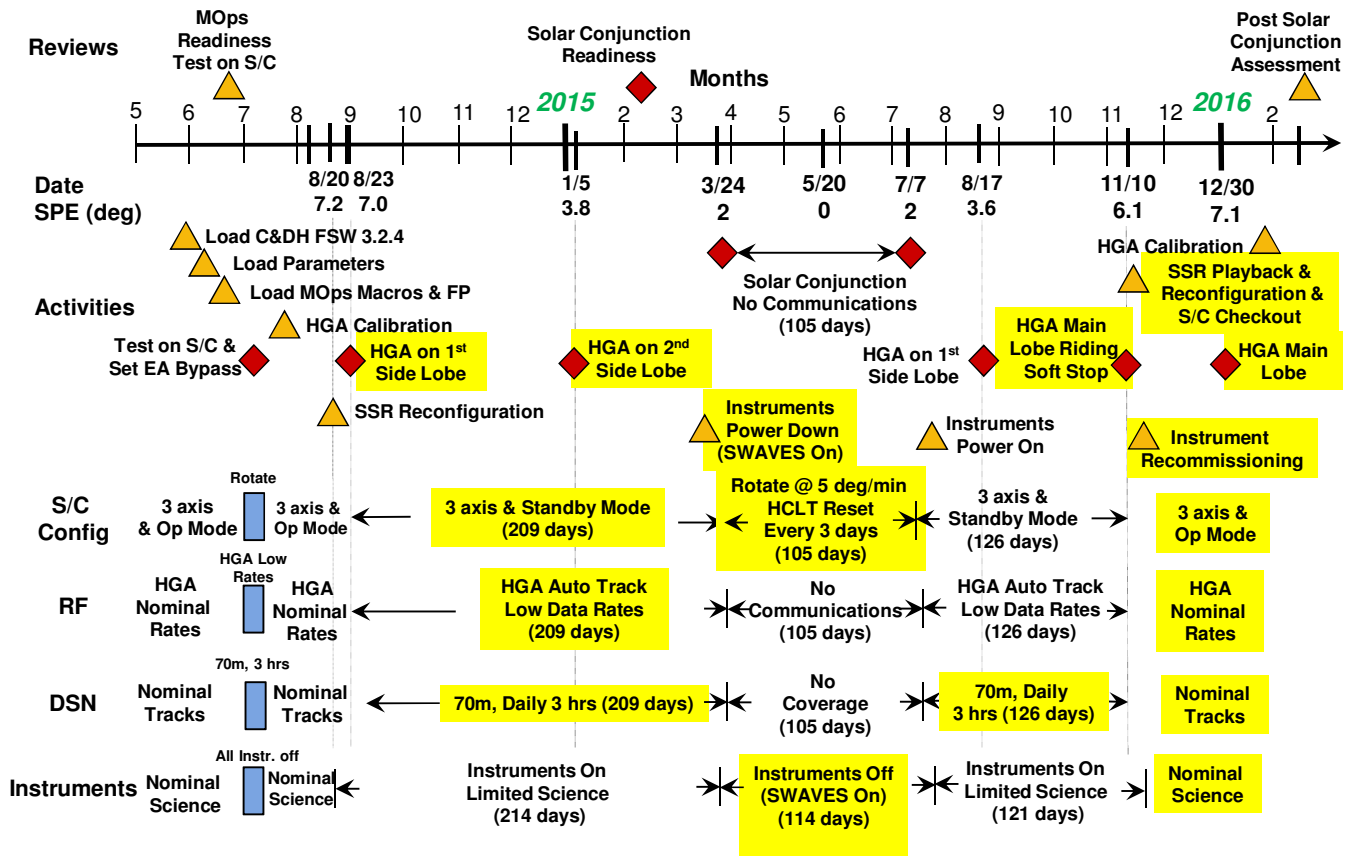


Figure 12. STEREO Ahead Timeline for Superior Solar Conjunction. Highlighted events are those that were tested on-orbit before superior solar conjunction.

was not responding to G&C torque commands. The observatory continued to rotate nominally as it was designed to do so with only three reaction wheels. Because the observatory was healthy, contingency response to this G&C anomaly was delayed until July 8th to allow for more reliable communications when the SPE angle reached 2°. Starting on June 29th, a three hour DSN 70 meter station tracked the Ahead observatory on a daily schedule as it continued to switch antennas each day and RF performance was found to be highly dependent on solar activity. Due to solar interference, telemetry frame reception varied widely from 13 to 94% on the HGA. While carrier lock was received on the low gain antennas (LGA), telemetry lock was never successful on the LGAs due to the low SPE angle.

At 0000 UTC on July 7th, the Ahead observatory returned to nominal 3-axis attitude control as planned and after the 35th and last HCLT initiated system reset on July 8th, post superior conjunction recovery operations began. Daily DSN communications on the HGA 2nd side lobe were resumed using an eight hour daily track for six weeks to playback the spacecraft data for analysis. Over the next few days, instruments were powered on and configured for continuing side lobe operations and spacecraft bus recovery operations were completed.

During the post solar conjunction recovery operations on the HGA 2nd side lobe, July 8th through 20th, the command success rate varied from 65% to 100% depending on solar activity. During this time, the SPE angle increased from 2.0 to 2.5°. While the downlink signal strength was very good during this time, the success rate for telemetry frames received also varied from 76% to 99% using the DSN 70 meter stations.

On November 9th, the Ahead observatory resumed operations using the main lobe of the HGA resulting in a 13 dB signal increase. The HGA rode along a 1° offset from the center of the main lobe until December 30th to keep the HGA feed assembly cool. This increased the HGA feed assembly temperature to 119° C, which was within the predicted range.

Even at a 1° offset, data rates increased significantly, 240 kbps on the downlink and 2000 bps on the uplink. The downlink rate gradually returned to the highest rate, 720 kbps, when communication on the center of the HGA main lobe returned on December 28, 2015. The National Oceanic and Atmospheric Administration (NOAA) antenna partners gradually were able to close the RF link on the space weather broadcast in between DSN or ESA tracks.

With the increased downlink rate, the 15 months of in-situ instrument space weather data on the SSR were finally able

to be played back twice and verified that all recorded data was received.

On November 17th, the Ahead spacecraft bus reconfigurations were completed for returning to nominal science operations. After 454 days of side lobe and solar conjunction operations on Ahead, daily SSR playback, commanding, and tracking operations resumed. Daily science data return was gradually restored to prime science levels of 5 Gbits by December 28th.

Post conjunction, all instruments resumed nominal data collection with no ill effects from being powered down for several months. The HGA feed assembly temperature gradually returned to within tested operational limits, < 90° C, with no ill effects from being overheated for over two years. Only one lingering issue resulted from the solar conjunction on the Ahead observatory. G&C fine pointing losses and the magnitude of the attitude roll error increased slightly post solar conjunction. The SECCHI imaging instrument team reported that the magnitude of the attitude roll error was periodically affecting the Heliospheric images causing the post processing star-fitting algorithm to fail. To improve roll error performance, the G&C X-axis control bandwidth was adjusted. The G&C Rate Merge capability, which enables rate measurements from all sensors to be combined to form a "better" rate estimate versus picking only one sensor as the source of the angular rate measurement, was also enabled, which reduced the noise on the X-axis angular velocity estimate by ~50%. However, the cause for the changed G&C behavior has not yet been determined. Wear on the reaction wheel bearings seems like a possible explanation.

8. LOSS OF AND EFFORTS TO RECOVER THE STEREO BEHIND OBSERVATORY

Having completed its on orbit testing prior to superior solar conjunction, communications were lost with the Behind observatory on October 1, 2014 after the HCLT-initiated system reset was observed during a DSN 70 meter support with the radio science receivers recording. Data extracted from the DSN radio science receiver (RSR) data proved invaluable as it led to the understanding that the gyro failure caused the spacecraft to spin up and turn away from the Sun. Within a few hours, the battery drained, and the spacecraft became very cold freezing all propellant. A NASA Failure Review Board (FRB) was convened and concluded that the loss of communications was due to a simultaneous double failure of G&C sensors. The first failure was the star tracker failing to lock which led to the powering on of the gyro unit. Over time, the spacecraft could thaw and slow down allowing the solar arrays to get sufficient power. Therefore the FRB recommended the project continue periodically trying to re-establish communications with STEREO Behind [18].

On the 25th attempt to re-establish communications with STEREO Behind, the DSN detected a strong downlink carrier at 2227 UTC on August 21, 2016 after contact was lost for over 22 months. At a spacecraft range of 2 AU, the observatory was found to be rotating slowly about its principal axis of maximum moment of inertia for which the uncontrolled attitude allowed some solar array input and continuous uplink and downlink communications on the LGA at emergency data rates. Over the next 22 continuous days, significant obstacles to recovery were overcome with a collaborative effort of the JHU/APL engineering team, NASA GSFC, DSN, Flight Dynamics Facility (FDF), GSFC Space Science Missions Operations (SSMO) scheduling, and Mission Operations teams. This consisted of:

- Reliably commanding a rotating spacecraft with uncontrolled attitude at a distance of 2 AU
- How to power on the spacecraft that was never designed to be off without collapsing the battery voltage
- Acquiring telemetry at 35 bps from a spacecraft that is rotating with an uncontrolled attitude
- Warming a frozen propulsion subsystem with a degraded battery and limited solar array input with an uncontrolled attitude
- Configuring, loading, and verifying command sequences and parameters with very limited telemetry
- Conducting an autonomous momentum dump in the blind and transitioning to Control and Data Handling (C&DH) standby mode and successfully receiving telemetry on the HGA indicating star tracker lock and decreasing system momentum.

However, system momentum level remained above the threshold for re-establishing attitude control with the reaction wheels alone. Due to the uncontrolled attitude, communication degraded and the last detection of the carrier was on September 23, 2016.

From the last telemetry received on September 18, 2016 and the telemetry assessment review held on February 24, 2017, main bus voltage is low, 3 out of 11 NiH₂ battery cells are bypassed, attitude remains uncontrolled, rotating about its principal axis of maximum moment of inertia. While likely all ~42 kg of hydrazine remains and is frozen, neither of the pressure transducers are functioning.

From the very limited telemetry (245 packets) received during the recovery attempt and many engineering team meetings, significant improvements were developed and tested on the hardware simulator which included:

- Optimizing data rates based on RF link performance, by adding 4 new uplink rates and 16 new downlink rates.

- Use of the $-Z$ LGA as it provides 2 dB better performance than $+Z$ LGA.
- A ground software process was developed to determine attitude and estimate solar array input using only Doppler data and ephemeris.
- To better protect the degraded battery while warming propulsion subsystem, recover the Behind observatory in the higher C&DH standby mode which allows use of the peak power tracking algorithm.
- Minimize fault protection rule usage to only those that will assist with recovery operations.
- Minimize battery loading during and after the autonomous momentum dump used to re-establish attitude control.
- As a propulsion leak may have occurred, close propulsion latch valves after each thrusting operation to minimize propellant loss and undesired specific impulse from leakage.
- Refined the autonomous momentum dump options based on extensive hardware testing and analysis
 - Use IMU1, which is has gyro axes co-aligned with the spacecraft axes, for autonomous momentum dump as it will null rates about Y and Z axes better and results in rotating about $+X$ axis pointed at Sun (power positive)
 - Power reaction wheels on after all momentum dumps have completed.
 - Do not use IMU2 as it causes increased rotation.
 - Do not command a slow “rotisserie” roll rotation for sweeping LGA by the Earth for communications but rather cycle LGAs each hour.

Assuming the DSN may detect the Behind downlink signal again, the MOT is prepared for returning the spacecraft to its nominal 3-axis stable power positive state having developed and tested 61 new procedures. After promoting to C&DH standby mode to enable use of the peak power tracker to better protect the battery, the primary objectives are to load necessary memory objects, i.e., command sequences and parameters, in parallel with warming the propulsion subsystem as shown in Figure 13. A tailored autonomous momentum dump is again required to reduce system momentum sufficiently for 3-axis attitude control on reaction wheels. Interestingly, the very same G&C components, IMU, ST, and thrusters, which led to the loss of communications anomaly, are required to re-establish attitude control and communications.

Based on G&C geometric analysis and GSFC modeling, periodic recovery tracks continue using minimal 70 meter DSN station and radio science receiver team support. With

the ingenuity of the DSN, two different acquisition sequences are being utilized to re-establish communications with STEREO Behind:

1. Frequency Segmented 1 kHz - To ensure command reception, a fast frequency segmented acquisition sequence consists of an 18 kHz frequency range divided into 18, 1 kHz segments, each swept at a 1 kHz rate, stepping down in frequency and then back up again. During each segment, the MOC sends battery recovery commands on the first day and on the second day, carrier recovery commands. This was the acquisition sequence that originally detected the Behind downlink in August 2016.
2. 4 kHz Sweep with Search Pattern – The DSN created a diamond shaped search pattern with 7 steps of 0.037 deg, dwelling 10.8 minutes/step. There are two diamond patterns of 4 steps to cover the area of the estimated ephemeris error. The starting point is offset 0.02 deg for 100% uplink optimization. Repeating each diamond pattern accounts for the 30 minute round trip light time (RTLTL). This search pattern acquisition sequence sends battery recovery commands at each step during the first day and on the second day, sending carrier recovery commands at each step.

9. LESSONS LEARNED

The significance of this work for future deep space missions, for which continuous fine pointing and/or a long superior solar conjunction is required, is that the mission must be designed to support it. The following lessons were learned for incorporation into future NASA missions.

1. Add value based requirements for the extended mission phase for NASA missions. NASA missions are designed for the duration of the prime science success criteria. They do not reflect the reality for average NASA deep space observatory lifetime, which is typically greater than 15 years [19]. During development, value based requirements should be discussed for continuing the mission beyond the prime science phase to include all subsequent mission significant orbital events. For example for STEREO, adding a single requirement for safe survival of the months long superior solar conjunction would have uncovered the following:
 - HGA feed thermal issue
 - Unmodifiable 3 day HCLT initiated system resets
 - Star tracker power off for each system reset
 - No RF margin on LGAs at a 2 AU range
2. Use a value based science data return requirement. The STEREO mission required an annual average of 5 Gbits/day per observatory as opposed to requiring a data return percentage. This simplified flight and

ground software, mission operations concept of operations, and DSN track time usage. This allowed for a manageable, unattended track operations implementation with reduced MOT staff. It also provided project flexibility in responding to DSN schedule changes.

- Use a decoupled instrument operations concept if possible. Instrument teams are responsible for their own instrument commanding and instrument health assessment for decoupled instrument operations. This requires prelaunch allocation of shared resources, i.e., power, thermal, pointing, bus bandwidth, SSR storage, etc. It significantly reduces MOC complexity and minimizes MOT phase E staffing.

should be oriented on the spacecraft in a way that permits maximum flexibility in combining outputs while covering three mutually perpendicular axes.

- Operate the Star Tracker as cold as possible to accelerate reacquisitions.
- Do not make the hardware command-loss timer (HCLT) unmodifiable. Rather, design the HCLT duration as an uploadable parameter. If this feature had been available, we would have set the timeout value to a large number to prevent the 35 system resets during the Ahead observatory blackout period. This action would have prevented the reaction #3 wheel over-speed latch-up.

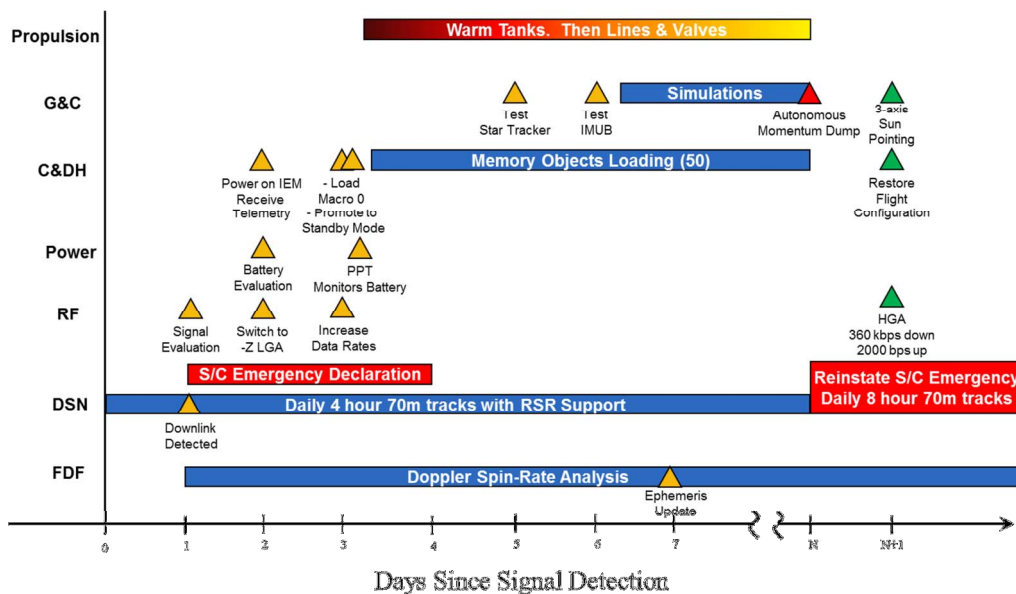


Figure 13. STEREO Behind Recovery Timeline

- Success of launch, phasing orbits, prime science and extended mission phases is due in large part to extensive prelaunch systems testing on each observatory.
- Add a common emergency frequency for all NASA missions which would allow rudimentary emergency contact between any two NASA missions. Had this been in place, the NASA Mars Atmosphere and Volatile Evolution (MAVEN) observatory might have been able to send the one command per day required to keep the HCLT on either spacecraft from expiring. NASA is currently studying this possibility.
- Counting on RLGs for very long missions is risky; include option to operate on an intermittent basis.
- If a spacecraft has redundant IMUs, allow for cross strapping between individual units so as to permit full three-axis coverage using any combination of sensors capable of providing measurements along any three non-collinear axes. Further, individual IMU units

10. Allow the system reset hardware response to be modified post-launch, i.e., EEPROM, not field-programmable gate array (FPGA). For example, STEREO's unmodifiable reset sequence turns the star tracker off. The powering on and subsequent slow star reacquisition of the star tracker was a contributing cause of the Behind loss of communication anomaly.

11. Set the battery charge current to maximum at start-up power initialization and

after going into low state of charge operation to allow maximum charging capabilities with available solar array power. This design change would improve the odds of recovering a spacecraft from a depleted battery condition.

- Provide MOT the ability to easily and completely disable autonomy, using, say a short hardware command providing ability to cut-off autonomy at extremely low uplink bit-rates. Our inability to cut-off autonomy slowed Behind recovery operations twice, i.e., autonomy caused wheels to spin-up, then inability to communicate.

10. CONCLUSION

With STEREO Ahead and Behind, we have the first stereoscopic view of complex and dynamic solar wind structures and larger coronal mass ejections, the first views of the backside of the Sun, and vastly improved our multi-point detection of energetic particles within the

heliosphere. The unique 360 degree perspective offered by the two STEREO spacecraft has transformed our understanding of how the Sun operates both in terms of the underlying physical processes but also in terms of dramatically improving our capability in space weather prediction. Not only has the STEREO mission advanced our understanding of solar and heliospheric physics, but the unique challenges of the mission itself have considerably advanced our understanding of the technical hurdles in operating missions well beyond the primary science phase.

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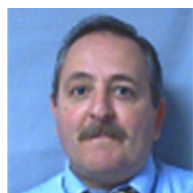
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Biography



Daniel A. Ossing received a B.S. in Marine Engineering, from the Massachusetts Maritime Academy in 1982 and an M.S. in Electrical Engineering from The Johns Hopkins University in 1989. As a member of the Principal Professional Staff he has been with the JHU/Applied Physics Laboratory for more than 32 years. He has been the mission operations manager of NASA's STEREO mission since 2008. Concurrently, he was also the mission operations manager for the first JHU/APL dual cubesat mission, MBD. He has conducted mission operations for the ISRO Chandrayaan-1, NASA LCROSS, NASA TIMED, and MDA MSX missions. His career started as an Engineering Officer for ARCO Marine transporting Alaskan north slope crude oil.



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Georgia. de Nolfo received her B.S. and M.S. from the University of Chicago and her PhD in 1997 from Washington University, St. Louis. She spent 4 years as a postdoctoral scholar at the California Institute of Technology and as a National Research Council Fellow at NASA/Goddard. Since then Dr. de Nolfo has worked in experimental astrophysics at NASA/Goddard focusing on instrument development, mission support, and data analysis of energetic particles. Dr. de Nolfo has served on numerous astrophysics teams (e.g., high-altitude balloon-borne missions, CALET) in addition to the Advanced Composition Explorer (ACE) team. Currently Dr. de Nolfo is providing instrument hardware for several upcoming CubeSat missions including a terrestrial gamma-ray flash payload, TRYAD, and an astrophysical gamma-ray burst payload, BurstCube. Dr. de Nolfo is Deputy Project Scientist for the ACE and STEREO missions.



David A. Quinn received a B.S. in Aerospace Engineering from the University of Maryland at College park in 1983 and a M.S. in Mechanical Engineering from George Washington University in 1998. He has been with NASA/GSFC for more than 28 years. His career at GSFC started with leading the Pointing Control System group for the Hubble Space Telescope during the launch, deployment, operation and first servicing mission. He was involved in operations, mission design, analysis, and flight dynamics for the Landsat-4, 5, & 7, TERRA, LRO, LCROSS, LADEE, and TESS missions. During his time at GSFC, he co-invented the formation flying technique fundamental to multi-spacecraft control efforts at GSFC. He also conceived and developed the CEGANS (Compound Eye GPS Attitude and Navigation Sensor) concept for which he received a U.S. patent in 2003. He authored a proposal for the Cross-Enterprise Technology Development Program (CETDP) for tethered formation flying development and was awarded funding to serve as the Principle Investigator for tethered formation flying development in support of the SPECS mission concept. Currently, he is the Mission Director for the NASA/GSFC Space Science Mission Operations branch where he has primary operations responsibility for the NASA TIMED, STEREO, MMS, and SOHO missions.