POLARISATION OBSERVATIONS WITH ISOCAM *

Ralf Siebenmorgen

ISO Data Centre, ESA Astrophysics Division, Villafranca del Castillo, P.O. Box 50727, 28080 Madrid, Spain.

1. ABSTRACT

An overview is given of the ISOCAM polarisation capabilities. The different polarisation modes, necessary steps in the data reduction and the calibration strategy are described. Deep raster observations in various optical configurations on the zodiacal light are presented. By assuming that the zodiacal light is unpolarised we derive the instrumental polarisation and find a mean fractional polarisation of $p \approx 1.0 \pm 0.3\%$. Measurements of unpolarised standard stars have been performed and here we find for the lw2, 3" lens configuration an instrumental polarisation of $p = 1.5 \pm 0.3\%$, consistent with the zodiacal light observations. With present processing techniques we achieve for moderately bright targets a $1\sigma = 0.5\%$ accuracy limit of linear polarisation.

2. OBSERVING MODES

Polarimetry with ISOCAM could be performed in a single, user-defined, narrow or broad band filter using the LW detector. The observations are made by observing the target through three separate polarisers. The polarisers have orientations with respect to space-craft Y, Z axis of 0^o, 120^o and 240^o. The orientation angle is measured where +Y axis has 0^o and angles are measured towards +Z direction (see ISO Satellite Handbook).

ISOCAM polarisation observations start with a raster measurement without polariser on the free entrance hole. The observer could then choose to rotate the polarisers:

1. on a single raster position or
2. perform rasters in one polariser followed by a move of the entrance wheel to the next polariser position and perform the next raster and so forth.

In both observing procedures, the rasters have been repeated in several observing cycles. The second observing mode was in particular recommended for extended targets. In this mode the nominal pointing position was corrected for the known source displacement on the detector while using the polarisers (see Section 6.1.). Details of the observational set-up and observation strategy are described in the CAM05 Observers Manual (Siebenmorgen, 1996).

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3. DATA REDUCTION

After dark correction, deglitching, flat–fielding, flux transient corrections have been performed the signal obtained through each polariser S_i which passes linear polarised light at position angle Θ_i is a function of the Stokes parameters (I, Q, U). It can be represented by

$$S_i = \frac{g_i}{2} \cdot \{I + k_i Q cos(2\Theta_i) + k_i U sin(2\Theta_i)\} \qquad (1)$$

where we neglect circular polarisation and denote polarisers throughputs (g_i) and polarisers efficiencies (k_i) as calibration parameters. By assuming $k_i = 1$ one finds:

$$s_i = \frac{S_i}{g_i} \qquad (2)$$

with standard deviation:

$$\Delta s_i = \sqrt{(\frac{\Delta S_i}{g_i})^2 + (\frac{S_i \Delta g_i}{g_i^2})^2} \qquad (3)$$

The total intensity is calculated by

$$I = \frac{2}{3}(s_1 + s_2 + s_3) \qquad (4)$$

with standard deviation:

$$\Delta I = \frac{2}{3}\sqrt{\sum \Delta s_i^2} \qquad (5)$$

and for the Stokes parameters:

$$Q = \frac{2}{3}(2s_1 - s_2 - s_3) \tag{6}$$

with standard deviation:

$$\Delta Q = \frac{2}{3}\sqrt{4\Delta s_1^2 + \Delta s_2^2 + \Delta s_3^2} \tag{7}$$

and

$$U = \frac{2}{\sqrt{3}}(s_2 - s_3) \tag{8}$$

with standard deviation:

$$\Delta U = \frac{2}{\sqrt{3}}\sqrt{\Delta s_2^2 + \Delta s_3^2} \tag{9}$$

One derives the fractional polarisation by:

$$p = \frac{P}{I} = \sqrt{q^2 + u^2} \tag{10}$$

where $q = \frac{Q}{I}$ and $u = \frac{U}{I}$.

with standard deviation:

$$\Delta p = \sqrt{\frac{(q\Delta q)^2 + (u\Delta u)^2}{p^2}} \tag{11}$$

where

$$\Delta q = \sqrt{(\frac{\Delta Q}{I})^2 + (\frac{Q\Delta I}{I^2})^2} \tag{12}$$

$$\Delta u = \sqrt{(\frac{\Delta U}{I})^2 + (\frac{U\Delta I}{I^2})^2} \tag{13}$$

The polarisation position angle is given by:

$$\Theta = \frac{1}{2}\mathrm{atan}(\frac{U}{Q}) \tag{14}$$

with standard deviation:

$$\Delta\Theta = \frac{1}{2}\sqrt{\frac{Q^2\Delta U^2 + U^2\Delta Q^2}{(Q^2 + U^2)^2}} \tag{15}$$

So far all parameters have been derived for the ISO space-craft system, e.g. plot +Y axis up and +Z axis left. The small jitter of the ISO telescope makes pointing offset corrections small. Standard registration techniques have so far only marginal improved the results.

For low s/n ratios one sometimes also specifies the de-biased polarisation given by:

$$p_{db} = \sqrt{p^2 - \Delta p^2} \tag{16}$$

4. CALIBRATION STRATEGY

The Stokes parameters measured on astronomical targets are contaminated by polarisation of the instrument and the sky background. The instrumental polarisation must be derived to calibrate the experiment. However, this requires knowledge of the calibration parameters such as the polarisation throughputs (g_i) and polarisation efficiencies (k_i). Both of them could not be derived from laboratory at the required accuracy. We here introduce polarisation weight factors (w_i) of the measured polariser intensities S_i. The polarisation weight factors serve as calibration parameters to correct for the instrumental polarisation. They are given by:

$$w_i = 2 \cdot \frac{S_i}{I} \tag{17}$$

its standard deviation can be estimated according to

$$\Delta w_i = \sqrt{(2 \cdot \frac{\Delta S_i}{I})^2 + (2 \cdot \frac{S_i \cdot \Delta I}{I^2})^2} \tag{18}$$

where I is the total intensity as measured through ISOCAM's entrance hole, ΔI its standard deviation and ΔS_i the standard deviation of the three polariser intensities.

We define the corrected intensities as :

$$s_i = \frac{S_i}{w_i} \tag{19}$$

and then calculate the Stokes vector (Eq. 4, 6, 8).

5. ZODIACAL LIGHT EXPERIMENT

The best measure of the instrumental polarisation is given by CAM05 raster observations on the zodiacal background. Assuming that the zodiacal background is flat and not polarised it is natural that any measured degree of polarisation should reflect the instrumental polarisation of ISOCAM. For the zodiacal light, we therefore write the Stokes parameters as:

$$S(zodi) = (I, 0, 0). \tag{20}$$

Observations have been set up in a 2× 2 or 3× 3 raster with a raster step of a few pixels. The first raster is performed through the free hole of the entrance wheel then a raster is performed using polariser 1, followed by a raster using polariser 2 and finally 3. The rasters using polarisers are repeated during 2 or 3 cycles.

The data reduction was performed using ISOCAM Interactive Analysis System (CIA). The individual exposures have been dark corrected, deglitched and coadded on each raster position. We do not notice strong flux transients on the detector and we do not have corrected for possible long term drifts (Miville–Deschenes, 1999). A simple average of all raster positions and cycles gives us the final image, where we calculate the total intensities (ADU/G/s) as for ISOCAM flat fields (Biviano et al., 1998) only on the central 11 × 11 pixels of the detector. Applying Eq. (18) we derive the polarisation weight factors. To calculate the Stokes elements U, Q one is free to normalize one of the weight factors, we set $w_3 := 1$.

The weight factors (w_i) for all observed configurations are given in Table 1. The Crab nebulae (Tuffs et al., this volume) has been observed in the LW3, 6" lens configuration. We analyzed those data and could retrieve flat fields in the different entrance wheel configurations. Those results are included in Table 1,2. As a consistency check we derived the polarisation weight factors as well from the background estimates of the mosaic images of the Crab, again by assuming zero polarisation of the background. We find that this method gives the same weight factors, down to a 0.1% level, as those derived from the zodiacal light flat fields.

Table 1. Polarization weight factors w_1, w_2 normalized to w_3 = 1.

Filter	λ_{ref}	lens	w_1	Δw_1 [%]	w_2	Δw_2 [%]
LW2	6.7	6	0.9862	<0.1	0.9937	<0.1
LW10	12.0	6	0.9763	<0.1	0.9926	<0.1
LW8	11.3	6	0.9829	<0.1	0.9886	<0.1
LW3	14.3	6	0.9845	<0.1	0.9937	<0.1
LW9	14.9	6	0.9873	<0.1	0.9957	<0.1
LW7	9.6	3	0.9824	2.1	0.9845	1.9
LW8	11.3	3	0.9638	3.0	0.9740	3.0
LW3	14.3	3	0.9614	0.4	0.9987	0.2
LW9	14.9	3	0.9749	2.0	0.9865	2.2
LW3	14.3	1.5	0.9737	4.4	1.0022	4.2

If one sets the polarisation weight factors to unity, one derives from the zodiacal light images a polarisation vector. Those vectors are given in Table 2. They do not prompt to a dependency on wavelengths nor on lens. If one would have an independent estimate of the instrumental polarisation one could derive an estimate on the polarisation of the zodiacal light. Already for the 3" lens configuration the signal of the zodiacal light becomes weak and ends up at large errors. For the 6" lens the mean instrumental polarisation is around $p = 1.0 \pm 0.3\%$.

Table 2. Polarization on zodiacal light assuming zero instrumental polarisation.

Filter	λ_{ref}	lens	p (%)	Θ
LW2	6.7	6	0.80 ± 0.1	24 ± 4
LW10	12.0	6	1.41 ± 0.1	29 ± 3
LW8	11.3	6	1.02 ± 0.1	18 ± 3
LW3	14.3	6	0.91 ± 0.1	26 ± 3
LW9	14.9	6	0.75 ± 0.1	28 ± 4
LW7	9.6	3	1.12 ± 1.28	11 ± 37
LW8	11.3	3	2.20 ± 2.05	16 ± 27
LW3	14.3	3	2.56 ± 0.90	37 ± 18
LW9	14.9	3	1.47 ± 1.47	22 ± 27
LW3	14.3	1.5	1.85 ± 3.3	40 ± 38

The zodiacal light calibration observations give a good measure of the LW flat fields (Biviano et al., 1998). By combining the flats through the polarisers to calculate for each detector element a Stokes vector one notice a residual also aligned polarisation pattern. Such a pattern is shown for the LW10 filter using the 6" lens (Figure 1). The polarisation pattern does not show a strong dependency on filter. It is more noisy for the 3" and 1.5" lens.

One corrects for the instrumental polarisation pattern in the data using the polarisation flat fields. If such a flat cannot be derived from the own observation one may inspect the flat library (Siebenmorgen et al. 1999). However, not for all optical configuration it was possible to obtain zodiacal light flat fields through each polariser at high enough precision. In such circumstances one should take a flat in the same lens configuration and close in wavelength. Although such an imperfect match in wavelength will result in some residual instrumental polarisation pattern. One example is shown in Figure 2 where zodiacal light images through the polariser in the LW10, 6" optical configuration is flat fielded by the corresponding LW9, 6" library flat. From those imperfect flat fielded images we calculate the polarisation vectors and find residuals of at most less than $p \approx 2\%$.

6. CALIBRATION STANDARD STARS

Calibration observations of photometric standard stars (HIC089474 and HIC085371) have been performed. The stars were measured in a 2 × 2 raster mode with 3" pixel field of view and a step size of 114". A number of 75 exposures of 2.1s integration time per raster and entrance wheel position have been taken. At the beginning a raster was performed through the hole of the entrance wheel followed by polarisation rasters where the polarisers have been rotated on each single raster position. The polarisation rasters have been repeated in three observing cycles.

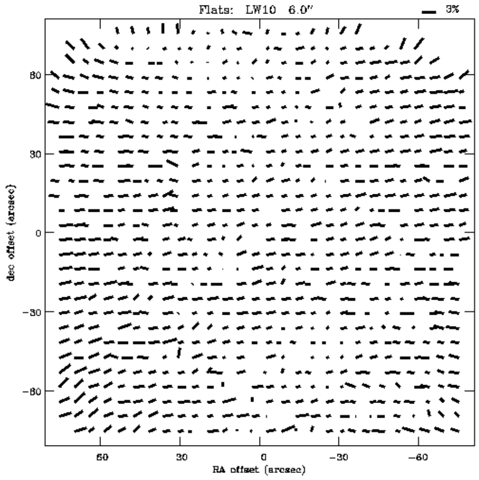

Figure 1. Polarization pattern of the LW10, 6" zodiacal light observations.

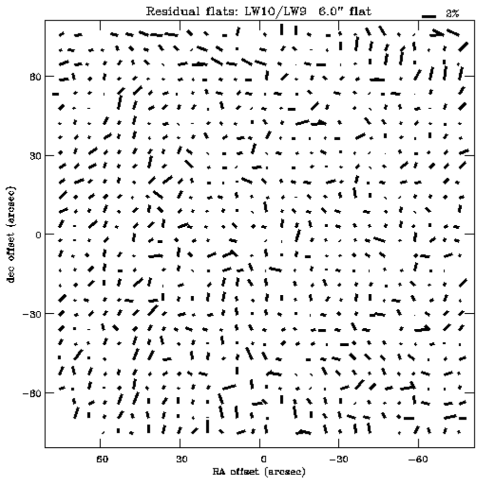

Figure 2. Residual polarisation pattern of the LW10, 6" zodiacal light image after flat fielding by the LW9, 6" polariser flats. The non perfect match of the flats in filter results in residual polarisation of at most less than 2%.

The data reduction was performed using CIA. Individual exposures were dark corrected, deglitched and transients corrected. As transient correction we applied the Fouks detector model. Results have been compared with other transient correction methods available, also an exponential fitting routine by Acosta (1998). It was found that they give similar or less good results, although the transient correction is not perfect for strong point sources. Exposures of the same raster position, entrance wheel configuration and observing cycle have been coadded. The so derived images have been flat corrected using the flat library. Photometry is done by following the steps described in the ISOCAM photometry report (Blommaert, 1998). Basically we integrate the flux in a 3 pixel circular aperture and get a background estimate from the mean flux in another 2 pixel wide circular annulus one pixel away from the source aperture. The same procedure is done on a model PSF (Okumura et al., 1998) to correct the derived source fluxes for losses in higher airy rings. On both images we consider a pixel mask of none good pixels. It is set on column 23 and on those pixels where residual flux transients, still after Fouks correction, are visible.

In total there are four direct photometric measurements of the photosphere of the star given by the 'hole' measurements. The photometric results of the hole measurements can be compared to model fluxes of the photometric standard star. We find that our procedure gives us an absolute photometric accuracy of better than 5% on the raster images. This is in good agreement to the general absolute flux calibration of the ISOCAM LW detector (Blommaert et al., 1998). By doing photometry on individual raster positions one has to be careful about the dead column. For example in the case studied here the brightest pixel of polariser 2 at the first and last raster position is 2 pixels away from column 23. Caused by the lens wheel jitter there may be other cases where the source may right fall on the dead column.

We then studied the result obtained after projection of the individual raster position into a mosaic image. We find that there are some additional ($\approx 3\%$) photometric uncertainties, which are due to:

- an enlarged PSF in the mosaic caused by the projection using satellite pointing information which includes still the random satellite jitter and
- because of residual transients, still visible as 4 "ghosts" sourounding the source.

Together this give rise to an additional polarisation uncertainty of $\approx 2\%$, so that projection of images into a mosaic is not recommended for strong point sources.

In Figure 3 we show the photometric results of the three polarisers and cycles measured on HIC085371 as observed in filter lw2, 3" lens. One notices that the polariser emission in the first cycle as compared to the second and third cycle is about 3% systematically lower. On the other hand there is a variation of less than 1% of the flux by comparing cycle 2 with 3. This can be understood in terms of residual transient effects and long term detector drifts. One has to remember that cycle 1 follows just after the raster using the entrance hole position, while the detector for cycle 2 and 3 has a more identical flux history, for both source and background fluxes. By taking the average over all measurements we find for the fractional polarisation in the lw2, 3" lens:

$$p = 1.5 \pm 0.3\%$$

at:

$$\Theta_N = 10^o \pm 5^o$$

The value is consistent with the instrumental polarisation derived from the zodiacal light experiment.

6.1. POLARISER DISPLACEMENT

The three polarisers show that the sources are displaced by several pixels on the detector array as compared to the source position obtained through the entrance hole. We take the latter as the nominal (zero)

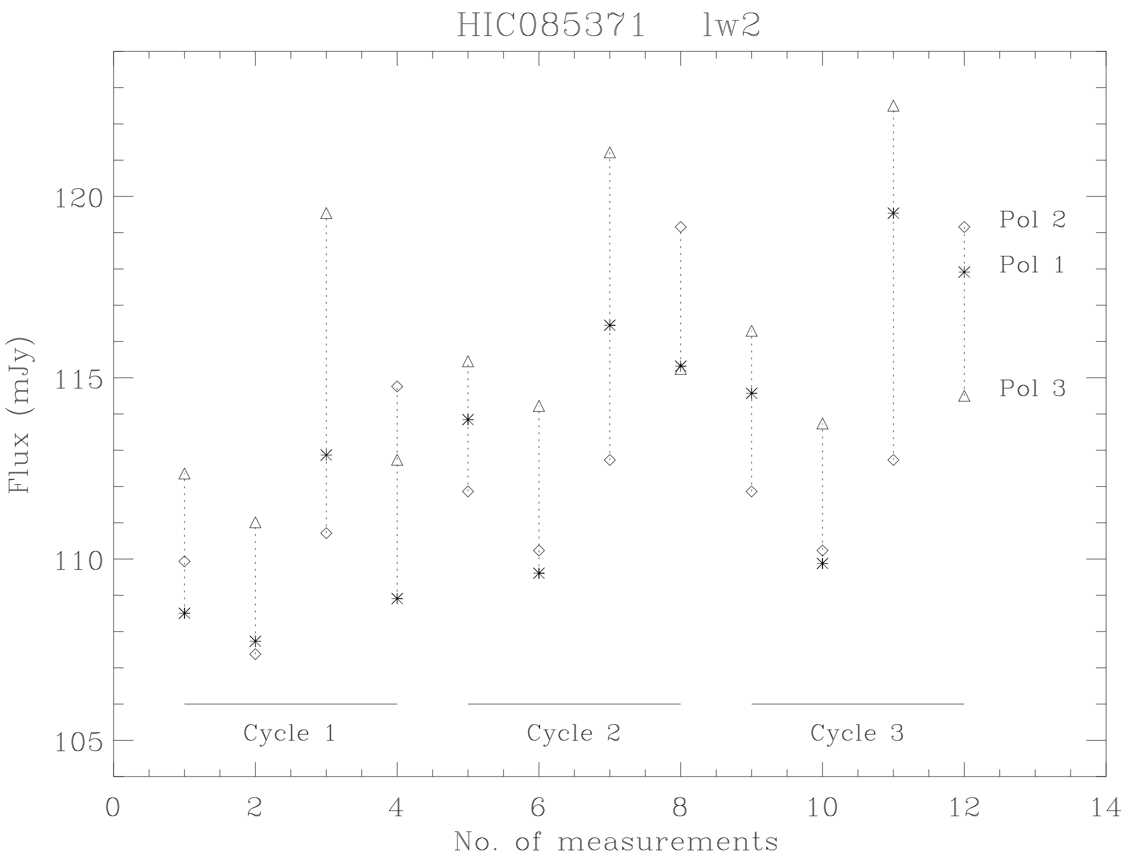

Figure 3. Sequential order of the photometry for polariser 1 (*), polariser 2 (◇) and polariser 3 (△) obtained at four different raster positions during three observing cycles.

position and measure the relative displacement (x, y) of the source center for each polariser. The result is given in Table 3. For polarisation observations using the observing mode designed for extended sources the displacements of the different polarisers have been corrected by shifting the nominal pointing position of the target in opposition to the numbers given in Table 3. As a consequence for this mode one is allowed to take as first order approximation the polariser images and calculate the Stokes vector without applying further registration techniques.

Table 3. Polarizer displacements in arcsec as measured with respect to the nominal hole position

Polarizer	$x \pm \Delta x$	$y \pm \Delta y$
	["]	["]
P1	-3.4 ± 0.1	-11.2 ± 0.3
P2	-8.9 ± 0.1	0.6 ± 0.3
P3	-3.0 ± 0.1	-4.7 ± 0.3

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