# Multiband Imaging Photometer for SIRTF

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## ABSTRACT

The Multiband Imaging Photometer for SIRTF (MIPS) provides the Space Infrared Telescope Facility (SIRTF) with imaging, photometry, and total power measurement capability in broad spectral bands centered at 24, 70, and 160μm, and with low resolution spectroscopy between 50 and 95μm. The optical train directs the light from three zones in the telescope focal plane to three detector arrays: 128x128 Si:As BIB, 32x32 Ge:Ga, and 2x20 stressed Ge:Ga. A single axis scan mirror is placed at a pupil to allow rapid motion of the field of view as required to modulate above the 1/f noise in the germanium detectors. The scan mirror also directs the light into the different optical paths of the instrument and makes possible an efficient mapping mode in which the telescope line of sight is scanned continuously while the scan mirror freezes the image motion on the detector arrays. The instrument is designed with pixel sizes that oversample the telescope Airy pattern to operate at the diffraction limit and, through image processing, to allow superresolution beyond the traditional Rayleigh criterion.

The instrument performance and interface requirements, the design concept, and the mechanical, optical, thermal, electrical, software, and radiometric aspects of MIPS are discussed in this paper. Solutions are shown to the challenge of operating the instrument below 3K, with focal plane cooling requirements down to 1.5K. The optical concept allows the versatile operations described above with only a single mechanism and includes extensive self-test and on-board calibration capabilities. In addition, we discuss the approach to cryogenic end-to-end testing and calibration prior to delivery of the instrument for integration into SIRTF.

Keywords: MIPS, SIRTF, Infrared, Cryogenic, Photometer

## INTRODUCTION

SIRTF is a cryogenically cooled space telescope to be operated as an observatory for the international science community (Bicay, Werner, & Simmons 1998). It will complement the other Astrophysical Great Observatories (Hubble Space Telescope, Compton Gamma Ray Observatory, and the Advanced X-ray Astrophysics Facility) to provide the opportunity for full multispectral observations. It also complements and expands upon groundbased and airborne infrared observatories by providing very low backgrounds that enable unique capabilities for sensitivity on celestial point sources and for measurement of extended emissions. The Multiband Imaging Photometer for SIRTF (MIPS) is designed to work with the other two focal plane instruments in SIRTF (the Infrared Array Camera (IRAC) and the Infrared Spectrograph (IRS)) to provide full capabilities for the infrared science appropriate to SIRTF. The specific responsibilities of MIPS are photometry, imaging, and determination of spectral energy distributions from 20 to 180μm.

To design a mission capable of a coherent body of science within stringent cost constraints, four science programs were used to define the SIRTF capabilities: 1.) Brown Dwarfs and Super Planets; 2.) The Early Universe; 3.) Protoplanetary and Planetary Debris Disks; and 4.) Ultraluminous Galaxies. MIPS plays roles in all four programs, and particularly in the latter three. Although the mission requirements are based on the four programs listed above, the resulting capabilities are revolutionary and can be applied effectively to many other problems in astrophysics. Such additional programs will be derived from current problems in astronomy at the time of the operations phase of SIRTF (2002 – 2007).

## INSTRUMENT REQUIREMENTS

Many of the objectives in the four defining science programs require efficient mapping of large areas on the sky. MIPS has therefore been required to take survey data simultaneously with all three of its detector arrays in a mode that supports efficient observatory operations. The minimum fields of view are to be 5x5arcmin for the 24 and 70µm bands and 0.5x5 arcmin (equivalent) for the 160µm band, the largest values compatible with current detector array technology and with the field available in the SIRTF focal plane. At the same time, to combat confusion noise the projected pixel scales and sampling in object space must allow for deep deconvolution of crowded fields to extract individual source signals.

MIPS must also be designed to support pointed observations of individual sources, to acquire more information than from surveys. In pointed measurements, photometry is to be possible in all three bands with systematic errors no more than 4%. The instrument spectral response must be sufficiently characterized to transform measured broadband flux densities to equivalent monochromatic values to 5%. Pixel sizes shall be $\lambda/2.2D$ or smaller in the three imaging bands to sample the Airy disk of the telescope beyond the Nyquist level, and precise offsetting on subpixel scales shall be provided to aid in superresolution processing. The pixel-to-pixel crosstalk shall be < 10% to prevent degradation of the optical MTF by the detector arrays. In addition, spectral energy distributions shall be measurable at spectral resolution of at least 10% from 50 to 95µm. Finally, it shall be possible to chop the sky against an absolute reference to measure extended surface brightnesses.

An overall requirement for MIPS is to operate at the natural background limit given the location of SIRTF in space and assuming reasonable detector quantum efficiencies. A number of other general requirements are imposed from programmatic considerations. All of SIRTF is tightly constrained with regard to both budget and schedule, and if necessary, other goals will be sacrificed to live within these boundaries. SIRTF has a required 2.5 year operational lifetime with a goal of 5 years; MIPS is being developed for a 2.5 year life with a factor of two design margin.

## DESIGN OVERVIEW

The MIPS instrument is comprised of a cryogenic optical assembly and warm electronics for instrument control and data collection. The cryogenic portion of the MIPS instrument is located within the SIRTF Multiple Instrument Chamber (MIC) along with IRAC and IRS. The MIC is the optical, mechanical, thermal, and electrical interface between the MIPS cryogenic optical assembly and SIRTF. The cold assembly, depicted in Figure 1, contains the three detector arrays: a 128x128 Si:As BIB (Blocked Impurity Band) focal plane assembly (FPA) responding to 27µm; a 32x32 array of Ge:Ga photoconductors that respond to 120µm; and a 2x20 array of Ge:Ga photoconductors, stressed to extend their photoconductive response to 200µm. These arrays provide photometric bands nominally centered at 24, 70, and 160µm and a low resolution spectroscopy mode covering 50 to 95µm. A cryogenic scan mirror mechanism (CSMM) modulates the signals and allows selection of different optical trains to allow two imaging pixel scales and a low resolution spectrometer with the 32x32 Ge:Ga array.

The warm electronics are shared with the IRS. These combined electronics provide circuitry for control of the three detector arrays, the scan mirror, and other cold instrument functions. In addition, they digitize the science and housekeeping signals and include a RAD6000 processor for data processing and formatting. The RAD6000 also receives commands from the spacecraft computer and sends formatted science and engineering data to it for compression and telemetry to Earth.

The instrument has four operational modes. “Scan Map” is designed for efficient mapping of large regions of sky by surveying along a line on the sky without accelerating and decelerating the entire observatory. Instead, the telescope boresight is commanded to track along the survey line and the MIPS scan mirror is driven in a sawtooth motion that compensates for the telescope scan and freezes the images on the detector arrays during an integration. The scan mirror is rapidly moved to a predetermined new position when the integration is complete. This method allows increased integration time compared to a more conventional sky survey mode, which would require many individual telescope pointings. In “Photometry and Superresolution”, the telescope points inertially and the scan mirror is used to move the source image on the arrays. Optical trains can be selected that over-sample the telescope Airy function in all three bands and the scan mirror motions provide for sub-pixel sampling on the arrays. The “Spectral Energy Distribution” mode uses a Ge:Ga optical train that includes a low resolution grating spectrometer ($\lambda/\Delta\lambda \sim 10$) that measures source continua shapes between 50 and 95μm. The “Total Power” mode allows the sky signal to be chopped against the dark interior of the instrument to allow measurement of the sky absolute surface brightness. This function also is used to characterize the DC offsets within the signal chain and to measure dark currents.

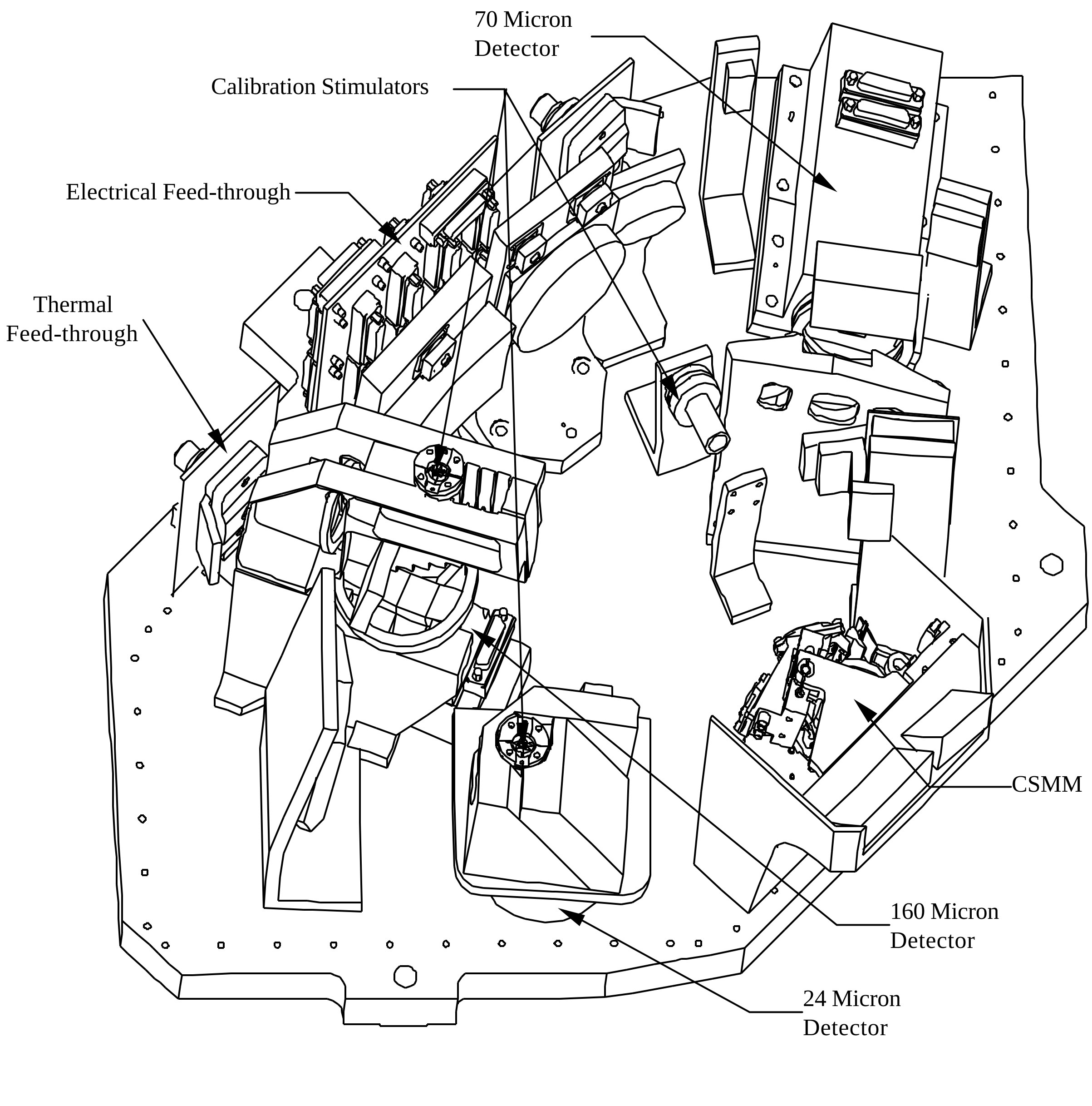



**Figure 1. The MIPS Cold Instrument Assembly.**

The instrument design was guided by several basic concepts. The wavelength of the 70μm band was selected to be as far as possible into the far infrared without having the sensitivity severely compromised by confusion by distant galaxies. This rationale will be made clear by the sensitivity parameters listed in Table 2 below. The 24 and 160μm bands are placed to bridge well (in a logarithmic sense) the spectral gaps between the IRAC 8μm band and groundbased observations at 350μm. Superresolution computer processing is an important goal for all three imaging bands; simulations demonstrated that pixels of ~ λ/2.5D are required for good performance. Small projected pixels take relatively long to accumulate enough photons to overcome read noise and if the cosmic ray hit rate is high compared with this time, their signal to noise can be seriously compromised. We found that λ/2.5D pixels with the 32x32 Ge:Ga 70μm array would have difficulty overcoming read noise in the SIRTF environment. Thus, the instrument includes a scale change for this band so a coarser (λ/1.8D) pixel scale can be used for maximum sensitivity. The rapid onset of confusion noise at 160μm conveniently compensates in many observations for the difficulties in manufacturing a filled array of stressed Ge:Ga detectors large enough to fill a 5x5 arcmin field of view with λ/2.5D pixels. The 2x20 pixel array planned for MIPS will reach the confusion limit quickly enough for many surveys that its small format will not limit overall performance. With both of the MIPS Ge:Ga arrays, very low frequency response components would compromise photometric performance, so a scan mirror is included in the design to allow modulating the signals (beam switching). Conventionally, a photometer such as MIPS would include a filter wheel with multiple bandpass filters to characterize continuum behavior. Because we could not afford a second mechanism, this function is provided by a low resolution spectrometer that is brought into use with the scan mirror, thus not requiring a dedicated wheel and motor.

## FOCAL PLANE ARRAYS

The Boeing Aircraft Company will manufacture the Si:As BIB array for the 24μm band. The device format is 128x128 pixels, each 75μm square. It has four output amplifiers reading out the pixels in an interleaved fashion. This type of detector can be degraded by ionizing radiation. However, the SIRTF devices are being manufactured with a very low level of minority impurities in the infrared-active layer, allowing them to operate at low bias levels which has been found to mitigate almost completely the effect of radiation damage. Between resets, the array will be read out every half second and the outputs for each pixel fitted by linear regression; the resulting read noise will be < 40 electrons. A detective quantum efficiency of > 27% and responsivity of > 3A/W are expected. The MIPS array is being constructed under a subcontract to Boeing from the SIRTF Infrared Spectrograph team, which has also led the array development. Van Cleve et al. (1995) provide further details about these arrays.

The 32x32 Ge:Ga array has been developed by the MIPS team and will be constructed by them at the University of Arizona. It will be the first high performance true large format array in the far infrared. Its design differs substantially from those used for shorter wavelength arrays, as a consequence of the properties of the Ge:Ga detector material.

High quality detector material is provided for this array by MIPS team members E. Haller and J. Beeman at Lawrence Berkeley National Laboratories. At the permissible level of Ga concentration, the absorption length is ~ 5mm. Achieving good absorptive quantum efficiency therefore requires a photon path of this order, but maintaining good photoconductive gain requires that the electrode separation be < 1mm. These constraints are satisfied by building the detectors in an edge-illuminated geometry, making them 2mm along the photon path, and placing a mirror at the back of the pixels so photons that escape are returned to the detector. The electrodes are placed transverse to the photon path, across a detector thickness of 0.5mm. The pixel size transverse to the photon path is set by the crosstalk requirement. The f/number of the illumination on the array for the λ/1.8D pixel scale sets a lower limit on the pixel size of ~ 250μm to avoid exceeding the permissible crosstalk from purely optical considerations. Given that fabrication tolerances will tend to broaden the distribution of photon paths in the detector, and that crosstalk will also result from the diffusion of free electrons, the minimum pixel size compatible with the crosstalk specification is 500μm square. The size adopted is 760x500μm, a geometry that permits a thin sapphire support to be placed between adjacent rows of detectors. The arrays are fed by a germanium optical wedge that hides this support to the incoming photons and provides a filled array with 760x760μm pixels. The readouts for these arrays are Capacitive Trans-Impedance Amplifiers (CTIAs) manufactured by a process developed with Hughes aircraft that provides good DC stability even at the array operating temperature of 1.7K. These readouts maintain the detector bias precisely as signal is accumulated or after cosmic ray hits, improving the detector behavior and minimizing electrical crosstalk between adjacent pixels. In MIPS, the arrays will be read out between resets at 8 Hz and the resulting frames will be sent to Earth for processing. A linear regression algorithm provides read noise of ~ 100 electrons rms. The expected detective quantum efficiency is ~ 20%, dark current < 150 e/s, and responsivity ~ 7 A/W. Further details about these arrays are provided by Young et al. (1998).

The design of the stressed Ge:Ga array is governed by other considerations. Although the absorption lengths are comparably long to those in unstressed Ge:Ga, it is impractical to apply enough force to pixels larger than $1mm^2$ in cross section. Room must be provided around the pixel for the stressing hardware. For the MIPS array, we have adopted a pixel spacing of 3mm perpendicular to the stress axis and 6mm along it. As is conventional with stressed detector arrays, the detectors are mounted in integrating cavities that are part of the stressing hardware, and a filled array is provided by collecting the photons with feed horns which convey them to the entrance apertures of these cavities. The readouts used with these detectors are of the same type as used for the unstressed Ge:Ga array. The MIPS arrays face an additional complication compared with conventional stressed arrays, in that the lead from the detector to the readout must be kept short (< 1cm) so that stray capacitance does not raise the intrinsic read noise. We achieve very low excess capacitance on the integrating node by mounting the readout within the stress harness, on the same alumna board that carries the detectors. For these arrays, the expected DQE is ~ 7%, the read noise ~ 100 electrons, dark currents < 200 e/s, and responsivity ~ 7 A/W. Further details can be found in Schnurr et al. (1998).

## SCAN MIRROR

The Ge:Ga photoconductors have a number of response time constants. The prompt response has good photometric characteristics but the long response, caused to first order by dielectric relaxation, makes accurate photometry difficult because it makes the signal dependent on the history of illumination of the detector. The drifts due to the slow response can also act as a noise floor, making detection of weak sources impossible. At the very low backgrounds in the SIRTF application, the slow response takes tens of minutes; a means of modulating the signal at a frequency of ~ 0.1 Hz can provide the benefits of response almost entirely in the fast regime.

The scan mirror developed by the Short Wave Spectrometer (SWS) team for the Infrared Space Observatory (ISO) was adopted as the basis for the modulator. This device had been space qualified, and since then has performed flawlessly during the ISO mission. T. DeGraauw, the SWS PI, kindly made the design available to us. A number of modifications were made for our application, but the MIPS device (Figure 2) retains the basic features of the SWS design. The mirror itself is mounted on a pair of Lucas flex pivots that permit $15^o$ of rotary motion. The motor coil is mounted on the rotating mirror carrier and acts against a fixed SmCo magnet. Together, these parts form a linear motor that is “bent” to accommodate the rotary motion of the mirror. The mirror position is sensed by a variable transformer and the position is controlled by a type I servo.

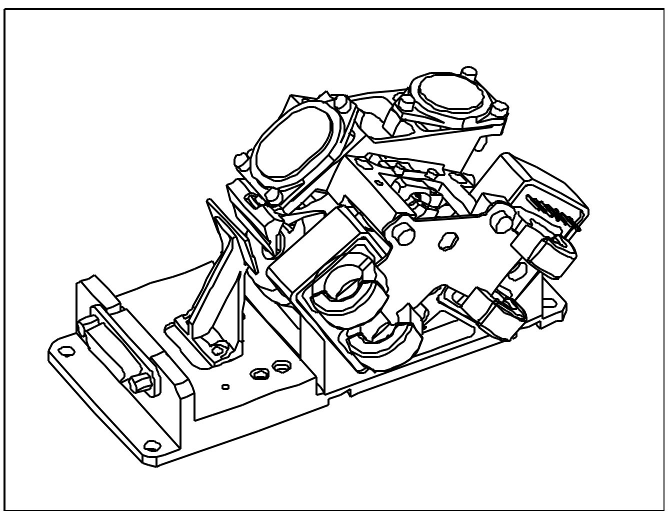


**Figure 2. MIPS Cryogenic Scan Mirror Mechanism.**

To guard against local heat causing emission that would be detected in the MIPS 160μm band, two measures have been taken to reduce the power dissipation in the mirror. The motor coils are wound with a copper wire with embedded superconducting strands. This wire permits operation at room temperature, but the coils become superconducting at the MIPS operating temperature where they have virtually no power dissipation. In addition, the SWS position transducer is replaced with a variable inductance device with lower power dissipation. Additional changes in the scan mirror include additional flexible conductors for the motor coils to provide redundancy, and provision for two easily removable mirrors.

The MIPS scan mirror and its performance are described in detail by Warden and Heim (1998).

## OPTICAL DESIGN

In the large field imaging and mapping mode, the 24 and 70µm bands have instantaneous fields of view of 5.3x5.3 arcmin, while the 160µm band has a field of 0.8x5.3 arcmin with the center column inoperative. The scan mirror can also deflect the beam to provide the "photometry and superresolution" and "spectral energy distribution" (SED) functions with the 32x32 Ge:Ga array. Table 1 summarizes the MIPS optical modes and parameters.

The 24 and 70µm arrays each require 5.3x8.1 arcmin focal plane footprints, the larger dimension being in the direction of the motion of the scan mirror, allowing for the image motion as the scan mirror is exercised for beam switching or scan mapping. The 160µm band uses a 5.3 x 3.5 arcmin focal plane footprint. All the fields are arranged to be in the same scan path so that one follows the other across the sky when the telescope is scanned in the direction of scan mirror motion. The total required focal plane footprint on the sky is 5.3x27 arcmin, including dead space between fields of view to keep the optical paths in the instrument separate. The location of the MIPS fields of view within the overall SIRTF focal plane is illustrated in Figure 3**.**

| Band | Mode | Array Format | Scanned FOV (') | Pixel Size (") | λ(μm) | F/# | λ/Δλ |
|---|---|---|---|---|---|---|---|
| 24µm | N/A | 128x128 | 5.3x8.1 | 2.5 | 20.5 – 26.5 | 7.4 | N/A |
| 70µm | Survey | 32x32 | 5.3x8.1 | 10 | 60 – 80 | 18.7 | N/A |
| 70µm | Superresolution | 32x32 | 2.6x4.1 | 5 | 60 – 80 | 37.4 | N/A |
| 70µm | S.E.D. | 32x24 | 4.0x.0.33 | 10 | 50 – 95 | 18.7 | 18 – 34 |
| 160µm | N/A | 2x20 | 5.3x3.4 | 15 | 140 – 180 | 46 | N/A |

**Table 1. MIPS Principal Optical Parameters**.

All MIPS bands have pick-off mirrors located in the SIRTF focal surface, redirecting the three fields of view into the MIPS volume. Re-imaging mirrors form images of the telescope exit pupil at the scan mirror locations and 1.5:1 images of the entry fields beyond the pupils. The optical trains of MIPS have been arranged to facilitate the use of a single scan mirror mechanism, carrying a mirror for each of the two "sides" of the instrument. In 70µm wide field mode, the field image falls directly through flat periscope mirrors onto the Focal Plane Array (FPA). In narrow field mode, it is directed by the scan mirror through 2:1 magnifying relay mirrors before returning to the periscope mirrors. In the spectrometer mode the field image is directed to a slit mirror and is then spectrally dispersed and re-imaged by a

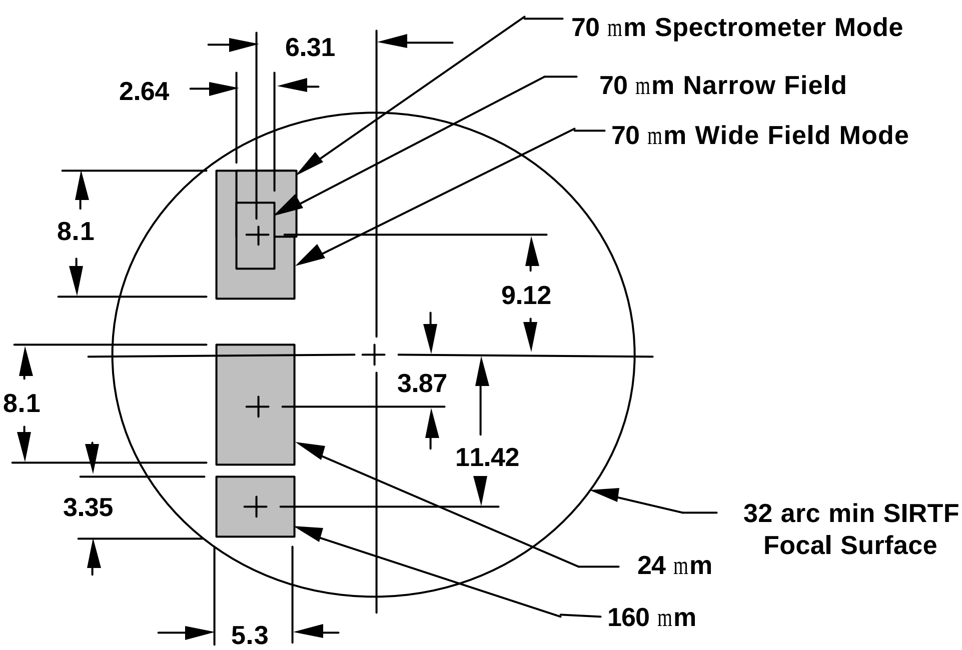



**Fig. 3 MIPS Fields of View in the SIRTF Focal Surface**

concave diffraction grating to the periscope mirrors and FPA. Also provided in the 70μm side of the instrument is a set of optics to project flat field illumination through the scan mirror pupil to the FPA. The 24 and 160μm fields share optic elements through the scan mirror, and are then respectively demagnified and magnified by relay mirrors to their FPAs.

Both relay trains include optical elements at final pupil conjugates where flat field illumination is provided. Principal apertures at the scan mirrors act to limit the instrument cone of acceptance to a diameter 10% larger than that of the SIRTF exit pupil. Figure 4 shows the MIPS optical layout.

The MIPS instrument has a total of five reverse bolometer IR sources for stimulation, flat fielding and self-test capabilities. All units are of dual element design for redundancy. As indicated above, sources for flat fielding all bands are placed near or projected to final pupil locations. The 24 and 70μm bands include additional units close to the FPAs for stimulation uses. The 160μm band has a single source assembly that is located near the final pupil and FPA.

All reflecting optical elements are flats or surfaces of revolution and are diamond turned directly in 6061-T651 aluminum alloy. Surface microroughness level and wavefront fabrication accuracy required for the MIPS optics are readily met with typical diamond turning processes. Only one surface (in the 24μm band) is required to be aspheric to achieve all design wavefront requirements. The diffraction grating is ruled directly in aluminum on a diamond turned spherical surface.

Filter bandwidths for imaging have $\lambda/\Delta\lambda \sim 4$. A multilayer coated dielectric filter/blocker is employed for the 24 μm band. For 70 and 160μm regions, interference filters of metal mesh on polymer film are used. Additional blocking filters are used to further reduce shorter wavelength leakage.

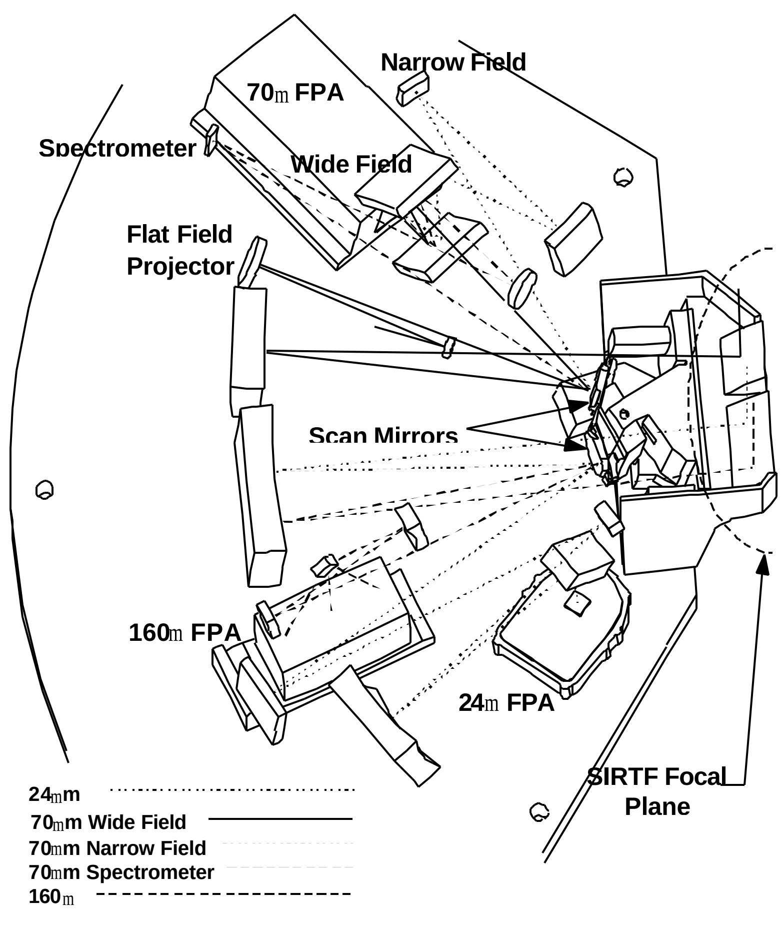
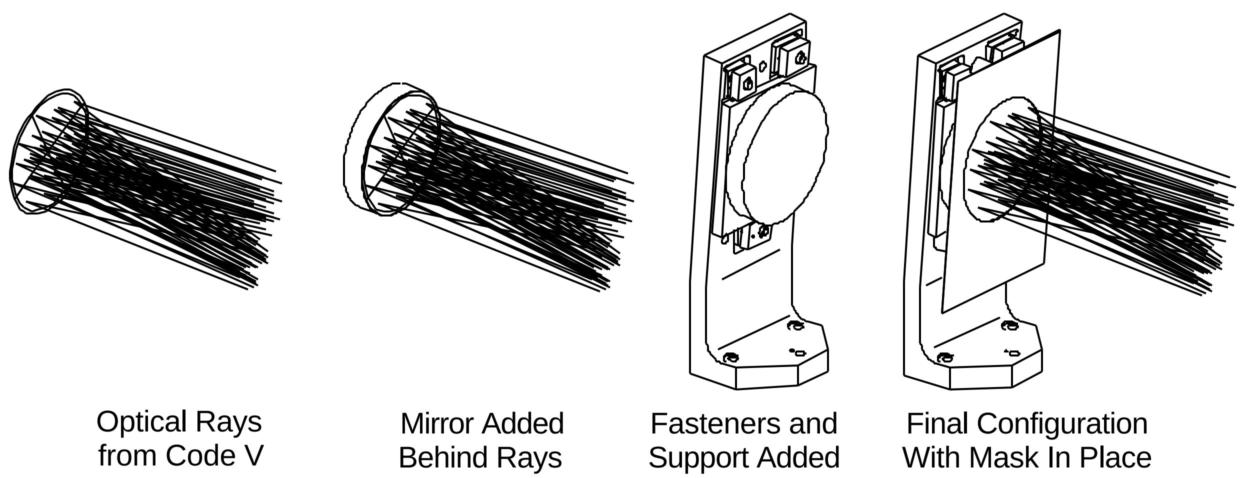



**Fig. 4 MIPS Optical Layout**

## MIPS MECHANICAL AND THERMAL DESIGN

The mechanical design is the focus for many of the other disciplines. The design must adhere to the specified interface while satisfying the requirements for optics, thermal, electrical, stray light, testing, and producibility. The mechanical design of the MIPS instrument proved to be a very challenging three dimensional puzzle. The optical path makes use of the entire envelope and the motions of the scan mirror further complicate the design. In addition, the operational temperature of 1.5K required a detailed thermal analysis. A total of 33 optical elements are needed as well as their corresponding brackets, masks, and mounts.

**Figure 5. Mechanical Design Sequence**




Designing an instrument for use in the far infrared has both advantages and disadvantages. Since the wavelengths are longer, the depth of focus is also longer and the positional accuracy requirements are much less stringent. Also, simple diamond turned mirrors with no subsequent finish have a very high far infrared (FIR) reflectance. The down side is that nearly all materials are reflective at these FIR wavelengths, so controlling stray light becomes a problem. Another disadvantage is that moving parts must operate cryogenically, and hence require extra attention. The only such part in MIPS is the Cryogenic Scan Mirror Mechanism (CSMM). The CSMM is primarily aluminum, but the mirror surfaces on it are accurately dimensioned so that they act as Lyot stops for the optical train. The pivot point for the mirrors is offset from the mirror surface, which produces some translation along with the rotation. The mirror surfaces, therefore, are slightly elongated.

The electrical cable from the scan mirror as well as the cables from the FPAs must pass through the cover of the instrument. The electrical and thermal feed-throughs were designed to be light tight. The thermal feed-throughs were made electrically insulated but thermally conductive by means of a sapphire washer.

The optical model was generated with Code V software which was then transferred by means of IGES files to Structural Dynamics Research Corporation's (SDRC) I-Deas Master Series solid modeler. The imported file is simply a collection of three dimensional lines with vertices showing where the mirrors should be. The mirrors were then given solid features and if any interferences were noted, the optical design was modified to eliminate the conflict. The iteration between the optical and mechanical design was performed almost daily at first to fine tune the design and make everything fit into the required volume. After the mirrors were placed, the other optical elements were added. This included filters, stimulators, and of course, the IR FPAs. Again, interferences were noted and the optical model was modified.

Ideally, an optical instrument uses cylindrical baffles to reduce stray light. For the MIPS instrument, however, the light paths crossed so often that tubular structures could not be used. Instead, stray light is controlled with masks such as a thin, flat surface directly in front of a mirror with an accurate hole machined in it to allow light to pass. The mask is painted black with a special far-infrared paint which is nearly 1 mm thick. The edge of the mask is not sharp as in visible instruments, but simply square cut so that the paint is actually the controlling surface.

The three Focal Plane Assemblies (FPAs) are quite different from each other and required different design considerations. The 24µm FPA is susceptible to irreversible damage from cosmic radiation. A fold mirror directly above the array along with 20mm thick aluminum shielding is used to create a labyrinth for the light to travel through while providing the necessary shielding in all directions as seen by the array, reducing the total mission dose to < 500 Rad. Also included in the 24µm shielding assembly is the blocking and band pass filter and the flat field and flood stimulators. The 70µm FPA needs to be mechanically attached to the MIPS baseplate yet accommodate the thermal expansion mismatch between the molybdenum FPA chassis and the aluminum baseplate. In addition, the FPA needs to be electrically and thermally isolated from the baseplate . The front of the FPA is securely attached to the baseplate and the back is supported by two flexures. By fixing the front of the FPA, the relative position of the focal plane surface to the mirrors remains constant between ambient and cryogenic conditions. Inconel is used for the structural supports with fiberglass insulating washers. A separate thermal strap connects to the thermal feed-through, which is cooled by a strap to the helium vessel. The 160µm FPA requires even more attention to cooling; the thermal isolation is incorporated inside the FPA assembly, with another dedicated thermal strap to the helium vessel.

Both thermal and structural analysis were required to validate the mechanical design. The two areas of thermal concern are expansion and conductivity. The first order solution for the dimensional change due to change in temperature is to make everything possible out of the same material. In this way, the entire assembly shrinks uniformly, residual stresses are reduced, and the alignment does not change much between ambient and cryogenic conditions. Aluminum alloy 6061-T651 was chosen because its cryogenic properties are well understood and well documented. In some areas, as in the case of the 70µm detector, other materials were specified so that flexures were needed to accommodate the change in thermal expansion. Even in cases where the same material is used on both sides of a joint, differences in temperature during cool down and warm up can be a problem so in many cases, a bolted connection was preferred over a bonded one because the temperature change was more gradual. The other major thermal concern was with the 70 and 160µm FPAs, which require high thermal strap conductivity to dominate the thermal conductance to the baseplate.

## ELECTRONICS DESIGN

To reduce the cost and mass of the SIRTF spacecraft, much of the electronics required by the IRS and MIPS are shared, including a warm electronics chassis, power supplies, the instrument processor (RAD6000) and the control and science data interfaces to the spacecraft computer. The IRS instrument has four Si FPAs and MIPS relies on the IRS electronics to control and readout the MIPS Si:As FPA. The block diagram of the combined electronics shown in Figure 6 identifies the MIPS electronics, the IRS electronics, and the common electronics.

The MIPS/IRS warm electronics are designed to be standby redundant; that is, two identical electronics boxes are flown; both boxes are connected to the FPAs and scan mirror in the cold instrument, but only one box is powered at a time. Each circuit that is connected to the cold instrument is designed so when the circuit is not powered it does not load the signal line running from the powered electronics box to the cold instrument. To provide further protection from failures, each Ge FPA is treated as two independent arrays. Independent clock and DC voltages are provided for each 16x32 half of the 70µm FPA as well as each 2x10 half of the 160µm FPA.

The MIPS/IRS warm electronics are housed in two identical ten slot chassis. The outside dimensions of each enclosure are approximately 340mm x 320mm x 204mm and the weight of each populated box is about 20Kg. Power dissipation of the electronics is expected to be about 64 watts. The electronics enclosure is designed to provide radiation shielding of the electronic components. The total dose inside the box is predicted to be 3.2krad(Si) for the nominal 2.5 year mission. All parts used in the design of the MIPS/IRS electronics will be selected for a total dose hardness of twice this level.

The diagram in Figure 7 shows the analog chain for the Ge FPAs. A total of 40 identical analog chains are provided in the MIPS warm electronics for the two Ge FPAs: 32 for the 70µm FPA and 8 for the 160µm one. The cable connecting the

FPA outputs to the MIPS warm electronics is over three meters long. Since this cable is routed from the 1.5K instrument out to the 300K warm electronics box, a low thermal conductivity wire is used for these conductors. Each cable contains 24 pairs of twisted pair manganin wire protected by an outer shield; each output signal is twisted with a complementary ground reference. The total capacitance of up to 700pF must be driven by the array output amplifiers. An instrumentation amplifier in the warm electronics, which helps reject common mode noise on the incoming signal and ground reference lines, receives the signals. The output of the instrumentation amplifier is summed with a DC offset voltage and then fed into a 1KHz two pole filter. The bandwidth of this filter was chosen to be low enough to limit the FPA noise bandwidth and yet provide a reasonable readout time for the FPA. The outputs of the 40 analog chains are multiplexed down to a single analog line, which is fed to the analog to digital converter (ADC) as shown in Figure 6. A 16 bit ADC is used to digitize the processed pixel data from the germanium FPAs. The overall Ge FPA signal chain has a gain of 7x. Only 14 bits of the available 16 bits are processed. 14 bits (~20 electrons per ADU) provides good sampling of the FPA read noise, full coverage of the full detector dynamic range and some margin to allow for mismatch between the DC outputs of the various FPA readouts.

The analog chain for the MIPS 24µm FPA is similar to the Ge analog chain shown in Figure 7. Four identical analog chains are provided for this FPA, one for each FPA output. A differential receiver provides common mode rejection for the incoming signal. A two pole filter is used to limit the bandwidth of the incoming signal. The filter bandwidth for this FPA is set at 40KHz due to the higher Si FPA pixel frequency. Four separate ADCs are provided within the IRS electronics to digitize the Si FPA pixel data. The digitized pixel data from the ADCs are merged and fed into the RAD6000 instrument processor.

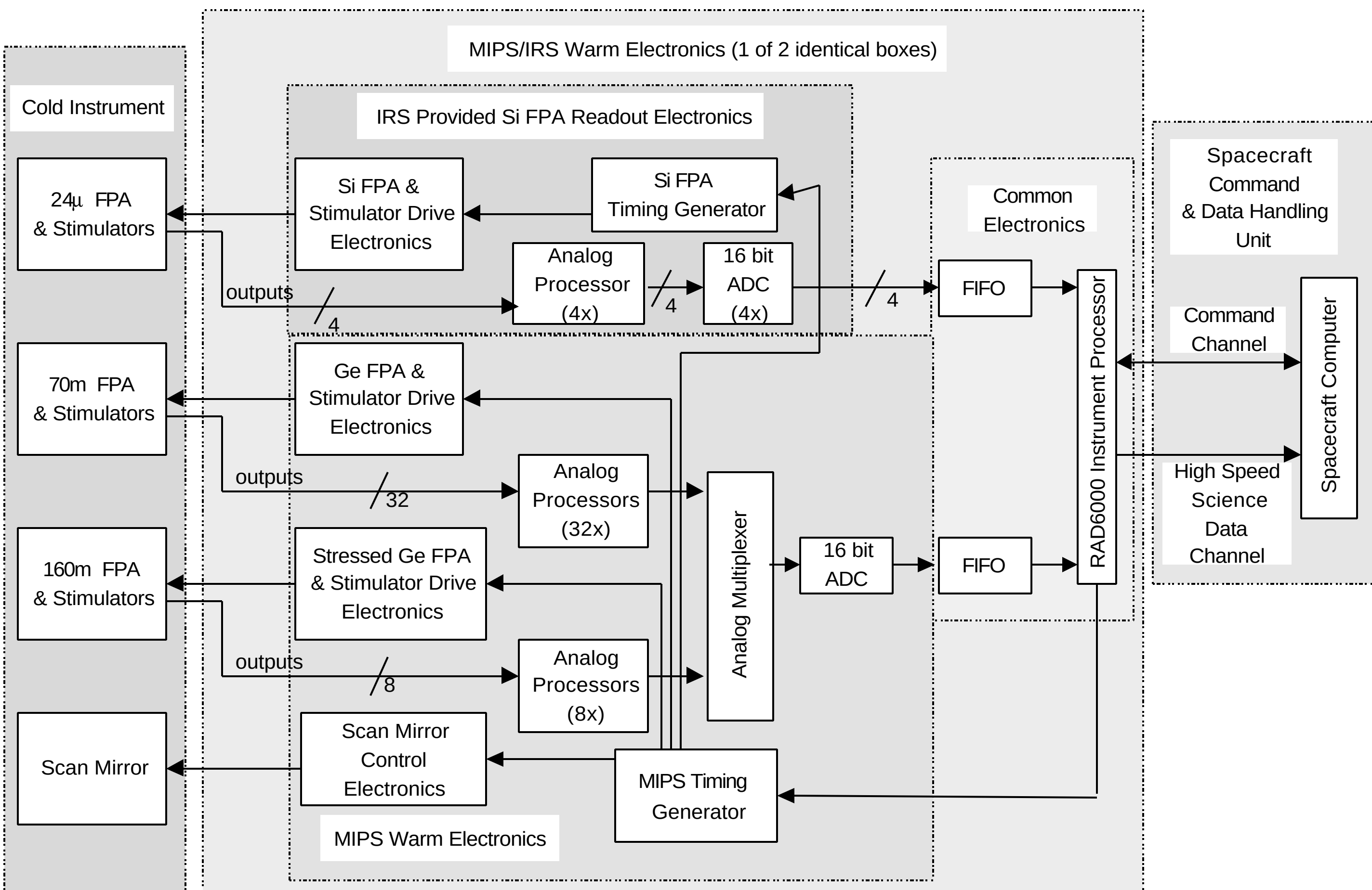



**Figure 6. MIPS Electronics Block Diagram**

As shown in Figure 6, a hardware timing generator is used to produce the clock signals for the two MIPS Ge FPAs, synchronization signals for the MIPS Si FPA, and deflection waveforms for the scan mirror. Synchronizing signals are fed from the MIPS timing generator to the IRS timing pattern generator, which produces the actual Si FPA clocking patterns. Both of these timing generators are implemented in hardware with no real time intrusions required by the instrument processor. The MIPS flight software controls the operation of these timing generators through register writes. In operation, the MIPS germanium FPAs will be read out at a frequency of 8Hz and the silicon FPA at 2Hz.

Drivers are provided in the MIPS electronics for the FPA calibration stimulator sources and the thermal anneal heaters. The timing generator produces the stimulator flash pulses, which are synchronized with the FPA readout. The thermal anneal heater timing is controlled directly by the instrument processor.

The CSMM is controlled by a type I analog servo system. The actual CSMM deflection angle is continuously monitored and compared with the commanded angle. The error signal between the actual and desired positions is integrated and used to drive the CSMM actuator. Mirror deflection commands are generated digitally by the timing generator and converted to an analog command using a digital to analog converter (DAC). The timing generator produces all the required CSMM deflection waveforms including chop waveforms and the sawtooth pattern required by the MIPS scan map mode. The higher currents required by the CSMM and by the FPA thermal anneal heaters are carried to the cold instrument over a cable constructed of phosphor bronze wire.

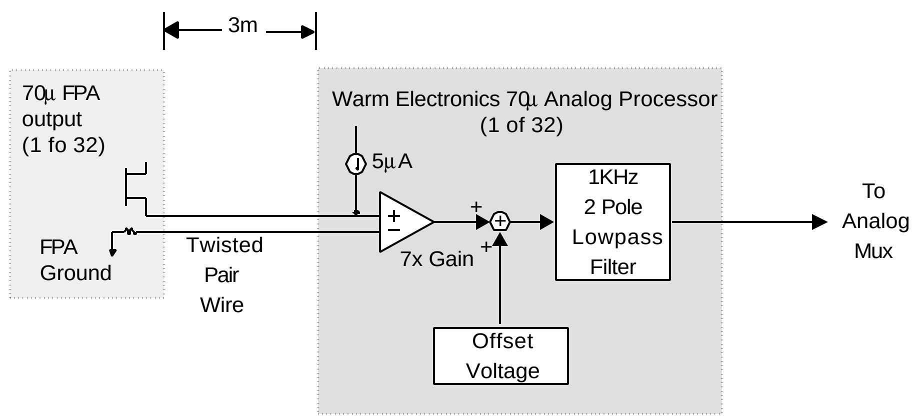



**Figure 7. MIPS Ge FPA Analog Chain Block Diagram**

## SOFTWARE

Figure 8 is a top-level block diagram showing the flow of information to and from the MIPS instrument. As shown in the figure, operational parameters are converted into the appropriate command blocks at the ground station, which are then uplinked to SIRTF. Instrument specific commands are received and distributed by the spacecraft command and data handler (S/C C&DH). The spacecraft C&DH provides the interface between the SIRTF spacecraft and the SIRTF instruments. The spacecraft C&DH sends the MIPS specific commands on to the MIPS processor where they are interpreted and executed by the Control Section Flight Software. Engineering and science data are gathered by the various components of the MIPS embedded flight software and downlinked, via the spacecraft processor, to the ground for processing. Figure 8 is a top-level block diagram showing the flow of information to and from the MIPS instrument. As shown in the figure, operational parameters are converted into the appropriate command blocks at the ground station, which are then uplinked to the SIRTF vehicle. Instrument specific commands are received and distributed by the spacecraft command and data handler (S/C C&DH). The spacecraft C&DH provides the interface between the SIRTF spacecraft and the SIRTF instruments. The spacecraft C&DH sends the MIPS specific commands on to the MIPS processor where they are interpreted and executed by the Control Section Flight Software. Engineering and science data are gathered by the various components of the MIPS embedded flight software and downlinked, via the spacecraft processor, to the ground for processing.

The Control Section Flight Software configures and controls the instrument components through four major electronics sections: the SIRTF Instrument Command and Data handling (C&DH) subsystem interface, the Control Section Electronics (CSE), the Silicon Detector Focal Plane Array (Si FPA) Interface Electronics, and the Germanium Detector Focal Plane Array (Ge FPA) and Cryogenic Scan Mirror Mechanism (CSMM) Interface. Within the MIPS electronics, the Control Section Flight Software provides the instruments with the computational, interface, and memory resources necessary for performing overall instrument control and science data collection and processing tasks. Commands are accepted through an RS-422 Command/Response Serial interface to the spacecraft C&DH and processed by the Control Section Flight Software. The engineering telemetry data are output by the Control Section Flight Software to the spacecraft C&DH via the RS-422 Command/Response Serial interface as well. Instrument science data and diagnostic data are output by the Control Section Flight Software to the spacecraft C&DH via the 1 MbRS-422 Science Data interface. The Si FPA Interface Electronics and the Ge FPA Interface Electronics provide the commanding and science data interface between MIPS detectors and the Control Section Flight Software. The Si and Ge FPA Interface Electronics also provide the control interface to the instrument stimulators and the instrument Si focal plane array temperature control. The Ge FPA Interface Electronics also provides the control interface for the MIPS scan mirror.

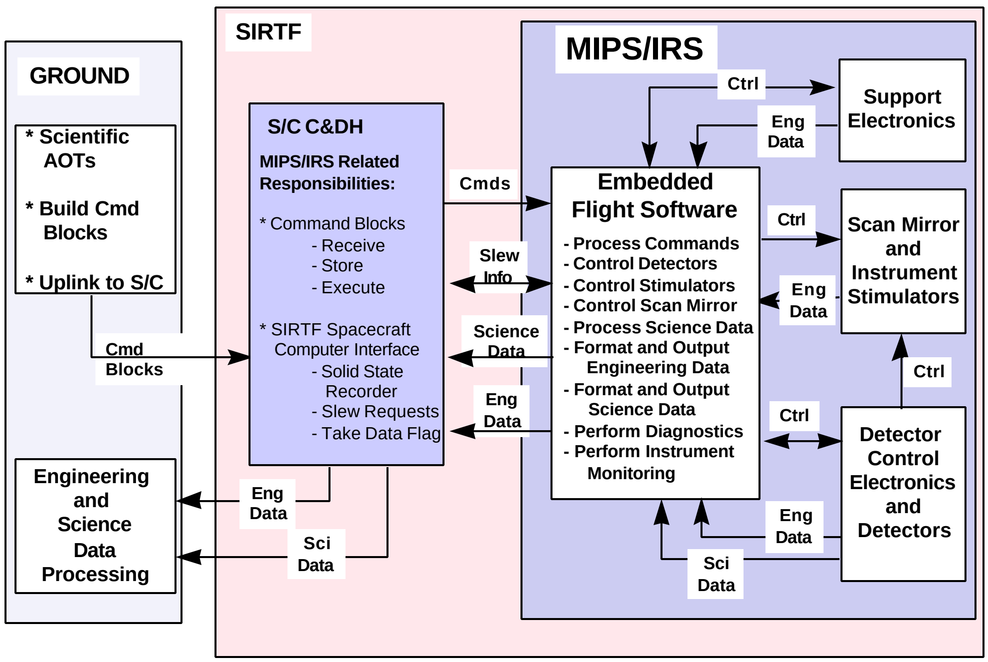



**Figure 8. MIPS Software Block Diagram**

To perform its main function of collecting and outputting science and engineering data within the constraints of the SIRTF system, the Control Section Flight Software provides the ability to operate the instrument in two separate software states: the boot state and the operate state. Within each software state, various subsets of the full set of commands and subsets of the full set of telemetry data are valid.

When power is applied to the main electronics of the MIPS instrument, the MIPS processor begins execution of the boot state flight software. The functions for the boot state software are:

- Provide the ability to upload and download data to/from the Error Detection and Correction / Electrically Eraseable Programmable Read Only Memory (EDAC/EEPROM) memory areas from/to the ground system via the S/C C&DH.
- Provide the ability to transfer the code from the EEPROM memory area into the EDAC RAM.
- Provide the ability to begin execution of the Operate state software at an uplinked address location.

- Provide the ability to monitor and output a subset of the full complement of engineering data indicating the current state of the instrument.
- Collect detector, memory dump, and diagnostic data telemetry.

To protect this basic upload and transfer capability, the flight software necessary to perform the boot state software functions resides in a write protected area of radiation hardened EEPROM. To reduce the complexity and increase the reliability of the boot state flight software, it has been written without incorporating the real-time operating system that is being utilized by the operate state flight software. The boot state flight software utilizes a basic cyclic executive to handle its operations.

After the boot state software has copied the operate state software from EEPROM to EDAC RAM, the instrument may be commanded into the operate software state where instrument science activities can be performed. All instrument calibrations, science observations and instrument diagnostic activities are performed by the operate state software. To accomplish this, the operate state software supports the following tasks:

- Configure and operate the MIPS detectors.
- Configure and operate the MIPS scan mirror.
- Configure and control the MIPS instrument stimulators.
- Collect detector, memory dump, and diagnostic data telemetry.
- Collect and monitor engineering data and scan mirror position data.
- Format and output science data to the RS-422 Serial interface.
- Format and output engineering telemetry data to the RS-422 Serial interface.

Multiple sequential observations may be performed while the instrument is in the operate state.

The Control Section Flight Software is written in the ‘C’ programming language and the operate state flight software utilizes the VxWorks Real-Time Operating System. The flight software was originally developed on a Motorola 603e PowerPC target processor, and will be ported to the Lockheed-Martin RAD-6000 flight processor for final integration and test. The PowerPC development environment is architecturally identical to the RAD-6000 environment with a much lower cost.

## INTEGRATION AND TEST

The MIPS integration and test flow (Figure 9) begins with bringing the Cryogenic Scan Mirror Mechanism (CSMM) together with the MIPS baseplate, optics and mounts. The somewhat forgiving tolerances on optical element positions revealed by wavefront analysis allow these aspects to be controlled by design and fabrication. Manual alignment of the MIPS system will be limited to optic pointing direction and focus adjustments. Simple alignment verification tests are performed before and after the completed “optical bench” assembly is subjected to vibration testing with dummy IR FPAs and spectral filters at room temperature and 77 K. Additional tests for alignment changes as a function of temperature are made at this time. The IR FPAs and filters follow their own parallel fabrication and performance/acceptance test paths. The IR FPAs and filters are integrated to complete the MIPS cold assembly. MIPS warm electronics concurrently complete a fabrication, functional test and environmental test sequence. Aliveness and mass properties testing of the cold assembly ready it for final performance test and calibration.

A critical element of the test and integration phase of the MIPS is characterization and calibration in a simulated orbital environment. To accommodate these tests a large volume, Low Background Test Cryostat (LBTC) will be constructed. The LBTC will provide a contamination free, self contained cryogenic enclosure for the MIPS instrument as well as the Performance and Calibration Apparatus (PCA) used during the testing and verification phase of the project. The cryostat design will provide a mechanical, electrical and photon "flight like" testing environment. Two Helium reservoirs will be employed in the design. The largest reservoir will be used to cool the MIPS and PCA, a 20"x20"x20" volume, to 4.5K. This reservoir will be pumped only during tests requiring the lowest background levels. A smaller pumped Helium reservoir will cool the FPAs to 1.6K or below.

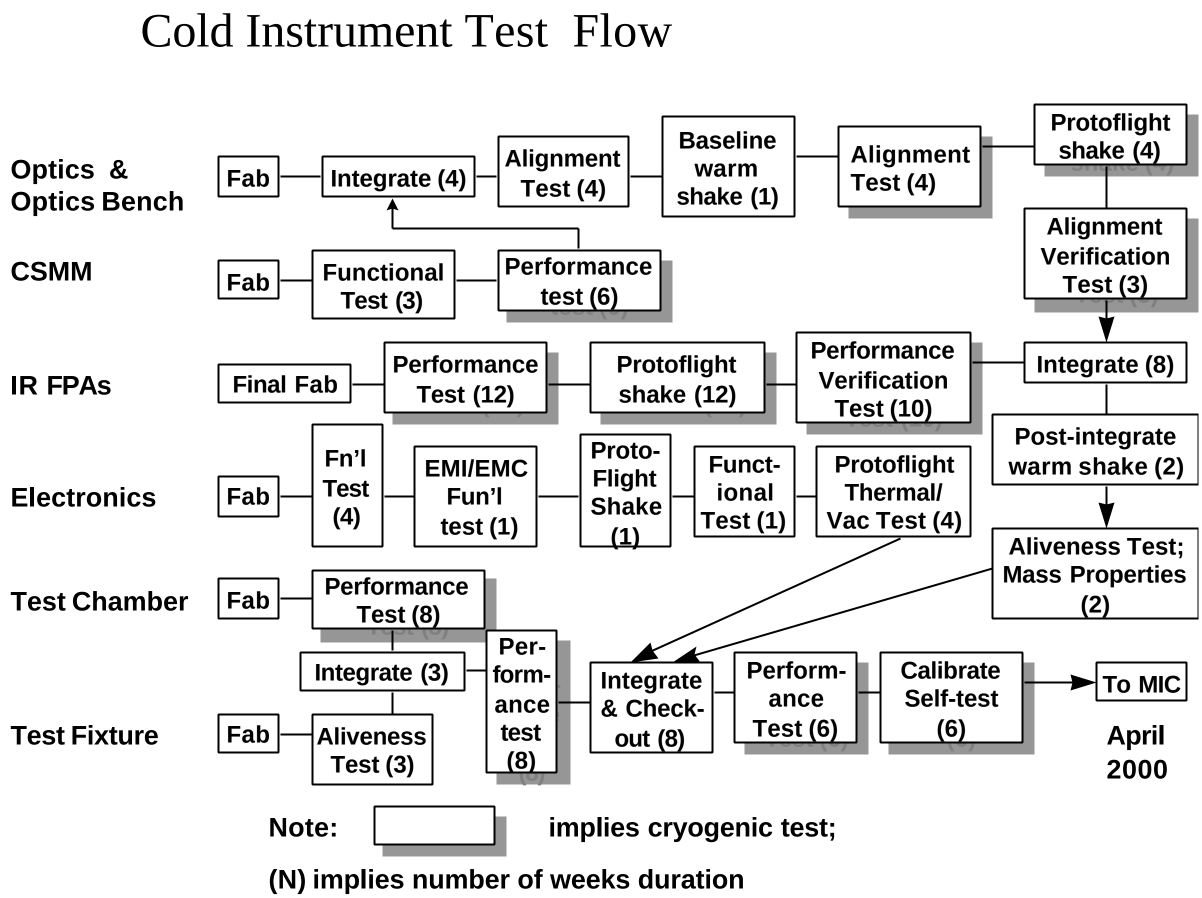



**Figure 9. MIPS Integration and Test Flow Diagram**

A cryogenic refrigerator will cool an intermediate photon shield to 20K as well as assist in pre-cooling the cryostat. The LBTC design will facilitate FPA operations at 1.6K for more than 24 continuous hours. Flight-like cables (nine, 3 meter, 51 conductor, twisted pair, managin and phosphor bronze) will be used to conduct signals and power to the instrument. Additional service wires will be used to monitor and control the PCA and thermometry.

The Performance and Calibration Apparatus (PCA) takes advantage of the MIPS internal scan mirror mechanism to provide the mechanical means to control test mode and image motion in the Low Background Test Cryostat (LBTC). Using the scan mirror mechanism it is possible to alternate between viewing full fields of uniform integrating sphere illumination to viewing point sources simulated by appropriately sized pinholes located in MIPS entry fields. The integrating sphere has four inputs with reverse bolometer sources similar to the flight units. Three of these are filtered to bandpasses similar to the flight instrument bands and one is unfiltered. Additionally a short wavelength source filtered to limit all MIPS in-band energy is used to explore short wavelength sensitivity. The pinhole assemblies have several holes located in field point positions that allow imaging tests as well as different axial heights for focus verification. They are back illuminated by previously calibrated reverse bolometer sources, facilitating absolute sensitivity tests. Figure 10 shows the test fixture apparatus in the LBTC.

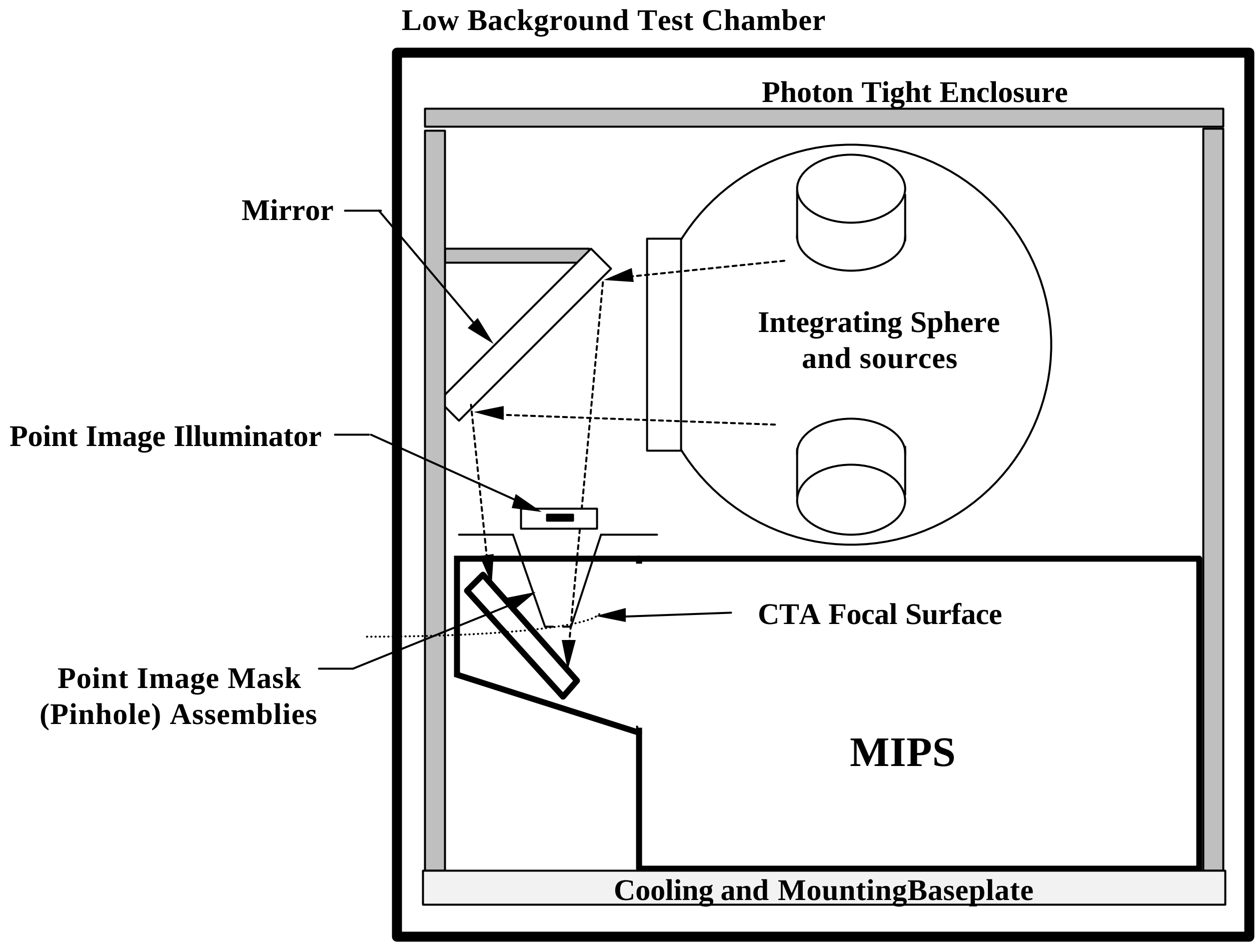



**Figure 10. MIPS and Test Fixture in the LBTC.**

## PROJECTED PERFORMANCE

The sensitivity that can be achieved with MIPS has been estimated from the instrument parameters and a model of the far infrared sky (Rieke, Young, & Gautier 1995). Table 2 summarizes the results. A more sophisticated simulation of the sky is under development, in which all anticipated noise sources are combined consistently into an artificial image of the sky to be used to practice data reduction techniques (Engelbracht et al. 1998). Preliminary results from this simulation indicate net performance levels in good agreement (within a factor of 1.5) with those in Table 2.

The tabulated detective quantum efficiencies represent the instrument requirements; measured values are higher, and the difference represents margin against the projected performance levels. The instrument optical losses are dominated by the transmission of the optical bandpass filters. The "CR factor" is an estimate of the factor the raw sensitivity will be degraded by hits on the detectors by energetic ionizing particles. It is anticipated that the telescope will add slightly to the natural background at 160μm, as indicated by the "telescope emission" factor. The telescope specifications also include an allowance for scattered light; in Table 2, we have assumed that the performance is measured in a part of the sky with no bright sources that would contribute such a background. Given these parameters, the photon-limited noise can be estimated, along with the confusion noise components due to infrared cirrus (in a low cirrus region of sky) and distant galaxies. These noise terms are combined quadratically to estimate the net one-standard-sensitivity level in a long (2000 second) integration. It is straightforward to compute performance levels for other integration times from the tabulated values.

| $\lambda$ ($\Delta\lambda$) | 23.5µm (6µm) | 70µm (20µm) | 160µm (40µm) |
|---|---|---|---|
| **DQE** | 0.2 | 0.1 | 0.05 |
| **Efficiency** | 0.4 | 0.45 | 0.5 |
| **CR factor** | 1.3 | 1.5 | 1.3 |
| **Telescope Emission** | 1.0 | 1.0 | 1.1 |
| **1-$\sigma$ Shot Noise** | 37µJy | 130µJy | 420µJy |
| **Cirrus Noise** | …. | ~15µJy | 300µJy |
| **Confusion Noise** | …. | ~55µJy | 1500µJy |
| **1-$\sigma$ Net Noise** | 37µJy | 140µJy | 1600µJy |

**Table 2. Noise Components in Deep Integration (2000 sec)**
**(tabulated values are one standard deviation on an unresolved point source)**

## SUMMARY

The MIPS concept has been carefully optimized during the unusually prolonged conceptual design phase of the SIRTF program. A powerful set of new technologies has been demonstrated for the instrument. Requirements, goals, budgets, and schedules are well defined allowing NASA's "cheaper, better, faster" guidelines to be implemented to provide a powerful instrument within budgetary constraints. The resulting MIPS instrument provides a flexible set of capabilities for surveying, imaging, studying source spectral energy distributions, and measuring the total power from the sky between 20 and 180µm Virtually all operating modes provide sensitivity at the natural background limit for the location of SIRTF in space. These capabilities are made possible by use of high performance infrared detector arrays, including the first such device for the far infrared. The MIPS will advance our capabilities for studying the far infrared sky by many orders of magnitude. Because there is as yet no plan for a far infrared mission to follow SIRTF into space, the archive of MIPS data will be an important astronomical resource for many years.

## ACKNOWLEDGEMENTS

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