# MISR: Protection from Ourselves ![1]

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*Abstract*— outlines lessons learned by the Instrument Operations Team (IOT) of NASA/JPL Terra's Multi-angle Imaging SpectroRadiometer (MISR) mission. It narrates a story of "MISR: Protection from Ourselves!" and describes, in detail, how the MISR instrument survived operator errors.

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## 1. INTRODUCTION: MISR INSTRUMENT AND EXPERIMENT DESCRIPTION

The Multi-angle Imaging SpectroRadiometer (MISR) launched in December 1999, is one of the Earth Observing System (EOS) Terra science instruments built to examine and monitor Earth's climate for 5 years. The instrument name is derived from the image gathering technique. MISR employs nine discrete cameras pointed at fixed angles, one viewing the nadir (vertically downward) direction and four each viewing the forward and aft directions along the spacecraft ground track. The eight off-nadir cameras are in pairs, either side of nadir, to provide the required spatial resolution and coverage on the ground. Information at a large number of scattering angles is of interest to the scientific community, and by including both fore and aft sensors this scattering angle coverage is greatly increased. Also, having both fore and aft views is essential in order to obtain similar viewing with respect to sunlight as the spacecraft passes over the northern and the southern hemispheres of the Earth, because the equatorial lighting effects are symmetrical. Figure 1 is a summary of its characteristics.

*1.1 Specifics*

- Mission life: 5 years
- Global coverage time: every 16 days, with repeat coverage between 2 and 9 days depending on latitude
- Crosstrack swath width: 360-km common overlap of all 9 cameras
- Camera Type: Pushbroom Camera Designations: An, Af, Aa, Bf, Ba, Cf, Ca, Df, and Da where fore, nadir, and aft viewing cameras have names ending with letters f, n, a respectively and four camera designs are named A, B, C, D with increasing viewing angle respectively
- View angles: 0, 26.1, 45.6, 60.0, and 70.5 degrees
- Spectral coverage: 4 bands (blue, green, red, and near infrared)
- Detectors: Charge Coupled Devices (CCDs), each camera with 4 independent line arrays (one per filter), 1504 active pixels per line
- Radiometric accuracy: 3% at maximum signal
- Detector temperature: -5 ±0.1 degrees C (cooled by thermo-electric cooler)
- Optical Bench temperature: +5 degrees C
- Instrument mass: 149 kg (328 lbs.)
- Instrument power: Approximately 135 W peak, 80 W average
- Data rate: 3.3 Megabits/second average, 9.0 Megabits/second peak
- Builder: Jet Propulsion Laboratory, Pasadena, CA California Institute of Technology

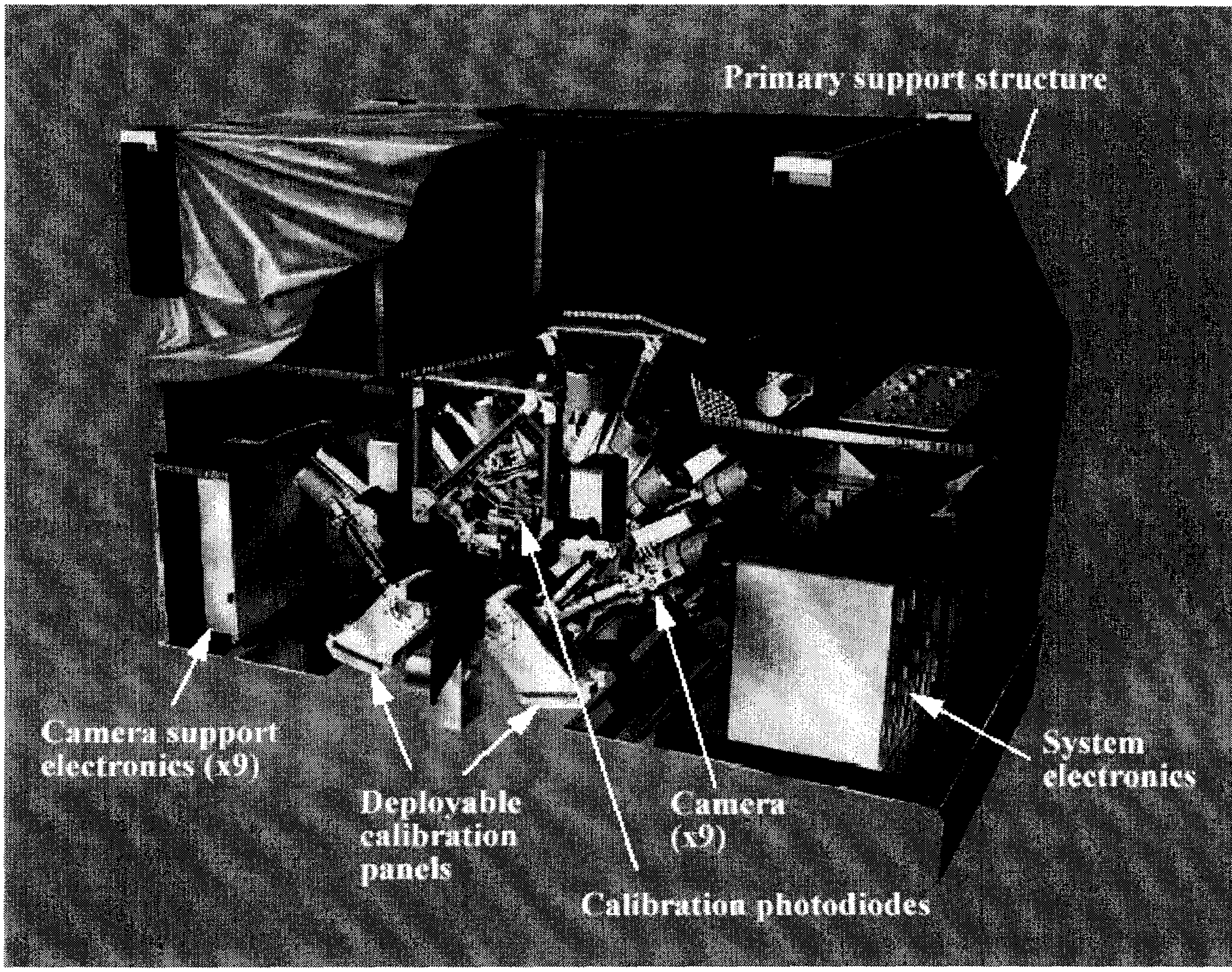


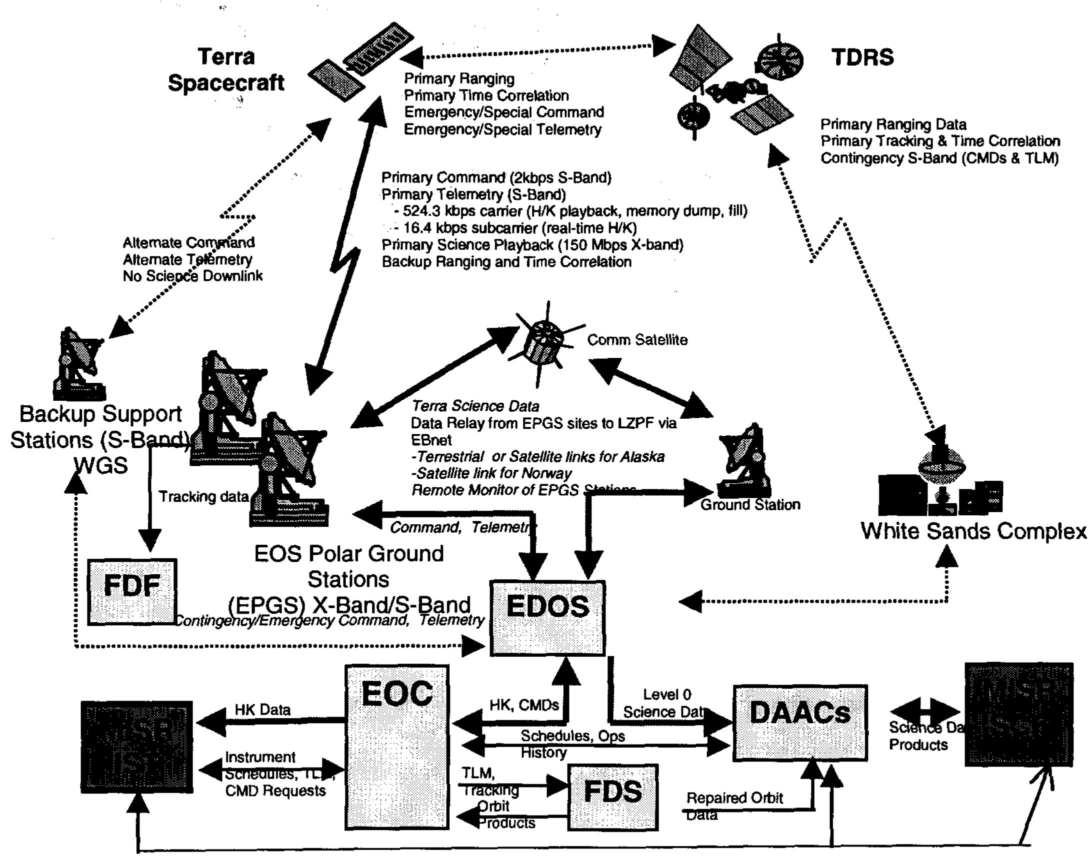

**Figure 1. Artist's rendering of the MISR instrument**

## 2. MISR Mission Operations

After launch, following instrument checkout phase, MISR has been operating continuously. Instrument activities are preplanned and scheduled. MISR science data uses an interface called Transparency Asynchronous Transceiver Interface (TAXI). During a nominal 24-hour period, the instrument cycles in Science Mode between TAXI_ON (recording data during Earth daylight) and TAXI_OFF (not recording data during Earth night) and various data acquisition modes each orbit. Regular calibrations of the instrument are conducted bi-monthly during normal operations to maintain the integrity of performance and several diode calibration sites are used each week. Data acquisition changes to account for seasons or specific activity monitoring and science team requests. For planning and scheduling, the MISR Instrument Operations Team (IOT) defines the beginning orbit boundary as the dark side equator crossing during the ascending node. Figure 2 shows MISR mission operations architecture.

## 3. MISR Flight Software

MISR Flight Software (FSW) does not permanently reside on the instrument. MISR PowerOn activates the firmware residing in MISR PROMs. The flight software will be loaded and then control switches from PROM to RAM. Whenever the MISR computer gets powered down, the entire flight software must be reloaded into memory while the instrument is executing the PROM code. To "jump-to" the flight software load, a command is issued to the instrument. This directs the Central Processing Unit (CPU) to halt the execution of the PROM code and begin the execution of the flight software from RAM. Minor changes to the MISR FSW can be done using patches, but the major changes require reloading the entire memory. Memory loads after the initial loads are expected to be rare except for anomalies. MISR initially places each 4 Kiloword load segment into a temporary buffer. Each memory load segment is verified by the MISR onboard computer by comparing a Cyclic Redundancy Check (CRC) value provided in the load initiate command with a value computed onboard. If these values and number of words match, MISR moves the memory load to the appropriate location based on the start address and word count in the memory load initiate command. The result of the onboard CRC check is reported in housekeeping telemetry. Memory loads are CPU-intensive and compete with the resources required for sensor data sampling and are only be performed when science data acquisition has ceased (MISR is in engineering or safe mode). If the full load is verified, a "jump to" command is issued to use the new software. This command is only used after a memory load is completed. The total size of the MISR flight software is approximately 60 Kilowords. There are also partial loads which are usually changes to the calibration tables. These loads are small and may be sent as often as once per month, although this makes bookkeeping difficult.




CMDs-Commands
DAAC-Distributed Active Archive Center
EDOS-EOS Data & Operations System
EOC-EOS Operations Center
EPGS-EOS Polar Ground Stations
FDF-Flight Dynamics Facility
FDS-Flight Dynamics System @EOC
HK-Housekeeping
IST-Instrument Support Terminal
LZPF-Level Zero Processing Facility
MISR SCF- MISR Science Computing Facility
TLM-Telemetry
WGS-Wallops Ground Station
WOTIS-Wallops Orbital Tracking Information System

Figure 2. MISR Mission Operations Architecture

## 4. MISR PLANNING AND SCHEDULING

The MISR IOT defines the activities and Baseline Activity Profiles (BAPs) required for MISR instrument operations. The MISR IOT schedules a detailed plan for each operations day and participates in the resolution of all conflicts between MISR-scheduled activities and those of the Terra spacecraft activities (such as maneuvers), a subsystem, or another instrument's plan.

The MISR IOT schedules the detailed plan by submitting a 32-day schedule once every month. The MISR IOT develops the monthly schedule upon direction from the co-investigator, including requests from the science team and calibration engineers. These include times MISR is able to view target observations using local mode and cal diode mode. Local mode is a high-resolution mode where each camera, sequentially, is put into full resolution (1x1 averaging) for all four spectral bands for about 50 seconds. The cal diode mode is used to turn on both sets of diodes (Hqe and Pin) for about 2 minutes, while the cameras are in Taxi_On mode. The 32-day schedule augments the activities already scheduled by the BAP. The Flight Operations Team (FOT) coordinates with the MISR IOT regarding any special observation activities (such as joint observations) or spacecraft maneuvers. The MISR 32 day schedule is created by the MISR Local Mode Selection (LMS) software after ingesting a file with the month's requested operations target sites. This LMS outputs a Short Term Schedule (STS) file, which is ingested into the EOS Operations Center (EOC) Mission Management System (MMS) and is automatically entered into Terra's timeline.

The MISR IOT reviews the scheduled MISR activities for both soft and hard constraint violations. If constraint violations exist, the MISR IOT will attempt to eliminate them by modifying (adding and deleting) activities directly on the MMS scheduling timeline, resulting in a conflict-free set of MISR activities that is scheduled

The cal diode activities are currently being scheduled manually on the MMS timeline, but in the future this task will be automated by the LMS software.

Once activities are scheduled, the FOT maintains the accuracy of activity execution times by updating daily (before 15:00:00 UTC) seven days of predicted times of the orbital events. In addition, on Mondays by 15:00:00 UTC, the FOT provides a 7 week prediction of orbital events. As new predictions become available, the FOT extends the MISR BAP to cover the time span of the predictions. The orbital events include the times MISR can view specified local mode and cal diode targets. The MISR IOT updates the MISR schedule once every month.

The list of possible local modes used by the local mode sequencing software is an EMOS configured item. The MISR IOT is responsible for initially defining the list and for submitting change requests. Figure 3 shows an example of MISR activity timeline.

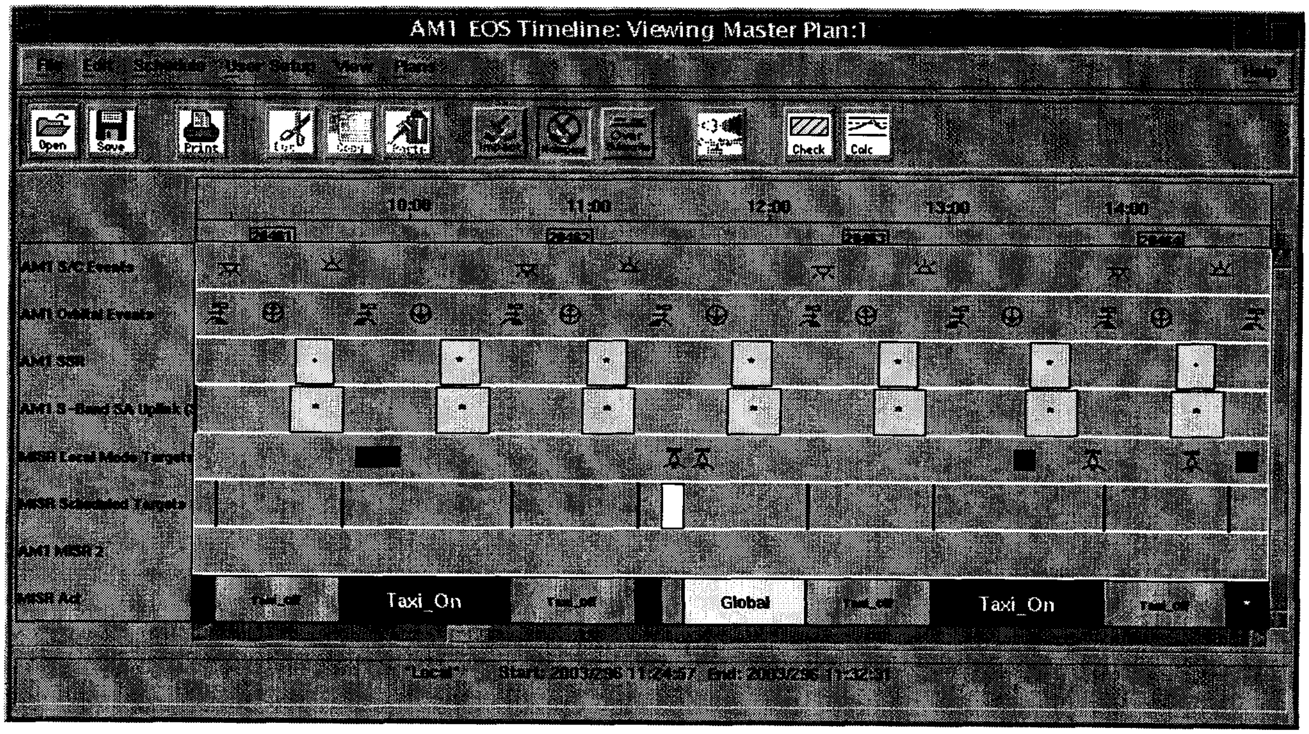



Figure 3
MMS Timeline displaying MISR activities and Terra uplink/downlink communications

## 5. MISR Real-time Operations

Real-time operations focuses on the functions performed immediately before, during, and after a scheduled contact with the Terra spacecraft. MISR IOT does not support routine real-time operations. However, during special planned instrument operations and unplanned real-time commanding like during MISR anomalies, IOT supports by monitoring the operations via the Instrument Support Terminal (IST) which is IOT's window into the EOC to check on instrument health and safety.

### *5.1 Telemetry Monitoring*

The Flight Operations Team (FOT) resident at EOC, Goddard Space Flight Center (GSFC) provides real-time telemetry monitoring of the spacecraft subsystems and instruments during all contacts, 24 hours per day, 365 days per year at the EOC to react to changing conditions. Before Terra's launch in December 1999, the MISR IOT trained the FOT on the proper operation and monitoring of MISR. The IOT defined the telemetry data, the operational limits, and the reaction for each out-of-limit condition. In the case of an anomaly, FOT reviews event messages to report all out of limit conditions as defined by the MISR IOT. When anomalous conditions occur (including out-of-limits conditions), FOT first safes the affected spacecraft or instrument system, unless the spacecraft or instrument entered a safe state due to onboard fault protection response. FOT then notifies the IOT. MISR IOT is responsible for the investigation and resolution of instrument anomalies. The FOT assists the IOTs with instrument anomaly investigations when requested by providing necessary data for analysis.

### *5.2 Real-time Commanding*

The FOT performs all real-time commanding of the spacecraft subsystems and instruments including individual commands, memory loads, and commands procedures. The FOT executes the commanding as defined in the Daily Activity Schedule. The FOT ensures that all scheduled commanding occurs as planned and notifies the affected IOT in the event a spacecraft or ground system contingency affects the planned commanding. Using the EOC C-Extended Command Interface Language (CECIL), the MISR IOT defined real-time command procedures ("procs") that include pre-planned real-time commands to be sent to MISR. The proc is then scheduled for real-time execution during a Tracking and Data Relay Satellite System (TDRSS) contact period. All commanding is executed via procs; no single real-time commanding is allowed. The procs are EOS Mission Operations System (EMOS) Terra ground system configuration items and are changed according to configuration management procedures.

### *5.3 Memory Loads and Dumps*

The FOT performs MISR memory loads and dumps when requested by the MISR IOT. The MISR IOT submits the memory loads to the FOT through the IST by posting the new files on the secure ftp server. After the load passes through the configuration management process, any of the loads over 4 Kilowords are partitioned into 4 Kiloword or smaller segments by EMOS. For each load segment, the EMOS calculates the CRC (Cyclic Redundant Check) and the correct load start address. The FOT then schedules and uplinks MISR memory load according to the parameters defined by the IOT during submission of the load with IOT on the console authorizing. Following uplink of each load segment, the IOT verifies the load segment by monitoring the MISR CRC check flag contained in the H/K telemetry. The CRC check flag is set to "pass" when the load initiate command is received. If the load segment fails to pass the CRC validation, the CRC check flag is set to "fail". In addition to the CRC check, the MISR IOT verifies full software loads by requesting a memory dump of the flight software. The IOT provides memory load changes no later than a few days before the scheduled upload. In the event of a contingency to reload the entire MISR software, the IOT provides the latest approved version of the MISR flight software. The FOT uplinks the load at the earliest available opportunity with IOT support for MISR to resume normal operations. The FOT performs memory dumps as requested by the MISR IOT. Following the memory dump the IOT verifies receipt of the requested number of data words and notifies the MISR FOT if the operation was successful. MISR Flight Software has been loaded into RAM only twice since launch.

### *5.4 Unplanned Commanding*

The MISR IOT submits real-time command requests to the FOT by faxing a Pass Plan Change Request (PPCR) form. In a contingency situation, the FOT responds to the requests at the first available opportunity. In non-contingency situations, these requests should be submitted to the FOT no later than 8 hours prior to the real-time contact in which the request is to be executed. For the purposes of real-time command requests, a contingency is defined as an event that puts the instrument or spacecraft at risk of permanent damage if action is not taken, contingency procs were prepared ahead of time and are archived by MISR IOT to be used in case of certain anomalous situations. The FOT responds to real-time command requests from the MISR IOT by reviewing the request, obtaining approval, as required, and uplinking the commands at the next available opportunity with the IOT monitoring the instrument and authorizing the command uplink. The IOT provides the rationale and urgency for each command request submitted to the FOT.

## 6. MISR HOUSEKEEPING DATA ANALYSIS

MISR IOT verifies the operational performance of all spacecraft subsystems and instruments in order to maintain an up-to-date knowledge of instrument operating characteristics, capabilities, and limitations. The team uses this performance verification in science data analysis and evaluation and as an input to ongoing science and operational planning activities. The MISR IOT verifies all aspects of instrument performance, throughout the life of Terra mission. The MISR IOT uses both internal and EMOS analysis software to provide the performance evaluation. The MISR IOT analyzes the housekeeping telemetry that is downloaded from the EOC and the engineering data contained in the instrument's science data available from the Distributed Active Archive Center (DAAC) to verify the performance of the instrument as required by the MISR Principal Investigator (PI). The MISR IOT informs the FOT of any instrument performance changes. The MISR IOT provides weekly reports on the status and performance of the instrument. The MISR IOT assists the FOT with investigation of performance anomalies requiring MISR instrument expertise. When the MISR IOT identifies an anomaly, the FOT assists with the investigation including requesting additional or extended telemetry contacts, executing unplanned procedures, uplinking unplanned commands and memory loads, and performing special data analyses. Figure 3 is an example of a daily analysis plot generated using housekeeping telemetry data.

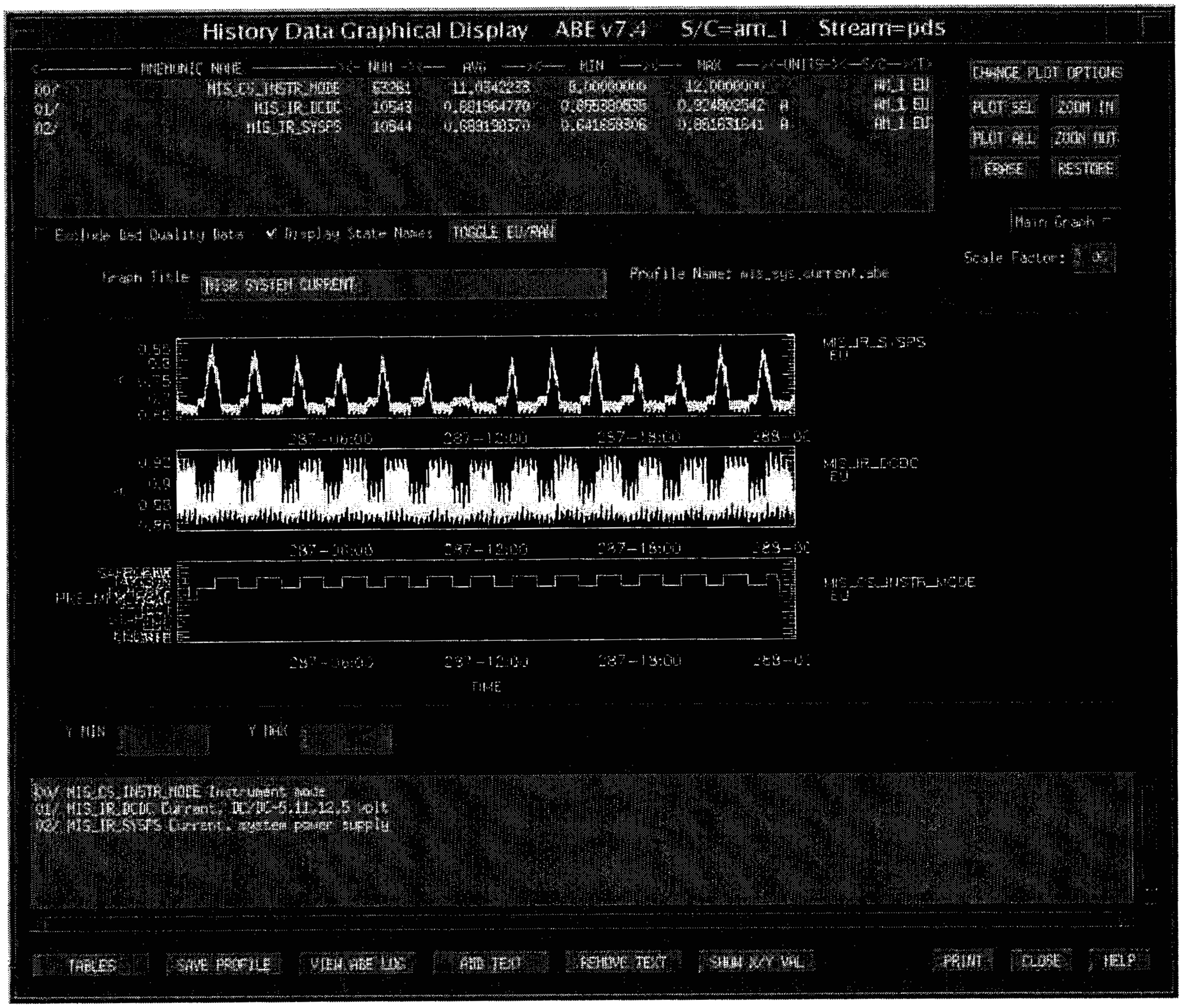



Figure 3 MISR daily analysis cplot

## 7. MISR Mission Operations Tools

The EOC (EOS operations center) facility is located at Goddard Space Flight Center (GSFC). The Instrument Support Terminal (IST), which is the main tool used for MISR mission operations, provides the IOTs with real time and off-line access to the EOC resources. It is a "window" into the EOC for the instruments. It was delivered to the IOT by Raytheon in Denver, Colorado. The IST provides the capabilities to:

- input information to the EOC Planning and Scheduling process and review the planned schedule for all Terra instruments and spacecraft operations;
- access the same displays available to the FOT in the EOC; and
- generate the same kind of statistics reports, trend plots, carryout data etc. that are available to the FOT in the EOC.

Telemetry is transmitted to the IST from the EOC, where it is de-commutated and displayed in both text and graphical forms. The IST consists of two SUN workstations and two PCs with NT operating systems. The NTs are used to monitor the MISR instrument health and safety data in real-time, develop real-time command procedures and send real-time commands to MISR during activation, nominal and contingency operations. The SUN workstations are used for planning and scheduling of observations and housekeeping data analysis.

## 8. MISR: Protection from Ourselves

Terra is the first EOS mission and as the flagship in the three satellite EOS constellation, it has gone through the normal growing pains and the IOTs through their learning curves. The MISR instrument is robust and is protected well by the software designed to do so. There have been several procedural changes to the anomalies and idiosyncrasies that have occurred, and these lessons learned were communicated to the Aqua Mission and to the Aura Mission. Overall, the MISR instrument is consistently delivering the optimal amount and quality of data.

### *8.1 Mis - communications Amongst Teams*

Throughout all phases of the MISR project (design, development and test and operations) a major emphasis should have been placed on good working level communications between all disciplines involved in the instrument operations. Information should have been freely communicated between the scientists, hardware engineers and software developers independent of organizational boundaries. Perhaps if the IOT sat in on the Integrated and Test (I&T) team meetings, the proper cross training could have been established. This suggestion has been implemented by the TES instrument and has been very useful to it's development.

### *8.2 Incomplete Documentation*

a. If the I&T or IOT team had properly documented changes made to calibration tables; an anomaly would have been avoided. When the calibration tables were updated about a year into the mission, a limit below the maximum was entered since the project did not plan to move the goniometer to any position further out than +38 degrees. The IOT assumed the calibration tables were updated with the maximum values and attempted to move the goniometer to the +58 degree position several times, the goniometer never arrived there. Assuming that this was just an idiosyncratic stop, the same values were commanded minutes later with the same result. When a third attempt of the same command was sent, the CPU locked up, thereby triggering a Telemetry Monitor (TMON) which put MISR into Safe Mode. This caused several days of lost science data while the anomaly investigation team re-constructed the events. Since this anomaly, it has been agreed that any changes are to be recorded and archived in both hard and electronic versions.

b. Another problem with incomplete documentation involves the planning of a Deep Space Calibration Maneuver in which Terra rotates through an along-track reverse 360-degree flipover. A lot of planning was done to support the maneuver activity in 2001 but the maneuver was cancelled. When the maneuver actually happened in 2003, many of the previous planning documents were incomplete and needed to be repeated. The maneuver was successfully completed twice during 2003 and another is being planned after the Aura launch. The investigation and plans for the first two, and the results, are documented and archived for future reference.

c. The idiosyncrasies that have been learned while on orbit are recorded only in short memos and are not compiled into a searchable database. Time and effort need to be spent on completing the transfer of these idiosyncrasies over to official documents that are kept active and online. All these idiosyncrasies should have been compiled into an official flight rules document, rather than a memorandum. This task has yet to be completed but is being planned now.

### *8.3 Familiarity Causes Carelessness*

After scheduling the MISR activities, the EOC sends out the Absolute Time Command (ATC) loads. These command loads are confirmed by the IOT twice per day, once in the afternoon and a second confirmation the following morning. A problem occurred when a Local Mode activity was not removed during a Terra Maneuver. To conduct a maneuver, Terra loses pointing accuracy during the entire maneuver, which corrupts any science data taken during that time. However, the IOT did not remove a Local Mode that was scheduled during a maneuver. This did not compromise the safety of the instrument but the data was useless and the science team had to be notified. The IOT has made a procedural change to confirm the activities are correct during the week prior to catch any potential errors before approving the ATC loads.

### *8.4 Keeping Flight Software Knowledge Intact*

The people who have developed the flight software have moved onto other development tasks and have taken the Flight Software knowledge with them. There needs to be a mechanism to maintain this important mission knowledge, and as it changes over time. A member of the IOT should have invested time in learning to use the MISR engineering model for testing purposes.

### *8.5 Telecons Important to Keep IOT Team Current*

As the MISR development team moved on and some retired, we have maintained contact with one of the most knowledgeable hardware and software engineers. We hold three teleconferences each week for the first three years of the mission and have now reduced the frequency to once per week. This can be increased again during specific anomalies or other investigations as needed.

### *8.6 What Protects MISR From Human Error?*

MISR has been protected with automated monitoring that uses yellow and red alarms limits for telemetry points to warn of anomalous conditions. A tightly controlled set of values notifies the FOT in the real time telemetry when conditions are close to or exceed the boundaries. There are also Telemetry Monitors that automatically command MISR to safe or survival when predefined temperatures, voltages telemetry points are out of limits. The FOT at the control center at GSFC notices when a red alarm is triggered or a Telemetry Monitor takes action and the FOT then contacts MISR IOT for analysis. There is also fault protection within MISR flight software that protects MISR from some human errors.

## 9. CONCLUSIONS

MISR is a robust instrument that has been operating without many problems for almost 4 years now, delivering a fairly complete set of data. The Terra spacecraft itself has also had only a few problems. More software to process the data is being developed as the uses of the data are diversifying. Operationally the IOT and the FOT have been able to maintain the health and safety of the instrument due to the protections put in place during the development phase. This has proven to be very useful with the human errors that have occurred, both from veteran MISR personnel and as new personnel are being trained. Several procedural changes have been made within the MISR IOT to further limit the instrument's exposure to errors. The lessons learned from Terra and MISR have been communicated to the Aqua and Aura missions in the hopes that they would not repeat the same mistakes.

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