PHOTOMETRIC CALIBRATIONS FOR THE SIRTF INFRARED SPECTROGRAPH

P. W. Morris[1,2], V. Charmandaris[3], T. Herter[3], L. Armus[1], J. Houck[3], and G. Sloan[3]

[1]SIRTF Science Center, California Institute of Technology, 1200 E. California Blvd., Pasadena, CA 91125
[2]NASA Herschel Science Center, California Institute of Technology, 1200 E. California Blvd., Pasadena, CA 91125
[3]Department of Astronomy, Space Sciences Bldg., Cornell University, Ithaca, NY 14853

ABSTRACT

The SIRTF InfraRed Spectrograph (IRS) is faced with many of the same calibration challenges that were experienced in the ISO SWS calibration program, owing to similar wavelength coverage and overlapping spectral resolutions of the two instruments. Although the IRS is up to ∼300 times more sensitive and without moving parts, imposing unique calibration challenges on their own, an overlap in photometric sensitivities of the high-resolution modules with the SWS grating sections allows lessons, resources, and certain techniques from the SWS calibration programs to be exploited. We explain where these apply in an overview of the IRS photometric calibration planning.

Key words: SIRTF, ISO, Infrared Instrumentation, Spectroscopy, Infrared Calibration Stars

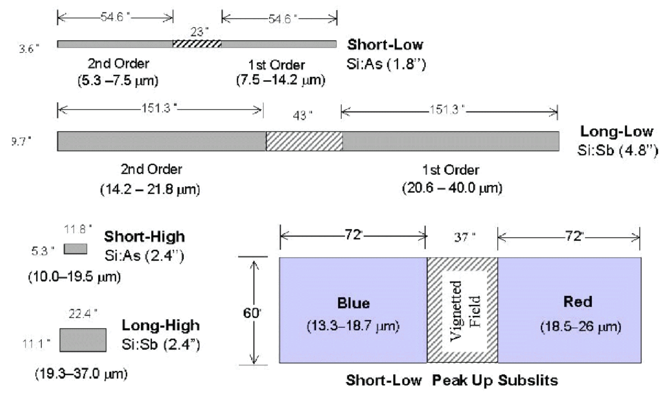

Figure 1. Schematic representation of the IRS slits (not to scale). The focal plane arrays are backside-illuminated BiB detectors in 128×128 pixel format. Detector materials, pixel sizes, and wavelengths associated with each module are indicated.

1. THE IRS CALIBRATION CHALLENGE

The IRS is one of three science instruments in the payload of NASA's Space Infrared Telescope Facility (SIRTF), and will provide spectroscopy over the 5.3−40 μm range at spectral resolutions $\lambda/\Delta\lambda \sim$600 between two echelle spectrographs, and $\lambda/\Delta\lambda \sim$100 between two long-slit spectrographs. One of the low resolution modules allows peak up imaging at 15 and 23 μm in two subarrays, so that celestial targets with with poorly known positions may be accurately placed in the IRS slits. The four instrument modules along with the cold electronics constitute the cold assemblies located within the multiple instrument chamber, which also houses the InfraRed Array Camera (IRAC) and the Multiband Imaging Photometer for SIRTF (MIPS). The IRS and MIPS share warm electronics, with savings in mass, volume, and cost. The slit dimensions, wavelength coverage, detector materials and pixel sizes for the four modules are schematically illustrated in Figure 1. Additional details on the performance characteristics of the IRS may be found in Houck & Van Cleve 1995, Roellig et al. 1998, and the SIRTF Observer's Manual.

One of the key design features of the IRS is the absence of moving parts. As a consequence, all inflight calibration activities must be performed while light from celestial sources enters through the IRS slits. This impacts the measurement of dark currents and photometric responses to both internal stimulators and external sources, as light from the extended zodiacal background, potentially the cold ISM, and variously from stars or other extended sources will fall on the IRS arrays. The Short Low module will also be susceptible to the effects of light entering through the peak up apertures and spilling from the imaging subarrays onto the spectrally dispersed portions of the array (Figure 2).

The challenge of shutterless operations for calibrating the IRS is being met by a combination of:

- A series of intensive functional and end-to-end tests in the laboratory, involving: the flight hardware, running from fabrication to integration with the observatory; tests with spare arrays at cryogenic temperatures in laboratories at Cornell University and at the Harvard Cyclotron Laboratory; and tests of the spare pass filters and filter assemblies in optics laboratories at Rochester University
- data processing methods to correct for stray light
- and the development of an iterative and flexible inflight calibration program which stresses (i) verification and update during the In-Orbit Checkout phase, (ii) monitoring performances and improving calibrations by iteration over the routine mission, and (iii) accounting for pervasive but variable background light.

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Full derivation of the spectral and Peak Up imaging flats and the absolute flux scales will be initiated during the science verification phase of IOC, and continued into routine operations. The IRS has flood illuminators in each module that can be used for measuring detector photocurrent, linearity, noise, and stability. However, the stimulators are non-imaging and produce a highly structured illumination pattern, and are intended for ground-based instrument tests without guarantees on flight performance. Photometric calibrations of the IRS must therefore rely chiefly on a network of astronomical calibration sources (ACSs). As the IRS does not have internal sources for wavelength calibration, celestial sources will also be observed to verify the calibrations established in the laboratory. The ground-based preparations and ACS selection process are similar to those undertaken for the SWS, due to the similar wavelength coverages and accessibility of flux densities up to several 10s of Jy by the IRS high resolution modules.

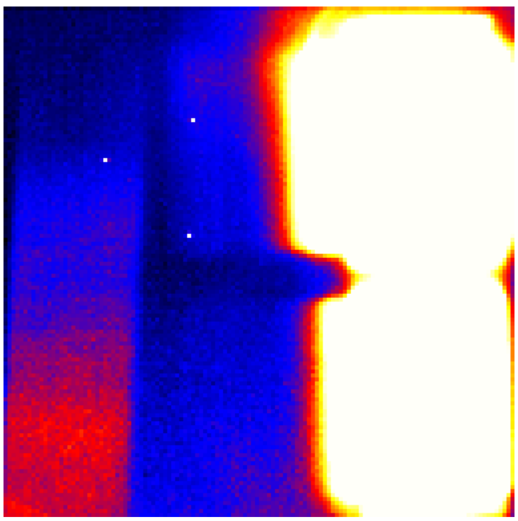

Figure 2. The Short Low array, showing light spilling from Peak Up subarrays on the right (red is at the top, blue on the bottom) onto the array. Light in the first spectral order can be seen on the left.

2. IRS PHOTOMETRIC CALIBRATIONS

2.1. Requirements

The IRS has a radiometric uncertainty upper limit of 5% (van Cleve 2001). The error budget takes into account the array dark and read noise properties, pointing-related flux losses, and residual fringing in the high-resolution flatfields. As the IRS slits are narrow (see Fig. 1), pointing-induced flux throughput error (assuming the "hard point 1" APE of 0.4″) is expected to be the dominant factor in the error budget. This condition is familiar in SWS calibrations. For the high resolution modules an additional factor of ∼2.5% at 1-σ is attributed to residual (not fully removed) fringes in the flatfields. Extensive testing of the algorithm which is used to identify a source in the IRS Peak-Up field and to subsequently place it on a slit, as well as simulations of the stability of the telescope tracking, indicate that for most IRS observation the 5% radiometric accuracy requirement can be met, following full verification of telescope pointing requirements, and validation of pipeline processing procedures.

The radiometric accuracy requirement does not include errors arising from uncertainties in reference data (e.g., synthetic spectral energy distributions) for the celestial standards used in the calibrations. Within the first year of operations, these errors are estimated to contribute (in quadrature) an additional 10% relative flux uncertainty across the SL and LL spectral orders, and 5% across the SH and LH echelle orders. The goal is to reduce these uncertainties to 5% in all orders by the end of the first year, so that the net uncertainty across any IRS order is 7% or less. The relative flux uncertainty between adjacent resolution element should be a factor of two or more less than this by the end of the first year of operations. The IRS does not have explicit requirements on absolute flux calibration. This is essentially tied to inter-order relative flux calibration.

2.2. Strategy

The baseline strategy for photometrically calibrating the IRS focuses on the spectral and Peak-Up array flats, once wavelength calibration has been verified on-orbit. The steps can be summarized as follows.

1. Coarse spatial pixel-to-pixel responsivities will be derived for the sensitive low-resolution modules (SL, LL, and SL Peak-Up) from dithered observations of the thermal emission from zodiacal dust grains. Peak-Up flats will also rely on dithered observations of a bright diffuse reflection nebula such as NGC 2071.
2. Refinements to the low-resolution flats, and initial derivation of the flats for the high-resolution modules will be achieved by smoothly scanning[1] are standard stars along the slits in the cross-dispersed direction.
3. A calibration database of early-type A dwarf stars will be built up over the mission, but a network that includes cool giants (G8−K5 III) and solar analogues is crucial due to limited visibilities and significant uncertainties (spectral typing and potential infrared excesses) among the A star candidates. The Vega phenomenon is possible around G dwarfs as well (e.g., Decin et al. 2000). The spectral-typing uncertainties can be alleviated by emphasizing stars selected for IRAC calibrations (Megeath et al., these proceedings).
4. The zody-based flats can be used to reveal significant departures in the energy distributions of stars observed with the SL and LL modules. The unrejected cool giants can be used to further discriminate A and solar-type stars with thermal infrared excesses.
5. Calibrations of the high resolution modules will be initiated solely from standard star observations, but will make

[1] Or, a synchronized "step-and-stare", whereby conditioning frames are taken during telescope motion, and exposures on the sky occur at a fixed sky position.

use of stars validated with the low-resolution modules, exploiting some overlap in the dynamic ranges of photometric responses the modules.

6. The final flats will be created by median averaging the resulting 2-D images, and using synthetic spectral energy distributions to remove the spectral signature of the star in the dispersed direction.
7. Point source flux calibration will be established, using a calibration analysis procedure to correct point-source diffraction losses and higher order terms in the flatfields. The "key-wavelength" concept used in SWS photometric calibrations will be employed for the IRS echelle and long-slit spectral orders.

2.2.1. The zodiacal light

Approximately 9 hours of observing the zodiacal light will be performed during IOC for flatfielding. Dithering will mitigate the effects of: cosmic ray events on the arrays which may not be fully corrected in the IRS data pipeline; and spatial structure in the zodiacal dust cloud at the arcminute scale. The thermal peaks are expected to differ with the solar elongation angle on any given observation date, and will vary over time with the SIRTF orbit. In particular, the differences in blackbody temperatures can be 15−20 K, according to (geocentric) predictions of the zodiacal thermal continuum based on COBE/DIRBE observations.[2] Pair-differencing these observations would induce gradients in both the SL and LL flats, most strongly in the SL module covering 5.3−14.2μm on the Wien side of the energy distributions (see Figure 3). Rather than pair-differencing, therefore, the COBE/DIRBE models must be used to divide the thermal continua out of the observations, leaving only the instrument responses. Averaging the flats obtained from different pointings will alleviate temperature uncertainties in the model.

It should be noted that uncertainties in the DIRBE-based zodiacal models range from ∼5% at the shortest wavelengths to ∼25% at the longest, but the uncertainty at 24μm has been reduced from ∼20% to ∼10%, using the SWS spectrum of NGC7027 in place of a KAO spectrum in the DIRBE calibrations. Generally speaking, however, confidence in the model over IRS wavelengths is lower than desired for flatfielding purposes. Moreover, spectral effects of potential silicate emission (Reach et al., in preparation) are unaccounted for in this model. The flats resulting from IOC observations of the zodiacal light must be regarded as coarse, producing relative uncertainties of 20% and 15% across each spectral order for the SL and LL modules, respectively.

2.2.2. Stellar calibrators

AV stars exhibit the strongest H-line spectra among all spectral types by definition of the Harvard classification scheme. If limited to earliest types A0-A1, the optical-infrared line spectra

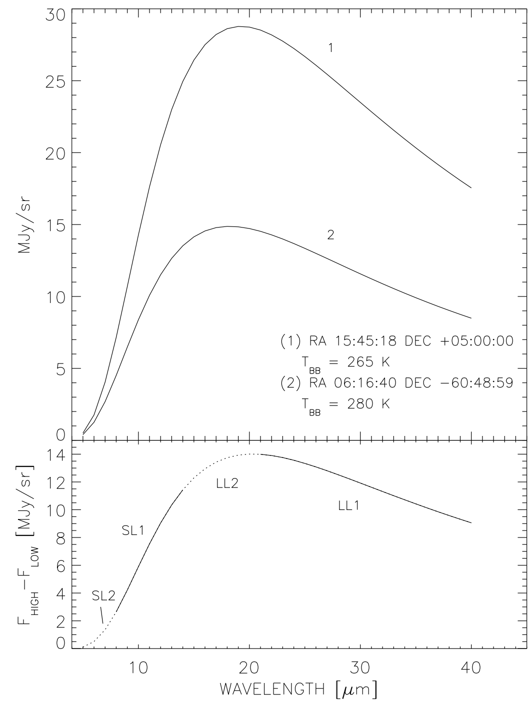

Figure 3. Predictions of zodiacal thermal emission at high and low ecliptic latitudes at the indicated positions, computed for 15 March 2003 using a COBE/DIRBE-based model (provided by W. Reach). The lower curve shows the difference of high and low zody continuum distributions, and the portions covered by the low resolution modules (where "SL2" identifies Short-Low spectral order 2, etc.)

are virtually free of metal lines, which mitigates discrepancies in synthetic spectral energy distributions imposed by limited input atomic data. Most A dwarfs suited to IRS sensitivities have not been well observed in the mid-infrared, and in many cases the spectral types and luminosity classes are uncertain from lack of high quality optical spectra. Reliable parameters are needed for generating the models on which the relative flux calibration will be based, eliminating those stars with peculiar spectra (i.e., the An, Am, and Ap stars) in the process. Initially the IRS can benefit from the IRAC ground-based program in which optical spectra are being obtained for the IRAC candidate photometric calibrators to better establish their spectral types (see Megeath et al., these proceedings). ¿From a calibration planning perspective, *all* A stars will be suspect for thermal dust emission until otherwise verified, which can involve observations of some sources at 70μm with MIPS. Sources with significant excesses observable with the low-resolution modules can be discriminated early by utilizing coarse calibrations based on the zodiacal light measurements. Methods for further discrimination are described below.

Vega (A0 V) and Sirius (A1 V) are both primary MK standards which, along with α Cen (G2 V), form the references for the network of infrared calibration stars in the scheme of M. Cohen and collaborators (see, e.g., Cohen et al. 1992, 1996).

[2] Made available as a SIRTF proposal generation tool by W. Reach at the SIRTF Science Center.

Both A stars should be included among the stellar calibrators for the high-resolution modules, allowing direct comparison with SWS observations of these stars, but both present known and potential difficulties.

Vega has suitable photospheric fluxes, but exhibits a thermal excess beginning near 12μm. The excess was not confirmed with the SWS, most likely for sensitivity reasons. However, the excess should be detectable with the IRS, whose LL and LH slit widths are respectively 151.3$''$ and 22.4$''$ in the spatial dimension. Vega will be observed but independently calibrated to investigate the strength of its infrared dust excess in the LH slit, followed up with LL1 spectra at short integration times, depending on the LH results. Sirius is a spectroscopic binary, but the light of the primary completely dominates the white dwarf companion over IRS wavelengths. Line velocity variations of the primary are also undetectable at IRS spectral resolutions. Its brightness is suitable for the LH module,but exceeds the saturation limits for most of the SH echelle orders. Neither Sirius nor Vega are visible during IOC, but are in SIRTF OPZ for at least 6 months at a time. Visibility constrains the number of A stars which can be observed early in the mission to only three or four, all of which must be verified to be infrared excess-free.

Additional calibrators will be drawn from stellar standards and lower effective temperatures, with some overlap in makeup of the SWS calibration program. The SWS could not take advantage of solar analogues over most of the ISO mission due to a combination of visibility and brightness limitations, but more of these stars should be accessible to the IRS. Solar analogues are emphasized in MIPS calibrations. Most sources will be selected from the final list of IRAC calibrators for highest confidence in spectral typing. The primary calibrator designated for monitoring purposes is HR6688 (K2 III), an SWS short-wave calibrator with well-determined stellar parameters. Ground-based observations and Uppsala MARCS-code synthetic spectra (Decin 2000) are available. As a primary calibrator, HR6688 will fill the same role as HR6705 did for SWS, i.e. providing a reliable component in the flux calibration and a fiducial for long-term trending on external sources.

A partial list of the primary sources is presented in Table 1. “Primary” sources constitute those which have good visibility to SIRTF, have well-determined physical properties (confined to the usual conditions of being single, point-like, non-variable, chromospherically quiet, etc.), and are photometrically referencable to ground based photometry from, e.g., the ISO GBPP, SIRTF cross-calibration IRTF, or IPAC 2MASS databases. For these primary sources we will seek the highest-fidelity synthetic spectra, such as provided through collaboration between the group of B. Gustafsson and the SWS team (see van der Bliek et al. 1996, Decin 2000, and Decin et al. 2001), as well as templated spectra for these and remaining sources through SIRTF contracts with M. Cohen.

The calibrations will not be based exclusively on an individual object or spectral class, though the early-type A dwarfs may be increasingly emphasized over the mission since they are more reliably templated according to spectral type with synthetic spectra (once validated to be free of thermal excesses) than are the yellow and red stars.

Table 1. Partial list of primary IRS calibrators

Source	Type	$F_{12\mu m}$ (Jy)	Comment
HR6606	G9 III	1.70	SL,LL,SH,LH
HR6688	K2 III	1.40	LL,SH,LH
HR6705	K5 III	155.1	LH
HR7018	A0 V	0.19	SL,LL,SH,LH
HD143187	A0 V	0.12	SL, LL
HR7187	G8 III	1.72	SL,LL,SH,LH
HD46190	A0 V	0.120	PU Red & Blue
Neptune	Planet	0.05	Red source
Mrk279	AGN	$\sim$0.2	Red MIPS x-cal

We recognize that *no* class of synthetic spectral energy distributions are error-free. A dwarf infrared photospheric line spectra are in disagreement between theory and observations of Vega and Sirius, for example, particularly in the lower Hu and Pf lines. This is not yet fully understood, but generally arises from inadequate constraints on certain contributing line formation mechanisms (e.g., stark broadening) in the mid-infrared (see and discussion following presentations in these proceedings by L. Decin and M. Cohen). At the other extreme, tolerances must be set for potential errors in the representation of the strong molecular bands in the cool stars. The SiO fundamental, spanning 7.7 to $\sim$10.5μm, is observable only in the first spectral order of the SL module. This and all other bands are out of the wavelength ranges of the remaining IRS orders. For SL1, the potential errors of the SiO band strength in models and independent observations are gauged to be $\sim$5% (integrated strength), as estimated from archive-phase SWS calibrations involving observations and the Decin (2000) MARCS model of HR6705, and ISOPHT calibration observations of HR7341 (K1 III) and the absolutely calibrated spectral composite from M. Cohen.[3] From these lessons, cool stars should be avoided in SL1 calibrations while the models are validated by iteration with independently-calibrated observations. No sources cooler than K5 will be used directly in IRS photometric calibrations. It should be pointed out that discrepancies in any reference data at the 5% level may not be resolvable by the IRS until well into operations.

2.3. Spectral leakage

Red sources such as Neptune and main belt asteroids will be used to detect flux leaking from blue wavelengths. The stellar standards all have negative spectral indices, and light which leaks from blue to red wavelengths will produce apparent red excesses in science observations if left uncorrected. Neptune is the primary red source to search for this effect. ISO observa-

[3] In both cases, the SiO fundamental was represented to be too weak, by $\sim$5% integrated strength, leaving apparent excesses in SWS and PHT-S spectra until corrected.

tions and models from E. Lellouch and M. Griffin are available. Neptune is not visible during IOC and is probably too bright for the LL module (chiefly LL1), however, so asteroids as represented by thermophysical models, or Titan by SWS spectra, may be observed with the IRS initially. The results of observing fast-moving solar system objects during IOC will depend on SIRTF tracking requirements being met.

3. DARK CURRENT MEASUREMENTS ON ORBIT

The fact that IRS has no moving parts implies that true dark currents cannot be measured in flight. Dark plus low-level sky offset measurements will be obtained several times per science campaign at preselected positions in the north (α=17:15:50, δ=+65:25:37, J2000) and south (α=6:16:40, δ=-60:48:59) CVZs. At these positions the contamination from stars and Galactic cirrus in the mid-infrared is minimal. Unfortunately, the areas that reach minimum cirrus emission, and which are also targets of a number of SIRTF deep surveys, are not in the CVZs. The warm thermal emission from the zodiacal light will generally dominate the sky offset, but the cooler cirrus may be detectable at the longer wavelengths of the LL module. Consequently, reference darks will be obtained (on less routine basis) at those positions (α=14:18:11.0, δ=+52:29:46.4, and α=12:36:49.90, δ=+62:12:58.0) as well. The status of the pixel dark current will also be monitored on the regular basis, following the behavior of the intra-order unilluminated parts of the array.

4. *Post Mortum* ON LESSONS LEARNED

The preceding overview contains a number of references to aspects of the SWS calibration program, where they most benefit photometric calibration planning for the IRS in resources and experiences. The referencing is seriously incomplete, as a number of the most important lessons learned by the SWS calibration team were learned *after launch*, rather than in the pre-launch planning stages. Several minor and several painful modifications to the Routine Phase Calibration Plan, distribution and focus of weekly calibration measurements, and composition of the ACS network were made over the mission in response to the varying sensitivities and aging of the detectors in a harsh radiation environment (Heras et al. 2000), to the performance of the spacecraft (pointing and tracking), and to the learn-as-we-observe nature of the calibration sources (leading to de-emphasis of the asteroids, for example). Pipeline software, and capabilities of the Interactive Analysis environment for iterative calibration analysis and pipeline development and debug were critical in this process. A balance between delivery schedule and adequate down time for software development and calibration analysis was difficult to achieve during the cold mission, however, resulting in a schedule too heavy with frequent pipeline and calibration update deliveries and a perpetual PV-like workload, to the detriment of analysis depth and adequate explanatory documentation to the science end user. This opinion is developed in hindsight, and an altogether different balance may be in order for SIRTF. The principal concern, based on the ISO experience, must be to have the *tools* ready to adapt to changes in performances after launch, as a matter of scientific survival.

REFERENCES

van der Bliek, N.S., Morris, P.W., Vandenbussche, B., et al., 1998, in IAU Symposium 189, Fundamental Stellar Properties: The Interaction Between Theory and Observation (Kluwer: Dordrecht), 89

van Cleve, J., 2000, Ball Aerospace & Technologies Corp. System Engineering Report S200117.Sys.00-006

Cohen, M., Walker, R.G., Barlow, M.J., Deacon, J.R., 1992, AJ, 104, 1650

Cohen, M., Witteborn, F.C., Carbon, D.F., Davies, J.K., Wooden, D.H., Bregmen, J.D., 1996, AJ, 112, 2274

Decin, G., Dominik, C., Malfait, K., Mayor, M., Waelkens, C., 2000, A&A, 357, 533

Decin, L., 2000, Ph.D. Thesis, Katholieke Universiteit Leuven

Decin, L., Waelkens, C., Eriksson, K., et al., 2000, A&A, 364, 137

Heras, A., Wieprecht, E., Feuchtgruber, H., et al., 2000, ExA, 10, 177

Houck, J.R., Van Cleve, J., 1995, Proc. SPIE Vol. 2475, 50

Roellig, T.L., Houck, J.R., Van Cleve, J.E. et al., 1998, Proc. SPIE Vol. 3354, 1192