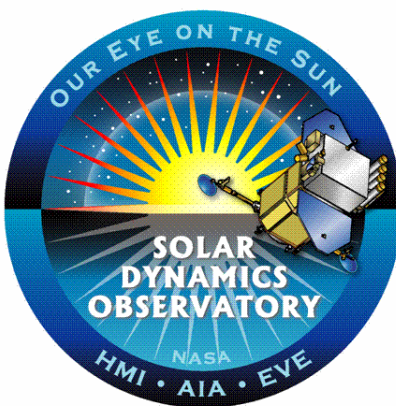# Ground System
## for the
## Solar Dynamics Observatory (SDO)
## Mission

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## ABSTRACT

NASA's Goddard Space Flight Center (GSFC) has recently completed its Critical Design Review (CDR) of a new dual Ka and S-band ground system for the Solar Dynamics Observatory (SDO) Mission.  SDO, the flagship mission under the new Living with a Star Program Office, is one of GSFC's most recent large-scale in-house missions.  The observatory is scheduled for launch in August 2008 from the Kennedy Space Center aboard an Atlas-5 expendable launch vehicle. Unique to this mission is an extremely challenging science data capture requirement.  The mission is required to capture 95% of all observation opportunities with a completeness of 99.99%.  Due to the continuous, high volume (150 Mbps) science data rate, no on-board storage of science data will be implemented on this mission.  With the observatory placed in a geo-synchronous orbit at 36,000 kilometers within view of dedicated ground stations, the ground system will in effect implement a "real-time" science data pipeline with appropriate data accounting, data storage, data distribution, data recovery, and automated system failure detection and correction to keep the science data flowing continuously to three separate Science Operations Centers (SOCs).  Data storage rates of ~ 42 Tera-bytes per month are expected.  The Mission Operations Center (MOC) will be based at GSFC and is designed to be highly automated.  Three SOCs will share in the observatory operations, each operating their own instrument.  Remote operations of a multi-antenna ground station in White Sands, New Mexico from the MOC is part of the design baseline.

## 1.0     MISSION INTRODUCTION

SDO is a cornerstone science research mission within the NASA Living With a Star program, a program dedicated to the study of the Sun-Earth connection.  SDO will observe the Sun's dynamics to increase understanding of the nature and sources of solar variability.  SDO mission formulation, observatory and ground system development, test and verification, launch, and on-orbit mission operations is the responsibility of the SDO Project, at the Goddard Space Flight Center (GSFC), located in Greenbelt, Maryland.

SDO will host a complement of three solar science instruments.  The Helioseismic and Magnetic Imager (HMI) is being developed by Stanford University, Palo Alto, CA.  HMI will study solar variability and characterize the Sun's interior and the various components of magnetic activity. The Atmospheric Imaging Assembly (AIA) is being developed by Lockheed Martin Solar & Astrophysics Laboratory (LMSAL), Palo Alto, CA.  AIA will provide imaging of the solar disk in several ultraviolet and extreme-ultraviolet band passes at high spatial and temporal resolution. The Extreme-Ultraviolet Variability Experiment (EVE) is being developed by the Laboratory for Atmospheric and Space Physics (LASP) at the University of Colorado, Boulder, CO.  EVE will measure the solar EUV irradiance with unprecedented spectral resolution, temporal cadence, accuracy, and precision.

The spacecraft bus design and fabrication is being performed at GSFC.  Integration of the science instruments and Observatory space environment testing will also be performed at GSFC.  The Observatory is scheduled for launch in August 2008 aboard an Atlas-V Expendable Launch Vehicle (ELV) from the Eastern Range at Kennedy Space Center (KSC). The Atlas-V will initially insert SDO into a Geosynchronous Transfer Orbit (GTO).  After spacecraft initialization and the health and status of critical housekeeping systems has been verified, a series of maneuvers designed to circularize the orbit will be planned and executed. These maneuvers will ultimately place SDO into its final geosynchronous mission orbit at 102 degrees West Longitude inclined at 28.5 degrees.  The SDO mission is planned for a minimum of five years with a goal of ten.

The chief driver to the mission operations concept is the large volume of sensor data produced by the three science instruments.  The combined science data rate after compression and telemetry encoding overhead is 150 Mbps.  This equates to approximately 1.4 Tera-bytes of science data per day.  The solution to this driving requirement is to place SDO in geosynchronous orbit allowing a dedicated NASA ground station to maintain constant communication with the observatory.  This will allow the high volume science data to be continuously downlinked and delivered in near-realtime to the Principal Investigators (PIs) at their respective Science Operations Centers (SOCs).

The SDO mission will be controlled and managed from the Mission Operations Center (MOC) located at GSFC.  The MOC is staffed by a team of Flight Operations Engineers who will be responsible for maintaining the Observatory's health and safety, configuration control, space-to-ground telecommunications, and all associated ground system operations for the life of the mission.

## 1.1    SPACE-TO-GROUND COMMUNICATIONS OVERVIEW

SDO real-time Telemetry, Tracking, and Command (TT&C) operations will be supported by three ground station satellite tracking networks.  The primary ground station will consist of two 18-meter dual-feed antennas located at NASA's White Sands Complex (WSC) in White Sands New Mexico.  Each antenna will be capable of command uplink and telemetry downlink at S-band, and telemetry downlink at Ka-band.  These 18-meter antennas will provide dedicated TT&C support to the SDO mission and are collectively referred to as the SDO Ground Station (SDOGS).  In addition to the SDOGS, Launch and Early Orbit (L&EO) and contingency S-band TT&C support will be provided to the mission by the Universal Space Network (USN), a commercial satellite TT&C service provider.  Additional contingency support will be provided by NASA's Tracking and Data Relay Satellite System (TDRSS).  Use of the TDRSS will consist of low-rate S-band Single Access (SSA) telemetry service and will generally be limited to the first 12 to 24 hours after initial orbit insertion.

The SDO command uplink and telemetry downlink data formats are compliant with the Consultative Committee on Space Data Systems (CCSDS) Advanced Orbiting Systems (AOS) standard.   The spacecraft design includes two independent Radio Frequency (RF) communications systems; one operating at S-band and the second operating at Ka-band.  The S-band system is designed to support downlink of spacecraft and instrument housekeeping telemetry (nominally at 67 kbps) and uplink of observatory configuration and control commands (nominally at 2 kbps).  Figure 1-1 illustrates the basic S-band End-to-End (ETE) dataflow.
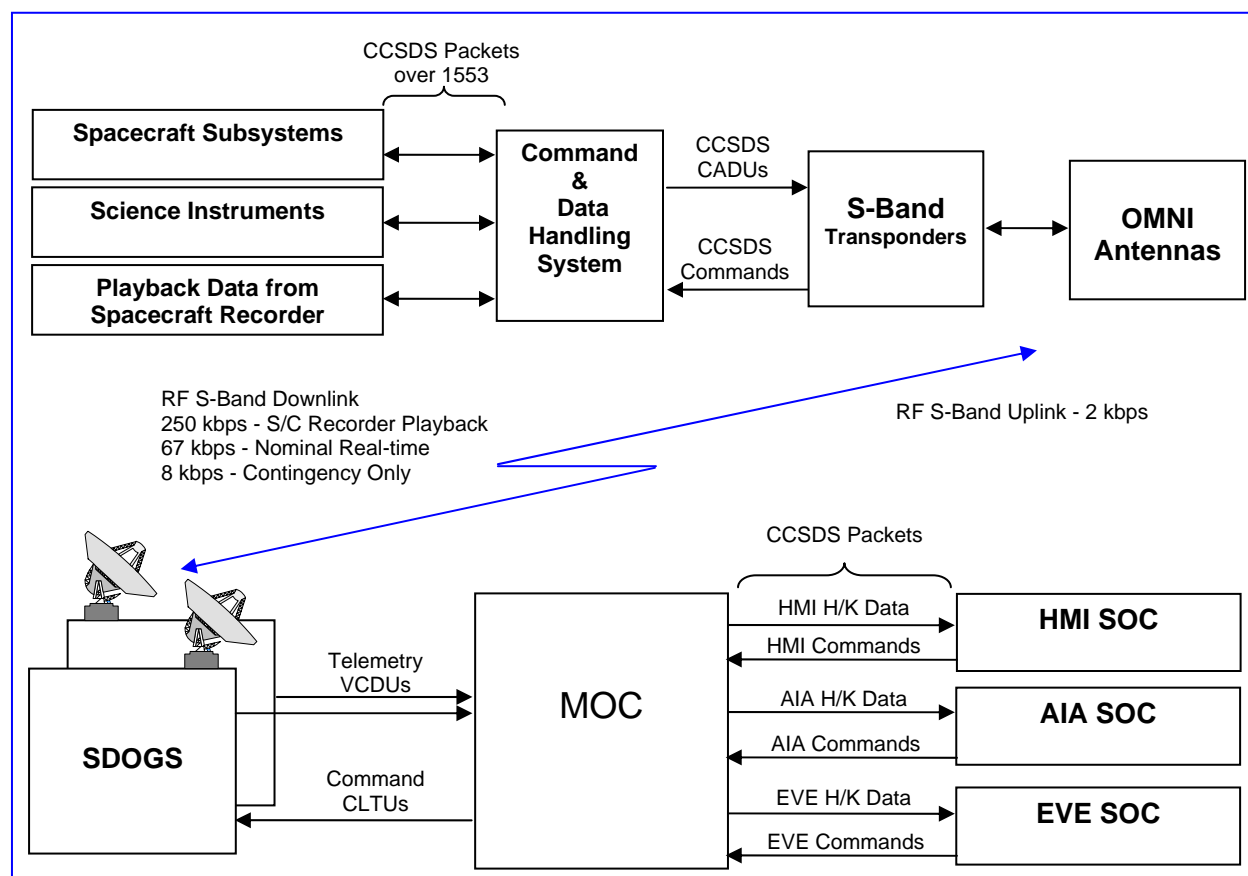


**Figure 1-1.  S-band Telemetry and Command ETE Data Flow Diagram** [1]

The Ka system is designed for downlink operations only.  During the mission, the science instruments (AIA, HMI, EVE) will continuously generate raw sensor data packets wrapped in frames referred to as Instrument Module Protocol Data Units (IM-PDUs).  The High Speed Bus (HSB) flight software residing on the spacecraft Command & Data Handling (C&DH) computer negotiates transmission of the IM-PDUs over a full-duplex IEEE 1355 SpaceWire data bus.  The C&DH wraps the IM-PDUs into CCSDS Virtual Channel Data Units (VCDUs), and transmits dedicated Virtual Channel data streams (several for each instrument) to the Ka RF system where they are downlinked through a High Gain Antenna (HGA) to the ground.  The Ka-band downlink is continuously acquired by the two SDOGS antennas.  Once through the RF receivers at the station, the science data is delivered at an Intermediate Frequency (IF) to the SDO Data Distribution System (DDS).  The DDS receives, demodulates, decodes, frame synchronizes, quality checks, stores, and distributes the science data to the instrument SOCs.  Figure 1-2 illustrates the basic Ka-band ETE dataflow.
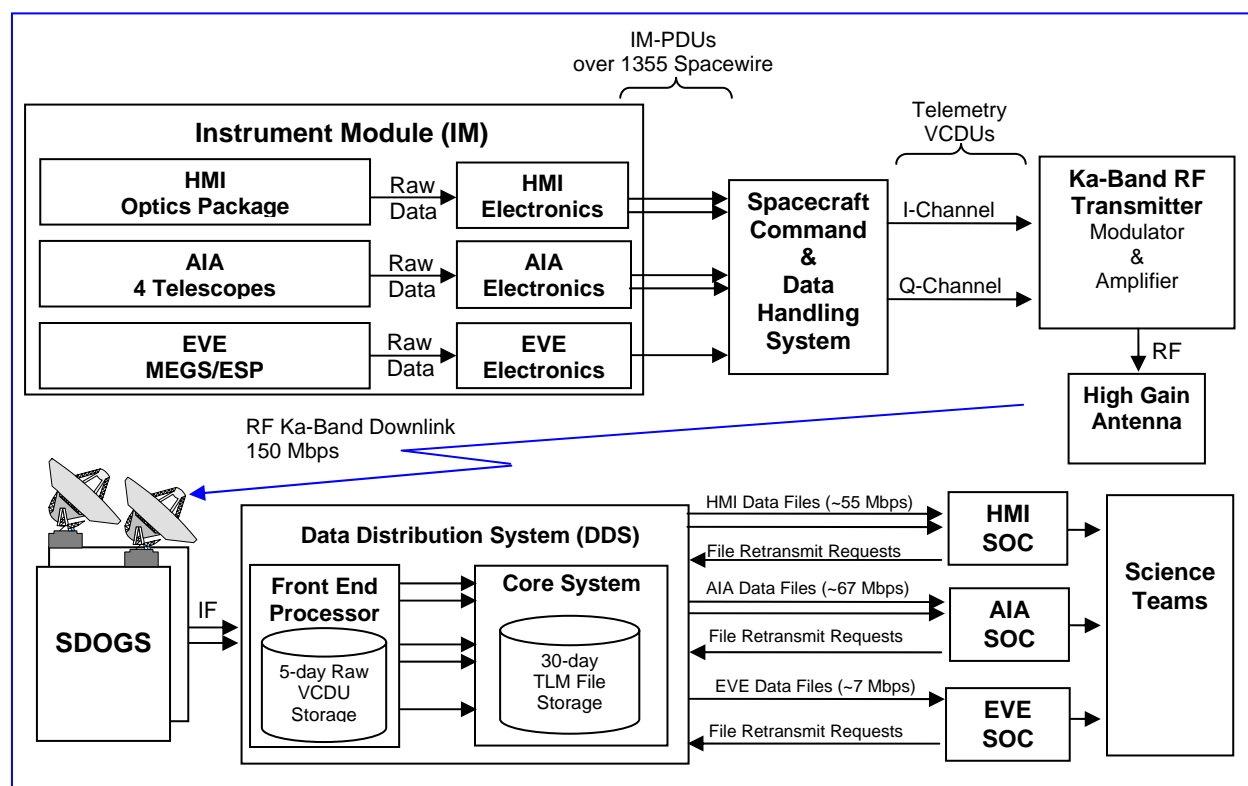
Both S-band and Ka-band systems are fully redundant.



**Figure 1-2.  Ka-band Science ETE Data Flow Diagram** [1]

## 2.0    GROUND SYSTEM DESCRIPTION

The two primary functions of the SDO Ground System are to:

1)   Monitor the health and safety of the observatory and control its operations, and
2)   Receive science telemetry from the Observatory and distribute to the science users
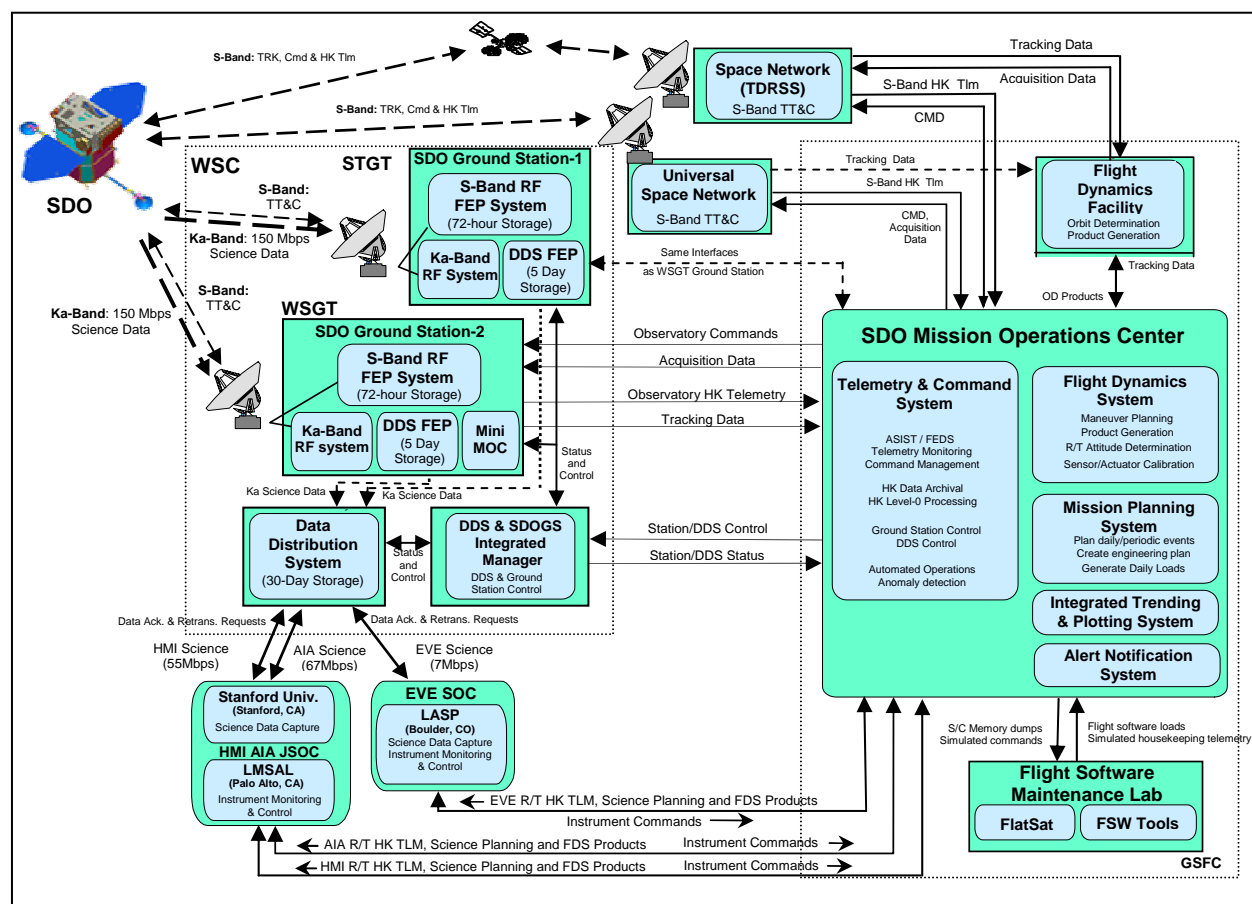
Figure 2-1 illustrates the SDO Ground System architecture.



**Figure 2-1. SDO Ground System Architecture Overview**

The SDO Ground System consists of five major elements as follow:

1) **Mission Operations Center (MOC)** - located at GSFC, the MOC supports the traditional real-time Telemetry and Command (T&C) functions, which allows the Flight Operations Team (FOT) to monitor the health and status of the observatory and to control its operations.  The MOC also provides mission planning, trending and analysis, remote control and monitoring of DDS and SDOGS functions, automated alert notification, and Flight Dynamics functions, including attitude determination and control and orbit maneuver computations.

# DIRE Microsatellite RCS thrusters

- RCS thruster can fire with pulses as short as 2 milliseconds for very fine pointing and maneuvering control of the deployable spacecraft

- Allows vehicle to collect regolith and return to the "mother ship"
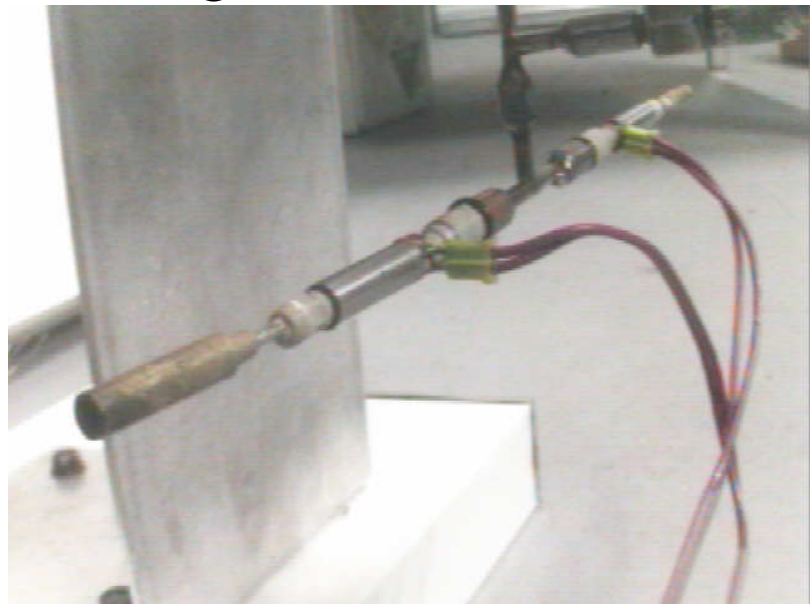
2) **SDO Ground Station (SDOGS)** - located in White Sands, the SDOGS consists of two SDO-dedicated 18-meter antennas and associated RF equipment and software.  The ground station provides the ground to spacecraft link on a continuous basis for Observatory telemetry downlink at both S-band and Ka-band and command uplink at S-band.

3) **Data Distribution System (DDS)** - located in White Sands, the DDS receives the science telemetry data, processes it into files and distributes them to the instrument teams in near-real-time.  The DDS also provides a short-term storage capability and supports data retransmissions as needed.  As part of the DDS design, the DDS/SDOGS Interface Manager (DSIM) provides the FOT with remote monitor and control functions of the DDS and SDOGS, from the MOC.

4) **Science Operations Centers (SOCs)** – the SDO ground system includes three SOCs, one supporting each of the science instruments.  Instrument operations including real-time command and control, health and safety monitoring, science planning, science production data processing, and long-term archive and distribution of the production data are the responsibility of the respective SOCs.  The EVE SOC is located at LASP at the University of Colorado, in Boulder.  The HMI and AIA SOCs are co-located in Palo Alto, CA.  The LMSAL has the lead responsibility for real-time command and control operations for the HMI and AIA instruments while Stanford University will be responsible for the HMI and AIA science production data processing including data reception from the DDS, level-1 (and above) processing, long-term mission archive, and distribution to the science community.

5) **Communication Network** - The ground system communication network provides connectivity between each of the ground system elements supporting all levels of data exchange and voice communications for SDO mission operations.  The ground system data circuits are dedicated to the SDO mission and are collectively referred to as the SDO Network (SDO-Net).  The SDO-Net includes a combination of OC3 fiber and T3 high data rate circuits between the DDS and the SOCs for science data transmission.  The SDO-Net also includes redundant fractional-T1 circuits supporting all critical real-time connections between the SDOGS, MOC, and SOCs for observatory housekeeping telemetry and command operations.

## 2.1   MOC DESIGN OVERVIEW

Figure 2-2 illustrates the primary SDO MOC components and interfaces.  During the mission, the MOC will be the focal point for operations.  It provides all necessary hardware and software functionality to allow the FOT to conduct command and control operations with the observatory.  The MOC is comprised of the following primary systems:

- Telemetry and Command (T&C) System - the MOC T&C System is the Advanced Spacecraft Integration and System Test (ASIST) system.  ASIST provides the observatory health and safety functions.  It receives and processes observatory housekeeping telemetry, provides Engineering Unit conversion, limit checking, alarm generation, display, and history storage.  It also provides the central control over spacecraft command generation, validation, uplink, and verification.

- Mission Planning System (MPS) - provides operations activity planning, scheduling, and spacecraft command load generation and management, and operations timeline generation functions.

- Flight Dynamics System (FDS) - provides orbit and satellite attitude support functions.  The FDS also provides spacecraft and instrument calibration and station-keeping maneuver planning functions.

- Integrated Trending and Plotting System (ITPS) – provides the necessary telemetry processing functions to create and maintain an Engineering Data Archive.  In addition, the ITPS includes tools used by the FOT to create engineering plots, compute telemetry statistics, and to trend and analyze selected housekeeping telemetry parameters from the archive.

- Alert Notification System (ANS) - receives observatory and ground system monitoring and status messages from the T&C system and other critical components of the MOC.  For specific Alert conditions, the ANS sends notices and alerts to on-call FOT and SOC personnel.

- Internal File Server (IFS) - is the MOC internal data storage system.  It is implemented as a Redundant Array of Independent Disks (RAID) and serves as a staging area for FDS products and tracking data files. It is the permanent archive for FDS products and MOC mission data.

- Data Product Server (DPS) - provides a secure interface for direct file transfers to and from remote users, including the SOCs.
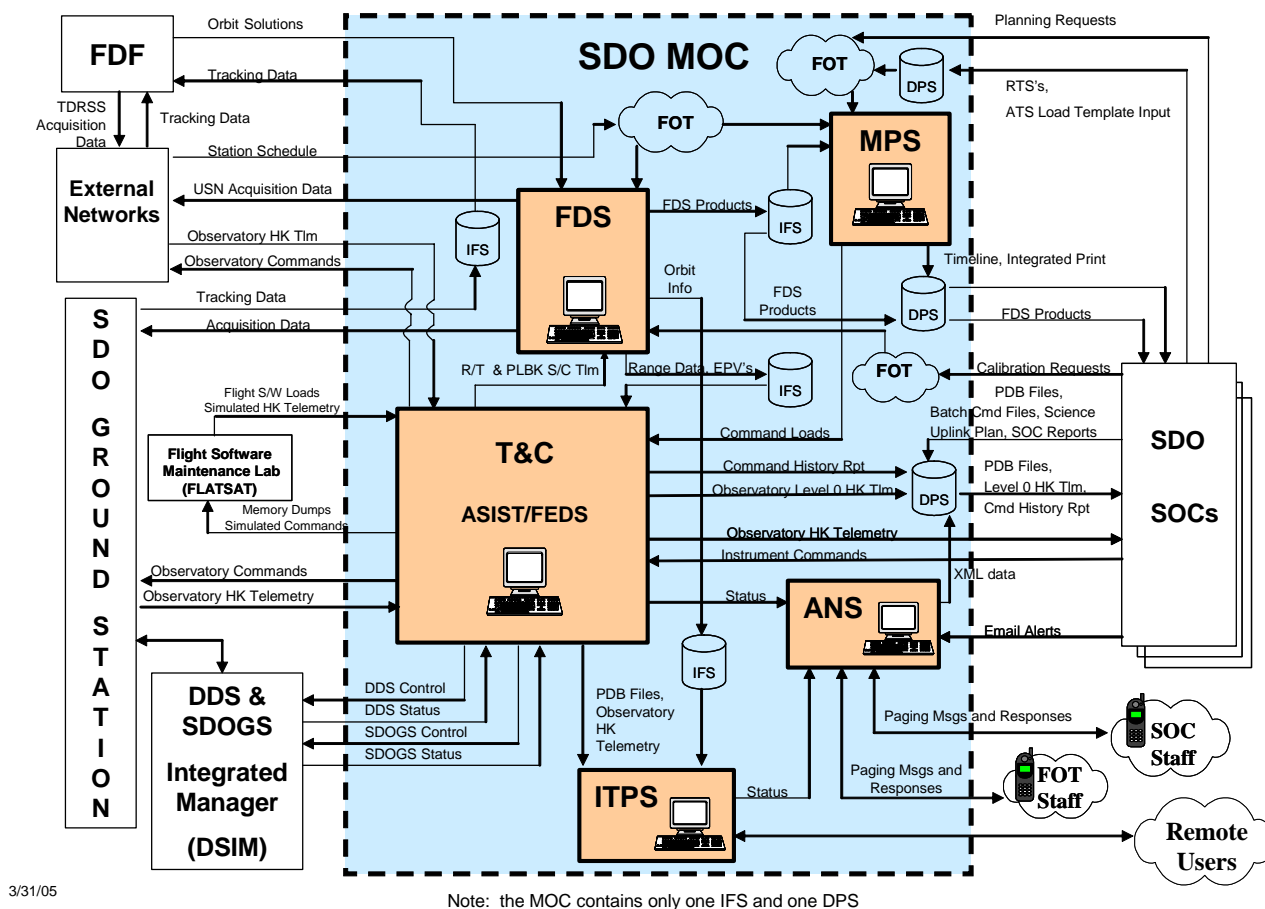


**Figure 2-2.  SDO MOC Elements** [2]

## 2.2     SDOGS DESIGN OVERVIEW

Figure 2-3 illustrates the SDOGS hardware architecture.   The SDOGS is comprised of the following primary Hardware Configuration Items (HWCIs):

- Dual-feed (Ka-Band\S-Band) Antenna Assembly
- Fiber Optic Assembly
- RF-Distribution Assembly
- Converter Assembly
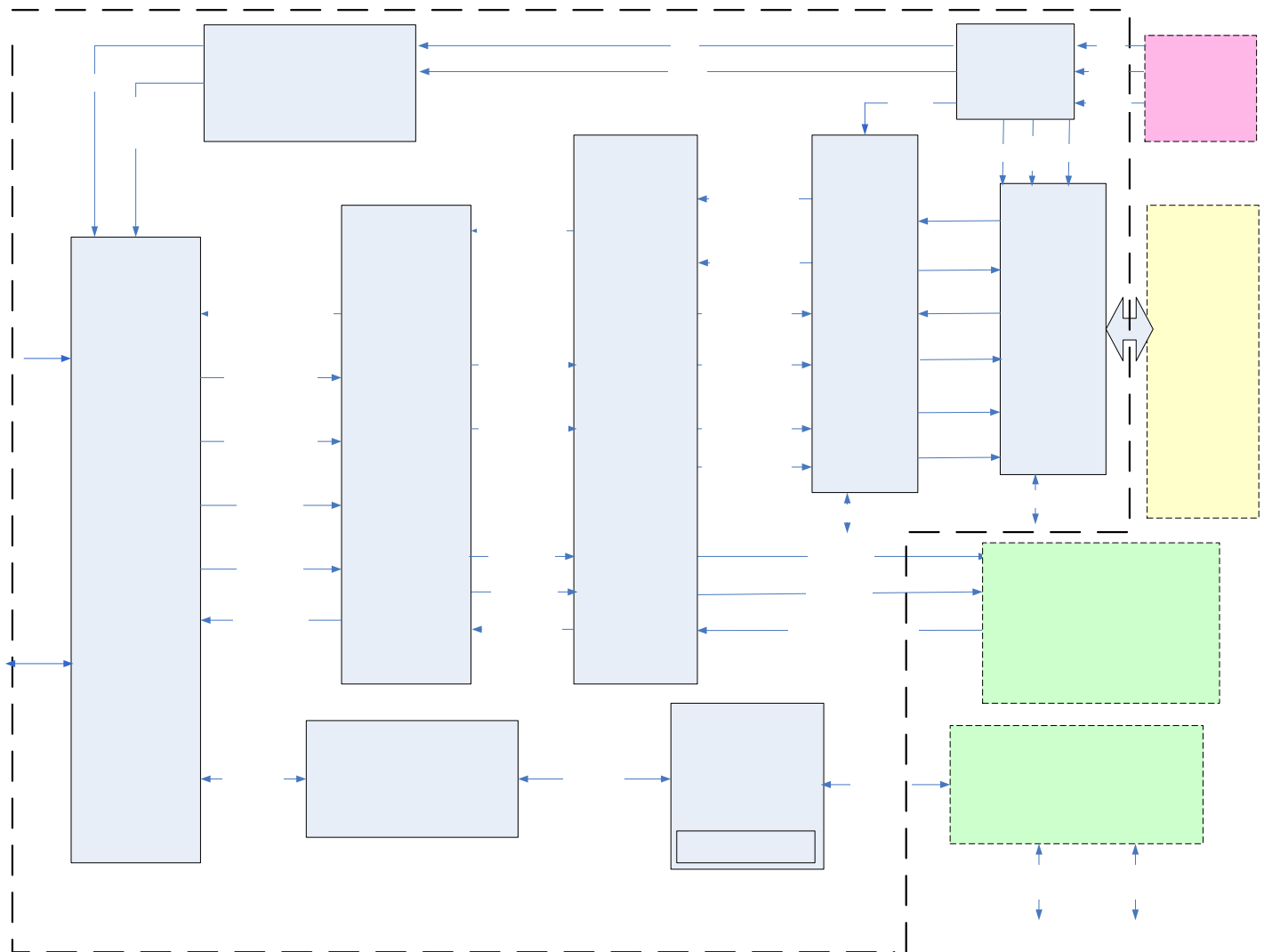- Receive Range Command Processor (RRCP)



**Figure 2-3. SDOGS Hardware Architecture [3]**

### 2.2.1  DUAL-FEED ANTENNA ASSEMBLY

The SDOGS design includes two SDO-dedicated 18 meter dual-feed S-band/Ka-band antennas.  The antennas are physically located approximately three miles apart, one at the TDRS White Sands Ground Terminal (WSGT) and the other at the Second TDRS Ground Terminal (STGT).  Both antennas fall within the SDO spacecraft HGA beam width and will be nominally configured for simultaneous Ka-band and S-band downlink reception.  Operationally, only one antenna's uplink will be configured for Observatory commanding at a time.

### 2.2.2  KA-BAND SYSTEM

The Ka-band system consists of two parallel strings, each string being comprised of an 18m parabolic dish antenna and sub-reflector in a Cassegrain configuration, Low Noise Amplifier (LNA) and RF down-converter.  The Ka-band telemetry downlink signal is received at 26.5 GHz and down-converted to a 720 MHz Intermediate Frequency (IF).  The 720 MHz IF is transmitted via a Fiber Optic Assembly to an RF Distribution Assembly which splits and redundantly routes the Ka IF to two high data rate Front End Processors (FEPs).  The two FEPs, part of the SDO Data Distribution System (DDS), perform data demodulation, decoding, and processing. Paragraph 2.3 describes the DDS in more detail.

The two Ka-band antennas will nominally auto-track the spacecraft RF signal to keep it within the narrow Ka-band beam width. However, for initial acquisition of signal, the auto-track system first finds and tracks the spacecraft downlink based on the signal strength of the wider S-band beam width.  Once the S-band receiver is locked, the SDOGS antenna system will autonomously transition over to the closed loop auto-tracking capability of the Ka-band receiver. The antenna system will also have the capability to perform a program-track of the spacecraft signal by following commanded spacecraft Azimuth and Elevation angles calculated by the MOC.

### 2.2.3  S-BAND SYSTEM

The S-band system consists of a low noise amplifier (LNA), fiber optic transmitters and receivers, down-converters, and two redundant Receive Range Command Processors (RRCPs). The RRCPs are a single box design providing the wide-band receiver, PCM demodulator, bit-synchronizer, de-randomizer, Viterbi-decoder, frame-synchronizer, Reed-Solomon decoder, and CCSDS frame processing, storage, and distribution services. Operationally, both RRCPs will be configured to perform S-Band signal processing, one configured as a Primary unit and the second as a hot-backup.  Only the Primary RRCP will be connected to the MOC for housekeeping telemetry and command operations.

### 2.3  DDS DESIGN OVERVIEW

Figure 2-4 illustrates the Data Distribution System (DDS).  The primary function of the DDS is to continuously receive the high-rate science telemetry from the SDOGS Ka-band system and to deliver the science data to the SOCs in near real-time.  The DDS is comprised of two main elements:

- Front End Processor (FEP) – There are two FEPs configured with each SDOGS Ka-band system.  Each FEP will redundantly receive the high-rate IF signal from the SDOGS Ka-Band system, demodulate, bit-synchronize, de-randomize, Viterbi-decode, frame-synchronize, perform Reed-Solomon decoding, and sort the data by CCSDS Virtual Channel.  The FEPs include a VCDU-server component which creates and stores files of VCDUs for processing by the DDS Core System.

- DDS Core System – The basic function of the DDS Core System is to continuously receive the science data from the VCDU-server, perform a VCDU-level quality check, and forward the best quality science data in near real-time to the SOCs.

## 2.3.1  FRONT END PROCESSOR

Two FEPs for each antenna provide full redundancy.  One is configured as Prime, and the second as a warm backup unit.  Both FEPs at each antenna site receive the IF signal which carries a SQPSK-modulated downlink signal at 300Msps, (150Msps I channel and 150Msps Q channel).  The IF is input to the FEP High Data-rate Receiver (HDR) which performs demodulation, Viterbi decoding, I & Q Channel recombining, frame synchronization, pseudo-random noise decoding, and Reed-Solomon Error Detection and Correction (EDAC).  The FEP VCDU-server component provides a 5-day temporary circular buffer for storage of science data in VCDU form which can be used for data replays and failure recovery when necessary.
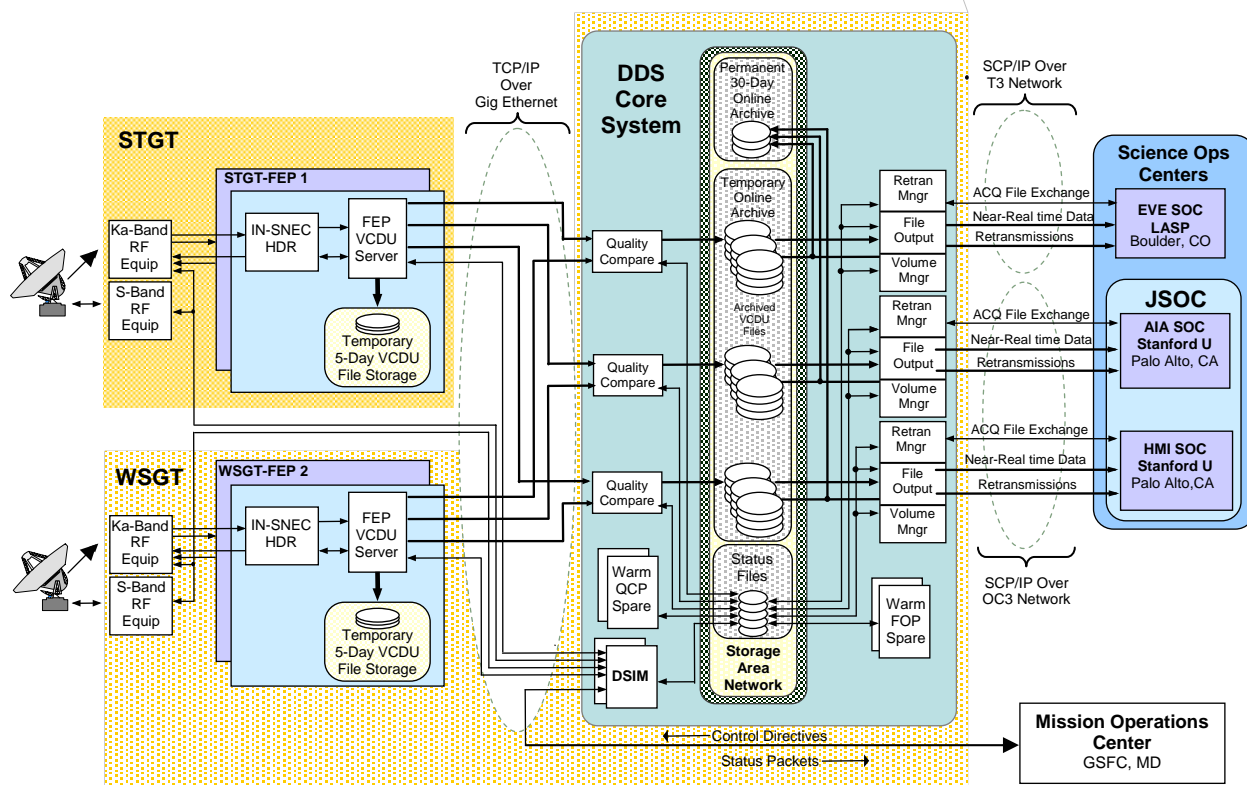


**Figure 2-4. Data Distribution System [4]**

Only one FEP at each antenna site is nominally configured to send VCDU data in near-real time to the DDS Core System.  The second FEP at each site is used only in the event of a failure of the Prime FEP and to support DDS Core System data recovery contingency scenarios.


### 2.3.2  DDS CORE SYSTEM

The main components of the DDS Core System are the Storage Area Network (SAN), Quality Compare Processor (QCP), File Output Processor (FOP), and a DDS/SDOGS Interface Manager (DSIM).

The SAN is a fault tolerant archive system consisting of several RAID disk systems.  It provides the central data repository for all DDS Core System applications and has a storage capacity of about 60 terabytes.  The SAN is sized to support 30 days of on-line storage allowing the SOCs to request retransmission of data files as necessary.

The DDS Core System design includes three QCPs, one configured for each of the three science instruments.  Each QCP continuously accepts two VCDU data streams, one from each of the two Primary FEPs.  The QCP compares the two VCDU streams, separates by Virtual Channel, and stores the best quality data in files on the SAN.  Each VCDU file is fixed-length and nominally contains approximately 1 minute of data.  The QCP also provides all data accounting and reporting functions.

As with the QCP design, the DDS Core System also includes three FOPs, one configured for each science instrument.  The FOP continuously reads the VCDU files from the SAN and transmits the files to the respective SOC using Internet Secure Copy Protocol (SCP).

The DSIM supports remote monitor and control functions of the DDS and SDOGS systems from the MOC.  The DSIM acts as a gateway between the MOC and the DDS and SDOGS components.  It maintains IP socket connections with the various hardware components that comprise the DDS and SDOGS, asynchronously polls these systems, receives and formats status packets from the polled systems, and transmits the status information to the MOC for remote processing and display.  Likewise, the DSIM accepts Control Directives from the MOC, determines the destination, and routes the Control Directive to the appropriate SDOGS or DDS component for local execution.


### 2.4    COMMUNICATION NETWORK

The communication network provides connectivity between each of the ground system elements supporting all levels of data exchange and voice communications for SDO mission operations.  The communication network is dedicated to the SDO mission and is collectively referred to as the SDO Network (SDO-Net).  The implementation approach is to lease circuits from a commercial carrier, purchase primary and backup Routers to deploy at each location and connect the local networks by the purchased bandwidth.  Figure 2-5 provides a high-level illustration of the SDO-Net, primary network nodes, and the network technology used to interconnect the nodes.
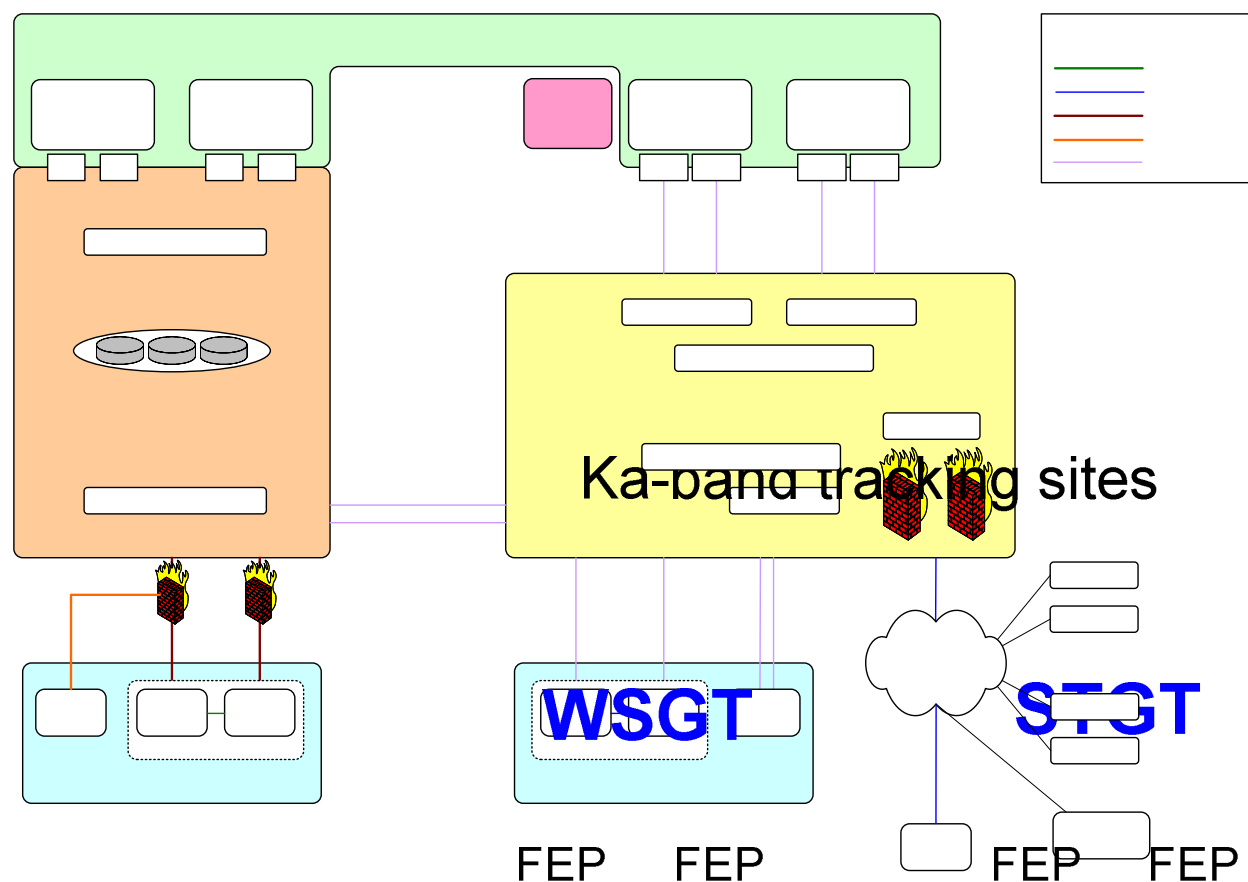
**Figure 2-5.  High-level Ground System Network Diagram**

The SDO-Net is basically divided into two functional networks, both are critical to the mission functions they support.  Both networks are implemented with either full redundancy, or can be reconfigured to reroute transmission of data using available bandwidth over other existing SDO-Net circuits.

The first network, implemented using redundant pairs of T1 or fractional (FT1) circuits, supports the real-time connections between the SDOGS S-Band RRCP systems, the MOC, and the T&C component of the SOCs.  This portion of the SDO-Net is primarily used for real-time transmission of observatory housekeeping telemetry and for command uplink operations.  It also supports transmission of tracking data from the SDOGS RRCPs to the MOC, and connection between the DDS DSIM and the MOC to support remote monitor and control of the DDS and SDOGS systems.  All transmission over this portion of the SDO-Net utilizes Transmission Control Protocol - Internet Protocol (TCP-IP).

The second network supports transmission of the high-rate science data between the SDOGS Ka-Band system, the DDS, and the Science Data Processing (SDP) component of the SOCs. All LAN connections at WSC providing interconnection between the DDS and SDOGS are implemented as Gigabit Ethernet (GigE).  A single T3 circuit provides the connection between the DDS and the EVE SOC and supports delivery of EVE science data at a rate of approximately 7 Mbps.

In addition, a pair of OC3 fiber circuits provides the connection between the DDS and the Joint Science Operations Center (JSOC) supporting the HMI and AIA instrument.  Nominally, AIA science data is delivered over one OC3 at a rate of approximately 67 Mbps and HMI science data is delivered over a second OC3 at a rate of approximately 55 Mbps.  In contingency situations, both AIA and HMI science can be routed over a single OC3.

The baselined DDS-to-SOC communication lines nominally provide 1.5 times the bandwidth of the maximum science downlink for each instrument.  The additional circuit bandwidth allows retransmissions to be done without impact on the real-time data distribution.

All network circuits and associated network hardware (i.e., routers and firewalls) that comprise the SDO-Net and support connectivity between the SDO ground system elements will be managed and maintained by the Internet Protocol Network Operations Center (IP-NOC) located at GSFC.

## 2.4.1  NETWORK SECURITY

The SDO communications network shall conform to the NASA NPR 2810 Information Technology (IT) security requirements.  SDO will utilize an isolated network approach between the SDOGS, the MOC and the SOCs to meet these requirements.  Firewalls will be in place at all sites with strict access rules to restrict connectivity and prevent unauthorized access.

## 3.0     MISSION OPERATIONS

For the purpose of this paper, the discussion on Mission Operations will be limited to the nominal Science Operations phase.  The Science Operations phase begins following successful completion of the Launch and Early Orbit (L&EO) spacecraft activation, checkout, and science instrument commissioning activities.  Operations during the Science Operations phase will focus on two primary mission requirements:

1) <u>Maintain the health and safety</u> of the observatory consistent with established mission and science objectives.
2) Plan and execute mission timelines in a manner that will <u>maximize science data return</u>

Primary responsibility for SDO mission operations resides with the GSFC Mission Director (MD) and the Flight Operations Team (FOT).  The MD has final authority regarding the observatory operations.  The MD oversees the planning process and approves the operational plan; chairs the Configuration Control Board; and has ultimate authority on contingency decisions.  The FOT is responsible for managing all activities conducted within the SDO MOC.  Initially, the FOT will staff the MOC around-the-clock (24 hours a day, 7 days a week).  Once into the Science Operations phase and after automated MOC operations have been satisfactorily demonstrated, MOC staffing will be reduced to Monday through Friday, 12-hours per day.

The SDO operations philosophy includes a basic division of responsibility between the FOT and Instrument Teams.   The Instrument Teams, operating from their own Science Operations Centers (SOCs), have primary responsibility for mission operations of their instruments.  This includes real-time health and status monitoring, instrument commanding, science planning, and science data processing and long-term archive and distribution.

## 3.1     HEALTH AND STATUS MONITORING

The operations concept includes continuous around-the-clock (24x7) downlink and delivery of the observatory housekeeping telemetry from both SDOGS antennas.  The housekeeping telemetry from each SDOGS antenna is demodulated and processed to the CCSDS VCDU level.  Error-free VCDUs (those that have passed the Reed-Solomon EDAC) are delivered over separate SDO-Net T1 circuits from WSC to GSFC to provide two completely separate and redundant delivery paths of the housekeeping telemetry to the MOC.  Two ASIST Front End Data Systems (FEDS) are configured to continuously receive the housekeeping telemetry, one stream from each of the SDOGS antenna systems.  This configuration provides inherent backup and protects against any single-point failure in the end-to-end real-time telemetry delivery path from the SDOGS antenna, through the SDO-Net, and to the MOC.

Routine health and status monitoring is an automated function of the MOC ASIST T&C system.  ASIST includes several standard database-driven tools designed for autonomous monitoring of the observatory health and status.  These monitoring tools, which run continuously while the SDO housekeeping telemetry is being received, are designed to verify that the observatory is in the expected configuration and that critical spacecraft housekeeping systems are performing within established operating limits.

The ASIST FEDS is also responsible for continuous real-time delivery of the instrument housekeeping telemetry packets to the SOCs via IP socket connections.  This connection is over a fractional T1 which supports both telemetry and command connections between the

MOC and SOC.  The SOC T&C systems will continuously receive their telemetry, perform instrument health and safety checks and verify that the instrument subsystems are performing as expected.  A subset of the most critical Instrument housekeeping telemetry will also be monitored by the MOC T&C system to provide backup in the event a SOC T&C system or network connection failure occurs.

During off-hours, the MOC ANS is configured to receive observatory and ground system monitoring and status messages from the T&C system and other critical components of the MOC.  For specific alarm conditions, the ANS alerts on-call FOT and SOC personnel via a two-way text message paging system.

The SDO flight system includes a Solid State Recorder (SSR) with sufficient capacity to store 24-hours of housekeeping data.  In the event of an anomaly that interrupts the real-time housekeeping downlink, SSR playbacks will be conducted to recover housekeeping data.

In addition to real-time health and status monitoring, the MOC ITPS system will continuously receive the housekeeping telemetry stream (both real-time and from SSR playbacks).  The ITPS is designed to receive specific telemetry packets (identified by APID) continuously from the ASIST FEDS.  Based on telemetry database definitions, the ITPS extracts the housekeeping telemetry parameters, converts to Engineering Units, limit checks, and archives the data.  Trending, statistics, and engineering analysis functions of the ITPS are used by the FOT to verify nominal observatory performance and to troubleshoot anomalies.

## 3.2    SPACECRAFT COMMANDING

The SDOGS provides the primary command uplink interface to the SDO observatory during mission operations.  The network IP socket interface between the SDOGS and the MOC for command operations is managed between the RRCP units at the SDOGS and the ASIST/FEDS at the MOC.  The SDO ground system architecture includes four RRCPs (two configured with each SDOGS antenna), and two MOC FEDS.  Operationally, only one SDOGS RRCP and one FEDS will be configured together to support commanding at any given time.

The SDO flight system design (spacecraft and instruments) supports both real-time ground-based commanding and the traditional on-board stored command capability.  All time-critical commanding, which is generally in response to flight system anomalies, will be automated using flight software Failure Detection and Correction (FDC).  The flight system FDC implementation will provide immediate commanding to safe and protect the observatory.  Examples include going to a Safe Hold mode in response to Attitude Control System (ACS) failures and shedding non-essential loads in response to Power System anomalies.

While the SDO mission includes a variety of activities that require ground-based commanding, none are time critical.  Examples of activities requiring ground-based commanding include:

- SDO Orbit Vector uploads (updated once per week)
- Reaction Wheel Momentum Unloading (Delta-H) maneuvers (once a month)
- High Gain Antenna Handover (once every 6 months)
- Station Keeping (Delta-V) maneuvers (once every 6 months)
- Instrument Calibration activities (every 1 to 3 months)

To support the reduced MOC staffing profile, routine commanding will nominally be limited to Monday through Friday while the FOT is present in the MOC.  This will allow the FOT to immediately address and correct command transmission anomalies.

Commands originating from the SOCs are transmitted to the ASIST Primary Command workstation as CCSDS Telecommand Packets.  The ASIST first performs source validation to assure that the command (based on APID) is authorized.  Each SOC is restricted to only commanding their instrument.  Once validated, the ASIST performs the required Command Link Transmission Unit (CLTU) formatting and Command Operating Procedure-1 (COP-1) protocol processing.   Each command is transmitted to the primary SDOGS RRCP system which provides command uplink processing.  The RRCP performs the following functions:

- Command Socket Management with the MOC FEDS
- Receipt of SDO CLTUs from the MOC FEDS
- Command Echo Generation and transmission to MOC FEDS
- 16 KHz Subcarrier Generation
- Forward Link Sweep function
- Forward link Command Modulation at 2 kbps

Once a command is uplinked, the spacecraft RF and C&DH systems perform command demodulation, decoding, validation, and distribution to the destination system over a 1553 bus.

## 3.3    SCIENCE DATA CAPTURE REQUIREMENT

An important consideration during the Science Operations phase is the science data capture requirement primarily driven by the HMI instrument.   Helioseismology requires long uninterrupted periods of observation, which will be achieved with 22 individual 72-day periods within the 5-year mission.   For one 72-day period to be considered complete, the Ground System must capture 95% of all possible observation time.  The remaining 5% is covered in the SDO Science Data Capture Budget which accounts for science data outages and interruptions expected during the mission.  These outages/interruptions include:

- Operations – thruster based maneuvers, HGA handovers
- Instrument/Science Calibration – Roll & Off-point maneuvers
- Orbit – Eclipses (including thermal and alignment recovery)
- Ground Station – signal attenuation due to rain and equipment problems
- Completeness – Bit Error Rate

Secondly, for all data that is acquired to be complete, the Ground System must account for 99.99% of all downlinked HMI data.

The AIA and EVE instruments have less stringent data capture requirements with an availability of 90% and completeness 99.9% and 99.6% respectively.

The FOT in conjunction with the instrument operations teams will be responsible for tracking science data losses.  Planned events causing data loss will be scheduled in order to satisfy the requirements for data capture and completeness.  In the event that more than 5% of the data is lost before a 72-day period is completed, the PIs may jointly elect to start a new 72-day period over which the 95% data capture requirement will be enforced.

## 4.0  REMOTE CONTROL OF SDO GROUND SYSTEM ELEMENTS

During the L&EO operations, the SDOGS and DDS will be staffed.  However, during the nominal Science Operations phase, these systems will be mostly unattended and will be remotely monitored and controlled from the MOC by FOT personnel.  On-site personnel will be leveraged from the WSC TDRS Maintenance and Operations (M&O) staff to support periodic inspection visits, preventive maintenance, repairs and occasional troubleshooting.  Specialized personnel may be sent on location in case of failure.

All components that comprise the SDOGS and DDS have their own local control interface which will be used for pre-launch development, integration, and test.  All pieces of equipment are directly controllable from their own control panels, and this local control can be exercised as a backup to the normal remote control if necessary.  In addition, the local displays of several of the SDOGS and DDS systems can be redirected over the network to the MOC allowing native displays and tools to be accessed from the MOC as if the user were physically co-located with the system.

The operational concept is identical for both SDOGS and DDS control systems: monitor and control parameters are defined for each piece of equipment to be controlled.  The DDS/SDOGS Interface Manager (DSIM) serves as the central control system allowing the MOC to receive equipment status and process it in a way similar to spacecraft housekeeping telemetry including Engineering Unit conversions, upper and lower limits, discrete state text conversions, color display specifications, and other display options.  Likewise, the DSIM will include the capability to receive Control Directives allowing the FOT to configure and operate the SDOGS and DDS hardware and software.

The Ground Station Control system main functions are as follows:

1)  Monitoring:  Displays inform the FOT of the status of each piece of equipment.  The planned approach is to develop graphical displays that represent the SDOGS and DDS in the form of functional block diagrams.  Color coding will be employed where the status of each piece of equipment is indicated by the color of its icon (green, yellow or red).  Limit violations are color-flagged and logged. Lower-level displays provide more detail on a given piece of equipment, for example data storage information, statistics on number/sizes of files, disk drive utilization, status of clean-up "chron" jobs, etc.

2)  Control:  The FOT can send "instructions" to reconfigure a given piece of equipment, correct an anomaly or switch to a redundant unit.  These instructions will be defined in the form of MOC Systems Test and Operations Language (STOL) procedures compatible with the ASIST T&C system.

3)  Configuration:  There is a predefined set of station configurations.  Each will be set-up automatically using tested and approved STOL procedures.  This improves the speed and accuracy of the configuration, ensures reliability since the procedures are placed under configuration control, and reduces the risk of error by removing human intervention.

4)  Statistics and Quality Information:  This information consists of statistics regarding the number of telemetry frames received, number of commands uplinked, etc.  These statistics will be available from the SDOGS for the housekeeping telemetry and from the DDS for the science telemetry.

## 5.0    AUTOMATION AND LIGHTS-OUT OPERATIONS

In addition to the SDOGS and DDS systems being designed to operate without human intervention, the MOC includes several features that are designed to allow the MOC to continuously process housekeeping telemetry and to monitor and verify the observatory's health and safety when the MOC is not staffed.   Such operations are referred to as "lights-out" operations.  MOC lights-out features include:

- Monitoring for Data Presence – The ASIST T&C system includes a Data Presence monitor designed to generate an Alert Message when a telemetry VCDU has not been received for a period of 10 seconds.  Loss of Data Presence is a critical alert condition which the ANS system detects and notifies the FOT.

- Parameter Limit Monitoring - The ASIST T&C system includes standard database-driven high/low limit checking.  This feature will be employed for all critical observatory telemetry and ground system monitor points.  Out-of-limit conditions are detected by the ANS and the FOT is notified.

- Monitoring of Unexpected Event Messages – The SDO flight software design includes generation of Flight Status Messages in response to specific anomaly conditions.  These messages are processed by the ASIST T&C system similar to the way ground system-generated messages are handled.  The ANS system will be configured to monitor for these messages and alert the FOT when detected.

- Time-ordered Script/Procedure Execution – This feature is inherent in the ASIST STOL and Linux operating system.   Routine activities such as transfer of tracking data from the SDOGS to the MOC and basic file management functions will be automated through a combination of STOL procedure and Linux Shell scripts.

- Monitoring of Real-time Critical Systems – Real-time critical systems including the ASIST, FEDS, SDOGS RRCP, and ANS systems will include the periodic generation of an "I'm Okay" message.

- ANS Backup System Monitoring – The MOC design includes a Prime and Backup ANS system.  Each ANS will pulse the alternate system to determine its operational status.  If the Primary ANS "I'm Okay" status is lost, the backup ANS will take control and assume the Primary role.  If the Backup ANS "I'm Okay" status is lost, the Prime ANS will alert the FOT.

- Internal Redundancy for Storage of Mission Data – All MOC and DDS file servers are implemented using level-5 RAID technology providing built-in data backup and recovery.

- DDS DSIM Failover - The DDS design includes a Prime and Backup DSIM system. Each DSIM will pulse the alternate system to determine its operational status.  If the Primary DSIM "I'm Okay" status is lost, the backup DSIM will take control and assume the Primary role.  If the Backup DSIM "I'm Okay" status is lost, the Prime DSIM will generate a Fault Status for the Backup and report it to the MOC ASIST and ANS systems.  The ANS system will be configured to monitor for DSIM Fault messages and alert the FOT when detected.

- Full End-to-End Redundant S-band Strings – The SDO ground system design includes full redundancy from the SDOGS antennas through two separate T1 network connections and

to the MOC ASIST/FEDS.  This protects against any single-point failure in the S-band string as telemetry will continue to flow through the alternate string.

## 6.0    SUMMARY

The SDO ground system is an evolutionally architecture combining a mix of legacy ground system components with several new designs addressing the specific needs of the SDO science mission. These new components include the dedicated dual S-band/Ka-Band antenna systems comprising SDOGS, the high-speed science Data Distribution System, a dedicated large bandwidth SDO network and large data storage systems at each SOC.

The SDO ground system operations concept likewise combines typical NASA/GSFC operations practices with new concepts as the result of the architecture. Mission operations new to NASA/GSFC include the remote control of the SDOGS and DDS, distributed instrument operations performed by each SOC and the monitoring of continuous downlink of both observatory engineering and science telemetry streams.

The SDO ground system design has been vetted by independent NASA/GSFC management and technical engineers and received strong endorsements of the operations concepts. In approximately two years the implementation of the architecture will be completed and validated against the functionality of the actual observatory and external interfaces.  Stay tuned!

## 7.0    REFERENCES

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