STEREO Guidance and Control System On-Orbit Pointing Performance

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The Solar TErrestrial RElations Observatory (STEREO) mission is the third mission in NASA's Solar Terrestrial Probes Program. The mission employs two nearly identical spacecraft to provide the first stereoscopic measurements of the Sun and to reveal the nature of the Sun's coronal mass ejections. The Sun-pointed imaging instruments require very tight pointing of their boresights and small jitter with a significantly relaxed roll requirement. In this paper, we describe the STEREO pointing requirements and provide an overview of the guidance and control system. We conclude by describing the similarities and differences in on-orbit pointing performance of each of the observatories.

INTRODUCTION

The Solar TErrestrial RElations Observatory (STEREO) mission is the third mission in NASA's Solar Terrestrial Probes Program. The 2-year mission, with a 2-year extension through 2010, employs two nearly identical spacecraft in heliocentric orbits to provide the first stereoscopic measurements of the Sun and reveal the nature of the Sun's coronal mass ejections (CMEs).[1] The two spacecraft, named Ahead (because its orbit is ahead of the Earth) and Behind (because its orbit is behind the Earth), were launched on a single Boeing Delta II rocket from Cape Canaveral Air Force Station, Florida, on 26 October 2006 at 0052 UTC. After 3 months in phasing orbits to target lunar swingbys—one for Ahead and two for Behind—the two spacecraft entered their respective heliocentric orbits, drifting away from the Earth at approximately 22°/year. The trajectories are shown in inertial and rotating reference frames in Fig. 1.

Each STEREO spacecraft includes two instruments and two instrument suites. The primary instrument suite driving guidance and control (G&C) system requirements is the Sun–Earth Connection Coronal and Heliospheric Investigation (SECCHI) instrument suite. Comprising four instruments—the extreme ultraviolet imager (EUVI), two white-light coronagraphs (COR1 and COR2), and the heliospheric imager (HI)—SECCHI is able to observe the solar corona and inner heliosphere from the surface of the Sun to the orbit of

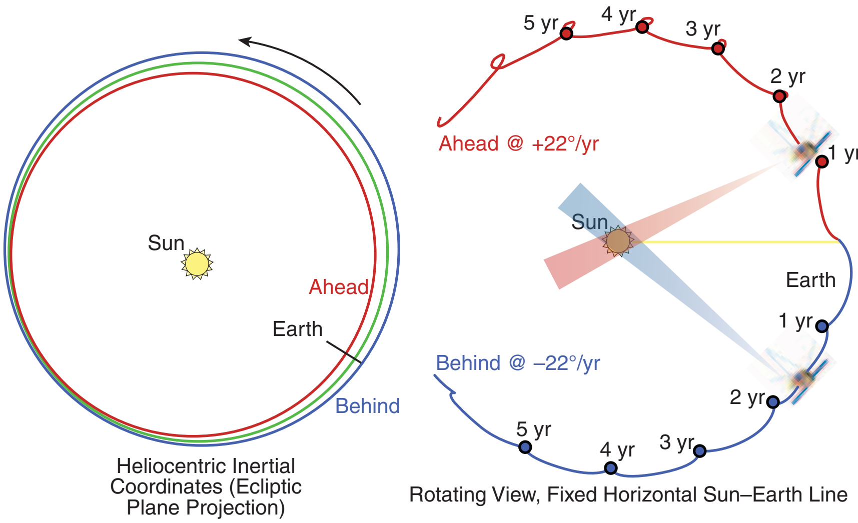

Figure 1. North-ecliptic-pole view of the STEREO spacecraft heliocentric orbits.

Earth. The two coronagraphs, COR1 and COR2, along with the EUVI and guide telescope (GT) are mounted on an optical bench in the middle of the spacecraft, and together they compose the Sun-Centered Imaging Package (SCIP) (Fig. 2). The three Sun-pointing instruments on SCIP require very tight pointing of their boresights toward the center of the Sun to observe CME initiation and propagation and a very stable platform, i.e., minimal jitter, to prevent image smear and enable 3-D image reconstruction. Roll requirements about the spacecraft-to-Sun line are significantly relaxed compared with SCIP's Sun-pointing requirements.

Two other instrument sets factor into the instrument-pointing stability challenge of STEREO. The *In situ* Measurements of PArticles and CME Transients (IMPACT) suite includes a set of instruments mounted on a 4.5-m boom that is deployed in the antisunward direction. STEREO/WAVES (S/WAVES) is an interplanetary radio burst tracker composed of three 6-m-long antennas. IMPACT and S/WAVES (Fig. 2), coupled with the deployable solar arrays and a high-gain antenna (HGA), made control-structure interaction a key concern in the design of the G&C system. [The final instrument, the PLAsma and SupraThermal Ion Composition (PLASTIC) investigation, was not a driver for the G&C design.]

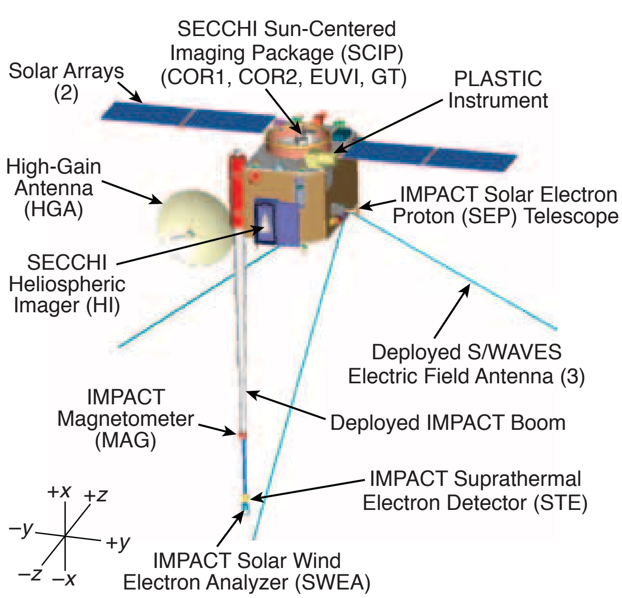

Figure 2. The STEREO spacecraft and coordinate axes.

POINTING REQUIREMENTS

The nominal STEREO mission attitude keeps the spacecraft +*x* axis centered on the Sun with the Earth in the *x*–*z* plane on the –*z* side of the spacecraft (Fig. 3). This attitude is maintained at all times except during instrument- and antenna-calibration maneuvers and during propulsive maneuvers (orbit adjustments that occurred in the phasing orbits and the dumps of accumulated angular momentum that occur routinely on both spacecraft throughout the mission).

The fine Sun-pointing requirements are driven by the SECCHI instruments, specifically those mounted on the SCIP, to provide clear images and to enable image-to-image correlation (Fig. 4). Specific STEREO requirements refer to three terms, accuracy, jitter, and windowed stability, which are defined as follows[2]:

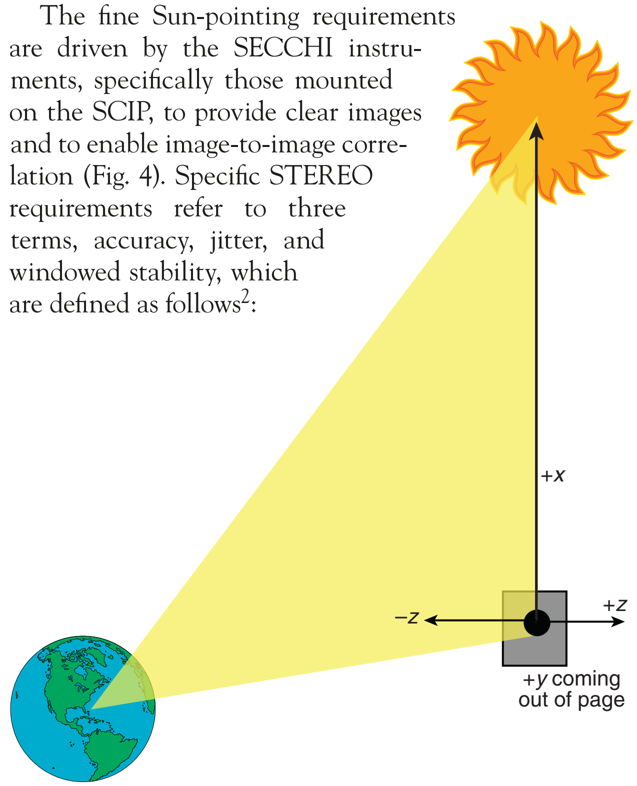

Figure 3. Nominal STEREO Sun-pointing orientation.

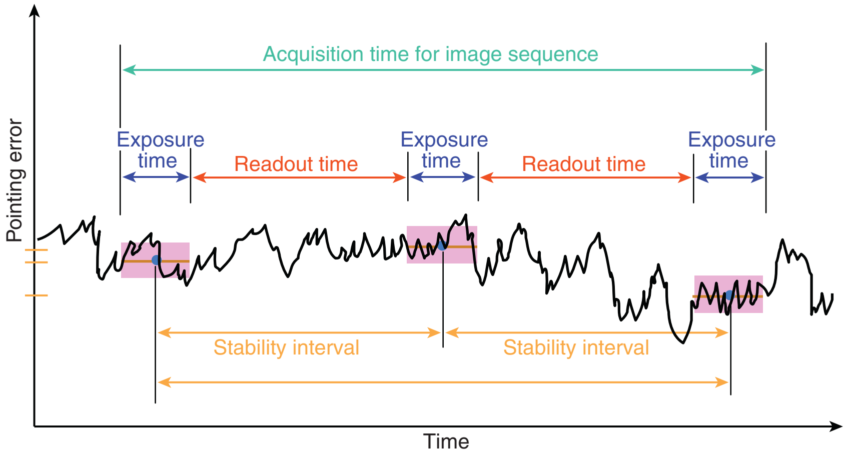

Figure 4. Imaging-time relationships driving STEREO pointing requirements.

Table 1. STEREO pointing requirements for accuracy, jitter, and stability.

	y and *z* performance (arcsec)	Roll (*x*-axis) performance (arcsec)	Window times (s)
Accuracy	$3\sigma_a \leq 7.25$	$3\sigma_a \leq 2100$	—
Jitter	$\sigma_j \leq 1.53$	$\sigma_j \leq 204$	$T_j = 15$ (30 as a goal)
Windowed stability	$\sigma_{sw} \leq 1.90$ (Stability-1)	$\sigma_{sw} \leq 402$	$T_s = 10.2$, $T_j = 0.1$
	$\sigma_{sw} \leq 3.75$ (Stability-2)	$\sigma_{sw} \leq 402$	$T_s = 25.2$, $T_j = 1.0$

- **Accuracy** is the root-mean-square (RMS) pointing error, σ_a, of the line of sight (LOS) over any interval of time (window width $T \to \infty$).
- **Jitter** is the RMS pointing error, σ_j, of the LOS *within* an interval of T_j seconds. The jitter window T_j is defined by the integration or measurement time for a single instrument observation. The range of T_j is different for each SCIP instrument, and the value for each instrument can change during normal operations.
- **Windowed stability**, σ_{sw}, is the RMS change in the LOS from the centroid time of one measurement to the centroid time of another measurement. The stability window (T_s) is referenced from the centroid of the first measurement to the centroid of the second window and from the centroid of the first measurement to the centroid of the third measurement. Each measurement is separated by a readout time. For STEREO, these readout times can either be 2.3 s or 4.6 s in duration. The stability window is graphically illustrated in Fig. 5 and shows its relationship to jitter.

With the above definitions, the requirements[3] that the system is expected to meet are given in Table 1. The two windowed-stability requirements are referred to as Stability-1 and Stability-2 for the 10.2-s and 25.2-s windows, respectively. Because the SCIP instruments are relatively insensitive to orientation about the spacecraft-to-Sun line, the roll requirements are very much relaxed relative to the boresight-pointing requirements and are comparatively easy to meet. All of these metrics can be computed as described in Ref. 2 either in the time domain as an expectation value or in the frequency domain as a weighted integral of the power spectral density of the attitude error (where the weighting function varies with the metric).

G&C SYSTEM

Each of the nearly identical STEREO spacecraft is three-axis-stabilized with fixed solar arrays for power generation as well as a steerable HGA for heliocentric orbit communications. A complement of Sun sensors, a star tracker (ST), redundant inertial measurement units (IMUs), the GT, reaction wheel assemblies, and a monopropellant hydrazine propulsion system are used by the G&C system to keep the two STEREO spacecraft three-axis-stabilized. The system is selectively redundant.

All sensor data and actuator commands are fed over a Mil-Standard 1553B data bus to/from the onboard flight computers (Fig. 6). The G&C algorithms run in the flight computer at 50 Hz and determine spacecraft state and compute errors, and issue commands to the actuators (wheels and thrusters) to maintain control.

Sensors

The primary sensors used by the G&C to maintain fine Sun-pointing are the ST, the IMU, and the GT.

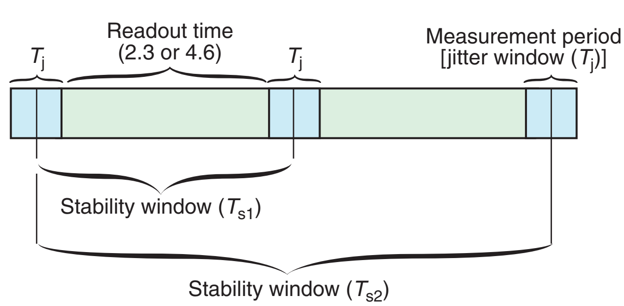

Figure 5. Illustration of jitter and stability windows.

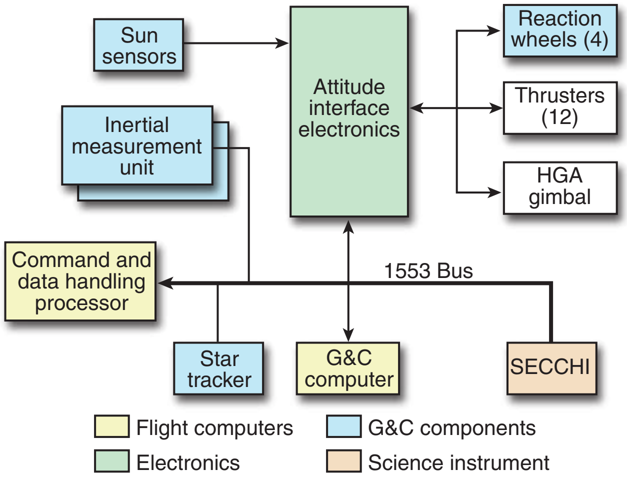

Figure 6. G&C component interconnections.

The single, nonredundant ST on each spacecraft provides fine, three-axis inertial pointing knowledge during all phases of the mission at 10 Hz. After initial GT acquisition, the ST is primarily used to provide roll knowledge. A single IMU (the second is a cold spare) contains gyros and accelerometers that provide three-axis, incremental angle, and linear-velocity (only used when firing thrusters) measurements. IMU data (100 Hz) are provided to the flight algorithms, which use the last valid measurements in the control loop to propagate the inertial attitude knowledge between ST updates.

The GT, part of the SCIP instrument suite, provides the fine-pointing error signal.[4] Its axes are nominally aligned with the spacecraft axes (Fig. 7). It reports to the G&C (at 250 Hz) the *y* and *z* components of the apparent unit vector to the Sun as measured in the GT coordinate system (the assumption being that the *x*-axis component is approximately one). It has an acquisition range of slightly >15 arcmin and a fine-pointing range of approximately 70 arcsec. The GT is able to report the off-Sun pointing error to an accuracy of 0.4 arcsec, 3σ, in each axis for a single measurement; averaging can further reduce the error. Five 250-Hz samples are passed to the G&C flight computer for processing every 20 ms (50 Hz).

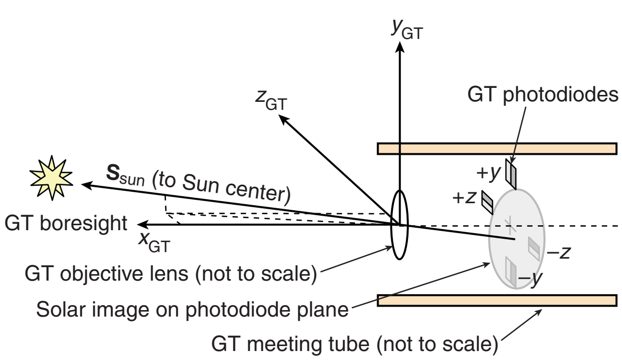

Figure 7. GT coordinate system and Sun vector measurement.

A five-head, low-accuracy Sun sensor system providing nearly 4π-steradian coverage is used as the safing sensor. It is not used in the nominal mission mode, although simulations have indicated that it may be adequate to enable GT capture in the event of an ST failure.

Actuators

Four reaction wheel assemblies, arranged in a typical, pyramidal configuration, are the primary actuators for each STEREO spacecraft. The wheels, models RSI 12-75/607 manufactured by Rockwell-Collins, Deutschland GmbH (formerly Teldix), have a torque capability of 75 mN·m and an angular momentum storage capacity of 12 N·m·s. All four wheels are operated simultaneously to maintain three-axis attitude control while providing an extra degree of freedom to redistribute angular momentum among the wheels. The wheels were carefully selected and placed on each spacecraft in an effort to minimize disturbances at the SCIP induced by static and dynamic wheel imbalances.

Dumping of accumulated angular momentum due to solar-pressure torques is accomplished with a monopropellant hydrazine blowdown propulsion system. Twelve thrusters, each nominally providing 4.4 N of force, are arranged in three sets of four with any set of four thrusters providing three-axis attitude control torque capability (via double-canting of each thruster) in addition to the nominal force in the particular direction. During a momentum dump, the thrusters are used to maintain attitude control while the wheels are torqued to their commanded momentum states.

Control Design

In some sense, the STEREO G&C design is quite simple: just point at the center of the Sun virtually all of the time. The complication was that potential control-structure interactions represented a significant challenge to the G&C design given the arcsecond pointing requirements. Almost from the beginning, modeling efforts included incorporation of a finite element model of the structural response at the sensor and actuator points of interest to assess their effects on pointing. The low-frequency structural response to static wheel imbalances was found to be dominated by the deployed S/WAVES antennas, the IMPACT boom, the solar panels, and the HGA.[5] Because of the uncertainties in structural modeling, the resulting G&C algorithms were developed to provide a highly parameterized and robust feedback control system. The algorithms include hundreds of on-orbit, tunable parameters that enable customization of the performance on each spacecraft. Liberal use of input and output filters, switchable processing options, and alignment parameters for all sensors and actuators allowed a single flight-software application to be used on both spacecraft yet enabled tuning to accommodate the idiosyncrasies of each.

In fine-pointing mode, the G&C design is simplified by the fact that the GT provides a direct measure of the attitude error at a very high rate. A proportional-integral-derivative (PID) control algorithm results in commands that are sent to the wheels at 50 Hz to remove attitude errors. Angle errors are directly measured by the GT for the *y* and *z* axes, whereas the *x* (or roll) error angle is estimated from ST and ephemeris information to maintain the Earth in the spacecraft *x*–*z* plane. Angular rates are nominally measured by the gyros of the active IMU. However, the IMUs are mounted on the bottom deck of the spacecraft and sense vibrational motion that is different from that seen by the GT on the SCIP. An option is included in the flight-control algorithms to use a GT-derived angular rate for *y*- and *z*-axis rate estimates, providing a more direct measure of the motion at the SCIP. The HGA gimbal must also be stepped a few times a day to keep the HGA pointed Earthward; this commanding is done in an open-loop fashion on the basis of spacecraft and Earth ephemeris information. The fine-pointing requirement is relaxed when the HGA is rotated.

One important feature of the control design is what we refer to as "wheel-speed avoidance," and it was discussed in detail in Ref. 6. Wheel-speed avoidance takes advantage of the fact that when four wheels are used for attitude control, as long as no spin-axis is co-aligned with another, there is a null space for wheel torques. Wheel torques commanded in the null space produce no resulting torque on the body and can be used to redistribute angular momentum stored in the wheels without affecting spacecraft attitude. STEREO uses an autonomous approach to avoid ground-specified wheel speeds to minimize stiction effects and wheel-structure resonances that might otherwise adversely affect pointing. Extensive prelaunch simulations demonstrated that significant performance improvements were achievable by avoiding identified resonances.

Spacecraft Differences

Although the two STEREO spacecraft were designed and built to be as similar as possible, there are a couple of differences that are potentially significant to overall attitude performance. First, to set up the desired mission viewing geometry, the Ahead spacecraft was placed in a heliocentric orbit that is slightly smaller than the Earth's; as a result, Ahead slowly moves farther ahead of the Earth, as shown in Fig. 1. Similarly, Behind is currently in a heliocentric orbit that is slightly larger than the Earth's and Ahead's. As a result, the solar-pressure torque is larger for Ahead than it is for Behind, and, as expected, Ahead must dump accumulated angular momentum due to solar-pressure torques more frequently than does Behind. Consequently, the wheels are also spending proportionately more time in the higher speed regimes on Ahead than they are on Behind.

The other significant difference in the two spacecraft is their mass. Ahead and Behind were launched in a stacked configuration on a single Delta launch vehicle. Behind was the bottom spacecraft in the stack

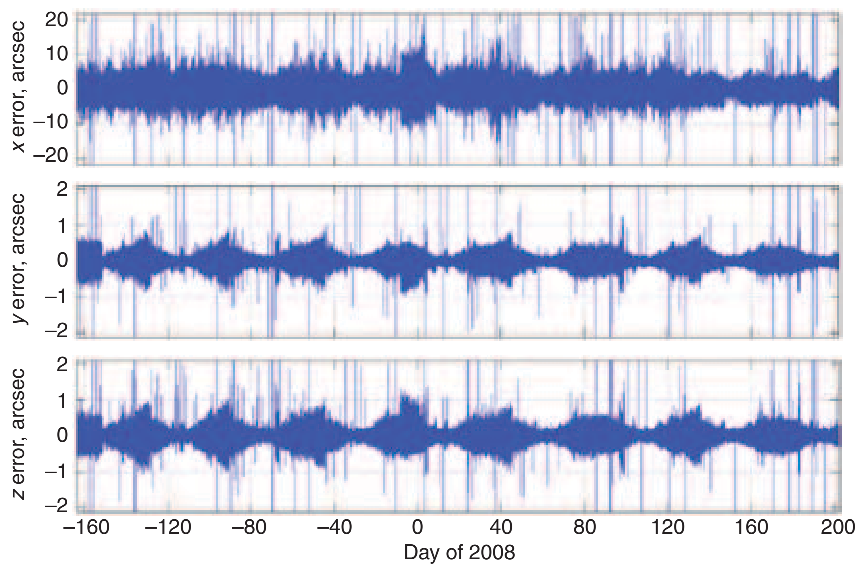

Figure 8. Attitude error for the Ahead spacecraft (in arcseconds).

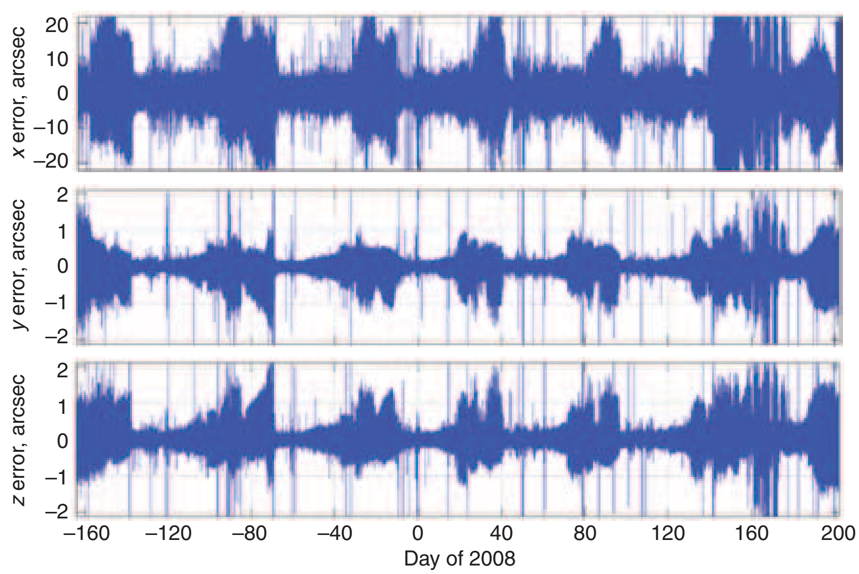

Figure 9. Attitude error for the Behind spacecraft (in arcseconds).

between Ahead and the launch vehicle. Consequently, its structure was designed to be a little heavier and stiffer to carry the increased loads at launch. It also retains the adapter on its top deck to which Ahead was fastened. As a result, it should have a slightly different structural response to the same disturbance applied to the same location on both spacecraft.

SYSTEM PERFORMANCE

After the 3-month phasing orbit period, when Ahead and Behind were maneuvered to their respective heliocentric orbits, the formal science phase of the mission began. During the science phase, except for infrequent instrument-calibration maneuvers and the regular angular momentum dumps, the Sun-pointing mission attitude is maintained. Attitude error about each body axis is shown for the 1-year period ending 19 July 2008 in Figs. 8 and 9 for Ahead and Behind, respectively. These errors are from spacecraft telemetry; for off-Sun pointing (*y*/*z*), they are essentially directly measured GT data. Roll about the Sun line (*x*) is calculated onboard from IMU and ST data. The roll error is included for completeness; it is at least an order of magnitude better than the requirements and is not discussed in detail.

The overall *y*/*z* error is seen to be generally within an arcsecond on each spacecraft, with occasional brief excursions to higher values. These errors are caused by known events such as HGA repositioning steps and other maneuvers. Also very evident is the cyclic nature of "good" and "bad" pointing, with a period of about 40 days for Ahead and 60 days on Behind. This period is the time between momentum dumps, and in Figs. 10 and 11, the strong correlation between pointing error and wheel speed is evident. The absolute values of wheel speed and momentum are plotted; the momentum dumps are at the peaks of wheel speed and momentum. Each momentum dump resets the angular momentum to a vector value with approximately the same magnitude but opposite direction, doubling the time between dumps when compared with the time that results if momentum is reset to zero each time. The net effect of this is the saw-tooth pattern of wheel speeds seen in Figs. 10 and 11. It is very evident that the best pointing occurs with low wheel speeds. This pattern is very clean and repeatable for Ahead, but for Behind, it is noticeably worse and the correlation with wheel speed is less clear.

The seemingly chaotic appearance of the wheel speeds when they are near zero is due to the previously discussed wheel-speed-avoidance algorithm, which redistributes

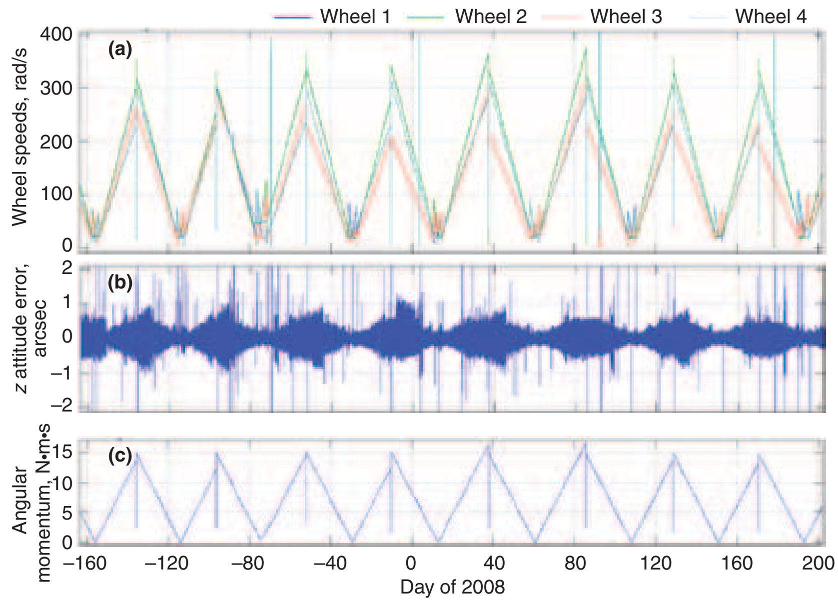

Figure 10. Wheels speeds (a), *z*-axis attitude error (b), and angular momentum magnitude (c) for the Ahead spacecraft.

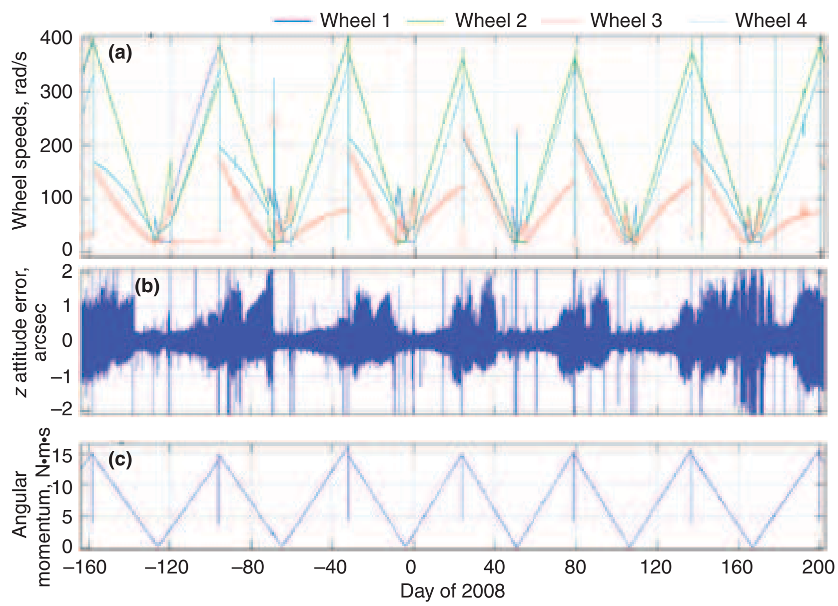

Figure 11. Wheels speeds (a), *z*-axis attitude error (b), and angular momentum magnitude (c) for the Behind spacecraft.

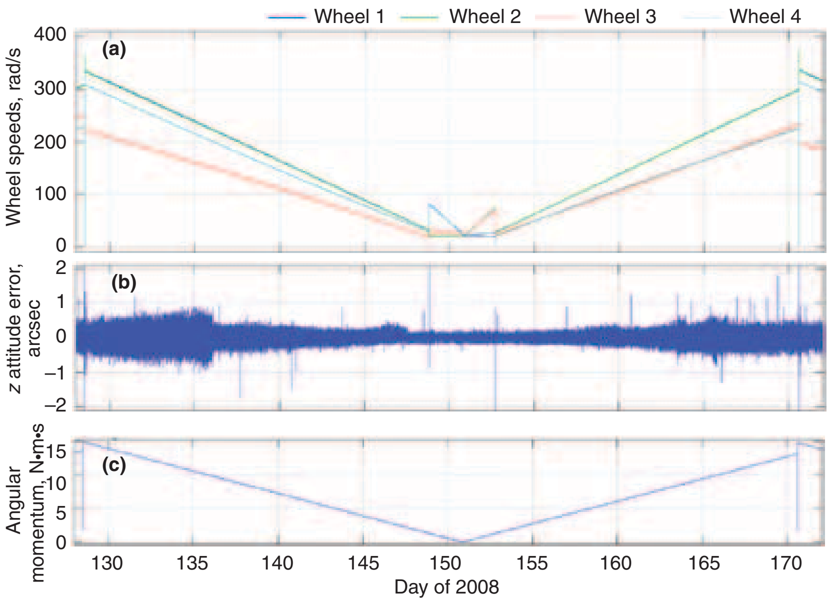

Figure 12. Wheels speeds (a), *z*-axis attitude error (b), and angular momentum magnitude (c) during a single angular-momentum-dump cycle on the Ahead spacecraft.

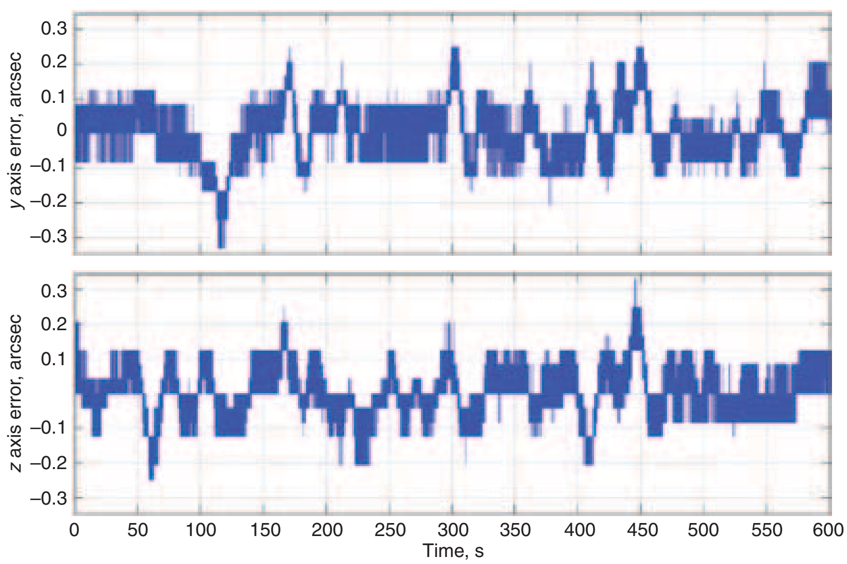

Figure 13. Off-Sun attitude error measured by the GT for Ahead at time 2008:157:20:25:15Z.

the four wheel speeds when needed so that none is within a specified keep-out interval. For STEREO to date, the only wheel-speed-avoidance band used is within 20 rad/s of zero, chosen to minimize time with possible wheel stiction. The net effect of this is several speed pattern resets when avoidance is active. This effect can be seen in Fig. 12, which is a blowup of a single momentum cycle from Fig. 10 on Ahead; Behind performance is similar to Ahead's. At each speed pattern reset, there is a pointing disturbance, but no wheel dwells at or near zero speed for a long time, thus avoiding repeated disturbances due to stiction at wheel-speed reversals.

Typical Performance During a Good Attitude-Error Period

Typical attitude errors during a good period are shown in Fig. 13. These error data were directly measured from the Ahead GT on day 157 of 2008. The GT data were sampled at 250 Hz and were usually available for ~10 min every day. Figure 14 is the same data in the frequency domain, with the mean wheel speeds for the data span shown and plotted. It is evident that the GT experiences a noticeable disturbance at the wheel-speed frequencies, but those frequencies are not the dominant error frequencies. The largest-amplitude disturbance is at ~0.55 Hz, which is the first-bending-mode frequency of the S/WAVES booms. This frequency is always present in power spectral density (PSD) plots of GT error. It is well outside the *y*/*z* control bandwidth (of order 0.01 Hz); however, it has not been a problem for the instruments. Also noticeable on Fig. 14 are spikes at frequencies of approximately 1.2, 10, and 50 Hz, which are the solar panel first-bending modes, the ST update rate, and the G&C control update rate, respectively. These spikes are also always visible in GT PSD plots, but they do not contain much energy. In addition, a 100-Hz harmonic of the 50-Hz control cycle is always visible. Behind's data during its good periods are similar to Ahead's data.

Typical Performance During a Bad Attitude-Error Period

A typical period of bad attitude error (for Behind, day 93 of 2008) is shown in Fig. 15. These data are 250-Hz GT data, similar to those in Fig. 13. The large errors are indicated by spikes, roughly 2 min apart. These spike anomalies have been noted since early in the mission, but a definitive explanation of their cause has remained elusive. The spikes occur on both spacecraft, but they are much more prevalent on Behind, where in fact they are the limiting factor for fine-pointing performance. They are clearly not just vibrational resonance at wheel-speed frequencies, which are much faster

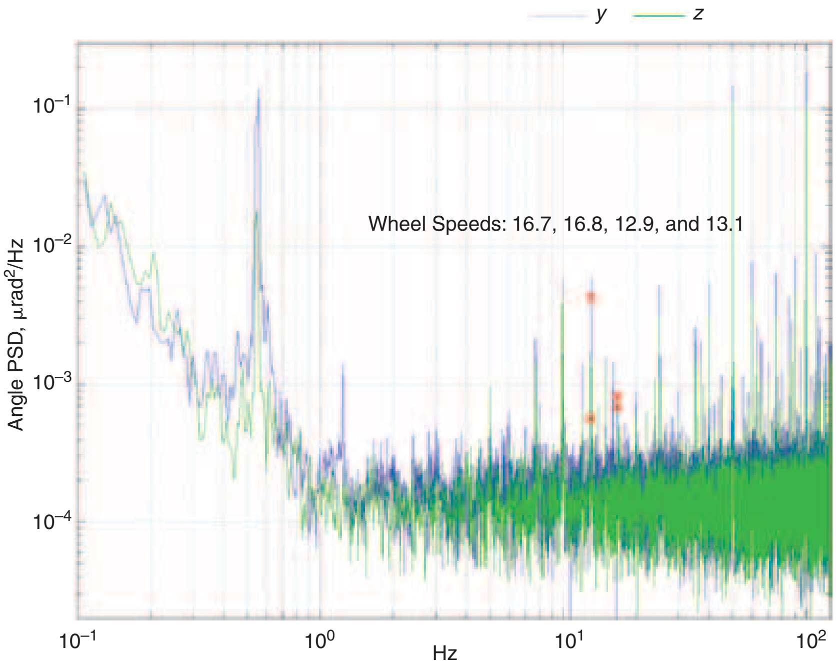

Figure 14. GT reported off-Sun error PSD for Ahead data from Fig. 13.

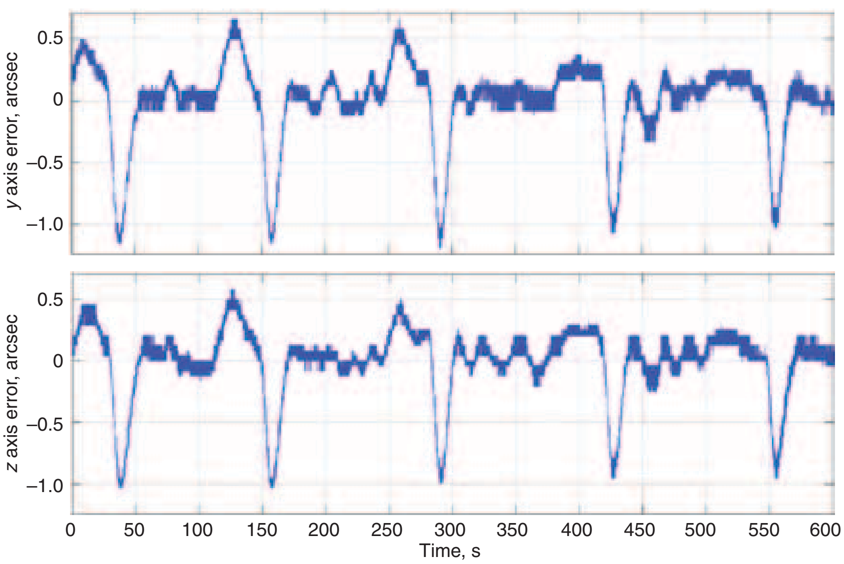

Figure 15. Off-Sun attitude error measured by the GT for Behind at time 2008:093:19:15:58Z.

Table 2. Performance metrics for typical good and bad data spans.

	Ahead good data (arcsec)			Behind bad data (arcsec)	
	y	*z*	Requirement	*y*	*z*
Accuracy	0.077	0.070	2.42	0.312	0.268
Jitter	0.055	0.051	1.53	0.178	0.157
Stability-1	0.097	0.090	1.9	0.389	0.344
Stability-2	0.113	0.104	3.75	0.520	0.451

The Ahead good data correspond to the data plotted in Figs. 13 and 14; the Behind bad data correspond to the data in Figs. 15 and 16.

than ~0.01 Hz. This conclusion is reinforced by the data shown in Fig. 16, the same data as Fig. 15 in the frequency domain. This figure looks very similar to Fig. 14, which shows a good period. The wheel-speed disturbances are noticeable, but they are not particularly large and are clearly not at the frequency of spike recurrence in Fig. 15. One possible explanation for the spikes that has been investigated is possible variation in wheel friction,[7] but we have not yet been able to identify a mechanism for this behavior.

Performance Versus Requirements

As should be clear from the figures, STEREO pointing performance to date has been quite good even during the bad periods, but how does it compare to the requirements presented in Table 1? Metrics are computed with the STEREO weighting functions for the typical good and bad data of Figs. 13 and 15, and they are compared with the requirements in Table 2. The good STEREO metrics are much better than the corresponding limits. Figures 15 and 16 and Table 2 show that the spikes degrade the metrics noticeably from good data, but the metrics for bad periods are still well within the limits. To date, STEREO G&C performance has been successfully meeting the pointing requirements and enabling the collection of large volumes of high-quality images.

Performance Improvement with Use of GT-Derived Rate

The rate-feedback term in the onboard pointing-control law (for the *y*/*z* components) can optionally be obtained from gyro data or from rates derived from the GT-measured off-Sun angles. Prelaunch simulations indicated that best performance was expected with use of the GT-derived rates. The GT is in principle less noisy than the gyros, and because GT is also used for the angle error term, issues such as cross-coupling due to IMU/GT co-alignment uncertainty can be avoided by using GT rates. However, early in operation, gyro rates were used until GT rate use was enabled on day 213 of 2007 for Ahead and day 207 for Behind. Figure 17 shows attitude error from days 190 to 242 of 2007, and the time GT rate use began is noted. The improvement in pointing performance is evident.

Table 3 gives metrics (larger of *y*/*z* axis) in arcseconds for each spacecraft, for 10-min, 250-Hz GT data sets on days (in 2007) just before and just after GT rate use was enabled. The improvement in Ahead is significant and immediate, for all metrics, as is also evident in Fig. 17. However, the improvement in Behind pointing immediately after enabling the GT rate (day 208) is minimal at best because Behind was in a bad period at that time, and the spikes limit the pointing performance. As shown in Fig. 17, Behind entered a good period around day 228, and the metrics for that day are much improved.

CONCLUSION

The challenge in designing a G&C system for STEREO was to design a single, flexible, and configurable set of algorithms that can be tuned in-flight to handle the idiosyncrasies of individual spacecraft that might not behave in-flight as modeled on the ground. To date, as is evident in the data, the STEREO G&C system has easily exceeded all mission pointing-performance requirements for each spacecraft. Despite the fact that the two spacecraft are nearly identical, there are noticeable differences between the pointing performances of the two, including some interesting attitude-error spike behavior. The rich set of tunable parameters has allowed performance to be tweaked on each spacecraft and should continue to enable each of the STEREO spacecraft to meet pointing requirements during the extended mission.

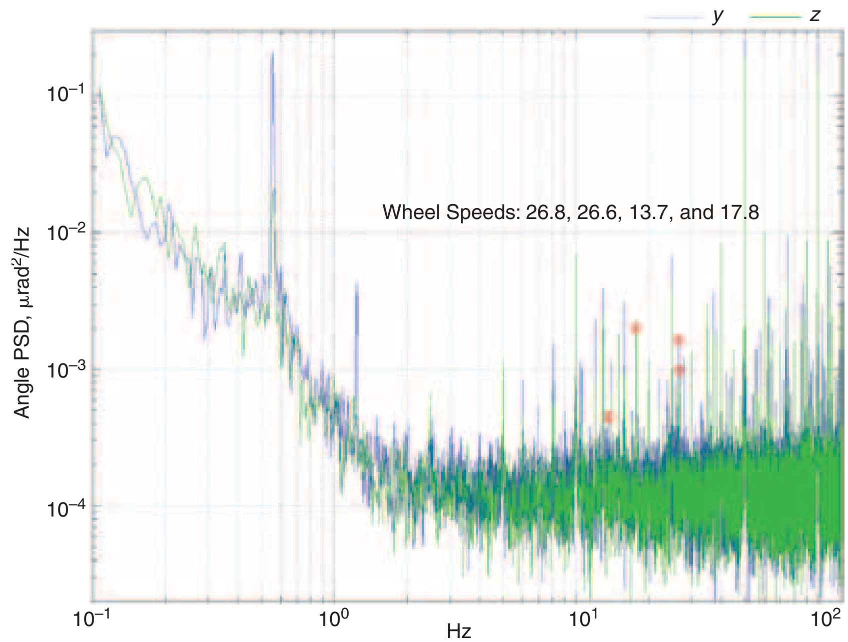

Figure 16. GT reported off-Sun error PSD for Behind data from Fig. 15.

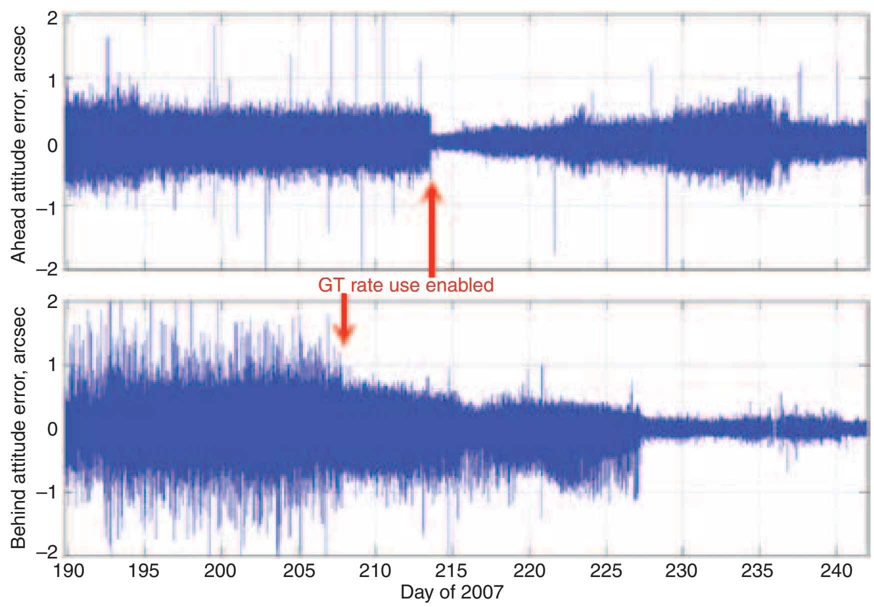

Figure 17. Ahead (a) and Behind (b) *y*-axis attitude errors before and after enabling use of the GT rate.

Table 3. Effect of GT rate use on attitude performance metrics.

Day	Accuracy (arcsec)	Jitter (arcsec)	Stability-1 (arcsec)	Stability-2 (arcsec)
Ahead				
212	0.179	0.149	0.307	0.303
214 (with GT rate use)	0.066	0.052	0.087	0.098
Behind				
206	0.381	0.300	0.641	0.637
208 (bad day with GT rate use)	0.388	0.273	0.594	0.670
228 (good day with GT rate use)	0.070	0.055	0.102	0.110

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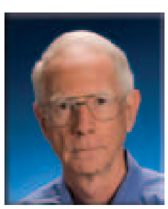

J. Courtney Ray