ANALYSIS OF ISOPHOT CHOPPED OBSERVATIONS

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ABSTRACT

Chopping between the source and 1 or 2 background positions was an ISOPHOT observing mode for faint source photometry. More than 7000 observations of this type were performed during the mission. We review the main instrumental effects related to chopping, and describe the data reduction steps and calibration strategies developed for this mode. A robust signal processing has been invented which allows to derive reliable difference signals from a chopped pattern. Signal losses dependent on chopper frequency and flux change have been assessed from comparison with staring observations. Chopper offsets have been investigated from the analysis of non-detection measurements. The current data reduction scheme, as implemented in the automatic processing of OLP10, achieves accuracies in general better than 30%. Far-infrared observations of faint sources close to the detection limit may have higher uncertainties, partly due to cirrus confusion which is a severe limitation of this observing mode.

Key words: ISOPHOT – Calibration – Chopped photometry

1. INTRODUCTION

Differential measurements using a chopper are a common technique in infrared astronomy to detect faint sources on top of a fluctuating bright background and to cancel out low-frequency detector noise. While changes in the telescope and sky background level are of no concern for a cold telescope in space, low-frequency detector noise can still occur, therefore ISOPHOT was equipped with a focal plane chopper. The modulation frequency, which was significantly below the ground-based applications of 10–20 Hz, was adjusted in discrete steps to the brightness of the source. For redundancy reasons a chopper plateau included a minimum of 4 integration ramps, thus for bright sources f_{chop}=0.5 Hz with $n_{ramp}>4$, while for faint sources $f_{chop}\ll$0.5 Hz with n_{ramp}=4 was the usual set up. The observer had the freedom to select one of the three chopper modulation cycles (rectangular, triangular, sawtooth), and the chopper throw. A detailed description of these options is given in The ISO Handbook (Vol. V, Laureijs et al. 2000). More than 7000 chopped observations were performed during the mission. In this paper we describe the main instrumental effects encountered and the basic steps of data reduction and calibration. Finally we summarise the performance status and give an outlook on possible future developments.

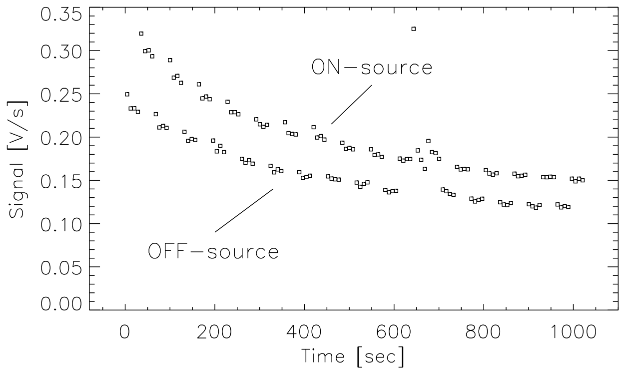

Figure 1. Example for a chopped observation of a faint source performed with the P1 detector. The alternating OFF-source and ON-source chopper plateaux (4 signal per plateau) are superimposed on a long term detector drift. At around 650 s measurement time a strong glitch disturbs one ON and one OFF plateau.

2. INSTRUMENTAL EFFECTS

2.1. LONG TERM DETECTOR DRIFTS

The most common "low-frequency detector noise" in chopped ISOPHOT measurements is a long term signal drift. Since the time scales of these drifts are typically much longer than the length of a chopper cycle, chopping can successfully eliminate the low-frequency variation if a sufficiently large number of chopper cycles (at least 4 ON–OFF pairs) was executed. As an example, Fig. 1 displays a chopped observation of a faint source performed with the P1 detector, where the alternating OFF-source and ON-source chopper plateaux are superimposed on a long term detector drift. Since this drift is a variation of the detector responsivity, the difference signals extracted from consecutive ON and OFF plateaux scale with the absolute signal. After correcting for this variation the normalised difference signals are turned to be very reproducible.

2.2. SHORT TERM DETECTOR TRANSIENTS

Chopping between background and source positions causes a periodic change of illumination on the detector which – under the low background conditions experienced by ISO – may in-

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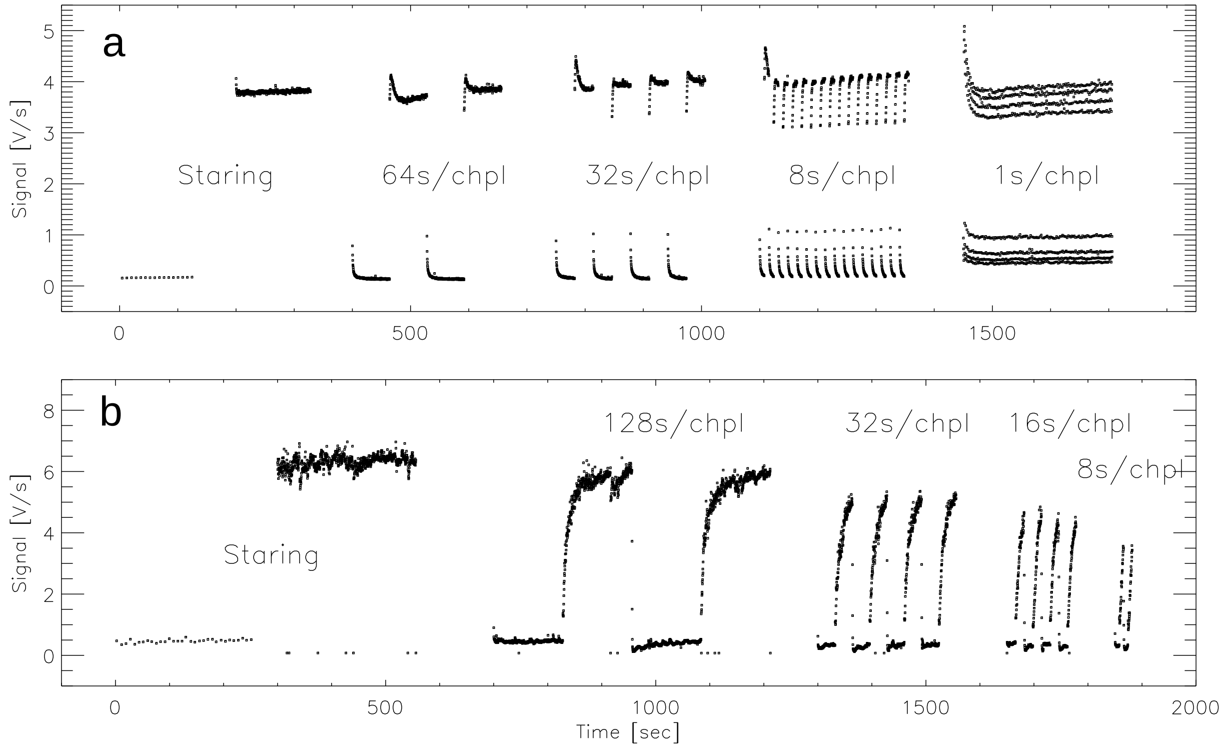

Figure 2. Sequences of chopped observations of the same target performed with increasing chopping frequency (expressed by the chopper plateau time). For reference the sequences are preceded by staring observations of the off-source and on-source positions. (a) P2 detector; (b) C100 detector central pixel (Pix. 5).

troduce short term signal transients over the length of the chopper plateau time. Due to these transients, in general the ON–OFF difference signals derived from chopped measurements differ from the ones obtained in staring mode. Figure 2 displays the two basic types of short term transients observed in the ISOPHOT detectors. After a chopper transition from background to source the P2 detector exhibits a steep signal rise, sometimes even with an overshoot, and then relaxes to the final signal level (Fig. 2*a*). The measurement sequence demonstrates what happens when a bright source is observed with increasing chopping frequency: first the measured ON–OFF signal is the same as the difference signal measured in staring mode, or even higher than that due to the overshoot, but at very high frequencies a significant signal loss can be observed.

The other basic type of transient is represented by the C100 detector (Fig. 2*b*). There is no overshoot phenomenon, and the initial rise of the signal is much slower than for the P2 detector. Since the signal follows a monotonically increasing curve, a higher chopping frequency simply leads to an increasing underestimation of the true signal difference, i.e. to signal loss.

2.3. Chopper offset

In a chopped observation source and background(s) are measured along different beam paths through the telescope. If the illumination of the focal plane is not perfectly homogeneous, an artificial non-zero ON–OFF difference signal, the *chopper offset*, might result. A positive chopper offset can mimic the appearance of a faint point source, while a negative one can hide a real source. In Sect. 3.3 we discuss the importance of this effect for the ISOPHOT detectors.

2.4. Cosmic glitches

The main source of random noise in ISOPHOT observations is due to cosmic glitches. In chopped measurements the time spent continuously on a sky position is relatively short and the signal is often not stabilised within the plateau. Therefore elimination of the glitches using the statistical methods developed for staring mode observations is not efficient, and special algorithms, like the one described in Sect. 3.1, have to be implemented.

3. Data reduction steps and calibration

3.1. Patterns of chopped measurements

In order to improve the efficiency of deglitching and increase the S/N in chopped measurements, we developed a method which makes use of the periodicity of the observation. First the long term transient is corrected for by computing the median signal of each chopper cycle and scaling all cycles to the same absolute signal level representative of the second half of the measurement. Then the chopper cycles are superimposed and the pair-wise difference signals, computed from the individual readouts within the integration ramps, are sorted into

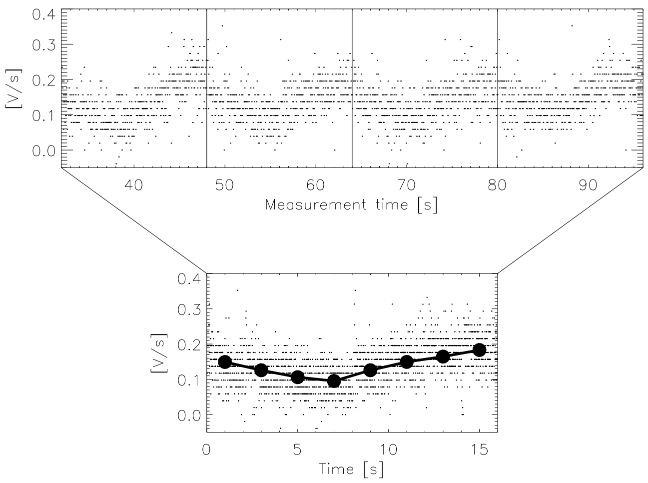

Figure 3. Schematic view on how to generate a pattern from a chopped measurement. The upper panel displays 4 chopper cycles of a C100 Pix. 5 sky measurement; each point is a pair-wise difference signal computed from the individual readouts within the ramps. The lower panel explains how the chopper cycles are over-plotted and averaged in order to derive the 8 signals of the pattern. Note that at a very low absolute signal level the shape of the pattern may be influenced by the digitalisation process.

8 bins according to their phase within the chopper cycle. The readouts within each bin are averaged in order to create an 8-point *pattern* (Figure 3). The first 4 points of the pattern are related to the background while the last 4 points are representative of the source position. In order to eliminate cosmic glitches an outlier-resistant averaging routine was used (the IDL procedure biweight-mean.pro from the Freudenreich AstroContrib Library), which assigns less weight to deviating data points. The resulting pattern has a high signal-to-noise and makes clearly visible short term transients within the chopper plateau. In those measurements which have 2 background positions 2 patterns are generated, which are then averaged so that the formal error bars of the final pattern represent the brightness difference between the 2 background positions, too.

In Figure 4 we display the typical pattern shapes of three ISOPHOT detectors. The patterns are sorted by the time per chopper plateau and binned according to the ON–OFF difference signal. The patterns of the P1 detector are the most regular ones; the typical step-function shape indicates the lack of any observable short term transients apart from the faintest signal levels. Signals of the central pixel of the C100 detector (Pix.5), on the other hand, are never stabilised within a chopper plateau, and they show slow monotonic transients similar to the ones in Fig. 2*b*. The pattern shapes of the C200 detector are dominated by a strong immediate signal jump appearing at each chopper transition, otherwise the signals within a chopper plateau are rather constant. At faint signal level, however, the pattern shapes of all detectors are different from the patterns at high signal level.

3.2. Extraction of difference signal from chopped patterns

After generation of a pattern the next step is extracting the ON–OFF difference signal. Due to the transients within the chopper plateaux the resulting ON–OFF signal depends on the way in which the 4 signal values of a source or background plateau are combined into one single number. (In the standard ISOPHOT data reduction scheme the first signal of each chopper plateau would be automatically discarded. In most patterns, however, the first signals look undisturbed and we do not discard them). A simple average is not the optimal solution for all pattern shapes, e.g. in the case of overshooting signals a median is more robust. It is crucial to define rules for the signal extraction, and to apply them in a consistent way for the assessment of the signal loss and chopper offset. The signal extraction rules adopted for OLP 10 are listed in Tab. 1. These rules are somewhat arbitrary definitions which try to find a compromise between eliminating the less reliable data points and maximising the used measurement time for the typical pattern shapes of the different detectors. The numeric values determined in the next sections for chopper offset and signal loss correction are based on these rules.

Table 1. Rules of signal extraction from patterns of chopped measurements in OLP 10. All 4 points of a chopper plateau are used.

P1, P2	– discard the max and min for both source and background plateau – average the non-discarded two points of source and of background plateau – subtract background from source
P3	– compute the max of the source plateau – compute the min of the background plateau – subtract background from source
C100	– compute the average of the source plateau – compute the average of the background plateau – subtract background from source
C200	– discard the first half of each chopper plateau – average the non-discarded two points of source and of background plateau – subtract background from source

3.3. Determination of the chopper offset

In order to learn about the importance of the chopper offset (Sect. 2.3) for the ISOPHOT measurements and to work out a correction scheme for it, the brightness distribution produced by a flat extended source should be known along the path of the chopper mirror in the focal plane. An analysis of datasets of very faint sources – supposedly non-detections - obtained with the C100 and C200 detectors (Haas 1998) indicated that the chopper offset is detectable in these observations. The results suggested that the relative amplitude of the offset depends on

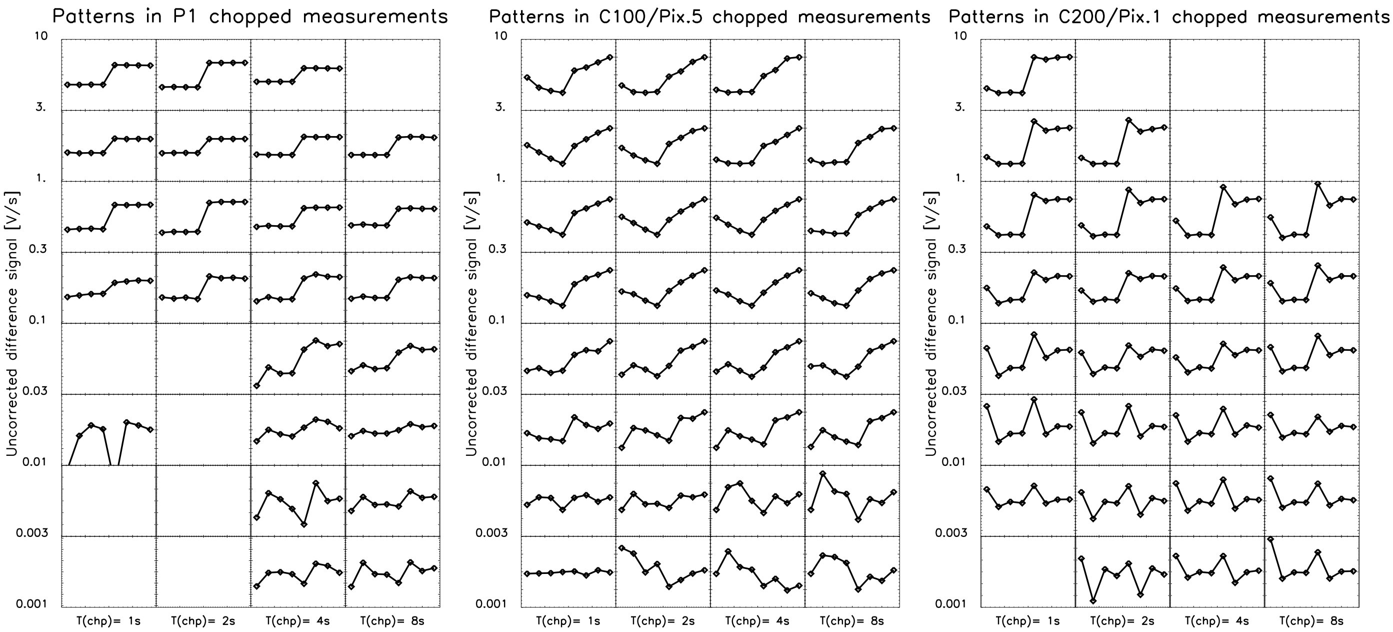

Figure 4. Average patterns of three ISOPHOT detectors, sorted by the time per chopper plateau and binned according to the measured ON–OFF difference signal. Left: P1 detector, Centre: C100 detector Pix. 5., Right: C200 detector Pix. 1.

the chopper throw, on the filter, and on the chopping frequency, and its value is typically in the order of a few percent of the sky brightness.

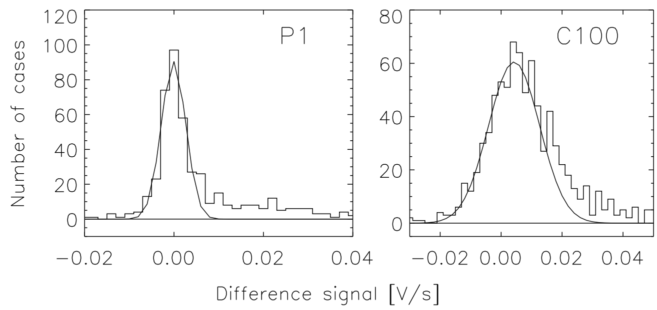

Figure 5. Histogram of the difference signals for the P1 and C100/Pix. 5 detectors with t_{chp}=8 sec. The low difference signal part of the histograms (left hand side of the signal distribution) is assigned to non-detections and fitted with a Gaussian in order to estimate the chopper offset value.

For the preparation of OLP10 we followed a simpler approach, and assumed that the dominant factor in determining the chopper offset is the time per chopper plateau. For a given detector all chopped observations performed with the same chopping frequency were collected, regardless of the filter and of the chopper throw. Then an ON–OFF difference signal was extracted from each pattern, and the histogram of these difference signals was analysed. Figure 5 shows these histograms for two detectors and for $t_{chp} = 8$ s. In the case of the P1 detector a narrow peak appears at small signal differences extended with a tail towards more positive ON–OFF signals. We interpret the peak as due to non-detections and the positive tail as due to real and detected sources. The position of the peak, determined by a Gaussian fit to the low signal part of the histogram, is very close to zero suggesting that no chopper offset occurs in combination with the P1 detector. The histogram of the central pixel of the C100 detector, on the other hand, indicates a slight positive shift in the peak position (5 mV/s), which we adopt as the absolute value of the chopper offset and correct the C100 chopped observations for it.

3.4. Signal loss correction

Due to the short term detector transients (Sect. 2.2) the ON-OFF difference signals derived from chopped measurements differ in general from the ones measured in staring mode. This deviation is determined primarily by the chopping frequency, but since the timescales of the transients depend on the illumination, the discrepancy may also be influenced by the source and the background brightness levels. In the following we assume that the really important factor is the change of illumination rather than the absolute brightness levels of the source and background.

The task is to apply a correction on the measured chopped difference signal ΔS^{meas}_{chop} in order to reproduce the signal level which would have been measured in staring mode ($\Delta S_{staring}$). Since the change of illumination is reflected in the measured chopped signal, one can write:

$$\Delta S_{staring} = \Delta S^{corr}_{chop} = f(\Delta S^{meas}_{chop}, t_{chp}) \quad (1)$$

We determined a functional relationship between $\Delta S_{staring}$ and ΔS_{chop} for each time per chopper plateau separately, by analysing a set of dedicated calibration measurements (like the ones in Fig. 2). In the case of the P1 and P2 detectors the calibration datasets were supplemented by observations of normal stars from the ISO Archive, whose predicted photospheric fluxes could be converted into V/s signal by using the default

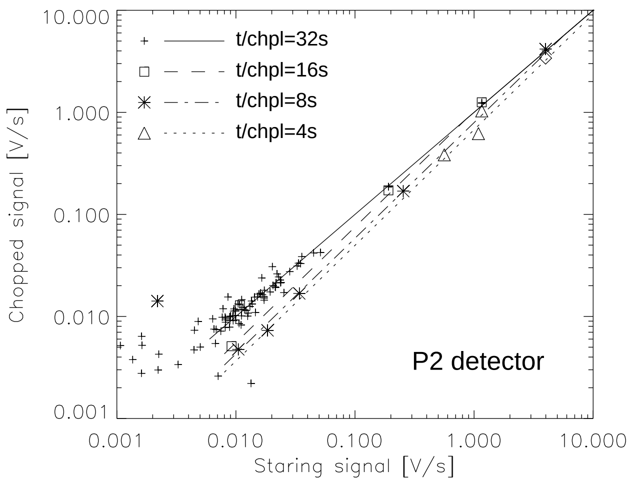

Figure 6. Relationships between the ON–OFF difference signals measured in chopped mode (ΔS_{chop}) and in staring mode (ΔS_{star}) for different t_{chp} values for the P2 detector (represented by the different line styles). The individual symbols represent the original observations of normal stars from which the relationships have been derived.

responsivity. This method was not applicable to the P3, C100, and C200 detectors where the default responsivity is not accurate enough. In these cases we utilised chopped FCS measurements where the illumination conditions are precisely known.

As an example Fig. 6 displays the relationships between $\Delta S_{staring}$ and ΔS_{chop} for different t_{chp} values for the P2 detector. Over-plotted are the original observations from which the relationships have been derived. Although at high signal level no significant signal loss can be observed, in faint source observations with $t_{chp}\leq 8$ s the measured chopped difference signal is only 30-50% of the staring value. The probable physical explanation is that under low illumination conditions the characteristic timescale of the initial signal rise seen in Fig. 2a becomes significantly longer.

The P1 detector does not show any obvious signs of signal loss, in accordance with the very regular step-like patterns of this detector (Figure 4). In the case of the P3 and C100 detectors, on the other hand, the measured chopped difference signal is almost always significantly lower than the true signal. The only rare exceptions are observations with $t_{chp}\geq 32$ s where the detector has enough time to reach a stabilised level. The C200 detector is rather insensitive to chopping due to a high initial signal jump (Figure 4), thus the chopped signals never deviate from the staring ones by more than 10–20%.

4. PHOTOMETRIC CALIBRATION

Each chopped observation (or a sequence of chopped multi-filter observations) is accompanied by a calibration measurement performed by chopping between the two on-board standard lamps (FCSs). This calibration scheme is based on the idea that performing the sky and FCS measurements in a nearly identical way (the optical powers of the FCS lamps were adjusted to the expected brightnesses of the on-source and off-source positions) is the best recipe to calibrate chopped measurements. The chopped FCS measurement, however, are relatively short (typically 32 s in total), and in many cases their quality seems to limit the photometric accuracy. For OLP 10 it was decided to use the default rather than the actual responsivity for the P2 detector (the responsivity behaviour of this detector along the revolution is rather reproducible). For the far-infrared detectors (P3, C100, C200) the default responsivity is less accurate, because the actual responsivity can vary significantly from one orbit to the next. In this case one is forced to use the chopped FCS data. The P1 detector does not show any sign of signal loss (Sect.3.4) and its responsivity is rather reproducible along the orbit. Using default responsivity or evaluating the accompanying chopped FCS measurements gives similar results; in OLP10 the calibration is based on the chopped FCS measurements.

5. STATUS OF CHOPPED PHOTOMETRY

5.1. PHOTOMETRIC ACCURACY

The typical photometric accuracies achieved in OLP 10 are listed in Tab. 2. In the case of the C100 detector the photometry is based on the central pixel of the array (Pix. 5), because a reliable signal loss correction could be developed so-far only for this pixel. The central pixel is sufficient for point sources, but in the case of small extended sources the flux densities could be underestimated. As an example for chopped photometry with ISOPHOT, Fig. 7 shows the results of observations of the Vega-type star HR 4295. The chopped data, obtained with the P1, P2, and C100 detectors and evaluated by OLP 10, match the ground based and IRAS results, and delineate the strong far-infrared excess characteristics of the Vega-phenomenon.

Table 2. Accuracies for chopped photometry achieved with the Legacy Pipeline, OLP 10. The values are derived from observations and include the sky confusion noise. For C200 no reproducibility could be determined due to cirrus confusion of the reference target.

detector	flux range [Jy]	abs. accuracy [%]	reproducibility 1 σ of 6 samples [%]
P1	0.06 – 10	<30	<15
P2	0.2 – 20	<30	<10
P3	$\geq$1	<30	<10
C100	$\geq$1	<30	<15
C200	$\geq$2	<40	–

5.2. LIMITATIONS DUE TO CIRRUS CONFUSION

Spatial fluctuations in the background signal, due to varying cirrus structure or unresolved galaxies, place a strong limitation on the detection of faint sources. The sky confusion noise

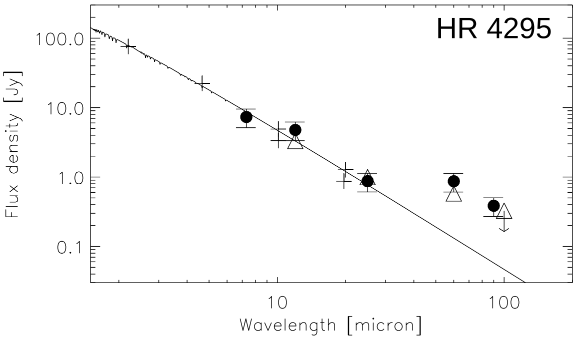

Figure 7. Spectral energy distribution of the Vega-type star HR 4295. Solid line: *expected photospheric emission;* filled circles: *ISOPHOT chopped observations;* plus signs: *ground based photometry;* triangles: *IRAS Faint Source Catalogue. The error bars correspond to 30% of the measured flux.*

increases with increasing separation between the source and background positions, and with increasing surface brightness. Chopped observations on high background with only one background position and large chopper throw are among the most affected cases, and sky confusion noise often dominates the uncertainties at $\lambda \geq 100\mu$m. Estimation of the expected confusion noise value can be computed using the formulae of Kiss et al. (2001).

5.3. Comparison to other faint source observing modes

At the beginning of the ISO mission chopping was the recommended observing mode for very faint point sources. Then, realising the instrumental effects specific to chopping (Sect. 2) two new observing modes were introduced. *Telescope nodding*, a periodic switch between source and background done by repositioning the telescope rather than moving the chopper mirror, could avoid chopper offsets. In *minimap mode*, used in combination with the array cameras ISOPHOT-C, a small map was performed around the source for each detector pixel. This method minimised the confusion noise and maximised the observing efficiency. The two new observing modes achieved higher signal-to-noise than chopping was able to do, therefore the number of chopped observations decreased towards the end of the mission. Nevertheless, chopping remained an active observing mode, and about 7000 chopped observations have been carried out during the mission, forming a significant block of ISOPHOT's legacy.

6. Future Directions

There are several alternative solutions for the calibration and data reduction issues, which may work better for particular observations than the ones implemented in OLP10. Fourier time analysis of chopped measurements to extract the difference signal without creating a pattern (Haas et al. 2000), and trained neural network algorithms to predict the true ON–OFF signal directly from the pattern (Bianchi & Ábrahám 2000) are promising possibilities, but a general assessment of their advantages is still to be done. In order to improve the photometric accuracy of chopped observations performed with the P3, C100, and C200 detectors a better understanding of the accompanying chopped FCS measurements is desired. Finally it is worth mentioning that the huge data base of ISOPHOT chopped observations could provide a unique opportunity to study the time constants of low-background photoconductive infrared detectors/readout electronics under space conditions.

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