PROCESSING STEPS AND SIGNAL ANALYSIS OF ISOPHOT POLARISATION OBSERVATIONS AT 170 MICRON

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ABSTRACT

We present a detailed description of the structure and performance of the ISO astronomical observing template PHT51 which was used to measure the polarisation of astronomical targets in the far-infrared at 170 μm. We describe the data processing steps up to the mean signal per measurement. Special attention is given to the assessment of the instrumental stability and consistency. We have evaluated all background observations obtained with PHT51 in order to derive the instrumental polarisation. The results are compared with the previous assessment.

Key words: ISO; infrared astronomy; polarisation.

1. ISOPHOT POLARISATION OBSERVATIONS AT 170 MICRON

Very high signal-to-noise ratios ($S/N > 150$) and a detailed assessment of the instrument stability during an observation are required to measure polarisation in the infrared. Polarisation observations at 170 μm with ISOPHOT were performed using the astronomical observing template PHT51. The design of the template was aimed at achieving the best possible signal stability per integration in a given instrument configuration (such integration is hereafter referred to as "measurement") and providing sufficient redundancy for consistency checks among the measurements. An AOT PHT51 consists of at least 8 measurements collected in the following way:

1. Pointing on target and subsequent activation of the C200 detector
2. Rotate the filterwheel 2 (CHW2) to C_160

   Repeat steps 3–5 until the requested integration time per polariser is accumulated:

3. Rotate filterwheel 1 (CHW1) to PHT-C polariser 1 (0°) and perform measurement of 128 s
4. Rotate CHW1 to PHT-C polariser 2 (120°) and perform measurement of 128 s
5. Rotate CHW1 to PHT-C polariser 3 (240°) and perform measurement of 128 s
6. Rotate CHW1 to PHT-C 'no polariser' position. and perform a sky measurement of 128 s
7. Perform the calibration measurement in staring mode on the ISOPHOT internal reference source. This *fine calibration source* FCS1 is heated and measured for 128 s.
8. The electronics are set to standby and the instrument is reconfigured to default mode.

The PHT51 logic rounds the requested integration time per polariser to the nearest higher multiple of 128 s with a minimum of 256 s. This minimum integration time ensures at least 2 polariser cycles, which provide a consistency check of the relative signal variation between polarisers.

In several projects a minimap sequence of 6 PHT51 observations was applied to perform (1) 4 observations for a 2×2 raster map with 1 pixel displacement and the source centred on each pixel, and (2) 2 background observations, one before and one after the raster map, usually the same background position is taken. This observing method yielded a raster map consisting of 3×3 image pixels centred on the source. The advantages of this mode are:

- the highest source-to-background contrast is obtained because the source is centred on a detector pixel instead of the array centre.
- the central position of the map is measured by each detector pixel in the same way, and has therefore a 4-fold redundancy, which serves as a consistency check.
- the 2 background observations should give identical results assuming that the instrumental polarisation is stable in time.

In-orbit tests have shown that centring the point source on the 2×2 detector pixel C200 array yields considerably less than the expected 20–25% source signal on each detector pixel. At 170 μm, only 53% of the point source flux falls on the 4 detector pixels, and only 10–15% on each of these pixels individually. In contrast, when centring a source on a detector pixel, the fraction of the point source flux falling on the pixel is about 60%. Consequently, the minimap method provides a factor 3–4 increase in the point source S/N (Laureijs, 1999).

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2. SIGNAL PROCESSING OF PHT51 POLARISATION DATA

PHT51 aimes at highly stable and high S/N measurements with sufficient redundancy. The processing of the data should give a fair representation of the noise per measurement after removal of glitches and an assessment of the instrumental drift/variations (overall instrument stability) during the entire observation period. Only the relative variation of the signals between the polarisers is relevant for the determination of the polarisation parameters. Since the relative variation is only of the order of a few percent, one should be extra careful in guarding that each processing step is performed consistently on all polariser measurements. In the standard processing the following steps have to be carried out:

- Removal of disturbed readouts.
  Each integration ramp contains a number of readouts which are considered as less reliable. These readouts are flagged and discarded in the remaining processing steps. Standard processing removes the last readout of each ramp which is assumed to be disturbed by the reset pulse. In addition, the first fraction of a ramp is removed. This is based on the observation that the first readouts strongly deviate from a linear rise in time.

- Ramp linearisation.
  Integration ramps are not straight but show systematic deviations from linearity. In order to improve the accuracy of the slope fitting, a ramp linearisaton correction is applied.

- Deglitching readouts: removal of "bad" readouts.
  ISOPHOT interactive analysis (PIA, Gabriel et al., 1997) offers two deglitching algorithms. The standard (default) algorithm iteratively analyses the mean voltage increase in a ramp and compares this with the increase from readout to readout. If the readout difference is larger than a given threshold than the difference is replaced by the mean voltage increase. The second algorithm, the "two threshold" method, analyses the voltage increase from readout to readout. A larger than normal increase due to a glitch is recognized and all subsequent readouts are flagged and discarded until the rate of increase has dropped to below a second threshold.

- Determination of the ramp slope in V/s (=signal).
  After an integration ramp has been cleaned from non-linearities and glitches, the slope is fitted and an uncertainty is derived assuming a first order polynomial.

- Deglitching signals: removal of "bad" signals.
  The signal distribution of a measurement is analysed and outliers from a local distribution are flagged and discarded.

- Removal of unstable parts of a measurement using a drift recognition algorithm.
  The "Mann" algorithm checks whether a significant systematic signal variation occurs during a measurement, it assumes either a monotonically increasing or decreasing signal. If such a variation in a signal series is detected, the first time-half of the series is discarded. A full description of the algorithm can be found in Laureijs et al., 1999.

- Determination of the mean signal level of a measurement.
  The standard way of determining the final signal level is by computation of the weighted average. The weights are the uncertainties determined for the slopes of the integration ramps. In some cases the weighted average can be biased by a few signals with a very small uncertainty. For such cases the weighting should be switched off.

- Correction for the reset interval
  The signal level has a non-negligible dependence on the duration of an integration ramp (=reset interval). ISOPHOT signals of the same detector are corrected for this effect by a calibrated transformation to the equivalent signal for a reset interval of 1/4 s. The transformation includes both an additive term and a multiplicative factor.

- Subtraction of the dark signal.
  At 170 μm, the dark signal is equivalent to a flux density of about 20–40 mJy per detector pixel with a maximum revolution-to-revolution variation of a factor 3. At the end of a revolution the dark signal can vary significantly on timescales comparable to the measurement time.

- Signal linearisation.
  The responsivity of the C200 detector is not constant but depends on the illumination level. This effect is corrected for by transforming the signal such that the resulting responsivity becomes constant and independent of signal level. The correction for the C200 detector in the 170 μm filter is relatively small.

All processing steps have been implemented in PIA. With this software package one can enable, disable, and/or customize each processing step.

A large fraction of the PHT51 observations contain only 4 readouts per ramp. The standard processing discards the first and last readouts, giving only two readouts to determine the signal. Tests performed by us and others (see Clemens et al., 1999) have shown that keeping the otherwise discarded readouts improves the S/N of the 170 μm measurement without harming the determination of the polarisation. Note that for ramps with few readouts, only the two threshold deglitching method can still recognize outliers, the standard method is only effective on ramps containing more than 15 readouts.

Most important steps are the deglitching, the removal of the unstable part of a measurement and the determination of the final signal level per measurement from the distribution of signals. In Fig. 1 we show an example of the signals in a measurement.

Corrections like the reset interval correction, ramp and signal linearisations are of secondary importance for the polarisation measurements because the absolute flux calibration is less relevant for the determination of the polarisation parameters and because the signal levels of the three polariser settings are usually very similar. However, the absolute signal level becomes important in the subtraction of the background. Uncertainties due to the signal linearisation

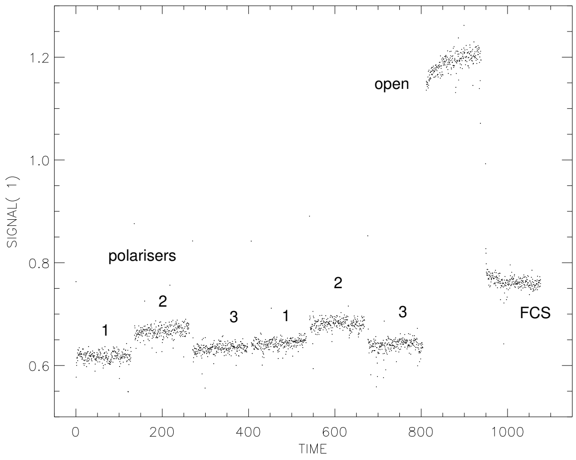

Figure 1. The signals of the measurements of a given PHT51 as a function of observing time in s. This observation consists of 8 measurements and contains 2 polariser cycles, each polariser measurement is labelled by the number of the polariser. The sky (no polariser) and FCS measurements are denoted by "open" and "FCS", respectively.

are largest when the background signal is of similar strength as the source signal.

In general, the statistical uncertainty of the mean signal of a polariser measurement is much smaller than the scatter among the different cycles of the same polariser.

3. ANALYSIS OF SIGNAL STABILITY

The design of the observation template PHT51 in combination with the application of the minimap sequence provides high quality data for a detailed assessment of the overall signal stability of the instrument. Since all observing parameters including pointing were identical for the background observations in a minimap, a comparison between the signals of the two observations gives an assessment of the instrumental stability during the minimap observing period which is usually around 2.0 hours.

We have measured the average signal s_{pn} of each polariser n from the background observations of a number of minimaps. The results are presented in Fig. 2 where we have plotted for each pixel the signal ratios s_{p2}/s_{p1} and s_{p2}/s_{p1} between the first and second background observation for 10 background pairs. The estimated uncertainty in each signal ratio is in nearly all cases less than 2%.

Fig. 2 shows that the signal ratios of the second background observation are on average systematically lower than those of the first background observation. For a number of cases the drop can be as high as 5%. There is no general preference for a particular pixel, although pixel 3 appears to be the least affected. Fig. 2 suggests that the C200 detector pixels seem to be less responsive to small signal variations during the second background observation. The effect occurs for signal variations which are pos-

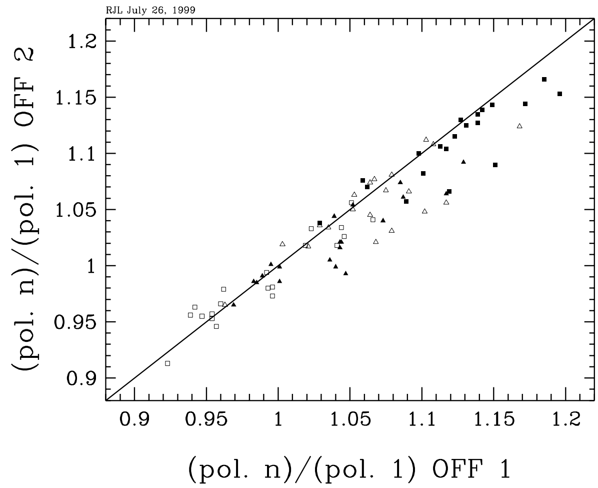

Figure 2. Comparison between the signals in polarisers 2 and 3 of the first ("OFF 1") and second ("OFF 2") background observation (on the same position) of a minimap sequence. The polariser signals from different cycles were averaged and normalised to the average signal of polariser 1. The relative signals of the 4 C200 detector pixels are indicated by different sympols: filled triangles: pixel 1, filled squares: pixel 2, open squares: pixel 3, open triangles: pixel 4. The solid line is the identity.

itive with respect to the signal in polariser 1 (i.e. $s_{pn}/s_{p1} > 1$). This might be caused by the brighter source observations which were collected in between the two background observations. However, a physical explanation cannot yet be givens.

4. INSTRUMENTAL POLARISATION FROM SKY BACKGROUND OBSERVATIONS

If the sky at 170 μm has a low polarisation degree which is randomly orientated, the signal ratios s_{p2}/s_{p1} and s_{p3}/s_{p1} averaged over a large sample of background observations can be used to derive the instrumental polarisation. We have processed all background observations with PHT51 and determined the signal ratios. In case two background observations were obtained at the same position we computed the weighted average of the signal ratio pairs for each pixel. The resulting ratios as a function of absolute signal level are presented in Figs 3 and 4.

Especially for pixel 1 we find that the ratio s_{p2}/s_{p1} tend to be lower for signal levels higher than 1.4 V/s. This variation is only marginally present for s_{p3}/s_{p1} (Fig 4) suggesting that the variation is caused by the signals of polariser 2 and not of polariser 1. For pixel 3, the ratio s_{p3}/s_{p1} is very constant over the entire signal range. The scatter around the mean ratio for pixels 1, 2, and 3 appears smaller for s_{p3}/s_{p1} than for s_{p2}/s_{p1}. This result suggests that the 3rd polariser measurement is more stable than the 2nd polariser measurement w.r.t. the first polariser measurement.

In Table 1 we list the mean signal ratios for each pixel. We excluded 3 background positions which

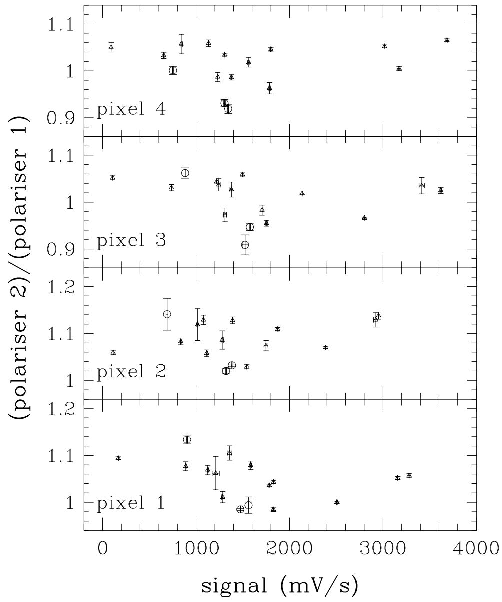

Figure 3. The signal ratios s_{p2}/s_{p1} for each C200 detector pixel are plotted as a function of absolute signal level of the first polariser. The signal ratios were obtained from 16 background positions on the sky. The circles indicate the observations which have been excluded for the determination of the mean signal level in Table 1.

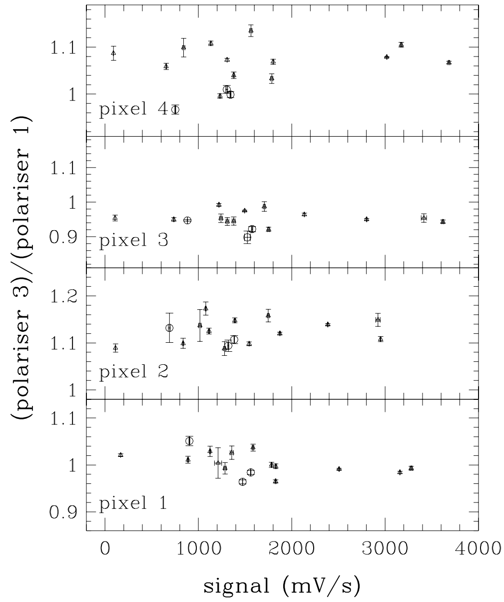

Figure 4. Similar as Fig 3, for signal ratios s_{p3}/s_{p1}.

show for nearly all pixels and polarisers large systematic deviations from the general distributions (cf. Figs. 3 and 4). Two of these positions are associated with the Crab nebula , one position is in the neighbourhood of the B213 dark cloud . Reason for the discrepancy could be significant intrinsic polarisation of the background positions.

Table 1. The mean signal ratios obtained from observations of 13 background positions, the uncertainties are the rms of the sample.

pixel	s_{p2}/s_{p1}	s_{p3}/s_{p1}
1	1.051±0.035	1.004±0.020
2	1.093±0.033	1.125±0.027
3	1.016±0.033	0.956±0.018
4	1.027±0.031	1.073±0.035

The resulting instrumental polarisation values per pixel are compared to previous values obtained by Klaas, et al. (1999) in Table 2. Our uncertainties in polarisation degree and angle were derived from the uncertainties of the mean in the signals. Klaas et al. had only 7 measurements available, the analysis presented here has better statistics and is more refined in terms of signal processing. For all pixels except pixel 4 we find good agreement between the polarisation angles of the two datasets. However, the polarisation degrees of all pixels except pixel 4 show significant discrepancies between our values and those of Klaas et al.

Our instrumental polarisation vectors have been derived from only very extended emission regions (background) whereas Klaas et al. (1999) also included point sources (stars) in their analysis. The differences between the two sets of instrumental polarisation vectors could be due to uncertainties in the beam profile for each pixel-polariser combination.

Table 2. The instrumental polarisation vectors derived from the signal ratios in Table 1 and previous values from Klaas et al, 1999.

	This work		Klaas et al.	
pixel	P (%)	Θ (°)	P (%)	Θ (°)
1	3.60±0.63	–62.0±5.0	4.9±0.3	–57.1±0.8
2	7.79±0.68	82.8±2.3	5.5±0.3	87.7±1.1
3	3.99±0.62	–37.4±4.4	6.1±0.3	–39.5±0.8
4	4.59±0.73	70.8±4.6	3.4±0.3	–76.5±1.8

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