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STEREO Ground Segment, Science Operations, and Data Archive

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Abstract Vitally important to the success of any mission is the ground support system used for commanding the spacecraft, receiving the telemetry, and processing the results. We describe the ground system used for the STEREO mission, consisting of the Mission Operations Center, the individual Payload Operations Centers for each instrument, and the STEREO Science Center, together with mission support from the Flight Dynamics Facility, Deep Space Mission System, and the Space Environment Center. The mission planning process is described, as is the data flow from spacecraft telemetry to processed science data to long-term archive. We describe the online resources that researchers will be able to use to access STEREO planning resources, science data, and analysis software. The STEREO Joint Observations Program system is described, with instructions on how observers can participate. Finally, we describe the near-real-time processing of the "space weather beacon" telemetry, which is a low telemetry rate quicklook product available close to 24 hours a day, with the intended use of space weather forecasting.

Keywords STEREO · Space weather · Science operations · Data archive · Solar observations

1 Introduction

The STEREO ground system provides the means for planning the STEREO mission, communicating the plans to the STEREO observatories, assessing and maintaining the health and safety of the observatories, and providing detailed data products from these processes to the

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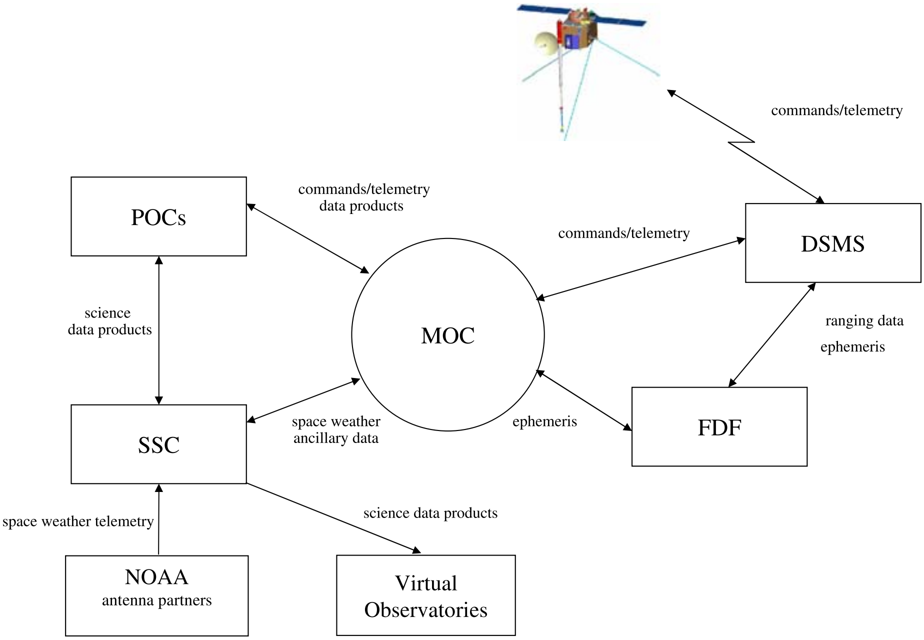

Fig. 1 STEREO ground segment teams and interfaces

STEREO community. Of primary interest to the community are the science data collected, which are brought down from the observatories daily and ultimately reside at the STEREO Science Center for retrieval by the international science community and the general public.

The STEREO ground system consists of several operations centers which each play a role in the STEREO science mission. These operations centers are distributed across the world and consist of the Mission Operations Center (MOC), four Payload Operations Centers (POCs), the STEREO Science Center (SSC), the Flight Dynamics Facility (FDF), and the Deep Space Mission System (DSMS) which operates the Deep Space Network (DSN). The STEREO ground segment provides the means for these operations centers to perform their individual tasks as well as to communicate necessary data products between centers and the observatories. Figure 1 depicts the STEREO ground segment teams and interfaces. The STEREO Mission Operations Center is located at the Johns Hopkins University/Applied Physics Laboratory in Laurel, MD, and is the center that operates the observatory bus and serves as the collection and distribution point for the instrument commands and telemetry. The Payload Operation Centers are the instrument operations centers that generate the commands for each of the four STEREO instrument suites and monitor instrument health and safety. These centers are located at the Naval Research Laboratory in Washington, DC; the University of California–Berkeley in Berkeley, CA; the University of Minnesota in Minneapolis, MN; and the University of New Hampshire in Durham, NH. These are the home bases for the instrument POCs, but they are able to operate remotely when necessary and also maintain a presence at the MOC. The SSC, located at the Goddard Space Flight Center in Greenbelt, MD, provides science coordination and serves as the STEREO archive. Also located at GSFC is the FDF, which performs STEREO navigation services. The DSMS is operated by the Jet Propulsion Laboratory in Pasadena, CA, with ground stations in California, Madrid, Spain, and Canberra, Australia.

1.1 Mission Requirements and the Ground System Design

The top-level requirements levied on the STEREO ground system which influenced the ground system design can be broken down into four major components:

- All instrument operations will be decoupled from the spacecraft bus operations. The instruments and the spacecraft bus will be operated almost entirely independent of each other. The same can be said about the ground elements (the POCs and the MOC).
- The ground system will support subsystem development, observatory integration, and mission operations.
- The spacecraft and ground system will be designed to deliver an average of 5 Gbits of science data per day per observatory to the instrument POCs and the SSC.
- The MOC will provide the data products to the SSC and instrument Payload Operations Centers (POCs). These data products consist of Level 0 telemetry data and Mission Support Data.

Decoupled instrument operations has the effect of greatly simplifying mission operations and the ground planning tools. The STEREO mission is ideal for implementing this separation of spacecraft and instrument operations as there are essentially no shared resources. The spacecraft continually points at the Sun and therefore no coordination is required for encounters and enough power is available to support all instrument operations at all times. In addition, the SSR is portioned such that each instrument (or instrument suite) has its own partitions for recording science data and each POC is responsible for managing its partitions. There are some events that require spacecraft and instrument coordination, such as calibration maneuvers and software loads, but these are coordinated individually and occur infrequently.

The STEREO ground system has evolved over time to support the mission as it is developed. The early system consists of "mini-MOCs", which are single workstations that support subsystem development. Each mini-MOC contains the same command and control system which is built up into the I&T MOC and the MOC. The mini-MOC contains its own archive within the workstation, while the I&T and Flight MOC is more distributed with an archive and tools specific to I&T and Mission Operations. This concept has been used at APL for many past missions and simplifies spacecraft and operations development.

The data return requirement of 5 Gbits per day on average primarily determines the duration of the DSN tracks and hence is the largest factor in the DSN scheduling process. Throughout the STEREO mission, the track durations are increased as the supported data rates are reduced. The daily track times planned for STEREO take into account data from past deep space missions such as the number of missed tracks, delayed acquisitions, and safe mode demotions. Enough additional track time has been scheduled and the SSR is large enough to support daily downlink of "extra" data such that the yearly daily average should be realized.

There are many data products produced by the STEREO MOC which fulfill the requirements and desires of the mission and instrument teams. These products are produced through the planning, control, and assessment processes and are distributed through an ftp server in the STEREO MOC.

1.2 Spacecraft and Mission Operations

1.2.1 STEREO Spacecraft

Each of the two STEREO spacecraft are nearly identical with selective redundancy. The spacecraft bus was built by JHU/APL with NASA Goddard Space Flight Center (GSFC) procuring the instruments. The entire spacecraft was integrated at JHU/APL. The spacecraft design is described more fully in Driesman and Hynes (2007), but a short summary is given here to lead into the discussion of operations.

The spacecraft bus consists of six operational subsystems supporting a payload suite of four instruments. The spacecraft bus is designed around an Integrated Electronics Module (IEM). The IEM is a single box that contains the Command & Data Handling (C&DH), Guidance and Control (G&C), and Solid State Recorder (SSR) on plug-in cards. A MIL-STD-1553 bus architecture is used for command and telemetry between the IEM and the instrument Data Processing Units (DPU), Guidance and Control (G&C) processor, Transponder, Star Tracker, Inertial Measurement Unit (IMU), and Power subsystem.

The C&DH subsystem provides real-time, timetagged, macro, and autonomy command capabilities. It uses a Rad 6000, 25 MHz, 32-bit processor that formats all spacecraft bus telemetry into CCSDS compliant packets. An 8.5 Gbit RAM Solid State Recorder (SSR) is used for data storage of all science and engineering data. An Oven Controlled Crystal Oscillator (OCXO) is used for time reference.

The RF Communications subsystem provides simultaneous X-Band (XB) uplink, downlink, and navigation data using one High Gain Antenna (HGA) and two Low Gain Antennas (LGA). The LGAs provide communications from launch through the phasing orbits and is used for emergency communications when the spacecraft is in Earth Acquisition mode. The HGA consists of a gimbaled, 1.2 meter, parabolic dish with a 180-degree gimbal travel. It will be used when the spacecraft range is greater than 0.2 AU. There are five XB uplink rates, 125, 500, 1,000, and 2,000 bps for normal operations and 7.8125 bps for emergency operations. The RF Communications subsystem is designed to use the DSMS 34-meter Beam Wave Guide (BWG) antennas, although any 34 m or 70 m antenna with XB uplink and downlink can be used.

The G&C subsystem provides three-axis attitude control of the spacecraft and also controls the pointing of the HGA. Nominal orientation of the spacecraft will have the $+X$-axis of the spacecraft pointed at the Sun within 0.1° and the HGA, near the Z-axis, will be pointed at the Earth within $\pm 0.35^\circ$. The G&C subsystem consists of one Rad 6000 processor, the Attitude Interface Electronics (AIE)/1553 Board, three attitude sensors, an Inertial Measurement Unit (IMU), Star Tracker, and Digital Solar Attitude Detectors (DSAD), and two control actuators, Reaction Wheel Assemblies (RWA) and the Propulsion subsystem.

The AIE/1553 Board provides the 1553 digital interface between the analog G&C components, i.e., DSADs, RWA, HGA gimbal, and thrusters, and the C&DH subsystem. It consists of an electronics board in the Power Distribution Unit (PDU).

During a serious spacecraft emergency (processor reboot, hardware Low Voltage Sense (LVS), or command loss timeout) the spacecraft will go through a system reset and enter Earth Acquisition (EA) mode. Both processors will reboot and the C&DH/EA processor will come up using the EA application. The EA application combines the functionality of the C&DH application along with basic G&C functionality, i.e., using measured data only it will maintain attitude control (inertial knowledge will not be known). The G&C processor will reboot and reload the G&C application; however, it will essentially be idling since it will not be receiving G&C sensor data nor have control over the G&C actuators. The EA application will point the $+X$ axis of the spacecraft at the Sun, switch to the summed LGAs, reduce the downlink and uplink rates to a minimum, and go into a 5°/min roll about the X-axis.

The IMU (redundant) provides spacecraft rate and acceleration data using Ring Laser Gyros and accelerometers. The Star Tracker can autonomously identify up to nine stars, using a 16.4° × 16.4° field of view (FOV), with brightness between +0.1 to +5.5 magnitude. There are five DSADs each with a ±64° FOV to determine the Sun location with an accuracy of 0.5°.

Four RWA provide pointing control. As system momentum builds in the RWAs, it will be dumped, approximately every 13 days, using the thrusters in the Propulsion subsystem. While the G&C can autonomously perform momentum dumps, they are expected to be planned and controlled by mission operations so as to avoid any interference with science data collection.

The Propulsion subsystem consists of two hydrazine propellant tanks, one transducer, three high-pressure latch valves, and 12 4.5 N m thrusters. There will be sufficient propellant to dump momentum for five years with a 10% leakage allowance.

The Power subsystem employs two fixed GaAs/Ge solar arrays (SA). Power is managed by a Peak Power Tracker (PPT) to provide an unregulated 22 to 35 V DC bus. A 23 ampere-hour NiH_2 battery provides power from launch to SA deployment and for Low Voltage Sense (LVS) conditions.

The Thermal subsystem is a passive design using blankets, radiators, and thermostatically controlled heaters. All instruments are thermally isolated from the spacecraft structure

1.2.2 STEREO Mission Operations

The STEREO mission consists of continually pointing at the Sun as the observatories move away from the Earth at 22 deg/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 mode and the observatory remains thermally stable. Each instrument has its own partitions to use on the SSR which are typically set by Mission Operations to an overwrite mode. This leaves the spacecraft and instruments with no power, thermal, or SSR constraints other than managing the amount of data being placed in their SSR partitions. However, there are a two resources that are shared between the instruments which must be managed. These are the downlink during the phasing orbits, and the Stored Command Buffer (SCB) in the C&DH. The SCB is 20 kbits in size and must be managed so as not to overload it. This space is primarily used by the SWAVES instrument, but is also available to PLASTIC and IMPACT. The SSC will be managing these two resources by negotiating between the instruments for the available downlink during early operations and by coordinating the use of the SCB during the mission.

Telemetry is received from the observatory by the DSN during daily tracks. During most of the track, the SSR is played back and collected by the DSN Central Data Recorder while the real-time telemetry is flowed directly to the MOC. These real-time data are made available to the POCs through a socket connection to the MOC. The real-time data can also be "played back" from the MOC archive via a socket connection. The Central Data Recorder will ftp the full data set from the track (both real-time and SSR playback) in 30-minute files. Once all these files are collected by the MOC, they will be processed into level 0 data for each instrument and the SSC and be made available to the instrument POCs and the SSC within 24 hours after receipt of all the data from the DSN via ftp from the STEREO Data Server in the MOC.

Also during each track, commands will be uplinked to the spacecraft beginning early in the track. Following the upload of spacecraft commands, instrument command queues will be opened and commands that have been forwarded to the MOC in advance will be uplinked in a round-robin fashion for each POC. Following this command uplink, the POC command queues may be opened to allow real-time commanding by the instrument POCs.

The POCs will maintain the health and safety of their instruments from review of the telemetry data received and commanding in the process just described. In addition to this, autonomy is onboard the observatory which can power off the instruments at their request or when the spacecraft requires for health and safety purposes.

1.3 Telemetry and Data Processing

Figure 2 illustrates conceptual flow of command and telemetry data between the ground-based observatory 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 teams at their home POC. In Fig. 2, begin at the POC Planning, on the far right, where instrument commands are produced. The 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 (MOC Authorize and Route) there is some checking performed, then these commands are queued for eventual uplink to the instrument. Along with the command packets, the POCs will append timing information that indicates the time span (earliest and latest times) over which the command packet may be uplinked to the spacecraft instrument. Real-time command packets, when uplinked to the spacecraft, are immediately routed by the spacecraft bus to the appropriate instrument and time tagged command packets are stored in the instrument's stored command buffer in the observatory bus Command and Data Handling (C&DH) system. Conceptually, the command packet goes "directly" from the POC to the instrument, since the MOC, ground station and spacecraft bus are merely the delivery system. This delivery system notifies the POC of the delivery status of the command message.

Whereas the POCs produce instrument commands, the MOC produces spacecraft bus commands. This is depicted in the "inner-loop" on the data flow diagram (Fig. 2). Starting at the MOC Planning process, the Mission Operations Team (MOT) prepares command messages to the spacecraft bus to operate it during the next day. These command messages are queued for uplink (MOC Authorize and Route) just like the instrument commands, only they go to a different destination (via the C&DH Routing Service). Real-time commands are immediately routed, by the C&DH processor, to the appropriate spacecraft subsystem and timetagged and macro commands are stored in the C&DH processor. The MOC receives delivery status of the command packets just as the POCs do.

The onboard instruments produce science and engineering data (Instrument Data Collection) in response to the uplinked command messages. The data produced by the instruments are sent to the spacecraft data system in the form of CCSDS telemetry packets. Similarly, engineering data produced by the spacecraft bus are also formatted into CCSDS packets. These packets produced by the instruments and the spacecraft bus and conveyed to the spacecraft data system (C&DH Combine) are stored on the Solid State Recorder (SSR) within the spacecraft data system (C&DH Recording). During a ground track with the spacecraft, the contents of the SSR are transmitted to the MOC (C&DH Frame Packaging).

On the ground (Ground System Telemetry Routing), real-time data are forwarded to the MOC and POCs, while all recorded data are sent to the STEREO Data Server (SDS). All instrument data will be processed into level 0 data files and sent to the POCs for further processing and analysis, and to the STEREO Science Center for mission archival. The cycle repeats, with the POCs preparing instrument commands for still another day in space. Spacecraft bus data are routed to the MOC (MOC Assessment) where an assessment function is performed. The MOC spacecraft bus planning process then repeats.

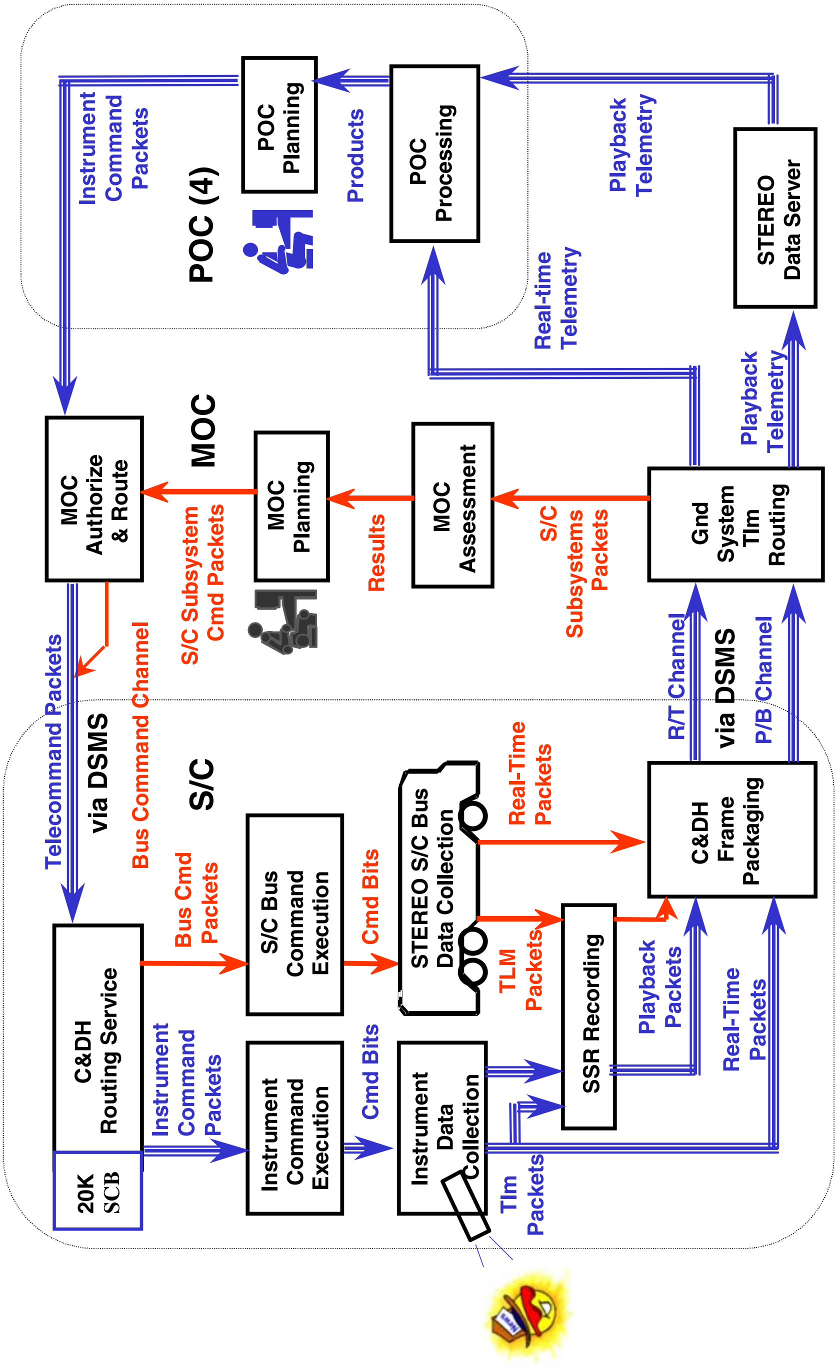

Fig. 2 Decoupled instrument operations data flow

2 STEREO Mission Operations Center

The MOC 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 DSN. Recovery of spacecraft bus engineering (state-of-health) telemetry and the performance analysis based on this telemetry is also performed at the MOC. The MOC receives instrument command messages from the POCs and, after verification that the command ApIDs are appropriate for the POC they came from, queues these for uplink to the spacecraft based on 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. The MOC does control the instrument power service and can power off an instrument at the request of the POC. In addition, an instrument can autonomously request to be powered down through the spacecraft fault protection system.

2.1 Local Area Network Architecture

Figure 3 illustrates the MOC and the supporting network architecture including interfaces to other mission operations elements. Restricted IONet communication lines connect the MOC primary and backup command workstations to the DSN through a firewall. PCs running Memory Allocation Examiner (MAX) are the only other computers on the Prime Restricted IONet network. These workstations are connected to the Ops "Demilitarized Zone" (DMZ) network through another firewall. The Ops DMZ network houses the assessment workstations and a series of X-Terminals which can display real-time and playback telemetry data to the spacecraft engineering team within the MOC. The Ops DMZ also contains the STEREO Planning system software, real-time telemetry servers, the POC command acceptor, the STEREO Data Server, the second-level archive which stores decommutated spacecraft telemetry for trending, and the Spacecraft Hardware in the Loop Simulators. The Ops DMZ Network is in turn connected to the Internet via a third firewall. The SSC, POCs, and the FDF connect to the Ops DMZ via the Internet to retrieve STEREO Data Products from the SDS and to deliver instrument commands via the POC Command Acceptor. Should the Internet be inaccessible to the POCs or SSC, the Ops DMZ can be accessed through a modem pool. Two additional STEREO workstations will be housed in the APL Multi-Mission MOC which is an Operations facility located in a different building within the APL campus. These workstations are for emergency state-of-health command and telemetry and would be used should a disaster consume the STEREO MOC. These machines are maintained with current files and software for this purpose.

2.1.1 STEREO Telemetry Flow

Real-time telemetry from each STEREO spacecraft will flow from the spacecraft into the DSN and be routed through the Restricted IONet to APL on a low-latency delivery path with complete data delivery not guaranteed. These data are flowed to the Ops DMZ network where they can be viewed in real-time by the spacecraft engineering team or the POCs either locally or remotely. The data are stored for several days on the data servers where they can be played back via instant replay in the MOC or across the Internet at the request of the POCs. The SSR playback data are recorded at the Central Data Recorder (CDR) at JPL where they are sent to the MOC in half-hour segment Intermediate Data Record (IDR) files over the

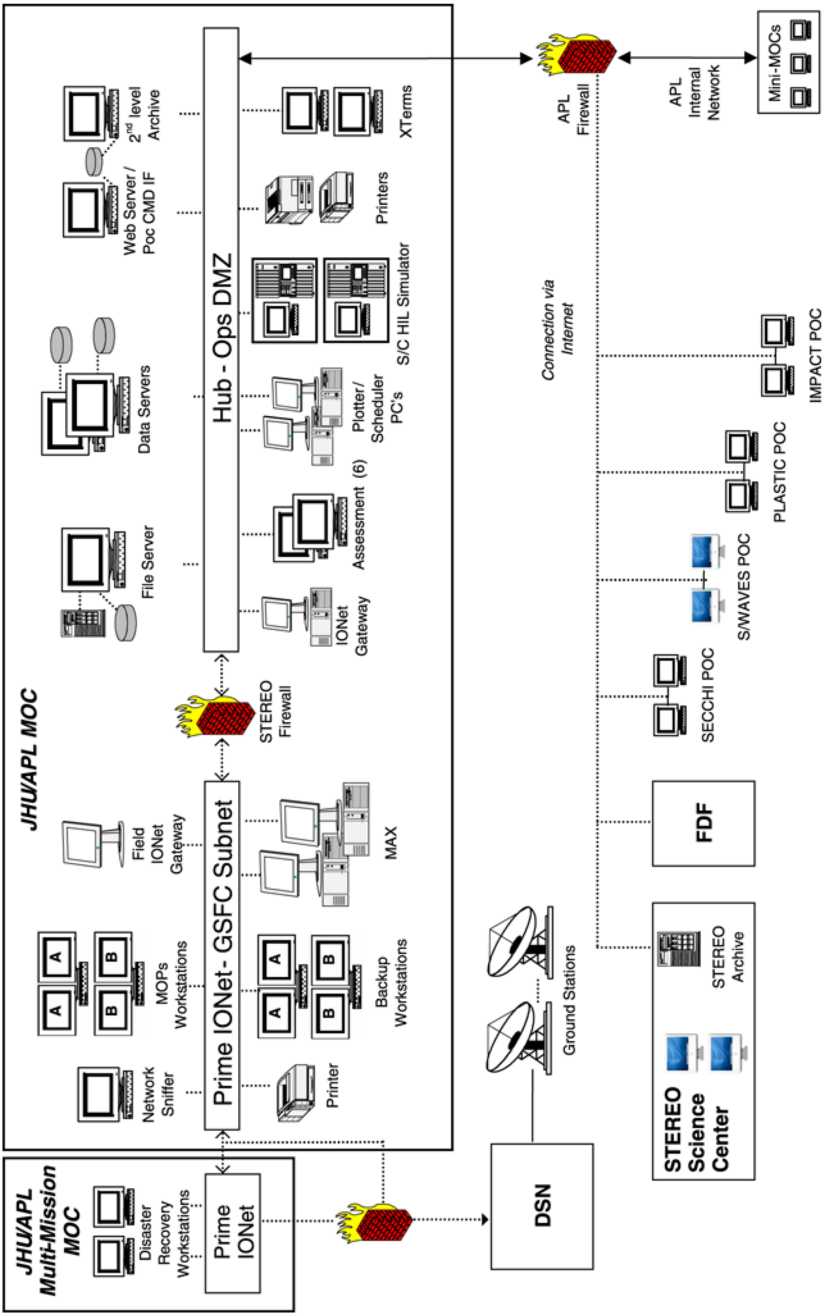

Fig. 3 MOC network architecture

Internet. These data are guaranteed complete and are the data that will be used to populate the raw archive and generate level 0 data. Daily, and upon complete playback of the SSR and MOC receipt of all the IDR files from the CDR, level 0 data are processed for each of the instrument POCs and the spacecraft housekeeping data. Level 0 data are time ordered with duplicates removed. Each day level 0 files are produced for the previous day, the preceding day, the day before that, and for 30 days earlier. This allows for the delivery of data that may have resided on the SSR for a few days and it is expected that the file from 30 days ago will be the final delivery with the complete data for that day. Due to the volume of data in the SECCHI POC partitions, each of these level 0 files are produced in 4-hour segments where all the other level 0 files are produced for a 24-hour period. Once generated, the level 0 files are placed on the STEREO Data Server (within 24 hours from receipt of the IDR files from the DSN) where they can be retrieved by the POCs and SSC. These files are maintained on the SDS for 30 days when they can be removed after receipt of the Archive Products List from the SSC indicating that they have retrieved the data.

2.1.2 STEREO Command Flow

The IMPACT, PLASTIC, SECCHI, and SWAVES POCs will send to the MOC Command Messages that contain the information needed to configure and control their instruments. These command messages will be sent to the MOC at least eight hours prior to the start of the track that they are scheduled for uplink. The MOC shall authenticate and perform minimal syntax checks on the command messages, and sends an Authorization Return Receipt message back to the POCs facility indicating the message status. If the POCs want to delete previously transmitted command messages prior to their upload, the POC verbally sends the MOC a command flush request. Based on the command delivery time information included in the command message header, the MOC shall forward the validated queued command messages to the Deep Space Mission System (DSMS) interface for transfer to the spacecraft in a round-robin format between the POCs. Finally, the Command and Data Handling (C&DH) process on the spacecraft shall forward the commands to the 1553 bus for instrument retrieval. Actual command execution success or failure will be indicated in instrument telemetry telltales. In addition to verification of instrument commands through instrument telemetry, the As Run Track Plan and the Command and Packet History data products are sent out to assist in tracking instrument commands.

During instrument commissioning, instrument special events such as software loads, and during instrument emergencies, real-time commanding by the instrument POC is also available. In this case, the commands flow directly from the POC, through the POC Command Acceptor in the MOC where they are transferred to the Restricted IONet and flowed directly to the DSMS and up to the spacecraft. The MOC can control which POCs will be commanding in real-time and during emergencies, instrument commissioning, and software loads, will restrict realtime commanding to a single POC.

Within the C&DH subsystem on the spacecraft there is also an Instrument Stored Command Buffer. The SWAVES, IMPACT, and PLASTIC POCs may use this Stored Command Buffer to load time tagged commands for their respective instruments. This 20 k buffer will store instrument packets until the UTC time associated with the command packet when it will then forward it to the instrument. The POCs and SSC manage this buffer such that it is not overfilled and following each track the MOC will produce a Stored Command Buffer report indicating the command packets within the buffer to assist in managing it. The Stored Command Buffer on the spacecraft can also be flushed of instrument commands by the MOC, at the request of each POC.

2.2 MOC Personnel

The STEREO Mission Operations Team at APL will launch with 14 team members. This 14-member team will be reduced to 12 by the end of the phasing orbits. The launch team organization consists of:

1 Mission Operations Manager
4 Real-time controllers
8 Spacecraft Specialists
1 Anomaly Officer.

Following the phasing orbits the team will operate without the Anomaly Officer and with the Mission Operations Manager also serving as a Spacecraft Specialist. At launch +6 months the team will transition to unattended tracks and will reduce to eight Spacecraft Specialists. At Heliocentric Orbit +1 year the team is expected to reduce again to six Spacecraft Specialists for the remainder of the mission.

Each of the above positions will have the following responsibilities:

- Mission Operations Manager (MOM): The Mission Operations Manager will be responsible for verifying the readiness of the ground system for launch. The MOM will also be the primary maneuver planner during the phasing orbits, prepare the weekly status report for the MOC, and serve on the post launch Configuration Control Board. Following completion of all spacecraft maneuvers, the MOM will also serve as one of the Spacecraft Specialists.
- Real-Time Controller: The real-time controllers will be the primary interface with the DSN for each real-time track. They will configure the ground system, verify readiness for each track with the DSN Station, and handle ground system contingencies.
- Spacecraft Specialist: The Spacecraft Specialists will serve as the Planners, real-time spacecraft evaluators during DSN tracks, and perform spacecraft assessment. The Spacecraft Specialist team will rotate through these roles on a weekly basis.
- Anomaly Officer: The Anomaly Officer is unique to early operations. This role will consist of organizing the larger team (Mission Operations and Spacecraft Engineers) to solve anomalies early after launch. The Anomaly Officer will be intimately familiar with the Contingency Handbook and will be able to effectively lead the team in resolving anomalies.

2.3 Other Ground Segment Elements

2.3.1 Deep Space Mission System

The Deep Space Mission System (DSMS) will be used to provide communications to both spacecraft from launch to end of life (EOL). The use of all three DSMS antenna facilities, Goldstone, Madrid, and Canberra, are required to determine the elevation component for the navigation of each spacecraft. Nominally, one 3.5- to 5-hour track, depending on spacecraft range, centered every 24 hours per spacecraft will be conducted using the 34-meter BWG subnet.

The MOC is connected to the DSMS via Restricted IONet links. Commands will be flowed to the DSN 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 using legacy UDP service. Playback data received at the DSN station will be flowed to the Central Data Recorder at JPL where they will in turn be flowed in half-hour increments to the MOC via FTP as IDR files. Orbit data for each spacecraft will be provided to DSMS from the FDF for acquisition and ranging data will be distributed from the DSMS to the FDF for orbit determination purposes over the Restricted IONet.

2.3.2 Flight Dynamics Facility

The Flight Dynamics Facility (FDF) at Goddard Space Flight Center determines the orbits of the observatory from tracking data provided by the DSN ground stations, and 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 transfers this information to the STEREO MOC via the FDF Products Center.

Locally, Delta launch and ascent support will be provided by the FDF Expendable Launch Vehicle (ELV) Support Team, whose role it is to provide the following: (1) launch vehicle acquisition data delivered to tracking sites supporting the ascent, and (2) an orbital insertion state vector based on Delta internal guidance telemetry. The orbital insertion state vector obtained in this way provides the first indication of the status of the achieved orbit. The orbital insertion state vector will be delivered by the ELV team to the FDF STEREO orbit determination team and to the APL Mission Design Team for evaluation. At the FDF, the insertion vector may also be used to update tracker acquisition data and to become a "seed" vector for the orbit determination process. Once the two spacecraft have been acquired by two DSN stations, tracking data for each will begin to flow to the FDF. The FDF will perform orbit determination operations on a daily basis, obtaining and delivering to APL a state vector solution at least once per day. Ephemeris files based on these solutions will also be generated and delivered to APL and JPL.

The FDF will continue collecting tracking data during all tracking passes in the early orbit phase, and Orbit Determination (OD) solutions will be updated at intervals following sufficiently extended orbital solution arcs. However, after the first 24 hours these updates are expected to occur at least once daily leading up to the first apogee (A1). OD updates will be computed daily starting seven days in advance of maneuvers to support timely maneuver planning at APL. For all maneuvers, OD updates will be obtained with an epoch just prior to maneuver ignition and again at an epoch just after maneuver burnout. These OD updates will support maneuver reconstruction and calibration activities by the APL Mission Design Team. The FDF will also support maneuvers by measuring the observed component of delta-V along the station line-of-sight to the spacecraft, where applicable. This radial delta-V observation will be communicated to the APL Mission Design Team for use in maneuver calibration activities.

The phase of the mission between the first apogee of the phasing loops and the lunar swingbys will continue to be operationally intense. The FDF will continue collecting tracking data according to the daily support schedule. By definition, this phase of the mission extends to two weeks after the lunar swingbys that propel the spacecraft into heliocentric orbit. The FDF OD team will expect the possibility of orbit maneuvers around the time of every perigee and apogee. For STEREO-A, there is also a likelihood of a trim maneuver(s) following the first lunar swingby to re-target the second swingby. The APL Mission Design Team will keep the FDF apprised of updates to the mission timeline and provide predicted burn details as needed. The FDF will in turn model maneuvers into ephemeris files in cases where the span includes maneuver epochs.

During heliocentric orbit, the mission will settle into a routine phase starting immediately after the lunar swingbys, with no more orbit maneuvers expected for the duration of the mission. The tracking schedule changes as the observatories move further from the Earth with increased contact time as the data rates are lowered. The FDF will continue to collect the DSN tracking data on this schedule and will evaluate the tracking data as necessary.

2.3.3 NOAA

During the periods that the STEREO observatories are not in DSN contact, each will be broadcasting a low-rate "space weather beacon" telemetry stream. The National Oceanographic and Atmospheric Administration Space Environment Center (NOAA/SEC) has taken on the responsibility of coordinating ground stations at various locations around the world to collect this telemetry and transmit it to the SSC. This process is described in more detail in Sect. 5.3.

3 STEREO Science Center

The STEREO Science Center (SSC)—located at the NASA Goddard Space Flight Center in Greenbelt, MD—serves four main functions for the STEREO mission. First, it is the prime archive of STEREO telemetry and data, and serves that data to the international science community and to the general public, both through its own Web site, and through interaction with virtual observatories (see Sect. 5.5.1). 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 heritage of the SSC arises from experience acquired in operating earlier solar physics payloads: NASA's Solar Maximum Mission (SMM) (Bohlin et al. 1980), and the NASA/ESA Solar and Heliospheric Observatory (SOHO) (St. Cyr et al. 1995). In particular, we are building on the experience of the Solar Data Analysis Center (SDAC), which grew out of the earlier SMM Data Analysis Center to support many other missions, including SOHO.

The task of the SSC is not exactly the same as that of the SMM or SOHO Experiment Operations Facilities (EOF). In many ways, it's much simpler, because the SSC has no direct role in instrument commanding. However, the other major roles of the SOHO EOF—science coordination, data archiving, and public outreach—are duplicated in the SSC. In addition, the SSC has the completely new responsibility of collecting and processing space weather beacon data, as discussed in Sect. 5.3.

3.1 Local Area Network Architecture

A major design objective of the SSC was to build as much as possible on existing facilities within the NASA GSFC Solar Physics Laboratory. Not only does this result in a considerable cost savings, but it also gives us a major leap forward in expertise to draw on. The primary STEREO archive will be co-located with the Solar Data Analysis Center (SDAC) which currently serves the SOHO archive, among others.

The STEREO archive will be stored on a series of external RAID storage systems, connected to servers through high-speed fiber optic switches. RAID systems provide high levels of reliability and data integrity. The use of a fiber optic switch allows several servers to all share the same data archive. Other servers will also be able to access the data through the network, using one of the fiber-connected nodes as an NFS server. Tasks will be split between servers for load balancing and reliability. There will also be sufficient redundancy in case one or more of the servers fails. The servers will be essentially interchangeable, so that tasks can be easily redistributed to better optimize the system.

A secondary archive will be maintained in a separate building at Goddard, where the Solar Physics Laboratory is housed. This separate (and potentially smaller) archive will provide several functions. First, it will ease access to the data for SSC personnel and others in the Solar Physics Laboratory. Second, it will provide some redundancy in case the primary archive becomes unavailable. Finally, it allows Web traffic to be split up. Under nominal conditions, general information about the mission will be served from the secondary archive, while data access will be from the primary archive. The primary and secondary archives will be on completely separate networks, so one of the two archives will still be available even if the entire other network is down.

STEREO news releases, and other public affairs materials, will be served from a separate NASA-wide portal site, which will further split Web traffic. When Web traffic increases due to high-profile news stories, very little of that traffic should impact the primary archive Web server.

Data on the primary archive site will be backed up internally within the SDAC, and also delivered on a regular basis to the NASA National Space Science Data Center (NSSDC) for disaster recovery and final archive. Data on the secondary archive will be mirrored from the primary archive, and not backed up independently. Frequent backups will be made of all Web pages and software directories on both the prime and secondary server.

3.2 SSC Personnel

The STEREO Science Center is under the direct management of the STEREO Project Scientist and Deputy Project Scientist. Day-to-day operations are managed by a Chief Observer, who is primarily responsible for the science coordination aspect of the mission, and also oversees all the other SSC activities. Hardware and operating system maintenance is provided by a System Administrator, while two Senior Programmers provide general software development and maintenance. A Data Scientist assists the international science community to use the data from the mission, and assists with the science coordination. Science analysis and science planning activities will also be assisted by post-doctoral scientist during mission operations. Education and public outreach activities are assisted by a Web Designer/Graphics Artist, and a Media Specialist.

Many of the technical positions will be shared with the SDAC, while the education and outreach personnel will be shared with SOHO and Living With a Star. This provides us not only with cost savings, but also expedites the coordination and sharing of expertise.

4 Science Operations Concept

4.1 Science Planning Cycle

The STEREO science planning strategy is based on the successful system used for the SOHO mission (St. Cyr et al. 1995). SOHO started out with a series of planning meetings, beginning with quarterly long-range planning meetings, and being further refined through monthly, weekly, and finally daily meetings. STEREO will use the same basic concept; however, since the level of instrument commanding will be far less than on SOHO, the smallest increment of regular meetings during regular operations will be weekly.

4.1.1 Science Working Group Meetings

The STEREO Science Working Group (SWG), consisting of the STEREO Program Scientists, Project Scientist, Deputy Project Scientist, and the Principal Investigators and designated members of each of the instrument teams, will set the overall science policy and direction for mission operations, set priorities, resolve conflicts and disputes, and consider observing proposals. During STEREO science operations, the SWG will meet several times a year to consider the long-term period starting in one month's time and form a general scientific plan. If any non-routine operations are required—such as non-standard telemetry allocations—the requests must be formulated at this SWG meeting. Calibration activities, such as spacecraft rolls, will be defined.

4.1.2 Monthly Teleconferences

The long-term plan will be refined during monthly planning teleconference calls of the Science Operations Working Group (SOWG), composed of the PIs or their team members, together with a representative of the SSC. These teleconferences will assess progress in achieving the scientific goals of the planned investigations, and to discuss the objectives for operations starting in a month's time. This gives time for coordinated observations to be set up, and any deficiencies in observing sequences to be identified. Inputs to the monthly meeting are made by each instrument team and common objectives are identified. The output of this meeting is a schedule showing when each instrument will be operating, whether joint or individual observations are being made, ground observatory support, and a backup plan if these conditions are not met. Requirements for telemetry rate switching should be identified together with any spacecraft operations which may affect the observations, for example, momentum dumping. Conflicts between instruments for resources are resolved, and disturbances are identified.

4.1.3 Weekly Optimization

A weekly "virtual meeting" of the SOWG considers the week starting in approximately three days time, and this is when the detailed plans for all the STEREO instruments are synchronized. It will be convened by the SSC, and will be either a teleconference or computerized communication, depending on the complexity of that week's operations. The intention is to lay out a definitive plan with timings, flag status, disturbances, etc. This meeting will have the conflict-free DSN schedule available.

Any conflicts in the planned use of the spacecraft command buffers will be resolved during the weekly optimization meeting.

The weekly meeting will also be the forum for instrument teams to give advance notice of any special operations or changes to the plan for future weeks. The DSN forecast schedule will be available for the week commencing in 10 days time and the strawman proposal will be available for the week following that.

While the Project Scientist will be responsible for the implementation of the scientific operations plan, execution of the plan will be carried out by the SOWG, led by the SSC.

4.2 Routine Weekly Schedule

The weekly planning process is illustrated in Fig. 4. Operational weeks are defined to run from Monday to Sunday. The planning process starts two weeks ahead (marked "Plan W"

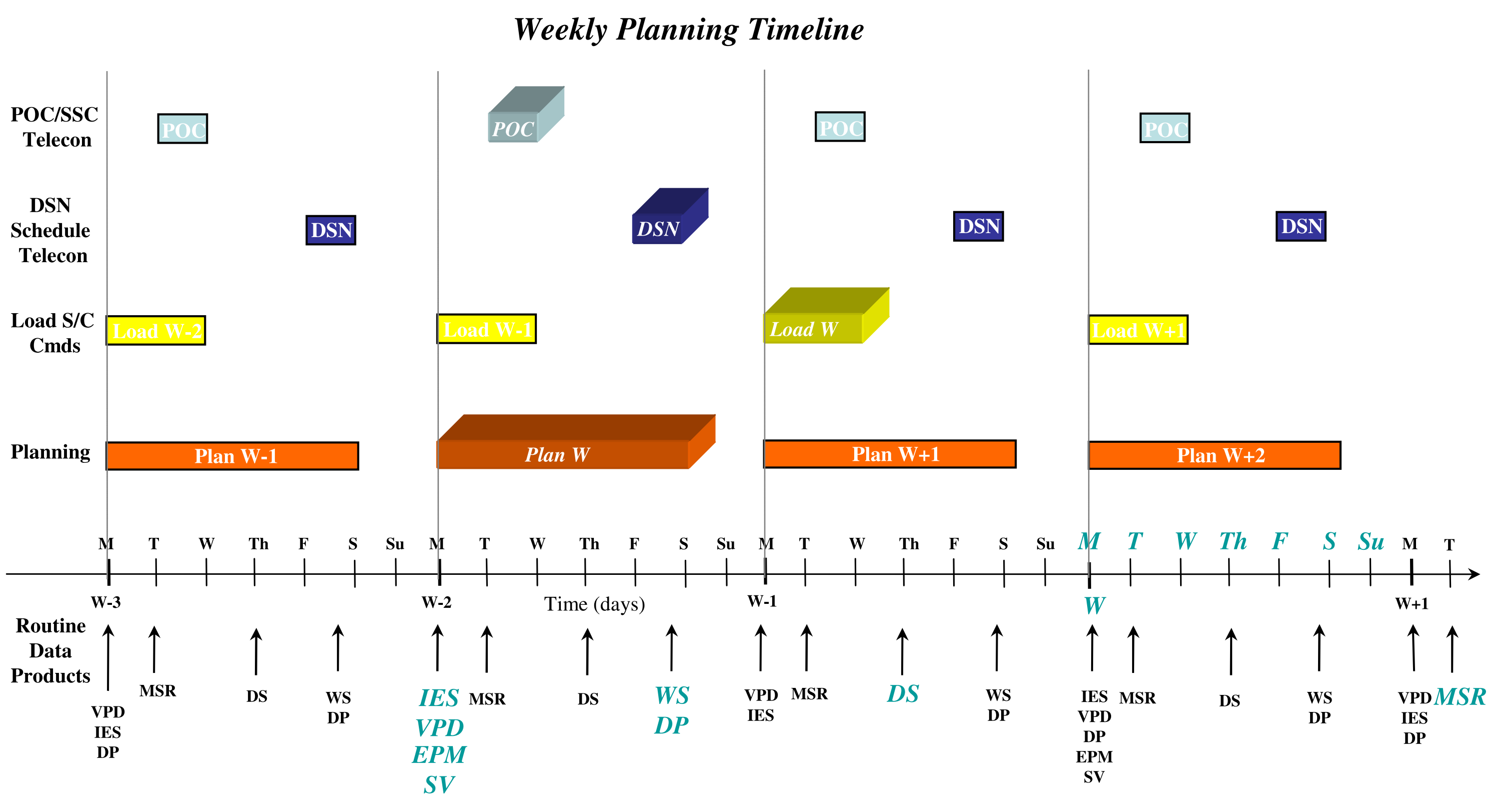

Fig. 4 Weekly planning timeline. The week being planned is at the far right, and the *highlighted boxes* represent the planning and commanding activities for that week. The *acronyms along the bottom* represent the availability of various ancillary data products

in the diagram). At that time the relevant ephemeris products (EPM and SV), Viewperiod files (VPD), DSN Schedule (DS), Momentum Dump Predictions (DP), and Instrument Event Schedules (IES) are delivered to the MOC and distributed to the instrument teams. The MOC Status Report (MSR) covering the previous week is also generated. A weekly teleconference is held between the MOC, SSC, and instrument teams to coordinate shared resources and events, such as telemetry rates and instrument rolls. A separate weekly teleconference is held between the MOC and DSN to determine the daily pass schedule. Command loads are varified using a software simulator, and a Weekly Schedule (WS) is published. The uplink of the verified command load occurs in the week prior to the week being planned.

On a daily basis an assessment is made of telemetry data from the previous day, to review any alarms, plots of selected telemetry points, and the as-run track plan. Commands are checked through the software simulator to verify the command load, constraints, and C&DH memory states. A two-person check is made of each command load.

Under normal operations, each observatory will have one pass per day. An effort will be made to have these passes occur during normal east coast work hours whenever possible. The passes for two observatories are planned to be consecutive, although some overlap is possible.

4.3 Infrastructure for Campaign Coordination

4.3.1 Network Exchange of Information and Data

The primary mode for campaign collaborators to access information about the STEREO science schedule will be through the World Wide Web. The STEREO schedule will be distributed on the Web in both text and graphical formats.

Information will also be passed through e-mail lists, using a list server program such as Majordomo. Sufficient protections will be put on the lists to keep spam mail off the list, and to keep outsiders from learning the e-mail addresses of users.

4.3.2 Telephone and Fax

Besides the network interfaces, the SSC will also have phone and fax facilities available for information transfer to and from campaign collaborators. Conference call facilities are also available.

4.3.3 STEREO Data Archive

The STEREO data archive at the SSC, described more completely in the following, will play an important role in campaign coordination. As well as being the site where observers will retrieve the most recent schedules, the latest observational data will be available to assist in planning.

4.4 Planning for Collaborative Observations

STEREO will participate in the successful Joint Observation Program (JOP) system used by SOHO and several other missions. Having a combined JOP system facilitates the sharing of information between missions, as well as providing a unified interface to researchers. Observers who wish to make collaborative observations with STEREO should first write up a draft summary of their plans, including science goals, dates, observing plans, and collaborating observatories. Detailed information about how to write up the JOP description is given on the SSC Web site at stereo-ssc.nascom.nasa.gov/resources.shtml. Observers who are unfamiliar with the instrument capabilities should contact the instrument teams first to make sure that the instrument is capable of the planned observations. Once the JOP write-up is ready, it should be sent via e-mail to stereo-ssc@listserv.gsfc.nasa.gov. The SSC will forward copies of the message to the relevant instrument teams, but the authors are welcome to contact key members in the teams directly, so long as they keep the SSC informed as well.

To determine how much advance notice is required, one should refer to the STEREO planning cycle described earlier. The initial notification is recommended before the Science Working Group meeting, but that won't always be possible. At the very least the request should come in at least one to two months before the proposed observations, to make sure that it can be discussed at the monthly teleconference. Detailed plans for the observation should be in hand at least two weeks ahead of time to fit within the STEREO planning process.

Most of the STEREO observations are made in a synoptic mode. JOPs should be considered to cover not only the cases where special observations are requested, but also when the normal synoptic observations from STEREO are essential to an observing program. The JOP write-up will ensure that the instrument teams are aware of the collaborative observations, so that other activities such as calibrations do not interfere. The JOP also serves as a mechanism for organizing the collaborative analysis of data from multiple sources.

5 STEREO Data Products, Archiving, and Access

5.1 Telemetry

The MOC stores telemetry packets from the two STEREO spacecraft for 30 days, during which these data are accessed by the instrument teams for processing, and mirrored over to the SSC for permanent storage. A socket interface allows the instrument teams and the SSC to copy packets in real time, and to play back earlier periods still stored at the MOC. The final telemetry are distributed as a secure file transfer.

5.2 Science Processed Data

Each instrument team processes at their home institutions their own telemetry into higher level data files, which are then copied to the SSC for permanent archiving and serving to the community. This process is illustrated in Fig. 5. The SSC is also working with various organizations, such as the Rutherford Appleton Laboratory (RAL) in England, and the Multi-Experiment Data and Operation Centre (MEDOC) in France, to act as mirror sites for the STEREO data.

SECCHI images, and S/WAVES radio data, will be available in detector units, with software available to convert to a higher level of calibration (see Sect. 5.5.3).

Data from the IMPACT and PLASTIC instruments will have calibrations applied to them, to convert from detector units into physical quantities. This process is expected to take about two months. Besides the full-resolution data, lower-resolution summary data will be generated, and the IMPACT and PLASTIC data will be merged to produce higher-level products (e.g., shock identifications and characterizations). These higher level products will be available from the Space Science Center of the University of California at Los Angeles.

Together with the science data files, each team will produce summary images or plots, and will process their data to generate event lists.

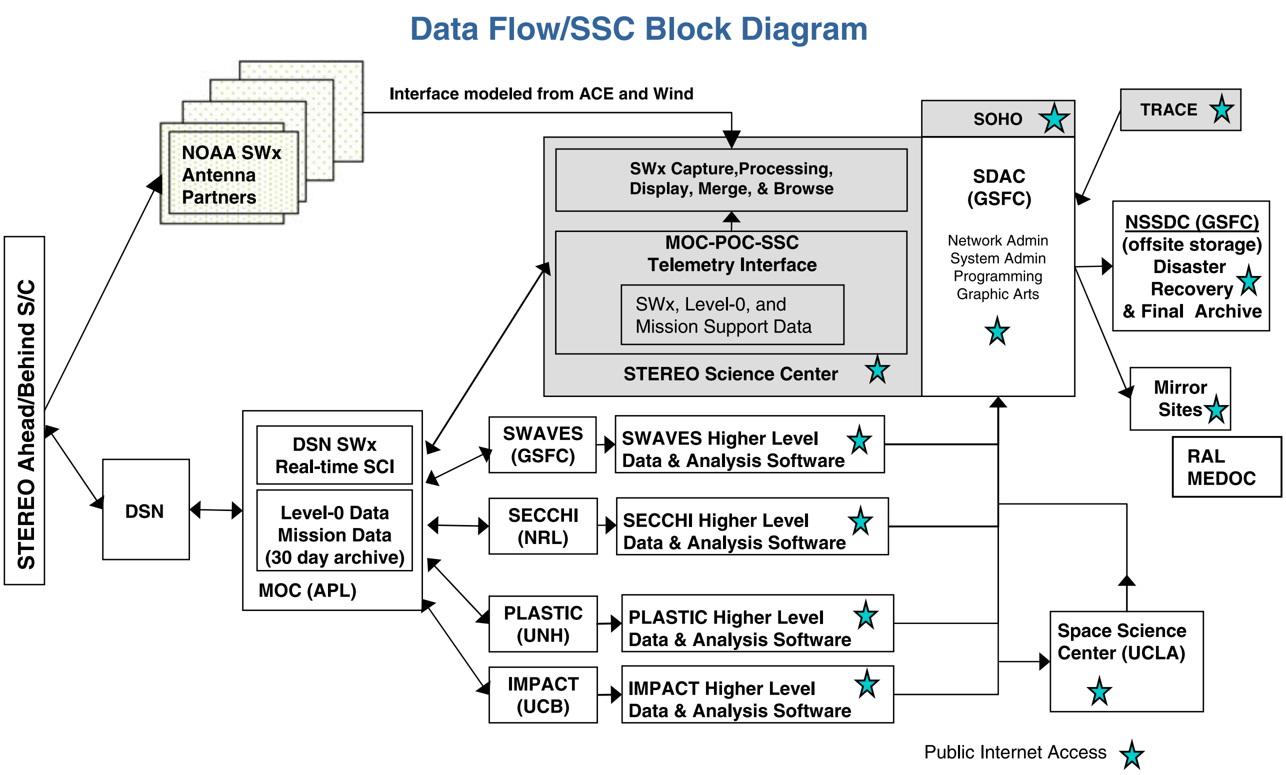

Fig. 5 Data processing flow diagram. Spacecraft telemetry is processed by the instrument teams into higher level products, which are transferred to the STEREO Science Center for distribution and archive. Data are also available from the instrument teams home institutions

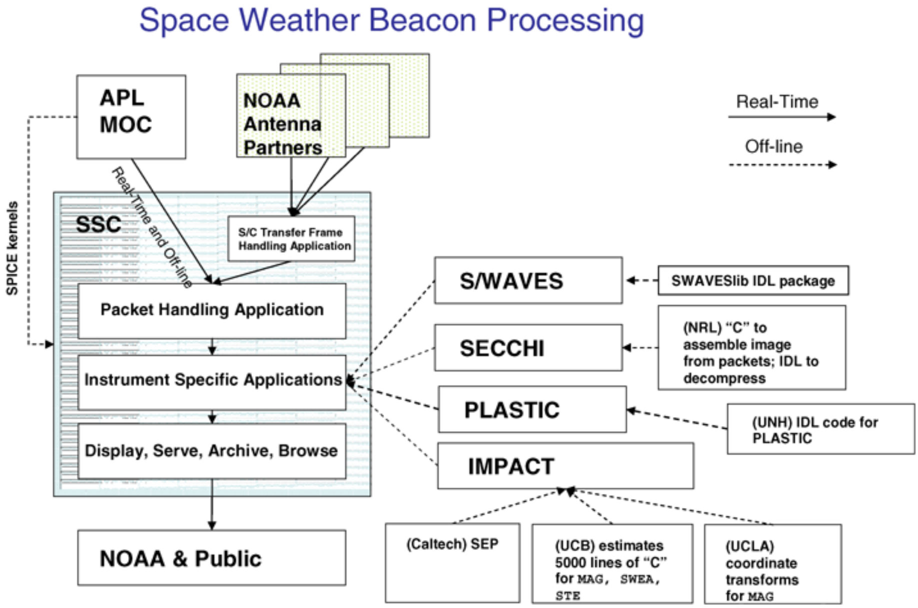

Fig. 6 Beacon processing flow diagram. Real-time telemetry packets, and interim beacon frames from NOAA Antenna Partners, are merged together into a combined telemetry stream, and processed using software provided by the instrument teams

5.3 Space Weather Beacon Data

Along with the normal science telemetry, the instruments on the two STEREO spacecraft will generate a special low-rate telemetry stream, known as the space weather beacon. Outside of DSN contacts, this space weather beacon stream will continue to be broadcast at a rate of approximately 633 bits per second. Various antenna partners around the world, coordinated by the National Oceanographic and Atmospheric Administration (NOAA), will collect this telemetry and pass it on to the SSC in near-real-time via a socket connection over the open Internet. The SSC will collate these data from the antenna partners, sort the packets together into time-order, and run software provided by the instrument teams to process this telemetry into data files. These data will be put on the SSC Web site at stereo-ssc.nascom.nasa.gov in near-real-time, within five minutes of receipt of all needed telemetry. The space weather beacon data flow is shown in Fig. 6.

5.4 Ancillary Data

As well as the level-0 telemetry files, the STEREO Data Server at the MOC will make other data products available for mission planning purposes. These products include ephemeris files and other DSN products, observatory and instrument schedules, telemetry dictionaries, status reports, log files, and converted spacecraft housekeeping files. The most current files will be available from the STEREO Data Server, while the STEREO Science Center will serve as the long-term archive.

5.4.1 SPICE Ephemeris Products

The STEREO orbit and attitude data are provided as "SPICE kernels." SPICE (for Spacecraft, Planet, Instrument, Camera-matrix, and Events) is a software package provided by the Jet Propulsion Laboratory Navigation and Ancillary Information Facility, and is used by the Flight Dynamics Facility to track the two STEREO spacecraft's orbits and attitudes. The SPICE package is available for Fortran, C, and IDL on a wide variety of computer platforms. Simple software calls are able to retrieve the spacecraft orbital position and pointing attitude in most standard heliospheric coordinate systems.

5.5 STEREO Data Archive

The STEREO Science Center will serve as the long-term archive for STEREO data during the mission. At the end of the active life of the data, all relevant mission data will be transferred from the SSC to the NSSDC for permanent archive. Data archived at the SSC will include:

- Level-0 telemetry files
- Ancillary data files from the STEREO Data Server
- Science processed data delivered by the instrument teams
- Space Weather Beacon products.

The archive is stored on a series of RAID-5 file systems mounted via fiber-channel and NFS on the SSC workstations. The file systems are backed up with nightly increments to external portable RAID systems, which are swapped monthly with offsite spares.

Access to the data files is through the SSC Web site at stereo-ssc.nascom.nasa.gov. A small subset of the ancillary data files, in particular the telemetry dictionaries, are archived but not made available on the Web. Otherwise, the bulk of the ancillary files are presented in the same directory structure as they appear on the STEREO Data Server. Level-0 telemetry files are served separately, organized into directories by observatory (Ahead or Behind), instrument, year, and month. The same organization is used for the space weather beacon products. Processed science data from each instrument is maintained in the same directory structure as it was delivered to the SSC.

5.5.1 Interaction with Virtual Observatories

The STEREO archive will be completely integrated with the Virtual Solar Observatory (VSO) (Gurman and Davey 2004). The entire design of the archive and data access system is being developed in parallel with the VSO design effort, and we are sharing personnel with the VSO.

In addition, STEREO will interact with the Virtual Heliospheric Observatory (VHO). Interacting with both virtual observatories is a complementary approach: the VSO interface will emphasize the imaging data, while the VHO interface will emphasize the in situ data. Personnel on the STEREO/IMPACT team are also involved with VHO.

Interactions with other virtual observatory efforts—for example the European Grid for Solar Observations, or the Virtual Space Physics Observatory—will be handled through one or the other of the two virtual observatories described above.

Web access to the VSO is through virtualsolar.org, and to the VHO through vho.nasa.gov.

5.5.2 Uniform Data Format

Data from the STEREO instruments will be available in one of two standard file formats. Image data from the SECCHI instrument will be provided in the Flexible Image Transport System (FITS) format (Hanisch et al. 2001), while data from IMPACT, PLASTIC, and S/WAVES will be provided in the Common Data Format (CDF) (Goucher et al. 1994). Use of standardized formats simplifies the data analysis, and opens the data to a wide range of software tools. Conversion programs between the CDF and FITS formats are available.

5.5.3 Data Analysis Software

During the planning for the SOHO mission, it was realized that there were a number of useful data analysis packages that had been developed for previous missions, and that it would be highly advantageous to collect all these packages into a single system. This led to the development of the Solar Software Library (Freeland and Handy 1998), also known as SolarSoft or SSW. STEREO software, both for the mission as a whole, and for the individual instruments, will also be delivered as part of the SolarSoft package. Thus, users will have a single unified way of downloading software for each of the STEREO instruments, as well as for other solar missions.

Another advantage of being part of the SolarSoft library is the rich collection of software already existing in the library, which is available both to the software developers of each instrument team, as well as to the individual scientist.

Within the SolarSoft library will be a separate directory tree for STEREO software. Beneath this top-level STEREO directory will be separate directories for each of the four STEREO instruments, for the SSC, plus a generic (“`gen`”) STEREO-wide directory. The main concentration will be on IDL software, but the SolarSoft system can also be used to distribute software written in other languages, such as Fortran or C source code.

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