STEREO Mission Operations

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Solar TErrestrial RElations Observatory (STEREO) mission operations team is tasked with maintaining the health of the two STEREO spacecraft, Ahead and Behind, and ensuring the flow of science data from the spacecraft to the science community. The STEREO ground system includes a STEREO data server for distribution of all of the data and products required for operation of the STEREO observatories, as well as two hardware-in-the-loop simulators for verification of commanding and analysis of anomalies. The STEREO ground system is uniquely divided between the two spacecraft such that communications with the two spacecraft can be simultaneous while minimizing the risk of confusion. This division has been consistent through all phases of STEREO operations: planning, real-time operations, and assessment. Particular consideration was given to the area of command and memory management, where differences between the two spacecraft must be maintained. Since the STEREO launch in October 2006, the mission operations team has completed the phasing orbits/early operations checkout phase of the mission, transitioned to the heliocentric orbit/prime science mission, and completed a move to automated/unattended real-time operations, all the while focusing on the science data return and maintaining the health and safety of each of the spacecraft while operating with a minimal operations team size.

INTRODUCTION

The Solar TErrestrial RElations Observatory (STEREO) spacecraft successfully launched from Cape Canaveral Air Force Station, Florida, with a Boeing Delta II 7925-10L rocket on 26 October 2006 at 0052 UTC. One launch vehicle was used to launch the stacked STEREO observatories; STEREO A (Ahead) was mounted on top of the STEREO B (Behind) observatory. At 0117 UTC, the Delta third stage completed the injection of the STEREO stack into its highly elliptical orbit, and the two observatories separated from each other by the separation springs. Two minutes later, more separation springs separated STEREO A and STEREO B, and at 0120 UTC, all three objects emerged from the Earth's shadow into sunlight. By using the trajectory determined from the early Deep Space Network (DSN) tracking data, the launch injection itself was extremely accurate, with an estimated spacecraft stack underburn of 0.393 m/s, only about 0.1 σ.

The STEREO mission design used four phasing orbits, which lasted 2 months, to target three lunar swingbys, one for Ahead and two for Behind, to place each observatory in its correct heliocentric orbit (see Fig. 1). During this time, the spacecraft subsystems were checked out, and most instrument commissioning objectives were completed. Although the potential for a ΔV maneuver existed at each apogee and perigee, a possible total of 9 maneuvers for Ahead and 11 for Behind, only 4 maneuvers for Ahead and 6 maneuvers for Behind were necessary because of the very accurate launch injection. DSN track coverage during the phasing orbits consisted of continuous coverage for the first week, 24 h of coverage for each ΔV maneuver, and a daily 3-h track otherwise.

After the lunar swingbys, the prime science mission commenced on 22 January 2007, when the Behind spacecraft entered heliocentric orbit and both spacecraft were moving away from the Earth at a rate of 22°/year. The track schedule shifted to one daily 4-h track for each spacecraft with the primary objective to play back the solid-state recorder (SSR) data. The STEREO data return requirement, deliver 5 Gbits of data per day averaged over a year, was designed to maximize science data return at a reasonable cost to the mission. Therefore, there is typically only one daily opportunity to downlink any particular data, because the instruments continuously generate data and most SSR partitions are set to overwrite.

STEREO mission operations were designed around this data return requirement, and although loss of some data was deemed acceptable, maximizing data return was kept a priority. After 6 months in heliocentric orbit, STEREO returned a daily average of 7.0 Gbits of data from the Ahead spacecraft and 7.7 Gbits of data from the Behind spacecraft. STEREO employs decoupled spacecraft bus/instrument operations modeled after

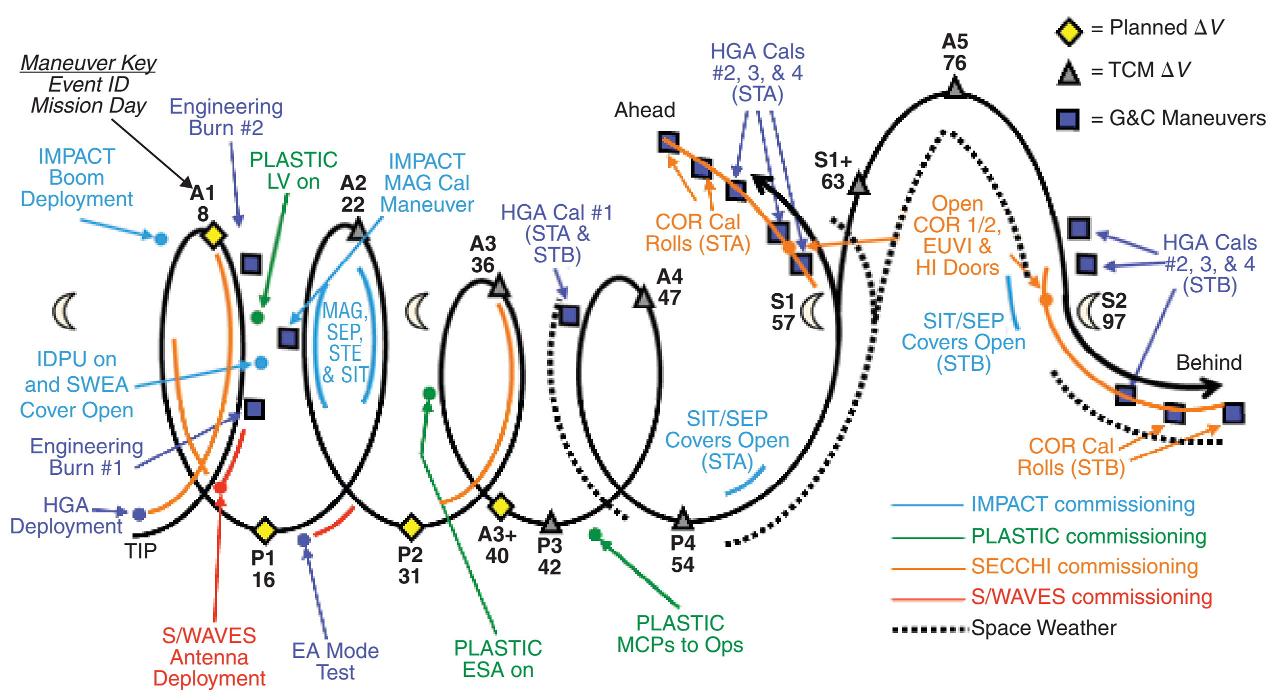

Figure 1. STEREO phasing orbits and significant early operations. A*x*, apogee *x*; Cal, calibration; COR1 and -2, coronagraphs 1 and 2; EA, Earth acquisition; ESA, electrostatic analyzer; EUVI, extreme ultraviolet imager; G&C, guidance and control; HGA, high-gain antenna; HI, heliospheric imager; IDPU, instrument data processing unit; IMPACT, *In situ* Measurements of PArticles and Coronal mass ejection Transients; LV, low voltage; MAG, magnetometer; MCPs, microchannel plates; P*x*; perigee *x*; PLASTIC, PLAsma and SupraThermal Ion Composition Investigation; S*x*, lunar swingby *x*; SECCHI, Sun–Earth Connection Coronal and Heliospheric Investigation; SEP, solar energetic particles package; SEPT, solar electron and proton telescope; SIT, suprathermal ion telescope; STA, STEREO A; STB, STEREO B; STE, suprathermal electron telescope; S/WAVES, STEREO/WAVES; SWEA, solar wind electron analyzer; TCM, trajectory correction maneuver; TIP, target interface point.

the Thermosphere, Ionosphere, Mesosphere Energetics and Dynamics (TIMED) program. Operating only the spacecraft bus and engaging a highly automated system, STEREO mission operations are able to use a small team to safely operate two spacecraft simultaneously. The STEREO ground system was developed to support this concept of highly automated operations from the APL Mission Operations Center (MOC) and multiple Payload Operations Centers (POCs). In addition, the STEREO ground system includes a STEREO data server (SDS) for distribution of all of the data and products required for operation of the STEREO observatories, as well as two hardware-in-the-loop (HIL) simulators for verification of commanding and analysis of anomalies. This paper will discuss the STEREO ground system used by mission operations as well as the processes and tools used by mission operations for planning, real-time operations, and assessment of spacecraft performance. These processes and tools allow for the safe operation of two spacecraft by a minimum number of staff while maintaining a high rate of science data return.

GROUND DATA SYSTEM/NETWORK ARCHITECTURE

The STEREO ground system was developed with the intention that the two spacecraft could be operated simultaneously and independently of each other. To achieve this goal, the ground system architecture is such that for most MOC functions, there are separate hardware/software components for each spacecraft. This approach minimizes the risk of confusion among operators and other personnel, and it allows for the simultaneous operation of both spacecraft. The STEREO ground system architecture is shown in Fig. 2 and described in the following paragraphs.

The STEREO ground system is segmented into several distinct network "zones." This design ensures the integrity of the STEREO spacecraft as well as STEREO and APL network resources. All real-time command and control of the STEREO spacecraft originates in the STEREO ground system Restricted IONet (Internet Protocol Operational Network). The Restricted IONet is a secure NASA network that places secure controls on the users and facilities. Each spacecraft has a primary and a backup command workstation in the Restricted IONet. Dedicated Memory Allocation Examiner (or "MAX") workstations for each spacecraft are also located on this network. Additionally, each spacecraft has a third command workstation, one that is remotely located in a separate building on the APL campus. These workstations would be used to ensure spacecraft health and safety in the event that the entire STEREO MOC becomes inaccessible.

The STEREO firewall isolates the Restricted IONet from the remaining components of the STEREO MOC

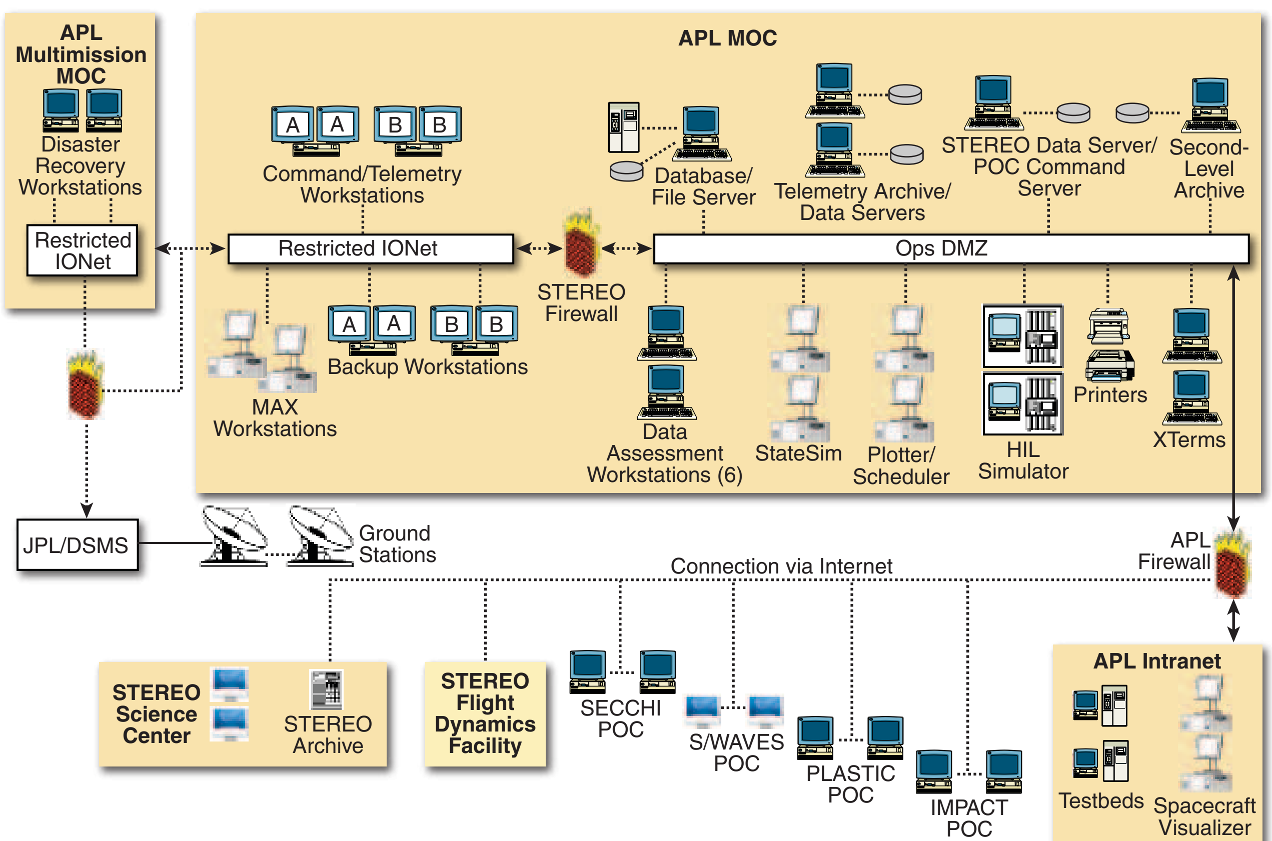

Figure 2. STEREO ground system architecture.

ground system, which reside in the operations "demilitarized zone" (Ops DMZ) network (which has fewer restrictions and is a less secure network). Among the equipment in the Ops DMZ are six STEREO assessment workstations (three per spacecraft), telemetry archive servers with 10-TB RAID (redundant array of independent disks) storage arrays (one system for each spacecraft), a second-level archive server, an SDS, and a database server. Additionally, each spacecraft has a dedicated HIL simulator with its own command and telemetry workstation.

An APL firewall isolates the Ops DMZ from the APL intranet. The STEREO development community functions in this network zone. Software development workstations and testbeds/mini-MOCs are connected to the APL intranet. This configuration allows the developers and testers to access their systems from other laboratory resources, such as employee desktop computers and laptops.

A separate dedicated network, known as the Science DMZ, supports instrument POCs located at APL. In addition to the APL-located instrument POCs, each instrument has primary POCs located at their home institutions, which also have access to the STEREO instrument command and telemetry servers, as well as the SDS, via an Internet connection. The STEREO Science Center (SSC) and the Flight Dynamics Facility (FDF), both located at Goddard Space Flight Center (GSFC) in Greenbelt, Maryland, also communicate with the STEREO MOC via the Internet by using FTP.

STEREO Data Server

The STEREO ground system consists of the APL STEREO MOC, the Deep Space Mission Systems (DSMS) ground stations, the instrument POCs, the FDF, and the SSC. To coordinate mission operations between these teams and return the science data to the mission scientists, a routine flow of data products is necessary. Figure 3 depicts the operational flow of data products for the STEREO mission. Most of these data products are available to the STEREO community through the SDS. The SDS consists of a webpage in the APL MOC where data products can be transferred to the community via FTP.

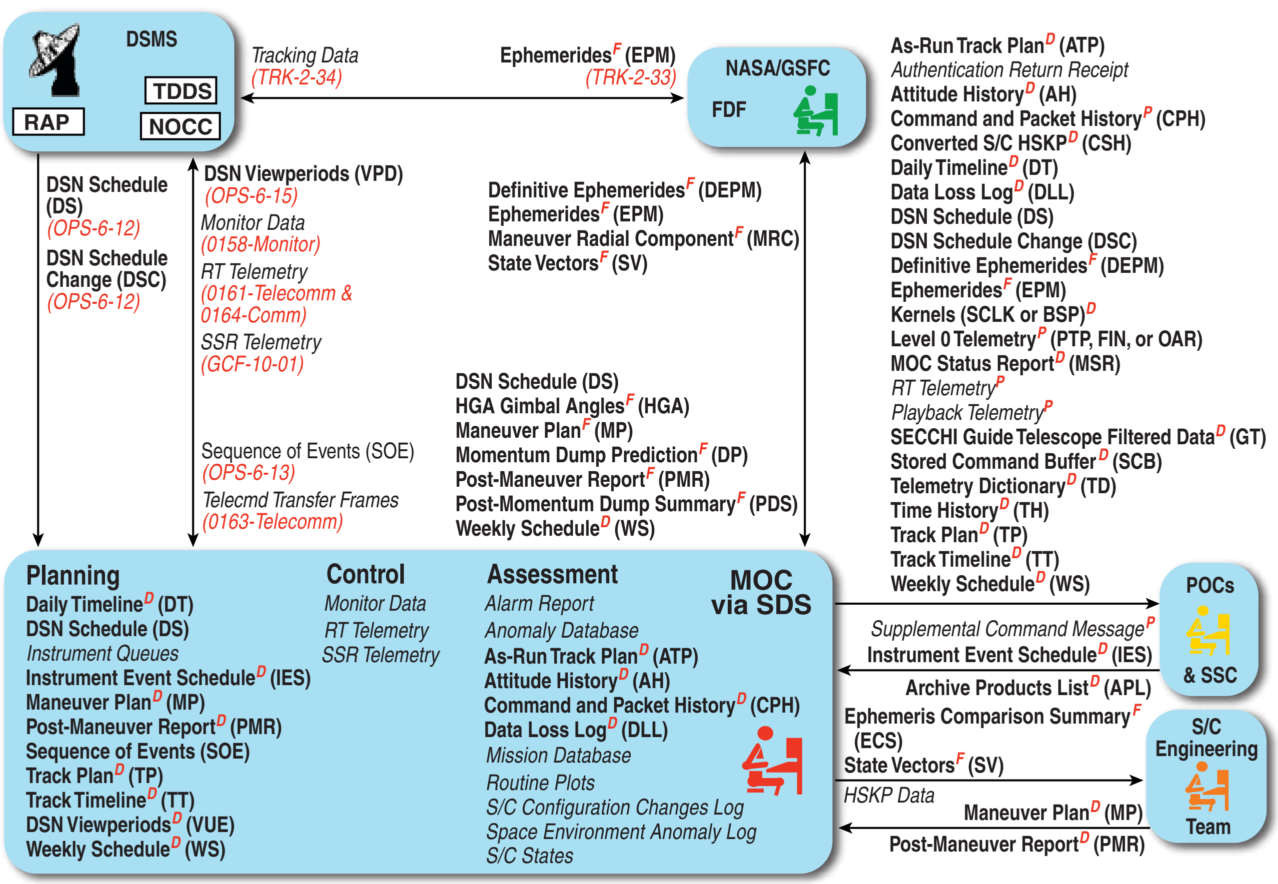

Figure 3. STEREO MOC ground network and data product flow. HSKP, housekeeping; NOCC, Network Operations Control Center; RAP, Resource Allocation Process; S/C, spacecraft; TDDS, Tracking Data Delivery System. **Bold**, product is stored on the SDS; *italic*, product is not stored on the SDS; D, defined in the MOC Data products document; F, defined in the FDF/MOC interface control document; P, defined in the MOC to POC and SSC interface control document.

HIL Simulators

Because STEREO is a two-spacecraft mission, the STEREO ground system includes two HIL simulators, designated HIL-A and HIL-B. The HIL simulators are distinct from the rest of the STEREO ground system in that they do not participate in sending commands to the two spacecraft and they do not process spacecraft telemetry. Rather, each of the simulators is a self-contained system, by and large isolated from the rest of the ground system, incorporating spacecraft engineering model hardware, flight software, a testbed platform that runs emulation software, and a ground segment (MOC and front end) to process simulator commands and telemetry.

The STEREO mission operations team (MOT) has used, and continues to use, the HIL simulators to perform a variety of activities:

- Validation of command scripts as a condition for scripts being made available for spacecraft commanding
- Rehearsal of mission-critical events, including launch and separation sequences, ΔV maneuvers, momentum dumps, instrument calibration maneuvers, etc., before their occurrence in the mission
- Verification spacecraft configuration changes, including parameter changes, macro sequence loads, modifications to the flight autonomy system, and flight-software changes, etc., before implementation aboard the spacecraft
- Development and testing of spacecraft contingency procedures
- Investigation of spacecraft anomalies
- Training of the MOT and, via mission rehearsal tests, engineering support teams

Developed over the 2 years leading up to STEREO launch, the HIL simulators are a configuration of the software testbed platforms used for unit-level testing during the integration and testing of STEREO. The HIL simulators, however, incorporate hardware and software improvements that extend the range of simulation fidelity to facilitate system-level testing so that emulated subsystems respond realistically to one another as well as to external inputs such as ground commands or fault insertions. Before launch, the HIL simulators were essential for mission operations testing and development efforts but, nevertheless, were still secondary to mission simulation tests conducted by using the actual STEREO spacecraft and associated ground support equipment (GSE) as the test platforms. Because the STEREO spacecraft would generally not be available for testing after launch, the validity of all mission operations postlaunch test efforts rested on the accuracy and realism of the HIL simulators as test platforms. Therefore, the simulators themselves were validated before STEREO launch; the comprehensive performance tests conducted on the simulators were the same as those used to validate the STEREO spacecraft. Simulator performance has, therefore, been well characterized, and all performance differences with the spacecraft are documented and well understood.

Despite the HIL-A/HIL-B naming convention, each of the HIL simulators is freely configurable to emulate, via minor changes to testbed settings and parameters, either the STEREO A or the STEREO B spacecraft because the two STEREO spacecraft are nearly identical in design. As indicated by the diagram color coding of Fig. 4, each of the simulators incorporates three component groups—spacecraft hardware (in blue), the testbed support system (in orange), and the ground segment (in green)—each of which is described below in detail. The two simulators are configured differently because of the incorporation within HIL-A of the power distribution unit (PDU) hardware that is absent from HIL-B. These component groups and the HIL-A/HIL-B differences are also depicted in Fig. 4.

Spacecraft Hardware

Both HIL simulators have at their core an engineering model of the spacecraft integrated electronics module (IEM), which includes a command and data handling (C&DH) processor card running C&DH or Earth acquisition (EA) flight software, a guidance and control (G&C) processor card running G&C flight software, an SSR, and a full IEM interface card. The simulator architecture has been implemented to support IEM functionality in simulation that is virtually indistinguishable from spaceflight operation. Besides regulating nearly all spacecraft functions and managing the spacecraft's 1553 bus, the IEM receives and transmits CCSDS-formatted (Consultative Committee for Space Data Systems) command and telemetry bit streams. Neither simulator has RF capability, so command uplink and telemetry downlink are strictly baseband.

There remain some spacecraft functions that are implemented through PDU hardware rather than the IEM, including critical functions such as the spacecraft separation sequence or the system-reset sequence. To retain this functionality in simulation, component boards of the spacecraft PDU were assembled into a partial PDU chassis that has been integrated into the HIL-A simulator. The partial PDU consists specifically of a PDU 1553 interface card and two command decoder cards, all of which are firmware-programmable and custom-built for STEREO. Because these three cards do not constitute a full PDU, extensive engineering was necessary to mate the "real" PDU hardware components to PDU components that exist only in testbed emulation. Only HIL-A incorporates a partial PDU; HIL-B relies exclusively on PDU emulation in testbed software. Although the emulation is, at best, a simplified PDU representation, it is nevertheless sufficient to support the preponderance of mission operations testing.

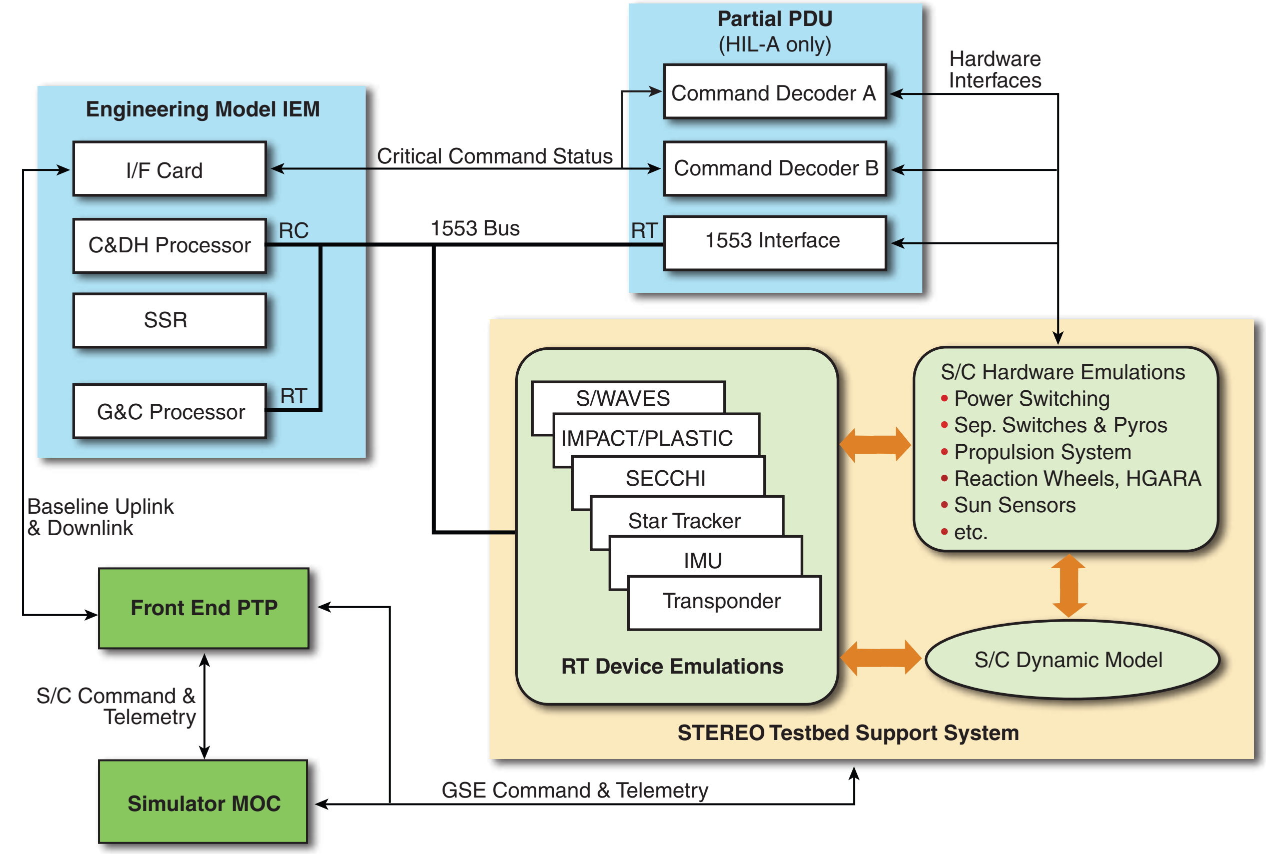

Figure 4. HIL simulator component groups and STEREO A/B differences. BC, bus controller; HGARA, high-gain antenna rotary actuator; I/F, interface; IMU, inertial measurement unit; S/C, spacecraft.

Testbed Support System

In both simulators, the spacecraft hardware components are integrated with a dedicated STEREO Testbed Support System (STSS) that, along with other simulator support functions, performs software emulations of spacecraft subsystems and components that aren't physically part of the simulator. The STSS resides on the 1553 bus and emulates the activity of remote terminal (RT) devices that were never incorporated as simulator hardware, devices such as the Deep Space Transponder, inertial measurement units, star tracker, and three instrument data processing units. The STSS software also includes extensive modeling of other spacecraft hardware functions, especially those functions controlled onboard the spacecraft through the PDU; these functions include all spacecraft-wide power switching, pulsed control of relays, pyro and thruster operation, reaction wheel and high-gain antenna (HGA) rotary actuator control, and Sun sensor measurement interfaces. Also modeled within the STSS software are the overall spaceflight system dynamics that determine how all sensor inputs respond to actuator outputs. Needless to say, these areas and layers of emulation/modeling are linked together so that the interdependencies among all spacecraft subsystems are captured in simulation.

Ground Segment

Each of the HIL simulators has a dedicated command and telemetry system and a dedicated front-end/programmable telemetry processor (PTP). The command and telemetry system is a UNIX workstation running the same EPOCH 2000 ground software used by the STEREO MOC to process simulator commands and telemetry. The command and telemetry workstation connects to both the front end and STSS via network socket connections, and it can control the configuration and functions of both by using GSE commands and telemetry. CCSDS-formatted spacecraft commands are sent from the command and telemetry system to the simulator IEM after being clocked and encoded at the front end. Inversely, spacecraft telemetry generated by the simulator IEM is "downlinked" as a frame-synced, CRC-encoded (cyclic redundancy code), randomized bit stream to the PTP, which passes the processed telemetry frames to the simulator command and telemetry system for display, storage, and additional processing. Note that the simulator command and telemetry system maintains a dedicated telemetry archive, so simulator data are never intermingled with actual mission data.

The simulator ground segment shares an architecture similar to that of the STEREO ground segment, with the simulator MOC performing most of the same functions as the STEREO MOC and the front end/PTP performing functions analogous to those of a DSN ground station. Because of this shared architecture, mission operations testing can be performed with the same command, control, and telemetry display facilities that are used for actual spacecraft operations on the IONet, and in most cases, scripted command sequences tested on the HIL simulator are directly usable in actual spacecraft operations.

STEREO MISSION OPERATIONS

Introduction

The APL STEREO MOT works in the MOC and has the primary responsibility of management of the spacecraft bus, including the development of command messages and the uplink to the spacecraft by way of the DSMS. Recovery of spacecraft bus engineering (state-of-health) telemetry and the performance analysis based on this telemetry are also performed at the MOC. The MOC receives instrument command messages from the POCs and, after verification that the command application identifiers (APIDs) are appropriate for the POC they came from, queues these for uplink to the spacecraft on the basis of start and expiration times appended to the command messages by the POC. The MOC does not directly verify any instrument commands and does not decommutate or analyze any instrument telemetry aside from currents and temperatures observed from the spacecraft side of the instruments. Each POC is individually responsible for the health and safety of its instrument. In addition to the POCs, the other external teams that support STEREO mission operations are the DSN; the FDF, which performs navigation for the STEREO mission; and the SSC, which is the primary archive of STEREO data and the focal point for education and public outreach. These external operations teams are described briefly below.

- **POCs:** The POCs are the instrument operations centers that generate the commands for each of the four STEREO instrument suites (SECCHI, IMPACT, S/WAVES, and PLASTIC) and monitor instrument health and safety. These centers are located at the Navel Research Laboratory in Washington, DC (SECCHI); the University of California, Berkeley (IMPACT), the University of Minnesota, Minneapolis (S/WAVES); and the University of New Hampshire, Durham (PLASTIC). These are the home bases for the instrument POCs, but they are able to operate remotely when necessary, and they also maintain a presence at the MOC.
- **DSN:** The DSN will be used to provide communications to both spacecraft from launch to end of life. The use of all three DSN antenna facilities—Goldstone, Madrid, and Canberra—is required to determine the elevation component for the navigation of each spacecraft. Nominally, a 3.5- to 5-h track, depending on spacecraft range, centered every 24 h per spacecraft will be conducted by using the 34-m beam wave guide subnet. The MOC is connected to the DSN via Restricted IONet links. Commands will be flowed to the DSN by using the standard Space Link Extension Service over the Restricted IONet, and real-time telemetry will be flowed from the DSN to the MOC over the Restricted IONet by using legacy user datagram protocol (UDP) service. Playback data received at the DSN station will be flowed to the Central Data Recorder at the Jet Propulsion Laboratory (JPL), where they will in turn be flowed in half-hour increments to the MOC via FTP as intermediate data recorder (IDR) files. Orbit data for each spacecraft will be provided to the DSN from the FDF for acquisition, and ranging data will be distributed from the DSN to the FDF for orbit determination purposes over the Restricted IONet.
- **FDF:** The FDF at the NASA GSFC determines the orbits of the observatory from tracking data provided by the DSN ground stations, and it generates predicted DSN station contact periods and predicted and definitive orbit data products. The FDF also generates orbital ephemeris data in support of orbit maneuvers that satisfy science and mission requirements, and it transfers this information to the STEREO MOC via the FDF Products Center.
- **SSC:** The SSC is located at the NASA GSFC and serves four main functions for the STEREO mission. First, it is the prime archive of STEREO telemetry and data, and it serves that data to the international science community, and to the general public, through its own website. It is also the collection site, processing center, and distribution point for STEREO space weather beacon data. Science coordination between the STEREO instruments, and between STEREO and other observatories, is performed through the SSC. Finally, the SSC is the focal point for education and public outreach activities.

The STEREO observatories continually point at the Sun as they move away from the Earth at a rate of 22°/year while remaining approximately the same distance from the Sun throughout the mission. In this orbit, the solar array input power is sufficient to cover any instrument/spacecraft mode, and the observatory remains thermally stable. Each instrument has its own partitions to use on the SSR, which are typically set by the MOT to an overwrite mode. Thus, the instruments are left with no power, thermal, or SSR constraints other than managing the amount of data being placed in their SSR partitions that is ideal for the decoupled spacecraft/instrument operations concept employed by STEREO.

This operations concept greatly simplifies mission operations and allows for a smaller operations team size and automated, unattended real-time operations for most of the spacecraft contacts.

The STEREO MOT at APL launched with 14 team members. This team was reduced to 12 by the end of the phasing orbits. The launch team organization consisted of one mission operations manager, four real-time controllers, eight spacecraft specialists, and one anomaly officer.

After the phasing orbits, the team operated without the anomaly officer, and the mission operations manager also served as a spacecraft specialist. Six months after launch, the team transitioned to unattended tracks and was reduced to eight spacecraft specialists (including the mission operations manager). One year after heliocentric orbit, the team was reduced again to six spacecraft specialists for the remainder of the mission.

The positions listed above have the following responsibilities:

- **Mission Operations Manager:** The mission operations manager was responsible for verifying the readiness of the ground system and the MOT for launch. The manager was also the primary maneuver planner during the phasing orbits. In addition, the mission operations manager prepares the weekly status report for the MOC and serves on the postlaunch Configuration Control Board. After the completion of all spacecraft maneuvers, the mission operations manager also can serve as one of the spacecraft specialists.
- **Real-Time Controllers:** The real-time controllers were the primary interface with the DSN for each real-time track. They configured the ground system, verified readiness for each track with the DSN station, and handled ground system contingencies.
- **Spacecraft Specialist:** The spacecraft specialists serve as the planners and the real-time spacecraft evaluators during DSN tracks, and they perform spacecraft assessment. The spacecraft specialist team rotates through these roles on a weekly basis. During unattended operations, the real-time evaluator works daily planning and real-time assessment.
- **Anomaly Officer:** The anomaly officer was unique to early operations. This role consisted of organizing the larger team (mission operations and spacecraft engineers) to solve anomalies early after launch. The anomaly officer is intimately familiar with the *STEREO Contingency Handbook*[1] and was able to effectively lead the team in resolving anomalies.

STEREO spacecraft mission operations are currently divided into three primary roles: weekly planning, daily planning/real-time assessment, and long-term assessment. The current team of eight is rotated weekly through these roles for each spacecraft, and the two people who are not assigned to one of these roles serve as a substitute for team members on vacation or sick leave as well as develop new spacecraft command sets and perform in-depth analysis of anomalies identified during the assessment process. Operations planning, real-time operations, and assessment are described in depth in the following subsections, and particular attention is given to some of the tools and concepts used to simplify the operation of two spacecraft simultaneously.

Spacecraft Operations Planning

The STEREO mission consists of two nearly identical spacecraft in heliocentric orbit at approximately 1 astronomical unit (AU), one ahead of the Earth and one behind it. The angular separation of the two spacecraft is gradually increasing with a drift rate of 22°/year for each spacecraft. The STEREO mission has a goal of 2 years. The mission phases are listed in Table 1.

Each three-axis-stabilized, constant Sun-pointing spacecraft continuously collects science data from four instrument suites. The spacecraft bus provides nominal attitude, power, thermal control, data storage, X-band communication, and rule-based autonomy. The nominal track schedule is one 4-h DSN track each day approximately centered every 24 h. Outside of a DSN track, the spacecraft is configured to continuously broadcast space weather data at a low bit rate to various NOAA-coordinated international antenna partners.

The STEREO MOC ground network (see Fig. 1) consists of interfaces to the DSN for telemetry, tracking, and command support, FDF for navigation support, instrument POCs for instrument support, and SSC as the science data center. The STEREO mission employs a

Table 1. STEREO mission phases.

Phase	Description	Duration
Launch/ascent	From liftoff to separation of both observatories from the launch vehicle and deployment of each observatory's solar arrays and HGAs.	2 h
Phasing orbit	From the end of the ascent phase to the final lunar swingby for each observatory. The duration of the phasing orbit phase of the mission will be different for each observatory.	51 days (Ahead) 89 days (Behind)
Prime science	From the point when both observatories enter the heliocentric orbit phase to 2 years from that date.	2 years

decoupled instrument operations concept, in which each instrument and the spacecraft bus are operated almost entirely independently of each other as described above. The instrument POCs are responsible for planning, scheduling, and generating instrument commands, instrument health and calibration, and any synchronization of instrument operations between spacecraft.

The STEREO MOT does not have unique roles and responsibilities for each staff member, i.e., each team member cycles through planning, control, and assessment roles, changing each week, one person for each role per spacecraft. This rotation scheme provides continuous cross-training of all staff for all mission operations roles, tasks, tools, and responsibilities and allows more scheduling flexibility.

For planning day-to-day spacecraft operations, an event-based approach was used. An event is a distinct, schedulable, operational activity for the spacecraft or instruments, e.g., beginning of track, start SSR playback, momentum dump, instrument calibration, etc. A platform-independent application, called Scheduler, was specified to allow each MOT member to conduct or view all planning information at his or her office desktop, the MOC, or a remote location (see Fig. 5). This program was developed as a web-based, PHP application that stores data in a MySQL database common to both spacecraft. It automatically ingests DSN schedules, maneuver plans, instrument event schedules, and view periods. Events with a routine frequency are automatically placed on the schedule, and the user can add/delete/modify any event. The application generates a weekly schedule and a track plan based on the Spacecraft Test and Operations Language (STOL) for each track. After the track is complete, the EPOCH event logs along with selected alarms are used as input to Scheduler, which automatically generates an as-run track plan for each track as a record of what occurred. To prevent confusion of data products between spacecraft, the user must select the spacecraft before editing any planning information, all data products created are kept online under different but identical directory structures, and each spacecraft-specific data product is marked with a header of Ahead or Behind.

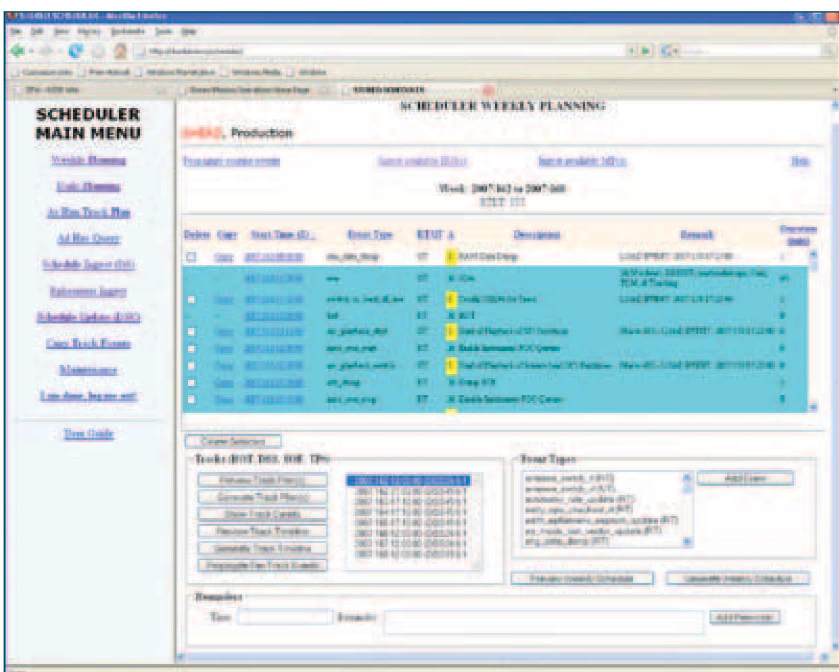

Figure 5. Weekly planning user interface.

Although Scheduler provides some high-level event-related constraint checks, detailed operational constraint checks occur in the software simulator, StateSim. The STEREO Scheduler and StateSim software are described below.

Scheduler

Planning operations for STEREO are accomplished by using a web-based scheduling application called Scheduler. Within the STEREO ground system, Scheduler imports data products from the SDS, interacts with users via a web browser interface, and generates data products, which in some instances, are eventually used in the STEREO telemetry and command system (EPOCH). Figure 5 shows the user interface for the weekly planning of the Ahead spacecraft.

The Scheduler application supports both a production mode and a test mode of operations. In the production mode, a separate directory structure within the STEREO ground systems allows Scheduler to interact with each observatory separately for the production of input and output data products for flight. Similarly, the test mode allows for the production of input and output data in support of testing on the HIL simulators for each spacecraft. This section mainly concentrates on Schedulers function in the flight or production modes of operations.

In general, operations planning and use of Scheduler consist of the following activities that are necessary to support a scheduled observatory DSN track:

- Track scheduling
- Maintenance activity scheduling
- Instrument command uplink scheduling
- SSR management
- Track plan generation

Track Scheduling: Scheduling of STEREO observatory tracks is done through the DSN scheduling system. With multiple users of the DSN system performing both short-term and long-term track planning, multiple schedules and schedule changes is the norm within the scheduling environment. The Scheduler application ensures that the latest DSN schedule or schedule changes have been ingested into the STEREO ground system. As an end result, the MOT reduces the time spent retrieving and reviewing track schedules.

Maintenance Activity Scheduling: One of the main tasks of the MOT is maintaining and evaluating the health of the spacecraft. For each observatory, coarse maintenance event planning is handled by the Scheduler application. Therefore, the MOT can schedule the frequency of routine maintenance events or schedule necessary sporadic events with assurance that an event will be initiated without delay. Examples of these types of events include the following:

- Updates to spacecraft and Earth ephemeris
- Time updates
- Wheel momentum management
- Instrument calibrations
- Spacecraft macro and autonomy maintenance
- Spacecraft and instrument software updates

Instrument Command Uplink Scheduling: Because of decoupled instrument operations on STEREO, instrument command uplink is handled via the POC queue manager. The management of the POC queues for uplink of instrument command is mainly handled through the Scheduler application during the weekly planning cycle. This method of commanding for the instrument greatly reduces the interaction with the instrument teams, typically leaving single weekly meetings for coordination of instrument uplink commanding.

SSR Management: Nominally, all science, space weather, and spacecraft housekeeping data are recorded onboard the spacecraft. The Scheduler application enables the STEREO MOT to control the downlink of the SSR data with onboard time tag and macro commands during the weekly planning cycle, thus enabling the ability to reduce communication time and increase data volume.

Track Plan Generation: After all track schedules, maintenance events, instrument commands, and SSR planning are coordinated throughout the planning cycle, the STEREO MOT generates track plans; the first step in this process is to check scheduling constraints of the planned events. Warnings are generated for any condition that may constitute a constraint violation, or a message indicating that a track plan has successfully passed generation is provided. This application reduces both human error and time spent manually reviewing what can be a set of complex procedures for the STEREO MOT.

The Scheduler application is a key ground software tool for STEREO mission operations. With the complexities of planning and operations for two spacecraft, Scheduler has allowed the simplification of these processes and tasks. Cost and time have been greatly reduced by using this tool.

StateSim

The purpose of the software state simulator named StateSim is to provide a high-fidelity model of the STEREO spacecraft through use of command bit strings and data structure dump packets from command and telemetry source files. The StateSim software is based on actual spacecraft C&DH and G&C subsystem flight-software code. The system is designed to perform faster than real-time spacecraft simulations to predict the timing and effect of stored memory (time tag and macro) and real-time command execution. StateSim produces several status reports and a model state file containing spacecraft final conditions that are propagated forward for each simulation (see Fig. 6).

The StateSim application has been previously used for several APL missions, and STEREO incorporated several new enhancements to improve and adapt the software capabilities for STEREO operations. The capability to model the autonomy system's preparation and arming of the spacecraft propulsion system for ΔV maneuvers and momentum dumps was added to analyze command execution and constraint violations for these critical events. The capability for real-time simulations to parallel process spacecraft commands and data structure dumps by using the packet header times in the telemetry dump files was added to ensure that the activities are processed in chronological order. The enhanced handling of spacecraft commands and dumps improved the MOT's ability to maintain memory objects and parameters, which ultimately increased the fidelity of StateSim. To reduce the challenges associated with event planning and executing simulations for two spacecraft, a new web-based front-end preprocessor was added to StateSim to implement a reasonable amount of automation to the simulation setup and execution process. The preprocessor user interface also includes the capability to execute the StateSim ancillary programs (buildDB and parmView), which allows the user to build the command databases and view data structure file contents.

The STEREO MOT developed the new intranet graphical user interface (GUI) for StateSim to improve the software command line interface, reduce the operational time required for team members, improve the recordkeeping process related to each simulation, and allow all team members to easily use this complex soft-

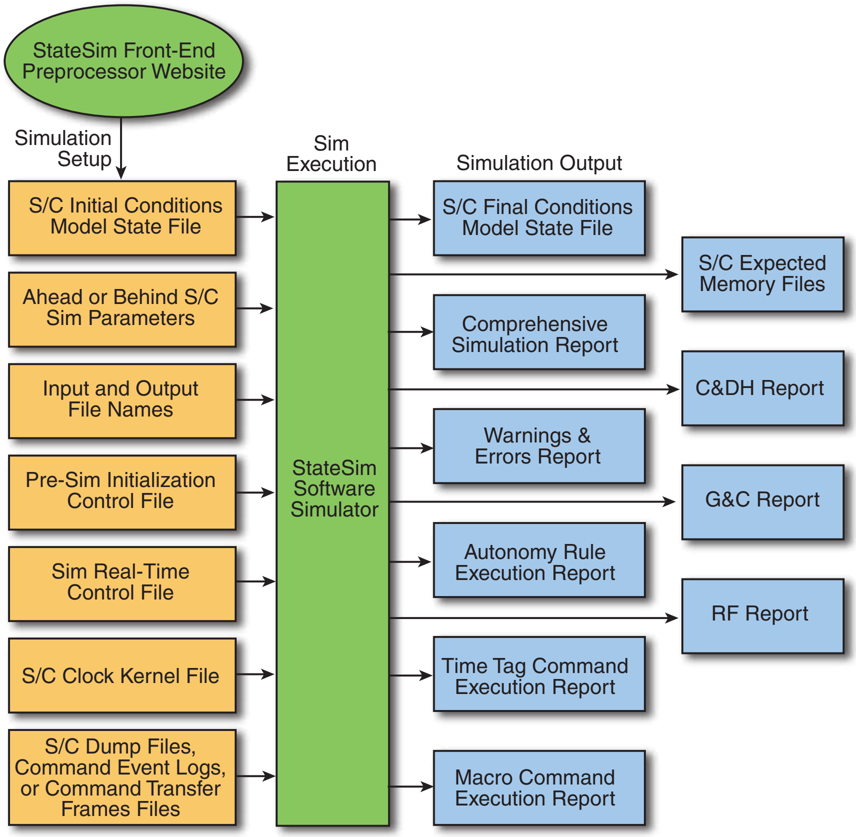

Figure 6. STEREO StateSim interface and data flow diagram. S/C, spacecraft.

ware tool. The StateSim front-end preprocessor consists of a multi-tabled MySQL database, Apache web server, PHP scripts, and the EPOCH connection programs. The EPOCH connector software runs on STEREO Ahead and Behind DMZ workstations to create an automated interface to the EPOCH stream to handle the remote commanding. The EPOCH relay software runs on the StateSim DMZ workstation to communicate with the EPOCH connector to provide remote commanding with the EPOCH stream. The Apache web server and interpreted PHP scripts are used to implement the web-based GUI. The MySQL database supports two spacecraft (Ahead and Behind) with two simulation environments (production and test), and it is used to store pertinent simulation data with a unique run identification number that can be queried online.

During the planning operations for STEREO, StateSim is used to validate the spacecraft weekly command loads and other activities that are generated from the planning software interface (Scheduler). StateSim is also used to maintain the real-time spacecraft configuration (modes and states), parameters, and memory objects through postprocessing of real-time spacecraft command logs and telemetry dump packets. Detailed operational constraint checking is performed for commands during each simulation, and StateSim alerts the user when constraints are violated.

Each STEREO planning week ends with a two-step process that includes a maintenance and planning simulation. First, the maintenance simulation is executed to update StateSim with the latest spacecraft real-time activities by using the previous week's EPOCH command event logs and spacecraft dump files. Next, by using the final conditions from the previous maintenance simulation, the planning simulation is executed with the Scheduler track plans to verify all planned spacecraft activities that will occur during the current week through the next 2 weeks.

To accomplish the two simulations, the weekly planner logs into the StateSim preprocessor website and makes a series of selections. The preprocessor software then reprocesses the STOL scripts that are listed in the selected Scheduler track plans to parse commands, insert necessary simulation times for waits and pauses, and parse keywords that allow the execution or skipping of conditional blocks of commands. Next, the preprocessor automatically executes the reprocessed STOL scripts through an EPOCH command and telemetry stream to generate an EPOCH command log file. Finally, the preprocessor software automatically executes the StateSim simulation by using the website selections and EPOCH command log file as the source input. Once the simulation is complete, the planner will review the StateSim output files and reports online to verify that the planning activities are error free.

The faster-than-real-time StateSim simulations provided STEREO with an efficient method for evaluating the planning activities of two spacecraft with a minimally sized operations team. The incorporated StateSim software enhancements greatly improved operational constraint checking and increased the fidelity of simulations. The addition of the web-based front-end pre-processor provided a better user interface and increased automation to help reduce time, cost, and complexity for STEREO mission operations.

Command Management

STEREO mission operations rely almost exclusively on *scripted* command sequences to control spacecraft and ground system activities during real-time tracks with the DSMS. All command scripts use STOL and are executed by the EPOCH 2000 Ground System Software.

Command Procedures and Templates: Command procedures are reusable command scripts that are directly accessible from and executable by the EPOCH 2000 Ground System Software. Command procedures may be initiated as a result of scheduled track plan execution or by operator intervention as a response to spacecraft or ground system contingencies. Templates, however, are command scripts that are available only to STEREO Scheduler software and define the command sequences associated with every schedulable event type. These template scripts are the building blocks that STEREO Scheduler software uses to assemble every executable track plan script. Despite this distinction that command procedures are "used" directly by EPOCH 2000 whereas templates are "used" only by the STEREO Scheduler software, both forms of command scripts are managed in a similar fashion.

To safeguard against operational errors stemming from confusion between command scripts and command script versions, command environments for the Ahead and Behind spacecraft and for the two HIL simulators are maintained in isolation from one another. As illustrated in Fig. 7, these environments closely mirror one another in structure and processes, but they are otherwise completely separate in terms of directories and file contents. Each environment is implemented as a separate workspace activated by user login via one of four dedicated UNIX user accounts. STEREO Scheduler software maintains four separate scheduling databases to support track plan generation in each of the four environments so that Ahead and Behind mission-planning activities can be performed in parallel without interference. Overall, this "virtual" separation between environments is maintained across all Ops DMZ-networked workstations in the STEREO MOC. The IONet command workstations, however, are each configured to support only one workspace configuration, either the Ahead operations or the Behind operations environment; this configuration enforces a stronger "physical" separation between workspace environments on the IONet so that only appropriate command sequences are available for uplink to each spacecraft.

The challenge in maintaining four separate workspace environments is ensuring that each environment remains up-to-date and continuously usable, only diverging from the others where absolutely necessary. First, any local editing of command scripts in any of the four public workspaces is not allowed because this introduces untracked changes to one environment while promoting neglect of the other three. Rather, all script-development activity is relegated to private workspaces, with each member of the MOT in control of his or her own script-development workspace. These private workspaces are each linked to a shared script library managed by the UNIX Revision Control System (RCS), which maintains a version archive of all command procedures and templates developed by the MOT. Through the RCS library, any version of any command script may be retrieved, enabling each private workspace environment to be completely reconfigurable to suit the script developer's needs. Once script changes are implemented and ready for deployment, they are "publicized" to the Ahead or Behind simulation environment for testing, or if testing is completed, script changes may be promoted to support Ahead or Behind spacecraft operations. These steps have been made as effortless as possible by employing UNIX shell scripts that automatically update the RCS library while managing file transfers between private and public workspaces.

Memory Objects: The STEREO flight-software applications manage memory objects that include parameters, command macros, autonomy rules, storage variables, time-tagged rules, computed telemetry, and structures. Most of these memory objects, the exceptions being time-tagged rules and structures, may be stored in electrically erasable programmable read-only memory (EEPROM) and are under configuration control.

Configuration control of flight-software memory objects is maintained utilizing a Concurrent Versions System (CVS) repository. The repository contains STOL procedures that load memory objects and configuration files that use ground software to generate dump and compare STOL procedures. Memory objects under configuration control are divided into the following functional groups for each spacecraft: fault protection, guidance and control parameters, power parameters, data handling parameters, and mission operations objects. Each functional group is maintained in a separate CVS module and is released as a new version when modifications are made and a release is approved by the STEREO Configuration Control Board.

Each release includes STOL procedures to load memory objects to or to dump and compare memory objects from random-access memory (RAM) or EEPROM for each spacecraft. The memory object releases are maintained on servers that are accessible by the mission simulator workstations and by the operational command workstations via rsync. Each release is tested on the HIL simulators before becoming an official release.

Flight Software and Flight-Software Patches: Flight-software release files include a binary file containing the compressed flight-software application, a binary file containing application boot information called the executable ID block (EIB), and a STOL procedure to load each of the binary files. Each release is under configuration control in the same directory structure as the flight-software memory objects. Flight software is developed, tested, and delivered to the configuration control directories by the STEREO flight-software development team. Mission operations load delivered flight software on

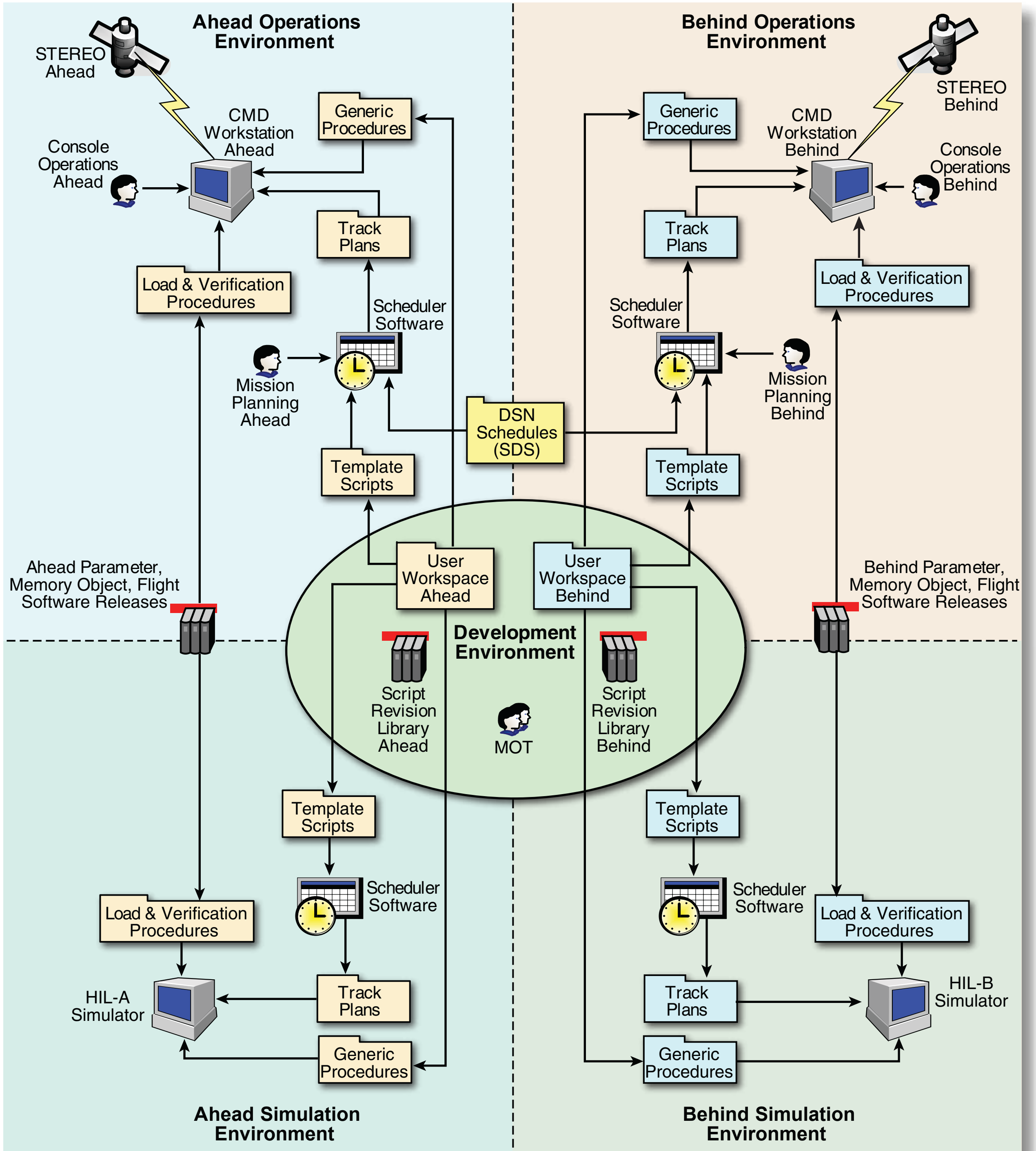

Figure 7. Ahead/Behind spacecraft and HIL-A/HIL-B operating environments.

the HIL simulators by using the procedures that are used to load the spacecraft.

Flight-software patches are used to change software currently loaded and running in processor RAM. Patches are used to correct or enhance software functionality without the need for a full flight-software load. Patches are maintained under configuration control in the directory structure used for flight-software loads. Like flight software, patches are developed, tested, and delivered to the configuration-control directories by the STEREO flight-software development team, and mission operations load delivered patches on mission simulators by using the procedures that are used to load the spacecraft.

Real-Time Operations: Command and control of the two STEREO spacecraft are performed from the STEREO MOC located in Modular Building 6 at APL. Commands and telemetry are routed through NASA's DSN at Goldstone, Madrid, and Canberra. The real-time operations are the same as those performed by the CONTOUR (Comet Nucleus Tour), MESSENGER (Mercury Surface, Space Environment, Geochemistry and Ranging), and New Horizons spacecraft. Unique to STEREO operations, however, was the necessity of controlling two spacecraft at the same time.

Page Displays: It was critical that members of the team be able to quickly identify which spacecraft they were monitoring in telemetry. Color-coded displays were used to identify each spacecraft: red for STEREO A and blue for STEREO B. Because the development of pages is often a time-consuming process (an average display page may take a week to develop), a single set of telemetry pages was developed. Environment variables set by the UNIX operating system when logging in identified which spacecraft the operator would monitor and would bring up either the red or blue pages.

STOL Procedures: Most command procedures were created to operate on either STEREO A or B, but as with the telemetry displays, some spacecraft command procedures were written to be executable on both spacecraft. When started, the STOL procedure monitored telemetry to identify which spacecraft was being commanded. For example, only one version of the negative acquisition procedure was written. On execution, the procedure identified which spacecraft was being commanded through environment variables. If problems with STEREO B were being worked, the logic in the procedure included checks to determine whether the STEREO A spacecraft successfully deployed from STEREO B and, if not, perform the deployment. Because STEREO A had no actuators to perform this function, these steps would be skipped.

Keeping one version of the procedure meant it was much easier for the engineering team to review. Multiple versions of the procedure would have generally led to a much larger development effort.

MOC Voice Communication/Headsets: Separate voice communications systems were required for each spacecraft. During the first launch rehearsal, MOT members found that voice communications using lines common to both spacecraft teams were too confusing. Personnel had to take great care to specify which spacecraft the conversation was about, and the risk of directing actions to the wrong spacecraft was deemed too great. Separate voice lines were established for each spacecraft, and strict protocols were enforced. At later launch rehearsals when the two spacecraft were given the same simulated failure, both teams worked the problems separately. The teams did not combine resources to work the same problem. As a result, the mission operations manager was given the task of monitoring both spacecraft to identify common problems and coordinate a response as necessary.

Track Automation: During the review process before launch, it was determined that STEREO mission operations would rely on software to automate real-time contacts. There were many reasons the STEREO spacecraft were good candidates for track automation. The spacecraft would be observer satellites, typically operating in a single mode. Few commands were expected on a daily basis. The operation of antenna hardware would be performed by DSN personnel. In addition, the spacecraft would use an advanced onboard fault protection system, which meant that no special and immediate responses would be required by the ground.

For command and telemetry, the STEREO mission uses the DSN, which operates behind a firewall on a secure network. A DMZ network that can monitor spacecraft telemetry exists, but it cannot send commands. Therefore, the design of the STEREO track automation system needed to be split into two sections. First would be the master control procedure, or MCP, to perform the mechanics of configuring to the correct DSN station and sending commands. A separate paging system, known as Tron, would perform state-of-health checks on the spacecraft.

Telemetry could be used to communicate between the two systems through database globals, which are essentially null values in the telemetry database that can be set by the ground. Although the paging system on the DMZ could not send information to the IONet, it could read the status of the MCP. Also, when the MCP is run in what is called "schedule mode," its execution could be monitored from the DMZ.

Given this baseline hardware and software configuration, a low-tech implementation using STOL was used for track automation. STOL is an interpreted language similar to Basic, and because it was familiar to members of the MOT, it could easily be modified by team members over the course of the mission as events warranted. In contrast, specially developed software routines generally require software specialists to maintain them.

The primary driver for the track automation software is the DSN Schedule, or the list of DSN contacts each day. This list was the only special requirement for track automation on other software in the MOC. The Scheduler mission-planning software would create a command procedure that would set database global variables on contact information for the next 21 days. This information included the following:

- Start and end times of each track
- DSN station
- DSN configuration to be used (which identifies the telemetry and command rates)
- Round-trip light time to be used
- Command procedure to be executed

Master Control Procedure: The MCP algorithm works as follows. Each hour, the MCP searches to determine whether an updated schedule has been created. When it is time for a track, the MCP performs the necessary operations to establish a command socket connection with the station and to receive its telemetry. The MCP monitors the station as it performs the uplink sweep. When it detects that the sweep is complete, a test command is sent to verify the uplink process. At that time, normal command operations can be performed. At the end of each track, the MCP monitors as the station brings down the command carrier and terminates the track. The MCP then disconnects from the station command socket, closes event logs, and waits for the next track.

The MCP supports limited failure recovery actions. If the spacecraft reports that it has changed modes (i.e., safe mode), then the MCP does not establish a command link. Most of the MCP failure recovery actions deal with problems establishing a command link.

The MCP can operate in either the attended or the unattended modes. In the attended mode, if the MCP encounters problems, the procedure pauses. In the unattended mode, the team is paged. Typically, the MOT will allow the MCP to run in the unattended mode to establish a command link and will switch to the attended mode to perform special operations.

The Tron Paging System: The MCP executes in a linear fashion, but the Tron program does not. The MCP waits until the next track, then waits until it is time to establish a command link, and so on. One of the first requirements for the paging system was to determine whether the MCP program stalled or hung for some reason. Therefore, Tron was implemented as a scanning program. Every 30 s, it performs a complete scan of the MCP status, network status, and spacecraft status. If it identifies that a track is in progress, it performs 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. Core checks are limited to the following:

- Any fault autonomy rule firing
- Spacecraft that are not in the operational mode
- Battery state of charge of <95%
- HGA pointing is disabled
- No command acknowledgment for any command
- No telemetry received for any 20-min period
- The IONet or DMZ is unresponsive
- The MCP procedure is hung

The extended checks grew from the health and safety checking procedure used at launch and consist of checks of well over 2000 telemetry points. A failure in any check could be responded to by either an email or a page. For example, if the battery temperature were yellow, an email would be sent out, and the team would deal with the issue the next day. However, if the same point were red, a page would be sent out, and the team could respond immediately.

Responsibility for monitoring the automation system and responding to pages rotates through the team on a weekly basis. Once paged, team members can remotely log in from their homes and monitor spacecraft telemetry. Once the problem is determined, the team sends out an additional page to the rest of the team telling them that the problem has been handled.

STEREO operations began using the MCP in January 2007 with all activities shadowed by personnel. The paging system came online in April with unattended tracks beginning in May. Typically, pages are made relating to failures with the command or telemetry links at the station. The team may get one page every 1 or 2 weeks.

ASSESSMENT

The objective of the performance-assessment function in mission operations is to maintain the health of the spacecraft bus systems and evaluate their performance to collect data. It also provides the capability to monitor degrading bus components to allow for optimization of spacecraft resources to meet the mission goals as well as the tools necessary to analyze data for anomaly investigations. Because STEREO is a decoupled instrument-operation mission, instrument-performance assessment is the responsibility of each POC.

Each spacecraft has a separate data path through the STEREO MOC, including separate telemetry archives. All spacecraft housekeeping telemetry is kept online in a raw format for the life of the mission, whereas a subset of decommutated telemetry is maintained in a relational database for anomaly investigations. Nearly all telemetry is identical for each spacecraft as well as the assessment tools. However, because of the slight differences in telemetry mnemonics and engineering unit conversion coefficients, there are separate telemetry databases for STEREO Ahead and Behind. The daily cadence of the mission results in a routine flow of spacecraft housekeeping data, thus allowing the use of daily, automated, assessment data processing (see Fig. 8). This automated data processing generates science telemetry data products as well as assessment data products, which are listed in

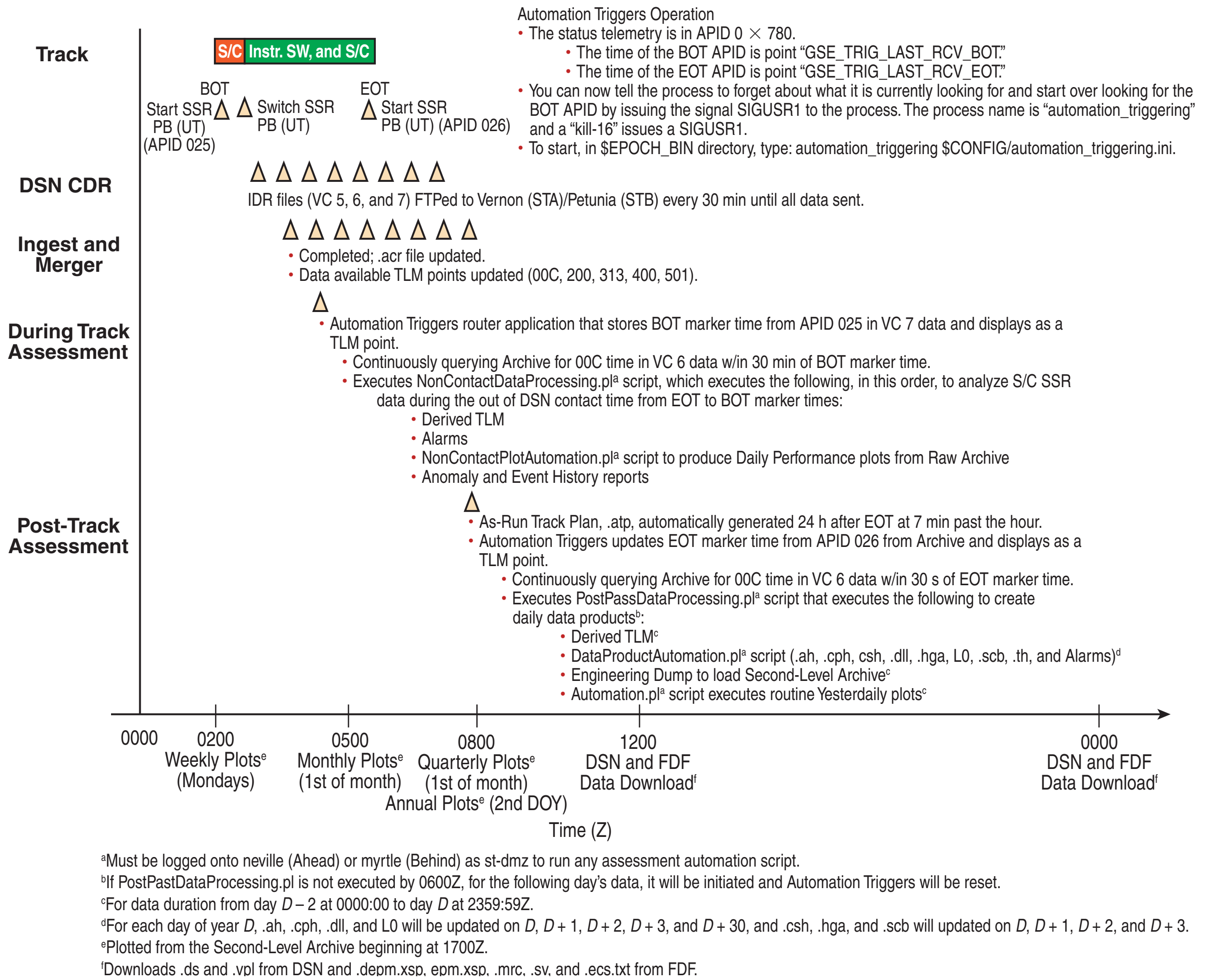

Figure 8. Assessment automated data processing. BOT, beginning of track; EOT, end of track; PB, playback; STA, STEREO A; STB, STEREO B; TLM, telemetry; VC, virtual channel.

Table 2. All assessment data products are made available to the greater STEREO project externally via the SDS.

Routine spacecraft bus performance assessment, as opposed to anomaly investigations, consists of regularly determining the status, configuration, and performance of each spacecraft bus subsystem. It consists of the following assessment tasks, which are used during real-time contacts and/or during off-line data processing.

Alarmed Telemetry Processing

Because the MOT cannot continually monitor all of the many hundreds of telemetry points that are alarmed, alarm telemetry processing is relied on to notify the MOT of an unusual operational condition on the spacecraft. Alarm telemetry processing is performed on all housekeeping data, including data generated in real time and data recovered from the spacecraft SSR and processed after contact. Alarm telemetry processing alerts the MOT of an out-of-red/yellow alarm limit, Δ limit, or a return-to-nominal condition via numerous display pages that are visible during a real-time contact. Similar conditions that occur between real-time contacts are listed in an alarm report that is generated autonomously off-line.

Command Verification

Just as it is important to assess the data being received from the spacecraft, it is equally important to verify the data being sent to the spacecraft. During nominal operations, the STEREO spacecraft and ground systems are configured to use Command Operation Procedure (COP-1) protocol. This protocol defines how the spacecraft knows that it is receiving commands in the right order as well as how the ground system knows which command is needed next. If problems arise during commanding that result in the commands failing to reach the spacecraft or failing to be correctly verified by the spacecraft, the MOT will be alerted of this condition in a manner similar to the telemetry out-of-limit condition described above. Should this condition occur, the MOT

Table 2. Data product schedule.

Data Product	Extension	Originator	Frequency
Archived Product List	apl	SSC	Daily
As-Run Track Plan	atp	MOC	Daily
Attitude History	ah.xc	MOC	Daily[a]
Command and Packet History	cph	MOC	Daily[a]
Converted Spacecraft Housekeeping	csh	MOC	Daily[b]
Daily Timeline[d]	dt.pdf	MOC	Daily
Data Loss Log	dlr	MOC	Daily[a]
DSN Schedule[d]	ds	DSN	Weekly
DSN Schedule Change[d]	dsc	DSN	Sporadic
Definitive Ephemerides	depm.xsp	FDF	Biweekly
Ephemerides	epm.xsp	FDF	[c]
Ephemeris Comparison Summary	ecs.txt	FDF	[c]
HGA Gimbal Angle	hga	MOC	Daily[b]
Instrument Event Schedule[d]	ies	POCs	Weekly
Kernels	sclk or bsp	MOC	Sporadic
Level 0 Telemetry	ptp, fin, oar	MOC	Daily[a]
Maneuver Plan	mp	MOC	Maneuver
Maneuver Radial Component	mrc	FDF	Post-maneuver
MOC Status Report[d]	msr.pdf	MOC	Weekly
Momentum Dump Prediction	dp	MOC	Momentum dump
Post-Maneuver Report	pmr	MOC	Post-maneuver
Post-Momentum Dump Summary	pds	MOC	Post-momentum dump
SECCHI Guide Telescope Data	gt	MOC	Sporadic
State Vectors	sv	FDF	[c]
Stored Command Buffer	scb	MOC	Daily[b]
Telemetry Dictionary	td	MOC	Sporadic
Time History	th	MOC	Daily
Track Plan	tp	MOC	Daily
Track Timeline	tt.pdf	MOC	Daily
Viewperiods	vue	DSN	[c]
Weekly Schedule	ws	MOC	Weekly

[a]For each day of year D, it will be updated on day D, $D + 1$, $D + 2$, $D + 3$, and $D + 30$.
[b]For each day of year D, it will be updated on day D, $D + 1$, $D + 2$, and $D + 3$.
[c]Phasing orbit, thrice weekly; heliocentric orbit, biweekly.
[d]These data products contain information on both observatories; all other data products are observatory-specific.

will follow specific procedures to diagnose and remedy the problem, with command resuming from where it left off.

Anomaly and Event Histories

STEREO flight-software applications have a unique feature that logs all of the anomalies and events that occur in the C&DH/EA and G&C processors; these anomalies are then recorded in separate SSR partitions. An anomaly is defined as an occurrence that deviated from the designed nominal spacecraft operation beyond acceptable limits, e.g., memory object copy failure, 1553 bus transaction errors, telemetry downlink overflows, error detection and corrections, etc. An event is routine operational information provided to the MOT with information on the status and configuration changes that are occurring in each C&DH/EA and G&C processor, e.g., telecommand packet receipt and routing, command execution, and anomalies. Note that each anomaly is double-logged on separate SSR partitions to prevent loss.

Any time an anomaly or event is detected by flight software, the application adds an entry to the respective anomaly or event history buffer maintained in processor RAM. The entry captures the time, an identifying error code, and, optionally, some auxiliary data. When 12 anomalies or events in RAM are stored, they are packetized and transferred to the respective partition on the SSR for later downlink at the beginning of the next DSN track.

In the MOC, the ground system decodes and displays the anomalies and events in real time, and as part of the daily automated assessment data processing, separate event and anomaly reports are created for each day.

Trend Analysis

Trend analysis is the periodic monitoring of all spacecraft bus components, including those that are known to degrade with time:

- Battery performance
- DSN received signal
- Gyro laser intensity monitors
- HGA pointing
- IEM currents and temperatures
- Instrument interfaces [except all data processing units (coupled)]
- Operational and survival heater currents
- Oscillator drift
- Propulsion subsystem
- Solar array and peak power tracker performance
- SSR usage
- Star tracker performance
- Sun-pointing performance
- Thermally isolated components
- Transponder performance
- Wheel momentum and speed

It consists of automatically generated plots that are produced on a daily, weekly, monthly, quarterly, and annual basis. Because there is no orbitally induced periodicity, the following various averaging time intervals are used:

- Every sample—daily
- Hourly—weekly and monthly
- Days—quarterly
- Weeks—annually

All of the performance-assessment processing is automated, and the output is available online. Each day, the MOT reviews the output of these assessment processes. This process allows the MOT to minimize the time required to determine the health and performance of each spacecraft.

In addition to the MOT, the performance-assessment function is augmented by in-depth analysis of subsystem performance by the spacecraft bus engineering team (SBET). The SBET has direct access to the performance-assessment outputs and the archived raw engineering telemetry so that any data may be accessed and processed to the satisfaction of the responsible engineer.

The MOT is responsible for the health and safety of both spacecraft buses. Therefore, they lead and coordinate investigations with the SBET into all spacecraft bus anomalies. Anomalies identified both during a contact or offline are investigated. A cumulative database of all spacecraft bus anomalies for each spacecraft bus, from integration and testing through end-of-life, is maintained.

CONCLUSION

The described STEREO ground system and mission operations were developed from the beginning to support a concept of highly automated operations. The STEREO ground system is uniquely divided between the two spacecraft, allowing simultaneous communications with the two spacecraft while minimizing the risk of confusion. The mission operations tools used for planning, real-time operations, and assessment of spacecraft performance allow for the safe operation of two spacecraft simultaneously. Specifically, separation of command and memory management between the two spacecraft is rigorously maintained. STEREO mission operations are being accomplished with a minimal number of staff while the science data return is kept well above the minimum requirement for mission success.

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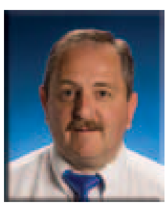
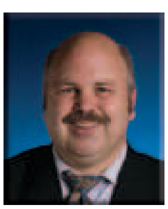
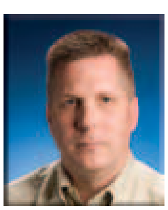

Daniel A. Ossing


George Chiu


Paul N. Boie


Timothy O. Krueger


Alan S. Faber


Timothy A. Coulter


Owen E. Dudley


David A. Myers