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Solar Terrestrial Relations Observatory (STEREO) Mission and Concept of Operations

Glen E. Baer
The Johns Hopkins University Applied Physics Laboratory
Laurel, MD USA 20723-6099
443-778-5069
glen.baer@jhuapl.edu

John E. Eichstedt
The Johns Hopkins University Applied Physics Laboratory
Laurel, MD USA 20723-6099
443-778-8738
john.eichstedt@jhuapl.edu

Daniel A. Ossing
The Johns Hopkins University Applied Physics Laboratory
Laurel, MD USA 20723-6099
443-778-8319
dan.ossing@jhuapl.edu

Abstract. The Solar Terrestrial Relations Observatory (STEREO) is a new NASA mission designed to increase the understanding of the origin and consequences of coronal mass ejections (CMEs). The mission will consist of two identical spacecraft at approximately 1AU from the Sun: one drifting ahead of the Earth and one behind. Simultaneous image pairs will be obtained by the spacecraft at gradually increasing angular separations over the course of the 2-year mission. The spacecraft launch date is scheduled for 2003. The concept of operations for this mission consists of independent and decoupled instrument and spacecraft bus operations. The Science Operations Teams will generate the instrument commands to accomplish the science objectives, and the STEREO Mission Operations Team (MOT) will support the spacecraft bus. All spacecraft servicing, including commanding and science data recovery, will occur during a daily ground track with the Deep Space Network. All science data will be flowed in near real-time to the Science Operations Center via the Internet. During the normal operations phase of the mission, each track will run autonomously with a small MOT to conduct planning and assessment tasks. The spacecraft and ground system will be highly autonomous, making this mission ideal for "lights out" operations.

Introduction

The Solar Terrestrial Relations Observatory (STEREO) mission and concept of operations are currently in the conceptual design phase at The Johns Hopkins University Applied Physics Laboratory (JHU/APL). The primary mission consists of two spacecraft in solar orbit obtaining simultaneous image pairs at gradually increasing angular separation. To keep the cost of the mission low, the concept of operating these two spacecraft will employ a high degree of autonomy, both onboard the spacecraft and in the ground system. The use of decoupled spacecraft bus and instrument operations has been implemented. Using this concept of operations, this design will call for a team of seven people working 5 days per week, 8 hours per day to operate both spacecraft. This paper will describe the current STEREO mission and concept of operations that will accommodate operations with a minimal team size.

Mission

As part of NASA's Sun-Earth Connections program, the STEREO mission will provide a totally new perspective on solar eruptions and their consequences for Earth. To provide the images for a stereo reconstruction of solar eruptions, one spacecraft will lead the Earth in its orbit and one will be lagging. Each will carry a cluster of instruments. When simultaneous telescopic images are combined with data from observatories on the ground or in low Earth orbit, the buildup of magnetic energy, the lift off, and the trajectory of Earthward-bound coronal mass ejections (CMEs) can all be tracked in three dimensions. When a CME reaches Earth's orbit, magnetometers and plasma sensors on the STEREO spacecraft will sample the material and allow investigators to link the plasmas and magnetic fields unambiguously to their origins on the Sun.

The STEREO mission consists of two identical spacecraft in heliocentric elliptical orbit in the ecliptic plane at approximately 1 AU, one ahead of the Earth and the other behind it. The angular separation of the two spacecraft will be gradually increasing with a drift rate of 20°/year for the leading spacecraft and −28°/year for the lagging spacecraft. The mission has a goal of 2 years with a possible extension of an additional 3 years. There are four mission phases for the 5 years, which are determined by the angle between the two spacecraft (S/C) (α). Each angular separation phase has specific science objectives as listed in Table 1.

Table 1. STEREO Separation Phases

Phase	S/C Angular Separation	Science Objective
Launch to 400 days	$\alpha \leq 50^o$	3D corona effects
400 to 800 days	$50^o \leq \alpha \leq 100^o$	CME physics
800 to 1100 days	$100^o \leq \alpha \leq 200^o$	Earth-directed CMEs
After 1100 days	$\alpha > 180^o$	Global solar evolution and space weather

Spacecraft Description

Each of the two STEREO spacecraft will be identical with no redundancy. The spacecraft bus will be built by JHU/APL with NASA Goddard Space Flight Center (GSFC) procuring the instruments and launch vehicles. The entire S/C will be integrated at JHU/APL.

The spacecraft bus consists of six operational subsystems supporting a payload suite of six instruments (Figure 1). The spacecraft bus is designed around an integrated electronics module (IEM). The IEM is a single box that contains the command and data handling (C&DH) and RF communications subsystems on plug-in cards. The cards within the IEM communicate over a PCI parallel data bus. A MIL-STD-1553 bus architecture is used for command and telemetry between the IEM and the instruments, guidance and control (G&C) subsystem, and power subsystem. An RS-422 high-speed data bus is also used for the science data interface between the IEM and the high rate instruments.

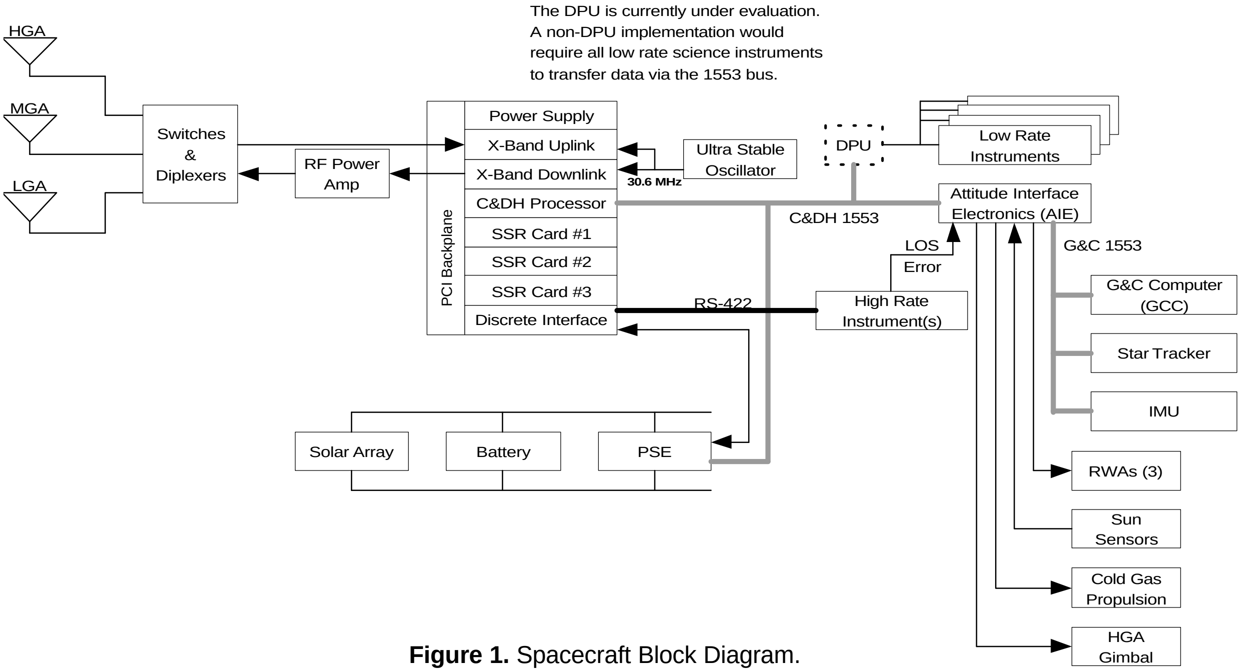
Spacecraft Operations

The spacecraft will be operated to collect data as the onboard instrument suite observes the solar regions of scientific interest. The spacecraft bus is operated to support this data collection by providing nominal attitude, power, navigation data, thermal control, data storage, and rule-based autonomy. It is expected that the spacecraft will operate nearly autonomously, requiring only minimal ground support to uplink occasional command messages and to recover science and engineering data on a daily basis. Nominally, one contact, or track, with each spacecraft will be scheduled each day for 4 or more hours. During the remainder of the day, the spacecraft will be collecting data, measuring its health, and responding to any anomalous operations. It will do this primarily by performing a continuous performance assessment function through observation of telemetry while evaluating pre-stored autonomy rules related to performance and operation. The goal of the Mission Operations Team (MOT) will always be to maintain a science data gathering capability, but it is likely that some onboard anomalies cannot be autonomously handled in a way that preserves normal operations. In these cases, the spacecraft may transition to a safe-hold or Earth acquisition mode where science data collection is suspended and all nonessential instruments and subsystems are powered down.

As part of the normally generated engineering telemetry, the spacecraft records all commands executed onboard, including real-time, time-tagged, macro, and autonomous command execution. Such data are necessary to assess the operational performance of the spacecraft bus.

Instrument Operations

During normal operations, all instruments will be powered, and time-tagged command capability will be enabled. For this mission, all instrument operations will be decoupled from the spacecraft bus operations, which reduces system complexity and cost. The spacecraft bus and the instruments will be operated independently of each other, as will the ground elements (the Science Operations Center [SOC] and MOC). This decoupling of instrument operations greatly simplifies the operations process, which traditionally requires these functions to be merged in a complicated manner.



The DPU is currently under evaluation. A non-DPU implementation would require all low rate science instruments to transfer data via the 1553 bus.

Figure 1. Spacecraft Block Diagram.

The SOC is responsible for the following operational tasks for all instruments:

- Planning, scheduling, and generating instrument commands
- Instrument health
- Calibration
- Synchronization of instrument operations between S/C

Instrument command loads will be assembled as packets and transferred to the MOC prior to a scheduled contact, or track. Separate command messages are required for each S/C. Included as part of the command packet transfer to the MOC will be certain identifying data to be used by the MOC to verify that an authorized source has generated and transferred the data. The SOC will attach data that specify both the earliest and latest times that the attached command packet may be uplinked to the instrument. The MOC is responsible for the delivery of the content of the packet(s) to the addressed instrument but assumes no responsibility regarding the actual commands.

The spacecraft will store command packets for distribution to the instruments at a later time. The aggregate size of memory available to all instruments for stored commands is enough to hold approximately 400 commands. Stored command packets may be individually time tagged with 1-s precision or may be part of a macro sequence.

An unpacketized broadcast message containing the following items will be distributed to all instruments once per second.

- Time
- Warning flags
- Sun keep-in violation
- Thruster firing
- Instrument power off
- Indication that the next housekeeping data set will be downlinked or recorded
- Spacecraft housekeeping data required for instruments

The spacecraft will poll the instruments for data via the MIL-STD-1553 bus (and science packets from the dedicated RS-422 high-speed link for the high-rate instruments only) according to a fixed schedule. It will either downlink the data in real-time or record it on the SSR.

The spacecraft will not process instrument data before recording or downlink; any processing or data compression will be done by the instruments. They will have no direct access to the solid-state recorder (SSR) and will not be able to retrieve data stored on it. The instruments will generate each science data packet according to the full Consultative Committee for Space Data Systems (CCSDS) telemetry packet format, including primary and secondary headers, checksums, etc. The maximum aggregate data collection rate for science packets from all instruments will be 408 kbps.

Housekeeping data from each instrument will be collected every second. The spacecraft will perform very rudimentary monitoring of these data strictly for fault protection. For example, one bit in the packet will be designated as a request by the instrument for the spacecraft to turn off its power. Other than this monitoring, the spacecraft will not process the instruments' housekeeping data. Each instrument will have housekeeping data in its science data packets if needed for science evaluation. A small amount of unpacketized "space weather" data from each instrument will be collected every second.

Data Flow

Figure 2 illustrates the flow of command and telemetry data between the ground-based spacecraft bus and instrument operations elements and the on-orbit STEREO spacecraft. The "outer-loop" depicts instrument operations. Using a decoupled instrument operations approach, all instruments will be operated by the instrument operations team at the SOC where instrument commands are produced. These command messages, which will be packetized along with some additional information needed by the MOC, are transmitted to the MOC via the Internet. At the MOC, the commands are checked and then queued for eventual uplink to the instrument. Along with the command packets, the SOC appends timing information indicating the time span (earliest and latest times) when the command packet may be uplinked to the instrument.

Real-time command packets, when uplinked to the spacecraft, are immediately routed by the spacecraft bus C&DH processor to the appropriate instrument. Time-tagged and macro command packets are stored in the instrument's allocated storage locations in the C&DH processor. Conceptually, the command packet goes directly from the SOC to the instrument because the MOC, ground station, and spacecraft bus are merely the delivery system that notifies the SOC of the delivery status of the command message.

Whereas the SOC produces instrument commands, the MOC produces spacecraft bus commands. This concept is depicted in the "inner-loop" on the data flow diagram

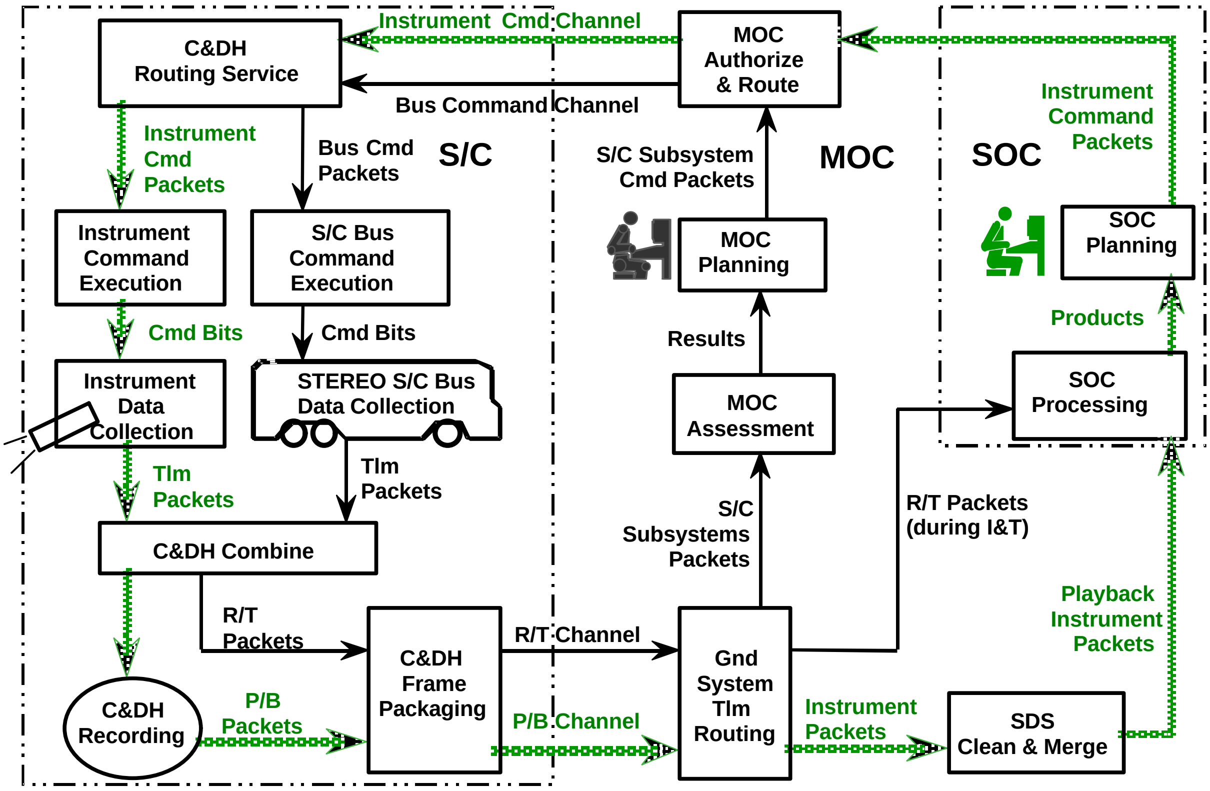


Figure 2. STEREO Mission Data Flow (cmd = command, tlm = telemetry).

(Figure 2). At the MOC, the MOT prepares command messages to the spacecraft bus to operate it during the next day. These command messages are queued for uplink just like the instrument commands, only they go to a different destination. The C&DH processor immediately routes real-time commands to the appropriate spacecraft subsystem, and time-tagged and macro commands are stored in the C&DH processor. The MOC receives delivery status of the command packets just as the SOC does.

The data produced by the instruments are sent to the spacecraft data system in the form of CCSDS telemetry packets as are engineering data produced by the spacecraft bus. The packets, produced by the instruments and the spacecraft bus and conveyed to the spacecraft data system, are stored on the SSR within the spacecraft data system. During a track with the S/C, the contents of the SSR are transmitted to the MOC.

On the ground, real-time data are forwarded to the MOC and to the STEREO Data Server (SDS), while all recorded data are sent to the server facility. All instrument data will be sent to the SOC for processing and analysis. The cycle repeats, with the SOC preparing instrument commands for still another day in space. Spacecraft bus data are routed to the MOC where an assessment function is performed. The MOC spacecraft bus planning process then repeats.

Command Data Flow

The MOC produces spacecraft bus commands, processes SOC-generated instrument commands, and provides a command gateway for all commands to the spacecraft. All instrument command messages from the SOC, along with some additional identifying and timing data, are sent to the MOC (Figure 3). At the MOC, the FTP Server and Authenticator validates the proper sender. (The SOC provides an encrypted source identifier and an application command packet identifier [destination instrument].) An authentication receipt is returned to the SOC.

Once a command has been authenticated, it enters a Staging Queue. There is one such queue for each instrument on each S/C. Appended to the command message (the command packet and header) is a start and expiration time specification. These represent the earliest and latest times that the command packet may be uploaded to the instrument as specified by the SOC. Once past the start time, the command packet is transferred to the Uplink Queue (again there is one for each instrument on each S/C). Command packets in the Uplink Queue are ordered by expiration times, so that those with the earliest expiration times are uplinked first. The MOT may examine the contents of the Uplink Queue to determine the number and size of the packets stored there.

All stored commands will be uplinked beginning at the next ground station track, as long as time permits (the track is of sufficient duration) unless the MOT places a “grocery bar” separating command packets within the queue. All commands to the left of the bar are uplinked, those to the right of the bar are prevented from being uplinked. This mechanism affords the MOT some degree of control of the uplink command packet traffic to the spacecraft.

The switch at the output (left side) of the Uplink Queue (Figure 3) will either enable, when closed, or disable, when opened, instrument packet command flow to the spacecraft. The queues can be flushed by MOT control. If the SOC desires to replace the content of an instrument uplink queue, either entirely or in part, the whole queue is flushed and must be totally reloaded. The MOC will issue notification (receipt) to the SOC of either a uplinked packet or a flushed queue.

Commands prepared for spacecraft bus operation are merged with instrument commands. Normal C&DH command packets are merged at the Framer (Figure 3). Here, spacecraft bus commands have priority, i.e., they are uploaded first. Commands destined to the spacecraft bus Uplink Critical Command Decoder (Virtual Channel 0) are merged at the Station Server with Uplink Critical Command Decoder command packets assigned a higher priority than spacecraft bus C&DH processor or instrument command packets (Virtual Channel 1). The status of command packet delivery to the C&DH processor or to an instrument or subsystem is provided via C&DH telemetry. This status is forwarded to the SOC for instrument command packet delivery as a return receipt. Thus the SOC is informed of the delivery, but not the verification of actual command content. This information must be provided by instrument telemetry, which can be processed only by the SOC.

Telemetry Data Flow

Figure 4 illustrates the flow of real-time and SSR playback telemetry data between the Deep Space Network (DSN) and the MOC and SDS. Real-time telemetry data are flowed from DSN to the MOC as supplemented telemetry frames (STFs). Playback telemetry data are flowed from the DSN to the SDS, again as STFs. In both real-time and playback data flows, the received packets are re-served to a packet-based server where telemetry packets are extracted and output as supplemented telemetry packets (STPs) and as CCSDS telemetry source (as the data were generated by the spacecraft) packets (TPs). In both cases, packet

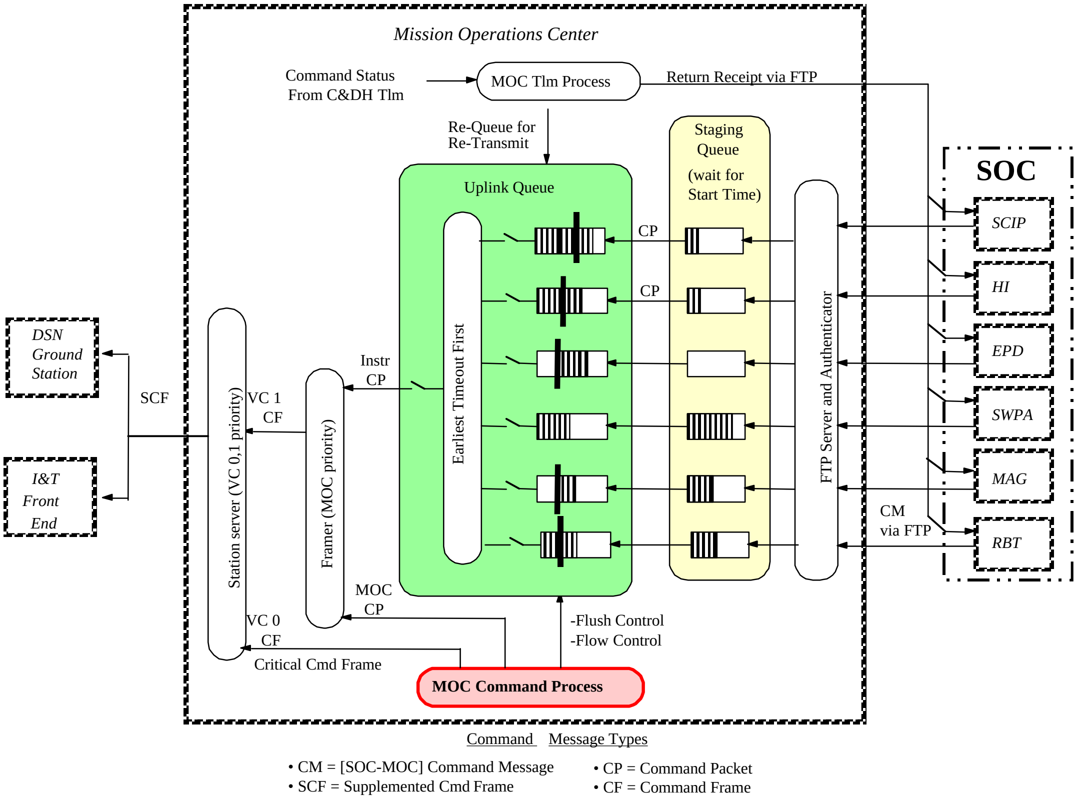


Figure 3. Command Data Flow.

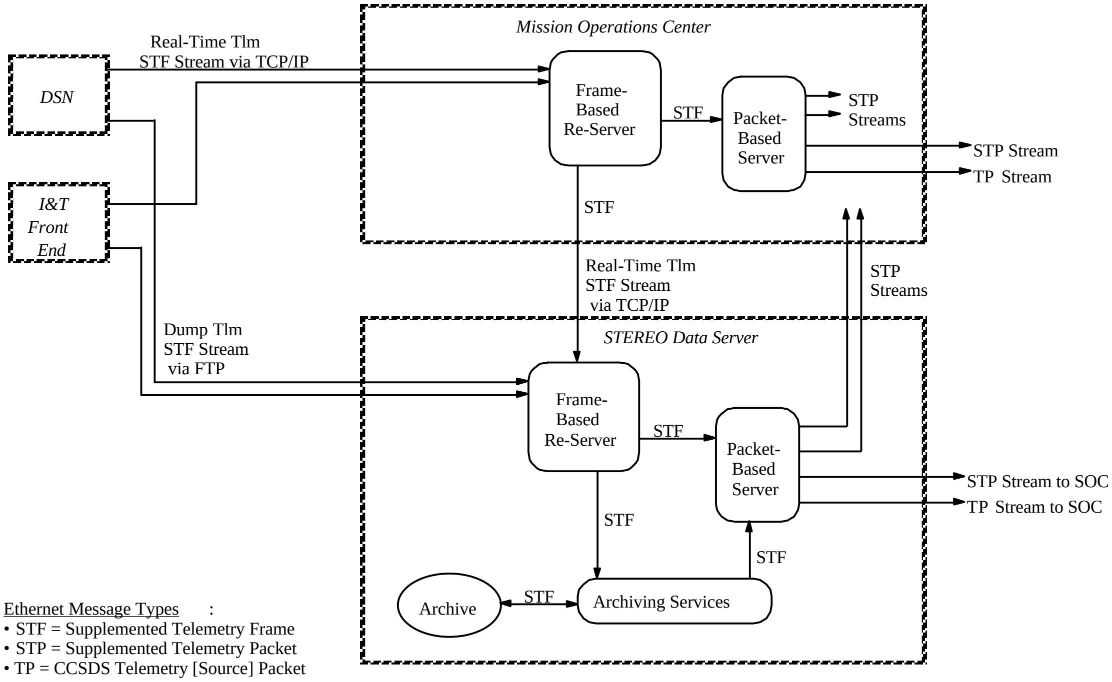


Figure 4. Telemetry Data Flow.

streams, a flow of packets placed end-to-end in time order as they were received, are produced. The MOC provides the real-time telemetry it receives to the SDS for storage. Telemetry packets stored by the SDS, including the spacecraft playback bus engineering telemetry, are provided to the MOC. For the SOC, real-time telemetry are "streamed" while playback data are file transferred.

Mission Operations System (MOS) Overview

The STEREO MOS consists of the two spacecraft, DSN ground stations, MOC, and SOC and their respective operational teams. The STEREO spacecraft will be operated by JHU/APL utilizing DSN for vehicle communications. The spacecraft bus and the instrument suite will be operated in a decoupled fashion: the MOC will support all spacecraft bus operations and the SOC will operate all instruments on both S/C, although communication between the SOC and the spacecraft will necessarily flow through the MOC. All spacecraft servicing, including commanding and data recovery, will occur during a single (nominal) ground track each day. This track will extend over a 4- to 8-hour window, depending on the vehicle range from Earth. Spacecraft command messages will be uploaded and real-time engineering data will be received and evaluated to assess spacecraft health. The SSR will be played back on each track and all science data flowed to the SOC in near real-time.

Missions Operations Center

The MOC, located at JHU/APL in Laurel, Maryland, has the primary responsibility of managing the spacecraft bus including the development of command messages and the uplink to the spacecraft by way of the DSN. It is operated by the MOT and is nominally staffed during business hours, 5 days per week. Recovery of spacecraft bus engineering (state-of-health) telemetry and the performance analysis based on this telemetry are also performed at the MOC. It receives instrument command messages (packets) from the SOC and, after verifying that the SOC has prepared the commands, queues these for uplink to the spacecraft based on start and expiration times appended to the command messages by the SOC.

Figure 5 illustrates the MOC and includes interfaces to other MOS elements. NASCOM (NASA Communications System) communication lines connect the MOC to DSN. Communications to the SOC are via the Internet, with a modem backup. Within the MOC are workstations to support spacecraft commanding, spacecraft bus monitoring and analysis, primary and backup databases, and user files.

The primary and backup command workstations are isolated from the rest of the MOC by a router/firewall. Commands to the spacecraft may *only* be issued from these workstations. Real-time telemetry is flowed through the firewall to the remaining workstations. Received telemetry (both real-time and SSR playback retrieved from the SDS) may be processed and displayed on these workstations. Main data paths are at least 100 Mbps Ethernet, with distribution within the MOC to some workstations and printers on 10 Mbps Ethernet. Unix-based workstations are provided for the MOT and spacecraft bus engineering team use. The SDS and the Spacecraft Simulator are also contained in the MOC.

STEREO Data Server

The SDS (Figure 6) is located at JHU/APL in the MOC and functions as the central repository of spacecraft bus engineering telemetry, command files, mission planning data, ground system telemetry and status, and external correlative measurement data for the MOC. The SDS may be accessed continuously (24 hours/day) via standard Ethernet/Internet-type communication lines.

The databases maintain the data products required by the users. These products, as shown in Figure 6, include real-time engineering telemetry, playback engineering telemetry and command files, WWW access to all databases, file services to access archived data, a mission assessment database, and archival and distribution services. The users will include the SOC, MOC, and Spacecraft Bus Engineering Team (SBET).

DSN

The DSN will be used to provide communications to both spacecraft from launch to end of life (EOL). 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, one track per day per spacecraft will be conducted using the 34-m beam wave guide antennas. The MOC is connected to the DSN via NASCOM links. Orbit data for each spacecraft will be provided periodically to DSN.

Science Operations Center

The SOC, located at the GSFC in Greenbelt, Maryland, has the responsibility for the operation and assessment of all instruments on the spacecraft. This includes the following instrument operational tasks:

- Planning, scheduling, and generating instrument commands
- Instrument health
- Calibration
- Synchronization of instrument operations between S/C

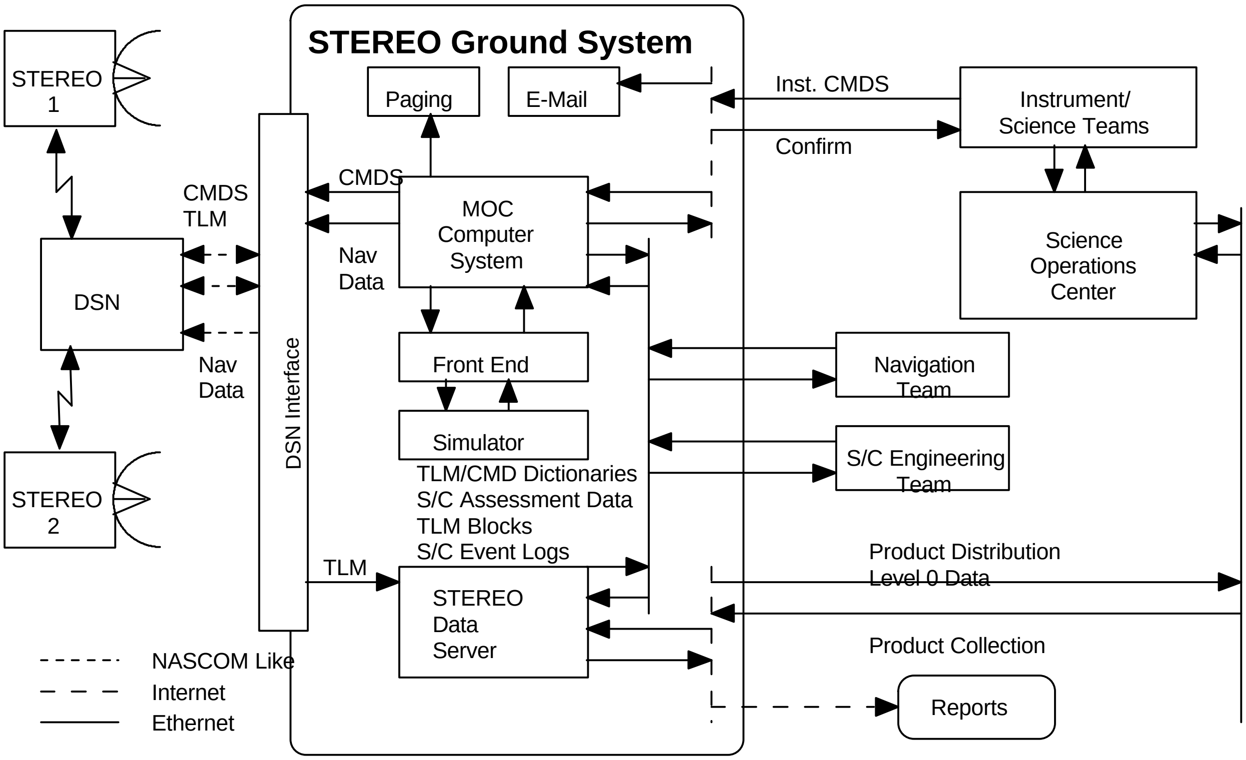


Figure 5. STEREO Ground System

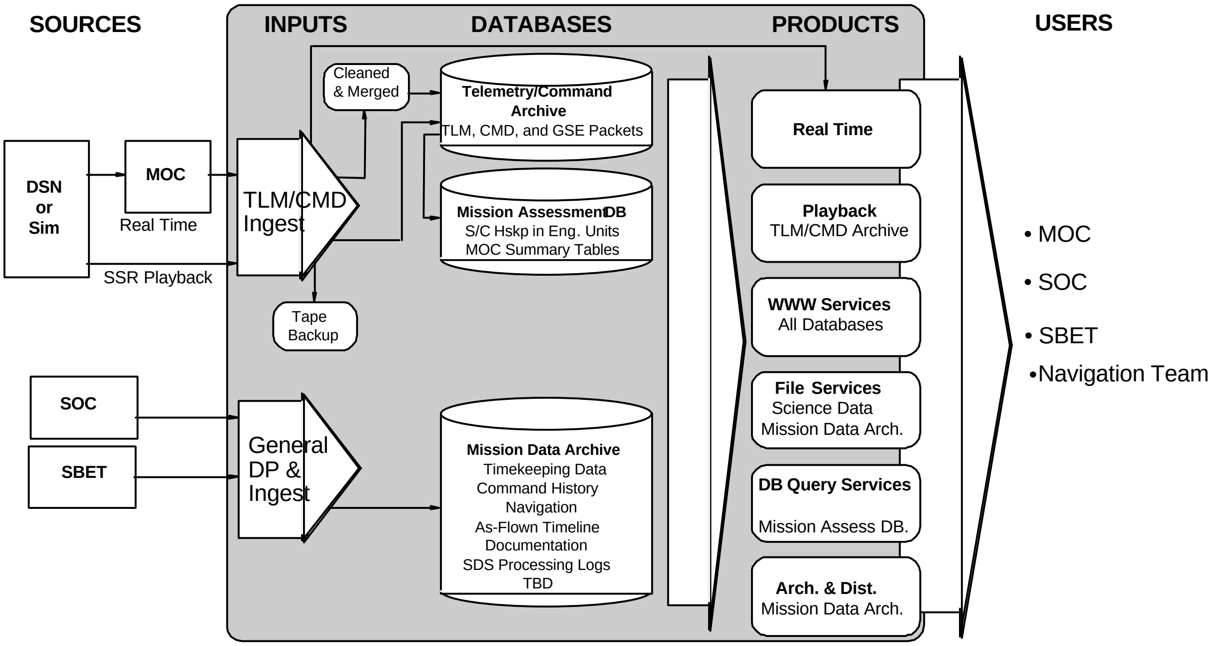


Figure 6. STEREO Data Server and Interfaces.

Instrument command loads will be assembled as packets and transferred to the MOC prior to a scheduled spacecraft track. Separate command messages are required for each S/C. The command packet transfer to the MOC will include certain identifying data to be used by the MOC to verify that an authorized source has generated and transferred the data. The SOC will attach data that specify both the earliest and latest times that the attached command packet may be uplinked to the instrument. The SOC will be responsible for the verification and validation of instrument response based on the uplinked command load. The MOC will be responsible for the delivery of the content of the packets to the addressed instrument, but assumes no responsibility regarding the actual commands.

Similarly, the processing of science and engineering data pertaining to all instruments is the responsibility of the SOC. Recorded science and engineering data will be available to the SOC via the SDS.

The SOC also has the responsibility for archiving all science data for the duration of the mission for both S/C. The MOC will provide, via the SDS, the following data products in file format to the SOC:

- Science
- Real-time space weather
- S/C bus and instrument engineering
- Attitude history
- Time correlation
- Navigation

The MOC is connected to the SOC via a commercial Internet connection with a modem backup and will use standard TCP/IP protocols. Real-time command and telemetry monitoring operations are expected to be available, although such operations are considered only as contingency operations (including the possibility of initial early on-orbit operations).

The SOC will be provided ground system planning information by the MOT, including the schedules for DSN tracks schedules, track plans, orbit data, S/C bus health, etc. All such information will be provided via the SDS.

Mission Operations Team

The following four teams will work to support the STEREO mission, although only the APL MOT is discussed here.

- Mission Planning Team (MPT)
- APL Mission Operations Team (MOT)
- DSN
- Science Operations Team

The MOC is staffed and operated principally by the MOT. The SBET and instrument teams (when the Test SOC is installed) will provide staffing to support specific operations.

The MOT is responsible for all spacecraft and commanding, the recovery of all spacecraft telemetry, the assessment of spacecraft bus performance, and the control, monitoring, and performance assessment of all ground components necessary to support these functions. During the Normal Operations mission phase, the MOT staff will be comprised of the following:

- Flight Operations Manager
- Spacecraft Specialists (2/vehicle)
- DSN Scheduler
- System Maintenance Engineer

The Flight Operations Manager is responsible for the following functions:

- Overseeing all operations
- Providing a central point of contact between the MOT and the external MOS
- Managing any adjustment to the operational schedules
- Occupying the position of a DSN Scheduler, when necessary

The Spacecraft Specialists are responsible for the following functions:

- Spacecraft bus operational planning and command generation
- On-line spacecraft control and readiness tests
- Spacecraft bus and ground system performance assessment
- Lead spacecraft and ground system anomaly investigations
- Operation of the S/C simulator

The DSN Scheduler is responsible for the following:

- Advance, weekly, and daily scheduling of DSN antennas for both S/C
- DSN liaison

The System Maintenance Engineer is responsible for the following:

- Normal maintenance and calibration of the MOC components
- MOC communication connections
- MOC software upgrades

Each Spacecraft Specialist will have detailed operational knowledge of the commands, telemetry, and constraints of each S/C. This will be acquired by assisting the SBET and I&T teams with S/C integration and test. Each Spacecraft Specialist will be able to perform all on-orbit operational activities for each S/C, i.e., planning, control, and assessment.

During the Early Operations mission phase, the MOC will be staffed 24 hours/day and 7 days/week. During the Normal Operations mission phase, the MOT staff will transition to business hours, 5 days/week. This will require the validation of many automated MOC procedures and autonomy rules on the S/C. Occasional off-business hours scheduling is likely to occur during some special operations including contingency activities.

Spacecraft Bus Engineering Team (SBET)

Although the MOT will be entirely capable of operating the spacecraft bus and will also be capable of detecting and responding to anomalies, the SBET is considered an essential and integral adjunct. The SBET consists of the spacecraft bus subsystem development teams and is part of the MOT. Together, they maintain the complete technical knowledge base regarding the operation and performance of the spacecraft bus. During the subsystem level testing and the follow-on spacecraft bus I&T phase, the MOT, working side-by-side with the SBET, will acquire the knowledge necessary to operate the spacecraft bus on-orbit. After launch, when operational anomalies are uncovered by the MOT, an immediate assessment will be made to ascertain the ability of the MOT, with the accrued knowledge and existing contingency procedures, to correct the anomalous operation within a reasonable time frame. If the anomaly is not clearly understood or if the recovery action is uncertain, the appropriate SBET will be notified and will support the MOT during the recovery process.

To maintain the SBET in a continuous state of readiness, the MOT will provide them periodic performance reports. The SBET will have access to all engineering telemetry stored on the SDS and will be able to access this from their office personal computers.

MOC workstations will be available to the SBET when direct support of on-orbit operations is necessary. Certainly this will occur during the Early Operations mission phase and most probably during periods of anomaly investigations.

Operations Planning

Operations planning will consist of the following activities necessary to support a scheduled track:

- Track scheduling
- Maintenance activity scheduling
- Managing the uplinking of instrument commands
- SSR management
- Timekeeping management
- Wheel desaturation management
- Navigation management
- Track plan generation

The STEREO operations planning consists of planning a week of tracks in advance. The STEREO planning week starts on Monday. For example, on Monday of Week 1, the MOT will be planning the following week. The MOT will determine the operational requirements of the spacecraft bus over the next week and will prepare the necessary command packets to satisfy these requirements.

Each day, the track schedule for the next day will be reviewed to ensure that it is current. A Daily Timeline (Figure 7) will be generated graphically depicting the significant operations on both vehicles for the next day. The final daily operations planning task is to generate a track plan.

Track Scheduling

The DSN track requirements for each spacecraft will be scheduled well in advance. Unlike most planetary missions, there is no encounter phase for the STEREO mission. Since the prime science phase is continuous, starting shortly after S/C checkout and continuing through to EOL, every track has the same priority.

Nominally, there will be one DSN track per day per spacecraft. Planned DSN track schedules for both S/C will be stored on the SDS.

Maintenance Activity Scheduling

A Maintenance Event (ME) is an activity scheduled on the S/C and executed via commands for the purpose of maintaining the health of any spacecraft bus subsystem or managing the resources of the spacecraft. The MOT is responsible for the evaluation of the spacecraft bus and will plan and schedule all MEs. With the assistance of the SBET, the health of the spacecraft will be managed by evaluating component performance and generating command sequences as MEs.

Maintenance activities for the instruments are the responsibility of the SOC and are not addressed in this document.

There are two categories of MEs: routine and sporadic. A routine ME has a set execution frequency, i.e., every track, daily, weekly, etc. A sporadic ME has no set execution frequency. A sporadic ME will be initiated based on evaluation of the telemetry data. A ME may consist of the following:

- Updating the S/C ephemeris
- Updating MET
- Desaturating reaction wheels
- Performing S/C engineering buffer dumps
- Maintaining spacecraft bus macros
- Maintaining autonomy rules
- Adjusting PPT voltage and temperature
- Implementing software changes

Managing the Uplinking of Instrument Commands

Instrument command packets will be uplinked during each track. These instrument command packets will be prepared in advance by the SOC for all instruments and will arrive at the MOC no later than 2 hours prior to the scheduled primary track. In general, however, instrument command packets should arrive well in advance of this deadline. Instrument teams are encouraged to forward command packets only once a week, which include packets designated for uplink each day of the week. The scheduling data, which will accompany the command packets, will indicate when to actually uplink these packets. Until then, they will be stored at the MOC. Briefly, the command packets will be augmented with two time tags. One time tag will specify the earliest time that the command packet can be uplinked to the instrument and the other will indicate the latest time that this can happen (the expiration time). Those command packets that have a start time that has been exceeded by the next track start time will be queued for uplink at that track to that S/C. Each instrument on each S/C will have its own set of storage buffers, staging, and uplink queues in the MOC.

The MOT is responsible for managing the command uplink for all spacecraft commands to the bus and to the instruments. Accordingly, the MOT must have some knowledge of just what is contained in the instrument uplink queues. Whereas the MOT does not have to be concerned with the actual instrument commands, it does have to know the quantity of data to be uplinked. The scheduled track will offer limited uplink capacity. Nominally, an hour of instrument command uplink time for each track has been set. This translates into approximately 450 kbits of instrument command data for all instruments per track per S/C. Commanding during this interval is not continuous. Rather, the command packets, packed into transfer frames, are uplinked and verified, transfer frame by transfer frame. The verification process can slow the uplink process somewhat. Also, any retransmissions will add additional delays. Therefore, instrument teams are encouraged to use their instrument commands as efficiently as possible.

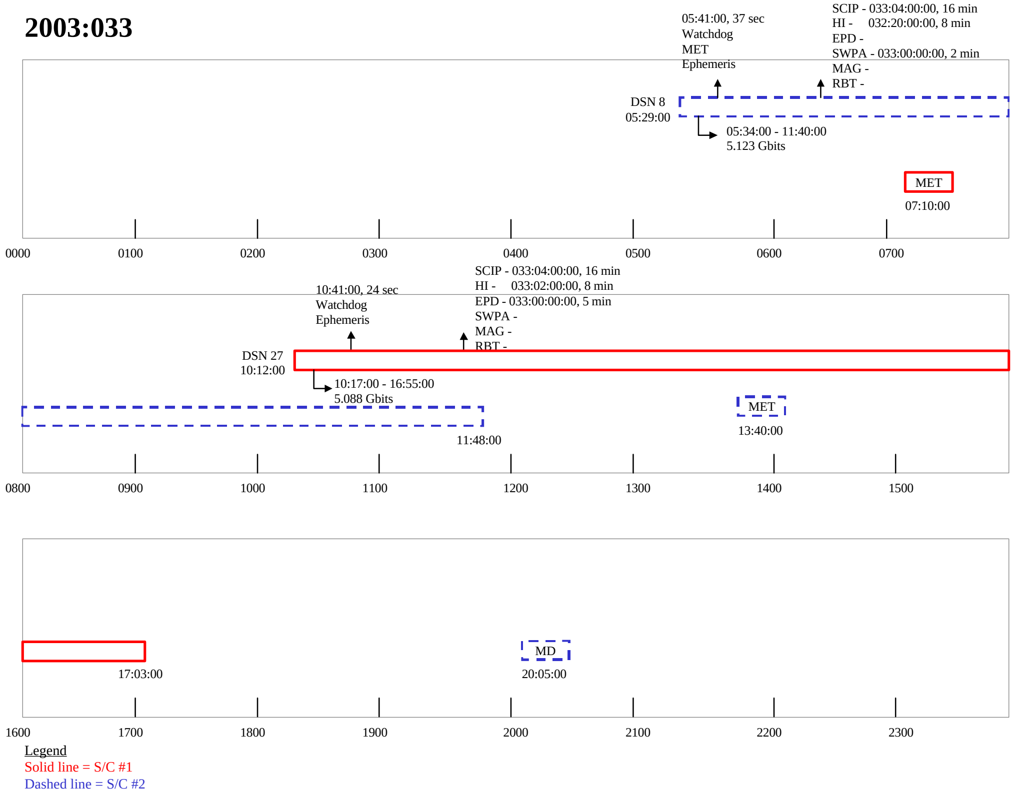


Figure 7. Daily Timeline.

The MOT will examine each instrument uplink command queue, sorted chronologically by expiration time, to assess the transmission time necessary to uplink the content. MOC software will provide the status of the content of the queue including expiration time and estimated transmission time of all queued commands. Further, the time to transmit all the commands in the uplink queues of all instruments will be provided. In the active command queue, those packets that will be uploaded during the upcoming track will be separated with a grocery bar from those that are being held back for a later track. The manipulation of this grocery bar by the MOT will provide the necessary traffic control of instrument commands so that the required instrument command packets to be transmitted, along with the real-time and time-tagged spacecraft bus command packets, will meet the track uplinking allocation time.

Manipulation of this grocery bar is the only control of the queued instrument command packets, except completely flushing (removing all command packets from) an instrument's queues. No editing control is available to the MOT. Flushing will only be permitted when authorized by the instrument team associated with that particular queue.

Spacecraft bus commands will receive priority during uplink operations and these can interrupt instrument command uploads. The MOT will actually have control over this process and can withhold spacecraft bus command uplink when necessary. The track plan, prepared by the MOT, will specify precisely what command packets—instrument and spacecraft bus, real-time and time tagged—are to be uplinked during a given track period.

SSR Management

As a baseline, the SSR will be played back on each track. For the STEREO mission, the manual MOT management of the SSR will be minimized. This will be done by implementing software on the S/C and in the MOC to monitor CCSDS transfer frames on each virtual channel. It will automatically detect and retransmit missing transfer frames during an SSR playback. The state of the playback reception at the end of a track will be saved for the next track.

Currently, the SSR recorded data are divided into four prioritized data streams: (1) G&C anomaly, (2) engineering anomaly, (3) science, and (4) nominal engineering.

At the beginning of an SSR playback, all G&C and engineering anomaly data are downlinked first, followed by science data, and then nominal engineering data. The amount of SSR data transmitted during a track will vary over the duration of the mission. Initially, the entire SSR will be played back each day. However, as the S/C-to-Earth range increases, the amount of SSR data played back will decrease. Eventually, during an 8-hour track, the entire SSR cannot be played back.

At the beginning of the mission, the SSR playbacks will be controlled by using real-time commands. As the mission progresses, to save communication time and increase the data downlinked, the control of SSR playbacks will transition from uplinked commands to an onboard autonomy rule.

An SSR log will be maintained on the Mission Data Archive in the SDS to provide a chronological history of all science data recovered to date.

Timekeeping Management

The Mission Elapsed Time (MET), as generated by the C&DH, will be maintained to the required 0.5 s of UTC for each S/C. This will be accomplished by a software process in the MOC that will periodically estimate the time offset, based on the S/C oscillator drift rate along with known system time delays (one-way light time and internal S/C time delays). This time offset or update will be periodically uplinked to the S/C as a time-tagged maintenance event to maintain the MET requirement. A history of the time updates for each S/C will be maintained in the Mission Data Archive on the SDS.

Wheel Desaturation Management

As S/C momentum builds in the reaction wheels, it will need to be dumped periodically using the thrusters in the propulsion subsystem. The MOT will monitor the RWA speeds and send commands as a time-tagged maintenance event to desaturate the wheels on each S/C. Nominally, this will be done approximately every 4 days. So as not to interfere with the science data collection by the instruments, the scheduling of these momentum dumping maintenance events will be done weekly. The momentum dumping schedule will be available to the SOC on the SDS.

Navigation Management

The G&C engineering team at JHU/APL will conduct the navigation management for each S/C. Using the Doppler range rate, ranging, and S/C attitude data, the S/C orbit will be determined using the Goddard Trajectory Determination System. Required navigation data will be stored in the Mission Data Archive in the SDS. S/C orbit data will be uplinked to the S/C guidance control computer and will be provided to DSN at required intervals for proper antenna pointing.

Track Plan Generation

The track plan is the data product that is used by the MOT to conduct a track. After all activities for the track have been scheduled, a track plan will be generated. It will list the following information chronologically:

- S/C ID
- Track ID
- S/C range
- Expected downlink bit rate
- DSN station
- AOS time
- SSR playback start time
- SSR playback total bits downlinked
- Spacecraft bus command uplink start time
- Spacecraft bus command total bits uplinked
- UT maintenance events (i.e., MET update, momentum dump, etc.)
- Real-time maintenance events
- Instrument command uplink start time
- Instrument command packets earliest uplink time and bit size (for each instrument)
- Instrument command start time total bits uplinked
- SSR playback stop time
- LOS time

Operations Control

Operations control will consist of those activities immediately prior to and following a scheduled track and will include a prepass readiness test and track operations. A prepass readiness of the ground facilities will include (1) data circuits to DSN, (2) voice circuits to DSN, and (3) MOC (elements required to support real-time operations).

This testing will ensure that the necessary elements of the ground system are functional and properly interconnected as required to support the prepared track plan. After the prepass testing, the respective operating teams will make any final configuration adjustments necessary to support the upcoming track.

Spacecraft commanding may only be initiated at the MOC command workstation. Three MOC workstations, protected by the security firewall, will be designated as command workstations. Two of these may be activated to support concurrent S/C commanding during the track and the other will be ready as a "hot" backup in case one of the active workstations fails. All MOC workstations may display processed telemetry data from both the spacecraft and the ground system. In general, the active command workstation will be dedicated to only commanding and its verification and to ensure that the track plan is properly executed. The remaining workstations will be used to monitor spacecraft and ground system performance via processed telemetry.

After a track has been completed, an As-Run Track Plan will be generated. It will essentially be a marked-up or as-flown Track Plan and will also list (1) amount of real-time data received, (2) amount of SSR data received, (3) available SSR space, and (4) status of all uplinks.

The STEREO MOT will transition to unattended tracks after the Early Operations Checkout phase.

Performance Assessment

The objective of the Performance Assessment function is to maintain the health of the spacecraft bus subsystems and evaluate their ability to collect data. Subsystem performance assessment consists of routinely determining the status, configuration, command verification, and performance of each spacecraft bus subsystem. The assessment tasks that will be performed by the MOT include (1) alarmed telemetry processing, (2) command verification, (3) trend analysis, and (4) providing data to the SBET.

Trend analysis will be conducted on critical subsystem components and on components that are known to degrade with time, such as the following:

- Battery voltage, pressure, temperature, state of charge
- Solar array temperatures and currents
- Operational and survival heater currents
- Propulsion tank pressure
- Other critical temperatures

These analyses will be conducted daily, weekly, monthly, quarterly, and annually.

The MOT will maintain a history of the changes to each S/C after launch in a configuration log. This record will be used to maintain the S/C during processor resets and also for anomaly investigations. A PC spreadsheet implementation of the configuration logs will be sufficient.

The performance assessment function will be augmented by the SBET's in-depth analysis of subsystem performance. The SBET will have direct access to the engineering telemetry database stored at the SDS, so any data may be accessed and processed to the satisfaction of the responsible engineer.

All of the performance assessment processing will be automated. Alarms processing, command verification, and trend analysis plotting will be done automatically.

Each day, the MOT will review the output of these assessment processes. This will allow the MOT to minimize the daily time required to determine the health and performance of each spacecraft bus. A Performance Assessment report for each S/C will be available on the Mission Data Archive in the SDS.

Anomaly Investigations and Resolutions

The MOT is responsible for the safety and health of both S/C buses. They will lead and coordinate investigations with the SBET into all S/C bus anomalies. Anomalies identified both during a track and during performance assessment will be investigated. A cumulative database of all S/C bus anomalies for each S/C bus, from I&T through EOL, will be maintained in the Mission Data Archive on the SDS.

To assist the MOT during unattended tracks, an automated alarm notification system will be implemented. It will consist of an automated paging system that will notify the on-duty MOT staff of any alarms received during a track. Additional supporting engineering data will be e-mailed to an offsite (e.g., at home) MOT staff member for further analysis of the problem. The notified MOT staff member can then determine the appropriate action to take, i.e., request additional tracks, download additional engineering data, consult the respective SBET, etc.

Conclusion

The STEREO spacecraft and ground system are being designed with a high degree of autonomy and decoupled instrument operations. Also, the STEREO mission itself is a fixed stare at the Sun with no pointing or orbit changes, making this mission ideal for "lights out" operations. Employing the use of the MOC and the MOT early in the development of the spacecraft to assist with the integration and test will yield an extensively trained team by the time the spacecraft are launched. These design attributes should result in a small operations team and low-cost flight operations for the mission.