Shuttle/Spacelab: Platform for a Cooled Infrared Astronomical Telescope

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Requirements imposed on the Shuttle/Spacelab by a large cooled infrared telescope fall into three general categories: 1) volume and weight carried into orbit to provide the needed facilities, especially the cryogen storage capacity; 2) stabilization and pointing; and 3) limitation of contamination of the telescope and surrounding atmosphere due to gasses and particles ejected from the Shuttle/Spacelab. These have been analyzed in conjunction with the preliminary design study of the Shuttle Infrared Telescope Facility (SIRTF). Volume and weight capacity are more than sufficient for standard 7-day Shuttle missions; the landing weight capability is marginal for extended (30-day) missions due to the increased SIRTF cryogen storage and the fuel cell reactant kits required for electrical power. The Spacelab Instrument Pointing System (IPS) performance has been analyzed and problems identified in angular coverage, pointing accuracy, and pointing stability. These are being solved by modifications in both the IPS and SIRTF. For contamination, the method of approach was first to establish allowable contamination levels based on the expected performance of the telescope as limited by natural phenomena or predicted technology state-of-the-art. Models of Shuttle contaminant emission were analyzed, and modifications to Shuttle subsystem design and operations (as well as telescope operations) have been recommended. The conclusion, based on analysis of the revised designs and operations, is that SIRTF will perform in the Shuttle/Spacelab at its design levels.

Nomenclature

CCD	= charge-coupled device
COM	= center of mass
FOV	= field of view
IPS	= instrument pointing system
LOS	= line of sight
NEP	= noise equivalent power
SIRTF	= Shuttle/Spacelab Infrared Telescope Facility
X_0	= Shuttle coordinate roll axis, in.
Y_0	= Shuttle coordinate pitch axis, in.
Z_0	= Shuttle coordinate yaw axis, in.

Introduction

THE infrared emission from both stellar and nonstellar objects is of importance in forming a complete picture of the basic processes of the universe. Some features, such as very cool gas clouds and protostellar objects, can be observed only in the infrared. Other areas of astronomical interest, such as galactic nuclei, typically are obscured by dust clouds that are quite transparent in the infrared but which are strongly attenuating at shorter wavelengths. Even objects that can be seen at other wavelengths reveal some of their most important information at infrared wavelengths; molecular spectra and the characteristic absorptions of some important solids are most prominent in the infrared.

The Shuttle Infrared Telescope Facility[1-3](SIRTF) is planned to provide a major advance in sensitivity of observations across the infrared spectrum from 1 μm to 1 mm. To accomplish its goal, SIRTF will operate in low Earth orbit, above most of the atmosphere. This eliminates the absorption by the atmosphere of the energy from astronomical sources, and greatly reduces the emission of background energy which interferes with astronomical observations. Further, the telescope can be cooled to cryogenic temperatures (to reduce interfering background due to self-emission) without condensing gasses on the telescope surfaces, which would degrade performance.

Requirements on the telescope are grouped in operational and performance categories. Operationally, the goal is that the system will provide the flexibility typical of a ground-based astronomical facility. First, the scientists must be able to install and check the instruments without working through additional personnel. Second, in orbit, SIRTF must acquire the astronomical object rapidly and with good reliability. Third, at least 20 min of uninterrupted viewing, with no contaminant events and with the telescope tracking within the ir diffraction limit, must be possible. Finally, the scientists on the ground must be able to receive the data directly and to change their observation program during the mission easily.

The performance goals for the telescope itself include, most importantly, diffraction limited resolution at 5 μm with a background limited sensitivity (noise equivalent power), for a field of view of 1 arcmin, of 10^{-17} W/Hz$^{1/2}$ in any 10-μm band from 5 μm to 30 μm, and of 10^{-16} W/Hz$^{1/2}$ in any 10-μm band from 30 μm to 200 μm. The telescope also is required to operate at wavelengths of up to 1 mm. These sensitivity requirements are exceeded by the present design; other requirements are reflected in the design characteristics that are discussed in subsequent sections.

Figure 1 shows a conceptual drawing of SIRTF mounted in the Shuttle payload bay. The remaining volume and weight may be occupied by small infrared instruments, compatible attached payloads of other disciplines, or free flyers.

The SIRTF telescope is mounted on the Instrument Pointing System (IPS) which in turn is mounted on a platform above the floor of the standard Spacelab pallet. (The IPS is being developed as part of Spacelab by the European Space Agency to provide a common pointing system for facility-class instruments.) This configuration allows SIRTF to utilize the full 60° half-angle cone pointing capability of the IPS.

Two supercritical helium tanks, each of 1300-liters (45-cu ft) capacity, will provide sufficient cooling for missions up to 30 days; one tank will suffice for 14-day and shorter missions. The favored configuration is to mount the cryogen tanks on the telescope; this eliminates the heat losses and technical risks in transferring the cryogen from pallet-mounted tanks.

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Index categories: Data Sensing, Presentation, and Transmission; Spacecraft Configurational and Structural Design (including Loads).

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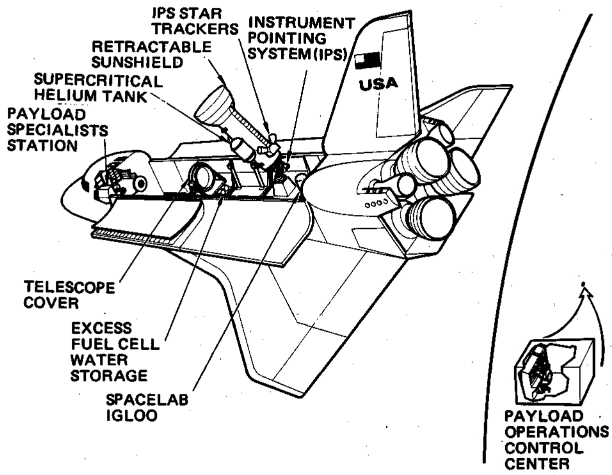


Fig. 1 Shuttle Infrared Telescope Facility (SIRTF).

Science data will be collected by replaceable instruments (e.g., photometers) located in the SIRTF focal plane. The science data will be digitized by a data preprocessor and transmitted through the Spacelab Remote Acquisition Unit to the Spacelab Experiment Computer for monitoring and, if necessary, further processing. The data then are transferred to the Shuttle data system for onboard processing and transmission to the ground. The command system follows, in reverse direction, the same path as the science data flow. Although it is expected that the observing program will be stored in the Spacelab Experiment Computer prior to flight, modifications and updating of the observing program can be made by the payload specialist on board or by the astronomers on the ground working through the Shuttle command system. SIRTF system parameters are shown in Table 1.

Three aspects of the interface definition between SIRTF and the Shuttle and Spacelab will be covered in this paper: 1) physical characteristics, weight and volume, 2) pointing and stabilization; and 3) contamination prevention in the surrounding atmosphere. In each of these areas, the Shuttle- or Spacelab-provided capabilities or functions are satisfactory if certain relatively minor modifications are provided.

Table 1 SIRTF system parameters

Telescope	
Aperture diameter	1.16 m
Field-of-view diameter	15 arcmin
Space chopping throw	±7.5 arcmin
Resolution	diffraction-limited at $\lambda = 5\ \mu m$ (3.5 arcsec diam)
Optics temperature	18-21 K
Sensitivity (NEP) (10-μm bandwidth)	
5-30μm (1-arcmin FOV)	1×10^{-17}W/Hz$^{1/2}$
5-30μm (diffraction-limited FOV)[a]	1×10^{-18}W/Hz$^{1/2}$
30-200μm (1-arcmin FOV)	1×10^{-16}W/Hz$^{1/2}$
Supercritical helium supply	
Open cycle (1300-liter tanks)	
7-14-day mission	1 tank
14-30-day mission	2 tanks
Data rate	3 Mbps
Power consumption (total maximum)	3 kW
SIRTF components	1 kW
Spacelab electronics	1 kW
IPS	1 kW
Mass	
7-day mission	
Launch	8,836 kg
Landing	7,912 kg
30-day mission	
Launch	19,229 kg
Landing	14,494 kg

[a] $8.3\times10^{-3}\lambda$ (μm) arcmin.

Physical Characteristics: Weight and Volume

Figures 2-4 show three possible configurations for mounting SIRTF in the Shuttle payload bay. The tables accompanying each of the figures show the major mass contributions, and the diagram shows the center-of-mass location within the Shuttle envelope along the length of the payload bay. Figure 2 shows SIRTF configured for a 7-day mission. Approximately half of the payload bay volume and half of the weight allowance is available for a second payload. The SIRTF telescope can be placed at any one of several positions along the payload bay length, and stowed pointing either forward or aft, thus accommodating a variety of additional payloads. The COM diagram shows, for example, the COM location with SIRTF mounted aft and a maximum mass secondary payload mounted forward.

Figure 3 shows SIRTF mounted for a 30-day mission. The payload bay volume and Shuttle weight capacity essentially are filled by the additional cryogen tank, fuel cell tanks (to supply the Shuttle and SIRTF) and water storage tanks required by the longer mission. It should be noted that the fuel cell reactant kits to meet the Shuttle power requirements occupy a major portion of what was available space in the 7-day mission.

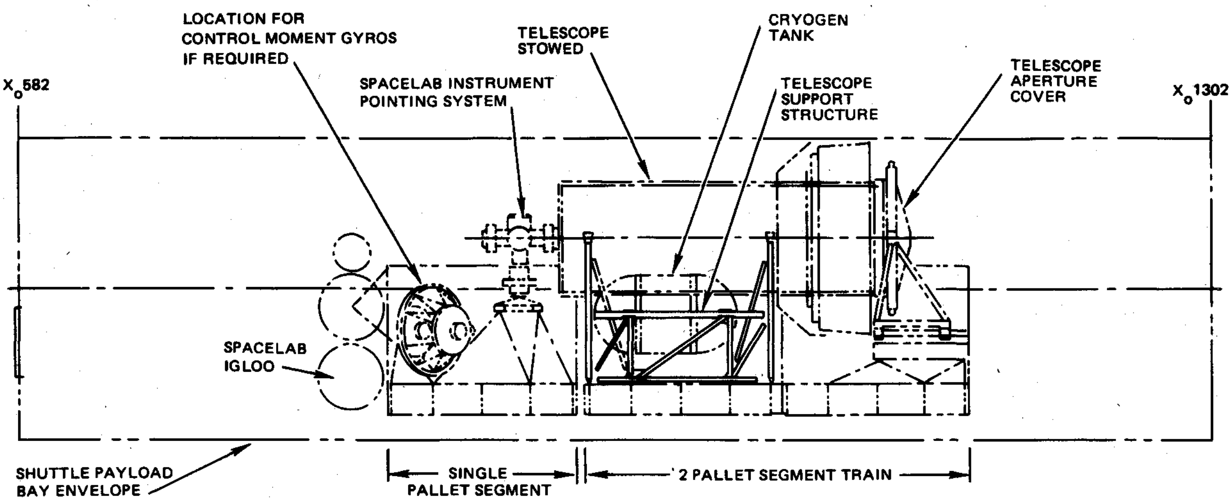
Figure 4 shows SIRTF (7-day mission configuration) mounted aft with a short Spacelab module mounted in the forward part of the payload bay. This configuration is advantageous because it allows the wide range of module-based experiments to be flown with SIRTF. The module provides the Spacelab Command and Data Management System without requiring the igloo (which is required for the pallet-only modes shown in Figs. 2 and 3). A 30-day mission is not possible with the module.

Pointing and Stabilization

The SIRTF telescope will be pointed and stabilized by the Spacelab Instrument Pointing System, with an additional internal fine stabilization subsystem. The IPS is an inside-out gimbal as shown in Fig. 5, which provides a maximum unconstrained volume for the IPS-mounted equipment. The IPS will be mounted above the Spacelab pallet floor on a pyramid base to provide maximum usage of the 60° half-angle cone provided by the IPS.

In order to provide the thermal isolation of the SIRTF optics which is necessary in order to achieve the desired sensitivity, the telescope structure consists essentially of two concentric cylindrical shells which are connected by a fiberglass cone structure. The gimbal structure is attached to the outer telescope shell, and the optics are supported by the inner shell. Because of its double-shell configuration the telescope cannot be made highly rigid. However, preliminary analysis has indicated that the lowest modal frequency of the telescope will be on the order of 30 to 50 Hz. The SIRTF design goal is that the rms jitter of the telescope image be less than 0.25 arcsec. Vibration at the telescope modal frequencies can cause an increase in the size of the image blur and hence, degradation of the telescope's performance and usefulness. This is one factor leading to the requirement for an internal fine stabilization system.

The second reason for an internal fine stabilization system is based on IPS characteristics. It is expected that some modal frequencies of the IPS will be much lower than the telescope lowest frequency, and will limit the stabilization loop to a bandwidth of less than 5 Hz. Thus, the IPS stabilization will not be able to correct for all telescope vibration excursions. Further, the basic pointing accuracy of the IPS may be insufficient to meet the SIRTF requirements.



	LAUNCH MASS		LANDING MASS	
	KG	LB	KG	LB
IPS PALLET	2463	5428	2460	5422
TELESCOPE PALLET TRAIN	4767	10511	4612	10169
EQUIPMENT UNDER CARGO BAY FLOOR	1449	3194	683	1506
ORBITER AFT FLIGHT DECK	157	346	157	346
TOTAL	8836	19479	7912	17443

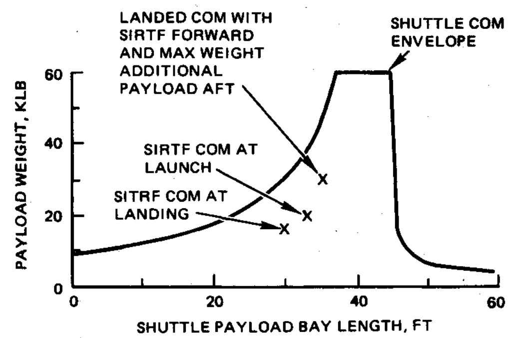
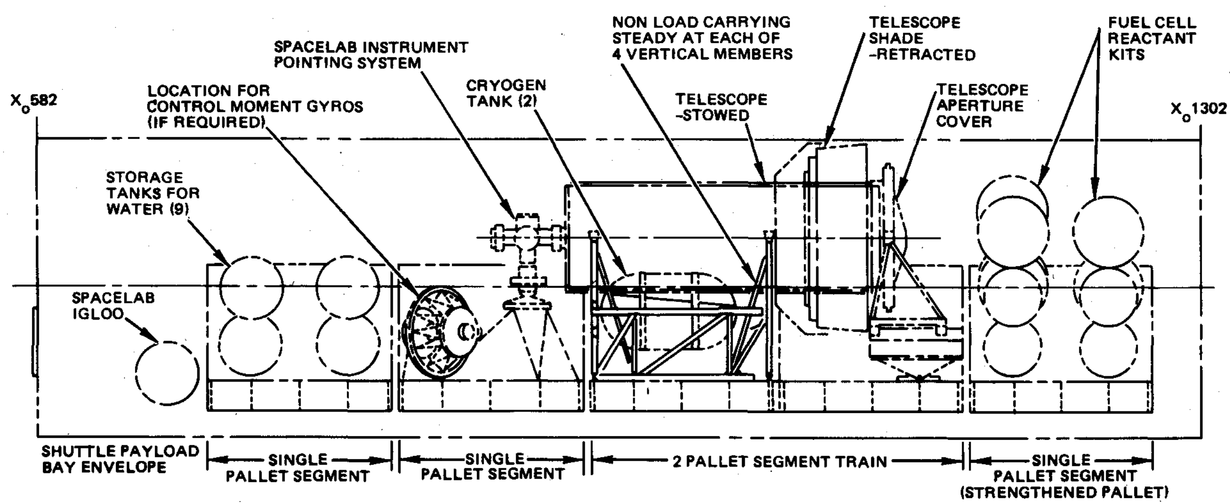


Fig. 2 SIRTF mounted on Spacelab pallets in Shuttle payload bay (7-day mission configuration).



	LAUNCH MASS		LANDING MASS	
	KG	LB	KG	LB
WATER STORAGE PALLET	1995	4397	1980	4365
IPS PALLET	1469	3238	1469	3238
TELESCOPE PALLET TRAIN	5220	11508	4886	10772
IPS KIT PALLET	5747	12670	2975	6359
EQUIPMENT UNDER CARGO BAY FLOOR	3748	8263	2207	4865
ORBITER AFT FLIGHT DECK	1050	2315	977	2154
TOTAL	19229	42391	14494	31953

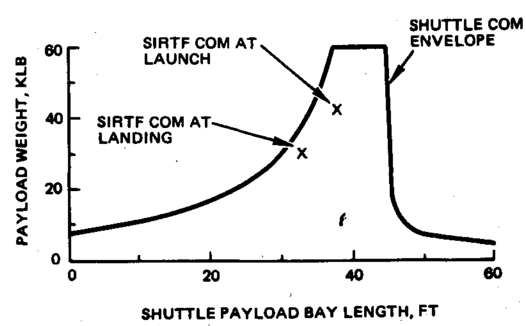
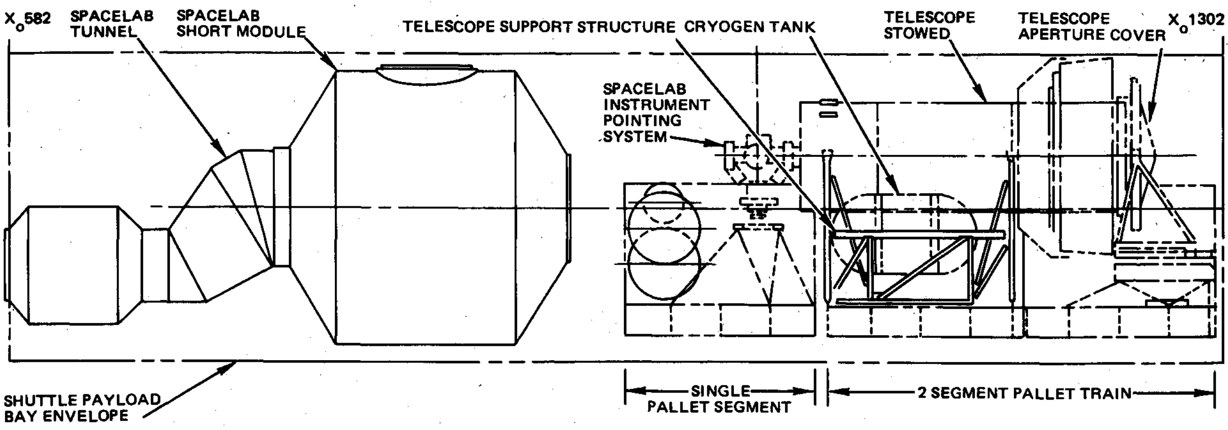


Fig. 3 SIRTF mounted on spacelab pallets in Shuttle payload bay (30-day mission configuration).



	LAUNCH MASS		LANDING MASS	
	KG	LB	KG	LB
IPS PALLET	1911	3212	1908	4206
TELESCOPE PALLET TRAIN	4767	10511	4612	10169
EQUIPMENT UNDER CARGO BAY FLOOR	1449	3194	683	1506
ORBITER AFT FLIGHT DECK	157	346	157	346
SHORT MODULE WITH TRANSFER TUNNEL	5332	11730	5332	11730
TOTAL	13616	29993	12692	27957

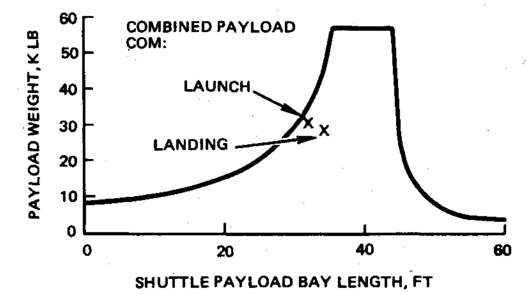


Fig. 4 SIRTF mounted on Spacelab pallets in Shuttle payload bay (7-day mission with short module).

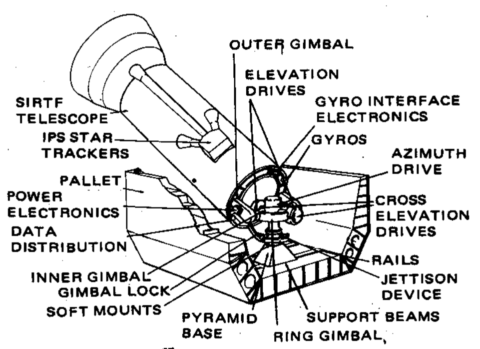


Fig. 5 IPS gimbal configuration.

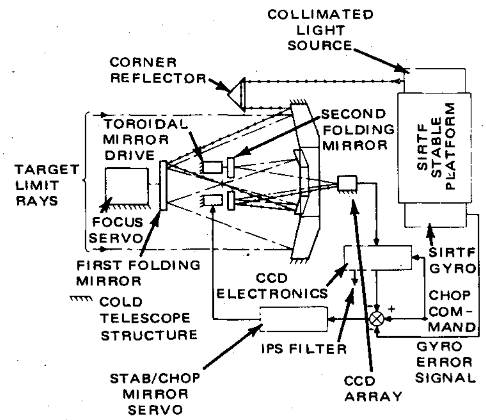


Fig. 6 Optical stabilization loop using CCD array detector.

Figure 6 is a block diagram of the SIRTF internal fine stabilization subsystem.[4,5] When a bright guide star is in the field of view, it is sensed by the charge-coupled device (CCD) array star tracker and the line of sight is stabilized by driving the steerable second folding mirror. Since the second folding mirror is small, light, and rigid compared to the telescope, it can be driven by servos with bandwidths higher than the lowest telescope frequencies as well as higher than that of the IPS stabilization system.

When only weak stars are in the field of view, the CCD sensitivity is insufficient to provide signals for correction of disturbances at the necessary bandwidth. The collimated source produces a stabilized artificial star which is sensed by the CCD array. The servo-electronics then drive the steerable second folding mirror to maintain the stability of the line of sight.

A further improvement is achieved by using the fact that there is an error between the gyro spin axis and the gyro case (which stabilizes the artificial star). The gyro output signals are used to correct the stabilization based on the artificial star. Since the gyro output signals drive the second folding mirror in an open-loop manner, the ultimate accuracy of the line of sight will be limited by uncertainties in the gyro scale factor and mirror drive servo. Past experience indicates that the LOS accuracy can be improved by as much as a factor of 20 by applying open-loop corrections to the autoalignment mirror. Gyro drifts are corrected periodically by reading the position of a guide star in the field of view and feeding the signal to the servo system.

The final element of the stabilization system is the feeding of a slaving signal from the SIRTF stable platform to the IPS servo (see Fig. 7). Because the Spacelab subsystem computer (which controls the IPS) and the Spacelab experiment computer (which controls the SIRTF) are connected to their respective units by data busses which may be pre-empted by other systems for periods of up to one second, they cannot be used as elements of the slaving loop. Hence, direct connections from the SIRTF gyro platform to the IPS servo will be required. Table 2 summarizes the predicted performance of the combined IPS-SIRTF stabilization system.

Radiometric Performance and Contamination

The SIRTF specification calls for a telescope design which will provide the levels of performance listed in Table 3. The

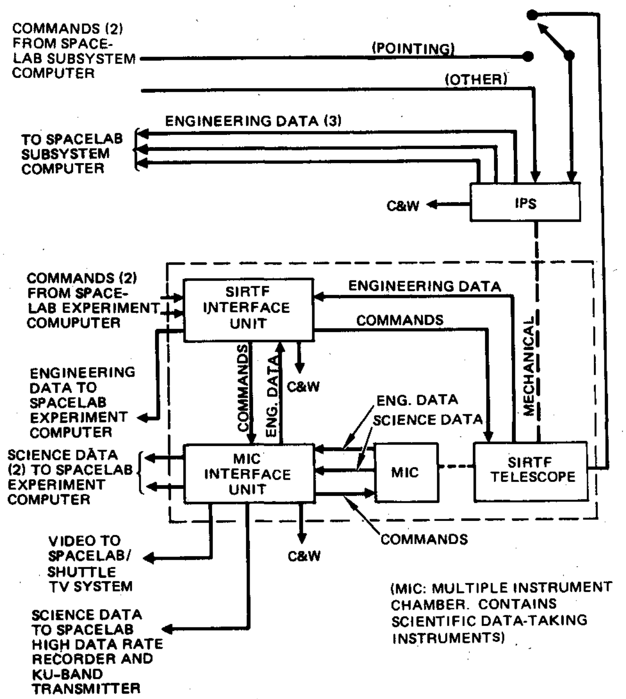


Fig. 7 IPS gimbal slaving.

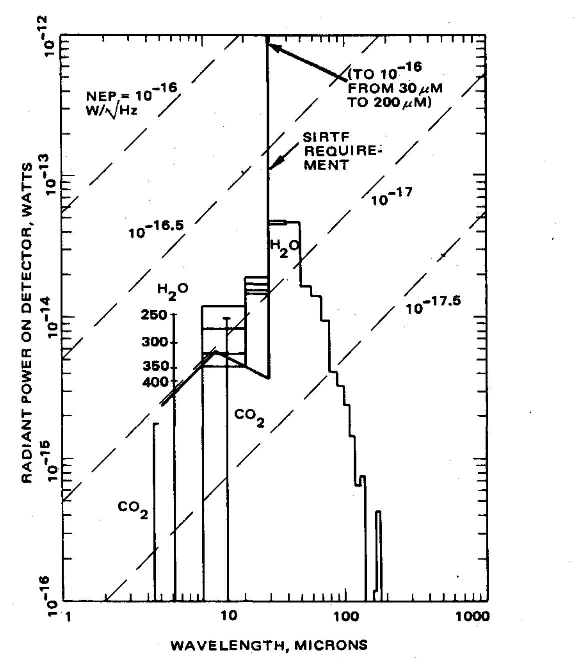


Fig. 8 Radiant power on the 1-arcmin-diam SIRTF detector due to water and carbon dioxide released by the Shuttle (horizontal bars indicate variation with altitude in 50-km increments from 250 to 400 km).

required sensitivity is achieved by cooling the telescope to 18 K (to meet the 200 μm requirement) or 21 K (to meet the 30-μm requirement). The 1-arcmin field-of-view requirement dominates in the 5-μm to 12-μm band, whereas the 8.3×10^{-3} λ arcmin FOV requirement dominates from 12-μm to 30-μm. However, the telescope sensitivity probably will be limited by external phenomena; residual atmosphere above the Shuttle, zodiacal emission, and molecular and particulate contaminants ejected by the Shuttle.[6] The Shuttle molecular contaminants are the phenomena of interest here.

Table 2 SIRTF-IPS stabilization performance

IPS gimbal angular coverage	
Coarse pointing	
Elevation	±60°
Cross-elevation	±90°
Azimuth	±180°
Fine pointing	
Elevation	±1°
Cross-elevation	±1°
Azimuth	±1°
IPS gimbal stabilization (bias + jitter)	
Coarse pointing	
All axes	±30 arcsec, rms to ±1 arcmin, rms
Fine pointing	
Elevation	±1 arcsec, rms
Cross-elevation	±1 arcsec, rms
Roll (about LOS)	±30 arcsec, rms
SIRTF gyro-platform stabilization (bias + jitter)	1 arcsec, rms (orthogonal to LOS)
Overall LOS stabilization[a] (bias + jitter)	1.4 arcsec, rms (orthogonal to LOS)

[a] With internal stabilization system and gyro feedforward signals.

Table 3 SIRTF radiometric performance specification

Wavelength range, μm	FOV diameter, arcmin	NEP, W/Hz$^{1/2}$-10 μm
5-30	1.0	10^{-17}
5-30	$8.3\times10^{-3}\lambda(\mu m)$	10^{-18}
30-200	1.0	10^{-16}

Figure 8 illustrates the situation with respect to the Shuttle-generated contaminants. The column densities assumed in Fig. 8 are 10^{12} molecules/cm^2 of H_2O and 2×10^{11} molecules/cm^2 of CO_2. Other assumptions relevant to the radiance values (e.g., temperatures) are discussed in Ref. 6. As Fig. 8 shows, one water and one carbon dioxide line exceed the SIRTF requirement level, although there is not enough energy in the lines to exceed the requirement over its 10-μm band. The only band where contamination will limit telescope performance is 10-μm to 30-μm where the H_2O rotational lines exceed the NEP requirement by about a factor of 3. The actual column density of water vapor will vary as a function of Shuttle operations, Shuttle orientation, and line of sight, as discussed in the following.

Figures 9 and 10 are plots of the individual contributions to the 10-20-μm and 20-30-μm water vapor rotation band background for various orientations of the Shuttle and the SIRTF LOS. The contributors considered are early desorption from the Shuttle surfaces, cabin leakage, and flash evaporator water. The flash evaporator location used is $X_0 = 1504$, $Y_0 = 127$, $Z_0 = 305$. Because position 1, LOS$+Z$ is looking directly at the sun, it has been disregarded. In position 3, the $50° + Y$ LOS is away from the sun.

Figure 9 shows that, for the 10-20-μm band, best performance will be attained in the $50° + X$ LOS orientation because of a negligible contribution from the flash evaporators. NEP's will range from 10^{-17} to 3×10^{-18} W/Hz$^{1/2}$. The contributions from early desorption and cabin leakage are comparable, so both would have to be reduced to improve performance significantly.

The performance at the other LOS positions will be degraded when the evaporators are operating. The radiant power on the detector is the appropriate parameter here, since the evaporator pulses will produce a changing background. This is in contrast to the steady background of desorption and leakage, the noise from which is due to photon arrival fluctuations.

Figure 10 shows much the same situation for the 20-30-μm band. The range of early desorption and leakage background is somewhat wider than for the 10-20-μm band, and the separation between these contributors and the evaporator levels is narrow. However, in both wavelength bands, design-

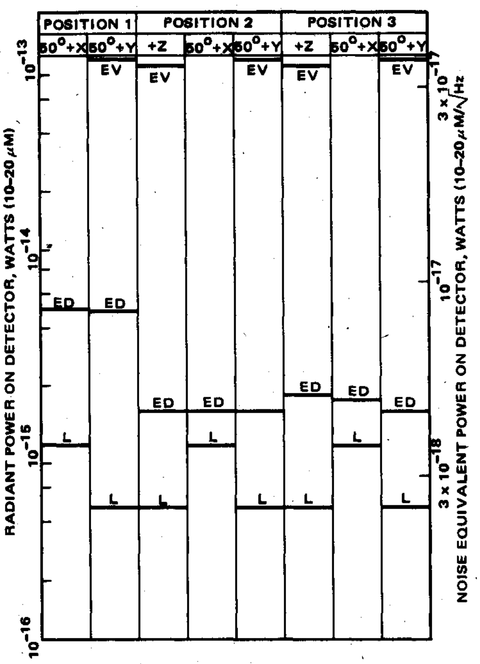


Fig. 9 Water vapor rotation band radiation (10-20-μm); ED = early desorption, L = cabin leakage, EV = evaporators, Position 1 = top of Shuttle and payload bay facing Sun, Position 2 = top of Shuttle and payload bay facing away from Sun and Earth, Position 3 = one side of Shuttle facing Sun (payload bay shaded), LOS $+Z$ = straight up out of payload bay, LOS 50° $+X$ = forward over cabin 50° from perpendicular to payload bay floor, LOS 50° + Y = over wings 50° from perpendicular to payload bay floor.

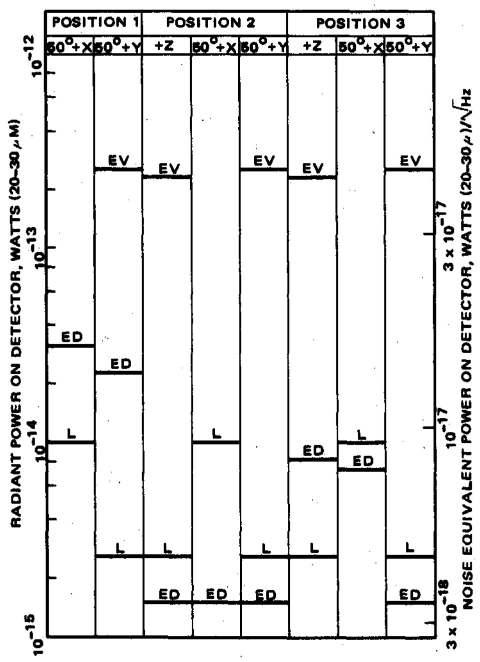


Fig. 10 Water vapor rotation band radiation (20-30-μm). Explanation of symbols given in Fig. 9 caption.

level performance will be obtained only along the 50° $+X$ LOS or when the evaporators are not being used.

Since the evaporators are a prime concern, SIRTF planning includes tanks for water storage during periods that the evaporators are not required for heat rejection. These tanks can be emptied periodically at times when observations will not be impaired by a high level of molecular water and/or ice particles in the Shuttle vicinity.

The water vapor column density produced by the small attitude control system engine firings is about 2.5 orders of magnitude higher than that shown in Fig. 9,[7] with the result that the limitation on sensitivity is 10-20 times worse than the requirement, i.e., in the low 10^{-16} W/Hz$^{1/2}$ region. Since these estimates do not consider scattering from the plume or by ambient atmosphere, they may be unrealistically high. However, there are two ways to minimize interference: 1) operation in the nose- or tail-down gravity-gradient mode to reduce engine firings to an absolute minimum, or 2) use of control moment gyros for Shuttle stabilization to eliminate the need for engine firings during observation periods. Gravity-gradient mode operation will make use of the combined SIRTF-IPS pointing system over large slew angles to provide the requisite long integration times.

Conclusions

The results of the Shuttle integration portion of the SIRTF preliminary design study show:

1) The volume and weight capability of the Shuttle is adequate for SIRTF needs and will allow the flying of a second payload or short Spacelab module on 7-day flights.

2) The Spacelab IPS pointing and stabilization system, with the addition of a SIRTF fine stabilization system, will provide the pointing freedom and stability necessary for SIRTF to reach its design goals.

3) Contamination from Shuttle effluents will be significant only in the band from 10-μm to 30-μm, where it will degrade performance by a factor estimated at 3. This degradation in general will occur only with the evaporators operating, so that it does not represent a significant degradation of performance.

Thus, SIRTF will perform in the Shuttle/Spacelab at its design levels.

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