Spacelab Infrared Telescope Facility (SIRTF)

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NASA has completed a preliminary design study of a 1.2-m, cooled infrared telescope for use on 7 to 28 day Spacelab missions. Beryllium optics, cooled to below 20°K with supercritical helium, are used. Noise in the infrared telescope will be less, by a factor of 10^3, than that of ground-based telescopes operating at 10 μm (when the telescopes are operated over comparable bandwidths and fields of view). The Spacelab infrared telescope facility will enable astronomers to see more than 30 times deeper into the universe than is now possible over most of its 5-200 μm optimum spectral range. Such capability will initiate a spectacular advance in our knowledge and understanding of the cool regions of the universe where molecules and dust are the predominant radiators and absorbers.

Introduction

CONSIDERABLE astronomical interest has been directed toward observations of the cool regions of the galaxy, where stellar and planetary formation may be taking place in clouds of gas and dust. Such clouds are, in turn, fed by mass loss from stars in later stages of evolution. The dust radiates primarily in the infrared and obscures shorter wavelengths. In some cases whole galaxies are radiating most of their energy in the infrared, indicating conditions quite different from those in our own and nearby galaxies. The processes associated with these conditions are of fundamental importance to astrophysics. They are best studied in the infrared, a region of the spectrum which cannot be observed well from within the Earth's atmosphere because of its absorption and emission.

The technology and capabilities of cooled infrared telescopes have been demonstrated in rocket and satellite surveys of the sky in several infrared bands. As the Space Shuttle becomes operational, it will offer a unique opportunity to take advantage of the space environment.

The obvious advantages of a space environment can now be fully utilized by the fast-developing science of infrared astronomy. A large, cooled infrared telescope will provide sensitivity at 10 μm that will be better by a factor of 1000 than that of the best ground-based observatory using detectors which can be reasonably anticipated for the 1980s. Astronomers have proposed that a 1-m telescope with 20°K optics, using detectors with noise equivalent power as low as 10^{-17} W/Hz$^{1/2}$, be built for infrared observations. The Space Shuttle and Spacelab will provide a base for such a telescope.

In this report, the research potential, the limitations, the design, and the operation of the Shuttle Infrared Telescope Facility (SIRTF) are discussed.

Science Objectives

Astronomical Sources

The astronomical problems that are best studied in the infrared (0.7μm $\leq \lambda \leq$ 1mm) are primarily those requiring observations of cool objects ($T \lesssim$ 4000°K) where molecules and solid particles are present. These objects include planetary atmospheres and surfaces, comets, asteroids, atmospheres of cool stars, interstellar gas and dust clouds, and galaxies enshrouded in dust. In addition, warm objects that are obscured in visible wavelengths by dust clouds become observable at longer wavelengths because the absorption cross-section decreases as $(a/\lambda)^n$ where a is the dust particle radius, λ is the wavelength, and n is of the order of unity. Some extragalactic objects emit so much radiation in the infrared that the energy source is difficult to explain, particularly when relatively rapid variations in intensity are observed. The sources of astronomical infrared radiation are discussed in detail in Ref. 1.

Astronomical objectives for a large cooled telescope in space have been discussed by several study groups, such as the Astronomy Working Group,[2] chaired by N. Roman in 1972-73; the IR panel of the Woods Hole NAS summer study,[3] chaired by W. Hoffman; and the IR panel, chaired by G. Neugebauer, of the space Science Board that met at Snowmass, Colo. in 1975. A report on the Snowmass meeting is to be published by the National Academy of Sciences.

The significant advantage of a cooled telescope, over one with optics at ambient temperature, is that the cooled optics (20°K) produce much less background radiation, allowing the most sensitive detectors to operate with a wide field of view and a large spectral bandwidth. Scientific objectives are chosen accordingly. Thus, faint infrared objects and extended infrared sources are the exclusive domain of the cooled telescope. High spectral resolution may be achieved with great speed and efficiency through the use of a multiplexing spectrometer such as a cooled Michelson inferometer. Such an instrument responds to all frequencies at once and can use a large field of view as well. Because the noise that it sees also comes from all frequencies and has high throughput, the instrument is not suited to infrared studies using warm telescopes; however, it is ideal for use with a cold telescope.

With high spectral resolution one can identify molecular species in cool gases, because most of the vibration-rotation lines and pure rotation lines of molecules lie in the infrared. Measurement of molecular spectra enables the determination of composition, temperature, and isotopic composition of the gas clouds or atmospheres under study. This information, in turn, provides clues about their origin and evolution. High resolution is also needed to examine fine structure lines of many atomic species that lie in the infrared. These are expected to provide information about the temperature and composition of HII regions (clouds that contain primarily ionized hydrogen, but also other ions and often dust).

From the foregoing discussion and from reports of the advisory groups cited, the following instruments are likely to be representative of an early focal plane payload: 1) A photometer package utilizing dichroic beam splitters, broadband filters and very sensitive detectors. This would be used for detecting and measuring absolute intensities of faint galactic and extragalactic objects and obtaining their broad-band spectral characteristics. It would also be used for mapping

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Index categories: Spacecraft Configurational and Structural Design (including Loads); Space Station Systems, Manned.

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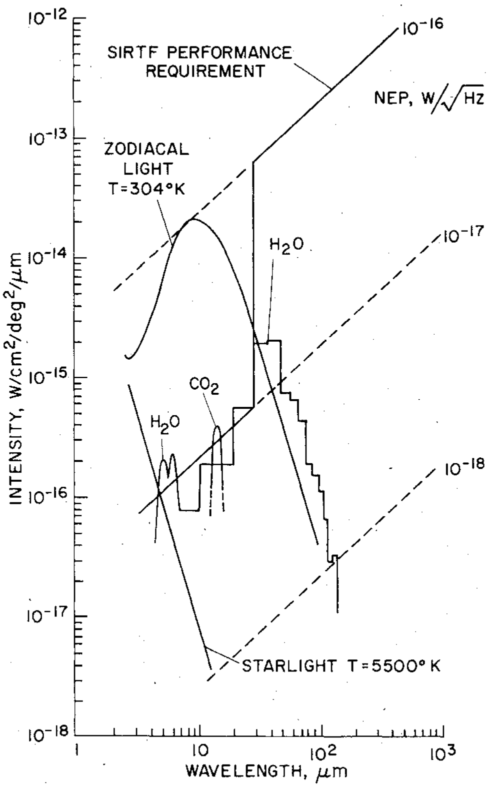

Fig. 1 Radiative background in Shuttle Environment; NEP is based on a 1-arcmin square field of view, a 10-μm bandwidth, and a 1-m clear aperture.

selected regions. 2) A photometer polarimeter package for measuring polarizaton of radiation in selected bands. 3) A Michelson interferometer to obtain medium or high resolution spectra to determine molecular and atomic species, temperature, and isotopic content. 4) A large detector array to provide a very efficient means of mapping in a selected wavelength band.

We must now examine the limitations of a 1 to 1.6 m, cooled telescope. The angular resolution of a well-stabilized telescope in space is limited by diffraction. The angle between the cetner and the first dark ring of the diffraction pattern of a point source is 1.22 λ/d.[4] Thus at 100 μm objects separated by much less than 20 arcsec cannot be resolved. When resolving power is the most important requirement, a larger telescope or even a spatial interferometer is required. Presumably these high-resolution devices would operate at ambient temperature, with consequent loss of sensitivity, until technology is sufficiently developed so that they, too, can operate at low temperatures. Further limitations on infrared telescope performance are imposed by background radiation sources as discussed below.

Limitations Imposed by Background Radiation

Although atmospheric absorption of infrared light is negligible above 200 km, emission from overlying atmosphere and zodiacal light is still present. The atmospheric emission, mostly from atomic oxygen at 63 μm and 147μm and from NO and NO+ at about 4 to 5 μm (Ref. 5), is reduced at higher altitudes; however, a limitation on Orbiter altitude eventually is imposed by the inner Van Allen belts, which grow rapidly in intensity above 400 km. Sensitivity of infrared detectors to high-energy particles is discussed in Ref. 6. The zodiacal light is a more limiting condition than the residual Earth atmosphere because of its continuum nature. A few preliminary observations of zodiacal light in the infrared have been made from rockets.[7] A model of the zodiacal infrared spectrum by Jarecke and Wyett[8] is shown in Fig. 1. The model is in fair agreement with the few data points obtained near the ecliptic, but the observations decrease in intensity much faster off the ecliptic than the model. The zodiacal background is well above the minimum flux detectable by SIRTF. This minimum flux level is based on the expected performance of detectors in the early 1980s. To detect signals as small as the NEP's shown in Fig. 1, the background must be subtracted by spatial chopping, just as with ground-based telescopes. In this technique, one of the mirrors in the optical train is oscillated so that a given detector sees the object plus background, and then the background only. The resulting AC signal is only from the object, unless there are spatial gradients in the background. Even with perfect background subtraction, the sensitivity will be limited by statistical fluctuations in the background intensity. Within the solar system, fluctuations in the zodiacal background are a fundamental limitation in the range of 5 to 30 μm.

In addition to infrared radiation from the natural background, there will be emission from the contaminants evolving from the Shuttle. The contaminant atmosphere of the Shuttle Orbiter has been modeled by Bareiss et al.[9] and by Rantanen and Ress.[10] The resulting infrared radiation has been studied by J.P. Simpson and F.C. Witteborn.[11] The strongest infrared emitters are expected to be particulates and water vapor. Astronomers have requested that the column density of infrared active molecules be kept below 10^{12} cm $^{-2}$ around the orbiter; this appears to be feasible after one day of offgassing. The resulting radiation from the pure rotation spectrum (beyond 10 μm) of 300°K water is shown in Fig. 1; collisional excitation may increase the effective temperature. Purely statistical fluctuations in this radiation would not be noticed by the SIRTF except between 6and 7 μm, where a strong vibration-rotation band of water may predominate over other noise sources.[11] However, spatial and temporal variations in the contaminant background radiation will appear as additional noise (or false signals) because the spatial chopping will subtract uneven or varying backgrounds.

Restrictions on the molecular contaminant environment for the Orbiter have been proposed by the Contamination Requirements Definition Group, chaired by R. Naumann (NASA-Marshall Space Flight Center). Spatial and temporal gradients in infrared radiation and total infrared radiation would be restricted to values below the limits of the SIRTF sensitivity (Table 1). Such restrictions can only be set as performance goals. Estimates based on the contaminant models already discussed indicate that the SIRTF performance will not be impaired by molecular contaminants, provided that the vernier thruster system is not used and the water vents are closed during periods of observation. Compliance with these constraints appears to be feasible; the constraints are discussed further in the operations section.

The problem of radiation from particulates, discussed in detail in Ref. 11, is especially difficult because of the lack of relevant experimental data on the ejection of particulates from spacecraft. Particles observed near Apollo and near earlier manned spacecraft were mostly ice flakes. Even those near Skylab were probably ice. Because vents for liquids on the Orbiter can be kept closed during observation periods, and because wastes can be stored throughout the mission, ice flakes should not present a problem for Shuttle users. Other particulates, such as dust blown out through cabin leaks, dust ejected from surfaces, or particles from rocket exhausts are expected to cause some loss of data because they may appear as infrared sources in the telescope's field of view. Particles can be detected by SIRTF if they are larger than 2 μm in radius, have a temperature greater than 300°K, and are within about 10 km of the telescope. Atmospheric drag will sweep most particles past the telescope at relatively short distances where they will appear as out-of-focus images in the focal plane. Spatial chopping will subtract the resulting background much of the time, but not all; the actual fraction of observing time that is affected depends on the particle size and velocity distributions. The astronomers who have been participating in

Table 1 SIRTF characteristics

Telescope	
Optical layout	Double-folded Gregorian
Aperture diameter	1.16 m
Field-of-view diameter	15 arcmin
Effective focal length	8 m
f-number	6.9
Area obscuration	25 percent
Overall visible transmittance to video sensor	60 percent
Diffraction limit wavelemgth	5 μm
Sensitivity (noise equivalent power) for 10 μm bandwidth and 1-arcmin field-of-view	
5 μm to 30 μm	10^{-17} W/Hz$^{1/2}$
30 μm to 200 μm	10^{-16} W/Hz$^{1/2}$
Space chopping throw, maximum	± 7.5 arc min
Pointing accuracy	
Azimuth and elevation	± 1 arc sec
Around line of sight (Roll)	± 30 arc sec
Pointing stability, RMS	0.25 arc sec
Mass	
Empty	2013 kg
28-day mission	2348 kg
Maximum mass moment of inertia about IPS	
Length	16,400 kg-m^2
Sunshade retracted	
Sunshade extended	508 cm
Outside diameter of body	729 cm
Outside diameter of sunshade	174 cm
Maximum angle of line of sight from *z*-axis	292 cm
	± 60°
Thermal subsystem	
Head load, maximum	7.3 W
Primary mirror temperature	14-16°K
First folding mirror temperature	18-22°K
Supercritical helium flow rate	0.1–0.5 g/sec
Cryogen required, nominal	
7-Day mission	700 liters
28-Day mission	2600 liters
Cryogen pressure	6 atm
Cryogen reservoir temperature	5-10°K
Launch hold time	12 hours
Overall system at launch	
Total mass of SIRTF components	
7-Day mission	3845 kg
28-Day mission	4638 kg
Mass of payload-chargeable Orbiter/Spacelab components:	
28-Day mission	13,415 kg
Overall length in payload bay (excluding electric power kits)	9 m

the SIRTF study have requested that no more than one particle larger than 5 μm cross the SIRTF field of view (15 arc min) per orbit. This goal has been set for the Shuttle, but the actual performance will not be known until monitoring instruments[12] are flown on early Shuttle flights. Early tests will determine operational-procedure changes needed to reduce particle sightings to a tolerable level.

Another contaminant problem, deposition of water vapor on cold optical surfaces with consequent absorption of infrared radiation, will be alleviated by a continuous purge of helium gas out the telescope barrel. This purge is also needed to prevent deposition of the atomic oxygen in the ambient air onto the cold surfaces. The purge gas can be provided by a fraction of the helium needed for cooling.

Advantages and Alternatives for Shuttle-Launched Infrared Telescopes

The preceding discussion has dealt with the main disadvantage of Spacelab relative to an unmanned satellite as an observatory site: contamination. This potential limitation is expected to be largely overcome by careful operational procedures, and is thus outweighed by the Shuttle's practical advantages. The most basic advantage of Shuttle use is the large weight and volume available for payloads. This allows relatively inexpensive design, since ultra-light structures are not required and existing technology can be used directly. Secondly, although direct manned access is not required, the presence of trained astronauts will allow designers to depend on their assistance to backup critical systems rather than incorporating expensive redundancies. In addition, a manned operation capability reduces dependence on automated systems for infrequently performed functions and allows operational flaws to be corrected without losing the mission. Finally, a large cost-saving will accrue to Shuttle payloads because the facilities can be returned, experiments (focal plane instruments) can be changed, and missions reflown without repeating the extensive preparation necessary for previous space missions.

Operations from an unmanned spacecraft would have the potential advantages of lower contamination levels and increased observation time but preflight preparation would be more difficult because of the requirement for reliable operation over a long time period. This also requires extremely careful attention to integration of power, data link, command pointing, and long-term cryogen supply with the telescope. For large, cooled infrared telescopes, it appears that the increase in observation time provided by the unmanned spacecraft at the expense of operational flexibility and serviceability is probably not cost-effective. Also, there is

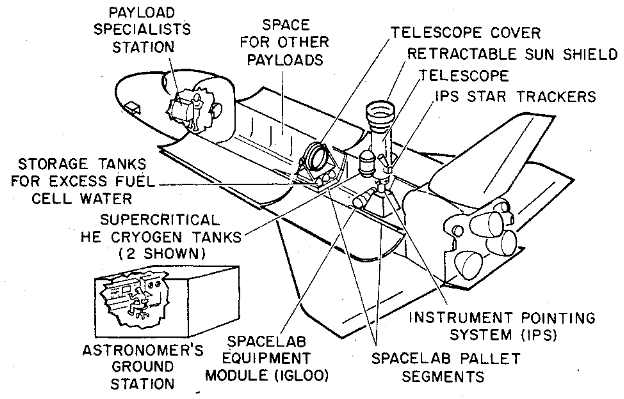

Fig. 2 SIRTF inflight configuration on Shuttle/Spacelab.

good reason to believe that constraints on Shuttle operational procedures and choice of Spacelab materials will prevent contamination from limiting the SIRTF performance. Moreover, as will be described subsequently, the telescope is essentially self-contained so that the option of converting it to a free-flying observatory always exists.

Another approach to infrared astronomy on the Space Shuttle would be an ambient-temperature telescope that could be larger than the SIRTF. Such a facility would be relatively insensitive to the contamination and natural infrared background because it is inherently a much less sensitive instrument. The background from the ambient mirror results in an NEP of over 10^{-15}W/Hz$^{1/2}$ in a 10 μm bandwidth and 1-arcmin field-of-view in the important 5-30 μm range, where SIRTF provides at least 100 times less noise. It could be used for studies that would benefit from a spatial resolution capability approaching that of ground-based telescopes but with better sensitivity than for many wavelengths. However, there is a serious problem associated with the development of this approach: if ambient-temperature telescopes with apertures greater than 1.6 m in diameter are to be built without undertaking mirror material development, the mirror material will have to be selected from one of the ceramics already developed for reflecting telescopes. Even an extremely lightweight ceramic primary mirror will have a long thermal time constant and low thermal conductivity. The resulting long time required to reduce the thermal gradients in the mirror may seriously limit observation. As long as these thermal gradients exist, they will be a source of noise during spatial chopping. Another consideration affecting any proposed use of an ambient-temperature telescope is the expectation that the free-flying Large Space Telescope will accommodate infrared focal plane instruments on some missions. In that event, those missions could achieve many of the same objectives as the large ambient attached telescope.

SIRTF Design

The SIRTF preliminary design has been described in Ref. 13. The present discussion reviews essential features and supplements Ref. 13 by adding information that has recently been developed.

A sketch of SIRTF as it might appear on a Spacelab mission is shown in Fig. 2. The 9-m length of SIRTF fills about half of the payload bay, leaving space and mass available for compatible sortie payloads or for a separable spacecraft. A pallet-only configuration is depicted because most payloads proposed for Spacelab pressurized module missions will have operational requirements that conflict with astronomy operations. For missions longer than 14 days, some of the remaining payload bay may have to be used for additional fuel cell reactants to generate the power required by the Orbiter and Spacelab components.

It is anticipated that early missions will be shared with a free-flying spacecraft that will be launched before infrared observations begin. However, it is possible that for these early flights, the rest of the bay might be used for attaching small sounding-rocket-class infrared or other astronomy telescopes.

In Fig. 2, the telescope is shown mounted on the Instrument Pointing System (IPS) provided by the European Space Agency. The IPS is, in turn, mounted on a Spacelab pallet. Because the IPS must be disconnected from the telescope for launch and re-entry, the telescope is clamped and supported in a special cradle. The cradle and the pallet on which it mounts

Table 2 SIRTF support required from Shuttle/Spacelab

7-Day mission, rear location	
Launch mass	8480 kg
Return mass	7530 kg
28-Day mission, rear location	
Launch mass	18,053 kg
Return mass	13,340 kg
Prelaunch	
Environment	Class 10,000 N_2 purge in bay
Access for cryogen fill	4-12 hr (prior to launch)
Power	Internal to maintain vacuum
On-orbit	
Orbit characteristics, nominal	300 km, 28.5° to 57°
Power, nonoperating	0.1 kW
Power, operating, nominal	2 kW
Downlink data rate, maximum	1 megabit/sec
Uplink data rate	25 kilobit/sec
Special requirements-on-orbit	
Near-real-time ground monitor (TDRSS)	
Vernier RCS only—minimized firing rate	
Restriction of water dump, fuel cell purge, other damping	
Orbiter attitude and rate information	
Trained operator onboard, voice link to ground	
Operator backup to critical functions	

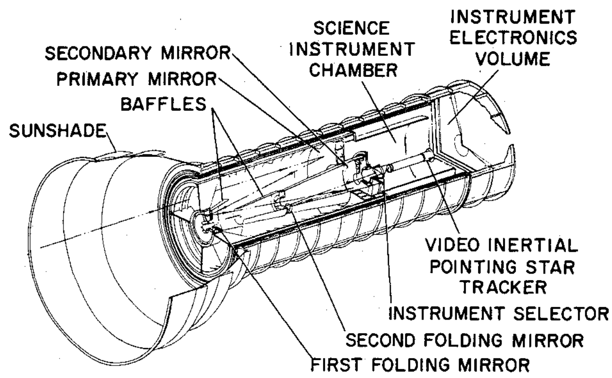

Fig. 3 SIRTF telescope cutaway view.

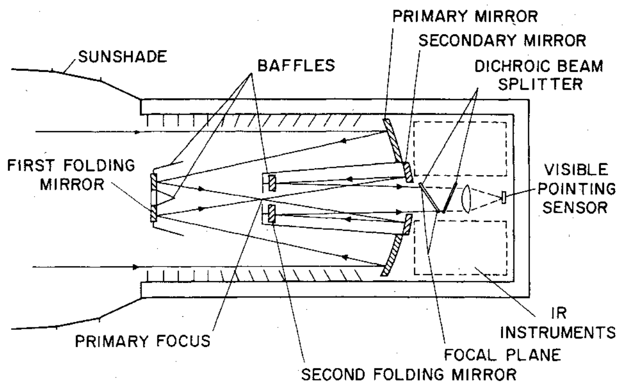

Fig. 4 SIRTF optical system.

are not shown in the figure. At the aperture end of the SIRTF telescope, a cover provides a vacuum seal, vacuum interconnect, and calibration facility. The cover rides on the telescope for launch and re-entry but is retracted onto the third pallet when the telescope is erected. The cover must be reconnected for re-entry to minimize contamination that could make the task of refurbishment more difficult.

The pallet that supports the IPS has sufficient capacity to allow control-moment gyros (CMG's) to be mounted if they are needed to supplement Orbiter stabilization and avoid frequent firing of the reaction control thrusters. However, analysis has indicated that CMG's will probably not be required for the present definition of Shuttle capability. Shown in Fig. 2 are storage tanks for fuel-cell-reaction-generated water. On missions that last more than 7 days, such tanks will be required for storage of water that is not needed for life support; they will be in addition to the storage tanks normally included. Storage of this water will preclude its overboad dumping and consequent contamination of the environment. An inert gas system will be used to expel the stored water prior to re-entry, thereby reducing the landing weight and adjusting the center of gravity. Alternatively, the water could be dumped every 7 days, but the observation time of about one orbit would be lost at each dumping.

Some of the support that will be needed from the Shuttle/Spacelab is listed in Table 2. These requirements do not appear to exceed the limits of the Shuttle capacity as long as the Tracking and Data Relay Satellite System (TDRSS) is available. The smallest margin for any of the facilities is in data recording during dead spots in TDRSS coverage. The downlink data rate in Table 2 is much higher than that given in Ref. 13; not only was the latter in error (low by a factor of 10) but recent study has also dictated an increase in maximum data rate.

The overall characteristics of the SIRTF system are summarized in Tables 1 and 2. The returned mass and center-of-gravity of the 28-day-mission SIRTF will require that such missions only be shared with a nonreturned or very light payload, unless systems and operations can be shared to reduce weight. However, the masses given in Tables 1 and 2 are maximum estimates, and include ballast for re-entry center-of-gravity control, so the margin is better than the tables appear to indicate.

The central feature of SIRTF is, of course, the telescope. A cutaway view of the telescope is shown in Fig. 3; a diagram of the optical system is shown in Fig. 4. It is a double-folded Gregorian configuration having an aperture diameter of just under 1.2 m. This optical layout was chosen after analytical comparisons were made with conventional Cassegrain optics. One of the advantages of the folded Gregorian design is that a cooled field stop can be located at the primary focus. This reduces the energy from out-of-field sources that can reach the detectors and thus reduces the effective background. The conical baffle between the secondary and second folding mirrors is also cooled so that its radiated energy is an insignificant contribution to the background at the detector.

The second concave (secondary) mirror images the primary mirror precisely onto the second folding mirror so that the folding mirror can be tilted without changing the image of the primary mirror at the second focal plane. Spatial chopping can, therefore, be implemented using this mirror without introducing scan noise from off-axis light scattered by condensed materials or by dust on the primary. The beam does move across the first folding and secondary mirrors, but these are better protected from off-axis radiation by the baffles and from contaminants by flow of expended cooling gas out of the telescope focal plane area. Use of the flat second folding mirror as the chopping mirror, unlike scanning with a figured secondary, does not degrade image quality—coma and defocus are, therefore, much smaller than the diffraction limit.

The second folding mirror can also be used for fine stabilization, as will be described subsequently, without introducing new mechanisms and infrared noise sources. Focus adjustments will be made by linear motion of the first folding mirror.

Another key feature of the telescope design, which dictated an upper limit on the size of this first major cooled space instrument, is the use of beryllium for the mirror material. The physical properties that make beryllium attractive for cooled infrared applications are: high stiffness-to-weight ratio; dimensional stability with time and after thermal cycling; very high ratio of thermal conductivity to thermal expansion, particularly at temperatures below 77°K; and acceptance of surface finishing that provides good infrared reflectivity without overcoating. The major drawback of beryllium for such applications is that the material has different coefficients of thermal expansion in the axial and transverse crystal directions. Without special material processing, the mirror blanks would also have this characteristic. To circumvent this problem, a special processing technique has been developed: the material is powdered, mixed to achieve random axis distribution, and hot-press-sintered to regain most of its strength. Present capability for producing these special mirror blanks provides for a maximum size of about 1.6 m for the finished mirror. Preliminary work has indicated the a 1.6-m diameter SIRTF telescope would be feasible on the Shuttle; however, the telescope mounting cradle could not be mounted on a standard pallet and some restrictions on viewing angles from the Shuttle bay might be necessary. Also, smaller cryogen tanks would be needed to provide clearance. In order to define the most flexible interfaces; the 1.2-m aperture has been used in the preliminary design of SIRTF. However, much of the work that has been done is also directly applicable to the larger size.

The infrared energy focused by the telescope can be directed to any one of several scientists's instruments by means of a rotating dichroic beam splitter, as shown in Fig. 4. The large space behind the primary mirror can contain as many as six different instruments, so that several kinds of arrays, photometers, and/or spectrometers can each be used by the

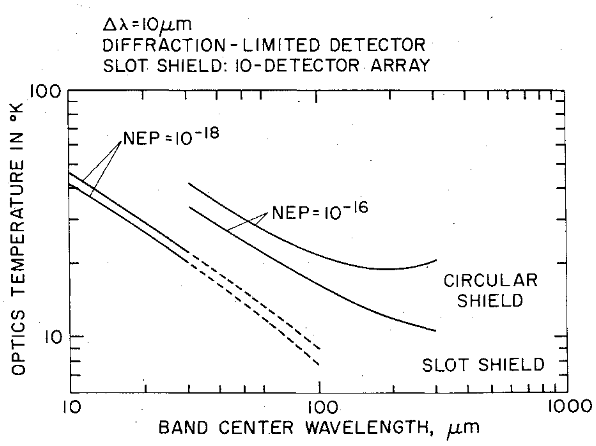

Fig. 5 SIRTF performance.

investigators. These instruments will normally be operated at temperatures below the basic telescope temperature to reduce self-emission and electronic noise. Temperatures between 1°K and 12°K will be required. The separable container for the instruments, called the Multiple Instrument Chamber (MIC), will be designed so that different degrees of cooling for each instrument can be provided; some instruments will be able to contain their own provisions for achieving very low temperatures.

Since the telescope optics and baffles must be operated at temperatures near 20°K, the choice of cryogens is limited to hydrogen and helium. Liquid cryogens are difficult to handle in zero gravity: the gas and liquid phases do not separate, thus making venting of boiloff gas a difficult problem. Solutions to the problem have been proposed but they have not been tested in space. This narrows the choice to solid hydrogen or to supercritical hydrogen or supercritical helium. Supercritical helium, which can be stored at temperatures of about 5°K, has already been flown in deep space on the Apollo missions.[14] In addition, it can be expanded through a Joule-Thompson valve to produce the even lower temperatures (4°K or less) needed for some of the detectors in the MIC. Thus, a single cryogenic system could be used for all cooling, at least for the early missions. If hydrogen were to be used as the cryogen, a helium system would still be required in the MIC for the detectors.

Another important attribute of a supercritical helium system is its flexibility—by increasing or decreasing the flow rate the telescope temperatures can be adjusted to match the requirements of specific instruments. This will reduce cryogen usage in comparison to systems that would have to constantly maintain the telescope temperature at the lowest valve needed. This feature also allows a modular approach to the cryogen tankage; that is, the number of tanks can be varied to meet mission requirements. For instance, a 7-day mission designed to concentrate on short-wave infrared measurements might require that the temperature of the warmest mirror (first folding mirror) be maintained below 22°K, and a single partially-filled cryogen tank could be used. A mission of 14 days, designed for concentration on long-wavelength photometry, would require two nearly full tanks to cool the telescope sufficiently to maintain the temperature of the warmest mirror below 19°K for most of the mission. The relation of optics temperature requirements to the wavelength at which observations are to be made is shown in Fig. 5 (from Ref. 13) for two detector shielding approaches and for the sensitivities that are required by the SIRTF specification.

As previously mentioned, supercritical helium also has the advantage that, after some of its heat capacity is used in the MIC and mirror area, it can be expelled through the inner baffle area to prevent condensible gases and other contaminants from reaching the cold interior optical surfaces. Unpublished calculations, by Hughes Aircraft Company and by Masahide Murakami at Ames Research Center, indicate that at the lowest helium flow rate (0.1 g/sec) the deposition rate of oxygen is much lower than that required to form a 0.1-μm layer on the primary mirror, even for the longest SIRTF missions.

An important consideration for any telescope is the method of pointing it at the desired object. This is a special problem with infrared telescopes because their objectives are often nonvisible. The SIRTF telescope must be pointed with an accuracy of about 1 arcsec in azimuth and elevation, and to about 30 arcsec around the telescope optical axis (roll). The roll accuracy is needed for off-axis tracking as discussed below, and is more than adequate for polarization studies. Stabilization of 0.25 arcsec rms is required. This pointing performance cannot be obtained if the sensors used are not directly coupled to the optical path. This is especially true for SIRTF because the inner cooled section must be thermally isolated from the ambient-temperature outer shell and this relatively flexible connection allows movement between the sections. This design problem is solved by using a pointing sensor at the focal plane.

As shown in Fig. 4, the visible portion of the beam passes through the beam splitter to the focal plane sensor optics. These optics provide a 30-arcmin-diameter field on the sensor so that the sensor can use stars near the edge of the telescope's 15 arcmin field-of-view. This allows an invisible infrared source to be tracked by using off-axis, visible stars. It is necessary to employ at least two guide stars when tracking off axis, in order to achieve the required accuracy around all three axes. A special system, called the Video Inertial Pointing (VIP) system,[15] is being developed to provide tracking error information based on as many as 10 stars in the field of view. VIP will use a multi-element charge-coupled-device array as the focal plane sensor. The Jet Propulsion Laboratory is presently developing techniques for interpolating the outputs of a 400-by-400 element array to provide the requisite accuracy for use in VIP. This type of pointing sensor can also provide a video presentation of the focal plane to the astronaut and to the astronomer on the ground; experience with balloon and aircraft programs has shown the value of this feature in allowing verification of the star field location.

The VIP will include a microprocessor to apply star magnitude thresholds, perform analog-to-digital conversion, perform position interpolation, and provide rms pointing errors both to the IPS gyros and to the pointing mirror servo drive for instantaneous pointing corrections. Acquisition and initial pointing will use the standard IPS star tracker array until the VIP focal plane sensor has acquired the programmed guide stars. The VIP system is described fully in Ref. 15.

When there are no guide stars as bright as $m_v = 11$ in the SIRTF telescope field of view, a laser source provides a high-bandwidth link between the external gyros and the internal sensor. The operation of this laser link is described in Ref. 13.

SIRTF requires a very high probability that guide stars will be in the tracker field of view for any infrared source location. To meet this requirement, guide stars of $m_v = 14$ may have to be used. Because of the multiple reflections in the folded Gregorian telescope, the mirrors must be silvered to minimize losses of visible energy prior to reaching the sensor. Techniques for depositing silver onto beryllium have been developed and tested and this does not appear to be a problem. However, overcoatings on the silver cannot be used because absorption of infrared energy by the overcoating may be unacceptable: as a result it will be necessary to maintain a vacuum or an inert atmosphere in the telescope at all times to protect the surfaces.

The sunshield is shown in Figs. 2 and 3 in the fully extended position. In the extended position, the shield shape approximates a paraboloid and it is cryogenically cooled. Made in three segments, the sunshield retracts over the end of the telescope for stowing. The inner surfaces are aluminized so that radiation from the earth at 30° or more to the line of

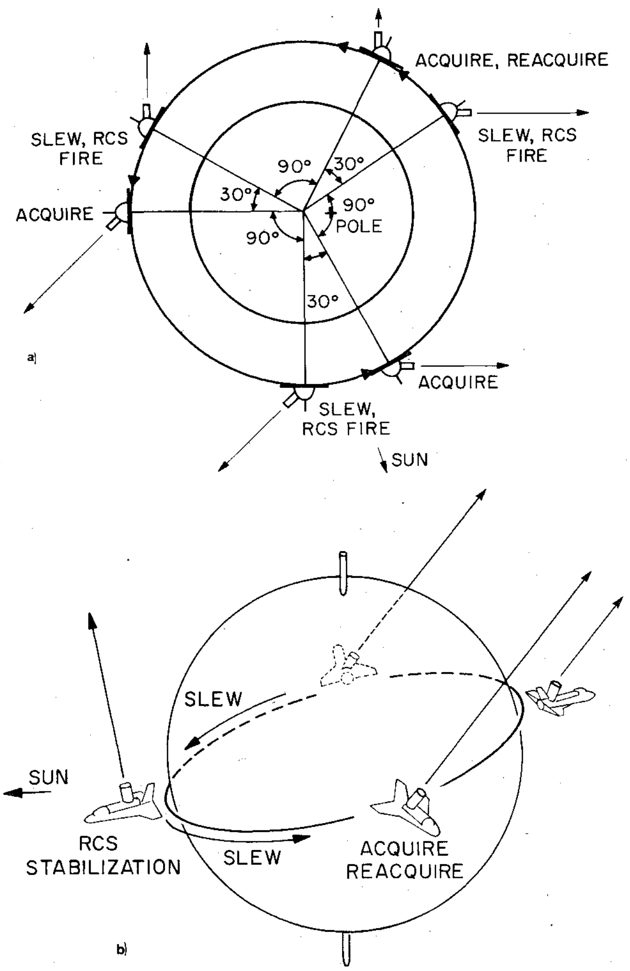

Fig. 6 Orbital orientation. a) Maximum sky coverage. b) Maximum viewing time between RCS firings.

sight, and from the sun at 45° or more from the line of sight, is reflected out of the sunshield. This design feature plays a major role in reducing the heat load into the telescope aperture and thereby reducing the cryogen use rate.

SIRTF Operations

Plans for on-orbit operations of SIRTF, the Space Shuttle, and ground control are guided by the need to provide maximum time for observing the astronomical objects of interest with minimum interference from contamination.

Prior to launch, the SIRTF will be loaded onto the orbiter under class 10,000 cleanroom conditions. The interior of the telescope will be maintained at a vacuum or will be helium-purged, except for short periods. If access to the interior is required, cleanliness requirements more strict than class 10,000 will be complied with. SIRTF will arrive at the launch site with its instrument payload integrated and its cover door shut. Cryogen will be loaded several days before launch and topped off several hours before launch. The cover door will not be opened until after approximately 24 hours in orbit to allow time for the Orbiter to offgas. Prior to opening, calibrations may be performed using sources internal to the SIRTF cover-door assembly. On the ground, special windows in the cover will allow alignment checks.

Once observations start, firing of the vernier rocket control system must be minimized. The Orbiter attitude will be set as desired for observing, and pitch, yaw, and roll rates that will avoid the need to slew the Orbiter through large angles will be initiated. The telescope gimbal (IPS) will perform the major slewing motions but large-angle slews will require too much time and will be avoided in flight planning. The telescope must pick a new object about three to four times during each 90-min orbit because, depending on orientation, its orbital motion brings a given object too close to (within 30° of) Earth in ¼ to ⅓ of an orbit.

One possible orientation for the Shuttle during SIRTF observations is shown in Fig. 6a. In this case the orbiter z-axis (out of the Shuttle bay) is continually aligned with local vertical, and the x-axis (longitudinal) is normal to the orbit plane. This orientation might allow observation of three objects per orbit for up to 20 min each, but there are some important qualifications. First, the drift rate for the Orbiter in this orientation may become high enough that the reaction control system (RCS) low-level thrusters will fire for several minutes. If this happens, the contamination from the reaction products may take several more minutes to clear. Second, AIRTF must acquire the guide star(s) and then the infrared object rapidly—this will be facilitated by the automatic or semi-automatic acquisition and pointing system previously described. Third, the Instrument Pointing System (IPS) gimbal servo torque capability to reorient rapidly the SIRTF telescope, with its very large moment of inertia, is marginal. Consequently the IPS development is being carefully reviewed.

A longer period between RCS firings can be obtained by stabilizing the orbiter in a tail-down (x-axis aligned with local vertical) orientation as shown in Fig. 6b. Analysis shows that only very infrequent thruster firings are required to damp out "pendulum" oscillations around this orientation. Although angular freedom of the telescope is limited by the need to prevent radiation from the earth or the orbiter nose from entering the aperture shade, it can be shown that 42% of the sky can be covered from this attitude. A 30° tilt from local vertical permits a much larger fraction to be observed.

One of the most important operational features of SIRTF will be the capability it provides for virtually direct control by astronomers from the ground. The ground operator will have access to near-real-time data via the Tracking and Data Relay Satellite System (TDRSS) for most of the flight, and with the presently defined uplink capability, he will be able to update the onboard control system with new observing programs as necessary. He will also be able to receive the output of the focal plane visual sensor and to guide manual operation by the trained astronaut, if such operation is necessary. This is similar to the approach that has been developed for the Kuiper Airborne Observatory's 91-cm infrared telescope.

The role of the payload operator will evolve with the use of the observatory. At first his role will be largely diagnostic; he will ascertain, through direct visual observation, that the telescope system is indeed functioning mechanically (door opens properly, mounting moves telescope properly, and he will serve as a back-up to some of the automated systems. If trouble occurs he will make repairs in accordance with instruction received from the ground. The computer will be preprogrammed with an observing sequence so that the telescope will operate automatically most of the time. All changes to this routine, whether from the ground or cabin, will be routed through the computer to check for violation of constraints (sun and Earth angle, interference with Orbiter structure). Small manipulations of the telescope, such as centering a faint star when several others are nearby, or making unprogrammed offsets from given objects, are best done by the onboard payload operator. Manipulations requiring judgment and iterative operations are easier from space because commands from the ground are delayed from a few tenths of a second to several seconds between initiation and verification of result (e.g., motion of a star on a ground-based TV in response to a command to offset the star). In addition, the Orbiter will be out of contact with the TDRSS during part of each orbit; for these periods only the payload operator and the computer will be available to respond to malfunctions or other deviations from expected behavior.

Astronomers on the ground will receive data in near-real time whenever possible. All remaining data from TDRSS blank periods will be recorded and dumped once per orbit. Investigators will be expected to analyze their data sufficiently, within minutes after receipt, to determine whether their instrument is working properly and whether their signal levels are reasonable within minutes after receipt. Decisions to change objects or instruments from the programmed sequence will be made on the ground and relayed either to the scientist-astronaut, or directly to the computer.

Concluding Remarks

The 1,2-m, cooled infrared telescope offers an enormous (by a factor of 1000 at 10 μm) improvement in sensitivity over any existing or currently planned telescope in the 5 to 200 μm wavelength range. The spectroscopy, photometry, and mapping of which this instrument is capable will greatly increase our understanding of star formation, planet formation, and galactic evolution. SIRTF will undoubtedly result in many discoveries, just as improvements in visible and ultraviolet telescopes have done in the past. But the magnitude of the improvement is much greater than that possible in visible and UV astronomy, because the latter have received much more attention and have thus realized more of their potential.

Careful design studies have shown that a 1 to 1.6-m telescope with reflecting optics for astronomical use in space is indeed feasible, and well within existing technology. Furthermore, it can be built to produce less infrared noise, in any 10 μm band (between 5 and 30 μm), to a 1-arcmin field-of-view detector than is expected from the space background. Such a telescope will be by far the most powerful tool available to infrared astronomers in the early Shuttle era.

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