Space Congress

SIRTF: The Fourth Great Observatory*

Larry Simmons, James Fanson, William Irace, Johnny Kwok, and Michael Werner

SIRTF Project, Jet Propulsion Laboratory, California Institute of Technology
Pasadena, California 91109

ABSTRACT

The Space Infrared Telescope Facility (SIRTF), the fourth of the Great observatories, will look through a new window on the universe. Using SIRTF, the astronomical community will be able to explore the in frared universe with a depth and precision complementary to that achieved by NASA's other Great Observatories—the Hubble Space Telescope (HST), the Advanced X-ray Astrophysics Facility (AXAF), and the Compton Gamma Ray Observatory (GRO).

SIRTF will be the first mission to achieve unprecedented infrared sensitivity by fully utilizing a new generation of infrared detector arrays. The new detectors, combined with an 85-cm cryogenic telescope, will allow SIRTF to provide scientific capabilities so impressive that S1l<'l'I was designated the highest priority major new mission for all US astronomy in the 1990s.

This paper will provide a review of the S1l<"l'}' program—the science, mission design, facility, instruments and the implementation approach. Emphasis will be placed on those features of the program which will allow us to realize the great scientific potential of the Observatory in a resource-constrained environment.

INTRODUCTION

S1l{"l'I has been recognized as a key element in the NASA astrophysics program for over a decade. The Observatory has been restructured and redefined to be consistent with the new NASA paradigm of *faster/better/cheaper*. Innovat ions have played a major role in defining the new SIRTF. The science focus is sharply defined, the mission implementation uses a unique solar orbit, the (observatory has adopted a unique architecture, the science. instruments use available state-of-the-art infrared arrays, and finally, an implementation approach is being employed which promises to create a partnership between JPL and industry that will allow SIRTF to be implemented for the least cost consistent with capabilities expected 0[NASA's fourth Great Observatory.

In the fall of 1993, NASA was under great pressure to change the way large projects were conducted. In particular, costs had to be reduced and development times had to be shortened. In ibis environment SIRTF was redefined, resulting in the current concept, which provides a substantial part of the originally envisioned scientific capability at a fraction of the cost.

The scientific capabilities of SIRTF have been guided for over a decade by a Science Working Group (SWG) selected in 1984. The SWG reassessed SIRTF's scientific capabilities in the light of the pressure to reduce the mission scope and decided to rebuild SIRTF's scientific requirements around the needs of four specific science programs: Brown Dwarfs and Superplanets, The Early Universe, Protoplanetary and Planetary Debris Disks, and Ultraluminous Galaxies and Active Galactic Nuclei. These four areas were singled out as of particular importance for S1l<"l'I by the National Academy of Sciences' decadal review (the Bahcall Report), which in 1990 designated SIRTF as the highest priority major new mission for US astronomy.

The mission objectives of examining as efficiently as possible the infrared sky led to the innovative adoption of a heliocentric orbit for S1l{"1'1 . The Observatory will be launched on a Delta launch vehicle, ant] will be placed in an Earth-trailing 1 -AU orbit. This orbit eliminates viewing restrictions due to Earth occultations, reduces thermal heat loads associated with proximity to the Earth, and simplifies operations by having the Observatory in a slowly changing locat ion that accommodates flexible scheduling for command ing and for data t ransmission. S1l<"l"I will also conduct the mission using direct participation by the science community in operations. Data from S1l{-l'l' will be processed and disseminated 10 the science community using the Infrared Processing and Analysis Center (IPAC) located on the campus of Caltech.

The architecture of the Observatory is substantially different than that used in previous in frared missions. The telescope will be launched warm and cooled on-orbit, in large part by radiation to space. This architecture enables the launch of a large-aperture (0.85-meter) telescope in a very light-weight implementation. Using radiative cooling significantly reduces the quantity of cryogen needed over a 2 1/2-year mission life. The resulting mass reduction is essential to capabilities using a Delta class launch vehicle. The Observatory will provide a 1.8 K environment for the science instruments. TWO hundred and fifty liters of helium will be used 10 provide the environment for the instruments, and the helium boil-off will be used to reduce the telescope temperature from the 50 K that radiative cooling would provide to the 5.5 K required to make the longest background-limited wavelength observations. A major challenge for the observatory will be the provision of a pointing control system that has pointing accuracy of a few arc-seconds and stability of a fraction of an arcsec over long periods.

S11<"l'l will employ three instruments for the collection of scientific data. The Infrared Array Camera (IRAC) will provide imaging at 4 wavelengths between 3 and 8 μm. The Infrared Spectrograph (IRS) will provide both low- and high-resolution spectra between 5 and 40 pm, ant] the Multiband Imaging Photometer for S11<1"}' (MIPS) will provide long wavelength imaging between 12 and 180 pm. Each instrument will employ state-of-the-art detector arrays representing improvements of several orders of magnitude over previous in frared sensors used in space astronomy missions.

S11{"1'1: will use a unique implementat ion approach that includes a teaming arrangement between JPL, industry and the science community. The Observatory will be built by industry based upon a design developed jointly by J] 'l. and the science community. Once selected by a competitive process, industry team members will become part of the SIRTF team, and will work together 10 meet project commitments. The project must be accomplished within a fixed budget, which will require an unprecedented degree of cooperation. To conserve resources, the plan is to accomplish the majority of the work in a short period of time to minimize time-related costs. Clear responsibilities will be established to minimize redundant or overlapping efforts. The result is expected to be a demonstration of how, using the new paradigm of *faster/better/cheap er*, NASA can continue to conduct significant scientific missions using state-of-the-art technology with uncompromised performance.

SCIENCE OBJECTIVES

The flavor of SIRTF's scientific programs can be inferred from four examples, one drawn from each of the four scientific theme areas. SIRTF will be able to detect "brown dwarfs" — objects too low in mass to shine like stars --- if' they are common enough to constitute a significant fraction of the mass in the solar neighborhood. SIRTF will also be used to cart y out an ultra-deep survey of a small region of the sky to study galaxies as they appeared when the Universe was about one-tenth of its present age. S1l/-l'l; can study the composition of the dust in solar system like structures around other stars and compare it with that of the dust in the outer portions of our own planetary system. Finally, S11<l'l can peer into the central regions of the most energetic objects known in the Universe, to tell us whether they derive their power from large numbers of stars, from accretion of material onto black holes, or from as yet unidentified physical processes.

These examples illustrate S1l<-l'l"s possible contributions to the study of the four science themes chosen to define the mission requirements. Of course, a mission optimized for these four programs will have broad applicability to a much wider range of astrophysical investigations, and the mix of science to be carried out from SIRTF will be defined closer 10 launch by a peer-reviewed selection of investigations. Finally, in addition to its great power for the study of known scientific problems such as those defined above, SIRTF's great gain in observational capabilities gives this mission very high potential for unexpected discoveries.

MISSION DESIGN

Orbit Selection

SIRTF requires an orbit that is far from the Earth's thermal and radiation environment. A solar-orbit was chosen among three options. A circular 1 ligh Earth Orbit (111?3) with an altitude of 100,000 km would place the Observatory beyond the trapped radiation environment, but this option was rejected because of the high energy required to circularize the transfer orbit from low-Earth altitude. The 1.2 libration point is also ideally suited for astronomical observations. It is a dynamic equilibrium point about 150-nlillion kilometers from Earth along the Sun-1 arth line where the Sun-Earth gravity is balanced by the centrifugal] force. But it 100 was rejected because it requires a propulsion system and precise navigation and maneuvering throughout the mission lifetime. The solar orbit that was selected is actually an escape orbit from Earth. Given the proper injection energy and direction from the launch vehicle, the observatory is given a push to barely escape Earth gravity, but not enough energy that it leaves Earth rapidly. After separation from the launch vehicle, the observatory does not require any propulsion for targeting and maneuvering, thus eliminating the need for a propulsion system on board, and a navigation learn before and during flight operations.

Figure 1 gives a view of the solar orbit from the ecliptic pole. Earth is fixed at the origin of this rotating coordinate system, and the Sun is at 150-million kilometers along the negative x-axis. The observatory is about 0.32 AU from the Earth at the end of a 2 1/2-year mission. The loops in the figure are a result of the eccentricity of the solar orbit. At aphelion, the observatory is moving away because it is moving slower than the Earth, and vice versa at perihelion.

Launch Vehicle

Because of performance and cost considerations, the observatory will be launched by a Delta II vehicle, 'There are two versions of the Delta II that are suitable for SIRTF. The 7920 is a two-stage vehicle with nine strap-on solid boosters. The 7925 is the same as the 7920 with an upper-stage for high-energy missions. The selection between the 7920 and the 7925 is essentially a trade between payload mass capability and volume. The 7925 can inject about 1200 kg into the solar orbit whereas the 7920 can inject 775 kg. On the other hand, the upper stage in the 7925 uses almost half the payload volume in the standard 9.5-ft fairing. Initial assessment indicates that the flight system can satisfy all mission requirements and stay under the mass limit of the 7920 capability. The 7925 can he a backup option with the standard 10-ft diameter fairing and adding 2 ft in length.

Unlike planetary launch opportunities, the solar orbit does not have a restriction on time of year to launch. However, the time of year to launch affects which part of the sky can be observed first. One added advantage of the solar orbit is that it does not require a parking orbit to achieve a precise escape orbit. Using a direct ascent orbit increases the payload capability of the 7920 by about 70 kg and is included in the 775-kg capability.

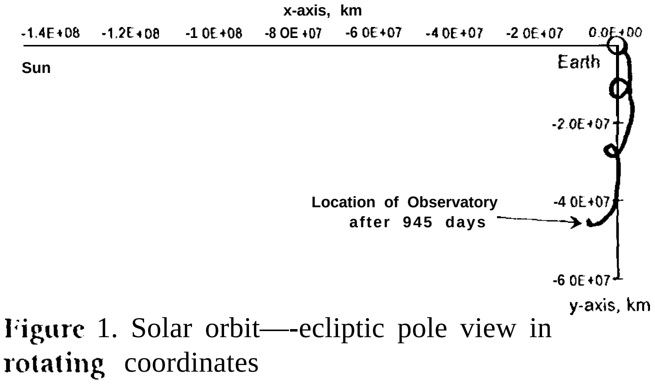

Figure 1. Solar orbit—ecliptic pole view in rotating coordinates

Command, Telemetry, and Tracking

One disadvantage of the solar orbit is that it slow] y drifts away from the Earth and therefore requires a nigh-Gain Antenna (HGA) to communicate with the Earth. A fixed HGA mounted at the bottom of the Observatory is chosen for simplicity and risk-free operations. As a result, observations must be interrupted to downlink data to Earth. The HGA antenna is supplemented by Low-Gain Antennae (LGAs) for emergency and low-rate communications.

SIRTF will use the Deep Space Network (DSN) for command, telemetry, and tracking The nominal stations to be used are the 34-m High-Efficiency (HEF) stations. The stations and the transponder provide X-band communications. Current plan for commanding is once per week using the Low-Gain Antennas at 2 kbps. Uplink can be performed during an observation as well as simultaneously with downlink. Telemetry downlink is planned once every 12 hours. The observatory supports several data transmission rates. A downlink rate of 45 kbps is used with the LGAs during the first 80 clays of the mission when continuous monitoring is required and Sun-Earth-Probe angle prevents use of the HGA. The nominal downlink rate is 2.2 Mbps. Near the end of the mission, the 70-meter DSN stations may be required to maintain the 2.2-Mbps rate. Otherwise, the downlink rate may be dropped to 1.1 Mbps. The maximum downlink rate of 2.2 Mbps is the. current limit of the DSN telemetry decoding equipment on the ground.

Unlike Earth orbital ant] interplanetary missions that require frequent tracking updates ant] precise orbit determination, the only navigation requirement for the solar orbit is to have sufficient knowledge of the Observatory location for DSN antenna pointing. Two-way Doppler provides tracking data. At X-band frequencies, acquisition of the Observatory location by the 34-m antenna requires an angular knowledge of 0.03)". Once an initial Observatory location is established, it is possible to predict several months into the mission without further tracking data.

OBSERVATORY DESIGN

SIRTF is composed of three major systems: the Cryo-Telescope Assembly (CTA), the Spacecraft (S/C), and the Science instruments (SIs). The. CTA consists of a cryostat containing a 250-liter superfluid helium tank and an instrument chamber for housing the S1s, a telescope assembly of 0.85-m aperture, and all of the thermal shields and radiators necessary to achieve the required cryogenic operating temperatures in orbit. The S/C consists of the usual subsystems for command and data handling, power generation and distribution, telecommunications, pointing control, and reaction cent rol. Three S1s comprise the payload, each consisting of a cold portion that is housed in the C-l'A, and warm electronics that are housed in the S/C. The launch mass of the Observatory is 750 kg.

Warm Launch/Cryo-Telscope Assembly

SIRTF employs an innovative architecture which differs fundamentally from the approach taken on previous cryogenic space telescopes (such as lRAS and ISO), and that offers significant size and mass reductions. The conventional approach surrounds the telescope, vapor cooled shields, superfluid helium tank, and instruments in a vacuum vessel that is launched cold. Following launch, a vacuum cover is opened to allow infrared radiation to enter the telescope. The need for a large vacuum vessel adds unnecessary weight and bulk. in the warm launch approach employed by S1l<'I'F, only the superfluid helium tank and the instruments arc contained in a vacuum vessel—the telescope, vapor cooled shields, ant] outer shell are all outside of the vacuum vessel, and arc launched warm. The resulting compact cryostat is housed beneath the telescope assembly, as shown in Figure 2.

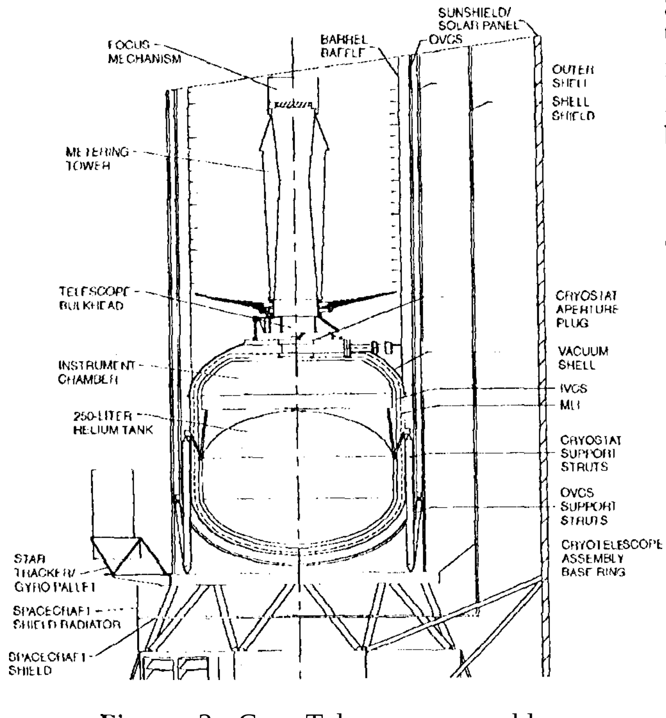

Figure 2. Cryo-Telescope assembly

Once in orbit, the telescope, outer shell and intermediate shields cool bypassive radiation to space until the outer shell reaches approximately 50 K. The CTA is shielded from the Sun by an insulated sun-shield which is covered with solar cells for power generation. After the telescope has passively cooled to 50 K, a conductive thermal link connecting it to the outer shell is opened, and the telescope is further cooled by superfluid helium vapor to an operational temperature of 5.5 K. A small vacuum cover (called the cryostat aperture plug) is then opened, admitting infrared radiation into the instrument chamber. Initial cooldown (o 50 K is expected to take about 7 clays; final cooldown of the telescope to 5.5 K may require an additional 2 weeks.

Surrounding the cryostat and the telescope is a vapor-cooled shield that contains an annular aperture radiator, and this is further surrounded by the outer shell of the Observatory. Between the sun-shield and the outer shell is an important v-shaped intermediate shield that contains a large aperture radiator. This shell-shield intercepts nearly all of the heat (30 W) that leaks through the insulation of the sun-shield, and radiates it out to space. Similarly, a shield between the cryostat and the S/C intercepts the parasitic heat from the S/C and radiates it to space.

The warm launch architecture exploits the geometry of the solar orbit, where the anti-Sun side of the observatory always views cold space-—]{ar[h is newer a heat source. The superfluid helium cryogen is thus used primarily to carry away the heat dissipated by the S1 focal planes (8 mW); parasit ic heat from the spacecraft and solar panel is intercepted and radiated to space passively. As a result, a 2.5-year mission duration is achieved using only 250 liters of cryogen, compared to 2140 liters used to achieve a 1 .5-year mission duration on 1S0.

Telescope

The proposed SIRTF telescope (shown in Figure 3) is a Ritchey-Chretien design, diffraction limited at 6.5 μm. Major advances in technology enable this 0.85-m aperture telescope to weigh less than 50 kg. Optical parameters at both cryogenic and ambient temperature are contained in 'l'able 1. An ambitious technology demonstration program was undertaken by NASA to produce an all-beryllium telescope meet ing the S1l{-l'l; requirements. The primary mirror assembly of Ibis telescope (shown in Figure 4) has hccn completed and is currently under test. The remainder

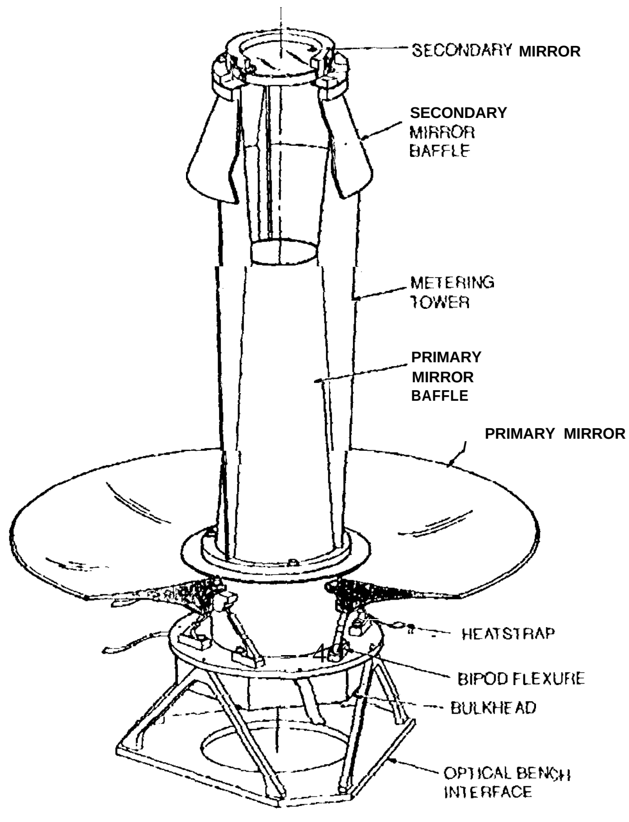

Figure 3. Telescope assembly with test optical bench interface

Table 1. Optical parameters at 5.5K and 293K

Optical Parameter Description	Cryogenic Temperature (55K)	Room Temperature (293K)
System Parameters		
Focal Length	10,200 mm	10,213.26 mm
f/#	12	12
Back focal length (PM vertex to focus)	340 mm	340.442 mm
Field of view (diameter)	320 arc min	32.0 arc min
Spectral bandpass	3 µm - 200pm	3pm -200 µm
Aperture Stop		
Location	at primary mirror	at primary mirror
Diameter of OD obscuration	850 mm	851.105 mm
Diameter of ID obscuration	320 mm	320.416 nun
Linear obscuration Radio	03765	0.3765
Primary Mirror (hyperbola)		
Radius (concave)	2040 mm	.2042.652 mm
Conic constant	1,00284	-1.00284
Clear aperture	same as aperture stop	same as aporture slop
f/#	1.2	1.2
Secondary Mirror (hyperbola)		
Radius (convex)	-274.524	-274,881
Conic constant	-1.526131	.1.526131
Clear aperture (OD)	135 mm	135.176 mm
Clear Aperture (ID)	38,846 mm	38.846 mm
PM to SM spacing	896361	897.526
Note : ΔL/L for Be is	%	

of the telescope is scheduled to be completed and tested later this year.

Spacecraft

A block diagram of the S/C is shown in Figure 4. Because the SIRTF orbit is far from Earth, a reaction control system is required to desaturate the reaction wheels used by the PCS. Gaseous nitrogen has been selected for this system, and a propellant tank is located in the center of the spacecraft bus. Reaction control thrusters are located on outriggers to maximize the available torque, and to minimize the likelihood of contamination of the cold CTA surfaces.

The surface of the sun-shield is populated with solar cells that generate 300-W average power at end-of-life. Average power usage is expected to be 250 W.

Pointing Control System

One of the more challenging requirements of the SIRTF S/C is to achieve a high performance and flexible pointing control capability with an affordable design. The Pointing Control System (PCS) provides the capability to safely and accurately point the line-of-sight of the telescope at a science target, and to either stabilize the line-of-sight or perform controlled scans across the sky. The PCS is also used to orient the high-gain antenna toward Earth for telecommunications links.

The PCS is required to point the line-of-sight of the telescope in absolute coordinates 10 an accuracy of 5-arcsec rms radial. This ensures that the desired target will fall within the field-of-view of a visible light quad cell detector located in the focal plane, or a 10-micron peak-up array, which is part of the IRS Science instrument. Once a target is found in one of these two "[targeting" arrays, a precision offset is executed to locate the target onto one of the science arrays or spectrograph slits to an accuracy of 0.4-arcsec rms radial.

Once the target has been placed onto the desired science detector, the PCS can maintain the line-of-sight of the telescope stable to 0.6-arcsec rms radial over a duration of 500 seconds. Alternatively, the line-of-sight of the telescope can be scanned across the sky at selectable rates from 2 to 20 arcsec/sec. Scanning is used primarily in conjunction with the MIPS instrument, which contains an internal scan mirror on a flyback mechanism that can "freeze frame" a scene on the science detector over short integrations (typically 5 seconds) and thereby step across the sky, imaging in a mosaic fashion.

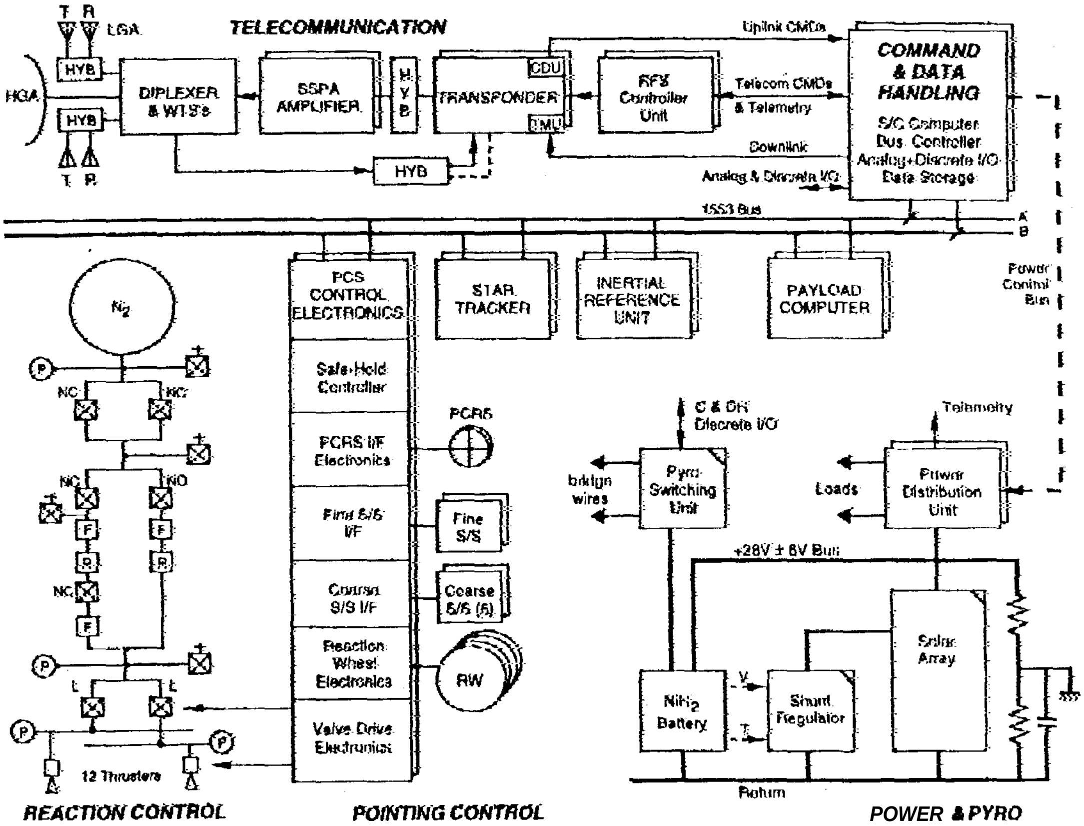

Figure 4. Spacecraft System Functional Block Diagram

SCIENCE INSTRUMENTS (S1)

SIRTF contains three science instruments, each of which is developed under the direction of a Principal Investigator (PI). The three instruments are the Infrared Array Camera (IRAC), the infrared Spectrograph (IRS), and the Multiband imaging Photometer for SIRTF (MIPS). These instruments, taken together, provide a wide variety of imaging and spectroscopic modes from 3 to 180 µm. To simplify operations and reduce overall mission costs, SIRTF is designed such that only one instrument is operated at a time.

Each instrument consists of both cryogenic sensor subassemblies and warm electronics subassemblies. These are interconnected by electrical signal cables which pass through the various insulating layers of the cryostat.

The cryogenic subassemblies share a cylindrical (21-cm-high x 42-cm-radius) instrument chamber which is located within the cryostat, as shown in Figure 2. These cryogenic subassemblies perform all optical processing of the telescope input brain ancl deliver the resulting signal to the infrared detector arrays, which produce a low-level analog output signal. For both reliability and cost reasons the number of mechanisms in the cryogenic instrument subassemblies has been kept to a minimum (two).

The instrument warm electronics subassemblies provide all the necessary electronic housekeeping for detector operation and readout, including bias voltage and clock generation, analog-to-digital conversion, compression, formatting, and presentation to the spacecraft for storage and subsequent transmission to Earth. Cost, mass, and power savings are achieved by appropriate sharing of general-purpose computing, power conditioning, ancl other electronic functions among the instruments. Instrument warm electronics modules are located within the S/C. bus .

In each instrument the most critical performance-determining components are the infrared detectors ancl their associated cryogenic readout circuits. Each instrument team has successfully conducted a detector and readout development which has drawn on a variety of industrial, academic, and governmental organizations. in all cases, SIRTF flight instrument detectors have a long technology development pedigree and represent the state-of-the-art in infrared detector technology.

The operating temperature of both the detectors ancl the telescope place unique demands on the cryogenic system. As the wavelength of operation increases, required operating temperature decreases. At the shorter infrared wavelengths the InSb array detectors must operate at approximately 15 K. The mid-infrared band Si:As and Si:Sb Blocked impurity Band (BIB) array detectors require approximately 5 K and 3 K, respectively, and the far-infrared stressed Germanium photoconductor array detectors require the lowest operating temperature—approximately 1.4 K. Somewhat higher maximum allowable telescope temperatures are permitted in each case ranging from 100 K to 5.5 K.

The instruments access the focal plane of the SIRTF telescope through individual flat "pickoff" mirrors, whose positions are fixed in the shared telescope field of view. The. fields of view of the various instrument apertures projected onto the sky are shown in Figure 5. Only a subset of these fields is active at any time, depending on the selected instrument and the operating mode of that instrument as described below. Also shown in Figure 5 are Pointing Calibration Reference Sensors (PCRS), which are used to coalign the instrument with the star tracker.

IRAC Description

The Infrared Array Camera (IRAC) is a four-channel imager packaged in a single module. Simultaneous wide-field images at 3.5, 4.5, 6.3 and 8.0 μm are possible with 25% bandwidth at each wavelength. Two adjacent fields of view in the SIRTF focal plane support the four channels in pairs as shown in Figure 5.

Light enters the instrument via two pickoff mirrors which feed similar channels, each consisting of a

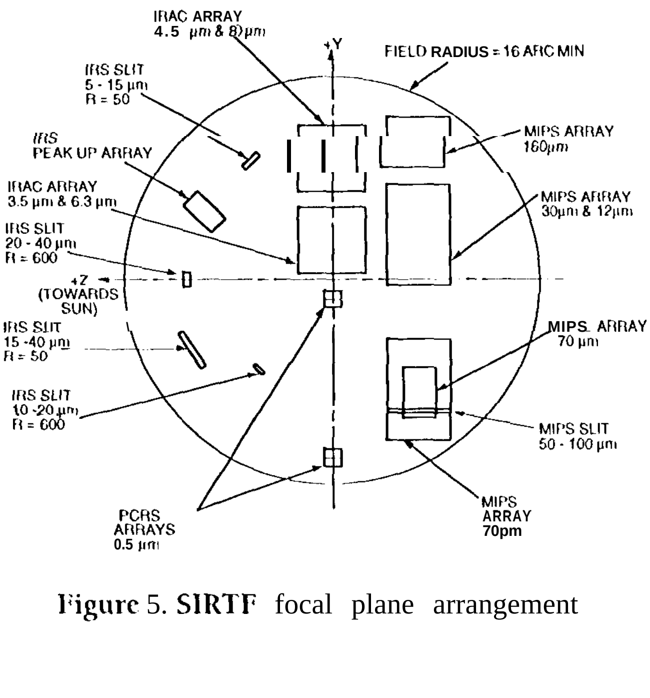

Figure 5. SIRTF focal plane arrangement

beam splitter and a pair of lenses and fold mirrors. Light shortward of 5 μm reflects off the beam splitters and is focused on the InSb arrays; light longward of 5μm passes through the beam splitters and is brought into focus on the Si:As BIB arrays. Filters in front of each array determine the central wavelength and bandwidth of each channel.

The IRAC occupies an approximately 30-degree sector of the instrument chamber volume. Key to the compact packaging is the use of silicon asphere refractive optics. The focal plane parameters and projected performance of the IRAC are shown in Table 2.

IRS Description

The IRS is comprised of four separate cold optical assemblies or "modules" which are independent of each other both optically ant] mechanically. Two of the modules produce one-dimensional, low-resolution spectra with a one-dimensional image along the slit. The other two produce two-dimensional echelle-format moclerate-resolution spectra with 7 to 10 spectral orders on the array. A portion of one of the low-resolution short-wavelength modules is used to produce 10-mm "peak up" images to aid in identifying sources and to help calibrate the Observatory pointing system.

The optical design of each module is optimized to achieve simplicity and ease of fabrication, integration and test. A typical module consists of a slit, a fold mirror, a collimator, a grating, an echelle (for high-resolution modules only), a camera, and an array. '1'here are also stimulators to provide health checks for the array ant] to monitor transmission of the optical train. Each module contains one infrared detector array, with either an arsenic-c] oped silicon (Si:As) blocked impurity band detector (BIB) or an antimony-doped silicon (Si:Sb) BIB detector. All four assemblies are packaged into slightly less than a 180-degree wedge of the instrument chamber volume. The focal plane parameters and projected performance of the IRS are shown in '1'able 3.

MIPS Description

The MIPS instrument comprises a single cold optical assembly which contains five distinct optical trains that can be operated in one of three data gathering modes: 1) image in three bands simultaneously, 2) Image with high magnification at 70 μm, low-resolution spectroscopy from 50 to 100 μm. A single axis scan mechanism is included to modulate the signal on the Germanium detectors to provide good photometric performance, and to select among the three instrument operating modes.

The instrument utilizes a Si:Sb array of identical design to that in the IRS. in addition, two gallium-doped germanium (Ge:Ga) arrays are used, one with 32 X 32 pixels that respond up to 120 μm, and the other with 2X20 pixels, each subjected to a mechanical stress to extend its photo conductive response 10180 μm. The cold assembly is packaged into a 90-degree wedge of the instrument chamber volume. The focal plane parameters and projected performance for MIPS are summarized in Table 4.

ACKNOWLEDGMENTS

The "warm launch" architecture for cryogenic space telescopes was developed by Dr. F. J. Low (University of Arizona), and his contributions to the SIR-I F concept arc gratefully acknowledged . The work described in this paper was carried out at the Jet l'repulsion Laboratory, California institute of "1'ethnology, under an agreement with the National Aeronautics and Space Administration.

Table 2. Projected IRAC Performance

Band (]1,11)	Detector Type	Detector Format (pixels)	Spectral Resolution (λ/ λ)	Field of View (arcmin)	Pixel Size (arcsec)	Sensitivity 500s/50 (μJy)
3.5	InSb	256 X 256	4	5,1 X5.1	1.2	2.6
4.5	InSb	256 x 256	4	5.1 X5,1	1.2	3.3
6.3	Si:As (BIB)	256 x 256	4	5,1 X5.1	1.2	18.1
8.0	Si:As (BIB)	256 x 256	4	5.1 X5.1	1.2	30,9

Table 3. Projected IRS Performance*

Module	Band pm	Detector Type	Detector Formal (pixels)	Spectral Resolution (λ/ λ)	Slit Size (pixels) d	x-d	Pixel Size (arcsec)	Sensitivity 500s/50 (μJy)
Short 1.0'	5-7.5	Si:As(BIB)	128 x 128	***50***	***2***	***30***	1.8	***100*** μJy
	7.5-15			***50***	***2***	***30***	1.8	***550*** μJy
	10(pcak up)			2	32	***30***	1.8	$3x10^{-18}W/m^2$
1 ong-1.o[1]	14-21	Si:Sb(BIB)	128X128	***50***	***2***	***30***	***4.8***	***1500*** μJy
	21-40			***50***	***2***	***30***	4.8	1500 μJy
Short Hi	10-19.5	Si:As(BIB)	128X 128	600	2	5	2.4	3x10"'VWI11)2
Long Hi	19.5-38	Si:Sb(BIB)	128X128	***600***	2	5	4.8	$3x10^{-18}W/m^2$

* The required image quality is achieved only over 32 by 30 pixels. A FOV of up to 3' x 1.5' may be possible with reduced image quality.

[1] The grating operates in more than one order with order-sorting filters. The slit lengths shown arc pcr order: d: dispersion direction (slit width); x-d: cross-dispersion direction (slit length). It is likely that the exact FOV of the peak-up, and the slit length of the 10 modules, will change somewhat as the optical design is further developed.

Table 4. Projected MI I'S Performance

Operating Mode	Band (pm)	Detector Type	Detector Format (pixels)	Spectral Resolution (λ/ λ)	Field of View (arcmin)	Pixel Size (arcsec)	Sensitivity 500s/5σ (μJy)
1	12	Si:Sb(BIB)	13x128	4	***0.5 x 5.3***	***2.4"***	100
	30	Si:Sb(BIB)	110 x 128	4	4.1 X5.3	2.4"	150
	70	Ge:Ga	32 x 32	4	5.3 x 5.3	9.4"	530
	160	Ge:Ga (stressed)	2X20	4	0.5 x 5	15"	7500
2	***70***	Ge:Ga	32 x 32	4	2.6 x 2.6	5"	870
3	**50-100**	Ge:Ga	32 x 32	20	0.3' x 5.4"	9.4"	3500

SPIE

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SIRTF Project, Jet Propulsion Laboratory, California Institute of Technology
Pasadena, California 91109

ABSTRACT

The Space Infrared Telescope Facility (SIRTF) will explore the birth and evolution of the Universe with unprecedented sensitivity. SIRTF will be the first mission to combine the high sensitivity achievable from a cryogenic space telescope with the imaging and spectroscopic power of the new generation of infrared detector arrays. The scientific capabilities of this combination are so great that SIRTF was designated the highest priority major mission for all of US astronomy in the 1990s.

The astronomical community will use SIRTF to explore the infrared universe with a depth and precision complementary to that achieved by NASA's other Great Observatories—the Hubble Space Telescope 01 ST), the Advanced X-ray Astrophysics Facility (AXAF), and the Compton Gamma Ray Obsm'story (GRO) in their respective spectral bands. The launch of SIRTF in 2001 will permit contemporaneous observations with 1 lS"l' to study forefront problems of astrophysics,

This paper provides a comprehensive review of the S1l<-l'}' program-- the science, the mission design, the facility, the instruments, and the implementation approach. Emphasis will be placed on those features of the program—including the use of a solar (heliocentric) orbit and the adoption of a novel warm-launch cryogenic architecture—which will allow us to realize the great scientific potential of SIRTF in a resource-constrained environment.

INTRODUCTION

SIRTF has been recognized as a key element in the NASA astrophysics program for over a decade. The observatory has been restructured and redefined to be consistent with the new NASA paradigm of *faster/better/cheaper*. Innovations have played a major role in defining the new SIRTF. The science focus is sharply defined, the mission implementation uses a unique solar orbit, the Observatory bas adopted a unique architecture, the science instruments use state-of-the-art in frared arrays, and finally, an implementation approach is being employed which creates a partnership between J]']. and industry .

in the fall of 1993, NASA was under great pressure to change the way large projects were conducted. in particular, costs hacl to be reduced and development times hat] to be shortened. in this environment SIRTF was redefined, resulting in the current concept, which provides a substantial part of the originally envisioned scientific capability at a fraction of the cost.

The scientific capabilities of SIRTF have been guided for over a decade by a Science Working Group (SWG) selected in 1984. The SWG reassessed SIRTF's scientific capabilities in the light of the pressure to reduce the mission scope and decided to rebuild SIRTF's scientific requirements around the needs of four specific science programs: Brown Dwarfs and Superplanets, The Early Universe, Protoplanetary and Planetary Debris Disks, ant] Ultraluminous Galaxies and Active Galactic Nuclei. These four areas were singled out as of particular importance for S1l{-l'l' by the National Academy of Science's decadal review (the Bahcall Report), which in 1990 designated SIRTF as the highest priority major new mission for US astronomy.

The mission objectives of examining as efficiently as possible the infrared sky led to the adoption of an innovative solar orbit for SIRTF. The observatory will be launched on a Delta launch vehicle, and will be placed in an Earth-trailing orbit. This orbit eliminates viewing restrictions due to Earth occultations, reduces thermal heat loads associated with proximity to the Earth, and simplifies operations by having the Observatory in a slowly changing

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location that accommodates flexible scheduling for commanding and for data transmission. Data from SIRTF will be processed and disseminated to the science community using the Infrared Processing and Analysis Center (lI'AC) located on the campus of Caltech.

The architecture of the observatory is substantially different from that used in previous infrared missions. The telescope will be launched warm and cooled on-orbit, in large part by radiation to space. This architecture enables the launch of a large-aperture (0.85-meter) telescope in a very lightweight implementation. Using radiative cooling significantly reduces the quantity of cryogen needed over a 2,5-year mission life. The resulting mass reduction is essential to using a Delta class launch vehicle. The Observatory will provide a 1.4 K helium bath environment for the science instruments. Two hundred and fifty liters of helium will be used to provide the environment for the instruments, and the helium boil-off will be used to reduce the telescope temperature from the 50 K that radiative cooling would provide to the 5.5 K required to make the longest wavelength background-limited observations. A major challenge for the Observatory will bc the provision of a pointing control system (PCS) that has pointing accuracy of a few arcsec and stability of a fraction of an arcsec over long periods.

SIRTF will employ three instruments for the collection of scientific data. The Infrared Array Camera (IRAC) will provide imaging at 4 wavelengths between 3 and 8 µm. The Infrared Spectrograph (IRS) will provide both low- and high-resolution spectra between 5 and 40 pm, and the Multiband imaging Photometer for SIRTF (MIPS) will provide long wavelength imaging between 12 ancl 180 µm. Each instrument will employ slate-of-the-arl detector arrays representing improvements of several orders of magnitude over previous infrared sensors used in space astronomy missions.

S1l<"l'l' will use a unique implementation approach that includes a teaming arrangement between JPL, industry and the science community. The observatory will be built by industry based upon a design developed jointly with JPL and the science community. Once selected by a competitive process, industry team members will become part of the S1l{"l'l' team, and will work together to meet project commitments. The project must be accomplished within a fixed budget, which will require an unprecedented degree of cooperation. 10 conserve resources, the plan is to accomplish the majority of the work in a short period of time to minimize time-related costs. Clear responsibilities will be established to minimize redundant or overlapping efforts. The result is expected to be a demonstration of how, using the new paradigm of *faster/better/cheaper*, NASA can continue to conduct significant scientific missions using state-of-the-art technology with uncompromised performance.

SCIENCE OBJECTIVES

The kcy scientific questions posed by SIRTF's four defining science programs include the following:

Brown Dwarfs and Superplanets

The presence of "missing mass" or "darkmatter"—which is unseen but which makes its presence felt by its gravitation] effect on stars and gas—is a persistent and puzzling feature of astrophysical systems. In our Galaxy, for example, there is strong evidence for a spherical halo of dark matter which contains -90% of the mass of the Galaxy but has not been identified by direct observation in any of the many spectral channels available to modern astrophysics. One as yet untested possibility is that a substantial component of this dark matter is in the form of "brown dwarfs"—objects with masses less than -0.08 Me—which are too low in mass to generate the high central temperatures and pressures required to trigger the nuclear fusion reactions which power stars. Brown dwarfs, while much cooler and less luminous than stars, should glow faintly in the infrared as the internal heat generated in their formation diffuses. sl]<~'~—operating in a survey mode--will be able to detect brown dwarfs if they are common enough to constitute a significant fraction of the dark matter in the solar neighborhood.

The quest for solar systems outside our own is part of the fundamental motivation for astronomical exploration. The recent detection by radial velocity measurements of Jupiter-sized companions to three nearby solar--type stars indicates that many types of planetary systems will be found, and SIRTF will play a crucial role in continuing this search. The reason for this is that Jupiter is also a brown dwarf, because it has a substantial internal energy source and actually radiates to space several times more heat than it absorbs from the Sun. Larger planets radiate proportionately greater amounts of power, and SIRTF can detect the infrared emission from planets just a few times more massive than Jupiter if they are orbiting the nearest stars.

The Early Universe

SIRTF is a time machine which allows us to explore the distant past. The expansion of the Universe means that more distant objects are moving away at higher velocities, and the finite speed of light implies that we see more distant objects as they were at earlier times. Finally, the visible and ultraviolet radiation from a receding object is shifted into the infrared by the familiar Doppler effect. As a result of this "redshift," infrared observations can probe the past by studying starlight from very distant-— and very young,-—galaxies. SIRTF will be used to carry out an ultra-deep survey of a small region of the sky with the aim of detecting galaxies as they appeared when the Universe was about one-tenth of its present age. The observations will be carried out simultaneously at several near-infrarecl wavelengths to gather information on the galaxies' spectra which will permit a determination of their distances and hence their true luminosities. This survey will provide critical tests of our models of the formation and evolution of galaxies.

This area is one of many in which SIRTF's scientific programs could overlap those of the other Great Observatories, particularly 11S1' and AXAF. In this case, the recently completed HST deep-field survey contains many distant galaxies which would appear in SIRTF's deep images of the same field. Comparing infrared [SIRTF] and visible [11S"1"] data on these galaxies would provide important insights into galaxy evolution and would establish a context for the interpretation of the data on more distant galaxies which might be seen only by SIRTF.

Protoplanetary and Planetary Debris Disks

Infrared observations are particularly important for the study of the earliest phases of star and planet formation. It is believed that the formation of stars and planetary systems begins with minor density enhancements in the interstellar medium and accelerates through successive stages of collapse and fragmentation, ending with the emergence of a newly -formed star out of the cocoon of dust and gas within which it was born. This condensation and collapse occurs within dense clouds which are impenetrable to optical and ultraviolet radiation, but can be penetrated by infrared observations. In addition, particularly in the earliest stages of collapse, the. protostellar material is at such low temperatures that it radiates only in the infrared. S1l<-l-l' will be able to study protostars and their environments at all evolutionary stages, and SIRTF's large arrays will enable rapid surveys of large star-forming regions to provide an unbiased assessment of the number and properties of the newly forming stars. Of particular importance will be searches for evidence of circumstellar disks within which planets may be forming. These will produce characteristic signatures discernible. in the complete spectral energy distributions obtainable with SIRTF's wide wavelength coverage.

Even when the process of planetary formation is completed, it may leave behind a persistent residue in the form of a tenuous planetary debris disk which is replenished by continued collisions among cometary- and asteroid-sized objects. The discovery of such solar system-sized debris disks—visible by their infrared radiation—around nearby solar-type stars was one of the principal accomplishments of SIRTF's predecessor mission, IRAS. S1l{-l'l; ean study these systems in detail, providing images which may delineate the central, dust-free regions inferred from IRAS' observations. It has been suggested that these central voids signal the presence of planetary bodies which may be sweeping up the interplanetary dust. SIRTF can also explore the possible connection between these debris disks around nearby stars and the. structure in our own solar system exterior to the orbit of Neptune, which is known as the Kuiper Belt, the reservoir of short-period comets. SIRTF's spectrographs will compare the composition of the dust in extra-solar debris disks with that of the dust in newly appearing Kuiper Belt comets. The amount of dust to be found in the Kuiper Belt appears to be orders of magnitude less than is associate] with the most prominent debris disks found by IRAS, but SIRTF will have the sensitivity to image a disk orbiting the nearest solar-type stars, even if it is as tenuous as the Kuiper Belt.

Ultraluminous Galaxies and Active Galactic **Nuclei**

Understanding Active Galactic Nuclei (AGN) has been a major thrust of modern astrophysics for more than 3 decades. AGNs—quasars and Seyfert galaxies—arc very compact, very luminous, and contain highly excited gas which exhibits high velocity motions. Infrared luminous AGN have been known since the early 1970s, and it was shown at that time that many AGN emitted the bulk of their luminosity at infrared wavelengths. The IRAS data broadened this picture by showing that far infrared-emitting galaxies are the dominant population of high-] uminosity extragalactic sources in the local Universe, more numerous and more luminous than quasars in the same region. These objects test our physical understanding because their high luminosities cannot be sustained by the normal processes of stellar energy generation. It is generally thought that AGN are powered by the gravitational energy released as matter accretes onto massive blackholes, but many details of this picture remain uncertain.

SIRTF will be a unique observatory to explore infrared luminous galaxies over 90% of the age of the universe, and will clarify the relation of these systems to AGN discovered via other techniques, as well as addressing the deeper question of the relation of AGN to the evolution of galaxies in general. With SIRTF, the deep surveys that will be undertaken will provide large databases of targets for detailed studies as well as for statistical analyses of the evolution of infrared bright galaxies. The multiwavelength aspect of these surveys will provide a powerful way to select the most distant and luminous infrared bright galaxies for further study by SIRTF. The spectroscopic capability of SIRTF will permit the determination of redshifts, and hence the luminosities of the most extreme systems discovered. The SIRTF spectrograph will, in addition, be able to probe the centers of dust-enshrouded nuclei, ant] thereby determine the nature of the excitation of these systems and their underlying power sources. Because SIRTF can detect these objects at truly cosmological distances, these investigations will explore not only the character of the in frared luminous galaxies but also the early history of the Universe.,

Some of SIRTF's possible contributions to the study of the four science themes chosen to define the mission requirements have been described. in Figure 1, we compare the expected sensitivity of SIRTF with the predicted brightness of a group of targets representative of the four themes. Of course, a mission optimized for these four themes will have broad applicability to a much wider range of astrophysical investigations, and the mix of science (o be carried out from SIRTF will be defined closer to launch by a peer-reviewed selection of investigations. These will certianly include programs stimulated by the scientific results from the European Space Agency's recently launched Infrared Space observatory (ISO) mission. In addition to its great power for the study of known scientific problems such as those defined above, SIRTF's great gain in observational capabilities gives this mission very high potential for unexpected discoveries.

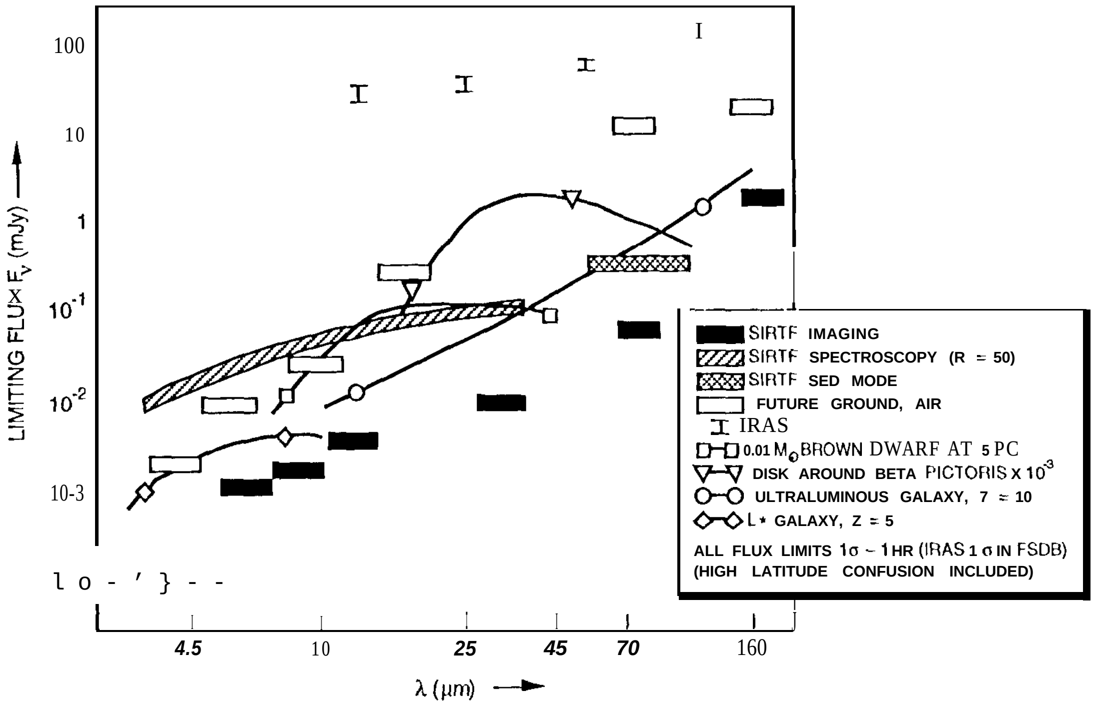


Figure 1. Sensitivity of SIRTF, of future ground-based and airborne infrared telescopes-ancl of the IRAS survey—compared to the brightness of typical SIRTF targets. Except for IRAS, where the results from Faint Source Survey arc given, the plotted sensitivities arc one-sigma after one hour of in tegrat ion.

Orbit Selection

SIRTF requires an orbit that is far from the Earth's thermal and radiation environment. A solar orbit was chosen among three options. A circular high-Earth orbit (HEO) with an altitude of 100,000 km would place the observatory beyond the trapped radiation environment, but this option was rejected because of the high energy required to circularize the transfer orbit from low-Earth altitude. The L2 libration point is also ideally suited for astronomical observations. It is a dynamic equilibrium point about 1.5-million kilometers from Earth along the Sun-Earth line where the Sun-Earth gravity is balanced by the centrifugal force. But it too was rejected because it requires a propulsion system and precise navigation and maneuvering throughout the mission lifetime. The solar orbit that was selected is actually an escape orbit from Earth. Given the proper injection energy and direction from the launch vehicle, the Observatory is given a push to barely escape Earth gravity, but not enough energy that it leaves Earth rapidly. After separation from the launch vehicle, the observatory does not require any propulsion for targeting and maneuvering, thus eliminating the need for a propulsion system on board, and a navigation team before and during flight operations.

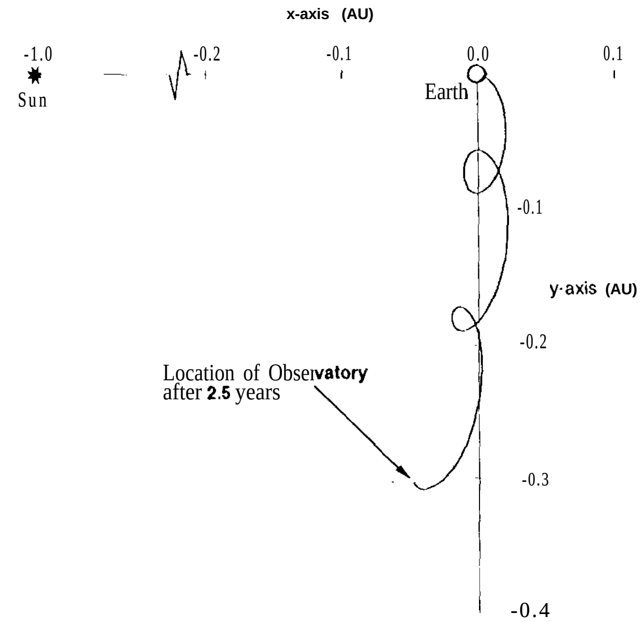
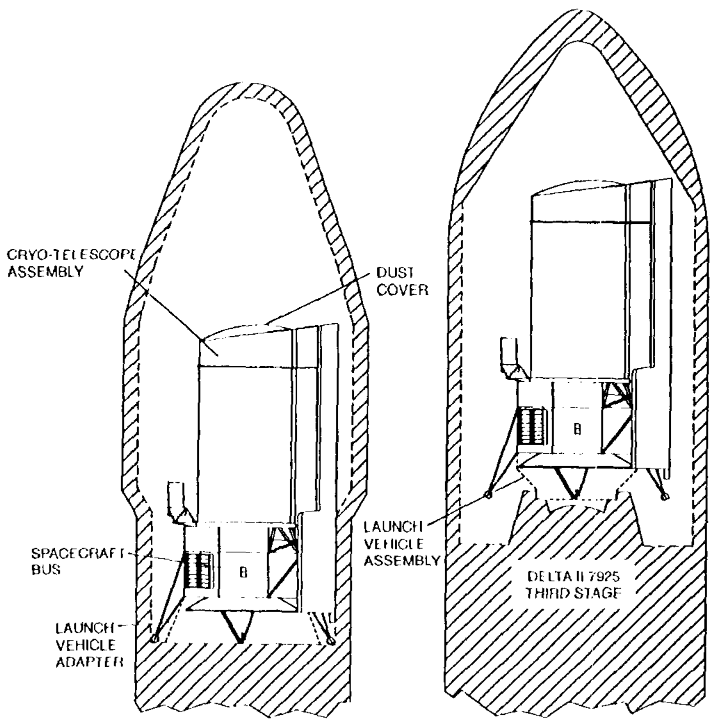


Figure 2. Solar orbit-ecliptic pole view in rotating coordinates

Figure 2 gives a view of the solar orbit from the ecliptic pole. Earth is fixed at the origin of this rotating coordinate system, and the Sun is at 150-million kilometers along the negative x-axis. The observatory is about 0.32 AU from the Earth at the end of a 2.5-year mission. The loops in the figure are a result of the eccentricity of the solar orbit. At aphelion, the observatory is moving away because it is moving slower than the Earth, and vice versa at perihelion.

Launch Vehicle

Because of performance and cost considerations, the Observatory will be launched by a Delta 11 vehicle (Figure 3). There are two versions of the Delta 11 that are suitable for SIRTF. The 7920 is a two-stage vehicle with nine strap-on solid boosters. Tbc 7925 is the same as the 7920 with an upper-stage for high-energy missions. The selection between the 7920 and the 7925 is essentially a trade between payload mass capability and volume. The 7925 can inject about 1200 kg into the solar orbit whereas the 7920 can inject 775 kg. On the other hand, the upper stage in the 7925 uses almost half the payload volume in the standard 9.5-ft fairing. Initial assessment indicates that the flight system can satisfy all mission requirements and stay under the mass limit of the 7920. The 7925 can be a backup option with the standard 10-ft diameter fairing and an additional 2 ft of length.



DELTA II 7920 9.5 FT FAIRING

DELTA II 7925 10 FT STRETCHED COMPOSITE FAIRING

Figure 3. Launch configurations

Unlike planetary launch opportunities, the solar orbit does not have a restriction on time of year to launch. However, the time of year of launch affects which part of the sky can be observed first. One added advantage of the solar orbit is that it does not require a parking orbit to achieve a precise escape orbit. Using a direct ascent orbit increases the payload capability of the 7920 by about 70 kg and is included in the 775-kg capability.

Command, Telemetry, and Tracking

One disadvantage of the solar orbit is that it slowly drifts away from the Earth and therefore requires a High-Gain Antenna (HGA) to communicate with the Earth. A fixed HGA mounted at the bottom of the Observatory is chosen for simplicity and risk-free operations. As a result, observations must be interrupted to downlink data to Earth. The HGA antenna is supplemented by Low-Gain Antennae (LGAs) for emergency and low-rate communications.

SIRTF will use the Deep Space Network (DSN) for command, telemetry, and tracking. The nominal stations to be used are the 34-m High-Efficiency (HEF) stations. The stations and the transponder provide X-band communications. Current plan for commanding is once per week using the low-Gain Antennas at 2 kbps. Uplink can be performed during an observation as well as simultaneously with downlink. Telemetry downlink is planned once every 12 hours. The Observatory supports several data transmission rates. A downlink rate of 45 kbps is used with the LGAs during the first 80 days of the mission when continuous monitoring is required and Sun-Earth-Observatory angle prevents use of the HGA. The nominal downlink rate throughout the rest of the mission is 2.2 Mbps. Near the end of the mission, the 70-meter DSN stations may be required to maintain the 2.2-Mbps rate. Otherwise, the downlink rate may be dropped to 1.1 Mbps. The maximum downlink rate of 2.2 Mbps is the current limit of the DSN telemetry decoding equipment on the ground.

Unlike Earth orbital and interplanetary missions that require frequent tracking updates and precise orbit determination, the only navigation requirement for the solar orbit is to have sufficient knowledge of the Observatory location for DSN antenna pointing. Two-way Doppler provides tracking data. At X-band frequencies, acquisition of the Observatory location by the 34-m antenna requires an angular knowledge of 0.03 deg. Once an initial Observatory location is established, it is possible to predict several months into the mission without further tracking data.

Flight and Ground Trades

The current SIRTF design is only a concept that demonstrates feasibility within a cost target. The actual design awaits the selection of industry team members. The solar orbit provides a flight environment that is conclusive to simple design and operations. However, there are still many flight and ground trade studies to be performed. The aperture shade and solar panel sizing directly affect the availability of viewing regions. The amount of on-board memory affects the demand and schedules of the DSN stations. The design of the flight data systems affects the complexity of the ground sequencing and command generation processes. The use of Consultative Committee on Space Data Systems standards and the definition of the telemetry packets affects the data reduction processes. The design of the pointing control system affects observation planning and pointing reconstruction. The instrument operating modes affects the flight data system, flight software, the pointing control system, and the data reduction and analysis process. With the solar orbit and its quiescent environment, fault protection and safing should be much easier but still require careful consideration. The demanding cryogenic performance of the telescope and the instruments requires ground and flight calibration and verification.

One innovative concept requires further investigation. It is called "event driven sequencing." SIRTF in a solar orbit is ideally suited to implement event driven sequencing. Spacecraft activities are generally performed relative to an absolute timing based on the spacecraft clock. The concept of event driven sequencing is to let the successful or failed execution of a scheduled event decide what the next event should be. For instance, if a scheduled observation cannot be completed due to the inability of the star tracker to lock on to a guidestar, the on-board flight computer would move up the next observation without waiting for the scheduled amount of time to clock out. The technique would also allow operations, such as large Observatory slews and star acquisitions, to take their natural time instead of having to be accurately modeled in advance in the command sequence. Another area to be explored is whether SIRTF would benefit from utilizing one of the emerging standards for command logic such as Spacecraft Command Language, System Test and Operations Language, or the adaptation of Manufacturing Messaging System.

0BSERVAT0R% DESIGN

S11<l'1' is composed of three major systems: the Cryo-Telescope Assembly (CTA), the Spacecraft (S/C), and the Science Instruments (S1s). The CTA consists of a cryostat containing a 250-liter superfluid helium tank and an instrument chamber for housing the S1s, a telescope assembly of 0.85-m aperture, and all of the thermal shields and radiators necessary to achieve the required cryogenic operating temperatures in orbit. The S/C consists of the usual subsystems for command and data handling, power generation and distribution, telecommunications, pointing control, and reaction control. The launch mass of the Observatory is 750 kg.

Warm Launch/Cryo-Telescope Assembly

S11<-l'l; employs an innovative architecture which differs fundamentally from the approach taken on previous cryogenic space telescopes (such as (he Infrared Astronomy Satellite (IRAS) and the Infrared Space observatory (1 S0)), and that offers significant{ size and mass reductions The conventional approach encloses the telescope, vapor cooled shields, superfluid helium tank, and instruments in a vacuum vessel that is launched cold. Following launch, a vacuum cover is opened to allow infrared radiation to enter the telescope. The need for a large vacuum vessel adds unnecessary weight and bulk. In the warm launch approach employed by S11<'1'1', only the superfluid helium tank and the instruments are contained in a vacuum vessel—the telescope, vapor cooled shields, and outer shell are all outside of the vacuum vessel, and arc launched warm. The CTA is shielded from the Sun by an insulated sun- shield which is covered with solar cells for power generation. The resulting compact cryostat is housed beneath the telescope assembly, as shown in Figure 4.

Once in orbit, the telescope, outer shell and intermediate shields cool by passive radiation to space until the outer shell reaches approximately 50 K. After the telescope has passively cooled to 50 K, a conductive thermal link connecting it to the outer shell is opened, and the telescope is further cooled by superfluid helium vapor to an operational temperature of 5.5 K. A small vacuum cover (called the cryostat aperture plug) is [hen opened, admitting infrared radiation into the instrument chamber. Initial cooldown to 50 K is expected to take about 7 days; final cooldown of the telescope to 5.5 K may require an additional 2 weeks.

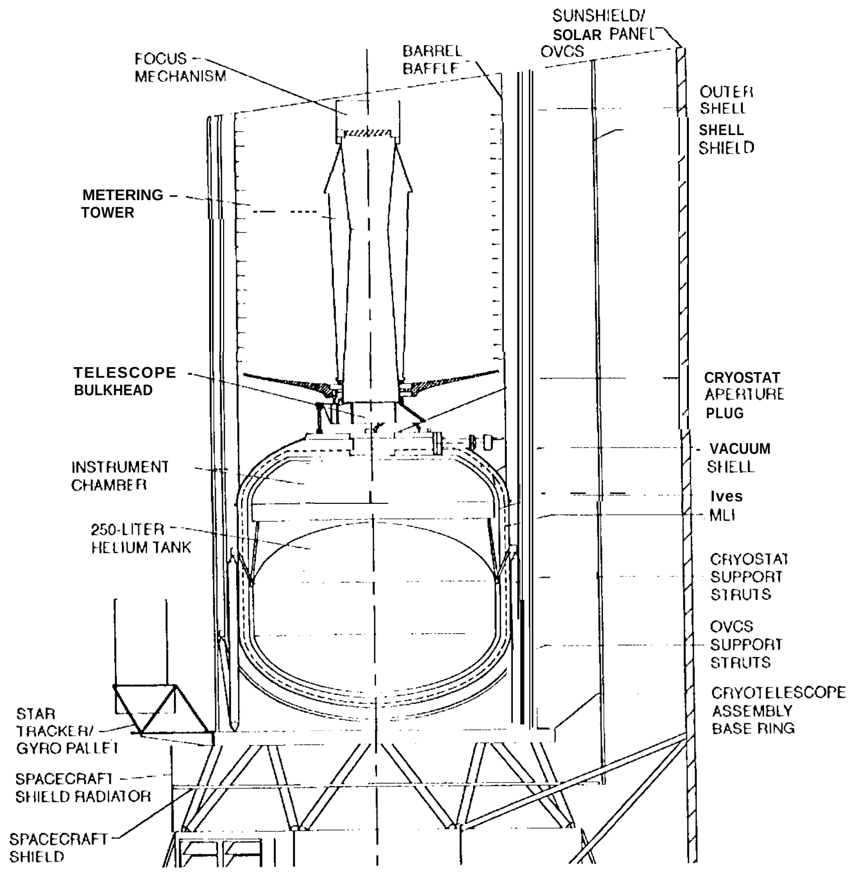


Figure 4. Cryogenic telescope assembly

Surrounding the cryostat and the telescope is a vapor-cooled shield that contains an annular aperture radiator, and this is further surrounded by the outer ashen of the observatory. Between the sun-shield and the outer shell is an important v-shaped intermediate shield that contains a large aperture radiator. This shell-shield intercepts nearly all of the heat (30 W) that leaks through the insulation of the sun-shield, and radiates it out to space. Similarly, a shield between the cryostat and the S/C intercepts the parasitic heat from the S/C ant] radiates it to space.

The warm launch architecture exploits the geometry of the solar orbit, where the anti-Sun side of the Observatory always views cold space-] :arth is never a heat

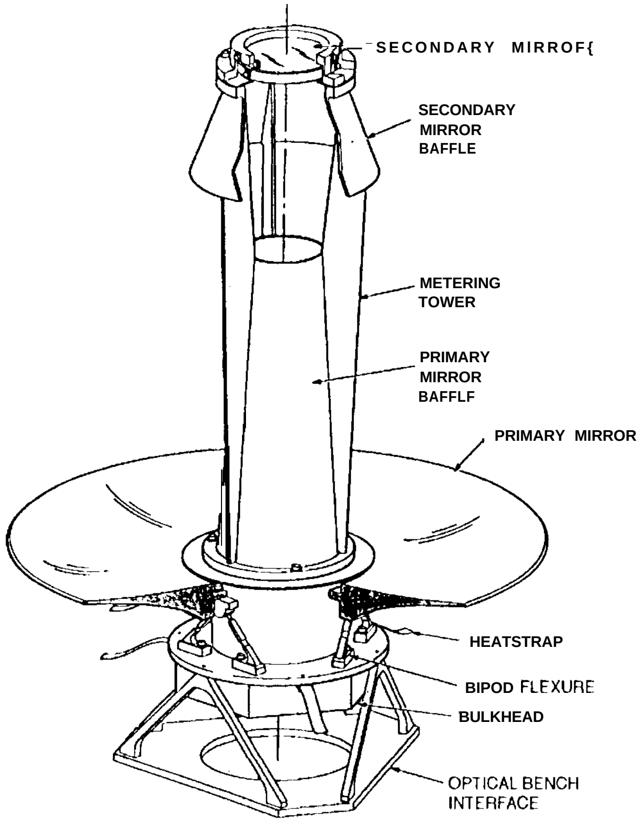


Figure 5. Telescope assembly with test optical bench interface

Table 1. Optical parameters at 5.5K and 293K

Optical Parameter Description	Cryogenic Temperature (5.5K)	Room Temperature (293K)
System Parameters		
Focal Length	10,20Q mm	10,213.26 mm
f/#	12	12
Back focal length (PM vertex to focus)	340 mm	340442 mm
Field of view (diameter)	3?.0 arc min	32.0 arc min
Spectral bandpass	3 μm -200 μm	3pm -200 μm
Aperture Stop		
Location	at primary mirror	at primary mirror
Diameter 01 OD obscuration	850 mm	851.105 mm
Diameter ol ID obscuration	320 mm	320.416 mm
Linear obscuration Ratio	0.3765	0,3765
Primary Mirror **(hyperbola)**		
Radius (concave)	-2040 mm	-2042.652 mm
Conic constant	.1.00284	-1 ,00?84
Clear aperture	same as aperture slop	same as aperture slop
f/#	1.2	1.2
Secondary Mirror (hyperbola)		
Radius (convex)	-274.524	-274,881
Conic constant	-1.526131	-1.526131
Clear aperture (OD)	135 mm	135,176 mm
Clear Aperture (ID)	38.846 mm	38.846 mm
PM 10 SM spacing	896361	897.526
Note : ΔL/L for Be is C	%	

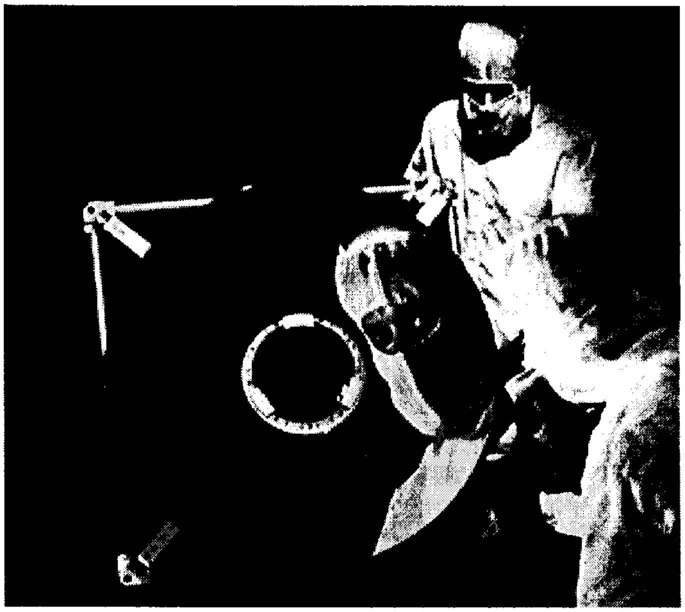


Figure 6. Primary mirror assembly

source. The superfluid helium cryogen is thus used primarily to carry away the heat dissipated by the S1 focal planes (8 mW); parasitic heat from the spacecraft and solar panel is intercepted and radiated to space passively. As a result, a 2.5-year mission duration is achieved using only 250 liters of cryogen, compared to 2140 liters used to achieve a 1.5-year mission duration on 1S0.

Telescope

The proposed SIRTF telescope (shown in Figure 5) is a Ritchey-Chretien design, diffraction limited at 6.5 μm. Major advances in technology enable this 0.85-m aperture telescope to weigh less than 50 kg. Optical parameters at both cryogenic and ambient temperature are contained in "Table 1. An ambitious technology demonstration program was undertaken by NASA to produce an all-beryllium telescope meeting the SIRTF requirements. The primary mirror assembly of this telescope (shown in Figure 6) has been completed ancl is currently under test, Testing to date has demonstrated that the primary missor performs in a predictable, repeatable manner that will meet SIRTF requirements. The remainder of the telescope is scheduled to be completed ant] tested later this year.

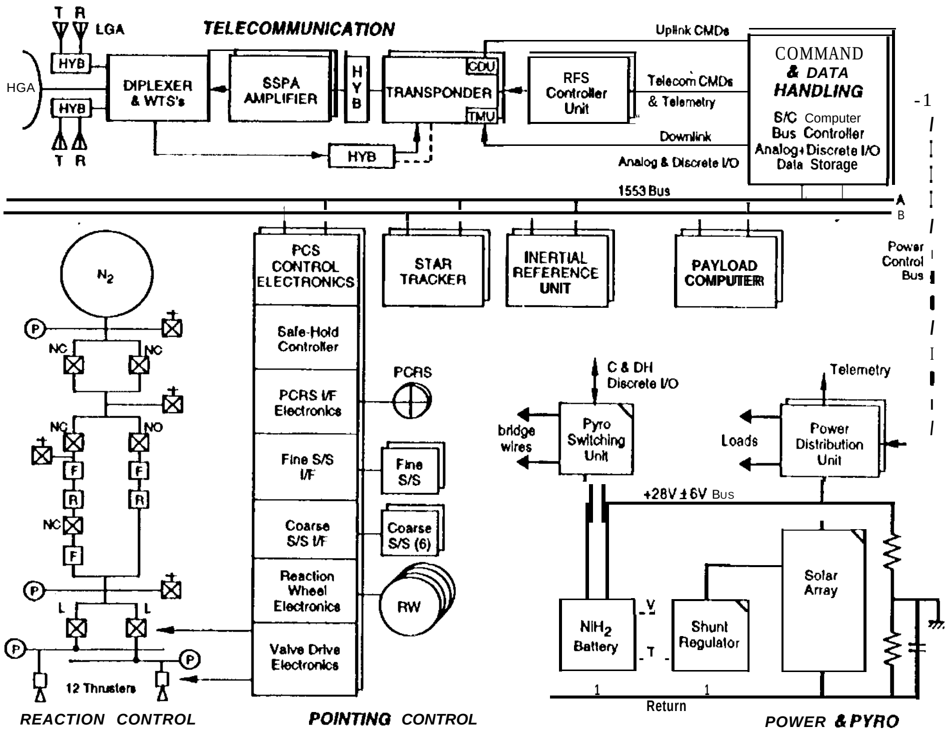


Figure 7. Spacecraft System Functional Block Diagram

Spacecraft

A block diagram of the S/C is shown in Figure 7. Because the SIRTF orbit is far from Earth, a reaction control system is required to desaturate the reaction wheels used by the PCS. Gaseous nitrogen has been selected for this system, and a propellant tank is located in the center of the spacecraft bus. Reaction control thrusters are located on outriggers to maximize the available torque, ant] to minimize the likelihood of contamination of the cold CTA surfaces.

The surface of the sun-shield is populated with solar cells that generate 300 W average power at end-of-life. Average power usage is expected to be 250 W.

Pointing Control System

One of the more challenging requirements of the SIRTF S/C is 10 achieve a high performance and flexible pointing control capability with an affordable design. The PCS provides the capability to safely and accurately point the line-of-sight of the telescope at a science target, and to either stabilize the line-of-sight or perform controlled scans across the sky. The PCS is also used to orient the high-gain antenna toward Earth for telecommunications links,

‘] ’he PCS is required to point the line-of-sight of the telescope in absolute coordinates to an accuracy of 5-arcsec rms radial. This is sufficiently accurate to place the target near the center of one of SIRTF's 5 x 5 arcmin imaging arrays. For observations that require more precise pointing accuracy, the 5 arcsec rms radial accuracy is sufficient to assure that the target falls witbin the field-of-view of either a visible light quad cell detector (PCRS), or a 10-μm “peakup” array. Once a target is found using one of these two targeting arrays, a precision offset is executed to locate the target onto one of the science arrays or spectrograph slits to an accuracy of 0.4-arcsec rms radial.

Once the target has been placed onto the desired science detector, the PCS can maintain the line-of-sigl)t of the telescope stable to 0.6 arcsec rms radial over a duration of 500 seconds. Alternatively, the line-of-sight of the telescope can be scanned across the sky at selectable rates from 2 to 20 arcsec/sec. Scanning is used primarily in conjunction with the MIPS instrument, which contains an internal scan mirror on a flyback mechanism that can ‘{freeze frame” a scene on the science detector over short integrations (typically 5 seconds) ant] thereby step across the sky, imaging in a mosaic fashion.

SCIENCE INSTRUMENTS (SI)

S11<”1’1’ contains three science instruments, each of which is developed under the direction of a Principal Investigator (1’1). The three instruments are the IRAC, the IRS, ant] the MIPS. These instruments, taken together, provide a wing and spectroscopic modes from 3 to 180 pm. To simplify operations and reduce overall mission costs, SIRTF is designed such that only one instrument is operated at a time.

Each instrument consists of both cryogenic sensor subassemblies ant] warm electronics subassemblies. These are interconnected by electrical signal cables which pass through the various insulating layers of the CTA.

The cryogenic subassemblies share a cylindrical (21 -cm-high x 42-cm-radius) instrument chamber which is located within the cryostat, as shown in Figure 4. These cryogenic subassemblies perform all optical processing of the telescope input beam and deliver the resulting signal to the infrared detector arrays, which produce a low-level analog output signal. For both reliability and cost reasons the number of mechanisms in the cryogenic instrument subassemblies has been kept to a minimum (two).

The instrument warm electronics subassemblies provide all the necessary electronic housekeeping for detector operation and readout, including bias voltage and clock generation, analog-to-digital conversion, compression, formatting, and presentation to the spacecraft for storage and subsequent transmission to Earth. Cost, mass, and power savings are achieved by appropriate sharing of general-purpose computing, power conditioning, and other electronic functions among the instruments. instrument warm electronics modules are located within the S/C bus

In each instrument the most critical performance-determining components are the infrared detectors and (heir associated cryogenic readout circuits. Each instrument team has successfully conducted a detector and readout development which has drawn on a variety of industrial, academic, ant] governmental organizations. In all cases, SIRTF instrument detectors have a long technology development pedigree and represent the state-of-the-art in infrared detector technology.

The operating temperature of both the detectors and the telescope place unique demands on the cryogenic system. As the wavelength of operation increases, required operating temperature decreases. At the shorter infrared wavelengths the InSb array detectors must operate at approximately 15 K. The mid-infrared band Si:As and Si:Sb Blocked Impurity Band (11111) array detectors require approximately 5 K and 3 K, respectively, and the far-infrared stressed Germanium photoconductor array detectors require the lowest operating temperature—approximately 1.5 K. Somewhat higher maximum allowable telescope temperatures are permitted in each case ranging from 100 K to 5.5 K.

The instruments access the focal plane of the SIRTF telescope through individual flat “pickoff” mirrors, whose positions are fixed in the shared telescope field of view. The fields of view of the various instrument apertures projected onto the sky are shown in Figure 8. Only a subset of these fields is active at any time,

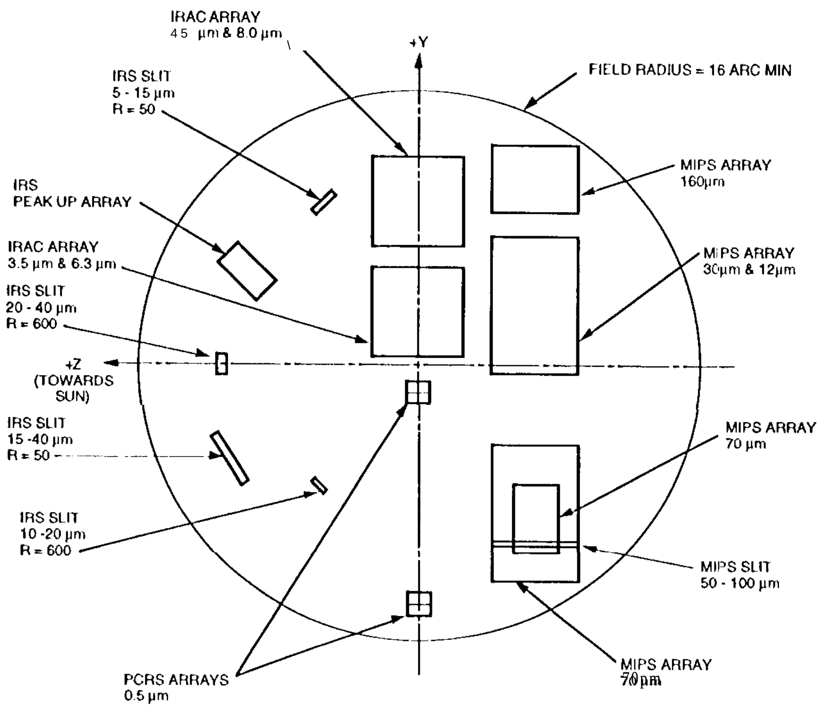


Figure 8. S1 RTF focal plane arrangement

depending on the selected instrument and the operating mode of that instrument as described below. Also shown in Figure 8 are Pointing Calibration Reference Sensors (PCRS), which are quad cell detectors used to calibrate the instrument alignment with the spacecraft star tracker.

IRAC Description

The Infrared Array Camera (IRAC) is a four-channel imager packaged in a single module. Simultaneous wide-field images at 3.5,4 .5,6.3 and 8.0 µm are possible with 25'% bandwidth at each wavelength. Two adjacent fields of view in the SIRTF focal plane support the four channels in pairs as shown in Figure 8.

Infrared radiation enters the instrument via two pickoff mirrors which feed similar channels, each consisting of a beam splitter and a pair of lenses and fold mirrors. Radiation shortward of 5 µm reflects off the beam splitters and is focused on the InSb arrays; radiation longward of 5 µm passes through the beam splitters and is brought into focus on the Si:As BIB arrays. Filters in front of each array determine the central wavelength ancl bandwidth of each channel.

The IRAC occupies an approximately 30-degree sector of the instrument chamber volume. Key to the compact packaging is the use of silicon asphere refractive optics. The focal plane parameters and projected performance of the IRAC are shown in Table 2.

IRS Description

The IRS is comprised of four separate cold optical assemblies or "modules" which are independent of each other both optically and mechanically. Two of the modules produce low-resolution spectra with a one-dimensional image along the slit. The other two produce two-dimensional echelle-format nloclerate-resolution spectra with 7 to 10 spectral orders on the array. In addition, a portion of one of the low-resolution short-wavelength modules is used to produce 10-µm "peak up" images to aid in identifying sources and to help calibrate the Observatory pointing system.

Table 2. Projected IRAC Performance[1,2]

Band (pm)	Detector Type	Detector Format (pixels)	Spectral Resolution ($\lambda/\Delta\lambda$)	Field of View (arcmin)	Pixel size (arcsec)	Sensitivity 500s/50 (µJy)
3.5	InSb	256 x 256	4	5.1 X5.1	1.2	2.6
4.5	InSb	256 x 256	4	5.1 X5.1	1,2	3.3
6.3	Si:As (BIB)	256 x 256	4	5.1 X5.1	1.2	18.1
8.0	Si:As (BIB)	256 X 256	4	5.1 X5.1	1.2	30.9

Table 3. Projected IRS Performance[3]

Module	Band µm	Detector Type	Detector Format (pixels)	Spectral Resolution ($\lambda/\Delta\lambda$)	Slit Size (pixels) d	x-d	Pixel Size (arcsec)	Sensitivity 500s/50
Short Lo†	5-7.5	Si:As(BIB)	128X128	50	2	30	1.8	100 µJy
	7.5-15			50	2	30	1.8	550 µJy
	10(peak up)*			2	32	30	1.8	3X1O ^{18}W/m^2
Long-Lo†	14-21	Si:Sb(BIB)	128X128	50	2	30	4.8	1500 µJy
	21-40			50	2	30	4.8	1500 µJy
Short Hi	10- 19.5	Si:As(BIB)	128X128	600	2	5	2,4	3X1 0^{-18}W/m^2
Long Hi	19.5-38	Si:Sb(BIB)	128X128	600	2	5	4.8	3X1 o ^{18}W/m^2

* The required image quality is achieved only over 32 by 30 pixels. A FOV of up to 3' x 1.5' may be possible with reduced image quality.

† The grating operates in more than one order with order-sorting filters. The slit lengths shown are per order: d: dispersion direction (slit width); x-cl: cross-dispersion direction (slit length). It is likely that the exact FOV of the peak-up, and the slit length of the Lo modules, will change somewhat as the optical design is further developed.

The optical design of each module is optimized to achieve reliability and case of fabrication, integration and test. There are no moving parts in the IRS module. Each module contains one infrared detector array, with either an arsenic-doped silicon (Si:As) blocked impurity band detector (BIB) or an antimony-doped silicon (Si:Sb) BIB detector. All four assemblies are packaged into slightly less than a 180- degree wedge of the instrument chamber volume. The focal plane parameters and projected performance of the IRS are shown in Table 3.

MIPS Description

The MIPS instrument comprises a single cold optical assembly which contains five distinct optical trains that can be operated in one of three data gathering modes: 1) image in three bands simultaneously, 2) image with high magnification at 70 μm, and 3) low-resolution spectroscopy from 50 to 100 μm. A single axis scan mechanism is included to modulate the signal on the Germanium detectors to provide good photometric performance, and to select among the three instrument operating modes.

Table 4. Projected MIPS Performance[4,5]

Operating Mode	Band (pm)	Detector Type	Detector Format (pixels)	Spectral Resolution (λ/Δλ)	Field of View (arcmin)	Pixel Size (arcsec)	Sensitivity 500s/50 (μJy)
1	12	Si:Sb(BIB)	13x128	4	0.5 x 5,3	2.4	100
	30	Si:Sb(BIB)	I1OXI28	4	4.1 x 5.3	2.4	150
	70	Ge:Ga	32 x 32	4	5,3 x 5.3	9.4	530
	160	Ge:Ga (stressed)	2X20	4	0.5X5	15	7500
2	70	Ge:Ga	32 x 32	4	2.6 x 2.6	5	870
3	50-100	Ge:Ga	32 x 32	20	0,3' x 5.4'	9.4	3500

The instrument utilizes a Si:Sb array of identical design to that in the IRS. In addition, two gallium-doped germanium (Ge:Ga) arrays are used, one with 32 x 32 pixels that respond up to 120 μm, and the other with 2 x 20 pixels, each subjected to a mechanical stress to extend its photo conductive response to 180 μm. The cold assembly is packaged into a 90-degree wedge of the instrument chamber volume. The focal plane parameters and projected performance for MIPS arc summarized in Table 4.

IMPLEMENTATION APPROACH

SIRTF will not be the first space project confronted with a limited budget, but it will be a leader in developing new ways of conducting space projects to assure that the greatest possible mission return is obtained for a cost which cannot be exceeded. The cost for the definition (Phase B), design (Phase C), and development (Phase D) of S11<1'1' has been fixed at $450M. As has been described elsewhere in this paper, an exciting science mission of discovery is possible with this low-cost mission.

SIRTF will not have contractors in the traditional sense, but rather a team will be formed consisting of people from the most capable companies in the United States. The team members will be integrated into a single SIRTF Team called an Integrated Project Team (IPT). The various team members will have clear areas of responsibility and well defined products which they will be expected to provide. The difference between an IPT and the traditional project structure lies in the collective recognition that every member of the team must succeed. That is, the team members learn to help each other or the entire project will collapse and be terminated.

The SIRTF team will be organized along the lines shown in Figure 9. The responsibility for overall conduct of the project will rest with the Project Manager at JPL. The organization will be relatively flat in that those responsible for each identified area will also be responsible for the overall success of the project. Science activities will include assuring the needed capabilities will be achieved in the implementation of the facility, and providing adequate access to SIRTF will be included for the general science community. Planning activities will be continuous to assure that the project

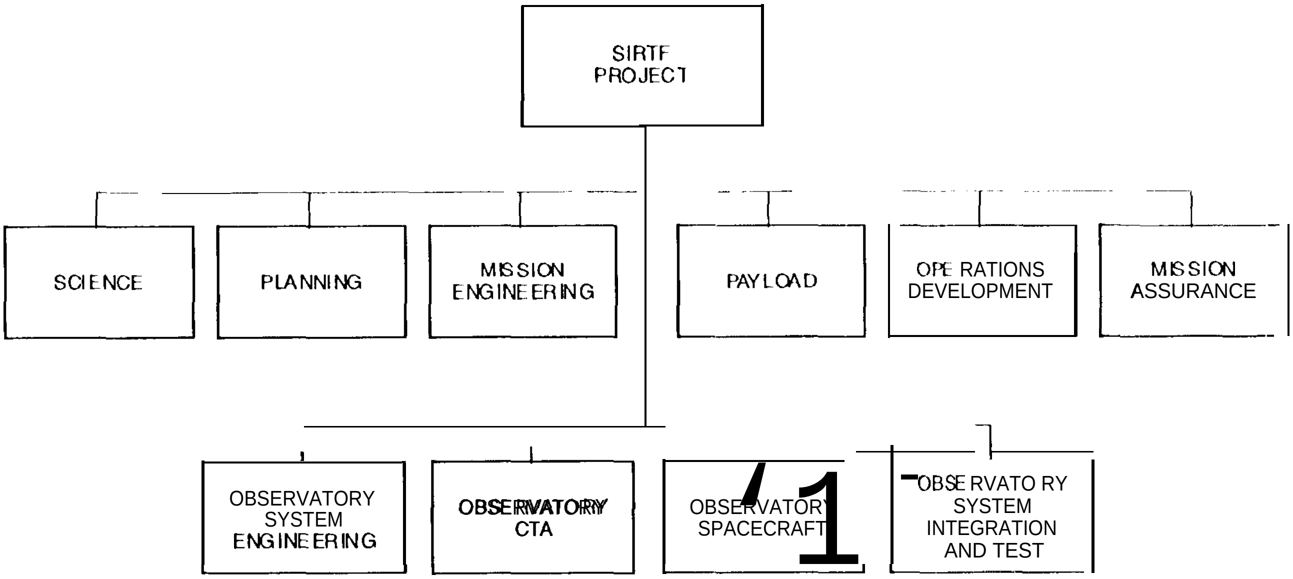


Figure 9. SIRTF Project Organization

is looking ahead for opportunities to reduce cost or improve capabilities as the project proceeds. Payload activities will coordinate the development of the science instruments that are the reason for putting SIRTF into space. Operations Development will be a vital part of the development process to assure that the systems developed can be readily operated to maximize the return of scientific information from the mission. Mission Assurance will contribute to the entire process by bringing to SIRTF the best practices and know-how that can be incorporated into a cost-constrained mission.

The flight system for SIRTF will be developed by four team elements. System engineering will be provided by a System Design Team (SDT) composed of members from all elements of the project. The Cryo-Telescope Assembly (CTA) will be provided by an industrial team member who will basically be responsible for all of the "cold" elements of the Observatory except the science instruments and any positioning sensors needed for pointing or control of the Observatory. The S/C will also be provided by an industrial team member who will be responsible for the warm parts of the observatory except the science instruments, and all elements necessary for pointing and control of the Observatory. An industrial team member will also be selected to be responsible for System Integration and Test (SIT), which will include system integration engineering, physical integration of the CTA and S/C, followed by system-level performance and environmental testing. The SIT team member will also be responsible for coordination of launch services for the project.

By working together, and contributing to a common data base, team members will have ready access to information needed to assure that decisions made achieve the most for the resources expended. Financial resources, schedules, and work progress will all be reported in a manner that allows the entire IPT to ascertain how the project is doing. Progress will be readily identifiable so that the IPT can work together for mutually beneficial solutions. Of course, there will be times when the IPT will be asked to make tough decisions, and it is expected that the IPT will pull together and make decisions that are best for the entire project.

It has been an objective of the project to be expeditious in the development process. This will provide results at the earliest opportunity, and is also expected to be key to containing costs. Decisions will be made early and changes will be discouraged. NASA requires that the project definition phase be used to complete the functions] (or preliminary) design, and the project successfully conduct both a Preliminary Design Review (PDR) and a Non-Advocate Review (NAR) which focuses on the project's implementation plans. Approximately 18 months have been allocated to this process (Phase B). Once approval (from both NASA and Congress) has been received, the IPT will initiate the detailed design and implementation (Phase C/D) of the agreed upon system. It has been estimated that this portion of the project can be completed in about 3 1/2 years. It is uncertain at this time whether the NASA budget can support a development cycle this short.

NASA is currently going through major changes. The Office of Space Science at NASA Headquarters, which is responsible for SIRTF, is making significant changes aimed at reducing the number of people at 1 leadquarters with oversight responsibility. This is expected to result in closer ties between projects such as SIRTF and those associated with the projects at Headquarters. More day-by-day information and decisions will have to be provided by the field center project offices (JPL in the case of SIRTF) to aid Headquarters in the administration of the projects. For SIRTF this will mean the 1] '1- will have to be mindful of Headquarters' needs, and will be expected to provide a larger fraction of the information than was provided in the past. It is expected that those at Headquarters will be considered ex-officio members of the 11''1', and that they will be candid in defining their needs. Recent experience has clearly indicated that the planned project structure will add to making this possible.

Developing SIRTF with an IPT will require that the team give early at tention to the development of a plan for the entire project. The plan must explain how the project will be organized, what its schedules will be, how its resources will be allocated, and what product will be delivered. One of the early challenges of the 11''1' will be to develop several schedule scenarios to give NASA the information it will need to provide the best funding schedule that satisfies both SIRTF and other NASA science objectives.

ACKNOWLEDGEMENTS

The "warm launch" architecture for cryogenic space telescopes was developed by Dr. F. J. Low (University of Arizona), and his contributions to the SIRTF concept are gratefully acknowledged. The work described in this paper was carried out at the Jet Propulsion Laboratory, California Institute of Technology, under an agreement with the National Aeronautics and Space Administration.

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