ISOPHOT Calibration Accuracies

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Chapter 1

Introduction

1.1 Short Instrument Overview

The ISO Photo-polarimeter ISOPHOT spans the full wavelength range accessible to ISO, from 2.5 out to 240 μm. This coverage is achieved with various subinstruments whose wavelength range is given in the subsequent Table 1.1. For more details we refer to the ISOPHOT Observer's Manual.

Table 1.1: Covered wavelength range and typical aperture sizes of ISOPHOT subinstruments. Note that for PHT–C the first aperture number denotes the pixel size, the second one the array size.

subinstrument	**detector**	**dimension**	**wavelength range** [μm]	**typical aperture size** ["]
PHT–P	P1	1	3 – 17	5 – 180
	P2	1	15 – 29	23 – 180
	P3	1	40 – 130	52 – 180
PHT–C	C100	3x3	40 – 130	43.5 / 138
	C200	2x2	100 – 240	89.4 / 182
PHT–S	SS	1x64	2.5 – 4.8	24
	SL	1x64	5.8 – 11.8	24

PHT–S is a spectrometer with a resolution of $\lambda/\Delta\lambda \simeq 90$

1.2 Completeness of Calibration Accuracy Assessment and Scientific Validation of Observing Modes

This document provides an overview of global calibration accuracies for the ISOPHOT instrument. It will be updated whenever revised or additional information will be available. This can be expected in the context of an upgraded OLP version which will involve a scientific validation of the products. The scientific validation of a specific observing mode comprises the end-to-end evaluation of a set of test cases, including the comparison with reference photometry (high quality photometry from other observatories, standard star models, etc.). This allows to establish the global calibration accuracies.

This version of the document contains information on

1) the photometric accuracy for point sources (including PHT-S)
2) the photometric accuracy for extended sources (including PHT-S)
3) polarimetric accuracy (including instrumental polarisation)
4) accuracy of PHT-S wavelength calibration

For an individual description of the well characterised instrumental effects, please refer to the ISOPHOT Data User Manual, for an overview of the impact of individual calibration steps on the accuracy, please refer to the ISOPHOT Error Budgets Document.

The two polarisation modes PHT50 (PHT–P) and PHT51 (PHT–C) are not end-to-end processed by the OLP pipeline. Please contact the ISOPHOT Data Centre in Heidelberg or the ISO Data Centre in Villafranca for details of the data reduction and calibration.

Currently there are instrumental effects of ISOPHOT which are not yet fully assessed and characterised. This means

1) the OLP processing of an invidual observation submode is not yet declared scientifically valid and no global calibration accuracies can be provided. An overview of the ISOPHOT Astronomical Observation Template (AOT) validation status is given in Table 1.2. This table also lists planned upgrades for both validated and unvalidated modes as well as the OLP version for which the upgrade is foreseen.
2) under certain circumstances, usage of extraordinary set-ups in a validated mode may have a significant impact on the final calibration accuracy of a given measurement. Please consult the Caveat chapter of the ISOPHOT Data User Manual to which degree a certain observational mode could be affected.

It is a goal of the ISO Post Operations Phase to scientifically validate the OLP processing of the outstanding ISOPHOT AOT submodes. A rough schedule is provided in Table 1.2. OLP V8.2 will be available around mid 1999, OLP V9.2 around mid 2000. This schedule has to be maintained and revisited with the progress in calibration.

Table 1.2: Status of Scientific Validation of ISOPHOT OLP AOT Processing, July 98. AOTs PHT03 – PHT19 are photometric modes with subinstrument PHT–P, AOTs PHT22 – PHT39 are photometric modes with subinstrument PHT–C, AOT PHT40 is the spectroscopic mode of PHT–S. AOTs PHT50 and PHT51 are the two polarimetric modes with PHT–P and PHT–C, respectively. They are processed by the pipeline only to raw data level. For a detailed definition of the individual AOTs, please refer to the ISOPHOT Observer's Manual.

AOT	**observation type**	**submode**	**scientifically valid since**	**next upgrades**	**foreseen in OLP Vx.y**
PHT03 (P)	multi-filter photometry	staring point source	V6	non-lin R & FCS aper	8.2
		staring ext. source	no	beam	8.2
		nodding	V6	non-lin R & FCS aper	8.2
		chopped point source	no	chop	8.2
		raster map	no	map cal & drift	8.2/9.2
PHT04 (P)	multi-aperture photometry	staring point source	no	beam & FCS aper	8.2
		staring ext. source	no	beam	8.2
		chopped point source	no	chop & beam	8.2
PHT05 (P)	absolute photometry	staring point source	V6	FCS aper	8.2
		staring ext. source	no	beam	8.2
PHT17 (P) 18, 19	sparse map photometry	staring point source	V6	non-lin R & FCS aper	8.2
		staring ext. source	no	beam	8.2
PHT22 (C)	multi-filter photometry	staring point source	V7	non-lin R	8.2
		staring ext. source	V7	non-lin R	8.2
		nodding	V7	non-lin R	8.2
		chopped point source	no	chop	8.2
		raster map	no	map cal & flat-field	9.2
PHT25 (C)	absolute photometry	staring point source	V7		
		staring ext. source	V7		
PHT32 (C)	oversampled mapping	chopped mapping	no	chop & map cal	9.2
PHT37 (C) 38, 39	sparse map photometry	staring point source	V7	non-lin R	8.2
		staring ext. source	V7	non-lin R	8.2
PHT40 (S)	spectroscopy	staring point source	V5		
		staring ext. source	V6	beam	8.2
		chopped point source	V6		
PHT50 (P)	aperture polarimetry	staring point & ext. source	V7	interactive processing & special FORTRAN routine	
PHT51 (C)	array polarimetry	staring point & ext. source	V7	interactive processing & special FORTRAN routine	
		raster	V7		

meaning of calibration upgrades:

non-lin R : correction for non-linearity of detector responsivity
for measurement sets covering a large flux range
FCS aper : correction for inhomogeneous illumination of PHT-P apertures by FCS
beam : beam profile corrections
chop : chopped photometry corrections
map cal : surface brightness calibration in maps
drift : correction of non-linear lon-term drifts
flat-field : refined flat-field corrections

Chapter 2

Photometric Accuracies

Three different kinds of photometric accuracies are provided in this document:

- **absolute accuracy** is a measure of the uncertainty of the absolute flux level of any source measured with ISOPHOT w.r.t. well known independently and absolutely calibrated flux standards, either black body standards or standard stars (Vega, Sirius) directly calibrated against black body standards. An absolute flux measurement with ISOPHOT has to involve a measurement against the internal reference source (FCS) in the same filter, because the latter one was calibrated against celestial standards.

- **relative multi-filter accuracy** is a measure of the uncertainty of a spectral energy distribution derived from an ISOPHOT multi-filter measurement with a measurement against the internal reference source in only 1 filter, i.e. the measurements in the other filters have to be tied to the absolute measurement by relative scaling factors. When establishing the relative multi-filter accuracies the systematic offset due to the absolute accuracy term had been subtracted. Therefore, absolute and relative multi-filter accuracy have to be added up for the appropriate measurements in order to derive the total photometric accuracy.
  For PHT-S the term multi-filter accuracy gives the accuracy of the relative spectral shape between different wavelength ranges (covered by groups of $\simeq$ 20 pixels).

- **relative flux reproducibility** is a measure how well a many times repeated observation of the same non-variable source gives the same flux.

Table 2.1 gives a summary overview of the currently achieved photometric accuracies with ISOPHOT. These values have been established as global values from an end-to-end processing involving all likely uncertainty sources. They have been derived during the scientitifc validation of the OLP V7.0 (cf. Report on the PHT Scientific Validation for OLP Version 7.0).
The reproducibility accuracies have been derived from special calibration monitoring programs repeating the measurements 15 to 25 times during a period of more than 1 year and with time intervals between one and six weeks.
Tables 2.2, 2.3 and 2.4 in the subsequent sections give more details on the calibration accuracy assessment, providing the AOT submode, a more detailed flux range specification, and the names of the flux standards used for the assessment.

Goals for photometric calibration improvements until the end of the ISO Post Operational Phase are provided in the corresponding sections.

Table 2.1: ISOPHOT Photometric Calibration Accuracy Overview. For the wavelength range of the detector system, please refer to Table 1.1.

detector	**source type** point / extended	**source brightness**	**typical on-source integration** [s]	**absolute accuracy** [%]	**reproducibility 1 σ of 20 samples** [%]	**multi-filter accuracy** [%]
P1	p	50 – 6000 Jy	32	10	5	20
P1	p	0.1 – 50 Jy	$\leq$ 256	30	10	TBD
P2	p	10 – 200 Jy	32	$<$ 15	2	10
P2	p	0.5 – 10 Jy	$\leq$ 256	$<$ 20	12	TBD
P3	p	0.5 – 25 Jy	32	15	7	20
P3	p	$<$ 0.5 Jy	$\leq$ 256	30	7	TBD
C100	p	0.5 – 25 Jy	32	10	$\geq$ 3	10
C100	p	$<$ 0.5 Jy	$\leq$ 360	30	20	TBD
C100	e	5 – 15 MJy sr^{-1}	32	20	10	$<$ 30
C200	p	1 – 900 Jy	128	20	10	TBD
C200	p	0.2 – 1 Jy	$\leq$ 240	30	10	TBD
C200	e	4 – 10 MJy sr^{-1}	64	20	6	$<$ 30
SS	p	2 – 5000 Jy	256	$<$ 30	$<$ 30	$<$ 30
SS	e	50 – 10^5 MJy sr^{-1}	256	$<$ 30	$<$ 30	$<$ 30
SL	p	1 – 5000 Jy	256	$<$ 30	$<$ 30	$<$ 30
SL	e	50 – 10^5 MJy sr^{-1}	256	$<$ 30	$<$ 30	$<$ 30

2.1 Absolute and Relative Filter-to-filter Calibration Accuracies for Point Sources

The final photometric accuracy depends on a proper background subtraction and color correction. Therefore, we give in Table 2.2 the observing mode used for verification of the calibration accuracy. In particular for faint sources, the simpler observing modes (off–on) are much less accurate than the ones optimised for faint source observations.

The calibration curves of the internal calibration sources (FCS) on celestial standards were established flux range by flux range using different sets of standards with appropriate brightness. This takes into account possible non-linearities of the ISOPHOT detector/read–out system. Therefore, we checked the calibration accuracy per flux range as far as possible.

For the checks measurements on known (calibration) sources were used, which are as far as possible independent of the data set used for establishment of the calibration curves of the internal calibrators. This was not always possible, but due to the reduncancy of calibration sources per flux decade, inclusion of a single measurement does not mean a circular argument in deriving the calibration accuracies. The names of the calibration sources used for the verification measurements are listed in Table 2.2, too. Due to limitations both in the number of test cases processed for scientific validation and in availability of suitable test cases not all observing modes could be addressed. In case of several examples covering the same flux range and showing somewhat different accuracy numbers the more conservative one should be used.

For PHT–S the quoted numbers are derived from a general assessment of the accuracy in deriving the spectral response function. Note that for PHT–S there is a direct conversion from the measured signal into flux density per wavelength range F_λ using this spectral response function established from a set of standard stars. There is no flux range dependent calibration using the internal calibration reference sources.

Table 2.2: Absolute and relative (filter-to-filter) calibration accuracies per detector achieved for various flux ranges in multi-filter mode. Hyphens indicate that no test case was available. Bold values indicate a significant improvement w.r.t. OLP V6.0, the version from which the time counter of the proprietary data period started. For the wavelength range of the detector system, please refer to Table 1.1.

detector	**AOT mode**	**flux range** [Jy]	**abs. accuracy** [%]	**rel. accuracy** [%]	**standard**
P1	P03 off & on	300 - 6000	**10**	15	α Boo
P1	P03, P05 off & on	70 - 1250	**10**	20	γ Dra
P1	P03, P05 off & on	50 - 1000	**10**	**10**	Sirius
P1	P03 nodding	2 - 10	30	–	HR 6817
P1	P03 nodding	2	35	–	HR 5986
P1	P03 nodding	< 0.1	20	–	HD 172323
P2	P03 off & on	100 - 200	≤ 5	5	α Boo
P2	P03, P05 off & on	25 - 40	10	10	γ Dra
P2	P05 off & on	~ 20	**15**	–	Sirius
P2	P03 nodding	3 - 6	≤ 25	–	HR 6132
P2	P03 nodding	3.5	≤ 5	–	HR 7310
P2	P03 nodding	0.5	≤ 10	–	HR 5986
P3	P03 off & on	10 - 25	**10**	20	α Boo
P3	P03 nodding	6 - 20	15	–	α Tau
P3	P03, P05 off & on	~ 5	**10**	30	γ Dra
P3	P03 nodding	~ 3.5	**15**	–	Sirius
P3	P03 nodding	0.6	≤ 15	–	HR 7310
P3	P17/18/19	< 0.2	30	–	HR 5981
C100	P22 off & on	6 - 25	5	10	α Boo
C100	P22, P25 off & on	~ 5	**10**	–	γ Dra
C100	P22 nod & minimap	~ 3.5	**15**	–	Sirius
C100	P22 minimap	0.2 - 0.6	5	–	HR 7310
C100	P37/38/39 4 times	< 0.2	30	–	HR 5981
C100	P37/38/39 2 times	< 0.1	30	–	SAO248381
C100	P37/38/39 2 times	< 0.1	30	–	IRC+60228
C200	P22 minimap	600 - 900	$<$ **10**	–	Uranus
C200	P22 minimap	50 - 120	25 (> 170 μm)	–	Ceres
	P22 minimap, P25		15 (< 170 μm)	–	
C200	P22 minimap	~ 0.5	15	–	γ Dra
C200	P25 off & on	~ 0.5	30	–	γ Dra
C200	P22 minimap	0.2 - 0.4	30	–	HR 1654
SS	P40 off & on	2 - 5000	< 30	< 30	
SL	P40 off & on	1 - 5000	< 30	< 30	

The goals for the improvement of the absolute and relative multi-filter photometry accuracy until the end of the ISO Post Operations Phase are the following:

- absolute accuracy bright sources: 10%
  ($f_\nu > 2$ Jy on intermediate background brightness, minimum on-source exposure time: 32 s)
- absolute accuracy faint sources: 20%
  ($f_\nu < 2$ Jy, S/N > 10, minimum on-source exposure time: 128 s)
- relative filter-to-filter accuracy: 10%
- absolute accuracy PHT-S: $< 20\%$
- relative accuracy PHT-S: $< 20\%$
- absolute accuracy chopped modes: $< 30\%$

2.2 Flux Reproducibility for Point Sources

The following Table 2.3 provides the flux reproducibility both for bright and faint sources. The bright source was measured in standard off-on mode, while the faint sources were measured in optimised faint source observing modes: telescope nodding for PHT–P and mini-map for PHT–C.
The flux reproducibility, a relative photometric accuracy, is not only determined by the detector stability, but also, in particular for wavelengths $\geq 100\mu$m by the structure of the sky background, since, due to the rotation of the focal plane on the sky, different background fields are seen at different times.

Table 2.3: 1 σ Flux Reproducibility per Detector for Bright and Faint Fluxes from Monitoring Programs. For the wavelength range of the detector system, please refer to Table 1.1.

detector	target	**flux** [Jy]	**standard deviation 1 σ** [%]	**no. of meas.**
P1	NGC 6543	8	5	15
P1	HD 172323	0.085	10	23
P2	NGC 6543	100	2	14
P2	HR 5986	0.67	12	15
P3	NGC 6543	100	7	15
P3	HR 7310	0.67	7	15
C100	NGC 6543	50	3	15
C100	HR 7310	0.23	20	23
C200	NGC 6543	15	10	15
C200	HR 6705	0.67	7	23

The goals for the improvement of the flux reproducibility until the end of the ISO Post Operations Phase are the following:

- for both bright and faint sources $< 10\%$.
  This needs mainly improved signal processing.

2.3 Absolute and Relative Filter-to-Filter Accuracies for Extended Sources

With the establishment of wavelength dependent solid angles for the ISOPHOT-C detector pixels extended source photometry with the ISOPHOT-C arrays has been scientifically validated for OLP V7.0. A variety of off-source background photometry has been compared with COBE/DIRBE annual map data. Note that this cross-calibration compares 3 arcmin ISOPHOT beams with 0.7 deg COBE/DIRBE beams. So far no cross-calibration of an ISOPHOT map covering a full COBE/DIRBE beam has been performed. The ISOPHOT–S spectral response function for extended sources is derived from the one for point sources by applying correction factors for the non-flat beam profile. Hence, all uncertainties of the point source spectral response function apply, cf. Table 2.2. On top of that a systematic positive flux correction of 10% for short wavelengths and 20% for long wavelengths has to be applied with the current spectral response function. This is due to an underestimate of the beam profile extent which is currently used in the calculations.
ISOPHOT-P extended source photometry has not yet been scientifically validated.

Table 2.4: Calibration Accuracy per Detector for Extended Sources for Various Flux Ranges. For the wavelength range of the detector system, please refer to Table 1.1.

detector	**flux range** [MJy sr^{-1}]	**absolute accuracy** [%]	**relative accuracy** [%]	**standard**
C100	5 - 15	20	< 30	COBE/DIRBE
C200	4 - 10	20	< 30	COBE/DIRBE
SS	50 - 10^5	< 30	< 30	
SL	50 - 10^5	< 30	< 30	

The goals for the improvement of the extended source photometry accuracy until the end of the ISO Post Operations Phase are the following:

- absolute accuracy $< 20\%$.
- relative filter-to-filter accuracy $< 20\%$.
- for PHT-P the same quality as for PHT-C, independent of aperture size.

2.4 Calibration Accuracies Achievable by Interactive Data Processing

As the OLP processing is automatic using default parameters for all processed measurements, it allows a homogeneous comparison of data sets of the same type of observing mode and hence to derive a set of commonly applicable uncertainties. Those are not subject to individual preferences of parameter settings during interactive processing and do not require the knowledge of special data reduction tricks. In general, standard OLP-type batch processing in ISOPHOT Interactive Analysis (PIA) provides identical accuracies.
The provision of a percentage number characterizing which improvements in calibration accuracy can be obtained by careful interactive processing is impossible, since so far no comprehensive systematic investigation was performed. Interactive Analysis uses the same set of general calibration files (cal-G) as OLP. The limitations due to photometric bias, e.g. the accuracy of the standard source fluxes, fully apply to interactive calibration, too. One can expect,however, to achieve a higher accuracy with IA for the following cases:

1) measurements with signal transients which do not stabilise during the measurement time, but which are long enough to perform a reasonable transient fit.

2) flat-fielding of maps, depending on the sampling mode and the dynamic range.

3) correction of non-linear signal drifts in maps.

4) detection of faint sources by refined deglitching and filtering.

The gain in final calibration accuracy with interactive analysis has, however, to be determined on a case by case basis.

Chapter 3

Polarimetric Accuracies

Polarisation degree and angle are derived from the relative intensity differences measured with three different polariser settings at 0, 120 and 240 deg orientation w.r.t. the focal plane. A key parameter for the achievable polarimetric accuracies is the source-to-background contrast. The background subtraction for each polariser setting has a significant impact on the S/N of the signal by the source alone, beside the relative stability of the detector during the measurement. The uncertainty values are derived from the reproducibility of the intensity per polariser setting in the different polariser cycles per measurement. Instrumental polarisations are listed in Table 3.2. The uncertainties are a combination of the reproducibility of the intensity per measurement and the scatter in the set of measurements used to derive the instrumental polarisation.

Table 3.1: Polarimetric Accuracies for Various Source-to-background Contrasts

detector	**target**	**source flux** [Jy]	**pol. deg.** [%]	**source/ backg**	**S/N source**	**1 σ pol. error per cycle** [%]
P2, P_25 (79")	XXX	400	~ 3	17	150	0.8
	XXX	~ 30	< 2	6.3	120	0.8
	XXX	~ 20	< 2	2	130	0.7
	XXX	~ 7	8	0.7	60	1.7
C200, C_160	3C 279	2.5	6	1.5 – 2	70 – 80	1.5 – 1.7
	3C 279	2.5	6	0.4	10 – 20	5 – 9
	3C 279	2.5	22	0.25	20 – 30	3 – 6
	3C 279	2.5	6	0.25	10 – 15	7 – 12
	α Boo	2.6	0	0.025	2	50 – 70

Note: Targets labelled XXX are from scientific programs which are not yet public domain.

Table 3.2: Instrumental Polarisation of ISOPHOT-P2 and ISOPHOT-C200

detector	filter	**inst. pol. degree** [%]	**uncertainty** [%]	**inst. pol. angle** [deg]	**uncertainty** [deg]
P2	P_25 (79")	3.0	0.2	-18.6	1.5
C200, pixel 1	C_160	4.9	0.3	-57.1	0.8
C200, pixel 2	C_160	5.5	0.3	+87.7	1.1
C200, pixel 3	C_160	6.1	0.3	-39.5	0.8
C200, pixel 4	C_160	3.4	0.3	-76.5	1.8

For the ISO Post Operations Phase no improvement of the quoted polarisation accuracies of individual sources is expected. The accuracy in the assesment of the instrumental polarisation may be slightly improved by the increase of the measurement data base used for its derivation.

Chapter 4

Wavelength Calibration Accuracies of ISOPHOT–S

As ISOPHOT–S has fixed gratings, no uncertainties because of mechanical jitter are involved. The wavelength scale has been best described by second order polynomials fitted to the measured central positions of 7 to 9 unresolved lines per detector array. The wavelength calibration is more accurate for the centre of the array than for the edge; both accuracy values are listed in Table 4.1.

Table 4.1: Wavelength Calibration Accuracy for ISOPHOT–S

array	**range** [μm]	**accuracy array centre** [μm]	**accuracy array edge** [μm]
SS	2.5 - 4.9	0.0020	0.0044
SL	5.9 - 11.7	0.0035	0.0078

For the ISO Post Operations Phase no further improvement in the quoted PHT-S wavelength calibration accuracy is expected.

Chapter 5

Reference Documents

1) ISOPHOT Observer's Manual
   U. Klaas, H. Krüger, I. Heinrichsen, A. Heske and R.J. Laureijs (eds.)
   Version 3.1 (April 7, 1994)
   and
   Addendum to ISOPHOT Observer's Manual
   R.J. Laureijs, U. Klaas, D. Lemke, U. Herbstmeier, and P. Ábrahám
   SAI/96-171/Dc
   Version 1.0 (August 5, 1996)

2) Report on the PHT Scientific Validation for OLP Version 7.0
   U. Klaas and M. Radovich
   SAI/98-049/Rp
   Version 2.0 (July 20, 1998)

3) ISOPHOT Error Budgets
   R.J. Laureijs and U. Klaas
   SAI/98-091/Dc
   Version 1.0 (in preparation)

4) ISOPHOT Data User Manual
   R.J. Laureijs, U. Klaas, P. Richards, and B. Schulz
   SAI/95-220/Dc
   Version 4.0 (October 1998)

Chapter 6

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