IN-ORBIT CALIBRATION OF ISOPHOT-S

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ABSTRACT

We report on the in–orbit calibration of staring and chopped observations performed with the spectrophotometer ISOPHOT–S. Staring observations are calibrated using a Spectral Response Function which depends both on the signal and the elapsed observing time. Chopped observations are calibrated with a signal dependent Spectral Response Function, which was obtained from a set of observations of standard stars covering a range in flux densities. Both methods are consolidated, implemented in the Offline Processing software, and produce photometric results with a general accuracy of 10% or better.

Key words: ISO – ISOPHOT–S – Calibration – spectrophotometry

1. INTRODUCTION

ISOPHOT–S was a low resolution grating spectrometer onboard the Infrared Space Observatory (Kessler et al. 1996), integrated as part of the ISOPHOT instrument (Lemke et al. 1996). It consisted of two simultaneously measuring linear arrays with 64 pixels each, and covering the wavelength ranges 2.5 to 4.9 μm (SS) and 5.9 to 11.7 μm (SL). The aperture size was $24'' \times 24''$. Due to its low spectral resolution ($\sim$100) and high sensitivity ISOPHOT–S was an ideal instrument for the detection of mid-infrared spectral features like PAHs or the silicate feature at 10μm even in very faint objects with a flux density of 100 mJy or below.

2. CALIBRATION STRATEGY

A detailed technical description of ISOPHOT–S can be found in Klaas et al. (1997). Due to technical reasons, the calibration and data reduction strategy has several features not common with other ISOPHOT detectors. The main difference is the inability to determine the actual detector responsivity by calibration measurements on the internal Fine Calibration Source. Thus the photometric calibration of ISOPHOT–S is simply a conversion from the measured signals (in units of V/s) to astrophysical flux units by means of a Spectral Response Function (SPRF hereafter). Subtraction of the dark current prior to the conversion, however, is necessary, especially when observing faint sources. The corrections for ramp linearity, reset interval, and signal linearity, routinely applied to other ISOPHOT detectors, are of minor importance and are not considered for ISOPHOT–S. In the next sections we discuss the subtraction of the dark current signal, and the derivation of SPRFs for staring and chopped observations.

3. THE DARK SIGNAL

Observing faint sources slightly above the sky background level, a high percentage of the measured signal is due to dark current (typical values are between 0. and 0.3 mV/s for the SS array and between 0.3 mV/s and 1 mV/s for the SL array). The Astronomical Observation Template for ISOPHOT–S, AOT P40, guarantees that any sky measurement is preceded by a short dark current measurement, although the observing time was too short to obtain a stabilised signal. In order to establish the general in–orbit behaviour of the dark signal, we have collected and analysed observations from two projects: 10 long measurements of 1024 s duration from the Zodiacal Light programme, and a large number of shorter (256 s duration) ones obtained from the regular monitoring of dark current over ISO's life.

3.1. Variation with exposure time

The evolution of the dark signal with exposure time can be described by an increasing exponential function with a typical timescale of $\sim$ 100 s. The functional form is:

$$S_{dk}(\lambda,t) = I_{dk}(\lambda) + I_{dk}^{cor}(\lambda,t)$$

$$I_{dk}^{cor}(\lambda,t) = A(\lambda) * exp(-t/\tau(\lambda))$$

This formula makes it possible that from measurements shorter than 512 s a dark current value corresponding to the measurement length can be subtracted. This correction is available in PIA (Gabriel et al. 1997) but not implemented in Offline Processing (OLP). Nevertheless, this correction is taken into account in the calibration of staring observations as shown in section 4.2.

3.2. Orbital variation

The variation of the dark signal with ISO's orbital position was determined from the shorter dark measurements, which were randomly distributed over the duration of the ISO science window. In the SL array the dark signal shows a high value at the beginning of the orbit, followed by a slow decline which extends up to the middle of the science window, about 5 hrs (see

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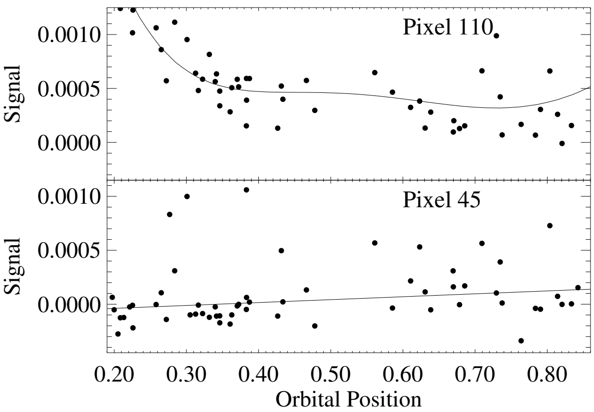

Figure 1. Orbital variation of dark signal. Pixels 45 and 110 correspond to the SS and SL arrays, respectively.

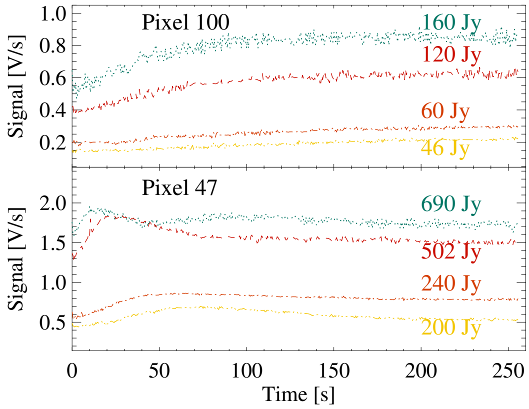

Figure 2. Transient curves for two pixels. It can be noticed that the transient response becomes faster when the flux increases.

Fig. 1). This trend is stronger for the longest wavelength pixels. We fitted this variation by a smooth function, which was then scaled to a higher absolute level determined by the long dark measurements. Thus the default dark current value, stored in a calibration file and subtracted in PIA and OLP, might overestimate the actual dark signal content in shorter observations. In the SS array there is no significant variation of the signal with orbital position (see Fig. 1). The reason for the orbital variation is a memory effect due to the bright illumination during the daily instrument activation by internal lamps. These lamps emit with maximum energy beyond $\sim 12\ \mu$m , which saturates the SL detector but gives almost no power at the SS wavelength range. The orbit dependent dark subtraction has been implemented in both PIA and the Offline Processing (OLP).

4. Staring Mode Photometry

4.1. Standard Spectral Response Function

Ideally the Spectral Response Function would be a constant value for each detector pixel. We made an attempt to obtain a constant SPRF from a set of observations of standard stars, but it turned out that such a function was not consistent at different flux levels. The reason why this simple approach cannot be applied to ISOPHOT–S is very likely the dependence of the signal transients on the signal level. Ground tests showed that the transient response becomes very slow at low illumination levels (Schubert et al. 1995). These tests also showed that the signal transients can be well modelled by a relatively simple expression, as derived by Fouks & Schubert (1995). However in–orbit measurements do not behave according to the mentioned model, especially for high fluxes a non–monotonic curve is observed in staring measurements which cannot be handled with the Fouks & Schubert formula (see discussion in Acosta–Pulido et al. 2000). The most likely reason for the different pre–flight and in–orbit behaviours resides in the operating mode: in–orbit the detectors are always switched–on at the beginning of any science observations, whereas in the ground tests the measurements were performed under stable conditions, a long time after the switch–on of the detector.

The net effect is that in the case of ISOPHOT–S the Spectral Response Function becomes a function which depends not only on the pixel but also on the exposure time and the absolute value of the signal. The new approach which takes into account these conditions is called *dynamic calibration*.

4.2. Dynamic Calibration

The principle of the dynamic calibration relies on the reproducibility of signal transients when the detector is exposed to similar flux, with a comparable previous illumination history. The short initial dark measurement in the P40 AOT guarantees this feature. Fig. 2 illustrates the principles: the detector's transient response strongly depends on the incoming flux level, becoming faster as the illumination level increases, but similar illuminations trigger similar responses.

It was also found that the operational temperature is a crucial parameter affecting drastically the shape of the transient curves. This was discovered when comparing observations of the same star, obtained during the initial Performance Verification Phase with others obtained later during the Routine Phase. Fortunately, the temperature of the detector was rather stable during this latter period.

Therefore a good coverage of calibration measurements is needed in order to cope with the full range of possible targets. Unfortunately we have to rely only on stellar calibrators which introduce a certain bias towards similar spectral shape, which is the Rayleigh–Jeans tail. During the ISO mission we could observe about 20 stars covering a range in flux from 0.1 Jy to 2000 Jy at 5 μm . The measurements were processed from ramps up to signals and deglitched, using PIA Gabriel et al. (1997). In this way we create a database of transient curves for each pixel and a range of fluxes. These curves were described using Chebyshev polynomials in order to be able to predict the signal at any time in a simple way.

It is worth to noticing that the flux illuminating a pixel detector contains not only the contribution of the target of interest but also of the sky background in that region. The sky background at the wavelength range of ISOPHOT–S is dominated by the zodiacal light which we modelled by the composition of an emission part, due to the dust heated by the sunlight (a blackbody of T$\sim$267 K; Ábrahám et al. 1997) plus a reflection part (a blackbody of T$\sim$ 6000 K; Matsumoto et al. 1996). The absolute scale of the composite model is set by a least square fit to COBE/DIRBE measurements from the Weekly Sky Maps at bands 2.2, 3.5, 4.9 and 12 μm . The background model is computed as surface brightness, therefore it has to be converted to the equivalent flux for point sources. The conversion factor has been derived after integration along the measured beam profile of the aperture.

In this way one can construct a spectral response function which depends on the time within measurement and the signal value at that time: $S_{meas}(\lambda, t) = S_{ph}(\lambda) + S_{dk}(\lambda, t)$ $S_{ph}(\lambda)$ is the signal due to detected infrared photons, which can be written as $R(\lambda, t, \phi_\lambda) \times \phi_\lambda$. $S_{dk}(\lambda, t)$ is the dark signal, its behaviour was discussed in section 3. After subtracting the time–independent dark signal we obtain: $S^{'}_{meas}(\lambda, t) = R(\lambda, t, \phi_\lambda) \times \phi_\lambda + I^{cor}_{dk}(\lambda, t)$ where ϕ_λ is the flux density received in the *i-th* detector pixel, which corresponds to wavelength λ.

For the practical implementation we have selected a set of times equally spaced in logarithmic scale (t=2^n; n=1,8). For a particular time we construct a transformation function from measured signal to flux, by fitting in logarithmic scale a smooth curve among the signals from calibration measurements and the assigned fluxes (see Fig 3). At the faint regime and during the initial observing time, the term $I^{cor}_{dk}(\lambda, t)$ may dominate. This will produce a negative signal, which can be also interpreted as an over-subtraction of the dark signal. Even in those cases, the proposed transformation function assigns the positive flux which corresponds to the asymptotic signal value. Finally we have two matrices: one containing the correspondence between signal and flux for any time and another containing weighting factors to give larger weight to the data values obtained at later observing times when signal approaches stabilisation. These matrices are used to calibrate staring ISOPHOT–S measurements in the OLP starting from version 9.0.

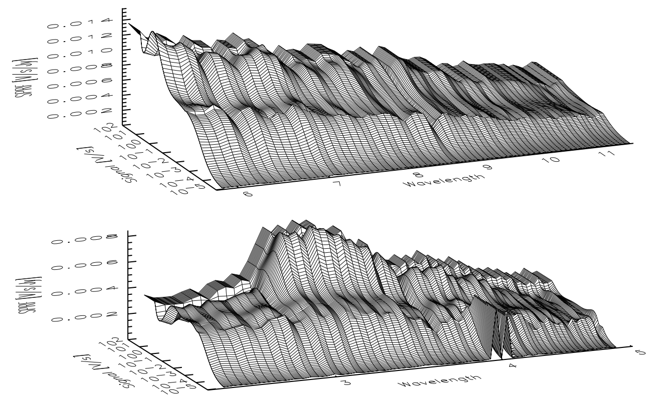

Figure 3. Dynamic Spectral Response Function.

We have performed self consistency checks by calibrating the calibration observations with the method described above. The results indicate a 10% accuracy along the flux range considered and good preservation of the spectral shape. More extensive testing on independent observations will be presented elsewhere.

5. CHOPPED MODE PHOTOMETRY

About 400 observations were performed in chopped mode with ISOPHOT–S. Most of these observations correspond to relatively faint objects for the sensitivity of the instrument. Under such circumstances the response of the detectors becomes very slow and up to 40% of the signal contrast may be lost, although this factor depends on the absolute flux level. In a first attempt to correct the signal losses we have used the Fouks–Schubert model. This model seems to work properly for calibration observations (moderately high contrast and relatively long chopper plateaux), similarly to ground tests (Acosta–Pulido et al. 2000). However for genuine science observations the signal contrast is usually very small, therefore the S/N becomes very small and the time per chopper plateau is very short relative to the stabilisation time. In this case correcting the signal losses with Fouks–Schubert model is prone to large uncertainties.

Alternatively we have developed a simpler approach, which calibrates the signal losses directly from chopped observations of reference stars. In this case there is no need for any model fitting, thus less uncertainty is introduced in the calibration process. We obtained observations of some of the faintest calibration stars. In total we have data for 7 different stars, covering a flux range between 0.1 to 30 Jy at 5μm . This range of flux includes about 90% of the science observations. despite a certain bias towards stellar–like spectral shape. At zero order we have produced a SPRF which is the average of those obtained from the 7 calibration stars: $SPRF^0(\lambda) \; =< \frac{S^{on}(\lambda) - S^{off}(\lambda)}{\Phi_\lambda} >$ where $S^{on}(\lambda)$ and $S^{off}(\lambda)$ are the detector signal measured from the calibration star and the background, respectively. The average is done over all calibration observations. We have noticed that the individual SPRFs show systematic variations with the brightness of the calibration stars up to 20% for the most extreme pixels. Therefore we introduced a first order correction which depends on the signal level as given by the following expression: $SPRF^1(\lambda) = f^{cor}(\lambda)\, SPRF^0(\lambda)\; f^{cor}(\lambda) = C_0(\lambda) + C_1\, log(S^{on}(\lambda) - S^{off}(\lambda))$. The resultant SPRF is presented in Fig. 4.

Self consistency checks show that 5–10% photometric accuracy is achieved and 10–20% deviations in the spectral shape,

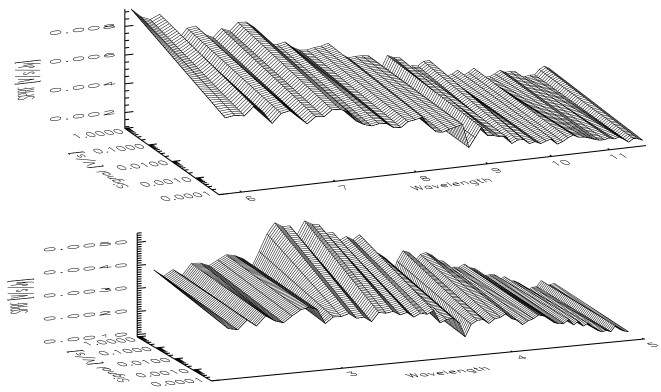

Figure 4. Spectral Response Function for chopped measurements.

the worse figures correspond to the brightest and faintest flux levels.

6. POSSIBLE FUTURE IMPROVEMENTS

The in–orbit calibration of ISOPHOT–S has reached a good accuracy level, about 10% in both staring and chopped modes. Nevertheless, there are still some aspects which can be improved, especially at the faint flux regime. Among the most important ones we mention:

- There is a possible vignetting effect when observing in chopped mode at very faint levels.
- The dynamic calibration of staring observations at faint fluxes was based very much on the COBE/DIRBE background measurements. Ideally the whole calibration should be become independent of it.
- There were few observations done in raster mode, which are still calibrated using a static SPRF. The transient behaviour of the signal still has to be investigated.

7. CONCLUSIONS

We presented the currently most accurate calibration procedures for ISOPHOT–S staring and chopped observing modes. For staring observations we proposed the use of a Spectral Response Function which depends on the signal measured for each detector pixel, at a given integration time. For chopped observations we found that an accurate calibration can be done by the use of a flux dependent SPRF: the zero order approximation is the average spectral response, then a correction which depends on the background subtracted signal. In both observing modes the expected accuracy is not worse than 10%.

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