DATA REDUCTION, CALIBRATION AND PERFORMANCE OF THE ISOPHOT POLARIZATION MODES*

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ABSTRACT

ISOPHOT provided unique polarization capabilities in the MIR and FIR. We give an overview of the ISOPHOT polarimetric modes. This includes characteristics of the polarizer hardware, the observation modes, the on-ground and in-orbit calibration, the basic steps in data reduction and the assessment of achievable accuracies. The $1\,\sigma$ accuracy of linear polarization is 1 per cent for sources with total fluxes of few Jy. The polarization processes in the IR and targets observed with ISOPHOT are summarized.

Key words: Polarization; Instrumentation: polarimeters; Methods: data analysis; Techniques: polarimetric; Infrared: general.

1. INTRODUCTION

The determination of the polarization degree of in general only partially polarized emission is based on the capability to measure small intensity differences through a set of differently oriented linear polarizers. This requires high S/N ratios with a stable instrument. The photopolarimeter ISOPHOT (Lemke et al. 1996) on board the Infrared Space Observatory ISO (Kessler et al. 1996) provided such capabilities over a wide wavelength and flux range for a wavelength regime which is only accessible by airborne and space-borne telescopes. Before ISOPHOT only a few FIR polarimetric measurements had been performed from the Kuiper Airborne Observatory (KAO, e.g. Novak et al. 1997). ISOPHOT is a unique polarimeter with regard to wavelength regime and sensitivity. In the following sections we give an overview of ISOPHOT's polarimetric capabilities and in-flight performance.

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2. GENERAL INSTRUMENT DESIGN FOR POLARIMETRY

ISOPHOT was equipped with two sets of polarizers, one in connection with the aperture photometer PHT–P, and another one with the array camera PHT–C. The polarizers were mounted on wheel 1 which served to select ISOPHOT's subinstruments, cf. Figure 1. Therefore, in principle, it was possible to perform polarimetry with all available filter and aperture combinations of the single detector aperture photometer and all filters of the array camera. For practical reasons, these numerous options had to be severely constrained in order to keep the calibration efforts – each instrumental set-up would have needed an individual assessment of the instrumental polarization – to a reasonable volume, cf. Section 5.

For comparison with polarimetric measurements at other wavelengths and with other telescopes it should be kept in mind that the observations with ISOPHOT were diffraction limited, with a size of the Airy disk of a point source of 21 arcsec at $25\,\mu$m and 143 arcsec at $170\,\mu$m. In the latter case the Airy disk is nearly as big as the size of the C200 array.

3. POLARIZER HARDWARE

Each set of polarizers comprised 3 polarizer grids with orientations of 0°, 120°, 240° w.r.t. the satellite y-axis. The MIR (PHT–P) polarizers consisted of a silicon substrate with incarved grating, spaced with 0.4 μm. They were purchased and characterized by MPI für Kernphysik. The FIR polarizers were a new development by MPI für Radioastronomie: parallel tungsten wires (67/mm) glued in copper frames, cf. Figure 2.

4. ON-GROUND CALIBRATION OF POLARIZERS

These polarizers were mounted into the cold ISOPHOT Focal Plane Unit and checked out in the

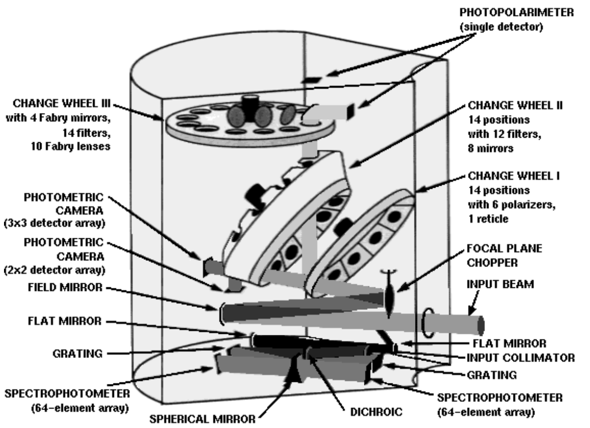

Figure 1. Schematic view of the ISOPHOT instrument. The polarizers are mounted on wheel 1, the subinstrument selection wheel. The NIR/MIR polarizers are combined with a flat mirror directing the incoming beam onto the PHT-P aperture section of wheel 2. The beam through the FIR polarizers goes directly towards the PHT-C filter section of wheel 2.

ISOPHOT ground calibration facility by using a pre-polarizer device (Wolf et al. 1994). The polarization efficiency P' was determined to be $\sim$ 90% for both sets, with an uncertainty of $\pm$ 3%. The polarizer orientations could be measured with an accuracy of $< 1.5°$. The specified orientations were achieved within $< 4°$ for the MIR polarisers, and $< 1°$ for the FIR polarizers. The current data analysis (Section 6.) assumes perfectly aligned polarizers and no mis-alignment uncertainty is considered in the total error budget.

5. POLARIZATION MODES

Due to the stringent sensitivity and stability requirements, the ISOPHOT polarization modes underwent careful commissioning. This comprised the assessment of instrumental polarization which is wavelength dependent. For the release of the modes to the community, the effort to characterize each individual polarimetric set-up had to be weighed up against the number of requested polarization observations. In the end, the ISO Science Operations Centre decided to restrict the publically offered modes to two with the most stably performing detectors (Laureijs & Klaas 1997):

- 25 μm filter of the P2 detector (79 arcsec aperture), defined as Astronomical Observation Template (AOT) PHT50, cf. Klaas et al. 1994.
- 170 μm filter of the C200 array (PHT51).

Major specially designed features for achievement of the best possible accuracies were the following:

- Verification of the measurement reproducibility by repeated cycles (≥ 2) through the 3 polarizers (0° - 120° - 240° - 0° - 120° - 240° ...)
- Consistency check of PHT-C array polarimetry by redundant measurements with all 4 pixels of the C200 camera. This was achieved by performing a 2x2 raster with one pixel length step size aligned with the array orientation, cf. Figure 3.
- For the removal of P2 long term detector drifts an additional 0° measurement was introduced at the end of each polarizer sequence. (0° - 120° - 240° - 0° ... 240° - 0°)

Figure 2. Magnified view of one of ISOPHOT's FIR polarizers. Individual tungsten wires can be recognized. The nominal wire diameter is 5 μm, the grating constant (distance of wires centre-to-centre) is 15 μm.

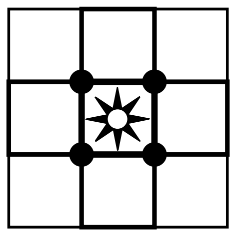

Figure 3. Polarimetric map with the C200 camera to achieve redundancy in polarimetric results for a centred point source. The four positions of the 2x2 raster are indicated by the filled dots. In the resulting 3x3 map the map pixels are identical to the detector pixels; the central map pixel is covered 4 times by all four detector pixels, the four map pixels arranged on the central cross are covered by two detector pixels each, and the corner pixels have a simple coverage.

6. STEPS IN DATA REDUCTION

¿From the drift corrected signals in the three polarizer settings, I_0, I_{120}, I_{240}, the three Stokes parameters of linear polarization, I, V, and Q, are derived per polarizer cycle according to the formulae for imperfect polarizers in Serkowski (1962):

$$I = 1/3 * (I_0 + I_{120} + I_{240}) \tag{1}$$

$$U = 1/(\sqrt{3} * P') * (I_{240} - I_{120}) \quad (2)$$
$$Q = 1/(3 * P') * (2 * I_0 - I_{120} - I_{240}) \quad (3)$$

The accuracy of the polarizer efficiency P' will only affect the finally derived polarization degree, as a multiplicative factor, it cancels out in the derivation of the polarization angle.

Sky background correction is done by subtraction of the Stokes parameters "off-target" from those "on-target":

$$I_{\rm on} - I_{\rm off} \;, \; U_{\rm on} - U_{\rm off} \;, \; Q_{\rm on} - Q_{\rm off}. \quad (4)$$

The instrumental polarization is corrected for by using normalized Stokes parameters u = U/I and q = Q/I:

$$u' = u - P_{\rm inst} * sin(2 * \theta_{\rm inst}) \quad (5)$$
$$q' = q - P_{\rm inst} * cos(2 * \theta_{\rm inst}) \quad (6)$$

Polarization degree and angle are calculated with:

$$P = \sqrt{u'^2 + q'^2} \quad (7)$$
$$\theta = 1/2 * arctan(u'/q') \quad (8)$$

For calculation of the polarimetric uncertainties the scatter of the signal in the different cycles

$$dI = 1/\sqrt{3 * n_{\rm cyc} - 1} * \sqrt{\sum_{i=1}^{3} \sum_{j=1}^{n_{\rm cyc}} (I_{\rm i,j} - \bar{I}_{\rm i})^2} \quad (9)$$

is an input parameter in the error propagation. The uncertainty in the polarization degree is taken into account in the de-biased polarization degree for low S/N ratios, according to Wardle & Kronberg (1974):

$$P_{\rm debias} = \sqrt{P^2 - dP^2} \quad (10)$$

All these basic reduction steps plus the corresponding error propagation both for maximum and Gaussian (partial derivatives are summed up quadratically) uncertainties are implemented in the FORTRAN code POLCALC which performs all the calculations from the input signals to the polarization results, including a listing of the individual Stokes parameters and the achieved S/N ratios. For the derivation of the input signals the ISOPHOT Interactive Analysis software PIA[1] is used (Gabriel et al. 1997, Gabriel et al. 1999) which provides the interface files to the FORTRAN code. On the long term the software will be fully integrated into PIA. A description of the signal processing of ISOPHOT polarization measurements can be found in Laureijs & Klaas 1999.

7. INSTRUMENTAL POLARIZATION

Instrumental polarization was determined in-flight by measurements of unpolarized sources, e.g. stars (at 25 μm: α Tau (150 Jy), γ Dra (40 Jy); at 170 μm: α Boo (3 Jy)) and background fields (Table 1). Differences for the individual C200 pixels are explained, since each of them has its individual field optics, stressing mechanism, integrating cavity and electrical contacts.

Table 1. Instrumental polarization degree $P_{\rm inst}$ and angle $\theta_{\rm inst}$ and their uncertainties (standard deviation of mean) determined as averages from a set of measurements of unpolarized sources.

detector	filter	$P_{\rm inst}$ [%]	$\Delta P_{\rm inst}$ [%]	$\theta_{\rm inst}$ [deg]	$\Delta\theta_{\rm inst}$ [deg]
P2					
79" aper.	P_25	3.0	0.2	-18.6	1.5
C200					
pixel 1	C_160	4.9	0.3	-57.1	0.8
pixel 2	C_160	5.5	0.3	+87.7	1.1
pixel 3	C_160	6.1	0.3	-39.5	0.8
pixel 4	C_160	3.4	0.3	-76.5	1.8

8. POLARIMETRY PERFORMANCE

Table 2 lists typical polarization accuracies derived from various commissioning cases. The most important parameters for the final accuracy are:

- The signal reproducibility in the subsequent polarizer cycles which is a measure of the robustness of this specific measurement against drifts.
- The source-to-background contrast. This is the main parameter for the ordering in Table 2. For C200 it proved to be of advantage, if the source was centred on a pixel rather than on the array (compare first two lines of 3C 279 results).

In conclusion, the 1 σ accuracy of linear polarization is 1% for sources with total fluxes of few Jy.

9. POLARIMETRY OF EXTENDED SOURCES

When performing polarimetry of extended sources, and in particular when making comparisons with the polarimetric vectors found at other wavelengths and with a different spatial resolution, one has to consider the instrumental footprints, i.e. the convolution of telescope PSF with aperture response of the individual pixels.

- When averaging over the PHT-P aperture size, the non-flatness of the aperture profile has to be accounted for.
- When averaging over a PHT-C pixel and inter-comparing the results from overlapping pixels, the symmetry of footprints and relative pixel offsets play a role.

These instrumental effects are not yet fully assessed.

[1]PIA is a joint development by the ESA Astrophysics Division and the ISOPHOT consortium.

Table 2. Polarization accuracies achieved for different source-to-background contrasts per polarizer cycle. The corresponding signal-to-noise ratio (noise term according to formula (9)) after background subtraction is given, too. The measurement sequence includes a photometric measurement which allows to determine the source flux. The polarization degree of 3C 279 turned out to be variable. Source/background ratios below 1 for C200 measurements result when the source is not centred on the pixel.

mode	target	src. flux [Jy]	pol. deg. [%]	src./ backg	S/N src.	1σ pol. error [%]
P2	NGC 7538	400	$\sim$ 3	17	150	0.8
P_25	6 Hebe	37	< 1	6.3	120	0.8
(79")	9 Metis	38	< 1	2	130	0.7
	Crab	9	8	0.7	60	1.7
C200	Crab	$\sim$ 15	8	1.4	150	1.4
C_160	3C 279	2.5	6	1.8	75	1.6
	3C 279	2.5	6	0.4	15	7
	3C 279	2.5	23	0.25	25	5
	3C 279	2.5	6	0.25	12	10
	α Boo	2.6	0	0.025	2	60

10. POLARIZATION MECHANISMS IN THE IR

Finally we will address the astrophysical application of this observing mode. Polarization measurements provide a powerful tool for the analysis of radiation processes which generate a prefered orientation of the E-vector.

In the IR, polarization is expected to be found for:

1) synchrotron radiation;
2) emission by elongated grains aligned by magnetic fields;
3) scattered radiation (by electrons, atoms & molecules, reflection & refraction at boundaries between two media).

Several astrophysical issues can be addressed by MIR and FIR polarization observations:

- The relative role of thermal and non-thermal radiation sources in AGNs and SNRs can be determined. A high polarization degree is a sign of non-thermal (synchrontron) radiation. Often the spectral energy distribution of a synchrotron source shows a "break" which indicates the maximum of the electron energy. The FIR is a wavelength range where this break can occur.
- The bulk of FIR continuum radiation in all types of sources comes from dust grains with equilibrium temperatures between 20 and 100 K. In case these particles are not spherically symmetric and are oriented by a magnetic field, a net polarization should be observed. In that way they are tracers for the direction and ordering of the local magnetic field. Examples are pre-stellar condensations in the molecular cloud complexes of the Milky Way.
- The detailed surface properties of Solar System bodies which emit the bulk of their total energy in the MIR and FIR.

11. ISOPHOT POLARIMETRY PROGRAMS

In Table 3 we give an overview of all targets for which polarimetry with ISOPHOT was performed. It can be seen that practically all types of astronomical targets are represented by at least one object, from Solar System Objects to quasars. The majority of observations were performed on outflow sources. For most sources the polarization shall be used as a tracer for the direction of the local magnetic fields. Sources observed at both wavelengths are L 1551 and the Crab Nebula.

Table 3. Targets for which ISOPHOT polarimetry has been obtained. It is indicated in which of the two modes, i.e. at which wavelength, the observations were performed. The labeling of the polarization mechanism is according to the numbering scheme in the previous section 10. Acronyms for the object classes are: SSOs = Solar System Objects, MCs = Molecular Clouds, DCs = Dark Clouds, RNe = Reflection Nebulae, SNRs = Supernova Remnants, AGNs = Active Galactic Nuclei.

object class	target names	polar. mechanism	λ [μm]
SSOs	6 Hebe, 9 Metis	(3)	25
Outflows	NGC 7538, L 1551, HH 100	(2)	25
	NGC 1333, L 483, L 1157, IRAS0382, L 1448, L 1527, L 1544, L 155	(2)	170
MCs	TMC2, B213	(2)	170
DCs	GF9	(2)	170
RNe	NGC 7023	(2)	170
SNRs	Crab	(1) , (2)	25 , 170
Galaxies	NGC 1808, NGC 6946	(2)	170
AGNs	3C 279, BL Lac*	(1)	170

* source not detected due to cirrus confusion.

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