SIRTF - INHERITANCE, ADAPTATION, AND ADVANCEMENT

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ABSTRACT

SIRTF, The Space Infrared Telescope Facility, is scheduled for launch in December 2001. Development of the SIRTF mission combines the known with the new, building on previous mission experience while advancing the state of the art where needed to meet mission goals. The uniting of inheritance from previous missions, adaptation of existing capabilities, and advancement for scientific achievement has proven a potent combination in developing a low cost, reliable mission. This paper discusses the resulting operations design using an inherited planetary flight system, a multimission distributed ground system, and operations similar to constant encounter mode.

1. Introduction

SIRTF is the fourth and last of NASA's Great Observatories and is a cornerstone of the Origins Program. It is a companion observatory to the Hubble Space Telescope, the Chandra X-Ray Observatory and the Gamma Ray Observatory.

SIRTF combines the sensitivity of a cryogenic space telescope with the enhanced capabilities of new large format infrared detector arrays. It is ideally suited to the study of known astrophysical problems and has great potential for the discovery and exploration of new phenomena. SIRTF is also a pathfinder for technology needed for future astrophysics missions.

The design of the SIRTF observatory uses inheritance from many missions, with the command and data handling system an adaptation of the Mars 98 system. Upgrades and adaptations include an improved pointing control system, an enhanced sequencing engine, 2.2 Mbps downlink, and enhancements to other systems such as fault protection. The instruments include new infrared detector arrays, with increased frequency range and resolution. This, combined with the fact that the telescope is very cold (5.5K), provides an increased sensitivity that allows a large volume of data to be taken very quickly.

The SIRTF Ground Segment has two parts, flight operations, and science operations. Flight operations builds on inheritance and experience with Mars and other planetary missions, uses services available from the JPL Multimission Operations Center and the Deep Space Network, and includes a remote engineering team at the spacecraft contractor facility. The science operations center builds upon the heritage gained through IRAS, ISO, 2MASS and WIRE to perform SIRTF science operations.

The SIRTF project employs a "build a little, test a little" approach to the development of the end-to-end data system. Pioneered for JPL by the Mars Pathfinder program, it uses integrated systems deliveries throughout the development process, beginning more than three years before launch.

The SIRTF observatory is designed for easy operability. However, operating a full time observatory brings challenges unlike planetary missions with long cruises and brief encounters.

The operations processes must provide fast turnaround for large volumes of both commanding and data products. Advancements in spacecraft autonomy and ground segment design bring additional operational challenges in the areas of planning and sequencing.

2. Science and Mission Design

The SIRTF observatory will be operated for the scientific community for a minimum of 2.5 years, although predictions suggest that the cryogenic lifetime will extend beyond 5 years. The SIRTF observatory is designed to conduct infrared observations, taking images and photometric measurements from 3 to 180 microns and spectroscopic measurements from 5 to 100 microns. SIRTF is a direct follower of the Infrared Space Observatory (ISO), and is a bridge from ISO and the great observatories to the Next Generation Space Telescope. SIRTF will build upon the scientific basis established by two successful missions of the 1980s: the Infrared Astronomical Satellite (IRAS), launched in 1983, and the Cosmic Background Explorer (COBE) mission, launched in 1989. Both of these missions demonstrated the cryogenic technology and scientific benefit of liquid-helium-cooled telescopes and instruments in space.

The SIRTF mission will be different from the preceding missions in two critical ways. The first difference is that SIRTF will be the first observatory to use an Earth-trailing heliocentric orbit, which eliminates thermal interference from Earth and requires no propulsion system for trajectory correction. SIRTF will drift away from Earth at the rate of approximately 0.1 AU/year. For missions requiring cooling to temperatures near absolute zero, this choice of orbit presents a far more benign thermal environment than any geocentric orbit. Using a heliocentric orbit instead of an Earth-centered orbit also allows for much easier telecommunications since there are few periods of blackout due to Earth interference. Another benefit is a substantial reduction in Sun-Earth-Moon avoidance constraints. In heliocentric orbit, SIRTF's view of the celestial sky is limited by only two pointing constraints. First, the Observatory cannot point closer than 80 degrees in the direction of the sun for thermal reasons, and second, it cannot point more than 120 degrees away from the Sun direction for solar panel illumination rules.

The second critical difference is the warm-launch architecture. SIRTF's telescope assembly is launched at ambient temperature and allowed to cool radiatively in space. Only the focal-plane instruments and the cryostat are enclosed in the vacuum shell. This design reduces the in-orbit heat load to the cryostat, leading to a reduction in the volume of cryogen required. SIRTF carries 360 liters of liquid helium, affording an estimated lifetime of 5 years. For comparison, IRAS used 520 liters over 10 months, and ISO used 2140 liters in about 28 months. Immediately after launch, SIRTF will go through a 60-day period of in-orbit checkout. Roughly the first half of the checkout period (there is no cruise) will be needed to cool the telescope and checkout the engineering systems. The second half of the checkout will be used primarily for calibrating and commissioning the instruments. On the completion of checkout, the first cycle of nominal observing will begin.

Seventy-five percent of observing time will be available to the general scientific community, divided between legacy observations and general observations. Legacy observations are those which are large coherent programs whose data would be of lasting value to the wider astronomical community. Half or more of the first year's time will be devoted to legacy science to develop databases on which future SIRTF users can base follow up proposals. Legacy science data will be placed in a public database with no proprietary period. Selection of the legacy science teams will begin in November of 2000. Of the remaining twenty-five percent of the observing time, twenty percent will go to Guaranteed Time Observers (GTO) - members of the SIRTF Science Working Group and the three instrument teams - and five percent to the Director's Discretionary Fund. The first opportunity to participate will be with the call for Legacy Science Proposals in July of 2000. Calls for general proposals will then be made approximately every nine months through the mission.

Building on the background of previous infrared missions, SIRTF is well suited to the further study of known astrophysical questions and has great potential for new discoveries. The five-year mission allows participation by a wide range of the astronomical community.

3. Observatory - Spacecraft, Telescope, Instruments

The Observatory is the combination of the spacecraft, telescope, cryostat, and instruments. Lockheed-Martin Missiles and Space Corporation (LMMS) is building the spacecraft with Ball Aerospace and Technologies Corporation (BATC) responsible for the telescope and cryostat. Ball is building two of the three instruments as well. There is much inheritance in the design of SIRTF spacecraft, with contributions from many projects, including Chandra, Lunar prospector, ISO, and most notably, Mars 98. The command and data handling system and most of the spacecraft flight software are adaptations of the Mars 98 designs and are sisters to the in-test Mars 01 designs.

One area in which upgrades are necessary is in pointing. SIRTF uses the same pointing architecture - star tracker, gyro/reaction wheels - as ISO, but needs better resolution. It also needs an improved pointing control system over the inherited Mars 98 software, due to the different nature of the mission. The spacecraft provides pointing and control of at least 5.0 arc seconds accuracy with 0.3 arc seconds stability over 200 seconds, and 0.6 arc seconds stability over 500 seconds. It also tracks solar system objects at rates up to 0.1 arc sec/sec. Operationally, the spacecraft works on an "Operational Pointing Zone" (OPZ) concept. The OPZ is the annulus defined by the 80 degrees toward-Sun and 120 degrees away-from-Sun pointing constraints. Constraining the spacecraft to point only within the OPZ simplifies power, thermal, and pointing control.

Improvements have also been made in the on-board sequence engine, fault protection, and downlink telecommunications. There is a new flight software sequence engine, called the "Sequence Virtual Machine" (SVM) that controls execution of the stored command sequences and is more flexible than previous on-board sequencers. It allows some event-driven execution of activities, for instance allowing one activity to be initiated by the completion of another. The multimission ground system has been modified to enable the new capabilities. SIRTF is the first deep space mission to use a 2.2 Mbps downlink. That in turn requires major upgrades to the ground system to store and process the large volumes of data quickly. Fault protection functions are expanded for SIRTF, providing an additional reduced-functionality state called standby mode. It is easier and quicker to return to observing from standby mode than from safe mode, improving efficiency in the recovery from minor anomalies. The spacecraft also incorporates significant on-board autonomy in the areas of acquiring targets, initiating sequences, enforcing attitude constraints, and initiating fault protection responses.

The Telescope is a Cassegrain design with an 85cm aperture compared to IRAS's 60cm mirror, and has a maximum wavefront error of 0.07 when operated at 5.5K. It is lightweight beryllium, state of the art for ultra lightweight cryogenic optics. The cryostat provides the thermal environment needed to operate the telescope at 5.5K or lower, and a thermal sink to cool the instrument arrays to 1.4K or lower. The telescope itself is not in the cryostat and is launched at ambient temperature then cooled by radiation to space.

The instruments use the next generation of large format infrared detector arrays, with increased frequency range and resolution. Two of the scientific instruments, the Infrared Array Camera (IRAC) and the Multiband Imaging Photometer for SIRTF (MIPS), provide imaging from 3 to 180 micrometers using detector arrays operating at temperatures down to 1.5K. The Infrared Spectrograph (IRS) and MIPS provide spectroscopy from 5 to 100 micrometers. Among the three instruments, there are 10 instrument fields of view, all of which can view at all times. Both MIPS and IRS have detector inheritance from WIRE and flight software inheritance from HST's NICMOS. Design of the telescope/cryostat/instrument combination emphasizes lightweight cryogenic optics technology, minimizes the number of mechanisms, moving elements, and deployables, and limits the number of array types, multiplexers, and data formats. The essential new technologies - detectors and optics - have been demonstrated successfully and exceeded expectations.

The SIRTF Observatory is a combination of tried-and-true designs and advances in many areas, both hardware and software. The new capabilities achieved through these innovations will serve to enhance SIRTF's science program greatly and set new standards for future missions.

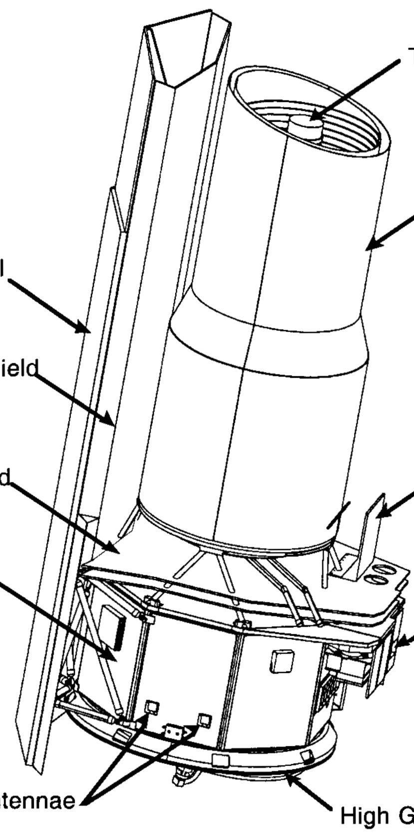

Figure 1 - SIRTF Observatory

4. Ground Segment

The SIRTF Ground Segment design is comprised of a Flight Operations Center (FOC) and a science operations center. These two organizations carry out all operational aspects of the SIRTF mission from cradle to grave.

The FOC is located at JPL and uses the services available from the Multimission Operations Center (MMOC) and the Deep Space Network (DSN). These services include command sequence translation and uplink; data receipt, decompression and preprocessing; real-time monitoring of spacecraft health, safety and communications; and generation of radiometric data necessary for determination of the Observatory's orbit. The services provided by the MMOC and DSN have a long and venerable history dating from early missions such as the Viking Mars lander. Currently, they provide services to many missions at once, e.g., Voyager, Galileo, Cassini, Mars Global Surveyor, Deep Space 1, Stardust, Ulysses, and many more. Upgrades to the multimission system are required for SIRTF to support the use of the Sequence Virtual Machine and the first use of the 2.2Mbps downlink rate. Flight operations will also incorporate a remote team at the spacecraft contractor facility in Sunnyvale, California for spacecraft engineering support.

The science operations center, called the SIRTF Science Center (SSC) is located at the Infrared Processing and Analysis Center (IPAC) on the campus of the California Institute of Technology in Pasadena. Science operations include both activities not previously supported by IPAC, and activities similar to prior IPAC programs (IRAS, ISO, 2MASS, WIRE, etc.) The new activities are primarily in the uplink area, with SSC developing new tools and processes for the creation, planning and scheduling of observations. The SSC is charged with operating the SIRTF science mission, including the solicitation, review, and selection of all observing programs, long and short range observation planning, and instrument performance monitoring after in orbit checkout. It is the organization responsible for creating and securing the scientific legacy of SIRTF with a uniform and reliably reduced, calibrated, and readily accessible archive of all scientific and supporting engineering data. The SSC is also responsible for the education and public outreach requirements for SIRTF. Subsystem heritage at the Science Center includes an adaptation of the Space Telescope Science Institute Spike scheduling tools and OPUS pipeline executive, IPAC Target Visualization Tools, and IPAC Archive Tools used for 2MASS and IRAS.

The Ground Segment for SIRTF has the most inheritance of all SIRTF areas. Many of the multimission services can be used with few or no changes for SIRTF. The major areas of advancement are SSC's performance of the uplink planning functions and the operation of an observatory using multimission services developed for deep space missions.

5. Development Process

SIRTF's development process is also a combination of the old and the new. SIRTF is employing a "build a little, test a little" approach to the development of the end-to-end data system that was pioneered for JPL by the Mars Pathfinder program. SIRTF's project team is also innovative, with team members selected early for earlier participation in design and development decisions.

The data system is developed in phases, with deliveries approximately 6 months apart in concert with new versions of the flight software. Each delivery includes a specific set of capabilities (negotiated with project teams) and focuses on preparation for use in the subsequent phase. This ensures that the ground system is deployed throughout the full project development lifecycle. Each data system build has a team coordinator and is presented to a review board to verify plans, provide demonstrations, and report results and issues.

As the builds progress, there is increasing formality, i.e., each deployment becomes more mature, the system performs better, with more capabilities, and the associated 'formality' and documentation improve. The goal of these incremental builds is to avoid "big bang" integration problems during the integration and test phases. Each build, called a "Facility Data System (FDS) Delivery" integrates and tests deliveries relating to:

- Ground system development at JPL & IPAC
- Flight software development at LMMS and BATC
- Integration and test activities at BATC, Goddard Space Flight Center, and LMMS

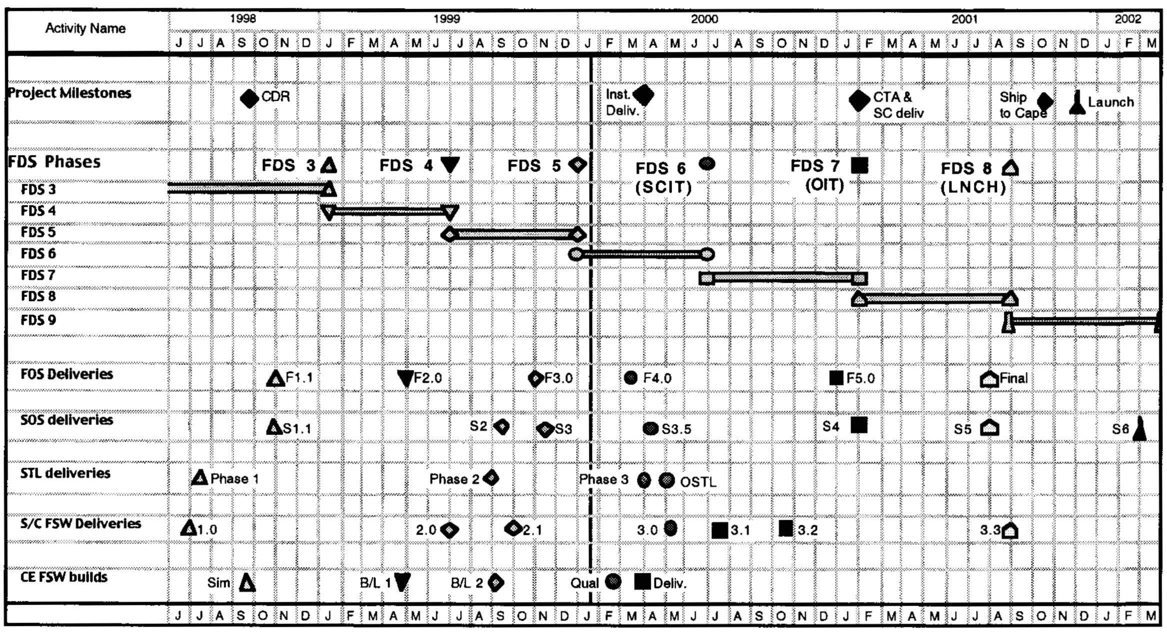

Figure 2 - FDS schedule

SIRTF is currently in the middle of Facility Data System Delivery #6 (FDS-6). FDS-3, FDS-4 and FDS-5 all used elements from each of the subsystems. Instruments are being tested with components of the system now and significant interface issues have been identified and fixed prior to hardware integration. The ground system itself will be functionally verified before Observatory integration and test, using a system test laboratory. The Observatory integration and test phase will verify the flight and ground systems in their final flight configurations using detailed mission scenarios.

The other development process innovation is a new teaming structure. Unlike most flight development programs where the design and requirements are first completed, then the contractors brought in to bid on development, the SIRTF Project tried a new approach. The project team members, including the industrial contractors, were solicited early enough to enable full participation in the preliminary design process. While JPL remains responsible for Project management, mission engineering, science management, and flight operations, the other team members have been actively working together during SIRTF's design phase. Systems engineering is distributed among the delivering organizations with only a small cadre retained in the project office. This management plan, designating subsystems and contractors as empowered, equal, and "all on the same team," changes the contractor-customer relationship positively but makes oversight more difficult. This teaming structure works because SIRTF design has a high reliance on heritage designs with previous qualifications. A capability driven design approach has been accepted and promoted, with additional requirements negotiated to match cost and capabilities. The team structure allowed team based design evolution with interface coordination in an integrated product team format.

SIRTF's new teaming structure and data system development strategy enable early proof of critical operational concepts and reduce schedule risk by early participation and integration.

6. Operations

SIRTF is designed for easy operability. The solar orbit provides continuous operations, the spacecraft and software support operation of only one instrument at a time, and the commanding strategies provide for autonomous operations between data downlinks. Operations concepts for SIRTF are adapted (or borrowed) from various missions including ISO, Mars 98, Hubble Space Telescope and Cassini. Enhancements to the operations concepts take advantage of the Sequence Virtual Machine's flexibility and the benefits of operating under a limited number of observing modes. The observatory itself is designed to survive at least seven days of unattended operations, allowing the small operations team time to recover from faults. Error reduction is built into the system to reduce the likelihood of a fault and fault protection can respond with two reduced functionality states. All operations teams share centralized databases and tools.

The Earth-following heliocentric orbit, unlike an Earth orbit, has no eclipses or occultations. This provides excellent sky access and visibility with a sun angle of 80-120 degrees and means that at any one time, 35% of the sky is visible. Any target entering the visibility zone will be observable for at least 40 days before re-entering the forbidden pointing zone. The visibility of each section of sky repeats approximately every six months, with continuous viewing of the ecliptic poles. This makes scheduling of observations much more flexible than in previous missions. The single instrument operation constraint allows observations in the schedule to be assembled into instrument campaigns lasting three to seven days, cycling among the instruments to minimize cryogen usage.

For science operations, the observatory will not be commanded in real time. All nominal commanding is via autonomous operations from stored sequences. A set of sequences is generated and uplinked to the observatory once a week, on a 1-week development schedule. These sequences contain both commands and calls to onboard programs called "blocks." Blocks are small sequence programs used to perform repetitive activities such as a turn to Earth or an instrument power up. They are coded and tested pre-launch, then stored onboard. Use of blocks reduces uplink bandwidth and also reduces commanding risks, since blocks are pretested before loading onboard.

Observing will be performed via Astronomical Observation Templates (AOT) designed to employ only seven distinct observing modes. This follows the ISO model of operations using a small number of templates. The AOT is an electronic form that prompts the user to fill in the necessary astronomical information and observing strategy. Each observation is constructed from one of these templates and is collected in a database. The Time Allocation Committee reviews the submissions and marks accepted proposals for inclusion in the scheduling process. The system is designed to process up to 1000 proposals every 9-12 month cycle.

During the scheduling process, the operations team selects a pool of observations for the upcoming week. Each target in the pool of observations is viewable for the entire week, but there may be more observations in the pool than can be observed in the allocated time. The scheduling software takes the pool and then includes engineering activities, optimizes timing and pointing, and creates the schedule. Items from the pool that are not scheduled are returned to the database for future scheduling opportunities. The scheduling system is designed to process up to 16,000 observations for scheduling per year, or about 320 per week. From the schedule, the set of sequences for one week of observing is generated. The figure below shows the uplink process flow and highlights where inherited systems have been adapted for SIRTF's needs.

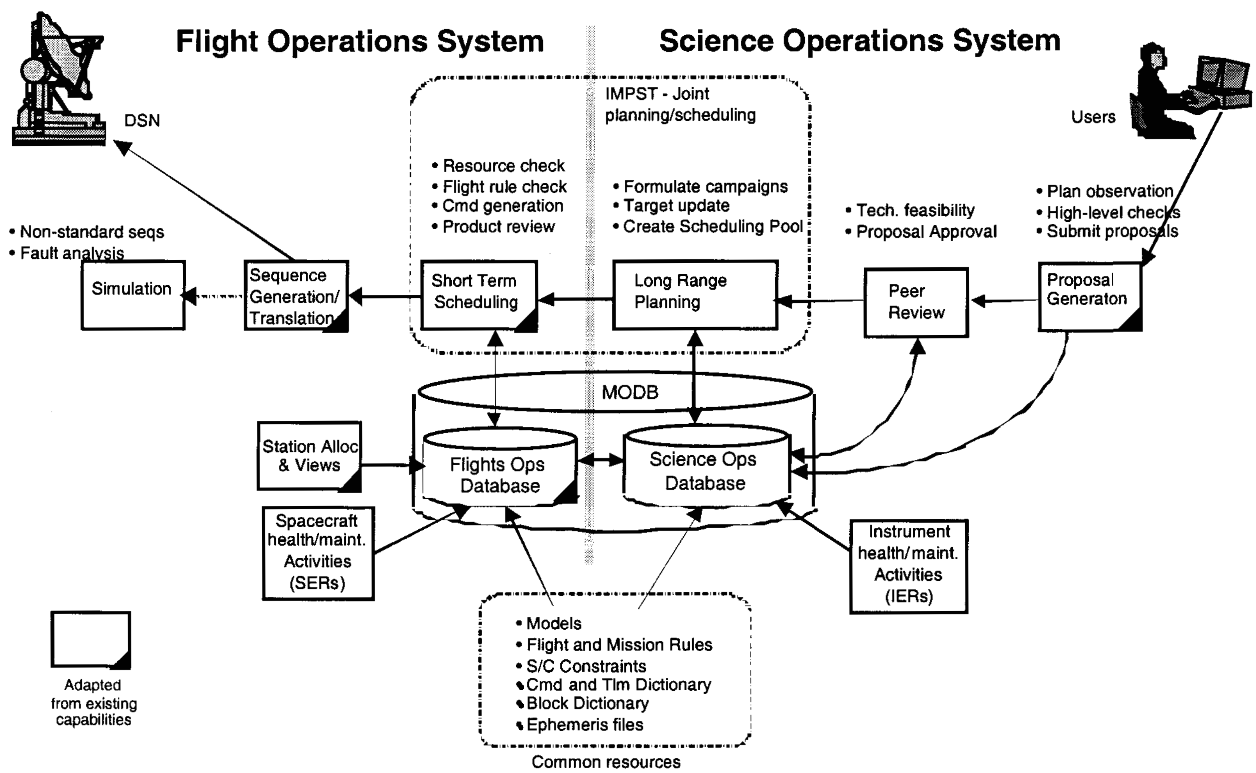

Figure 3 - SIRTF Uplink Process

Onboard, the flight software Sequence Virtual Machine (SVM) executes the sequences. This software controls the execution of the stored sequences autonomously. Sequences are "written" in virtual machine language (VML). This allows use of additional logic constructs and capabilities such as on board construction of commands at time of execution. Several virtual machines, or threads of execution, may be running simultaneously. The highest level machine runs a master sequence while the others run other sequences or blocks controlled by the master. This software allows some event-driven execution of activities in the sequences, for instance to begin observing as soon as pointing is complete. Since slewing and settling times are variable, this type of sequencing improves efficiency. The virtual machine software is still in development, and additional resources have been allocated to the ground system for early integration and test. There is currently an instance of the SVM in use by the ground system for testing. A simulator for SVM commanding is in the process of integration as well. Use of SVM capabilities is restricted by Flight Rules; SIRTF has chosen to restrict using any capabilities that are not expressly required by the operations concept.

During data taking, up to 4 Gbit can be stored in one 12-hr period. The data are written to solid state memory after lossless data compression. On-board, a 16 Gbit solid-state memory will permit SIRTF to store several 12-hour observing periods worth of data. Because the high-gain antenna on SIRTF is body-fixed, the sequence will pause the science program twice a day to point to Earth and downlink the previous period's stored data. At a 2.2 Mbps rate, the 4 Gbit stored in the preceding 12 hours can be downlinked in approximately 30 minutes. Telemetry is provided through NASA's Deep Space Network, with nominal one-hour downlink passes scheduled every 12 to 24 hours. Uplinks, at a rate of 2 kbps, will nominally occur at the same time as downlinks, but commands can be transmitted at a lower rate anytime via one of the low gain antennas.

DSN Operations processes the data to the transfer frame level and forwards it to the Flight Operations System. The FOS then decompresses the instrument data packets, reconstitutes the instrument frames, and delivers the instrument data packets to the Science Center. The FOS must deliver the 4 Gbits of processed and decompressed telemetry data within 12 hours of the end of the downlink. At the Science Center, the packets go through an automated analysis "pipeline" for data processing. The pipeline yields calibrated images in Flexible Image Transport System (FITS) format, which are then archived. The pipeline is designed to process up to 24 Gbits of instrument frame data per day and to process 12 hours of this data and deposit the data products into the archive in less than 6 hours. The figure below shows the downlink process flow and highlights where inherited systems have been adapted for SIRTF's needs. Note that the FOS adaptations are primarily for the 2.2 Mbps downlink rate.

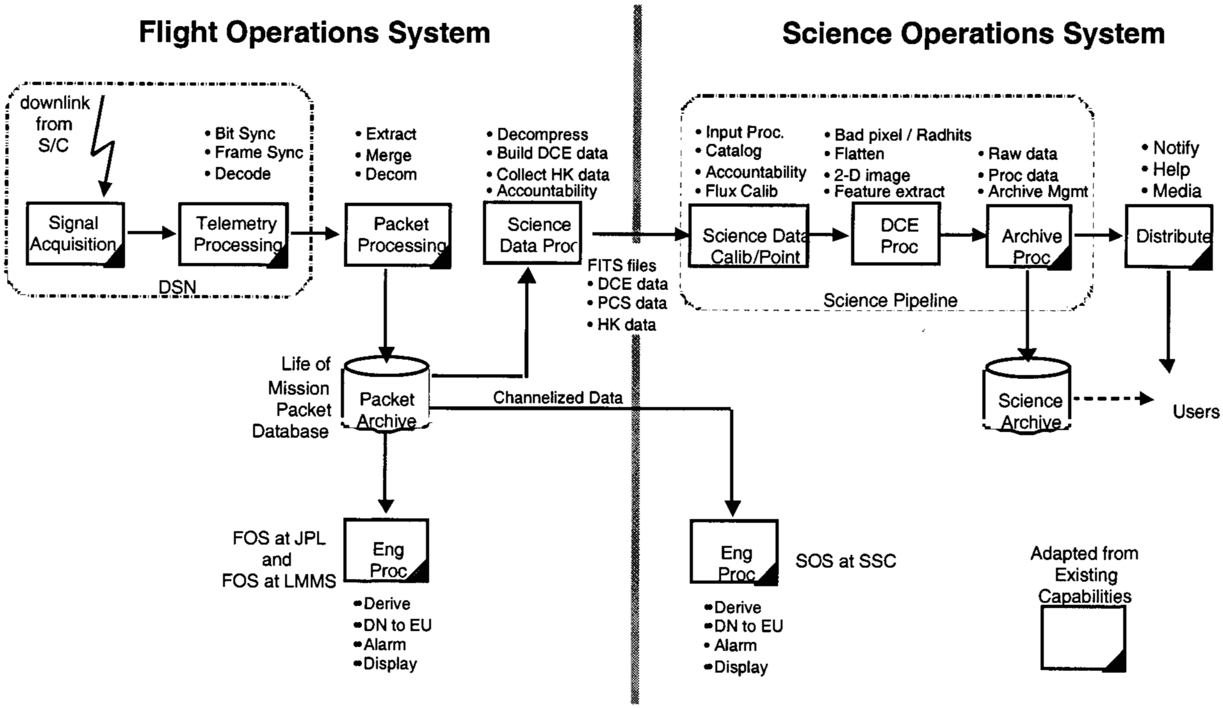

Figure 4 - SIRTF Downlink Process

The SIRTF system is designed to survive at least seven days of unattended operations. In the event of a fault, the observatory will respond from pretested scripts and programs. SIRTF has two reduced-functionality operations states: standby mode and safe mode. Standby mode will interrupt the observing program and wait for instructions from the ground. Safe mode is a more severe response, causing cancellation of observing, power off of the observing instrument, and a turn to Earth. It is expected that recovery from standby mode will take as little as one day but recovery from safe mode could take as much as a week.

Error reduction for SIRTF has been built into the system in several ways. Observations are generated using validated templates (AOT). These templates expand into blocks that are coded and tested before launch. The weekly schedule is created from a pool of observations, all of which are valid for that week. Error checks are performed at each development step, with critical checks performed several times in the process. Command validity checks are also performed onboard at execution time. For flight-ground compatibility, a single command database is maintained by FOS and is used by all flight and ground operations commanding software.

The operations team is staffed by a combination of flight operations and science operations personnel, including a spacecraft team at the spacecraft contractor's facility. The combined teams make extensive use of shared tools and databases. Due to the nature of SIRTF observing, operations are conducted around the clock, enabled by the use of the Multimission Operations Center at JPL. The downlink pipeline is automated as well, processing data whenever received. Operations processes are set up to generate one set of sequences per week, but also to respond to targets of opportunity such that they can be scheduled and observed within 24 hours of receipt of a valid observation.

Operation of the SIRTF observatory is a complex and demanding task. Design for operability has reduced system complexity and spacecraft autonomy has lightened the load on the operations team. Heavy use of multimission capabilities and built in safeguards help to reduce operational risk. SIRTF operations will be an interesting and challenging five-year mission.

7. Conclusions

SIRTF is an able partner to NASA's other three Great Observatories. Reaching out with the most sensitive infrared system ever flown, testing technologies needed for future missions, SIRTF pushes the boundaries of science. Yet, while reaching out, SIRTF is looking back, taking the best capabilities of its predecessors and making them its own.

SIRTF operations will also combine the old and the new by adapting tried-and-true deep space methods to operating an astronomical observatory, while ensuring the fullest participation by the scientific community.

ACKNOWLEDGEMENTS

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SIRTF Public Web Page: http://sirtf.caltech.edu/

ACRONYMS

2MASS	Two Micron All Sky Survey
AOR	Astronomical Observation Request
AOT	Astronomical Observation Templates
AU	Astronomical Unit
BATC	Ball Aerospace and Technologies Corporation
CE	Combined Electronics (IRS & MIPS instruments)
COBE	Cosmic Background Explorer
DCE	Data Collection Event
DN	Data Number
DSN	Deep Space Network
EU	Engineering Unit
FDS	Facility Data System
FITS	Flexible Image Transport System
FOC	Flight Operations Center
Gbit	Gigabits
GTO	Guaranteed Time Observers
HK	Housekeeping (telemetry data)
HST	Hubble Space Telescope
IER	Instrument Engineering Request
IMPST	Integrated Mission Planning and Scheduling Team
IPAC	Infrared Processing and Analysis Center
IRAC	Infrared Array Camera
IRAS	Infrared Astronomical Satellite
IRS	Infrared Spectrograph
IRU	Inertial Reference Unit
ISO	Infrared Space Observatory
JPL	Jet Propulsion Laboratory
Kbps	Kilobits per second
LMMS	Lockheed-Martin Missiles and Space Corporation
Mbps	Megabits per second
MIPS	Multiband Imaging Photometer for SIRTF
MMOC	Multimission Operations Center
MODB	Mission Operations Database
NICMOS	Near Infrared Camera and Multi-Object Spectrometer
OIT	Observatory Integration and Test
OPZ	Operational Pointing Zone
PCS	Pointing Control System
S/C	Spacecraft
SCIT	Spacecraft Integration and Test
SER	Spacecraft Engineering Request
SIRTF	Space Infrared Telescope Facility
SSC	SIRTF Science Center
STL	Software Test Laboratory
SVM	Sequence Virtual Machine
VML	Virtual Machine Language
WIRE	Wide-Field Infrared Explorer