

Infrared spectrograph for the Space Infrared Telescope Facility (SIRTF)

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ABSTRACT

The Infrared Spectrograph (IRS) will provide the Space Infrared Telescope Facility (SIRTF) with low and moderate-spectral resolution spectroscopic capabilities from 4 to 40 microns. The IRS is composed of four separate modules, with two of the modules providing $R \sim 50$ spectral resolution over 4 to 40 microns and two modules providing $R \sim 600$ spectral resolution over 10 to 37 microns. Each module has its own entrance slit in the focal plane and the IRS instrument has no moving parts. The low-resolution modules employ long slit designs that allow both spectral and one-dimensional spatial information to be acquired simultaneously on the same detector array. Two small imaging sub-arrays in one of the low-resolution modules will also allow infrared objects with poorly known positions to be accurately placed into any of the IRS modules' entrance slits. The high-resolution modules use a cross-dispersed echelle design that gives both spectral and limited spatial measurements on the same detector array. The one-sigma continuum sensitivity requirements for the IRS low-resolution modules are 0.11 mJy from 6 to 15 microns and 0.30 mJy from 15 to 40 microns in 500 seconds of integration. The high-resolution modules' one-sigma line sensitivity requirements are 6.0×10^{-23} W-cm⁻² in the same integration time. Internal calibration sources allow the IRS to perform self monitoring of detector sensitivity changes. Careful thermal design allows all four modules to be powered up simultaneously and still input less than 4 mW total power into the SIRTF liquid helium bath. The optical, mechanical, thermal, and electrical design of the IRS is discussed, as is the IRS on-orbit operational concept.

Keywords: Infrared Astronomy, Spectroscopy, Infrared Instrumentation

1. SCIENCE GOALS

The Space Infrared Telescope Facility (SIRTF) is the last of the four Great Observatories to be developed by NASA. Superfluid helium-cooled optics and a heliocentric orbit will give SIRTF the ability to make infrared observations over a > 2.5 year period with unprecedented sensitivity¹. Three focal plane instrument, the Infrared Camera (IRAC), the Infrared Spectrograph (IRS), and the Multiband Imaging Photometer (MIPS) will share the SIRTF telescope focal plane. The entire SIRTF observatory design has been optimized to address four important scientific questions, with the Infrared Spectrograph playing a crucial role in all four.

1) *To search for and study brown dwarfs and super planets in the nearby solar neighborhood.* Onboard SIRTF, the IRAC instrument has been designed and optimized to conduct both deep and wide-area searches for potential brown dwarf and super planet candidates. Once such candidates are found, the IRS will be the ideal instrument for spectroscopic follow up, thereby confirming the identification. Furthermore, systematic studies of brown dwarf and super planet atmospheres can be conducted from 4 to 40 microns using the IRS without any interference from telluric absorption.

2) *To discover and study protoplanetary and planetary debris disks.* Surveys with the IRAC and MIPS instruments should yield a large sample of protoplanetary and planetary debris disk objects. Spectroscopic follow-up with the IRS will be crucial in determining the dust and gas composition of these disks. Similar IRS observations of objects in our own solar system will

help to determine the uniqueness of our planetary system and will greatly improve the estimates of the frequency of other life-bearing planets in the universe.

3) *To study ultraluminous galaxies and active galactic nuclei.* By measuring the location of the silicate feature, the IRS will be able to measure red-shifts out to $z \sim 2.5$ even in heavily dust-enshrouded objects. Together with far-infrared photometric measurements from MIPS, this information can then be used to determine the total luminosity of these objects. IRS line and band emission studies can also be used to elemental abundance and dust composition studies for the ultraluminous objects that are found.

4) *To study the structure and composition of the early universe.* Again, spectroscopic observations will be far more accurate in determining red-shifts than are photometric observations. Measurements of the red-shifted 1.6 μm spectral energy bump, the 3.3 and 7.7 μm UIR complexes, or the 10 micron silicate feature will be important in three-dimensionally mapping the early universe objects found by SIRTf.

In addition to the "Big Four" studies above, the extraordinary sensitivity of the IRS will permit new spectroscopic studies of a wide variety of faint astronomical objects. In order to carry out these studies, both low and moderate-spectral resolution capabilities are needed, coupled with extremely high sensitivity. The IRS instrument has a five-sigma sensitivity requirement of 0.55 mJy from 5 to 15 μm and 1.5 mJy from 15 to 40 μm in 500 seconds of integration time in the low resolution mode. This requirement applies averaged over the relevant wavelength range and at a smoothed spectral resolution ($\lambda/\Delta\lambda$) of 50. An additional line sensitivity requirement for moderate-resolution observations is $3.0 \times 10^{-22} \text{ W-cm}^{-2}$, 5-sigma, in 500 seconds of integration time. This requirement applies from 10 to 37 μm . Further details on the flowdown of the IRS science requirements into the IRS design can be found elsewhere².

2. OVERALL DESIGN PHILOSOPHY

In order to fit a Great Observatory into NASA's "Faster, Cheaper, Better" paradigm, the entire SIRTf program is being developed under severe cost and schedule constraints. The IRS instrument has adopted the following set of guiding design axioms to enable the instrument to be delivered within these constraints:

- The IRS detector focal planes will be 128 x 128 pixel Blocked Impurity Band (BIB) devices from Boeing North American
- The IRS will have all-aluminum housings and optics, except for a limited number of order-sorting and blocking filters
- The IRS will have simple reflective optics composed solely of flat gratings, surfaces of revolution on any powered mirrors, and will not contain any adjustment provisions other than initial shimming
- The IRS will have no moving parts
- There will be redundancy for only credible single-point failures
- The IRS will have a goal of 80% observing efficiency
- The IRS shall be cable of its own internal health assessment

Based on the science requirements and the axioms listed above, a preliminary design for the IRS has been prepared. This design has passed through a formal Preliminary Design Review in September, 1997 and the short-low module and instrument detector arrays have subsequently passed through formal Critical Design Reviews. This paper gives an overview of the IRS design to date.

The IRS instrument consists of two physically separated parts, the cold assemblies which are located within the SIRTf multiple instrument chamber and the warm electronics, which are located in the SIRTf spacecraft bus. As the design of the SIRTf observatory was refined over the years, it was found that cost, mass, and volume savings could be achieved by combining the warm electronics from the IRS and MIPS instruments. In order to keep the optical design simple and simplify the test and verification requirements, the IRS cold assemblies are composed of the four separate spectrograph modules shown in Table 1. Two of the modules provide low-resolution spectroscopy and two provide moderate spectral resolution. Each of the four IRS modules have their own pick-off mirror in the SIRTf telescope field of view. The short-low module incorporates two separate optical trains feeding different areas of the same focal plane detector array and provides both low-resolution spectroscopy and imaging. The imaging feature of this module will be used to accurately determine the positions of IR

objects which have poorly-known locations in the sky, so that they can be subsequently placed onto the other IRS entrance slits. In order to facilitate this function, the imaging section of the short-low detector array is further split into a blue section with a filter pass-band centered at 15.0 μm and a red section with a filter pass-band centered at 23.5 μm .

Table 1: The IRS instrument modules

Module	Detector Material	Wavelength Range	Resolving Power
Short-Low - Spectroscopy	Si:As (BIB)	6-15*	50-120
Short-Low - Peak Up		13-17 and 21-26	N/A
Long-Low	Si:Sb (BIB)	15-40	50-120
Short-High	Si:As (BIB)	10-19	~600
Long-High	Si:Sb (BIB)	19-37	~600

* The Short-Low spectrograph module will be capable of operation at wavelengths down to 4.0 microns in its spectroscopy mode, but without any performance requirements in the 4.0-6.0 μm range.

3. MECHANICAL DESIGN

The overall mechanical design of the cold assemblies portion of the IRS is shown in Figure 1. Each IRS module has its own enclosure and internal baffling and is attached to the common IRS baseplate by a three-point attachment.

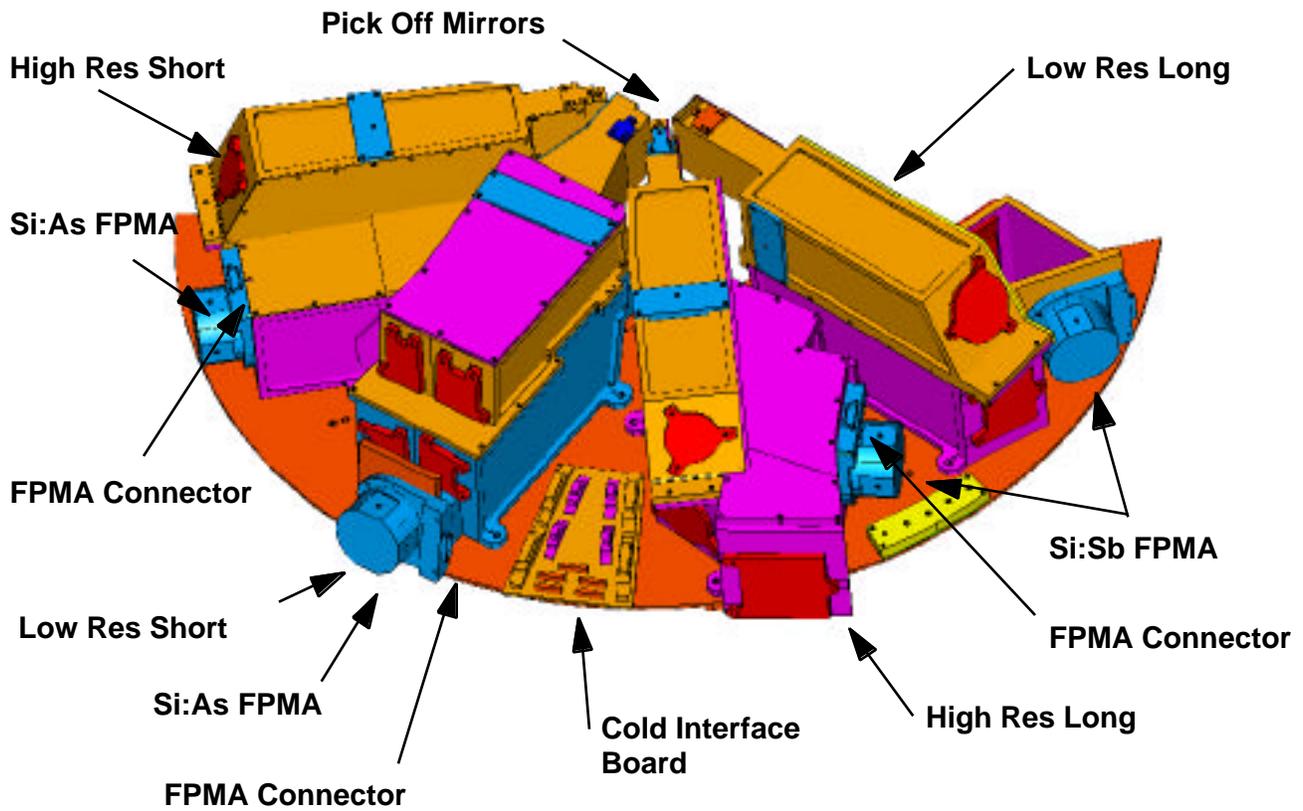


Figure 1. The IRS cold assemblies. The entire IRS cold section fits into a roughly 160° pie-slice section of the SIRTf Multiple Instrument Chamber (MIC).

The common baseplate is in turn attached through a three-point attachment to the floor of the SIRTf Multiple Instrument Chamber (MIC). In order to provide sufficient shielding to meet the ionizing radiation requirements of the IRS detectors, there is a minimum of 1.8 cm of path length through aluminum along any direction into each module's focal plane. For the most directions this aluminum shielding is provided as part of the detector Focal Plane Mount Assemblies (FPMA), but where needed some portions of the module enclosures have thickened wall sections. Each IRS spectrograph module has its own thermal link between its FPMA and the SIRTf helium bath; no thermal power is carried by the IRS baseplate. The entire IRS cold assembly, including the IRS common baseplate, has an estimated mass of 18.0 kg, including a 12% contingency.

4. OPTICAL DESIGN

The optical design of each of the IRS spectrograph chains was organized along a set of common design rules. The physical dimension of each module entrance slit width was set at $T_{\text{fl max}}/D$, where $T_{\text{fl max}}$ is the maximum wavelength of that module, D is the effective diameter of the SIRTf primary mirror (85cm) and T_{fl} is the SIRTf telescope effective focal length. Internally, each module then mapped this slit width geometrically across two pixels on its detector array. Slit lengths were set to be as long as possible, limited by the sizes of the detector arrays and the requirement to keep the different orders separated in the cross-dispersed echelle modules. All of the IRS module optics are over-sized by at least 30% to minimize internal diffraction effects and have their optical surfaces coated with protected gold to enhance their infrared reflectivity. With the exception of the imaging train of the short-low module, none of the modules have internal Lyot stops.

4.1 Short-low module The optical layout of the IRS short-low module is shown in Figure 2. The module enclosure houses two separate optical trains that are fed by two separate telescope focal-plane pick-off mirrors.

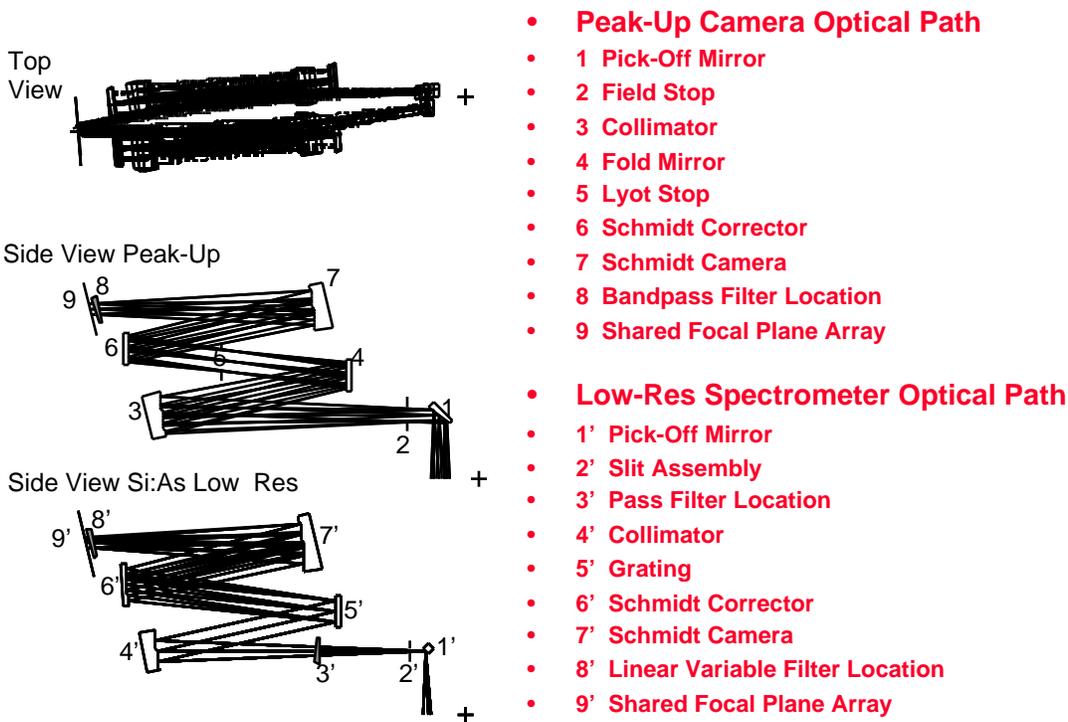


Figure 2. The IRS short-low module optical layout.

The spectrograph entrance slit of the short-low module is divided into two equal first and second-order portions. The actual order-sorting itself is accomplished by two focal plane linear-variable filters located near the short-low detector focal plane. The imaging optical train feeds two separate fields on the short-low detector array. Short and long-bandpass filters in front of each of these fields allow optimal positioning of any infrared point-source into any of the IRS spectrograph apertures. Although the short-low module imaging train can be used as a sensitive two-color infrared camera, its only design and performance requirements are to fulfill its pointing function. As a peak-up camera, the imaging train of the short-low module

has a requirement to measure the centroid of an object in the short-wavelength sub-array to within 0.15", single-axis, on a target brighter than 8.5 mJy at 14 μm in 80 seconds. The optical characteristics of the short low module are given in Table 2.

Table 2. The optical characteristics of the IRS short-low module

Spectrograph train entrance aperture size (dispersion x cross-dispersion directions)	2 x 30 pixels @ 3.75-7.5 μm (3.6" x 54.6" on sky) 2 x 30 pixels @ 7.5-15.0 μm (3.6" x 54.6" on sky)
Peak-up train entrance aperture size	45 x 33 pixels at 13-17 μm (81.9" x 60.1" on sky) 45 x 33 pixels at 21-26 μm (81.9" x 60.1" on sky)
Estimated peak-up train sensitivity when used as a camera (13-17 μm)	0.06 mJy, 1-sigma, in 40 seconds integration time
Spectrograph train resolving power (/)	50-120
Spectrograph train F/#	10
Peak-up train F/#	10
Grating ruling	5.84 lines/mm, blazed for 11.5 μm
Wavefront aberrations, including those due to manufacturing and alignment tolerances	/21 at 15 μm
Detector array anti-reflection coating	ZnS

4.2 Long-low module The optical layout of the IRS long-low module is shown in Figure 3. The module enclosure houses a single optical train fed by one telescope focal-plane pick-off mirror. The spectrograph entrance slit of the long-low module is divided into two equal first and second-order portions. The actual order-sorting itself is accomplished by two focal plane linear-variable filters located near the long-low detector focal plane. The optical characteristics of the long-low module are given in Table 3.

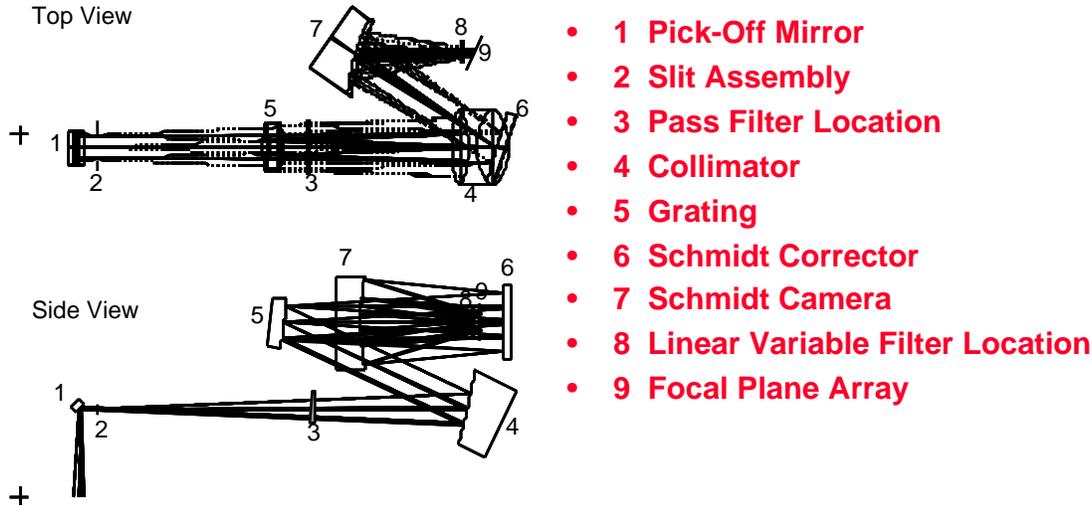


Figure 3. The IRS long-low module optical layout.

Table 3. The optical characteristics of the IRS long-low module

Entrance aperture size (dispersion x cross-dispersion directions)	2 x 30 pixels @ 15-21 μm (9.7" x 145.5" on sky) 2 x 30 pixels @ 21-40 μm (9.7" x 145.5" on sky)
Spectrograph resolving power (/)	50-120
Spectrograph F/#	3.75
Grating ruling	5.62 lines/mm, blazed for 31.5 μm
Wavefront aberrations residual to the design	$\lambda/38$ at 40 μm
Detector array anti-reflection coating	Diamond

4.3 Short-high module The optical layout of the IRS short-high module is shown in Figure 4. The module enclosure houses a single optical train fed by one telescope focal plane pick-off mirror. The spectrograph entrance slit of the short-high module was designed to be as long as possible, subject to the constraint of keeping the different spectral orders separated on the detector array. The optical characteristics of the short-high module are given in Table 4. As part of the IRS technology development, a spectrograph very similar in design to the IRS short-high module has been constructed and has operated successfully at various ground-based telescopes³.

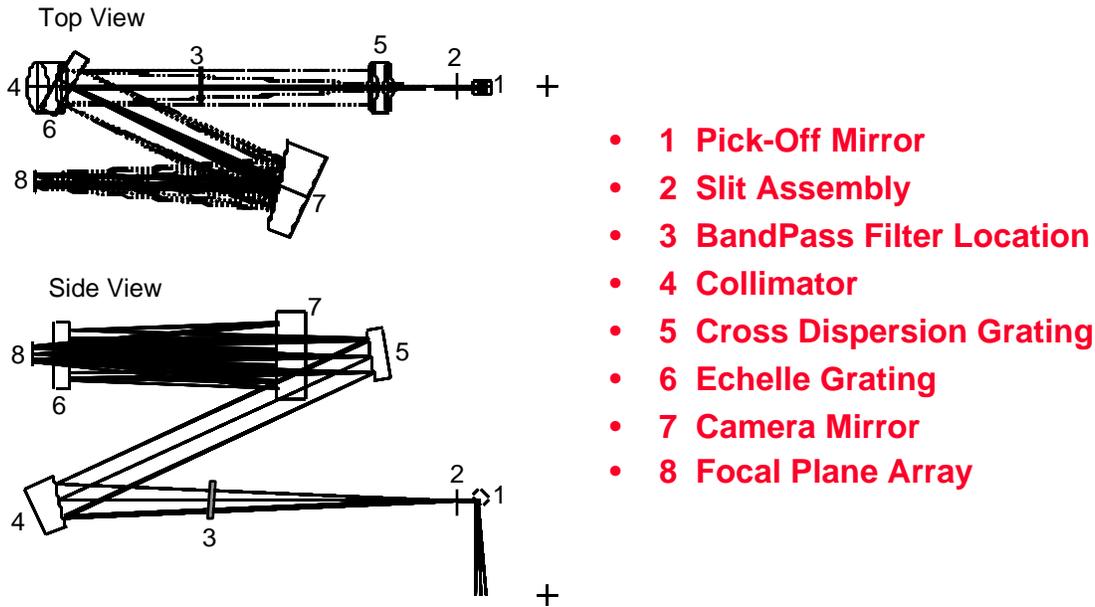


Figure 4. The IRS short-high module optical layout.

Table 4. The optical characteristics of the IRS short-high module

Entrance aperture size (dispersion x cross-dispersion directions)	2 x 5 pixels @ 10.0-19.5 μm (4.8" x 12.1" on sky)
Spectrograph resolving power (/)	~600
Grating rulings	5.01 and 2.37 lines/mm, blazed for 12.1 μm
Spectrograph F/#	10
Detector array anti-reflection coating	ZnS

4.4 Long-high module

The optical layout of the IRS long-high module is shown in Figure 5. The module enclosure houses a single optical train fed by one telescope focal plane pick-off mirror. The spectrograph entrance slit of the short-high module was again designed to be as long as possible, given the order separation constraint. The optical characteristics of the long-low module are given in Table 5.

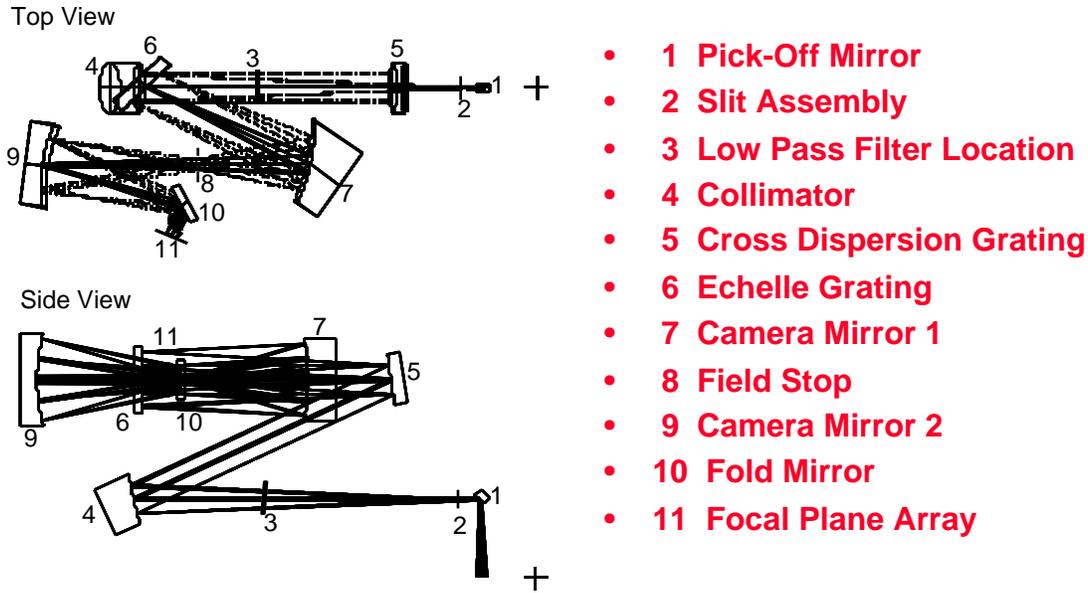


Figure 5. The IRS long-high module optical layout.

Table 5. The optical characteristics of the IRS long-high module

Entrance aperture size (dispersion x cross-dispersion directions)	2 x 5 pixels @ 19.0-37.0 μm (9.7" x 24.2" on sky)
Spectrograph resolving power (/)	~600
Grating rulings	4.46 and 2.02 lines/mm, blazed for 27.1 μm
Spectrograph F/#	7.5
Detector array anti-reflection coating	ZnSe

5. FOCAL PLANE DETECTORS

The IRS detector arrays are of a backside-illuminated Blocked Impurity Band (BIB) design. Both of the detector array technologies that will be used in the IRS have passed a critical design review and are now in production for the IRS flight instrument. Each detector consists of two parts: (1) a detector assembly that contains the detector material itself arranged in a 128 x 128 square pixel pattern bump-bonded to an underlying cryogenic multiplexer, and (2) a nearby satellite chip, which provides clocking functions and a low-impedance output signal driver. In separating these two chips, the power dissipated in the output driver transistors does not directly couple into the infrared detectors themselves. Both the detector array assembly and the satellite chip are packaged in a focal plane mount assembly (FPMA) which also provides electrical connections to the outside and ionizing radiation shielding. The SIRTf helium bath temperature will be less than 1.8K. Therefore, supplemental heating is needed to raise the IRS detector arrays to their required operating temperatures. This function is provided by a small heater and temperature sensor co-mounted with the detector assembly which is thermally isolated from the FPMA by a fiberglass box structure. The design requirements and the measured performance of the IRS detectors can be found in Table 6. A more detailed description of the IRS detectors can be found elsewhere⁴.

Table 6. The IRS Focal Plane Detectors

Detector Parameters	Si:As		Si:Sb	
	Requirements	Measured Performance	Requirements	Measured Performance
Format	128 x 128	128 x 128	128 x 128	128 x 128
Read Noise (rms)	< 20 electrons	20 electrons	< 40 electrons	20 electrons
Dark Current	< 10 e-/s	< 10 e-/s @ 6.5 K	40 e-/s	< 40 e-/s @ 5.0 K
DQE	> 0.30 @ 8-20 μm >0.30* /8 @ 5-8 μm	> 0.35 (8-20 μm) > 0.70 @ 20.6 μm > 0.35 @ 26.0 μm	>0.30 @ 14-36 μm	0.30 @ 9-32 μm
Well depth	10^5 electrons	> 2 x 10^5 electrons	10^5 electrons	> 2 x 10^5 electrons
Pixel Size	75 x 75 μm	75 x 75 μm	75 x 75 mm	75 x 75 μm
Corrected Linearity	< 0.5% up to specified well depth	Meets	< 0.5%	Meets
Response Variation	< 10%	< 10%	< 10%	< 4%
Operability	> 95%	> 98%	> 95%	> 99%
Cross-talk	< 2%	< 2%	< 2%	Not yet measured
Area Fill Factor	> 85%	100%	> 85%	100%
Operating Temp.	4.7 to 6.2 K		3.8 to 5.0 K	
Latent Images	< 2%	Meets with appropriate operational procedures	< 2%	Meets with appropriate operational procedures
Anneal Temperature *	20-30K		20-30 K	
Radiation Damage **	< 5% with $i_d > 40$ e-/s	Meets with proper shielding	< 5% with $i_d > 160$ e-/s	Meets with proper shielding
Responsivity Stability	1.0% over 640 s	Meets with proper temperature stability	1.0% over 640s	Meets with proper temperature stability
Dark Current Stability	< 3 e/s over 640 s	Meets with proper temperature stability	< 12 e/s over 640 s	Meets with proper temperature stability
Power Dissipation	< 1.0 mW average into cryogen, including anneals	0.9 mW @ 6.2K	< 1.0 mW average into cryogen, including anneals	0.7 mW @ 5.0K

* Thermal annealing to heal ionizing radiation damage in the detectors arrays is expected to be needed roughly once every 7 days during non-solar flare periods.

** Studies have shown that the accumulated ionizing radiation damage that does not anneal out causes a slow, graceful degradation of the detector array performance, primarily by increasing the dark current on some fraction of the pixels.

6. WARM ELECTRONICS

The IRS/MIPS combined electronics are composed of two identical units for redundancy, with only one of these units powered up at any given time. Furthermore, according to one of the cost-saving design rules for the SIRTf observatory, only one of the SIRTf focal plane instruments can be powered up and taking data at a time. Since the IRS and MIPS instruments share a common warm electronics suite, this means that only the cold assemblies of one instrument will be powered down while the other instrument is operating.

The parts of the combined electronics that are relevant to the operation of the IRS are shown schematically in Figure 6. Two separate power and data backplanes (CS and IES) are utilized to reduce digital noise pick-up in the low-signal level analog detector lines. The IRS/MIPS combined electronics has its own instrument computer, a radiation-hardened RAD 6000 CPU board with 128 Mbytes of volatile memory and 3 Mbytes of non-volatile memory, that runs the active instrument, processes commands, and stores science and engineering data for subsequent transmittal to the spacecraft computer and the ground. A dedicated I/O board provides the proper communication protocol with the host spacecraft computer and provides filtered

communication with the boards on the analog signal bus. A data acquisition board monitors selected analog and digital signal levels, such as temperatures and digital-to-analog converter settings. The IRS silicon detectors are controlled and clocked by one board, while the detector output signals are amplified, filtered, and converted to 16-bit digital form in another board. The estimated mass of the IRS/MIPS combined electronics is 40.6 kg, including a 15% contingency.

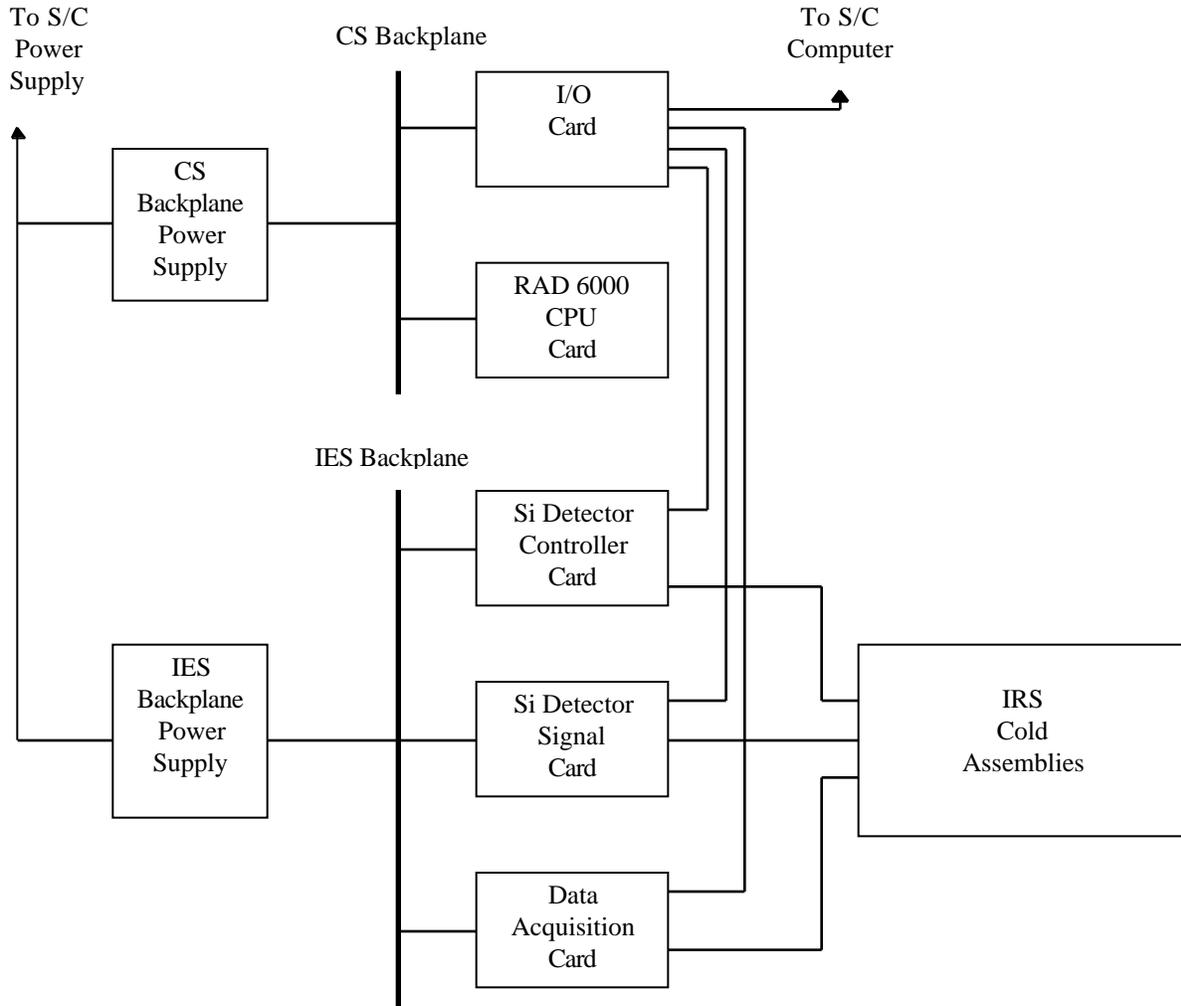


Figure 6. A schematic diagram of the IRS-relevant parts of the IRS/MIPS combined warm electronics

7. ESTIMATED PERFORMANCE

The current estimates of the expected IRS continuum and line sensitivities are given in Figures 7 a and b. It can be seen that the predicted IRS sensitivity is comfortably better than the IRS average requirement levels over most of its wavelength range. When the IRS sensitivity is averaged in a root-squared-sum sense, the average 1-sigma, 500 second IRS sensitivity is 0.077 mJy from 5 to 15 microns, 0.21 mJy from 15-40 microns, and $2.76 \times 10^{-23} \text{ W-cm}^{-2}$ from 10 to 37 microns in the high-resolution mode. As can be seen in Figure 7a, the sensitivity of the short-low module starts falling dramatically below 4.5 microns, due to sharp reductions in the Si:As detector quantum efficiency and a similar drop in the grating efficiency. The SIRTf observatory will be capable of centering an object in any of the IRS spectrograph slits to within 0.4" and then will be capable of holding it there to better than 0.6" over 500 seconds (all 1-sigma radial). This performance will then enable the IRS to measure line ratios between its two high-resolution modules in sources with no continuum to better than 7%.

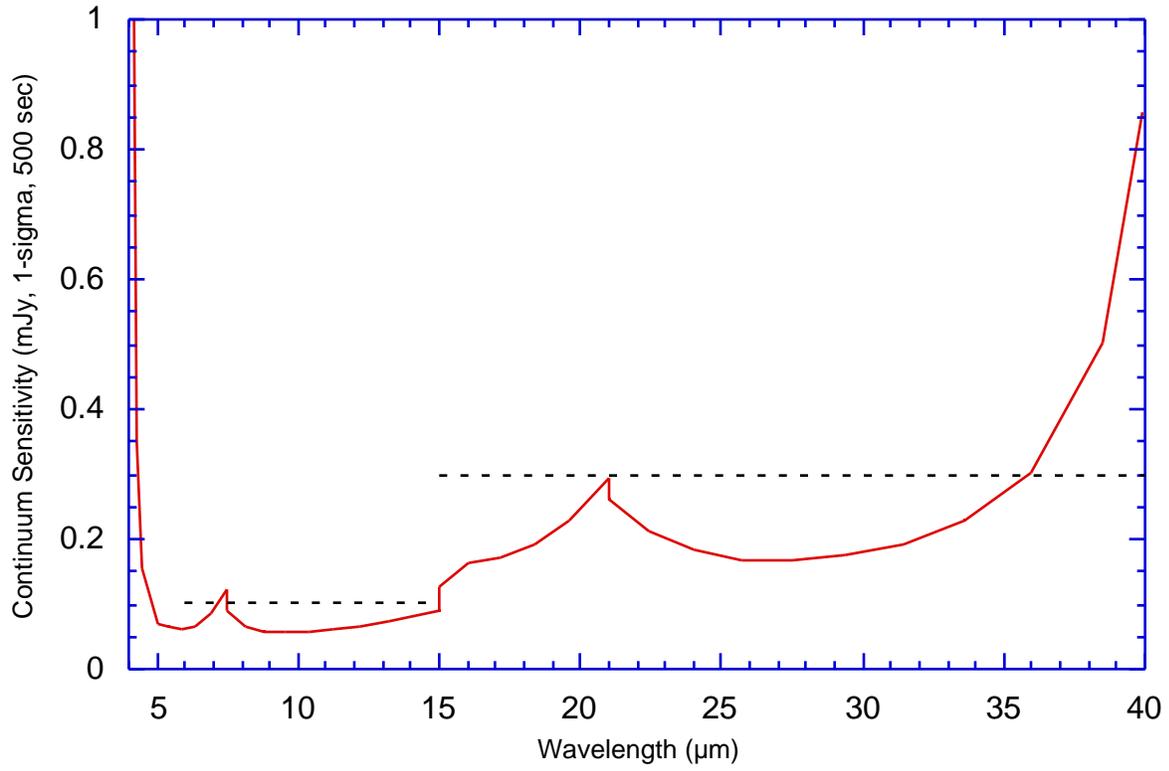


Figure 7a. The point-source continuum sensitivity of the IRS short-low and long-low modules. The dashed line indicates the average continuum sensitivity requirement.

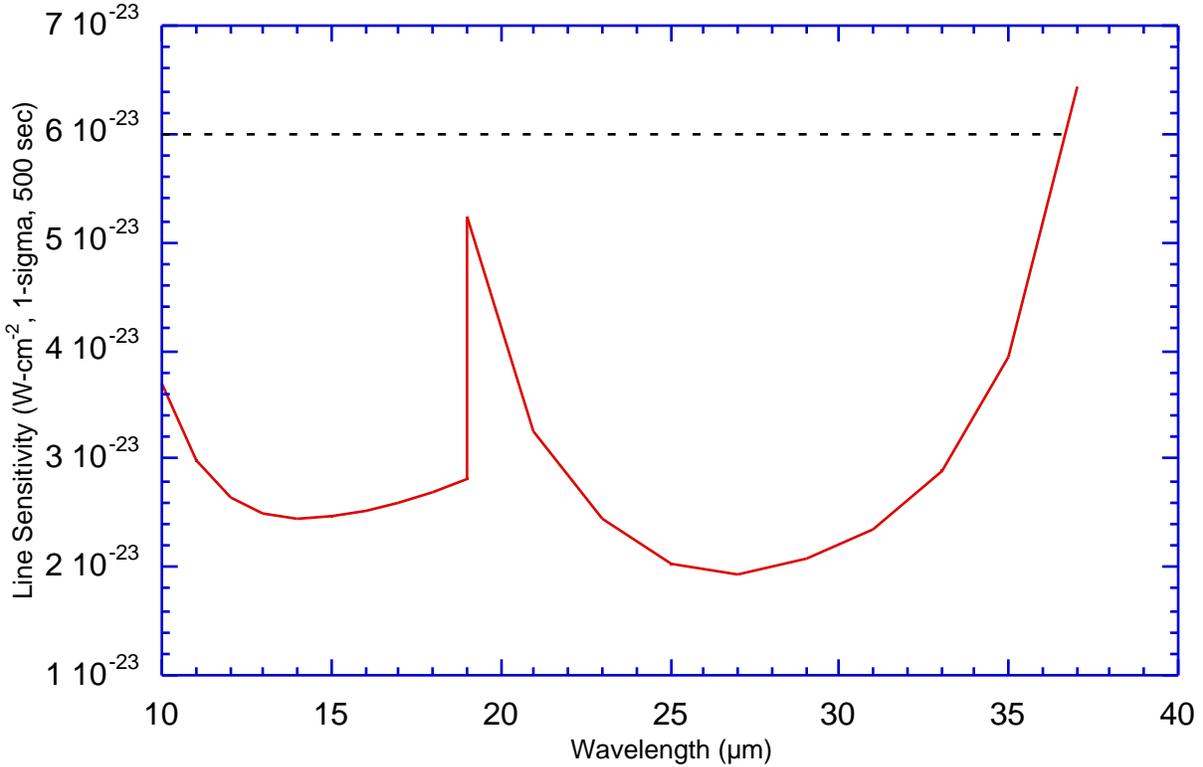


Figure 7b. The point-source line sensitivity of the IRS short-high and long-high modules. The dashed line indicates the average line sensitivity requirement.

8. IRS OPERATIONS

The IRS can be used by the SIRTf observatory in any of three operating modes: fixed inertial staring; spectral scanning; and solar system tracking. The fixed inertial and solar system tracking modes are similar, in that the selected IRS spectrograph slit stays centered on the object of interest. In the spectral scanning mode the spectrograph slit is slowly scanned across the sky while the detector is read out continuously, allowing small regions of the sky to be concurrently spectrally and spatially mapped very efficiently. In all of these modes only one IRS module will be taking data at a time, although switching between modules can occur very rapidly.

9. ACKNOWLEDGMENTS

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