ISOPHOT Error Budgets: Derive_SPD Processing Steps

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Reference documents

ISOPHOT Calibration Accuracies
U. Klaas, R.J. Laureijs, M. Radovich and B. Schulz
ISO-SOC internal document, SAI/98–092/Dc
Version 2.0 (October 1998)

Report on the PHT scientific validation for OLP version 7.0
U. Klaas, M. Radovich et al.
ISO Data Centre, SAI/98–049/Dc
Version 2.0 (July 20, 1998)

ISO Data Users Manual for OLP
R.J. Laureijs, U. Klaas, P.J. Richards, Bschulz
ISO Data Centre, SAI/95–220/Dc
Version 4.0 (October 1998)

Contents

1 Introduction

The ISOPHOT data processing and accompanying flux calibration of science observations contain calibration factors and a large number of corrections which have been determined mostly from dedicated in-orbit calibration observations. Since the calibration factors and corrections have a finite accuracy, each will contribute to the total error budget of an observation. The impact of a certain parameter on the photometric accuracy can vary from mode to mode. Due to the many observing modes that can be employed, the determination of the photometric uncertainty of a given observation is not straightforward and may require knowledge of specific details of the observation.

This document provides a detailed description of the different elements that contribute to the overall ISOPHOT error budget up to Derive_SPD. The document follows closely the ISOPHOT pipeline processing scheme which is fully described in the IDUM version 4.

In a later version of this document we will include the error budgets for Derive_AAR. The remainder of this document contains the sections:

- Section 2: definitions are given of the terms releated to ISOPHOT photometric accuracy issues.
- Section 3: the uncertainties introduced in each relevant processing step in Derive_SPD is described. Instrumental corrections and the photometric calibration are performed in Derive_SPD.
- Section 4: summarizes the instrumental effects not corrected for in OLP version 7.
- Section 5: some extra attention is given to the uncertainties in the (point) source flux due to the subtraction of the background emission. ISOPHOT observations provide several methods for separating the source from the background flux.

2 Definition of terms

statistical uncertainty:
comes in whenever the mean or median value is derived of a sample of signals. ISOPHOT's measurement principle is based on collecting a large number of redundant data points: several non-destructive read-outs to establish the slope (=signal in V/s) of an integration ramp and several integration ramps to make up the final signal. The statistical uncertainty is determined by the width of the signal distribution and includes photon noise and detector noise.

systematic uncertainty:
comes in (1) whenever the sample of signals contains non-random outliers or (2) whenever a data point is subject to a arithmetic operation (scaling, addition, or subtraction) which requires parameters obtained from independent calibration observations. The uncertainty of the calibration parameters can be purely statistical. An important fraction of the systematic uncertainty comes from the FCS measurement. An error in the detector responsivity derived from the FCS signal causes the same (systematic) scaling error in the flux densities of the sky measurements.

photometric bias:
is the photometric uncertainty in ISOPHOT-data due to uncertainties in the predicted fluxes of the celestial standards upon which the ISOPHOT flux or inband power calibration tables are based. The input fluxes of the photometric calibration standards are based on model predictions [1]. The photometric accuracy of celestial standards can vary from object to object (e.g. due to type of

asteroid, spectral type of star, particular planet, etc) which may cause a different photometric bias for different flux regimes at a given wavelength. The photometric bias becomes important when comparing ISOPHOT data with results from other instruments. This term is important for the final absolute accuracy.

relative accuracy:
is the filter to filter or aperture to aperture accuracy for a given detector assuming a single value for the detector responsivity. The relative accuracy is of importance in a multi-filter and/or multi-aperture observation where a single FCS measurement is used to calibrate several sky measurements with different filters and/or apertures. The relative accuracy limits the accuracy in the determination of colours in case of multi-filter photometry and of extended emission components in case of multi-aperture photometry.

detection limit:
is the minimum point-source flux that can be detected within a given measurement time. The detection limit is determined by the source-background separation which depends on the observing strategy like minimaps, chopped observations, on- and off-position AOTs, sparse maps, nodding, etc. Cirrus and galaxy confusion are important external limitations depending on wavelength, background flux level, and spatial resolution. The photometric bias has no significant impact on the detection limit.

flux reproducibility:
determines the width of the flux distribution of a large sample of identical observations (same AOT with identical settings on the same target) obtained at different times during the ISO mission. The reproducibility gives a global assessment of the best accuracy that can be achieved for a given observing mode. It lumps together several uncertainties: the statistical uncertainty in the sky measurement, the systematic uncertainty due to the FCS calibration measurement and the uncertainties due to external noise sources. It can also be regarded as a measure of the stability of the instrument. This term becomes important in the analysis of variable sources.

3 Derive SPD level corrections/conversion steps

3.1 Discarding read-outs and destructive read-outs

synopsis: (1) statistical uncertainty increase due to decrease of effective integration time, (2) systematic uncertainty decrease by removing anomalous read-outs.

limitations and applicability:
none

description:
Removal of read-outs along an integration ramp that cannot be used for the derivation of signal (sect.3.5).

purpose correction:
Removal of read-outs that are known to show strong non-linear behaviour during the integration period. This correction prepares the data points (read-outs) for proper processing in the subsequent calibration steps.

uncertainty/noise introduced:
In the worst case the effective integration time is reduced by at most 50%. This happens in case of 4

read-outs per ramp where the first read-out and the destructive read-out are removed; consequently the predicted S/N is reduced by $\sqrt{2}$.

auxillary data:
Cal G file: PSELNDR

keyword(s):

USEDRS :	Use destructive readouts?	SPD header
DISCNDRS:	number of discarded non-destructive read-outs	SPD header

3.2 Discarding saturated read-outs

synopsis: (1) statistical uncertainty increase due to decrease of effective integration time, (2) systematic uncertainty decrease by removing anomalous data points.

limitations and applicability:
none

description:
Removal of a read-out plus remaining read-outs in a ramp as soon as this read-out falls above a certain threshold level in Volts.

purpose correction:
Above the threshold voltage the voltage for each read-out does not increase according to the photocurrent but remains at the same voltage level or drops. These read-outs have to be removed.

uncertainty/noise introduced:
The effective integration time decreases with the fraction of the saturated read-outs that have been removed. The loss in S/N depends on each specific case - fortunately only a small fraction of all ISOPHOT data need this correction.

auxillary data:
Threshold voltage levels for each detector subsystem.

keyword(s):
RAMPSAT: number of number of saturated ramps in measurement SPD header

3.3 Ramp linearization (PHT–P, PHT–C)

synopsis: (1) statistical uncertainty increase due to reset level variations within a staring measurement at a constant flux level. The statistical uncertainty is probably small: less than 2% unless the measurement is very long. (2) residual systematic photometric uncertainty for multi-filter and multi-aperture staring observations especially with detectors P3, C100 and C200. The residual systematic uncertainty after correction is estimated to be at most 10%. (3) residual systematic photometric uncertainty for measurements in which the signals cover a high dynamic range such as in maps with bright features and in chopped observations. The estimated systematic uncertainty is at most 10%. (4) systematic photometric uncertainty in PHT-S observations. Since the integration ramps for PHT-S observations are not linearized the residual systematic error is probably better than 20%.

limitations and applicability:
(1) no correction applied for PHT-S (2) strong signals with low bias detectors are not properly corrected.

description:
Removal of systematic non-linearities ("kinks") in integration ramps by adding to each read-out voltage a positive or negative voltage in order to obtain a linear or "straight" integration ramp. It is assumed that the deviation from non-linearity only depends on the read-out voltage level. This correction is applied to all detectors except PHT-S.

purpose correction:
The integration ramps are not straight but show systematic kinks and curvatures. The non-linearities cause systematically different slopes (signal level) for different parts of the ramp making the ramp signal an ill-defined parameter and a sensitive function of the voltage range covered by a ramp. The correction is based on the assumption that the deviation from linearity only depends on the CRE voltage level of a read-out. Consequently, a "straight" ramp is derived by adding a voltage correction to each read-out. The corrections were obtained from an empirical integration ramp constructed from averaging many representative integration ramps. The deviations of this average ramp from a generic straight ramp yield the correction terms (ΔV) as a function of read-out voltage. For the low bias-detectors (P3, C100 and C200) the non-linearity is not only a function of CRE voltage, but also a function of the detector photo-current. The charge accumulated on the integration ramp feeds back and reduces the bias voltage ("debiasing"). This effect depends on the voltage difference due to the charges above the reset voltage level. The stronger the photo-current, the bigger the downward curvature of the integration ramps. No specific correction is made for this effect. It should be noted that also all calibration observations were linearized with the same correction tables.

uncertainty/noise introduced:
In case the reset level changes within a measurement, the uncertainties in ΔV widens the signal distribution. Since the reset level changes only slowly in time for measurements of the same signal strength the contribution to the statistical uncertainty is small, less than a few percent is estimated. However, the reset level changes when the signal level varies. This can happen in obsevations using multi-filter, multi-aperture, chopped or mapping modes.

For PHT-S which is not corrected at all, and for P3, C100 and C200 which are low bias detectors, the ramp non-linearity is not removed completely. Since different signal strengths require different corrections, the residual error may cause systematic uncertainties depending on the signal strength.

- Case 1: in a multi-filter or multi-aperture observation with P3, C100, or C200 the integration ramps for each measurement possibly cover different dynamic ranges. The flux calibration is based on the voltage range in the FCS measurement which does not necessarily correspond to the range in a given sky measurement of that detector. A systematic uncertainty for each filter/aperture may arise from this effect.
- Case 2: for a given PHT-S measurement the read-out settings for all detectors are identical. Therefore, a measurement of a target with a bright spectral feature, or a target with a large gradient in the continuum will have PHT-S channels using different voltage ranges. In OLP a fixed responsivity is assumed per channel which results in systematic uncertainties for different flux levels.
- Case 3: maps (including sparse maps) with high dynamic range can have systematic uncertainties for different surface brightness regimes. The photometric uncertainty depends on the voltage range of ramps in the FCS measurement: is this range correspond to that of the brightest features in the map than the systematic uncertainty is highest for the weak flux regions in the map and vice versa.

auxillary data:
Cal-G files: PPCRELIN, PC1CRELIN, and PC2CRELIN. These files also contain the statistical uncertainties of the corrections.

keyword(s):
none

3.4 Ramp deglitching

synopsis: (1) statistical uncertainty reduction by removing outliers (2) (positive) systematic uncertainty reduction due to removal of positive glitches.

limitations and applicability:
A minimum number of 25 read-outs per ramp are required for application of the algorithm. Glitches occuring in measurements with less than 25 read-outs per ramp should be removed during signal deglitching (sect. 3.8).

description:
Replacement of an anomalous increase in voltage between two adjacent read-outs by the mean increase in the ramp. This is done in an iterative way using a kappa-sigma criterion. The method assumes that an integration ramp is linear.

purpose correction:
Glitches cause a voltage increase between adjacent read-outs which is higher than expected from a constant photocurrent. Such glitches can be isolated and corrected. Removal of these glitches lowers the scatter on the individual signals and removes a positive bias from the signal.

uncertainty/noise introduced:
The glitch spectrum is such that the glitches with the lowest energies have the highest frequency of occurence. The low energy glitches cause a small steady voltage increase which cannot be removed by this method. This causes a small positive signal bias, which is considered to be part of a systematic increase in dark signal (see sect 3.7).

auxillary data:
Default deglitching parameters:

N_{it}	=	4	number of iterations
N_{σ}	=	4.5	minimum number of standard deviations for glitch detection
N_{min}	=	25	minimum number of read-outs/ramp for application of algorithm

keyword(s):

RDITER:	number of iterations	SPD header
RDFSIG:	number of standard deviations for clipping	SPD header
RDMINP:	min. number of read-outs per ramp	SPD header
RAMPDEGL:	number of ramps deglitched	SPD header

3.5 Extraction of signals: first order polynomial fit

synopsis: derivation of the statistical uncertainty Δs of the signal per integration ramp.

limitations and applicability:
For ramps with 3 non-destructive read-outs no uncertainty in the signal can be derived. The signal uncertainty Δs is then set to zero.

description:
The signal (in V/s) per ramp is derived by fitting a first order polynomial to the ramp. The uncertainty is obtained from the mean of the residuals computed from the difference between the read-out and

model voltages, these uncertainties are used as weights in the determination of the mean signal per chopper plateau or raster point.

purpose correction:
Determination of a signal from the slope of an integration ramp.

uncertainty/noise introduced:
The scatter of the individual read-outs around the fitted slope of the ramp is a measure of the photon and detector noise. The scatter is also influenced by the previous correction steps. For ramps with 3 non-destructive read-outs only 2 read-outs are used for ramp fitting. The uncertainty in the signal is set to zero and the mean per chopper plateau or raster point is not weighted.

auxillary data:
None

keyword(s):

RAMPPCT:	percentage of ramps used for signal average	SPD header
RAMPUSET:	percentage of time used for signal average	SPD header

3.6 Reset interval correction (PHT–P, PHT–C)

synopsis: residual systematic error which depends on the difference in reset interval length selected for the sky measurement(s) and FCS measurement. In normal cases the residual error is better than 20%.

limitations and applicability:
PHT-S data are not corrected.

description:
The signal dependence on reset interval is removed by correcting all signals to one reference reset interval of 1/4 s. This correction reduces the systematic error between measurements of a given AOT.

purpose correction:
A given photocurrent yields different signals depending on the reset interval selected. This variation is fixed and has been determined in orbit from calibration measurements. To remove the effect all signals are corrected to the 1/4 s reset interval according to the relation:

$$s(RI = \frac{1}{4}\ sec,\ dr = 1) = A_0(RI,\ dr) + A_1(RI,\ dr) * s(RI,\ dr) \qquad V/s, \tag{1}$$

where $s(RI,\ dr)$ is the uncorrected signal taken with reset interval length RI and data reduction dr. The correction parameters A_0 and A_1 depend also on the detector. Since all signals of all measurements are converted, the correction becomes only relevant when comparing signals of measurements obtained with different reset intervals such as sky and FCS measurement.

uncertainty/noise introduced:
The consistency between signals of measurements in the same AOT is improved, especially for the comparison between sky and FCS measurement. The correction parameters A_0 and A_1 have uncertainties. The systematic uncertainty in the derived flux densities depends on the reset interval difference between the FCS measurement and sky measurement which can vary from 0 (=no uncertainty) to about 2^5 (maximum uncertainty introduced by this correction). The latter could happen in case a multi-filter or multi-aperture AOT is used where the dynamic range between the first and last sky measurement is high. If for a given reset interval the dynamic range of the ramp is below 1%

(0.01–0.02 V) the residual uncertainty becomes larger than 20%.

auxillary data:
Cal-G files: PxxRESETI, where $xx =$ P1, P2, P3, C1, and C2, referring to the various detector subsystems.

keyword(s):
None

3.7 Dark signal subtraction

synopsis: (1) residual systematic uncertainty in the sky measurement which depends on orbital position during measurement and space weather conditions. (2) residual systematic uncertainty in the FCS measurement causing an additional systematic photometric uncertainty for the sky measurements.

limitations and applicability:
The dark correction is highly uncertain at the end of a revolution. Not applicable to chopped or differential measurements where the sky background subtraction includes implicitly the dark signal subtraction. The background must be observed together with the target observation to ensure that the dark signals in source and background pointing are identical. The correction is not important for bright sources (cf. Table 1).

description:
The detector/CRE chain as well as the ionising radiation introduce an instrumental signal which causes a zero level offset ("dark signal"). The dark signal depends on the properties of the detector and the time of the observation in the science window. A time dependent dark signal is removed.

purpose correction:
Removal of a spurious (instrumental) signal.

uncertainty/noise introduced:
Observations in which a differential flux is measured are not affected by uncertainties in the dark signal correction. Examples are: chopped observations, absolute photometry observations in which the dark signal measurement is included, maps covering discrete sources, etc. Also, for observations for which the sky signal is much higher than the dark signal, the uncertainties are negligible.

Residual uncertainties in the dark signal correction becomes important for faint targets whose signals are close to the dark signal.

Systematic uncertainties in the dark signal subtraction of the FCS measurement affects the responsivity determination for all AOTs except for the absolute photometry AOTs (PHT05, PHT25) where a dark or FCS straylight measurement was performed. The signal uncertainties of the dark and straylight measurements contribute then to the statistical uncertainty.

To be consistent with the reset interval correction (Sect. 3.6, all dark signals except PHT-S are transformed to the equivalent signal for a reset interval of $t_{reset} = \frac{1}{4}$s. This introduces an additional uncertainty due to the residual uncertainties in the transformation. For some detectors the dark signal after transformation has become negative, this a consequence of the CRE properties and has no deeper physical meaning.

In Table 1 we give the equivalent fluxes for dark signals for each filter. Since the dark signal is time dependent, the average minimum value (column 2), average maximum value (column 3) along the revolution and the $1\,\sigma$ statistical scatter due to space weather effects from revolution to revolution (column 4) are listed for each filter. The dark signals increase along the revolution and the highest values are found for the end of the science window. A typical responsivity is assumed for each detector. For C100 and C200 the dark signals are available for each pixel. Since the dark signal values are similar for all C100 pixels except for pixel 6 we list pixel 6 and the average of the remaining 8 pixels. For C200 we list the average of the 4 pixels.

The table can be used to estimate the typical dark signal uncertainties.

Table 1: Dark signal equivalent fluxes, see text for explanation of columns

filter ID	$\mathbf{F}_{\nu,\mathbf{min}}$ mJy	$\mathbf{F}_{\nu,\mathbf{max}}$ mJy	$\mathbf{\Delta F}_{\nu}$ mJy
P1_3.29	468	544	323
P1_3.6	93	109	64
P1_4.85	92	107	64
P1_7.3	69	80	47
P1_7.7	352	410	243
P1_10	262	304	181
P1_11.3	929	1080	641
P1_11.5	168	196	116
P1_12.8	385	447	265
P1_16	709	824	489
P2_20	126	254	23
P2_25	121	245	22
P3_60	-196	1144	52
P3_100	-142	827	37
C_50	-36	561	111
C_60	-26	404	80
C_60pix6	573	1245	156
C_70	-27	416	82
C_90	-11	175	35
C_90pix6	248	539	68
C_100	-19	301	60
C_105	-37	567	112
C_120	-97	-64	7
C_135	-63	-42	5
C_160	-50	-33	4
C_180	-105	-69	8
C_200	-318	-209	23

auxillary data:
Cal-G files: PPDARK, PSDARK, PC1DARK, and PC2DARK for the different subsystems and include estimates of the statistical uncertainty.

keyword(s):
None

3.8 Signal deglitching

synopsis: (1) reduction of statistical uncertainty by removing outliers, (2) increase of statistical uncertainty due to decrease of effective integration time.

Table 2: Default parameters for signal deglitching

Parameter	**Value**	**Description**
min_deglitch	5	minimum points to apply
max_error	1 V/s	maximum error allowed if number of points is less than min_deglitch
n_iter	2	number of iterations of deglitch filter
n_local	20	number of points in local distribution
n_step	1	the number of points to move the 'box' for the local distribution each time
n_sigma	3	Rejection factor: number of standard deviations from local median.
n_bad	2	number of times point has to be flagged as 'bad' before it is rejected.

limitations and applicability:
For measurements with less than 22 signals per chopper plateau or per raster point the iterative method is not used, instead all signals with $\Delta s > 1$ V/s are removed.

description:
The distribution of a number of consecutive signals (=local distribution) is analyzed and outliers are removed according to a kappa-sigma criterion. This is repeated several times.

purpose correction:
Removal of signal glitches/outliers that are not recognized during ramp deglitching (Sect. 3.4).

uncertainty/noise introduced:
None, reduces the statistical uncertainty.

auxillary data:
see Table 2

Keyword(s):

MINDEG:	Min points for deglitcher	SPD header
MAXERR:	Max error if points ¡ MINDEG	SPD header
NITERATE:	No. of iterations of deglitcher	SPD header
NLOCAL:	No. of local points used by deglitcher	SPD header
NSTEP:	Deglitcher step size	SPD header
NSIGMA:	amount rms from local median	SPD header
NBAD:	badness count limit	SPD header
P??NSIG :	number of valid signals on plateau (??= P1,P2,P3,C1,C2)	(SPD record)

3.9 Discarding signals in chopped measurement

synopsis: (1) statistical uncertainty increase due to decrease in effective integration time, (2) systematic uncertainty decrease due to removal of highly unstable signals.

limitations and applicability:
The correction is only applied to chopped observations, PHT32 is also excluded. The signal redundancy per chopper plateau is minimized, often to 2 signals per chopper plateau or less.

description:
For chopped measurements in general, the plateaux show upward transients for the on-source signals and downward transients for the off-source signals. To minimize influences by the initial jump, the first half of all signals on a chopper plateau is discarded.

purpose correction:
Better definition plateau signal. The same method is used in the derivation of the correction factors for signal losses in chopped mode.

uncertainty/noise introduced:
The effective integration time is decreased by 50%, thereby increasing the statistical uncertainty by $\sqrt{2}$.

auxillary data:
Deglitch parameters.

3.10 Transient recognition

synopsis: (1) residual systematic uncertainty, in case the stability criterion is satisfied, the residual uncertainty is less than 5%, (2) residual systematic uncertainty, in case the stability criterion is not satisfied the systematic uncertainty is higher than 5%, (3) statistical uncertainty increase due to decrease in effective integration time for partial stable measurements, (4) residual systematic uncertainty: the independent FCS measurement can be stable, partly stable or unstable, causing a additional systematic uncertainty to the sky measurements.

limitations and applicability:
In case the stability criterion is not met, no signals are discarded. A minimum of 7 signals per measurement or raster point is required to perform the analysis.

description:
Transient recognition determines whether there is a significant systematic signal variation in a measurement by applying the Mann algorithm. In case such variation is present the first half of the signals is discarded, this is repeated until a stability criterion is achieved or 7 signals are remaining. The criterion for rejection is a variation in excess of 5%.

purpose correction:
Transient responsivity variation is an important cause of systematic error which is minimized by this correction.

uncertainty/noise introduced:
The magnitude of the transient variation depends on the type of detector, flux step (positive or negative), and exposure time. A large flux step to a higher flux under-estimates and a flux step to lower fluxes over-estimates the "true" (i.e. stabilized at $t=\infty$) measurement signal. In multi-filter and multi-aperture AOTs the flux step is tuned to become positive. However, the flux of the FCS is often lower than the last sky measurement (i.e. negative step) which yields a negative systematic uncertainty because the detector responsivity is overestimated. The null hypothesis for drift recognition is 5%. Therefore, if the integration time is sufficiently long ($>$ 32 sec) and the transient recognition algorithm yields a stable signal after the iteration, then it is most likely that the derived signal is within 5% of the "true" signal level. The same holds for the FCS measurement signal, which adds also a systematic uncertainty of at most 5% to the photometry via the systematic uncertainty in the responsivity.

auxillary data:
Parameters for the transient recognition algorithm:

$N_{min} = 7$, minimum number of signals for correction;
$\alpha = 0.05$, probability that the null-hypothesis is rejected.

keyword(s):

DRALPHA:	significance level	SPD header
DRMINPTS:	min. no. of points for Mann-test	SPD header
FITDRn:	Drift fit flag (T or F, n=measurement number)	SPD header

3.11 Signal averaging per chopper plateau

synopsis: derivation of the weighted standard deviation of the weighted mean signal per chopper plateau. This standard deviation will be used as the statistical uncertainty of the weighted mean signal.

limitations and applicability:
no limitations, always applied.

description:
Computation of the weighted mean of all valid signals on a chopper plateau or raster point (a staring measurement is regarded as one single chopper plateau).

purpose data reduction step:
Determination weighted mean signal and statistical uncertainty.

uncertainty/noise introduced:
Δs (sect. 3.5) is used as weight. Ramps with only 2 valid read-outs are weighted out since their weight have been set to zero. If all ramps in a measurement have 3 non-destructive read-outs per ramp (see section 3.5) all signals get the same weight by setting all weights to 1. This processing step yields the statistical uncertainty in the signal distribution.

auxillary data:
Number of valid signals on the plateau for averaging.

3.12 Chopper vignetting/offset correction (PHT-C)

synopsis: residual systematic uncertainty which is a fixed fraction of the background emission, the correction accuracy is better than 2%.

limitations and applicability:
Only applied to C100 and C200 chopped observations, the other detectors (PHT-P and S) show chopper vignetting/offset of less than 2%. Consequently, faint sources that are observed in chopped mode which are fainter than 2% of the background emission can have more than 100% systematic uncertainty.

description:
The chopper vignetting/offset is corrected by scaling the on- and off-target signals with a factor measured in-orbit.

purpose correction:
In case of a perfectly flat sky, the chopper offset/vignetting introduces a non-zero signal difference between on- and off-target signals. This effect causes a systematic error or even a non-detection of the source when the difference signal becomes zero. The effect is larger for bigger chop throws.

uncertainty/noise introduced:
The C200 observations in chopped mode are the most affected by this effect. The residual photometric uncertainty due to chopper offset/vignetting is better than 2% and scales directly with the level of the background. E.g if the background is 1 Jy in the pixel or aperture, then the systematic uncertainty is better than 20 mJy/beam.

auxillary data:
Cal-G files: PP1VIGN, PP2VIGN, PP3VIGN, PC1VIGN, PC2VIGN
no uncertainties are supplied in the Cal G file.

3.13 Determination of in-band power from FCS

synopsis: (1) residual photometric bias of better than 5–15% from the photometric accuracy of the celestial standards, (2) residual systematic uncertainty better than 5% from the statistical uncertainty in the calibration observations. This only holds when the sky signal is close to the FCS signal, otherwise signal non-linearities become the dominant source of uncertainty.

limitations and applicability:
(1) The heating power of the FCS should be within the 'soft' limits, the heating powers which have been used for comparison with the celestial standards are within these limits. Outside these limits the photometric bias can be higher than 15% due to uncertainties in the extrapolation. (2) For the aperture photometer PHT-P the inband power is normalized to the area in mm^2, the normalisation is based on a standard aperture. (3) For the camera arrays, the inband power given is per pixel.

description:
Based on the electrical heating power applied to the FCS, the power on the detector is obtained from the FCS calibration tables.

purpose correction:
Determination of the flux from the photometric reference (FCS) for a given electical power. This flux is used to calibrate all sky measurements The calibration table has been obtained from the comparison between the FCS signal for a given FCS electrical power with the signal from a calibration standard (calibration star, planet, or asteroid).

uncertainty/noise introduced:
The uncertainties in the FCS tables include the statistical uncertainty from the calibration observations, as well as systematic uncertainties in the predicted fluxes of the calibration target. All uncertainties in the FCS tables add up to the photometric bias of a given observation.

auxillary data:
Cal-G files PP1FCSPOW, PP2FCSPOW, PP3FCSPOW, PC1FCSPOW, PC2FCSPOW
no uncertainties are supplied in the Cal G file.

keyword(s):

CALFCS:	FCS used for cal calculations	SPD header
RAMPPCT:	percentage of ramps used for signal average	SPD header
RAMPUSET:	percentage of time used for signal average	SPD header

3.14 Detector responsivity PHT-P

synopsis: (1) statistical uncertainty in the responsivity from statistical uncertainty in the FCS signal (2) systematic uncertainty from a systematic uncertainty in the FCS signal (due to transients) (3) systematic uncertainty due to uncertainties in the aperture scaling (see section 3.17).

limitations and applicability:
(1) In case no valid FCS measurement is present, a default responsivity is applied. (2) the geometric scaling of the FCS power with the geometric area of the aperture introduces errors due to the non-homogeneous illumination by the FCS.

description:
The responsivity for the filter in which the FCS measurement is taken, is obtained from the FCS power on the detector (P_{fcs}) normalized to 1 mm^2 and the FCS signal s_{FCS} (see 3.13).

$$R = \frac{\langle s_{FCS} \rangle \cdot C_{det}}{P_{FCS}(p,f) \cdot A_{FCS}(p,f)} \qquad A/W, \tag{2}$$

where

- f indicates the filter,
- p indicates the FCS power
- $\langle s_{FCS} \rangle$ is the weighted mean signal of the FCS measurement (in V/s),
- C_{det} is the detector capacitance (in F),
- $P_{FCS}(p,f)$ is the normalized in-band power on the detector from the FCS (in W) for a given FCS power and filter,
- $A_{FCS}(p,f)$ is the aperture area of the FCS measurement in mm^2 for a given FCS power and filter.

purpose correction:
Determination of the responsivity of the detector, which is necessary to perform the flux calibration. The responsivity varies along a revolution due to cosmic ray impacts and there is a strong dependence on space weather environment.

uncertainty/noise introduced:
(1) The mean signal of an FCS measurement has a statistical uncertainty which propagates into the uncertainty of the responsivity. This error will contribute to the systematic uncertainty of the sky measurement(s). (2) the photometric bias propagates in the responsivity determination. (3) the geometric scaling to the aperture area adds no uncertainties in case a standard aperture is used for the FCS measurement otherwise uncertainties up to 100% are possible.

auxillary data: none

3.15 Detector responsivity PHT-C

synopsis: (1) statistical uncertainty in the responsivity from statistical uncertainty in the FCS signal (2) systematic uncertainty from a systematic uncertainty in the FCS signal (due to transients) (3) systematic uncertainty from statistical uncertainties in the illumination matrix (see sect. 3.18) (4) systematic uncertainty from the filter-to-filter response correction (see sect 3.19).

limitations and applicability:
(1) In case no valid FCS measurement is present, a default responsivity is applied, see sect. 3.16.

description:
The FCS measurement is used to determine the responsivity of each pixel $R(i)$ for the filter in which the FCS measurement is taken:

$$R(i) = \frac{\langle s_{FCS}(i,f) \rangle \cdot C_{det}}{P_{FCS}(p,f) \cdot \Gamma(i,f) \cdot \chi(i,f)} \quad A/W, \tag{3}$$

where

- f indicates the filter, i the pixel number,
- $\langle s_{FCS}(i,f) \rangle$ is the FCS signal per chopper plateau,
- C_{det} is the detector capacitance,
- $P_{FCS}(p,f)$ is the in-band power (in W) for a given FCS heating power p,
- $\Gamma(i,f)$ is the *illumination matrix*, and
- $\chi(i,f)$ is the correction matrix characterizing the filter dependent flat-field variations.

The illumination matrix $\Gamma(i,f)$ is needed to correct for the fact that the FCS illumination is not flat but varies from pixel to pixel in the C100 and C200 arrays. The detector flat field correction is necessary to obtain the same responsivity for each filter of the same detector.

purpose correction:
Determination of the responsivity of the C100 and C200 detector array, which is necessary to perform the flux calibration of each filter measurement.

uncertainty/noise introduced:
(1) The mean signal of an FCS measurement has a statistical uncertainty which propagates into the uncertainty of the responsivity. This error will contribute to the systematic uncertainty of the sky measurement(s). (2) the photometric bias propagates in the responsivity determination. (3) the illumination matrix is accurate to within 3% per pixel. (4) the detector flat field correction is accurate to within 5% from filter-to-filter.

auxillary data: none

3.16 Default detector responsivity

synopsis: systematic flux uncertainty due to flux dependence of the detector responsivity level from revolution to revolution.

limitations and applicability:
The P3, C100 and C200 detectors are more sensitive to space weather conditions and to the ionizing radiation at the end of a revolution. Per orbital phase element, the default responsivity is an average value for the complete accessible flux range (from background level to saturation). Any dependence on the total illuminated flux is not accounted for. This can cause discrepancies as high as a factor 3 as found from chopped photometry analysis.

description:
In case the FCS measurement is inadequate to determine the detector responsivity, the default responsivity is used. The default responsivity is a function of position along the orbit and was determined by averaging many responsivity measurements along a revolution.

purpose correction:
Determination of the detector responsivity during an observation.

uncertainty/noise introduced:
For the default responsivity it is assumed that the responsivity does not vary from revolution to revolution. This assumption is for the SS, SL, P1, and P2 detectors probably good within a few percent. The other detectors P3, C100, and C200 are more sensitive to space weather conditions. As a result, the default responsivities for a given observing date can be as uncertain as several tens of percent.

auxillary data: Cal-G files PPRESP, PC1RESP, PC2RESP
uncertainties are supplied in the Cal G file.

3.17 Aperture scaling of FCS measurements (PHT-P)

synopsis: systematic uncertainty due to use of non-standard PHT-P aperture and non-proportionality of flux with aperture area.

limitations and applicability:
Per PHT-P filter the FCS was calibrated in a standard aperture. For this the aperture scaling is not relevant. Non-standard apertures yield large uncertainties.

description:
The normalized power on the detector (in W/mm) obtained from the FCS calibration table has to be scaled with the size of the selected aperture (in mm^2) to obtain the actual FCS power.

purpose correction:
The actual power on the detector has to be scaled from the standard aperture (normalized to W/mm^2) to the selected aperture. In OLP7 it is assumed that the actual power is proportional to the physical area of an aperture. Dedicated calibration observations have shown that this assumption is wrong, especially for the biggest apertures (180″) for the P1 and P2 detectors.

uncertainty/noise introduced:
Due to the incorrect assumption (power proportional to aperture area) the photometric uncertainty is up to a factor $\approx$5 for the largest apertures w.r.t. the standard apertures.

auxillary data:
Areas of the apertures in mm^2

3.18 Correction for inhomogeneaous FCS illumination (PHT-C)

synopsis: systematic uncertainty due to residual flat field uncertainty

limitations and applicability:
possibly dependent on heating power

description:
The non-homogeneous illumination of the arrays by the FCS is corrected for by using a scale factor for each pixel (illumination matrix). The element values in the matrix are different for different filters.

purpose correction:
Improves the accuracy of the determination of the individual detector pixel responsivities.

uncertainty/noise introduced:
The illumination matrices have been determined in orbit. The minimum error in the determination of the matrices depends on the validity of the assumption that the illumination matrix is fixed for different FCS electrical powers. Residual errors in the illumination matrix decrease the consistency in calibration among the pixels. Table 3 lists the maximum 1 σ uncertainty for each filter in the array.

Table 3: Maximum uncertainties in the illumination matrix, plus corresponding pixel

filter ID	Maximum 1 σ uncertainty (%)	Pixel
C_50	16	1
C_60	10	9
C_70	10	3
C_90	12	5
C_100	16	1
C_105	20	7
C_120	13	3
C_135	10	3
C_160	8	3
C_180	10	1
C_200	10	3

auxillary data:
Cal-G files PC1ILLUM, PC2ILLUM
uncertainties are supplied in the Cal G file.

3.19 Detector pixel filter-to-filter response correction PHT-C

synopsis: residual systematic uncertainty: for C100: at most 5% for C_105 otherwise better than 3%; for C200: at most 6% for C_200 otherwise better than 3%.

limitations and applicability:
only applies to the photometric calibration of filters different from the filter for which the FCS is obtained.

description:
Homogenizes the responsivity of a detector pixel from filter to filter.

purpose correction:
The responsivity of the detector should per definition be identical for measurements with different filters of the same detector at the same time. This is not the case without this correction. This correction improves the photometric calibration for filterbands different from the one for which the FCS measurement is obtained.

uncertainty/noise introduced:
After correction, the C100 and C200 filter-to-filter calibration is better than 5% for C_105 otherwise better than 3% for C100 filters; for the C200 filters at most 6% for C_200 otherwise better than 3%. No uncertainty arises when the FCS measurement is obtained in the same filterband as the sky measurement.

auxillary data:

Table 4: Summary of uncertainties at SPD level

Correction	**sect.**	statistical uncertainty	**residual Systematic error**	**residual photometric bias**
Discarding read-outs	3.1	$\sqrt{(N_{ndr}+1)/(N_{ndr}-N_{dis})}$	none	none
Saturated read-outs	3.2	$\sqrt{(N_{ndr}+1)/(N_{ndr}-N_{sat})}$	none	none
Ramp linearization	3.3	$< 2\,\%$	20%	none
Ramp deglitching	3.4	none	none	none
Signal extraction	3.5	Δs	none	none
Signal deglitching	3.8	$< 1\,\%$	none	none
Reset interval	3.6	none	5%	none
Dark signal	3.7	none	cf. table 1	none
Discarding signals chopped meas.	3.9	$\sqrt{2}$	?	none
Transient	3.10	$\sqrt{N_s/(N_s-N_{trans})}$	5%	none
Averaging signals	3.11	Δs_{ave}	none	none
Chopper vignetting	3.12	none	2% for P,	none
			3% for C[a]	none
FCS power	3.13	none	$< 5\%$	15%
Responsivity PHT-P	3.14	none	$< 5\%$ (ΔA,)	none
Responsivity PHT-C	3.15	none	$< 5\%$ (Δa_{fcs})	none
Default responsivity	3.16	none	20%	10%
FCS Aperture correction (PHT-P)	3.17	none	$\Delta A > 100\%^b$	none
Illumination matrix (PHT-C)	3.18	none	$\Delta\Gamma < 5\%^b$	none
Detector flat-field (PHT-C)	3.19	none	$\Delta\chi < 5\%^b$	none

Notes
a: on total (source plus background) flux
b: for the biggest apertures ($99''$, $120''$, *and* $180''$)

Cal-G file PC1FLAT, PC2FLAT
uncertainties are supplied in the Cal G file.

3.20 SPD level uncertainties

A summary is provided in Table 4.

4 Instrumental effects not corrected for in OLP

4.1 Responsivity transients

Detector transients occur as soon as a change in detector illumination takes place. The resulting relaxation function after the flux step is not easy to model and depends on the flux step, type of detector, flux history, temperature of the detector, etc. PIA contains routines to apply theoretical or semi-empirical drift corrections, but it is to the observer's judgement to use the inter-actively derived fluxes.

The P1 and PHT-S detectors cause the largest responsivity transients causing a photometric bias of more than 100% for large flux steps and short (32 sec) integration times. Typical observations that can be affected at a level higher than 20% accuracy are:

- observations with PHT-S.
- observations with detector P1 and P2.
- multi-filter observations with PHT-P and with relatively short integration times ($t_{int} \leq$ 64 sec). Faint targets are more affected because the relaxation time is generally longer.
- PHT32 maps with high dynamic range. For very high dynamic range maps "ghosts" of bright point sources have been seen about 1 chopper sweep away from the actual targets.

4.2 Responsivity non-linearities

The AOT logic tries to perform an FCS measurement for which the power on the detector is close to the power on the sky. This is done because the responsivity has to good approximation a fixed value only when the power on the detector is in the same range within factors a few. For larger variations in illumination, responsivity non-linearities can become a major source of uncertainty in the flux calibration. Typical observations affected by non-linearities are:

- multi-aperture photometry. If the source is not point-like then going from a small (e.g. 52″) to a large aperture (of 180″) can easily give a factor 10 increase in power on the detector. Note that the FCS is always tuned according to the brightest flux.
- multi-filter photometry. For example the 11.3 and the 11.5 μm filters have a difference in transmission of a factor 5. On the other hand, targets with steep spectra (like stars) can also cause a high dymanic range in power on the detector.
- maps with high dynamic range. Usually the FCS is tuned accouding to the flux of the brightest source in the map, therefore the photometry of the weaker targets in the map will be biased. The morphology of bright extended sources will be distorted.

5 Uncertainties from background subtraction

There are several ways to subtract the background emission from the (source+background) emission obtained by pointing on target.

- by chopping. The chopper offset/vignetting (section 3.12) and signal losses due to the chopper modulation are introduced during the background subtraction. In OLP7 the default responsivity instead of the FCS measurement is used for the signal conversion to power on the detector. This adds a systematic error.
- by nodding. Assuming that the individual nodding plateaux have sufficiently long integration time (t_{int} > 64 sec) such that responsivity transient uncertainties are minimized, no extra photometric errors are introduced from the background subtraction.

Table 5: Summary of point source photometry methods

Method	statistical error	systematic error	photometric bias
chopping	$\sqrt{2}\Delta a$	ΔR_{def}	$\Delta C, \Delta V, \Delta f_{psf,array}$
nodding	$\sqrt{2}\Delta a$	ΔS_{on}	$\Delta f_{psf,array}$
minimaps	$\sqrt{2}\Delta a/\sqrt{N}$	ΔS_{on}	
mapping	$\Delta a/\sqrt{N}$	ΔS_{on}	$\Delta\Omega_{eff}$
P32 maps	$\Delta a/\sqrt{N}$	ΔS_{on}	ΔC, $\Delta\Omega_{eff}$
on/off pointing	$\sqrt{2}\Delta a$	ΔS_{on},ΔS_{off}	$\Delta f_{psf,array}$

- by separate on-source and off-source observations. The uncertainty depends on whether the same or different instrument settings were used for both observations. In the latter case the statistical and full systematic errors of both AOTs should be added, in the former case only the statistical uncertainties should be added.

- by "minimapping". Many C100/C200 point-source observations were performed by observing a "minimap" in which the source is centred in the map and in which raster parameters are such that all pixels of the C100/C200 array have been centred on target. No extra photometric uncertainties are introduced.

- by general raster mapping. In case the target is randomly positioned in the map one can extract the fluxdensity of sources in several ways: (1) by applying a point source fitting procedure. If the units in the map are in Jy/pixel the peak flux divided by the f_{psf} yields the point source flux. The fitting procedure require assumptions on the shape of a point source, therefore errors are introduced due to uncertainties in the assumed footprint profile. The error is smaller for oversampled maps. (2) by integrating the surface brightness contribution from the source by means of e.g. aperture photometry. The uncertainties are caused by uncertainties in the conversion from point source flux (Jy/pixel) to surface brightness (MJy/ster) which depends on the accuracy of Ω_{eff} the effective footprint solid angle.

- by PHT-32 mapping. This oversampled mapping mode is frequently used to minimize the cirrus confusion. Since a high frequency modulation of the sky brightness by the chopper is involved, signal losses are expected causing an underestimate of the source-background contrast. The error due to signal losses should be added to the flux extraction methods described in the previous point.

References

[1] Schulz B., Huth S., Kinkel U., et al. 1999 in "The Universe as seen by ISO", Eds. P. Cox and M.F. Kessler, proceedings ESA SP-427.

Table 6: explanation symbols:

Symbol	description
Δa	statistical error for one pixel assuming about the same error at different pixels and pointings
N	number of pixels that covered the source
ΔC	uncertainty the signal loss correction for chopped measurements
ΔV	chopper offset or vignetting uncertainty
ΔR	uncertainty in responsivity due to statistical uncertainty in FCS signal
ΔR_{aper}	uncertainty in responsivity due to non-standard aperture for FCS measurement
ΔR_{def}	uncertainty in the default responsivity
ΔR_{lin}	uncertainty in responsivity due to responsivity non-linearities
ΔS_n	systematic error of AOTn propagating from SPD
ΔR_{trans}	uncertainty due to responsivity transients
$\Delta\Omega_{eff}$	error in the effective solid angle
$\Delta f_{psf,array}$	error in the point spread function factor for the whole array
Δf_{psf}	error in f_{psf} for non-standard apertures