PACS Calibration Document

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Introduction

The purpose of this document is to compile all requirements on PACS calibration and, on a high level, the corresponding implementation and analysis procedures in a central file. While the document is the master plan for the in-flight calibration, it addresses also ground-based related issues in order to achieve a complete calibration scheme of the instrument. Therefore, it is also an applicable document for ground tests, beside other relevant documentation like the “PACS Test Plan” (PACS-ME-PL-012). This shall ensure that all necessary prerequisites for in-flight calibration are met, by identifying all calibration activities that can only be done on ground. Furthermore, it will help checking out and optimizing in-flight procedures to some degree already on ground.

The document will also provide an overview on resources, both with regard to implementation efforts as well as observing time estimates per requirement. The assessment of calibration needs and their frequency will provide feedback to AOT and Logic design. The outline of the calibration analysis will provide feedback to the IA design.

Structure of the Document

The major part of the document is organized in the form of requirements which make up individual subsections. As a long term goal a general calibration philosophy shall be developed out of this document. This includes the identification of priorities and cross-links between individual requirements.

Structure of the Requirement Description

Each requirement comprises the following items:

- Label & Title
- Objective
- Fulfilling or fulfilled by (identify cross links)
- Priority (3 classes)
  - A: core part of calibration system
  - B: necessary to achieve required accuracy
  - C: extension of instrument knowledge
- When performed / frequency (including ground tests)
- Required accuracy (driver for CIP design)
- Inputs, prerequisites
- Sources
- Calibration Implementation Procedure (CIP, high level only)
- Estimated time needed (from CIP)
- Calibration Analysis Procedure (CAP, high level only)
- Output, products
- Status / Version (some configuration control, in addition use of Concurrent Version System (CVS))

Grouping of Requirements

The requirements are grouped according to the following scheme:

1) Detector Systems
   - Bolometer Array Cameras
   - Photoconductor Array Cameras
2) Optical Components
   - Filters
   - Grating
   - Chopper
   - Imaging Optics
   - Internal Reference Sources
   - Telescope Pointing Quality
3) Full System Calibration Photometer
4) Full System Calibration Spectrometer
5) Optimized Observing Strategies for AOTs and Scientific Validation of AOTs
6) Cross-Calibration
7) Telescope
8) Space Weather effects
9) Interferences

Group 1) & 2) requirements cover those requirements where module level calibration makes up an essential contribution. These requirements are also driven by inputs needed for AOT logic, time estimator and Observer's Manual. Group 3) & 4) requirements cover the core inflight calibration. Due to their special nature, some requirements are put into separate sections. It is not the task of the PACS team to calibrate the Herschel telescope, on the other hand, detailed information on the telescope system, which has to come from other parties, is needed for the calibration of the PACS instrument. Therefore, from the PACS team side requirements concerning information on the telescope will be put into this section. The section Space Weather effects covers trends due to this factor, the section interferences is not an outline of EMC-type tests, but addressess calibration issues in case certain interferences should occur or remain in space.

Traceability with PACS Instrument Test Plan Items

In order to comply with the perspectives of the ground tests as outlined in Appendix-B of the PACS Instrument Test Plan (PACS-ME-PL-012), a matrix has been set up which associates ILT items with the relevant PCD requirements. The CIP descriptions of the PCD form the basis for the TCL or CUS scripts used for commanding the instrument during the ground tests. The latter ones will be described in a separate document.

ILT CQM Traceability

There are three different classes of test items:

F Functional tests: Their purpose is also to determine instrument set-ups for the calibration measurements.

P Performance tests: The main purpose of these tests is to establish the performance of individual subsystems, in particular after modifications to the instrument or warm-up/cool-down activities. It should be a standardized test sequence which is repeated each time to check the reproducibility or improvements.

C Calibration measurements: Full system calibrations characterizing the photometric, spectroscopic and spatial behaviour of the instrument.

The following two matrices list the relations for the ILT CQM tests for the photometer and spectrometer, respectively.

PACS CQM test - PCD requirements traceability matrix Photometer

CQM test	**PCD requirement**
F1.5 Functional test exercising all ..., sources and detector array read-outs	1.1.1 Control optimum pixel bias settings 1.1.5 Monitor detector temperature variations with time 1.1.6 Calibrate the variation of pixel offset with detector temperature 1.1.7 Monitor cooler recycling frequency 1.1.8 Measure bolometer time constants after switch-on 1.1.10 Measure time constants after a flux change 1.1.11 Measure the low frequency noise 1.1.16 Measure the signal dependence on chopping frequency 1.1.17 Measure the level of optical cross-talk in the detector 1.1.18 Measure the level of electrical cross-talk 1.1.21 Self-calibrate the responsivity of the detectors 2.3.2 Duty cycle of chopper waveforms 2.3.3 Optimum Positioning of chopper on internal reference sources 2.5.1 Temporal stability of PACS calibration sources 2.5.2 Spatial stability of PACS calibration sources 2.5.3 Time constants: heat-up & cool-down times of PACS calibration sources
P2.2 Focus definition	3.1.1 Photometer central pointing position (cf. P2.3)
P2.3 Relative alignment check spectrometer vs. photometer	3.1.1 Photometer central pointing position (cf. P2.2) 1.1.15 Establish the relative positions of the individual matrices
P2.4 Detector Performance	3.2.2 Monitor nominal responsivity variations with time (Monitoring_2 & Monitoring_3b, TBC)
P2.5 Spatial Performance	3.1.2 Relation between chopper position and angular displacement on sky 3.1.4 Photometer Point Spread Function (TBC)
C3.1 Absolute flux-calibration, linearity	3.2.3 Calibrate the photometer's non-linearity ⇒ 3.2.3 3.2.1 Derive photometer nominal responsivity ⇒ 3.2.3 3.2.4 Establish the linearity of the full system ⇒ 3.2.3 3.2.6 Noise and minimum detectable flux
C3.2 Flat-field	3.2.8 Measure the photometer full flat-field ⇒ 3.2.3
C3.3 Point Spread Function	3.1.4 Photometer Point Spread Function
C3.4 Distortion	3.1.3 Photometer Field of View Distortion
C3.8 Ghosts	3.1.5 Photometer Ghosts
C3.9 Stray light (ghosts)	3.1.6 Photometer Straylight
C3.10 Detector time response, stability	3.2.2 Monitor nominal responsivity variations with time
C3.11 Definition of PACS pass bands with TUFIR	3.2.5 Relative system response and colour corrections
C3.12 AOT Try-out & sensitivity	5.1.1 Optimized Observing Strategy for Photometry of Small Sources on external PS with decreasing contrast

PACS CQM test - PCD requirements traceability matrix Spectrometer

CQM test	PCD requirement
F1.5 Functional test exercising all ..., sources and detector array read-outs	1.2.1 Optimum detector bias settings 1.2.2 Optimum detector temperature settings 1.2.3 Dynamic range per selected integration capacitor ⇒ 1.2.11 1.2.6 Detector dark current 1.2.8 Signal dependence on chopper frequency 1.2.11 Linearity of CRE read-out 1.2.16 Time constant: switch-on spectrometer 2.3.2 Duty cycle of chopper waveforms 2.3.3 Optimum Positioning of chopper on internal reference sources 2.5.1 Temporal stability of PACS calibration sources 2.5.2 Spatial stability of PACS calibration sources 2.5.3 Time constants: heat-up & cool-down times of PACS calibration sources
P2.2 Focus definition	4.1.1 Spectrometer central pointing position and grating alignment (cf. P2.3)
P2.3 Relative alignment check spectrometer vs. photometer	4.1.1 Spectrometer central pointing position and grating alignment (cf. P2.2)
P2.4 Detector Performance	4.3.4 Flux reproducibility external sources, spectrometer (TBC)
P2.5 Spatial Performance	4.1.3 Spectrometer Point Spread Function (TBC)
P2.6 Spectral Performance	4.2.1 Grating wavelength calibration (selected λ, TBC) 4.3.8 Relative Spectral Response Function, spectrometer (selected λ, TBC)
C3.1 Absolute flux-calibration, linearity	4.3.1 Absolute flux calibration internal sources 4.3.3 Absolute flux calibration external sources ⇒ 4.3.1 4.3.5 Linearity with flux 4.3.6 Minimum detectable flux, spectrometer
C3.2 Flat-field	4.3.9 Flat-field spectrometer internal sources ⇒ 4.3.8 4.3.10 Flat-field spectrometer external sources
C3.3 Point Spread Function	4.1.3 Spectrometer Point Spread Function
C3.4 Distortion, grating alignment	4.1.1 Spectrometer central pointing position and grating alignment (cf. P2.3) 4.1.2 Spectrometer Field of View Distortion
C3.5 Relative Spectral Response Function	4.3.8 Relative Spectral Response Function, spectrometer
C3.6 Wavelength-calibration	4.2.1 Grating wavelength calibration
C3.7 Instrumental profile	4.2.2 Grating instrumental profile
C3.8 Ghosts (TUFIR)	4.1.4 Spectrometer Ghosts 4.2.4 Spectral Ghosts
C3.9 Stray light (ghosts) (TUFIR)	4.1.5 Spectrometer Straylight
C3.10 Detector time response, stability	4.3.4 Flux reproducibility external sources, spectrometer 4.3.2 Flux reproducibility internal sources, spectrometer ⇒ 4.3.4
C3.11 Definition of PACS pass bands with TUFIR	4.2.3 Spectral Purity
C3.12 AOT Try-out	5.2.2 Optimized Observing Strategy for Range Spectroscopy on external PS with decreasing contrast (TBC) 5.2.1 Optimized Observing Strategy for Line Spectroscopy

Calibration Plan

There is, with some freedom, a logical order how to arrange the measurements related to individual requirements. This is determined by:

1) Priority and prerequisites
2) Mutual dependence
3) Available calibration sources (at various test sites)
4) Calibration frequency (e.g. for reproducibility assessment)

Calibration Plan for CQM ILT

The detailed development of the Calibration Implementation Procedures has shown that a strong driver for the measurement sequences is minimizing overhead times due to stabilisation times of calibration sources. This makes it even necesary to interlace measurements belonging to different implementation procedures but utilizing the same calibration source set-up.

For the CQM ILT we assume currently that it is exclusively performed at MPE utilizing Optical Ground Segement Equipment (OGSE) internal and external calibration sources. These are:

1) OGSE internal BlackBodies (OGSE BB), extended emission
2) External BB (ext. BB) or hot plate in combination with a hole mask on a xy(z) stage simulating (movable) point sources
3) Water vapour cells in front of a hot plate producing absorption line spectra

These optical stimuli are described in detail in the PACS Cryo Test Equipment and OGSE Specification document (PACS-ME-DS-002).

Tests in combination with a Tunable FarInfared (TUFIR) laser source are TBD for CQM ILT.

In addition the PACS Internal Reference Sources (Int. CalSource) are used.

The following two tables list the measurement sequences for the photometer and spectrometer, respectively. The current PACS Master Schedule (scenario after CM#20) foresees that the CQM calibration of the two subinstruments will be performed during two different periods, starting with the spectrometer calibration. An exception is the AOT try-out which will be done together for both photometer and spectrometer at the very end of the test period.

A special test item are irradiation tests. These will be performed on detector module level. See introduction to section 1.2 and reqs. 1.2.12 – 1.2.15, 1.2.18 – 1.2.20., 1.2.22 – 1.2.23 for more details.

Sequence of measurements for CQM testing
Spectrometer calibration

PCD req./title	duration	sources
1.2.6 Detector dark current in combination with 1.2.2 Optimum detector temperature settings (1)	1 h	none OGSE dark pos.
1.2.1 Optimum detector bias settings in combination with 1.2.2 Optimum detector temperature settings (2)	4 h	OGSE BB or Int. CalSourc
1.2.3 Dynamic range per selected integration capacitor 1.2.11 Linearity of CRE read-out * depending on number of settings	8–30 h*	OGSE BB
4.1.1 Spectrometer central pointing position and grating alignment	TBD	ext. BB & xy stage & hole mask
4.2.1 Grating wavelength calibration	2-3 h	water vapour cell
4.2.2 Grating instrumental profile	2(?) h	water vapour cell
(4.3.4, 4.3.8, 4.3.5, 4.3.1, 4.3.6 may be ONE BLOCK with interleaving measurements per common OGSE BB Temp. to increase efficiency of sequence)		
4.3.4 Flux reproducibility external sources (incl. 4.3.2 Flux reproducibility internal sources)	TBD	OGSE BB +Int. CalSourc
4.3.8 Relative Spectral Response Function (incl. 4.3.9 Flat-field spectrometer internal sources)	2(?) h	OGSE BB +Int. CalSourc
4.3.5 Linearity with flux	TBD	OGSE BB
4.3.1 Absolute flux calibration internal sources (incl. 4.3.3 Absolute flux calibration external sources)	TBD	OGSE BB
4.3.6 Minimum detectable flux spectrometer	TBD	OGSE BB
4.3.4 Flux reproducibility external sources (incl. 4.3.2 Flux reproducibility internal sources)	TBD	OGSE BB +Int. CalSourc
4.1.3 Spectrometer Point Spread Function	TBD	ext. BB & xy(z) stage & hole mask
4.3.10 Flat-field spectrometer external sources	TBD	ext. BB & xy(z) stage & hole mask
in combination with 4.1.2 Spectrometer Field of View Distortion (4.1.2 may fulfill 4.3.10)	TBD	TBD
5.2.2 AOT try-out and sensitivity: “range spectroscopy” (includes responsivity monitoring)	TBD	ext. BB & xy(z) stage & hole mask (vary contrast)
5.2.1 AOT try-out and sensitivity: “line spectroscopy” (includes responsivity monitoring)	TBD	water vapour cell (vary abs. line strength)

Sequence of measurements for CQM testing
Photometer calibration

PCD req./title	duration	sources
1.1.7 Monitor cooler recycling frequency	TBD	none
Cooler ready 3.2.2 Monitor nominal responsivity variations with time	 TBD	 int. CalSourc
3.1.1 Photometer central pointing position	TBD	ext. BB & xy(z) stage & hole mask
3.1.2 Relation between chopper position and angular displacement on sky	TBD	TBD
3.2.2 Monitor nominal responsivity variations with time 3.2.1 Photometer nominal responsivity 3.2.3 Calibrate photometer's non-linearity 3.2.4 Establish linearity of full system 3.2.8 Measure photometer full system flat-field **(3.2.1, 3.2.3, 3.2.4, 3.2.8 is ONE BLOCK including further responsivity monitoring on Int. CalSourc)** 3.2.2 Monitor nominal responsivity variations with time	11 h (whole block)	int. CalSourc OGSE BB int. CalSourc
3.2.6 Noise and minimum detectable flux (1.1.12)	TBD	OGSE BB
1.1.7 Monitor cooler recycling frequency	TBD	none
3.1.4 Photometer Point Spread Function	TBD	ext. BB & xy(z) stage & hole mask
3.1.3 Photometer Field of View Distortion	3 h	ext. BB & xy(z) stage & hole mask
3.2.2 Monitor nominal responsivity variations with time	TBD	int. CalSourc
5.1.1 AOT try-out and sensitivity: "small source" measurement (includes responsivity monitoring)	TBD	ext. BB & xy(z) stage & hole mask (vary contrast)

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DOCUMENT CHANGE RECORD

Version	Date	Changes	Remarks
Draft 0	07-Dec-2001	–	New document.
Draft 1	20-Dec-2001	all	Sections 1–4 & 9 Inputs from 12/13-Dec meeting at MPE included.
Draft 2	18-Feb-2002	medium	Sections 1–4 & 9 missing requirements of first consolidated list included. Addition of some introductory remarks. Full CVS control. Input to IBDR.
Draft 3	23-Sep-2002	medium	Section 1.1 revised following first bolometer tests Sections 1.2, 2.3 & 2.5 upgrade
Draft 4	07-Feb-2003	medium	CQM high-priority reqs. defined at ICC#14 (sections 3.1, 3.2, 4.2, 4.3) upgrades in section 1.2, upgrades in section 6.1 (cross-cal).
Draft 5	02-Apr-2003	medium	CQM high-priority reqs. defined at ICC#15 (sections 3.1, 3.2, 4.2, 4.3) upgrades in sections 1.1, 2.3
Draft 6	18-Jun-2003	medium	CIPs & CAPs for more CQM high-priority reqs. (sections 3.2, 4.1, 4.2, 4.3) restructuring of Introduction section and inclusion of CQM test traceability matrixes and CQM measurement sequences upgrades in section 5 (AOT optimization) in line with AOT design brainstorming
Draft 7	30-Sep-2003	medium	CIPs & CAPs for more CQM reqs. (sections 1.2, 2.5, 3.1, 4.1) updates for irradiation tests of Ge:Ga at CRC-UCL (section 1.2) upgrade of CQM test traceability matrixes and CQM measurement sequences

Contents

Chapter 1

Detector Systems

1.1 Bolometer Arrays

It is not the purpose of this introduction to describe the general principles of bolometers, but rather to mention the specific properties of the PACS bolometer arrays that lead to specific calibration requirements.

One of the most specific aspect of the PACS bolometer arrays is that they will not be temperature-controlled. The focal plane will be brought to its operating temperature (300 mK) by the cooler, but there will be no active control to maintain this temperature. The slow drift of the focal plane temperature that will result will imply that there will be a slowly changing offset to all signals read from the thermometers placed on each pixel. In principle this offset drift should be fully predicable from the temperature measured on the focal plane. Verifying this is the aim of one calibration requirement.

To avoid relying on this too heavily, The PACS bolometer arrays are however equipped with two rows of blind pixels. These pixels are identical to the other pixels of the array with two exceptions: (1) they are closed on top so that they cannot receive light directly, and (2) they also have a heater implanted. At the start of any observation, the heater of each blind pixel is set so that their output signal is at the same level as that of the pixels seeing the sky. Their offset drifts should therefore be the same. As the readout process consists of differentiating the sky signal with both the blind pixel signal and a reference voltage, the temperature drift should be removed. More precisely, the normal readout process is the following: we first subtract a common reference signal to both both blind and “sky” pixels’ signals, and then make the difference between “sky” and blind pixels. Note that there is a possibility to cancel this differentiation and downlink the absolute signal from either the blind pixels, the sky pixels or the reference voltage. This facility will have to be used to investigate the drifts, and will be only accessible for calibration.

It is also worthwhile to mention that the blind pixels offer a way to directly derive the mean absorption efficiency of the detectors (i.e. the ratio of absorbed to infalling power), provided that the calibration sources are stable or that their power output can be accurately computed. Laboratory experiments have shown that the MOS circuits used to read the pixels (one per pixel) are very uniform over the arrays. Therefore any difference between the signal read on a pair of pixels is attributable to a difference in absorbed power between the two pixels. Thus when power falls on the “sky” pixels, the difference in readout voltages between “sky” and blind pixels (once the reference voltage has been removed) is due to the lack of power falling on the blind pixels. One can adjust the current injected in the blind pixels so that the readout voltage matches that of the “sky” pixels (on average). Once this is done, the product of the injected current and readout voltage on the blind pixels gives the mean power absorbed by the “sky” pixels. Dividing by the power that falls on the detector, for instance from the calibration sources, gives a way of measuring, or at least monitoring the detector absorption efficiency.

Another particular aspect to consider with the PACS bolometer arrays is their non-linearity: as the detection is basically a measure of the temperature, the larger the mean temperature, the smaller the increment of signal per increment of temperature. Over the whole operating range permitted by the bolometers, this non-linearity is very large. It will have to be calibrated to allow the measurement of very bright sources. However the main operating mode of the bolometer will be to measure relatively faint sources over the strong telescope and sky backgrounds. In that case it is expected that a linear approximation will be correct. Yet we will have to measure over which flux interval this approximation is correct.

Finally, one should remember that the time constants of the bolometer are rather short (10-20 ms). They are thus too short to be measured in the normal operating mode of the detector (where frames are summed on-board). In order to be able to measure them, a special read-out process exits where all readouts from a subsample of the pixels are down-linked. This mode will only be accessible for calibration.

Req. 1.1.1 Control optimum pixel bias settings

Objectives

The optimimum bias for the bolometer matrix pixels will be determined from ground-based calibrations, to achieve the best sensitivity when exposed to a typical sky background. These levels have to be determined on the ground and checked in-flight. Note that during at the module level (i.e. when we test the arrays prior to their integration in the instrument) we will not be able to accurately reproduce the radiation spectrum that the bolometers will see in space.

Fulfilling or fulfilled by

Self-standing

Priority

A

When performed / frequency

- Bias levels will be set during ground based calibrations, both at the module level and at the instrument level.
- Bias levels will be controlled in-flight every 2s by the health-monitoring on-board software.

Required accuracy

Not applicable.

Inputs, prerequisites

Science performance requirements to set the sensitivity objectives, prescriptions on the typical background and SED that the bolometers will be exposed to.

Sources

Calibrated black-bodies for ground-based tests (with or without chopper to modulate the signal). Standard stars or possibly the internal sources during the mission.

Calibration Implementation Procedure (CIP)

To determine the optimum biases, use a calibrated source and measure the noise level of the bolometers exposed to this source. Adjust the pixel biases so that the system gain is maximized while keeping the noise level within the specification. This includes also provision to make sure that no extra sources of noise are added. These biases should also allow for the existence of a relatively large linear operating range.

Estimated time needed

Not Applicable

Calibration Analysis Procedure (CAP)

Output, products

The table of optimum pixel bias. Possibly a set of tables for to account for different expected levels of background.

Status/version

Revised for draft 3 of the PCD

Req. 1.1.2 Nominal responsivity

Objectives

The responsivity is the essential calibration factor between the measured output voltage of the readout circuit and the incident illumination power onto the detectors. The responsivity of the bolometers may be affected by cosmic particle hits, it may vary in time due to aging of the detector or modification of the operating temperature. It can also change because of a modification of the mean background level on the detector (the bolometers are non-linear detectors). The nominal responsivity value is determined for a given mean background level and range of observable fluxes.

Note that during the module tests (i.e. when the detectors are not yet included in the instrument), we will not be able to expose the bolometers to a radiation spectrum similar in SED to the one they will see in operations. Also during these tests, what will be measured is the responsivity of the detectors alone. This will be different from the responsivity of the full system (see corresponding requirement).

Fulfilling or fulfilled by

Self-standing.

Priority

A

When performed / frequency

- during individual detector tests
- during ILT
- during PV

Required accuracy

$<$ 5% (goal)

Inputs, prerequisites

- Relative system response to derive in-band power from source spectrum.
- Definition of the operating background level

Sources

- Ground: Black-body sources
- Flight: celestial standards
- Flight & Ground: Internal calibration sources. They are specified with a stability of ΔT/T$< 10^{-4}$, which should be enough for our purposes.

Calibration Implementation Procedure (CIP)

In general this measurement is done by illuminating the detectors with a well determined in-band power and measure the output voltage. As the bolometers are operated differentially, here it will most likely consist of measuring a given power step over a background. And since the detectors are not linear, we will need to specify both the power step and the background level.

Estimated time needed

Calibration Analysis Procedure (CAP)

Output, products

Nominal responsivity table, possibly given for various levels of the mean illumination since the detector is non-linear.

Status/version

Revised for draft 3 of the PCD

Req. 1.1.3 Measure sensitivity variations inside the pixel

Objectives

To investigate the existence of sensitivity variations of a given pixel depending on the exact location where the peak of the flux falls. Although the size of the pixel with respect to the PSF should allow for an almost always nominal sampling, we cannot exclude these variations, especially for instance when the peak of the source falls very close to the pixel wall (since the wall's thickness is not negligible with respect to the pixel's width). These sensitivity variations, if they exists, modify the PSF, which in turn may have some impact on our photometric calibration.

Fulfilling or fulfilled by

At the full-system level, this will be fulfilled by the characterization of the detector PSF requirement (Req. 3.1.4 Photometer Point Spread Function).

Priority

B (could be C because it is hard to make).

When performed / frequency

In principle, this should start at the module level. However SAp does not foresee the availability of point sources in their local test equipment. In that case, this measurement will only be done at a later stage.

Required accuracy

$<$20% should be enough.

Inputs, prerequisites

none.

Sources

A point source delivering a constant power.

Calibration Implementation Procedure (CIP)

Perform rasters around a point source with sub-pixel or non-integer multiple of pixel step sizes. Note that due to the various pointing uncertainties during operations, we will probably have to solve simultaneously for the actual pointing and the sensitivity variation (this is in fact the PSF measurement CIP).

Estimated time needed

Calibration Analysis Procedure (CAP)

Output, products

A map of the sensitivity variation inside a pixel (more a typical map than an average since we will not be able to make this measurement for all pixels).

Status/version

Revised for draft 3 of the PCD.

Req. 1.1.4 Monitor Nominal Responsivity Variations with Time

Objectives

Although Herschel does not have a fast orbit, we could expect a variation of the nominal responsivity (measured under constant illumination conditions) with such parameters as the time since last activation of the instrument, last recycling of the cooler, glitch rate, etc…

Fulfilling or fulfilled by

Self-Standing. Photometric calibration measurement will probably not be done frequently enough to monitor that variation.

Priority

B

When performed / frequency

At the module level tests, since after that we will not be able to adress the detector individually (it will be included in the instrument and thus we go to the full system section). Since we can expect to have variations in many of the test equipment subsystems, we will probably only get an indication of the possible responsivity variations at the detector level.

Required accuracy

$<$ 5% (goal). This accuracy is driven by the final photometric accuracy we are aiming at.

Inputs, prerequisites

The nominal value of the responsivity.

Sources

Black-body sources. One could use the internal calibration sources as their specifications makes them stable enough for that purpose ($\Delta\mathrm{T}/\mathrm{T} < 10^{-4}$). However relying only on those implies that the detectors are already included in the complete instrument in which case we are dealing with a full-system requirement.

Calibration Implementation Procedure (CIP)

Repeat Nominal Responsivity measurements at predetermined points in time after *e.g.* switch-on, cooler recycling, …

Estimated time needed

Calibration Analysis Procedure (CAP)

Output, products

Responsivity correction factors as a function of elapsed time since determined events (switch-on, solar storm, etc…).

Status/version

Revised for draft 3 of the PCD.

Req. 1.1.5 Monitor detector temperature variations with time

Objectives

After recycling, the temperature provided by the cooler will slowly increase. Since the detector's temperature is not controlled, this will result in a slow increase of the detector's temperature (expected increase of temperature is 25 mK over the 46 hr of cooler operations). In turn this slow drift of the temperature produces a change in the offset of the signal delivered by each pixel. Since the whole instrument is temperature controlled, we do not expect that processes such as solar aspect angle will affect the temperature of the detector. We stress that this is mostly a monitoring activity since the effect of a temperature drift is taken away by the differential readout process using the blind pixels.

Fulfilling or fulfilled by

Temperature of the detector is measured every 2 s and transmitted in the housekeeping data.

Priority

B

When performed / frequency

A soon as a focal plane is available.

Required accuracy

$\sim$1 mK since the total expected temperature drift over the 46 hr hold-time of the cooler is 25 mK.

Inputs, prerequisites

None.

Sources

Not applicable.

Calibration Implementation Procedure (CIP)

Trend analysis of the housekeeping data.

Estimated time needed

Monitoring activity.

Calibration Analysis Procedure (CAP)

Output, products

None apart from specification on the reproducibility of the temperature drifts, and alerts when the drifts are faster and/or of larger amplitude than expected.

Status/version

Draft version, revised after the December 01 meeting.

Req. 1.1.6 Calibrate the variation of pixel offset with detector temperature

Objectives

The variation of the detector temperature results in dramatic changes of the pixel offsets. This is taken care of by the differential readout process where the signal from sky pixels is subtracted from that of blind pixels. However we will want to calibrate the variation of the pixel offset with temperature in order to be able to identify possible problems affecting individual pixels. It remains to be investigated whether the compression scheme is adequate to transfer frames with a mean value far different from 0, as would be the case here since no differenciation is done.

As side notes, let us add that there are two rows of blind pixels at the bottom of each matrix. For each column of sky pixels, the blind pixel signal is taken from the two blind pixels present in the same column. We are currently wondering whether to use the two blind pixels (the first one for the first 8 sky pixels, and the second one for the rest) or use only the pixel in the first row to protect ourselve from optical cross-talk. Also some of the blind pixel signal could be placed in the standard telemetry for checking purposes, but we have to make a choice: the rate of blind pixel readout is 640 Hz while the telemetry rate is 0.5 Hz.

Fulfilling or fulfilled by

Self-standing

Priority

B

When performed / frequency

Can start at module level tests, although we may only be able to get a first idea of the trend as (1) long measurements are always complex in ground-based test facility, and (2) there are many sources of perturbation on the ground.

Required accuracy

A few % on the drift amplitude over a timescale typical for a PACS observation.

Inputs, prerequisites

None.

Sources

Controlled illumination level to minimize all other sources of drifts. We could use the internal calibration sources since their stability specification appears adequate ($\Delta \mathrm{T}/\mathrm{T} < 10^{-4}$).

Calibration Implementation Procedure (CIP)

This will require switching the read-out mode of the bolometer from its standard mode where differenciation occurs on-board, to the transmission of only the sky signal or only the blind signal (both are possible).

Estimated time needed

Most likely a long term activity as the drifts are slow. Assuming in a first approximation that constant, one could break down that measurement into smaller one conveniently placed in a longer period of time.

Calibration Analysis Procedure (CAP)

Output, products

Parameterized fits for the drifts, with assessment of uniformity over the bolometer matrices and especially between blind and sky pixels.

Status/version

Revised for draft 3 of the PCD.

Req. 1.1.7 Monitor cooler recycling frequency

Objectives

The internal cooler ensures that the bolometers operate at the required temperature. It has to be regularly recycled to function. The recycling frequency is basically related to the rate at which the detectors heat due to various processes. Measurement and monitoring of this frequency is essential (1) to define the typical length of a feasible astronomical observation, and (2) to make sure that the instrument is in a correct health situation. The nominal hold-time for the cooler is 46 hr, with a 2 hr recycling time, making for a 48 hr cycle.

Fulfilling or fulfilled by

The information needed will be present in the instrument housekeeping data.

Priority

A

When performed / frequency

A soon as a focal plane is ready but will have to be done again in-flight to reflect the fundamental change of operating conditions. Note that neither at the module level test nor at the instrument level test, will we be able to actually check that the cooler cycle length is 48 hr. In both cases the hold-time of the test equipment is smaller.

Required accuracy

not applicable

Inputs, prerequisites

Documents describing the normal operations of the cooler (*e.g.* nominal hold time, . . .).

Sources

Not applicable.

Calibration Implementation Procedure (CIP)

Monitor temperature information in the housekeeping data that triggers cooler recycling. Monitor the evolution of the mean time between cooler recycling as a function of the epoch.

Estimated time needed

Not applicable, monitoring activity.

Calibration Analysis Procedure (CAP)

Output, products

Mostly a green light indicating that cooler operations are nominal, or an alert to investigate a potential problem.

Status/version

Draft version, revised after the December 01 meeting.

Req. 1.1.8 Measure bolometer time constants after switch-on

Objectives

During normal operations, the instrument will be regularly switched on and off (mostly to allow the cooler to recycle, and when HIFI is used). This process may generate long-term variations of such quantities as the bolometer gains, or offset drifts. The time constants for these variations will have to be measured in order to define the minimal time after switch-on at which operations can start, or correct for the drifts.

It is expected that the value of these time constants are such that 30 min after switch-on, the detector is in its nominal operating mode. The transtion time from switch-on to nominal mode can thus be absorbed within the cooler recycle time.

Note that in some cases, it may be difficult to trace drifts to the switch-on process as a number of other sources may lead to drifts in the detector properties.

Fulfilling or fulfilled by

Switch-on of the detector will always occur. Monitoring the detector during that time is also likely to occur at all times.

Priority

A. Needed at least to define when to start using the instrument after switch-on and to validate that the cooler recycle time covers the establishment of a nominal regime for the detector.

When performed / frequency

Measurements can be done as soon as we have an operating model of a focal plane. They will have to be repeated each time a new model of the instrument becomes available, and of course after launch. Possibly they should be repeated regularly to monitor the health of the instrument.

Required accuracy

One of the accuracy driver is the one we achieve on the nominal responsivity. Another driver is the one we achieve on the calibration of offset drifts with respect to detector temperature.

Inputs, prerequisites

None.

Sources

We will need a source of constant flux to monitor the detector noise and responsivity. This could be the internal calibrators as they are stable enough, or a reference section of the sky. There is one caveat to the use of internal calibrators: after their own switch-on, they have a time constant of $\sim$15 min. If they are switched off, or if the detector switch-on is too close to the internal calibrators one, then they cannot be used for this requirement.

Calibration Implementation Procedure (CIP)

Switch on the instrument while observing a reference, preferably extended, source of light. The exact observing mode will have to be determined taking into account the constancy of the different backgrounds and foreground.

Estimated time needed

1/2 hr to 1 hr to completely follow the settling of the detector to its nominal settings.

Calibration Analysis Procedure (CAP)

Output, products

Either provision of minimal operating time after switch-on or correction tables as a function of time since switch-on.

Status/version

Revised for draft 3 of the PCD

Req. 1.1.9 Measure time constants after cosmic ray impact

Objectives

The expected cosmic ray hit rate is currently estimated at 1 impact per pixel every 10 minutes (TBC). Though this is not very large, we will have to investigate the effect of these impacts on the detector and in particular see how long the detector takes to relax to its nominal state after a glitch. Current computations indicate that the time constants for the relaxation are very fast (typically 10-20 ms). Measuring them will require operating the detector in a degraded mode, where no coaddition of frame is done and only a subset of the array is downlinked.

Fulfilling or fulfilled by

Self-standing since it requires a dedicated operating mode for the instrument.

Priority

A. It is of priority A to check that the time constants are indeed very short and that the hit-rate is as expected. It is of priority B to actually measure the time constants since currently we probably do not need to correct for glitches, but will simply remove or mask the affected readouts.

When performed / frequency

Prior characterization on the ground is preferrable, although it may be hard to implement during the ground-based calibrations. A detector similar to the PACS detector will be exposed to an accelerator beam.

Required accuracy

$<$10-20% on the time constant should be sufficient.

Inputs, prerequisites

none.

Sources

Sources of radiation are not the most important aspect of this requirement. However it is preferable to make this measurement while observing a source of constant illumination to minimize all possible variation sources. The internal calibration sources are perfectly suitable for that.

Calibration Implementation Procedure (CIP)

Observe a source of constant illumination, switch the detector readout mode to the degraded mode where all frames from part of the arrays are downlinked.

Estimated time needed

Integrate until sufficient glitch statistics have been accumulated (depends on the actual glitch rate and the number of pixels that can be downloaded).

Calibration Analysis Procedure (CAP)

Output, products

- The range of values for the pixel time constants (as they may differ from pixel to pixel and we may not be able to measure them all).
- A prescription on how to handle glitched data (discard or correct).
- An estimation of the noise component due to glitch impacts.

Status/version

Draft version, revised after the December 01 meeting.

Req. 1.1.10 Measure time constants after a flux change

Objectives

Although the bolometers are fast detectors, flux changes, such as those induced by chopping, are not immediately followed by a corresponding change in the read-out value. We will need to measure the value of these time constants to estimate the highest possible chopping frequency as well as the fastest scan speed. We will also investigate whether the time constants are identical for an increasing or a decreasing flux change. Finally the dependence of these constants on the amplitude of the flux step will be characterized.

Currently these time constants are estimated to be in the range 10-20 ms. This is too fast to be measured in the normal operating mode of the detector where frames are coadded on board so we will need to operate in degraded mode where all frames are downlinked but only for a subset of the array.

Fulfilling or fulfilled by

Self-standing since it requires a special operating mode for the detectors.

Priority

A. We need to know these constants to correctly design the observing templates.

When performed / frequency

As soon as detectors are available as this is a key element in the design of the observing templates. Will have to be monitored regularly, including in-flight to detect possible changes in these time constants.

Required accuracy

$<$10-20% on the time constant value should provide enough information.

Inputs, prerequisites

none

Sources

At least two different levels of illumination. More would be better to investigate the dependance of these time constants on the flux level.

Calibration Implementation Procedure (CIP)

Select a region with varying flux levels and chop between two areas. On the ground, this can be done by applying a series of grey filters to a black-body, or by using a chopper in front of a black-body source. We should take care of exploring as many conditions as possible, i.e. amplitude of the flux step, length of the dwelling time on each flux level. It is probably better not to use the internal sources as to go from one source to the other requires going on the sky and thus the flux history may become quite complex. We need to simplify the flux history to the maximum in order to control the experiment. We will also need to switch the instrument to a degraded mode where all the frames are downlinked for a subset of the array in order to see the time constant.

Estimated time needed

Probably quite long if we want to investigate different flux levels.

Calibration Analysis Procedure (CAP)

Output, products

Mostly prescription on the observing templates.

Status/version

Revised for Draft 3 of the PCD.

Req. 1.1.11 Measure the low frequency noise

Objectives

The low frequency component of the noise is important to measure because it has impact on the ultimate sensisitivity that can be reached with PACS and also on the design of the observing templates (*e.g.* it defines the longest chopper plateau available). Its behavior also needs to be characterized as this has impacts on the data reduction strategy.

To be able to fulfill this requirement, we will need to have a definition of how low frequency is "low frequency noise". To low frequencies may not be reachable in the lab, or in space.

Fulfilling or fulfilled by

Typically this requires very long measurements to be done so this requirement can be fulfilled by the "time constant after flux change" requirement (Req. 1.1.10), although it may turn out that the design of the measurement is no longer compatible with that requirement.

Priority

A. But difficult to measure.

When performed / frequency

As soon as a focal plane is available. To be repeated with all instrument models that have detectors in them as well as in-flight. Since measuring that component of the noise requires a very quiet laboratory environment and long measurement, it is not clear that it is technically feasible on the ground.

Required accuracy

Inputs, prerequisites

None.

Sources

Stable source, preferably flat. The internal calibration sources can be used for that as their stability specification is strong enough.

Calibration Implementation Procedure (CIP)

Perform a chopped observation with increasingly long chopper plateaux and measure the evolution of the noise level as a function of the chopper plateau. This CIP has to be validated when all other sources of noise are known to make sure that it can indeed reach the objectives of the requirement.

Estimated time needed

Can be quite long (hopefully) as this depends on the actual spectral distribution of the noise.

Calibration Analysis Procedure (CAP)

Output, products

Prescription on the observing modes. Limit on the ultimate sensitivity.

Status/version

Revised for draft 3 of the PCD.

Req. 1.1.12 Measure the bolometers noise equivalent power (NEP)

Objectives

The Noise Equivalent Power (NEP) is a crucial piece of information that is usedto estimate the science capacities of the instrument. The NEP will must be measured as early in the development of the instrument as possible to allow for efficient science planning and for the development of such tools as the time estimator. This NEP must also be determined under typical operation conditions. The NEP should be measured separately for the blind and the sky pixels to obtain the best handle on the different noise sources. One could also measure the noise level on the reference polarisation (output voltage from the bolometer), however, by doing so one risks adding additional noise on the line that sets this polarisation.

Fulfilling or fulfilled by

Self-standing.

Priority

A. Mandatory for science planning

When performed / frequency

Measured as soon as detectors become available, then for each instrument model containing detectors. Measured again regularly in-flight to check for possible degradations of the detector quality.

Required accuracy

Driven by the requirement on the achieved photometric accuracy.

Inputs, prerequisites

The following inputs are needed to properly prepare the CIP.

- The non-linear region of the detecotr response (PCD requirement 1.1.13).
- The time-constant after a flux change (PCD requirement 1.1.10).
- The 1/f noise (PCD requirement 1.1.11)

Sources

Two calibrated illumination sources that provide a constant (with time) level of input flux. Either the OGSE blackbodies or PACS internal calibrators are adequate for this purpose.

Calibration Implementation Procedure (CIP)

In a nutshell, one requires a well-calibrated illumination source, knowledge about the optical throughput of the instrument and detector efficiencies to estimate the NEP. When the optical throughput of the instrument is not well-known – as is expected to be the case for PACS OGSE –, the NEP is typically measured in laboratories by chopping the bolometer between a “cold” and a “hot” source. Provided the relative and absolute source fluxes are known, the differenced signal between the “hot” and “cold” source is used to calibrate the instrument and proceed with NEP estimation. Fortunately, two such sources are available with PACS (two grey-body calibration sources) and in the OGSE (two black body sources). Either pair of illuminators is sufficient for this experiment. For ground-based measurement, the OGSE setup is more practical while the internal calibrators are better suited for in-flight measurements.

To measure the NEP, one calibrator should be set to about 70 K (TBC), or close to ambient telescope temperature. The second blackbody should be set to 90 K (TBC). The chosen setting must provide flux levels that avoid the non-linear region of the detector’s dynamic range (input from PCD 1.1.13). The settings should be changed or tweaked to ensure this is the case. The bolometer is chopped between the two flux sources. The minimum integration time for each pointing is set by the time-constant after a flux change (input from PCD 1.1.10) and should be chosen to avoid non-linear part of the response and to allow the bolometer signal to stablize. The maximum integration time for each pointing should be such that 1/f noise does not become significant (input from Req. 1.1.11). The integration time per pointing which satisfies both these requirements thus determines the chopping frequency. Repeat the measurements for both blue filters.

The CIP described here is for a simple chopped observing, which is likely to be the most commonly employed observing mode. However, the achieved Signal-to-Noise Ratio (SNR), and hence the NEP, will likely change is the observing mode is changed. Thus, the measurements must be repeated for each of the other observing modes of PACS for the detector subsystem. The CAP for each observing mode (see below) will remain the same.

Estimated time needed

Calibration Analysis Procedure (CAP)

The following expression can be derived from the definition of the NEP (see e.g. Rieke 1996):

$$\mathrm{NEP} = \frac{P_s (2T)^{1/2}}{S/N}$$

Where, P_s is the (calibrated) signal power incident on the detector, T is the integration time, and S/N is the measured signal-to-noise ratio of the detector.

The S/N actually achieved for a given P_s will likely depend on specific measurement strategies. This expression thus allows a relative NEP comparison between different PACS observing modes.

If the input signal is uncalibrated, then the (known) relative difference between the “hot” and “cold” calibrator must be used to calibrate the input signal.

Output, products

Values of the NEP for the different instrumental set-ups.

Status/version

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$Revision: 1.3 $
$Date: 2003/02/07 10:21:33 $
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Req. 1.1.13 Calibrate the detector non-linearity

Objectives

For large flux dynamics, the bolometer arrays are highly non-linear (the higher the flux level, the smaller the measured signal for a given input). We need to make sure this non-linearity is well calibrated although we will try to operate in regions of flux where a linear approximation is correct. This non-linearity calibration will have to be used when observing very bright sources (possibly planets) and even some of primary calibrators (Uranus inputs as much power on the array than the background).

Fulfilling or fulfilled by

Self-standing but restricted to the module level tests since after that the detector cannot be addressed independently of the full system.

Priority

A. We need to establish the non-linear behavior before we determine the operating flux dynamics.

When performed / frequency

As soon as detectors become available.

Required accuracy

Driven by the photometric accuracy we wish to achieve.

Inputs, prerequisites

None

Sources

a set of sources with well-known fluxes covering a representative dynamical range, as well as a set of background levels covering a very wide dynamical range.

Calibration Implementation Procedure (CIP)

Observe with an identical set-up a series of sources covering a range of input fluxes over a wide range of background levels.

Estimated time needed

Calibration Analysis Procedure (CAP)

Output, products

For each pixel a relative linearisation curve. These curves are normalized to give 1 for the range of fluxes we will have selected as the operating range.

Status/version

Draft version, revised after the December 01 meeting.

Req. 1.1.14 Establish the detector linearity

Objectives

Although the detector is globally non-linear, for small flux changes around a mean value, it can be considered as linear. In principle we will work under this linearity assumption. We will therefore verify that for the expected range of observed fluxes, the detector indeed behaves linearily.

Fulfilling or fulfilled by

Depending on the calibration strategy, could be fulfilled by the nominal responsivity calibration requirement (Req. 1.1.2) or by the non-linearity calibration requirement (Req. 1.1.13).

Priority

A. This is one of the basic assumption for the bolometer operations.

When performed / frequency

As soon as detectors and a controlled source of light become available. Will have to be repeated for each model of the instrument with detectors, as well as in-flight. Should be repeated regularly, more frequently than the non-linearity measurement.

Required accuracy

The accuracy here is driven by the final photometric accuracy required.

Inputs, prerequisites

The calibration of the bolometers' non linearity has been performed, and the range of operational backgrounds and fluxes has been selected.

Sources

Sources with well controlled fluxes falling in the interval defined as the operational one, over a background corresponding to the operational one.

Calibration Implementation Procedure (CIP)

Measure, with identical observing set-up, a set of sources with different fluxes although all within the operational range, all over the operational background. If possible slightly change the background to search for maximal allowed background change. On the ground this can be achieved by chopping between a reference and an adjustable black-body.

Estimated time needed

Calibration Analysis Procedure (CAP)

Output, products

Certification that the detector is linear within the operating range.

Status/version

Revised for Draft 3 of the PCD.

Req. 1.1.15 Establish the relative positions of the individual matrices.

Objectives

The detectors are made of 2 and 8 16×16 sub-matrices. In principle, CEA/LETI will align them with an accuracy better than $1/10^{\mathrm{th}}$ of a pixel in both the line and column directions (typically $\pm 40\,\mu$m). At room temperature this relative positionning will be measured at CEA/SAp with an accuracy of $1\,\mu$m. A measurement at operating temperature will not be possible on the QM or FM.

These values are important to consider when reconstructing the images. In case we use an iterative process to reconstruct scan maps, the exact geometry of the detector array can become of quite high importance.

Fulfilling or fulfilled by

Possibly covered when measuring the optical distortion. In fact, in the complete instrument, it will be hard to distinguish one from the other.

Priority

B. The laboratory measurement will probably be a good enough approximation of the real alignment.

When performed / frequency

Can be done on the ground since the pixels are almost macroscopic but only at room temperature. We cannot exclude that individual matrix expand/contract/rotate differently with respect to one another. Measured again in-flight as part of the optical distortion.

Required accuracy

$<$ 1/10 of a pixel in order not to be the dominant source of uncertainty in the optical distortion determination.

Inputs, prerequisites

None.

Sources

A plate with well-positioned holes or a rich star cluster.

Calibration Implementation Procedure (CIP)

Perform a scan map on a plate with well positionned holes or a rich cluster.

Estimated time needed

Calibration Analysis Procedure (CAP)

Output, products

In-plane displacement and rotation for each sub-matrix with respect to the spacecraft axes.

Status/version

Draft version, revised after the December 01 meeting.

Req. 1.1.16 Measure the signal dependance on chopping frequency

Objectives

Since the detector responds to a flux change with certain time constants, it may be that for high chopping frequencies, we only explore a part of the actual detector response. This translates into an effective gain which is less than the nominal one. We therefore need to calibrate the possible variations of the gain as a function of the chopping frequency. Note that this requirement may lead to the definition of the maximum chopping frequency allowed.

Fulfilling or fulfilled by

This may become obsolete depending on choices made of the implementation of the readout process for chopped mode.

Priority

A. This is in the chain leading to the photometric calibration of the data produced by the bolometers.

When performed / frequency

As soon as detectors and a source of relatively controlled illumination become available. Then repeated for all instrument models with detectors. Finally perfomed regularly in-flight as a health-monitoring activity.

Required accuracy

Driven by the accuracy we wish to reach for the final photometry.

Inputs, prerequisites

Sources

A well calibrated source on top of a background, both constant with time.

Calibration Implementation Procedure (CIP)

Perform chopped measurement on the source with varying chopping frequency.

Estimated time needed

Calibration Analysis Procedure (CAP)

Output, products

Either a table giving the gain corrections as a function of the chopping frequency or a prescription on the acceptable chopping frequencies for PACS.

Status/version

Draft version, revised after the December 01 meeting.

Req. 1.1.17 Measure the level of optical cross-talk in the detector

Objectives

Optical cross talk happens when light falling on a pixel actually manages to leak out (silicon, which makes up the pixel walls, is still quite transparent) and gets trapped in a neighborhing pixel. This will be hard to measure and distinguish from ghosts on the illuminated part of the array, but could have more problematic effects if light leaks out in the blind pixels (the signal of these pixels is subtracted from that of all the sky pixels, resulting in a dark line on the half column where cross-talk has occured).

It is still to be decided whether both rows of blind pixels are used or only the first one. In the latter case, optical cross talk becomes negligible since it can only affect the second row of blind pixels, that which is closest to the sky pixels.

Fulfilling or fulfilled by

Will probably have to be investigated in conjunction with ghosts.

Priority

A for the blind pixel side since this potentially affects the basic readout process.

B for the rest of the matrix as it will be hard to distinguish it from ghosts.

When performed / frequency

Start at instrument level tests as we need a point source. SAp does not intend to include in its test facility a point source simulator.

Required accuracy

typically $<$ 5% of the background level.

Inputs, prerequisites

None.

Sources

A bright point source to avoid uncertainties linked to small signal-to-noise ratios.

Calibration Implementation Procedure (CIP)

Observe a source at different locations on the array, specifically close to the blind pixel rows.

Estimated time needed

Calibration Analysis Procedure (CAP)

Output, products

If possible a cross-talk matrix to be able to correct for it.

Status/version

Revised for Draft 3 of the PCD.

Req. 1.1.18 Measure the level of electrical cross-talk

Objectives

Since signal from different pixels is carried outside the cryostat in wires that are attached together, mutual influence between these wires could in principle exist. Measure the level of this effect.

Fulfilling or fulfilled by

In principle, the measurement is the same than that for straylight and ghosts measurement since is typically involves moving a source on the array to look for correlated signal on the matrix.

Priority

B. Expected to be low.

When performed / frequency

As soon that we have detectors and a movable point source. Repeated for every instrument model with detectors and in-flight.

Required accuracy

$<$ 5% of the background.

Inputs, prerequisites

None.

Sources

A set of bright sources.

Calibration Implementation Procedure (CIP)

Scan a set of bright sources and look for “ghosts” appearing on pixels whose output is coupled to that of the most illuminated pixel.

Estimated time needed

Calibration Analysis Procedure (CAP)

Output, products

A cross-talk matrix to correct the read-out signal.

Status/version

Draft version, revised after the December 01 meeting.

Req. 1.1.19 Measure the detector global resistance

Objectives

The global resistance of the detector is our indicator to check that no pixel has gone into a short-circuit. When that happens the global resistance of the detector changes dramatically. The incriminated pixel also heats a lot which may be a danger for the rest of the instrument.

The global resistance is measured through the amount of current that goes to the detector (measured per matrix for the red channel and per couple of matrix for the blue channel) and the value is placed in the housekeeping data. It is the responsibility of the on-board software to monitor this value and accordingly switch-off the incriminated detector should it go beyond its nominal range.

Once a pixel goes into short-circuit, there is no way to recover it and the corresponding array has to be permanently shut down.

Fulfilling or fulfilled by

Monitored regularly on-board.

Priority

A. Basic safety measure.

When performed / frequency

starting at PV.

Required accuracy

10-20% (TBC).

Inputs, prerequisites

The nominal detector resistance.

Sources

none.

Calibration Implementation Procedure (CIP)

monitor the housekeeping data.

Estimated time needed

Calibration Analysis Procedure (CAP)

Output, products

safety warning when necessary.

Status/version

Draft version, revised after the December 01 meeting.

Req. 1.1.20 Measure the level of correlated noise on the detector

Objectives

Correlated noise is noise, since it appears as random, unexpected time variations a pixel readout, but that appears simultaneously on all pixels of the array (or on series of pixels that are not optically or electrically connected). Correlated noise will not disappear when pixels are averaged. In a complex environment such as the PACS one, there are many source that could create correlated noise on the array. We need to measure the level of this noise component as it affects the ultimate sensitivity of the instrument.

Fulfilling or fulfilled by

self-standing

Priority

It is of high priority to make sure that this noise component is very small compared to the other sources of noise. If this is true, then quantifying the level of correlated noise is not necessary.

When performed / frequency

As soon as detectors are available.

Required accuracy

This will depend on the level of other noise sources. Typically this level should be less than 10% of the high frequency noise.

Inputs, prerequisites

none

Calibration Implementation Procedure (CIP)

Correlated noise should in principle occur in any experiment if it is there. It is probably easier to search for it when observing a flat source as correlations may be hard to evidence, or be confused with cross-talk in complex fields.

Estimated time needed

Calibration Analysis Procedure (CAP)

Output, products

Hopefully a prescription that this noise component is negligible.

Status/version

Draft created for draft 3 of the PCD.

Req. 1.1.21 Self-calibrate the responsivity of the detectors

Objectives

With the blind pixels and the internal calibrators, there is a possibility to self-calibrate the detector. If we can trust the flux from the internal calibrators to be constant through time then one can use the heater on the blind pixels to search for the voltage required to match the power going through the blind pixels to that falling on the open pixels. This directly gives the conversion from volts to power of the detector.

To be suitable for absolute calibration of the detector, this experiment requires that the internal calibrators do not degrade through time. At the minimum however, it can serve as a health check on the detector+internal calibrators system.

Fulfilling or fulfilled by

Self-standing

Priority

C - This is more a “nice to have” rather than an absolute priority. It should however be tested as it provides a rather rapid way of deriving the absorption coefficient and of chcking the responsivity.

When performed / frequency

Once the instrument is assembled since we need to have the internal calibrators.

Required accuracy

Following the accuracy quoted in req. 1.1.2, this should be $<$5%.

Inputs, prerequisites

The internal calibration sources should be well calibrated so that the power falling on the detector can be computed with a sufficient accuracy. The responsivity derived in req. 1.1.2 is used for the consistency check.

Calibration Implementation Procedure (CIP)

The “self-calibration method” allows to measure the absorption coefficient and the responsivity. For this purpose, the internal calibration sources are used with their corresponding chopper positions. The following procedure is iterated for 2 internal calibration sources of different temperature and optionally for 2 blue filters.

- ** Loop on different heater voltages **
- Set a voltage of the blind pixel heater
- Data acquisition
- ** End of loop **

The blind pixels are downlinked independently together with the active pixels. The voltage values in the loop must be chosen to obtain blind pixel output values going down or up through the average ouptput value of the active pixels.

- Knowing the source flux F received by a pixel, the absorption coefficient α is derived by $\alpha = E/F$, where E is the thermal energy provided by a blind pixel heater with its current I and its voltage V, so $E = VI$.
- Then the responsivity R is derived by $R = \alpha(v_2 - v_1)/(E_2 - E_1)$, where v is the output voltage of the bolometer and the indices indicate the 2 calibration sources of different temperature.

Estimated time needed

Calibration Analysis Procedure (CAP)

First the absorption coefficient is derived, which is then used to derive the responsivity. The result is compared with the value obtained in req. 1.1.2.

- The data must be reduced separately for the blind and active pixels.
- Find by interpolation the voltage V and the current I of the blind pixel heater which give the value of the active pixels illuminated by an internal calibrator.
- Compute the absorption coefficient α by $\alpha = VI/F$ where F is the flux falling on one active pixel.
- Compute the responsivity R by $R = \alpha(v_2 - v_1)/(V_2 I_2 - V_1 I_1)$
- Check if this result is consistent with the value obtained in req. 1.1.2.

Output, products

The detector responsivity.

Status/version

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$Revision: 1.3 $
$Date: 2003/06/18 09:48:37 $
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Req. 1.1.22 Measure the relative system response of the detectors

Objectives

In order to be able to make the appropriate color corrections to the large bands of the photometer, we need to characterize the relative system response of all its component. This requirement deals with the bolometer. The aim is to determine the absorption efficiency as a function of wavelength. The normalization of this response is arbitrary.

Fulfilling or fulfilled by

Self-standing

Priority

A. Measuring a global relative response of the full instrument may be hard to do, and we may have to build it from the individual elements.

When performed / frequency

At module level if possible otherwise it may be very hard to access the real bolometer relative system response.

Required accuracy

$<$10% rms

Inputs, prerequisites

none

Calibration Implementation Procedure (CIP)

The light of a 900 K source is sent into a Fourier Transform Spectrometer. In a first setup, the light coming out of the spectrometer is reflected on a mirror and is then recorded by a reference detector. We thus get a first interferogram corresponding to the spectrum of the 900 K source. We then perform a second measurement where the mirror before the detector is replaced by a PACS matrix. We record a new interferogram of the spectrum of the 900K source. The PACS matrix is not switched on during the measurement.

Estimated time needed

Calibration Analysis Procedure (CAP)

With a fourier transform we recover the two spectra. In the first case, the spectrum S_1 measured is that of the source multiplied by (1) the response of the FTS, (2) the response of the reference detector and (3) the reflectivity of the mirror (1 at all wavelengths of interest). In the second case, for spectrum S_2, (3) is now the reflectivity of the detector.

Given the instrumental setup, what is not reflected is absorbed so the relative subsystem response is ($1-S_2/S_1$).

Output, products

A table of normalized response as a function of wavelength.

Status/version

Added for version 3 of the PCD. Revised for version 6 of the PCD

1.2 (Stressed) Ge:Ga Photoconductor Arrays

This Section describes calibration requirements for the spectrometer that deal with the characterisation of instrumental effects that are best or exclusively performed by on-ground tests at a modular or instrument level.

Most requirements deal either with

- the detectors or the CRE, or
- the effect of ionizing radiation

The first item covers requirements related to e.g. the linearity of the CRE, optimum settings for the detector bias and temperature, responsivity, responsivity, NEP, etc.

The second item covers the effect of ionizing radiation on the responsivity, dark current, noise properties, etc, as well as the feedback of ground-tests on the development and testing of de-glitching and ramp fitting numerical routines for the OBSW.

The effects of space radiation effects are an important effect to consider. A particle that hits a photoconductor deposits an amount of energy that depends on the type of particle, the detector material, and the length of the particle track.

The "ISO/FIRST Glitches Working Group, Final Report" (2001) describes how these effects have been handled in the reduction of ISO data, and makes recommendation for future missions, in particular FIRST/Herschel. Among their recommendations are: (1) that ground tests are mandatory to test the detector response and compare it to predicted ones ... and to confirm that deglitching and other algorithms for radiation background removal operate correctly, (2) detailed particle simulation analysis should be carried out before launch ... that should not only take into account protons, but also electrons, and secondary particles produced in the detectors and shield.

Information about the radiation environment in L2 can be found in the memo from J. Sorensen (2001) and the document by H. Evans (1997). It contains predictions, e.g. for the time integrated proton flux for a 4-year mission starting in 2007. From this, the average proton flux expected are 1400, 800, 150, 5 and 2 /cm^2/s at 0.1, 1, 10, 70 and 100 MeV.

With 11 mm shielding, typical for the Herschel satellite, protons below about 50 MeV are not expected to come through (Figure 9-1 in ECSS-E-10-04a). However, the detailed energy spectrum after shielding of solar protons is not available at this moment.

Equally, if not more, important are the effects of Galactic Cosmic Rays (GCR), which are dominated by protons. An example of the energy spectrum (including shielding by 10 mm Aluminium, but ignoring secondary particles) is shown in Dzitko (2001). The differential spectrum peaks at 500 MeV with a flux of 3×10^{-3} /cm^2/s/MeV, and 9×10^{-4} /cm^2/s/Mev at 100 MeV. Integrating over this differential spectrum leads to a GCR rate of about 4 /cm^2/s above 100 MeV.

Third, there are secondary particles and δ-rays which result from the interaction of the primary GCR with the shielding material. Details depend heavily on the shielding, but for ISOCAM the contribution of secondary particles and δ-rays to the total predicted glitch rate was equal to the one predicted from primary GCR (see Dzitko 2000).

Two test facilities have been discussed to perform radiation tests,

1) the Paul Scherrer Institute (PSI) (http://www.psi.ch/index_e.shtml),
   which has a cyclotron that can create the highest power in the world (590 MeV), and

2) the Cyclotron Research Centre at Louvain-la-Neuve (CRC-LLN) (http://www.cyc.ucl.ac.be/),
   which has a cyclotron build in the early-seventies that can accelerate protons to 80 MeV.

At the moment, tests are only foreseen at the QM level, to be held at CRC-LLN not before December 2003. Details of the proposed tests can be found in PACS-ME-TP-009.

Reasons for doing additional testing on the FM are: (1) the energy levels at CRC-UCL are too low to be representative, (2) the design of the FM is different from the QM, (3) at QM, only one linear array of 16 pixels is tested, which limits the possibility to investigate cross-talk, (4) curing issues might involve the internal blackbodies and hence need a complete system.

Literature:

H. Dzitko, 2000, Experimental Astronomy 10/2-3 (ISO Detector workshop), p. 279

H. Dzitko, 22 february 2001, SAp-PACS-HD-004, Evaluation of the cosmic ray effects on the PACS bolometers for the FIRST L2 environment

ECSS Space Environment Standard (ECSS E-10-04) http://www.estec.esa.nl/wmwww/wma/standards/ecss/ecss.html

H. Evans,4 March 1997, esa/estec/wma/he/FIRST/3, FIRST L2 radiation environment

Ana Heras, 21 August 2001, SAI/2001-013/Rp, ISO/FIRST Glitches Working Group, Final Report

J. Sorensen, 14 May 2001, 00-010/JS, FIRST L2 radiation environment

R. Katterloher, draft 5 September 2003, PACS-ME-TP-009, Test plan and procedure of glitch event rate and collected charge variation in the Ge-Ga detectors during proton irradiation at UCL-CRC

Req. 1.2.1 Optimum detector bias settings

Objectives

Responsivity and NEP of the photoconductors depend on the applied bias voltage. Usually the responsivity increases with the bias voltage. But increasing the electrical field inside the detector will eventually lead to an avalanche of collisional ionisations making the detector low ohmic and less sensitive. Hence there is a bias voltage range where the detector operates under stable conditions and the NEP shows a minimum. This optimum bias voltage range shall be determined for the photon level under operational conditions for spectroscopy. These parameters shall be determined on-ground. A verification or re-assessment in-flight appears only necessary, if the performance numbers of the spectrometer were considerably worse than expected.

Fulfilling or fulfilled by

Tests are combined with those for req. 1.2.2

Priority

A (on ground) / C (in-flight)

When performed / frequency

- [1] As part of the ground module characterization.
- [2] During ILT tests.
- [3] In-flight, should performance of spectrometer require a new optimization of the bias setting.

Required accuracy

The bias setting yielding a minimum NEP in the NEP vs. bias diagram for the majority of pixels should be selected. The NEP should be comparable with the expected $\mathrm{NEP}_{\mathrm{BLIP}}$.

Inputs, prerequisites

It should be verified that the detector read noise $\mathrm{NEP}_{\mathrm{RO}}$ is as specified (cf. req. 1.2.10).

Sources

Laboratory BBs, internal calibration sources, OGSE BB1 & BB2.

Calibration Implementation Procedure (CIP)

By varying the detector bias and temperature differential measurements for typical spectroscopic observing conditions (i.e. $7 \times 10^{-15}\,\mathrm{W} \leq \Phi_{\mathrm{B}} \leq 4 \times 10^{-14}\,\mathrm{W}$ cf. SCI-PT-IIDB/PACS-02126, 4.7.4) will be performed For the red detector array the corresponding OGSE BB temperature is around 20 K, for the blue array it is around 32 K. Small temperature differences of a few K between OGSE BB1 and BB2 will give the differential source signal. Since the red detector is not temperature controlled but coupled to the Helium bath via a cooling strap, no temperature optimization is performed for this detector.The bias voltage of the red detector is varied between 30 mV and 70 mV, in steps of 10 mV. The bias voltage of the blue detector is varied between 90 mV and 270 mV, in steps of 30 mV for each temperature setting between 2.1 K and 2.9 K, in steps of 0.2 K. Measurements with the blue array are done with the 2*nd* order sorting filter. Temperature and bias stabilization times have to be considered. The duration of each measurement shall be 128 s, with an integration time (reset interval) of 1 s, 256 NDRs.

Estimated time needed

Red detector:

OGSE BB stabilization 1 h; 5 bias settings: 30 s stabilization time + 128 s measurement time (13 min) → total: 1 h 13 min

<u>Blue detector:</u>

OGSE BB stabilization 1 h + 5 bias settings (60 s) + stabilization time (5 min) + 5×7 bias settings (30 s) + 30 s stabilization time + 128 s measurement time (92 min) $\rightarrow$ total: 2 h 37 min

Grand total $\sim$ 4 h

Calibration Analysis Procedure (CAP)

For each bias and temperature setting determine NEP according to its definition (cf. req. 1.2.10) for all pixels. For each pixel plot NEP vs. bias voltage and try to identify bias voltage corresponding to minimum NEP. (see PACS TIA Tests on Detector Module EM6, PACS-ME-TR-003 for an example). Identify possible spiky pixels and from which bias voltage level they start to be spiky. Produce 2D colour plots displaying the NEP values of the array pixels to show any gradient or the location of any hot, spiky or low performance pixels.

Output, products

Bias settings for low stressed and high stressed photoconductor array

Status/version

Full revision.

```
$Revision: 1.5 $
$Date: 2003/09/29 18:34:47 $
```

Req. 1.2.2 Optimum detector temperature settings

Objectives

Responsivity, NEP and dark current of the photoconductors depend on the operational detector temperature (applicable only to short wavelength array, the long wavelength array is coupled to the Helium bath). The detector temperature shall be tuned such that the NEP shows a minimum and the dark current is on a low level. This optimum temperature setting shall be determined for the photon level under operational conditions for spectroscopy. These parameters shall be determined on-ground. A verification or re-assessment in-flight appears only necessary, if the performance numbers of the blue spectrometer channel were considerably worse than expected.

Fulfilling or fulfilled by

Tests are combined with 1.2.1 and 1.2.6

Priority

A (on ground) / C (in-flight)

When performed / frequency

- [1] As part of the gound module characterization.
- [2] During ILT tests.
- [3] In-flight, should performance of spectrometer require a new optimization of the bias setting.

Required accuracy

The temperature setting yielding a minimum NEP in the NEP vs. temperature diagram for the majority of pixels (and not leading to excess dark current) should be selected. The NEP should be comparable with the expected $\mathrm{NEP}_{\mathrm{BLIP}}$.

Inputs, prerequisites

It should be verified that the detector read noise $\mathrm{NEP}_{\mathrm{RO}}$ is as specified (cf. req. 1.2.10)

Sources

Laboratory BBs, internal calibration sources, OGSE BBs

Calibration Implementation Procedure (CIP)

See CIPs for combined bias temperature scan in 1.2.1 and for determination of dark signals in 1.2.6. The temperature variation for the blue (low-stressed) array is between 2.1 K and 2.9 K in steps of 0.2 K.

Estimated time needed

See time estimates for 1.2.1 and 1.2.6 CIPs.

Calibration Analysis Procedure (CAP)

For each temperature setting determine NEP according to its definition (cf. req. 1.2.10) for all pixels. Plot NEP vs. temperature and try to identify temperature corresponding to minimum NEP. Also for each temperature setting determine dark signal. Verify that for temperature corresponding to minimum NEP no excess dark signal occurs for the majority of pixels. If that should be the case, a lower temperature setting has to be selected.

Output, products

Temperature setting for low stressed array.

Status/version

Full revision.

```
$Revision: 1.5 $
$Date: 2003/09/29 18:35:10 $
```

Req. 1.2.3 Dynamic range per selected integration capacitor

Objectives

The CRE is equipped with different integration capacitors in order to be able to cover a wide range in flux levels. It is expected that for most astrophysical sources the input flux will be dominated by the telescope background, so that the largest fraction of observations will be performed with the same capacitance (likely by the lowest one). The range of input currents, or equivalently input fluxes, over which the capacitors will work has to be established. The dynamic range per integration capacitor is defined by determining the minimum and maximum current for which a linear slope can still be fitted to the observed ramps. The lower end of the range determined by non-linearities of the CRE, digitization noise, upper end of the range determined by saturation. The dynamic range depends also on the selected reset interval value.

According to the “Requirements for the PACS-CRE” (PACS-ME-RS-002) the dynamic range of the output signal should be more than 2.0 V (goal).

Fulfilling or fulfilled by

Fulfilling by Req. 1.2.11 for measurement configurations yielding full dynamic range for a selected reset interval.

Priority

A, needed for AOT logic

When performed / frequency

1 As a part of the ground module characterization

2 During ILTs

Required accuracy

The dynamic range of the output voltage for a certain integration capacitor/reset interval combination due to a specified input flux from the sky plus the telescope background flux should be known with an accuracy of $\pm 20\%$.

Inputs, prerequisites

none

Sources

1 See setup as described in the documents “Test Procedure / Test Report, Functional Tests of PACS QM-FEEs” (PACS-MA-TR-004c) and “PACS Test Report, Results of Tests on QM FEE A02-038-15, Run 10/2001” (PACS-MA-TR-005).

2 OGSE BBs.

Calibration Implementation Procedure (CIP)

The basic strategy is to switch through all possible reset interval lenths for different illumination levels and this for all 4 integration capacitors. This provides a matrix of measurements with ramps of different dynamic range

Foreseen OGSE BB settings:

$T_{\mathrm{BB1/BB2}}$	Blue array	Red array
20 K$\pm x$		$\times$
25 K$\pm x$		$\times$
30 K$\pm x$	$\times$	$\times$
35 K$\pm x$	$\times$	$\times$
40 K$\pm x$	$\times$	($\times$)
45 K$\pm x$	$\times$	
50 K$\pm x$	$\times$	

Covered read-out parameters:

	C_{int}:	0.1	0.3	1.0	3.0
RI					
1/32		$\times$	$\times$	$\times$	$\times$
1/16		$\times$	$\times$	$\times$	$\times$
1/8		$\times$	$\times$	$\times$	$\times$
1/4		$\times$	$\times$	$\times$	$\times$
1/2		$\times$	$\times$	$\times$	$\times$
1		$\times$	$\times$	$\times$	$\times$
2		$\times$	$\times$	$\times$	$\times$
4		$\times$	$\times$	$\times$	$\times$

All reset intervals between 1/32 s and 4 s in steps of a factor 2 in time are used The loop over the reset intervals is repeated in reverse order (from long to short reset intervals). The measurements are performed in chopped mode (beam modulation by OGSE chopper) and have a duration of 128 s. Chopper plateaux times are 32 s to enable 8 ramps per chopper plateau for the longest selected reset interval. The NDR sampling is 1/256 s. Integration ramp row data shall be provided by the telemetry.

Estimated time needed

7 OGSE BB temperature settings $\rightarrow$ 7h stabilization time
5 T settings for red & blue detector each = 10
4 integration capacitors per T setting = 4
2x8 reset interval settings for each integration capacitor = 16
With 128s per measurement the total measurement time = $10 \times 4 \times 16 \times 128$s = 22.8h

$\rightarrow$ total time $\sim$ 29h

Should this be too long one might restrict the OGSE BB settings to the ones close to the telescope background, i.e. 20$\pm$x K and 25$\pm$x K for the red detector and 30$\pm$x and 40$\pm$x K for the blue detector. Furthermore, one may omit the largest capacitor value. Furthermore, one performs only one cycle through the reset interval timing.

4 OGSE BB temperature settings $\rightarrow$ 4h stabilization time
2 T settings for red & blue detector each = 4
3 integration capacitors per T setting = 3
8 reset interval settings for each integration capacitor = 8
128s = 2min per measurement total measurement time = $4 \times 3 \times 8 \times 128$s = 3.4h

$\rightarrow$ total minimum time $\sim$ 7.5h

The measurement time of 2min should not be reduced. In case of 4s reset intervals this means the acquisition of 16 ramps per chopper position.

Calibration Analysis Procedure (CAP)

For each OGSE BB T, each integration capacitor and each reset interval time and each pixel:

Determine minimum and maximum voltage by averaging voltages of 1st and last NDR of all ramps (note: in raw data voltages are reverse). Alternatively fit all ramps and determine reset level (zero point) and maximum voltage. In case of redundant measurements check for possible drifts (e.g. reset level drifts).

Divide maximum-minimum voltage range by full voltage range of the ADC and determine percentage of dynamic range. Take into account that the reset level may not correspond to the lowest voltage of the ADC range.

Determine the variation of the dynamic range with pixel (depends e.g. on the pixel responsivity).

If OGSE BB settings can be associated with in-band power values or monochromatic input flux densities in Jy the correlation between input flux and dynamic range of the output voltage can be established.

Output, products

The dynamic range per capacitor and selected reset interval vs. input flux.

Status/version

```
$Revision: 1.3 $
$Date: 2003/09/29 18:33:49 $
```

Req. 1.2.4 CRE check-out voltage

Objectives

The CRE check-out voltage is applied to the CRE resistor pixel. This allows to monitor the CRE integration without any impact by the detector. The voltage applied should lead to the same integration ramp slope as for the detector pixels. The level of the voltage may depend on the selected reset interval.

Fulfilling or fulfilled by

Priority

C?

When performed / frequency

Required accuracy

Inputs, prerequisites

Sources

Calibration Implementation Procedure (CIP)

Tune check-out voltage to have reasonable dynamic range of the integration ramps for the selected reset interval. Repeat this process for all selected reset intervals. This will need telemetry of the raw data.

Estimated time needed

Calibration Analysis Procedure (CAP)

Output, products

Status/version

Draft version

Req. 1.2.5 Signal-to-noise dependence on number of non-destructive read-outs per ramp

Objectives

Determine the variation of the SN ratio as a function of the number of NDR per ramp. The number of readouts is set by the reset interval as the readout rate is fixed at $\frac{1}{256}$ s. Effects of linearity of the ramps and the on-board processing (and compression of data) influence the optimal reset interval time.

Fulfilling or fulfilled by

Priority

When performed / frequency

Required accuracy

Inputs, prerequisites

Sources

Calibration Implementation Procedure (CIP)

Estimated time needed

Calibration Analysis Procedure (CAP)

Output, products

Status/version

Draft version

```
$Revision: 1.2 $
$Date: 2002/09/20 08:59:29 $
```

Req. 1.2.6 Detector dark current

Objectives

Measure the detector dark current, in each pixel, for the blue array for various detector temperatures. In principle the dark current cancels out by the differential measurements. The aim is to determine which fraction of the light current the dark current makes up and to optimize it for the blue array.

Fulfilling or fulfilled by

Related to 1.2.2 for blue array detector temperature.

Priority

B

When performed / frequency

1 During ILT tests

2 During PV phase

Depending on outcome of ILT, could be measured in orbit during PV.

Required accuracy

Inputs, prerequisites

All internal and external stimuli should be switched off to avoid straylight. This means that the measurement has to take place at the beginning of a test block before stimuli are powered up or after switch on the spectrometer avoiding to heat up the internal sources immediately.

Sources

For ILTs the OGSE is set up to dark position and all stimuli will be off.

The PACS internal calibrators should be off. Determine dark current level by looking onto one of the cold PACS internal calibrators. If there were any straylight concern, in-flight the telescope should be pointed to a 'blank' region of the sky.

Calibration Implementation Procedure (CIP)

ILTs:

The PACS internal calibrators should be off, and, if applicable, should be let to cool down sufficiently long. The OGSE Black Bodies should be off. The OGSE mirror M3 is put into dark position. If possible, the entrance to OGSE cryostat should be closed.

The measurement is performed in staring mode. The chopper mirror is deflected to a position to view one of the cold internal calibration sources. The read-out should be adjusted to a low signal level (e.g. reset time of 4s in combination with low integration capacity for both blue and red array). In order to check for wavelength independence of the dark signal (verification of straylight contribution) the measurement is repeated with both the 2*nd* and 3*rd* order sorting filter for the blue array. For temperature setting optimization of the blue array a temperature loop (addressing aspects of req. 1.2.2) is included varying the blue array temperature between 2.1 and 2.9 K in steps of 0.2 K.

Estimated time needed

Considering 5 temperature settings for blue array (red array is measured in parallel) and with repetition for 2*nd* and 3*rd* order sorting filter:

$10\times$ (60 s stabilization time $+256$ s measurement time) ≈ 1 h

Calibration Analysis Procedure (CAP)

For each pixel the dark signal is determined, for the blue array in dependence on the detector temperature. The dark current is

$$I_{\mathrm{dark}}[\mathrm{A}] = \mathrm{V_s}[\mathrm{V/s}]\mathrm{C_{int}}[\mathrm{As/V}]$$

The dark signal can be expressed as dark electrons

$$N(e^-)_{\mathrm{dark}} = I_{\mathrm{dark}}/Qe^- \qquad Qe^- = 1.60210^{-19}\mathrm{As}$$

The dark signals of all pixels shall be displayed in 2D colour plots to identify any gradient (possibly due to straylight) or the location of peculiar pixels.

Output, products

Should the dark signal makeup a noticeable fraction of the telescope background at any wavelength, then the dark signals of all pixels will be provided in a dark matrix to be subtracted from the row signals.

Status/version

```
$Revision: 1.4 $
$Date: 2003/09/29 18:33:20 $
```

Req. 1.2.7 Nominal Responsivity

Objectives

The responsivity is the essential calibration factor between the measured output voltage of the CRE (equivalent to the photo current onto the integration capacitor) and the incident illumination power onto the detector. The responsivity at detector level is measured when the optimum detector biases and temperature are determined. The requirement on possible variation in time due to for instance cosmic particle hits and the wavelength dependency of the responsivity are described in the full system section.

Fulfilling or fulfilled by

Measured together in 1.2.1 and 1.2.2

Priority

A

When performed / frequency

- [1] During module level tests

Required accuracy

$< 10\,\%$

Inputs, prerequisites

Relative system response to derive in-band power from source spectrum

Sources

Laboratory BB

Calibration Implementation Procedure (CIP)

Perform a differential (staring?) measurement for typical spectroscopic observing conditions
(i.e. 7×10^{-15} W $\leq \Phi_\mathrm{B} \leq 4 \times 10^{-14}$ W (cf. SCI-PT-IIDB/PACS-02126, 4.7.4)).

Estimated time needed

Calibration Analysis Procedure (CAP)

per pixel i:
$R_\mathrm{i} = \frac{S_\mathrm{i} \times C_\mathrm{int}}{\Delta\,\Phi_\mathrm{B}}$
S_i = amplitude of the modulated signal ([V/s])
C_int = selected integration capacity ([F] = [A s/V])
$\Delta\,\Phi_\mathrm{B}$ = difference power of modulated illumination ([W])

Output, products

nominal responsivity value per pixel, flat-field quality of arrays

Status/version

Second draft, detailed revision.

```
$Revision: 1.3 $
$Date: 2002/09/17 14:14:37 $
```

Req. 1.2.8 Signal dependence on chopper frequency

Objectives

Due to signal transients the height of the resulting differential signal may depend on the chopper frequency. In particular for high chopper frequencies signal losses may occur. Any signal dependence shall be characterized for the range of chopper frequencies which mean a reduction of telescope background and detector noise and an optimum chopper frequency be determined (which maximises differential signal in compromise with minimising noise).

Fulfilling or fulfilled by

Priority

A

When performed / frequency

- [1] During ILT tests
- [2] During PV

Required accuracy

$< 10\%$

Inputs, prerequisites

Specify chopper frequency range which leads to reduction of telescope background and detector noise. Add realistic offset signal due to telescope background.

Sources

Can be done with internal calibrators, but should also be done with external sources, either laboratory black body or celestial standard, because frequency dependence of detectors may be different (while chopping between both calibrators, there are short periods of crossing the sky field-of-view with the telescope background).

Calibration Implementation Procedure (CIP)

Chop between two stable different reference levels varying the chopper frequency. Repeat that for various difference signals covering the dynamic range from faint to bright sources (including sky and telescope background).

Estimated time needed

Calibration Analysis Procedure (CAP)

Output, products

Status/version

Second draft version, 15-02-02; rephrasing of “objectives”, addition to “prereqisites” item

Req. 1.2.9 Detective Quantum Efficiency

Objectives

Measure the detector quantum efficiency as a function of different detector bias settings and temperatures. The noise of the detector must be dominated by photon noise (BLIP = Background Limited Infrared Photoconductor case).

Fulfilling or fulfilled by

Can be derived from measurements under reqs. 1.2.1, 1.2.2 and 1.2.10.

Priority

C
will be measured together with the responsivity and the NEP and will come out of the data-analysis. The crucial parameters are the other two. The quantum efficiency is needed for calculations of the $\mathrm{NEP}_{\mathrm{BLIP}}$, i.e. in simulator and time estimator applications.

When performed / frequency

During module level tests

Required accuracy

Inputs, prerequisites

The illumination must be well determined and a corresponding $\mathrm{NEP}_{\mathrm{BLIP}}$ value must be derived according to the CAP description in req. 1.2.10.

Sources

blackbody; homogeneous illumination of the arrays

Calibration Implementation Procedure (CIP)

Illuminate detector pixels with well determined in-band power; for details see CIPs of 1.2.1 and 1.2.2.

Estimated time needed

no extra time

Calibration Analysis Procedure (CAP)

Definition of detector quantum efficiency η:

$$\eta = 4\,\frac{h \cdot c}{\lambda_{\mathrm{c}}} \cdot \frac{\Phi_{\mathrm{B}}}{NEP_{\mathrm{BLIP}}^2} \cdot B^2$$

h = Planck constant
c = speed of light
λ_{c} = central wavelength of band
Φ_{B} = illumination power
$\mathrm{NEP}_{\mathrm{BLIP}}$ = NEP as determined in CAP 1.2.10 for background limited case.
B = Bose factor = $\sqrt{1 + \frac{1}{e^{\frac{h\,c}{\lambda_{\mathrm{c}}\,k\,T_{\mathrm{BB}}}} - 1}}$
T_{BB} = blackbody temperature
k = Boltzmann constant

Note that the quantum efficiency can also be derived from the detector responsivity R. This requires, however, knowledge of the photoconductive gain G:

$\eta \cdot G = \frac{h \cdot c}{\lambda_c} \frac{R}{e}$

e = electron charge

This second approach can be used to cross-check the photoconductive gain.

Output, products

Quantum efficiency per detector pixel. This kind of measurement can serve as a cross-check of the efficiency of the fore optics and detector cavities with regard to measurements of reference detector pixels in other configurations.

Status/version

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$Revision: 1.2 $
$Date: 2003/02/04 19:08:54 $
```

Req. 1.2.10 Noise Equivalent Power

Objectives

The noise equivalent power (NEP) corresponds to that amount of illumination power that is needed to generate a signal-to-noise ratio S/N = 1 after 1/2 s of integration time in a chopped measurement (definition of 1 Hz bandwidth commonly used in astronomy, therefore the unit is W / $\sqrt{Hz}$). The noise signal has different sources, one is the photon noise, another one the read-out noise of the detector-CRE chain. The performance of PACS shall be limited by the photon noise of the telescope background represented by the $\mathrm{NEP_{BLIP}}$. The read-out noise of the detector system $\mathrm{NEP_{RO}}$ shall be below that, so that it never limits the PACS performance.

Fulfilling or fulfilled by

Bias and temperature dependence of NEP are covered by reqs. 1.2.1 and 1.2.2.

Priority

A

When performed / frequency

During module level tests

Required accuracy

$\mathrm{NEP_{RO}} = 5 \times 10^{-18}$ W Hz$^{-1/2}$

Inputs, prerequisites

Sources

Laboratory BBs

Calibration Implementation Procedure (CIP)

perform a differential measurement covering a range which extends significantly below and above the telescope background, 5×10^{-16} W $\leq \Phi_\mathrm{B} \leq 5 \times 10^{-13}$ W (cf. SCI-PT-IIDB/PACS-02126, 4.7.4 for the expected level of the telescope background). $\mathrm{NEP_{BLIP}}$ is proportional to $\Phi_\mathrm{B}^{1/2}$, $\mathrm{NEP_{RO}}$ should be fairly constant. Reducing Φ_B from the highest value, a range should be reached which is dominated by $\mathrm{NEP_{RO}}$ and hence the dependence on Φ_B would stop. The corresponding NEP level would be assigned to $\mathrm{NEP_{RO}}$.

Estimated time needed

Calibration Analysis Procedure (CAP)

$$NEP_\mathrm{i} = \frac{S_\mathrm{noise,i} \times (2\,\Delta\,t)^{1/2} \times C_\mathrm{int}}{R_\mathrm{i}}$$

With the definition of $\mathrm{R_i}$ in req. 1.2.6:

$$NEP_\mathrm{i} = \frac{S_\mathrm{noise,i} \times (2\,\Delta\,t)^{1/2} \times C_\mathrm{int}}{\bar{S}_\mathrm{i} \times C_\mathrm{int}} \times \Delta\Phi_\mathrm{B} = \frac{S_\mathrm{noise,i} \times (2\,\Delta\,t)^{1/2}}{\bar{S}_\mathrm{i}} \times \Delta\Phi_\mathrm{B}$$

with
$\mathrm{S_{noise,i}} = \sigma(\bar{S}_\mathrm{i})$ standard deviation of the mean differential signal determined from a chopper cycle ([V/s])
$\bar{S}_\mathrm{i}$ = mean differential signal determined from a chopper cycle ([V/s])
Δt = typical integration time = reset interval ([s] = [Hz]$^{-1}$, see note below)
$\Delta\,\Phi_\mathrm{B}$ = difference power of modulated illumination ([W])
$\mathrm{C_{int}}$ = selected integration capacity ([F] = [A s/V])

R_i = responsivity per pixel ([A/W])

Discussion of noise terms and typical integration time:
The NEP should be independent of the total measurement time. A small flux can be measured with a certain S/N ratio within a certain measurement time T:

$$\Delta\,\Phi = \frac{S/N \,\cdot\, NEP}{\sqrt{2\,T}}$$

Independence of the NEP of the measurement time and considering the integrating behaviour of the CRE can be achieved when using:
mean signal from n ramps with reset time t_{ri}:

$$\bar{S} = \frac{1}{n}\sum_{i=1}^{n} S_{\mathrm{i}}$$

standard deviation of measurement with n ramps:

$$sdv = \sqrt{\frac{1}{n-1}\sum_{i=1}^{n}(S_{\mathrm{i}} - \bar{S})^2}$$

standard deviation of mean:

$$\sigma(\bar{S}) = \frac{1}{\sqrt{n}}\, sdv$$

total measurement time: $T = n\,\cdot\,t_{\mathrm{ri}}$

$$NEP = \frac{\sigma(\bar{S})\,\cdot\,\sqrt{2\,T}}{\bar{S}}\,\cdot\,\Delta\,\Phi = \frac{\frac{1}{\sqrt{n}}\,\cdot\,sdv\,\cdot\,\sqrt{n}\,\cdot\,\sqrt{2\,t_{\mathrm{ri}}}}{\bar{S}}\,\cdot\,\Delta\,\Phi$$

$\Rightarrow$ Either use standard deviation of mean signal $\sigma(\bar{S})$ in combination with total measurement time T or standard deviation sdv in combination with basic integration time = reset interval time t_{ri} (ideally set to 1 s).

Output, products

Verification of NEP_{RO}

Status/version

```
$Revision: 1.5 $
$Date: 2003/09/30 15:59:25 $
```

Req. 1.2.11 Linearity of CRE readout

Objectives

Determine the linearity of the slope of the CRE output voltage ramps for all capacitors, within their dynamical ranges. It will also be investigated whether the derived signal depends on the selected reset interval length.

Fulfilling or fulfilled by

Fulfilled by req. 1.2.3 (dynamic range of the capacitors)

Priority

A; This process has to be analyzed as early as possible as it is a basic step in the processing of the data. The results can even affect the method of on-board processing.

When performed / frequency

1 As part of the module characterization on ground

2 During ILTs

Required accuracy

The deviation of second order fit from straight line should be less than 3% ("Requirements for the PACS-CRE", PACS-ME-RS-002).

Inputs, prerequisites

none

Sources

1 See setup as described in the documents "Test Procedure / Test Report, Functional Tests of PACS QM-FEEs" (PACS-MA-TR-004c) and "PACS Test Report, Results of Tests on QM FEE A02-038-15, Run 10/2001" (PACS-MA-TR-005).

2 OGSE BBs

Calibration Implementation Procedure (CIP)

See detailed CIP description of req. 1.2.3. For the investigation of the linearity of the CRE read-outs in particular those read-out combinations which lead to a large dynamic range are of interest.

Estimated time needed

See time estimate for CIP 1.2.3

Calibration Analysis Procedure (CAP)

There are two aspects:

1 The linearity of the ramps

2 The linearity of signals with reset interval time

For 1) measurements having ramps with a large dynamic range should be used preferentially (information will be available from the step determining the dynamic range). But also measurements with small dynamic range should be checked for initial non-linearities of the CRE integration (e.g. hook responses).

The linearity of the ramps can be checked by various methods, e.g.

a) fit ramps by line using chi-square method, plot read-outs and line fit and visually inspect for any systematic deviations;

b) use pair-wise read-outs for signal determination and plot slopes (signals) over mean absolute voltage of read-out pair. Any absolute voltage range with peculiar slope behaviour should show up in this way.

Depending on the non-linearity features decide on possible linearization procedures or on deselection of certain voltage ranges in the slope determination procedure.

For 2) for each OGSE BB T setting: For each capacitor and reset interval time setting and each pixel determine an average signal and its uncertainty from all ramps in a standard way (after verification of ramp linearity), e.g. by line fit in the simplest way (to further illustrate the method). Within the uncertainties the signals should be identical for each pixel. If this is not the case plot signal vs. reset interval time for each capacitor to search for systematic trends. If systematic trends cannot be removed by systematic linearization methods calibration files transforming signals between different reset intervals and integration capacitors (if possible restrict range by operational set-ups) must be established.

Output, products

Possibly files with prescriptions of ramp linearization definition of voltage or ramp ranges to be deselected (e.g. begin of ramp, destructive read-out)

Status/version

```
$Revision: 1.3 $
$Date: 2003/09/29 18:34:13 $
```

Req. 1.2.12 Ionizing radiation: Reset time, spectrometer

Objectives

Investigate the influence of ionizing radiation on the usable reset time interval.

Two aspects have to be investigated. One, the number of read-outs required to obtain an accurate slope determination (which will depend on the input flux), the glitch rate, and the OBSW processing in terms of deglitching and ramp fitting. Two, the possible change in the slope after the impact by a glitch (see also req. 1.2.19), and, related, if (part of the) data taken after a glitch can be used in the analysis.

Fulfilling or fulfilled by

Related to 1.2.19.

Priority

A

When performed / frequency

- Module level tests on high-stressed QM#3 at the Centre de Recherches du Cyclotron (CRC) at the Université catholique de Louvain-la-Neuve.
- FM tests at the Paul Scherrer Institute (TBC).
- PV

Required accuracy

not applicable

Inputs, prerequisites

Glitch rate predictions for the Herschel orbit. Full modelling of the energy spectrum of particles reaching the detector (protons, secondary particles, electrons and delta-rays), and their deposited energy.

Range of allowable values for the DR and NDR frequency.

Sources

On ground: a source of radiation and a source that provides an input flux comparable to the telescope background.

In PV observations of sources of different flux levels.

Calibration Implementation Procedure (CIP)

Module level test: Measure output signal as a function of time under various conditions of ionizing radiation (type of particle; energy; rate) and different detector settings. To be considered are the bias voltage, detector temperature, capacitance, low/high-stress module, reset time interval.

PV: on sources of different fluxes, obtain observations using different reset times (likely only for nominal detector settings).

Estimated time needed

Calibration Analysis Procedure (CAP)

Output, products

Status/version

```
$Revision: 1.9 $
$Date: 2003/09/26 15:51:23 $
```

Req. 1.2.13 Ionising radiation: Responsivity, spectrometer

Objectives

Investigate the influence of ionizing radiation on the responsivity of the spectrometer, also as function of time.

Fulfilling or fulfilled by

self-standing, related to 1.2.14 (Ionising radiation: Noise, spectrometer)

Priority

A

When performed / frequency

- Module level tests on high-stressed QM#3 at the Centre de Recherches du Cyclotron (CRC) at the Université catholique de Louvain-la-Neuve.
- FM tests at the Paul Scherrer Institute (TBC).
- PV

Required accuracy

Inputs, prerequisites

Glitch rate predictions for the Herschel orbit. Full modelling of the energy spectrum of particles reaching the detector (protons, secondary particles, electrons and delta-rays), and their deposited energy.

Sources

On ground: a source of radiation and a source that provides a relevant background level.

Calibration Implementation Procedure (CIP)

QM Module level test: measure the responsivity of the stressed and unstressed detectors for various bias levels and input powers [similar to the test described in PACS-ME-TR-001 'PACS TIA Tests on Detector Module 6' and PACS-ME-TR-003 'PACS TIA Tests on Detector Module 6-Part 2'], under different levels of particle impacts (in terms of particle type, energy, hit rate) as a function of time. One measurement without particle irradiation for each detector setting should also be performed. These measurements need to take a sufficiently long period of time (preferably upto 1-day if needed) to detect measurable changes in the responsivity in order to derive characteristic time scales for responsivity changes.

In-orbit: derive the responsivity using observations of celestial standards during an operational day.

Estimated time needed

Calibration Analysis Procedure (CAP)

Output, products

Status/version

```
$Revision: 1.9 $
$Date: 2003/09/26 15:51:23 $
```

Req. 1.2.14 Ionising radiation: Noise, spectrometer

Objectives

Investigate the influence of ionizing radiation on the noise voltage of the spectrometer detectors (as function of time, TBC).

Fulfilling or fulfilled by

self-standing, related to 1.2.13 (Ionising radiation: Responsivity, spectrometer)

Priority

A

When performed / frequency

- Module level tests on high-stressed QM#3 at the Centre de Recherches du Cyclotron (CRC) at the Université catholique de Louvain-la-Neuve.
- FM tests at the Paul Scherrer Institute (TBC).
- PV

Required accuracy

Inputs, prerequisites

Glitch rate predictions for the Herschel orbit. Full modelling of the energy spectrum of particles reaching the detector (protons, secondary particles, electrons and delta-rays), and their deposited energy.

Sources

On ground: a source of radiation and a source that provides a relevant background level.

Calibration Implementation Procedure (CIP)

Module level test: measure the noise voltage of the stressed and unstressed detectors for various bias levels and input powers [similar to the test described in PACS-ME-TR-001 ’PACS TIA Tests on Detector Module 6’ and PACS-ME-TR-003 ’PACS TIA Tests on Detector Module 6-Part 2’], under different levels of particle impacts (in terms of type of particle, energy, hit rate) as a function of time. One measurement without particle irradiation for each detector setting should also be performed.

Estimated time needed

Calibration Analysis Procedure (CAP)

Output, products

Status/version

```
$Revision: 1.10 $
$Date: 2003/09/26 15:51:23 $
```

Req. 1.2.15 Ionising radiation: Dark current, spectrometer

Objectives

Investigate the influence of ionizing radiation on the dark current (noise) of the photoconductors. The two instruments onboard ISO with Ge:Ga detectors come to different conclusions concerning the effect of glitches on the dark current. For ISOPHT the dark signal increased because of low energy glitches (ISO/FIRST Glitches Working Group Final report). LWS found no change in the dark current level from mid- to end of a revolution (Swinyard etal 2000, Explanatory Astronomy, 10, 157), which led to the conclusion that the glitches had no effect on the dark current. This was contrary to the expectation on basis of their ground calibration measurements.

Fulfilling or fulfilled by

related to 1.2.6.

Priority

C. This depends on the outcome of req. 1.2.6. If the contribution of the dark current is important than we need to know whether the ionising radiation has an impact.

When performed / frequency

- Module level tests on high-stressed QM#3 at the Centre de Recherches du Cyclotron (CRC) at the Université catholique de Louvain-la-Neuve.
- FM tests at the Paul Scherrer Institute (TBC).
- PV. Possible occasional measurement in routine phase.

Required accuracy

Inputs, prerequisites

Glitch rate predictions for the Herschel orbit. Full modelling of the energy spectrum of particles reaching the detector (protons, secondary particles, electrons and delta-rays), and their deposited energy.

Sources

On ground: a source of radiation

Calibration Implementation Procedure (CIP)

On ground: Determine dark current level with the OGSE closed. The dark current should be measured several times over a timespan of a PACS operational day.

In orbit: Determine dark current level by looking at the cold internal calibrators. The dark current should be measured several times over a timespan of a PACS operational day.

Straylight may be a concern to determine the “true” dark current. For the blue detector it may be possible to move the filterwheel in a blocked filter position.

Estimated time needed

Calibration Analysis Procedure (CAP)

Output, products

Status/version

```
$Revision: 1.9 $
$Date: 2003/09/26 15:51:23 $
```

Req. 1.2.16 Time constant: switch-on spectrometer

Objectives

The PACS instuments has several "operating modes" and it takes some time to switch from one to another. This requirement investigates these timescales.

The operating modes relevant for the spectrometer are: OFF, INIT, SAFE, STANDBY and PRIME (see PACS-ME-PL-005). SAFE mode is the preferred mode when SPIRE or HIFI are prime.

The change from SAFE to STANDBY is the switch of the CREs from their "off" to "standby" state and the switch-on of the bolometers. The stabilisation time for this is about 30 minutes.

The change from STANDBY to any of the PRIME modes will require about 5 minutes for the stabilisation of the CREs going from their standby to operational setting. All other instrumental setting require much less time than these 5 minutes.

The change from any PRIME mode to another PRIME mode will take of order a few seconds.

The thermal time constant for the internal calibrators is of order 15 minutes. [THIS IS POSSIBLY NOT YET CONSIDERED IN THESE NUMBERS]

Fulfilling or fulfilled by

Priority

B

When performed / frequency

ILT.

Required accuracy

Inputs, prerequisites

Sources

Internal calibration sources.

Calibration Implementation Procedure (CIP)

ILT internal calibrators: Determine the signal looking at the internal calibrators with the internal calibrators turned off. Switch-on the internal calibrators to function at their nominal operating temperatures and monitor the signal as a function of time. Determine the timescale for the signal to reach a constant level.

For other components: TBW

Estimated time needed

Calibration Analysis Procedure (CAP)

Output, products

Status/version

First draft version, typo corrections

```
$Revision: 1.6 $
$Date: 2003/09/22 15:20:43 $
```

Req. 1.2.17 Time constant: Bias change, spectrometer

Objectives

Determine the time constants for stable detector operation after changing the bias voltage. It is no expected that there will be a frequent switch in bias voltage once the optimum voltages have been found. Reasons for changes in bias voltage may be environmental effects in orbit leading to detector break-through conditions or increased noise for lower voltages than on ground.

Fulfilling or fulfilled by

Fulfilled by 1.2.1

Priority

C

When performed / frequency

1 Module tests

2 ILT

Required accuracy

There are two aspects:

1 The time to stabilize the bias voltage by the control loop to the new value should be known with an accuracy of 1s.

2 The impact of bias changes on the detector output signals should be monitored and signals should be stable within a few percent.

Inputs, prerequisites

Sources

Calibration Implementation Procedure (CIP)

The investigations are done as part of the bias optimization tests. Bias changes for the red detector are

30 mV	→	40 mV	(+33%)
40 mV	→	50 mV	(+25%)
50 mV	→	60 mV	(+20%)
60 mV	→	70 mV	(+17%)

and for the blue detector

90 mV	→	120 mV	(+33%)
120 mV	→	150 mV	(+25%)
150 mV	→	180 mV	(+20%)
180 mV	→	210 mV	(+17%)
210 mV	→	240 mV	(+14%)
240 mV	→	270 mV	(+13%)

The test procedure contains stabilization times of 30s after bias switch. The following measurement time amounts to 128 s so that time constants up to 2.5 min can be recognized.

Estimated time needed

No extra time on top of bias scans (see 1.2.1).

Calibration Analysis Procedure (CAP)

The house-keeping data of the bias voltage are monitored on-line and are evaluated off-line how fast the voltage settles to the new value. The detector output signals are checked for any drift which may be introduced by switching the bias voltage.

Output, products

If time constants are longer than 30 s, then these have to be taken into account for the operational procedure to switch bias voltages should this become necessary in flight.

Status/version

Third draft: full revision

```
$Revision: 1.7 $
$Date: 2003/09/30 15:59:25 $
```

Req. 1.2.18 Time constant: flux changes, spectrometer

Objectives

Investigate the time constants involved, related to signal transients after flux changes, both from glitches and chopping.

The required time constants on the transient behaviour are $\lesssim$100 ms (goal: $<$30 ms) [PACS-NT-DS-004]

The required duty cycle for the chopper is $>$80% which for a chopper frequency of 10 Hz implies a time constant for the chopper movement of $<$8.5 ms.

The expected glitch rate for the photoconductors is 0.1 per second per pixel with glitch tails estimated to be $<$0.5 sec.

Fulfilling or fulfilled by

Related to 1.2.8 (Signal dependence on chopper frequency) and 1.2.19 (Time constant: cosmic-ray hits, spectrometer).

Priority

B

When performed / frequency

Module level test at the Paul Scherrer Institute regarding the influence of glitches on the signal; ILT regarding the influence of the chopper on the signal; PV verification of results obtained during ground tests.

Required accuracy

Inputs, prerequisites

Sources

Not applicable. Any data obtained using burst mode and the chopper can be used.

Calibration Implementation Procedure (CIP)

Use burst mode to obtain better time resolution.

Estimated time needed

Calibration Analysis Procedure (CAP)

e-folding time scales (TBD).

Output, products

Status/version

Second draft version, 15-02-02, upgrade of "fulfill" item

```
$Revision: 1.9 $
$Date: 2003/09/30 15:59:25 $
```

Req. 1.2.19 Time constant: cosmic ray hits, spectrometer

Objectives

Investigate the behaviour of the detector after a glitch. Just like with flux steps, it can take a certain time before a pixel relaxes to its nominal state. Here we want to investigate the duration of such an event and how the pixel stabilizes after a glitch.

Fulfilling or fulfilled by

Related to 1.2.12

Priority

A

When performed / frequency

- QM Module level tests on high-stressed QM#3 at the Centre de Recherches du Cyclotron (CRC) at the Université catholique de Louvain-la-Neuve.
- FM tests at the Paul Scherrer Institute (TBC).
- PV

Required accuracy

10-20%.

Inputs, prerequisites

None

Sources

On ground: a source of radiation and a source that provides a relevant background level.

Calibration Implementation Procedure (CIP)

On ground: data as taken under requirement 1.1.12 will be sufficient, *unless* the time constant of the glitch tail is comparable to the average time between glitch impacts. In that case, some tests will have to be performed with a lower glitch rate, or, by interrupting the particle beam with a leaden plate (this is possible at CRC-UCL).

In-orbit: Observations on sources of constant illumination without OBSW steps of deglitching and in burst mode.

Estimated time needed

Calibration Analysis Procedure (CAP)

Output, products

Status/version

```
$Revision: 1.8 $
$Date: 2003/09/26 15:51:23 $
```

Req. 1.2.20 Time variation responsivity spectrometer

Objectives

Investigate the time variation of the responsivity of the spectrometer, both on the time scale of an operational day, as well as long term variations.

Fulfilling or fulfilled by

Fullfilled by 1.2.7 (nominal responsivity)

Priority

C

When performed / frequency

PV and routine phase

Required accuracy

Not applicable

Inputs, prerequisites

Time series of responsivity measurements.

Sources

Not applicable

Calibration Implementation Procedure (CIP)

Estimated time needed

Calibration Analysis Procedure (CAP)

Trend analysis of a time series of responsivity measurements.

Output, products

Status/version

```
$Revision: 1.9 $
$Date: 2003/09/22 15:25:06 $
```

Req. 1.2.21 On-board software processing, spectrometer

Objectives

The requirement relates to the processing steps of the data by the on-board software (OBSW). Steps considered are: pre-processing (e.g. linearisation), ramp fitting, glitch detection, ramp rejection, integration (averaging over ramps), temporal and spatial reduncancy reduction and lossless compression (which is also applied to the raw data when all these steps are bypassed).

In particular the ramp fitting, glitch detection and ramp rejection steps are of crucial importance in determining the ultimate scientific quality of the data. The relevant numerical codes of the OBSW will have configurable parameters/files as input, that can be uploaded.

The aim of the requirement is twofold: (1) determine the optimum choise of these parameters, and (2) determine the "pseudo-noise" introduced by the OBSW processing steps.

Fulfilling or fulfilled by

Priority

A

When performed / frequency

Different schemes for ramp fitting, glitch detection and ramp rejection need to be developed, with preliminary parameter settings set by simulated datasets.

A first analysis with possible refinements to the software and its associated parameters will be possible using the radiation test at the module level at CRC-UCL.

Data obtained in-orbit will be used for further refinements and final settings.

Required accuracy

Inputs, prerequisites

Sources

Calibration Implementation Procedure (CIP)

Compare raw data to data obtained using the OBSW processing using different values for the configurable parameters for different observing modes. Determine the optimum set of parameters by optimising the S/N on the reduced data, and characterise the "pseudo-noise" introduced by the OBSW processing.

Estimated time needed

Calibration Analysis Procedure (CAP)

Output, products

Status/version

```
$Revision: 1.8 $
$Date: 2003/09/26 15:51:23 $
```

Req. 1.2.22 Cross-talk, electrical, spectrometer

Objectives

Determine the electrical cross-talk between detector pixels of the spectrometer.

Fulfilling or fulfilled by

fulfilled by 1.2.12

Priority

B

When performed / frequency

QM Module level tests at the CRC-UCL (only a linear array will be available)

The possibility of using a γ-ray source next to the cryostat at MPE during ILT should be investigated.

In-orbit.

Required accuracy

Inputs, prerequisites

Sources

On ground: a source of radiation and a source that provides a relevant background level.

Calibration Implementation Procedure (CIP)

Analyse cosmic ray hits where only ONE pixel is hit. Check for the response of neighbouring pixels.

Estimated time needed

Calibration Analysis Procedure (CAP)

Output, products

Status/version

```
$Revision: 1.8 $
$Date: 2003/09/26 15:51:23 $
```

Req. 1.2.23 Curing, spectrometer

Objectives

Verify the effectiveness of possible different curing procedures. Determine the time constants involved after curing. Investigate the necessary frequency of curing.

Fulfilling or fulfilled by

Priority

A

When performed / frequency

After the radiation tests on the QM at CRC-UCL a first indication of the change in responsivity with time caused by radiation impacts is known.

If these tests indicate that curing is an issue the procedures need then to be determined on the FM. One possibility is to flash the detector, and for that the internal BBs are intended.

Verification of procedures in PV.

Required accuracy

Inputs, prerequisites

Sources

On ground: a source of radiation and a source that provides a relevant background level.

Calibration Implementation Procedure (CIP)

QM test at CRC-UCL: would it be possible to do first curing test using the equipment that provides the background radiation at these tests ? This might indicate which flux level is necessary for curing (or at least, the highest flux that is NOT enough for curing).

At FM the external blackbodies should have sufficient power (the detectors are required to cope with up to 10^{-7} Watt/pixel) to determine the flux level necessary for curing.

If the internal blackbodies can not provide this power [note that it is undesirable to change the temperature of the PACS internal blackbodies due to the long thermal timescales], then this will have severe consequences, and implies possible hardware changes [create open filter positions; heaters].

Estimated time needed

Calibration Analysis Procedure (CAP)

Output, products

Status/version

First draft version

```
$Revision: 1.8 $
$Date: 2003/09/26 15:51:23 $
```

Req. 1.2.24 Spectral Responsivity

Objectives

The aim is to characterise the relative spectral response of the low- and high-stressed Ge:Ga detectors. Of particular importance is the determination of the cut-off wavelength (i.e. the point where 50% of the maximum responsivity is reached), and to determine the unformity in responsivity over one detector module (see PACS-NT-DS-004 "Detector arrays: Design and Performance Specification").

Fulfilling or fulfilled by

Priority

A

When performed / frequency

During module level tests

Required accuracy

10 % (goal) in the relative measurement of a single detector. Uniformity of 15 % (goal) in the peak relative responsivity over 16 detectors.

Inputs, prerequisites

Sources

Described in PACS-NT-PL-002 "Relative Spectral Responsivity Measurement Configuration".

Calibration Implementation Procedure (CIP)

Described in PACS-NT-PL-002 "Relative Spectral Responsivity Measurement Configuration".

Estimated time needed

Calibration Analysis Procedure (CAP)

Output, products

For every pixel : the relative spectral response tabulated: (e.g. response : signal/flux density [(microvolts/sec)/(W/cm^2/Hz)] versus Wavelength [micrometer])

Status/version

```
$Revision: 1.7 $
$Date: 2003/09/22 15:32:39 $
```

Chapter 2

Optical Components

2.1 Filters

Req. 2.1.1. Filter transmission nominal

Objectives

The knowledge of the wavelength dependent absolute filter transmission is an essential part in the determination of the relative system response of the photometer. The relative system response is needed for sensitivity calculations with the time estimator and hence linked to the AOT logic as well as for the deduction of color correction factors. The absolute transmission of the photometric filters shall be measured.

Fulfilling or fulfilled by

Priority

A

When performed / frequency

As part of the ground module characterization. Filter transmission curves will be provided by the manufacturer, but also be measured independently.

Required accuracy

5% in peak (TBC) and with a resolution of 0.2 μm (TBC).

Inputs, prerequisites

Sources

Calibration Implementation Procedure (CIP)

Measure the transmission curve with a Fourier Transform Spectrometer (TBC).

Estimated time needed

Calibration Analysis Procedure (CAP)

Results are an outcome of the FTS measurements. A threshold above which the transmission values are meaningful shall be specified.

Output, products

Table: filter transmission versus wavelength, threshold of meaningful transmission values

Status/version

Second draft version, 14-02-02

Req. 2.1.2. Filter leaks

Objectives

Depending on the spectral energy distribution of celestial sources out-of-band filter leaks can lead to wrong photometric fluxes. The delivered filters should be checked for possible leakage inside the sensitive wavelength range of the detector systems. In-flight measurements on celestial standard sources with blue and red SEDs should confirm either no leakage or the amount of contamination by filter leaks.

Fulfilling or fulfilled by

In-flight fulfilled by 3.2.2 (Full System Calibration Photometer: relative system response and color corrections)

Priority

A

When performed / frequency

- [1] As part of the ground module characterization
- [2] During PV Phase as part of the full system calibration of the photometer

Required accuracy

Verify that the out-of-band suppression is as good as TBD. Probe that in steps of 10 μm (the bolometers are sensitive out to at least 400 μm).

Inputs, prerequisites

Sources

Calibration Implementation Procedure (CIP)

Measure the transmission curve with a Fourier Transform Spectrometer (TBC).

Estimated time needed

Calibration Analysis Procedure (CAP)

Results are an outcome of the FTS measurements. A threshold above which the transmission values are meaningful shall be provided.

Output, products

Table: filter transmission versus wavelength (extended range), threshold of meaningful transmission values.

Status/version

Second draft version, 14-02-02

Req. 2.1.3. Transmission of order sorting filters

Objectives

The Littrow-mounted grating is operated in 1st, 2nd or 3rd order, respectively to cover the full spectrometer wavelength range. Corresponding wavelength bands are 105–210 μm, 72–105 μm and 57–72 μm. Suppression of out-of-band contributions due to other grating orders is achieved by a dichroic beam splitter and order sorting filters. The transmission properties of the spectrometer order sorting elements shall be determined to verify that the transmission is nominal inside the specified wavelength range and sufficient suppression is achieved outside this wavelength range. Any shift of the order sorting filter wavelength range w.r.t. the specified band can lead to features in the instrumental response function. Insufficient higher order suppression will lead to wrong flux calibration, depending on the source SED.

Fulfilling or fulfilled by

In-flight fulfilled by 4.3.8 (Relative spectral response function, spectrometer)

Priority

B

When performed / frequency

- [1] As part of the ground module characterization. Filter transmission curves will be provided by manufacturer (TBC), but also be measured independently (TBC).
- [2] During PV Phase as part of the full system calibration of the spectrometer

Required accuracy

Verify that the transmission range is matched to the specified grating wavelength range within 1 μm (TBC). Verify that the out-of-band suppression is as good as TBD over the sensitive wavelength range of the photoconductor cameras.

Inputs, prerequisites

Sources

Calibration Implementation Procedure (CIP)

Measure the transmission curve with a Fourier Transform Spectrometer (TBC).

Estimated time needed

Calibration Analysis Procedure (CAP)

Results are an outcome of the FTS measurements. A threshold above which the transmission values are meaningful shall be provided.

Output, products

Table: filter/dichroic transmission versus wavelength (extended range), threshold of meaningful transmission values.

Status/version

First draft version, 14-02-02

2.2 Grating

Req. 2.2.1 Grating efficiency spectrometer

Objectives

The spectrometer uses a reflective diffraction grating in Littrow mount. The grating is a diamond ruled aluminium grating. Knowledge of the grating efficiency of the spectrometer (as function of wavelength) is important in view of the investigation of the overall sensitivity of the spectrometer. The grating efficiency, in combination with the responsivity of the detector and transmission of the filter determines the full system RSRF.

Fulfilling or fulfilled by

Ground-test. It is planned to perform an interferometric test (at CSL?) to measure the actual surface accuracy of the grooves.

It is not intended to measure the grating efficiency independently. What can be used is the theoretical grating efficiency. This has been calculated using the PCGRATE EM code. According to Norbert Geis, this calculation is assumed to be accurate up to 5However, assuming that everything is within the tolerances specified in the grating requirements doc, there should be no systematic errors more than 1%

It is foreseen to measure the FIR grating sample (10 cm size) performance with the FTS spectrometer at MPE. This measurement is expected to be deliver, at best, 10% accuracy in intensity, allowing large dicrepancies to be detected.

Priority

A

When performed / frequency

Required accuracy

The calculation of the efficiency is assumed to provide 5% accuracy.

Inputs, prerequisites

Sources

Calibration Implementation Procedure (CIP)

Estimated time needed

Calibration Analysis Procedure (CAP)

Output, products

Status/version

```
$Revision: 1.5 $
$Date: 2002/09/20 08:50:33 $
```

2.3 Chopper

The focal plane chopper is a central element of the PACS instrument, both for the photometer and spectromter part. It serves as

1) beam modulator allowing to perform differential measurements and step scans on the sky;

2) feeding-in mirror for the internal calibration sources to monitor the stability of the detectors.

An overview of its basic principle is given in “A Cold Focal Plane Chopper for the PACS Instrument of the FIRST (now: Herschel) Satellite - Tests of an Advanced Prototype” (PACS-MA-TR-001). Detailed specifications of the chopper performance are outlined in the document “Chopper Specification” (PACS-ME-RS-001). An overview of the module level tests is given in the document “Verification and test Plan for the PACS Chopper” (PACS-MA-PL-409). A 4 K life time test will verify that the chopper mechanics allows ≈ 570 million cycles in observation mode (on sky) and ≈ 63 million cycles in calibration mode (on internal calibrators).

Req. 2.3.1. Angular Calibration of the Focal Plane Chopper

Objectives

Establishment of the focal plane chopper (FPC) angular calibration (i.e. chopper deflection vs. read-out of chopper position sensors) on ground at the component level.

Determination of electrical, mechanical, and optical zero points. Verification of the on-ground zero-point calibration in-orbit. `I'm not sure about the definition of electrical zero point. Mechanical zero is where the chopper is when there is no current in the drive, I assume. Optical is what is defined below.`

The closely related angular calibration at the full system level using stars is discussed in Req. 3.1.2.

Fulfilling or fulfilled by

Priority

A

When performed / frequency

- [1] During component-level chopper verification by manufacturer
- [2] During ILT tests
- [3] During Performance Verification

Required accuracy

[1] 1 arcmin deflection. This corresponds to ≈ 0.2 of a blue photometer pixel, given the nominal conversion factor (N.Geis 13.2.03): 80.69arcmin rotation of the chopper mirror corresponds to 1arcmin movement 'on sky'.

[2,3] Max. offset relative to optical axis: 5 arcsec (less than two blue photometer pixels) (TBC, this is a tradeoff between a desire for best optical quality and maximum chop throw on one side, and the wish to do unchopped observations at a zero point that is almost current-less). Required stability 1 arcmin chopper deflection.

Inputs, prerequisites

Sources

- [1] During ground verification by manufacturer: optical Laser source
- [2] PACS internal calibrators, OGSE blackbody or OGSE window
- [3] PACS internal calibrators, telescope background

Calibration Implementation Procedure (CIP)

- [1] The chopper mirror is rotated in fine steps by increasing the current through the electromagnetic drive. The deflection of a Laser beam is measured with a CCD camera. This will establish a relation between chopper field plate readout and angular deflection. The zero position of the chopper will be measured with an alignment telescope, against a reference mirror which is equipped on the adapter (see document PACS-MA-PL-409, "Verification- and Test Plan for PACS Chopper", for more details).
- [2] In case of proper instrument alignment, the mechanical zero position of the chopper will point the bolometer array FOV in the middle between the two PACS calibration sources. Verify this by the following procedure: Set

an OGSE blackbody to a temperature producing a reasonable background, or use OGSE window and filter on LN2 shield to produce a reasonable and smooth background. Set both internal calibrators of PACS to temperatures producing a flux above this background. Then start a symmetric chop around the chopper zero position and increase throw in steps of 5arcsec, starting at a throw of 180arcsec. Once the chopper throw is big enough to reach the internal calibrators check the on-off subtracted images – are the 'jumps' at the edges of the images symmetric to the center?

The first CQM ILT will have no bolometers and only partial spectrometer arrays and requires a modification of this procedure using the spectrometer: Switch on internal calibrators, direct FOV at OGSE blackbodies that are cold or at least produce a signal differing significantly from internal calibrator signal. Set up spectrometer. Scan chopper slowly over the full range including and between the two internal calibrators, and define the optical zero as the mean between the two chopper positions where the central pixel of the spectrometer moves off/on the calibrators.

- [3] As [2] but with normal telescope background.

Estimated time needed

[2],[3] setup times plus a few minutes.

Calibration Analysis Procedure (CAP)

- [1] See document PACS-MA-PL-409 and references therein.
- [2,3] Subtract on-off and measure the positions of the 'steps' at the edges. Determine mean and compare to center of array.

  First CQM ILT: plot signal of central pixel as a function of chopper position and determine transitions off/on calibrators and their mean.

Output, products

- [1] Table: position sensor (field plate) read-out versus chopper angular deflection
- [2,3] Verification that chopper mechanical zero point is precisely on optical axis (or, if offset were too large, definition of an optical zero point around which chops have to be done). This requirement sets the 'defined chopper position' assumed in section 3.1 and 4.1 as the PACS optical axis around which normal chops will be symmetric.

Status/version

Now coordinated with 3.1.1 and 3.1.2. Special CQM ILT situation now considered.

`$Revision: 1.5 $`
`$Date: 2003/04/17 09:31:15 $`

Req. 2.3.2. Duty cycle of waveforms

Objectives

The chopper mirror should spend a high percentage of a chopper cycle in a defined (final) position allowing measurements, transition times should be minimal. For on-sky measurements a duty cycle $\geq$ 80%, for measurements on the internal calibration sources a duty cycle $\geq$ 70% (due to the larger throws) is required. On-sky measurements comprise various wave modes from square wave to triangular scans on many positions, on-calibration source measurements are square wave. Due to synchronization with the detector read-out, the measurement period may be shorter than the period the chopper is in a final position.

Fulfilling or fulfilled by

Priority

B

When performed / frequency

- [1] During ground verification by manufacturer
- [2] During ground tests
- [3] During Performance Verification

Required accuracy

The required duty cycle is $\geq$ 80% for any waveform on-sky and $\geq$ 70% for square wave modulation on calibration sources, both for the frequency range 0–10 Hz.

Inputs, prerequisites

Calibration of the chopper position sensor.

Sources

No source needed, internal measurement possible.

Calibration Implementation Procedure (CIP)

In order to verify the duty cycle the read-out of the chopper positional sensor (field plate) is used. Any chopped measurement is useful, but the operational frequency and chop throw range (including chop to internal calibrators) should be covered and also the various waveforms be executed.

Estimated time needed

Calibration Analysis Procedure (CAP)

The positional data with time are ordered according to chopper cycle phase. The fraction of on-position periods (all plateaux of a chopper cycle) within the specified plateau accuracy ($\pm$1 arcsec (TBC)) with regard to the total chop period is determined. This evaluation also serves to check the positional stability of the chopper.

Output, products

Verification of the waveform, including verification of the stability of the chopper deflection during the chopper plateau.

Status/version

Second draft version, specification of item output

```
$Revision: 1.2 $
$Date: 2002/09/17 14:11:20 $
```

Req. 2.3.3. Optimal Positioning of Chopper on Internal Reference Sources

Objectives

The focal plane chopper mirror is used to image the internal reference sources onto the detector arrays by deflecting it outside the sky field-of-view. The illumination of the detector arrays should be as homogeneous as possible, that means the calibrator sources should be imaged centrally onto the arrays.

Fulfilling or fulfilled by

Priority

A

When performed / frequency

- [1] During ILT tests, when combined operation of chopper and internal reference sources is possible
- [2] During satellite commissioning (no view outside the instrument necessary), if alignment due to launch load should be a concern

Required accuracy

The signal of the internal sources should be maximum and as much as possible flat over the arrays (accuracy depends somewhat on the properties of the internal sources).

Inputs, prerequisites

Chopper must have fine stepping capabilities in the deflection range on the internal sources to maximise signal and homogeneity of illumination.

Sources

Measurement on internal reference sources

Calibration Implementation Procedure (CIP)

Scan the chopper in fine steps (2") over a certain range around the nominal positions of the internal reference sources. Use both blue and red arrays of photometer and spectrometer channel to optimise internal reference source signal on the arrays.

Estimated time needed

Calibration Analysis Procedure (CAP)

Compare flatness and signal for the internal reference source frames depending on chopper step (are there any significant vignetting effects, if chopper mirror is outside the nominal internal reference source beam?)

Output, products

Table: for both calibrators position sensor read-out versus array in use.

Status/version

Third draft version, minor change,

```
$Revision: 1.3 $
$Date: 2002/09/17 14:17:05 $
```

2.4 Imaging Optics

This section collects a number of requirements mostly corresponding to modelling of optical components, in order to later optimally execute and interpret the instrument and system level spatial, spectral, and photometric calibrations.

Req. 2.4.1 Spatial Distortion: Photometer

Objectives

Model the spatial distortions induced by PACS, as input and interpretation aid for the photometer spatial calibrations described in Sect. 3.1

The fast Herschel mirror system induces a curved and distorted "focal bowl" in which PACS is located off center. PACS is designed for that situation, and to partly compensate for the distortion induced by the Herschel telescope. This makes the telescope focal plane an ill-suited location for many modelling and measurement tasks. The approach taken below is to provide optical modelling of (a) the combination Herschel and PACS and (b) the combination test optics and PACS which both can be confronted with actual measurements (Sect. 3.1.3). If ILT measurements on the combination test optics and PACS deviate significantly from the appropriate model, model predictions for Herschel and PACS can be corrected equivalently, provided the test optics is well understood. `do we need special tests on test optics alone to be sure?`

Modelling already done by N.Geis indicates distortions of up to 2/3 of a blue channel pixel if the chopper centers the FOV on the optical axis. Distortions will be larger when chopping with a significant offset.

Fulfilling or fulfilled by

Self-Standing

Priority

A

When performed / frequency

Before/during ILT

Required accuracy

Models must describe the relation between telescope and array coordinates to a small fraction of a blue pixel (1/10 TBC). This requires sufficient sampling of spot diagrams to obtain reliable centers of gravity.

Inputs, prerequisites

PACS, Herschel, and test optics optical model in Zemax

Sources

none

Calibration Implementation Procedure (CIP)

none

Estimated time needed

No observing time but computation intensive.

Calibration Analysis Procedure (CAP)

Use Zemax to compute spot diagrams for a large number of input positions on sky, and for several chopper positions. If possible make use of symmetries to reduce number of points (this may not be the case). Compute centers of gravity for spot diagrams. Derive transformations from array to telescope coordinates and vice versa (both are additionaly a function of chopper position), and fit suitable parametrizations.

Do this both for the ILT (test optics and PACS) and in-orbit (Herschel and PACS) situation.

Computation requirements: Needs a three dimensional grid (two spatial positions and chopper throw). Computations fast but setup time of software significant. Number of grid points to achieve desired accuracy and number of spots in spot diagram TBD.

Output, products

Parametrized transformations between array and telescope coordinates, for both ILT and in-orbit situations.

Status/version

Has to be converted into a workplan for modelling

```
$Revision: 1.2 $
$Date: 2002/12/11 15:08:33 $
```

Req. 2.4.2 Spatial Distortion: Spectrometer

Objectives

Model the spatial distortions induced by PACS, as input and interpretation aid for the spectrometer spatial calibrations described in sect. 4.1

The same general considerations as for the photometer section apply. The requirements are relaxed in some sense because of a smaller array and larger pixels, but diffraction in the slicer induces additional complications: Spatial distortion is in addition a function of wavelength, and the relation between array and telescope coordinates is for one dimension not a simple trend but somewhat modulated with position inside a pixel.

Fulfilling or fulfilled by

Self-Standing

Priority

B

When performed / frequency

Before/during ILT

Required accuracy

Models must describe the relation between telescope and array coordinates to a small fraction of a spectrometer pixel (1/10 TBC).

Inputs, prerequisites

PACS, Herschel, and test optics optical model in Zemax.

Sources

none

Calibration Implementation Procedure (CIP)

none

Estimated time needed

No observing time but computation intensive.

Calibration Analysis Procedure (CAP)

Use Zemax and Glad to compute centroids for a large number of input positions on sky, for several chopper positions and several wavelengths. Make use of symmetries to reduce number of points, if this is possible. Compute centroids. Derive transformations from array to telescope coordinates and vice versa (both are additionally a function of wavelength and chopper position), and fit suitable parametrizations.

Do this both for the ILT (test optics and PACS) and in-orbit (Herschel and PACS) situation.

Computation requirements: Needs a four dimensional grid (two spatial dimensions, wavelength, chopper throw), Computing effort TBD (Zemax calculations with Glad ”corrections”?). Number of grid points to achieve desired accuracy TBD.

Output, products

Parametrized transformations between array and telescope coordinates, for both ILT and in-orbit situations.

Status/version

Needs to be converted into a modelling workplan

```
$Revision: 1.2 $
$Date: 2002/12/11 15:16:35 $
```

Req. 2.4.3 Spectral Distortion

Objectives

Model spectral distortion induced by PACS (i.e. deviations of the surfaces of constant wavelength from a plane in the datacube), as input and interpretation aid for the photometer spectral calibrations described in sect. 4.2. Modelling already done by N. Geis indicates 'smile-shaped' shifts of the order 1 spectral pixel, depending on grating angle and pixel. The shift varies along the spectral dimension of the array, i.e. there is local nonlinearity.

Fulfilling or fulfilled by

Self-Standing

Priority

B

When performed / frequency

Before/during ILT

Required accuracy

1/5 of a spectral pixel (TBD)

Inputs, prerequisites

PACS, Herschel, and test optics optical model.

Sources

none

Calibration Implementation Procedure (CIP)

none

Estimated time needed

No observing time but computation intensive.

Calibration Analysis Procedure (CAP)

Use Zemax to compute spot diagrams for a number of wavelengths.

Output, products

Examples of spectral distortion for a number of wavelengths.

Status/version

Needs to be converted into a modelling workplan

```
$Revision: 1.2 $
$Date: 2002/12/11 15:25:00 $
```

Req. 2.4.4 Straylight Suppression in Optics

Objectives

Characterize straylight inside PACS. The instrument is designed to minimize straylight (baffles, black paint etc.) but verification is highly desirable. Both a full end-to-end PACS straylight model and tests using directed far-infrared radiation appear impracticable. The approach taken is to use simple qualitative tests with optical laser light during assembly of the instrument. Related topics at system level are addressed in requirements 3.1.6, 4.1.5, and 7.3.

Fulfilling or fulfilled by

Self-standing

Priority

B

When performed / frequency

During assembly of instrument, taking into account insertion of optically intransparent filters

Required accuracy

Qualitative tests

Inputs, prerequisites

Sources

Optical laser

Calibration Implementation Procedure (CIP)

Send laser light into instrument at various angles

Estimated time needed

Calibration Analysis Procedure (CAP)

Check whether light shows up at undesired locations.

Output, products

Status/version

Draft

```
$Revision: 1.3 $
$Date: 2002/12/18 10:23:01 $
```

Req. 2.4.5 Optical Throughput

Objectives

Quantify effects relevant for the throughput/transmission of the instrument that are not covered by other requirements. Such information is needed to properly interpret the system level (photometric) response. Explicitly covered by other requirements but related are: Filter transmissions (2.1), Grating efficiency (2.2.1), Detector responses (1.1.2, 1.2.7.) Detector spectral responses (1.1.22, 1.2.23) Two factors remain to be quantified:

- Mirror reflectivities. The large number of reflections in the folded light path induces an overall noticeable effect despite high individual reflectivities.
- Diffraction losses in the spectrometer. Mirrors and grating are somewhat oversized but induce losses in particular at long wavelengths.

Fulfilling or fulfilled by

Self-standing

Priority

B

When performed / frequency

Before/during Instrument Level Tests

Required accuracy

10% each for total mirror reflectivity losses and diffraction losses. These numbers do not enter the final photometric calibration accuracy, but rather are needed to find out whether the measured absolute response is in line with expectations for the PACS design.

Inputs, prerequisites

Sources

none

Calibration Implementation Procedure (CIP)

Estimated time needed

No observing time in ILT or orbit.

Calibration Analysis Procedure (CAP)

Mirror reflectivities: Estimate total loss on the basis of the number of reflections for a particular light path, and assuming wavelength-independent 99$\pm$0.5% reflectivity (TBC) for each reflection (This reflectivity is notoriously ill-known and difficult to measure). Example: For 13 reflections in one of the bolometer paths the total loss is 12% (6 to 18%).

Spectrometer diffraction losses: TBD Modelling or estimates, sampling wavelength dependency at a few points.

Output, products

Status/version

Early incomplete draft

`$Revision: 1.2 $`

$Date: 2002/12/11 16:03:28 $

2.5 Internal Reference Sources

The internal reference sources are used to monitor the performance of the detector arrays. They serve as transfer calibrators for regular but less often performed flux calibrations on celestial standards. They shall provide a uniform illumination of all pixels in all detector arrays. Their fluxes shall be comparable to that from the telescope to avoid changes in the IR-radiation load. An overview of their basic principle and performance requirements is given in the document “Calibration Source Performance Requirements” (PACS-ME-RS-010). Basic measurement schemes on module level are outlined in this document as well. A more detailed design of the calibration sources is provided in the document “FPFPU Calibration Source Interface Control Document” (PACS-KT-ID-007). More detailed aspects on the Calibration sources can be found in “FPFPU Calibration Source Interface Control Document”, PACS-KT-ID-007. Results from the first sub-unit level test can be found in “Emissivity of PACS Calibration Source Baseline Model”, PACS-ME-TR-010 and “Calibration Source Thermal Characteristics: Test Results and Analysis for the Baseline Model”, PACS-ME-TR-011.

Req. 2.5.1. Temporal stability of PACS calibration sources

Objectives

Both PACS detector types, bolometers and photoconductors, show drifts in their responsivity induced by ionizing radiation hits. For accurate absolute photometry these drifts have to be monitored by frequent transfer measurements against a stable reference source which itself is absolutely calibrated against a laboratory blackbody or celestial standards. Such a source must be highly stable over a time period covered by a celestial calibration and reproducible in illumination in order to be not the limiting factor in the final photometric accuracy. Its long term stability must be monitored against celestial standards.

Fulfilling or fulfilled by

In-flight fulfilled by 3.2.2 (monitor nominal responsivity variations of photometer with time) and 4.3.2 (flux reproducibility internal sources, spectrometer).

Priority

A

When performed / frequency

- [1] As part of the on-ground module characterization
- [2] During ILT tests
- [3] In-flight monitoring program

Required accuracy

The steady state stability (achieved ~ 1 h after switch-on of the sources) should be as good as 0.05 % peak-to-peak over all time periods between 0.1 s and 1 week. This means a relative temperature stability of 10^{-4} for the heater (cf. document "Calibration Source Performance Requirements" (PACS-ME-RS-010)).

Inputs, prerequisites

Sources

BB reference sources for ground tests, non-variable celestial standards in-flight.

Calibration Implementation Procedure (CIP)

- [1] On-ground module characterization (measurement plan given in PACS-ME-PL-022). Emissivity measurements of the first PACS calibration sources have been performed and lead to an emissivity value of 19 ± 4 % (specification between 4 and 16 %!). Adjustments with respect to the emissivity have been made (by KT) and model predictions gave now an emissivity value of about 10 % (detailed measurements: still to be done).

  The thermal characterization of the first calibration source gave a reproducible resistance-temperature relationship for the PT500. Balistic heating and cool-down characteristics were recorded in the full required temperature range. Steady state values were obtained over several hours.

  Currently, the calibration source characterization takes place at CSL, including control electronics (PID servo loop). This will result in a characterization of the temporal stability and the time constants for heating up and cooling down phases.

- [2] ILT tests:

  a) repeated long lasting exposures, if possible with a blocked entrance beam of the test cryostat (assuming no detector drifts).

b) alternating chop sequences on external BB (extended source) and internal calibration sources.

c) calibration source measurements (against the OGSE black bodies) for different FPU temperatures (expected temperature range is between about 3 and 6 K).

These measurements are, most likely, covered by the foreseen test procedures and require therefore no additional test.

- [3] In-flight: repeated checks against same celestial standard. Raster mode to illuminate as many pixels as possible to show stability of homogeneity, too.

Estimated time needed

Calibration Analysis Procedure (CAP)

a) analyse calibration source signals on absolute level (and relative to the OGSE black bodies) before and after long exposures

b) analyse short term stability of the calibration sources by looking at the signal ratios for alternating chop sequences on external BB (extended source) and internal calibration sources.

c) Find calibration source / OGSE black bodie measurements with the same instrument and black body settings, but different FPU temperatures. Analyse the OGSE to calibration source signal ratios as a function of FPU temperatures.

Output, products

Status/version

Second draft version, minor upgrade,

```
$Revision: 1.4 $
$Date: 2003/09/30 15:50:37 $
```

Req. 2.5.2. Spatial stability (isotropy and homogeneity) of PACS calibration sources

Objectives

The calibration sources shall uniformly illuminate all pixels of the photometric cameras in order to monitor their flat-field behaviour. For the spectrometer a uniform illumination of the grating is important for the assessment of the spectral flat-field.

Fulfilling or fulfilled by

Related to 3.2.8 (Measure the photometer full system flat-field) and 4.3.9 (Flat-field spectrometer internal sources). Related to 2.3.3 (Optimal Positioning of Chopper on Internal Reference Source).

Priority

A

When performed / frequency

- [1] As part of the on-ground module characterization and modelling of the calibration source behaviour
- [2] During ILT tests
- [3] In-flight

Required accuracy

The isotropy of the sources in surface brightness averaged over the exit aperture is required to be better than 0.05% for all angles of exitance within ± 11.5 deg from the source axis (definition of illuminated field of view). The homogeneity shall be better than $\pm$ 5% (cf. document "Calibration Source Performance Requirements" (PACS-ME-RS-010)).

Inputs, prerequisites

Sources

BB reference sources for ground tests, celestial sources in-flight.

Calibration Implementation Procedure (CIP)

The isotropy of the PACS calibration sources can be tested in the following way:
a) in chopper direction by scanning the calibration sources (different chopper amplitudes) against an OGSE black body (see req. 2.3.3). b) perpendicular to the chopper direction via an externally flat-fielded detector array (isotropy in spacecraft z-direction over the size of the detector array).

- [1] On-ground module characterization: see document PACS-ME-RS-010.
- [2] ILT tests:
  - a) Comparison of signal pattern of arrays from illumination with internal calibration source with that of scan with point-like BB source (only for illuminated pixels) (flat enough external illumination unlikely?).
  - b) Scan of internal calibration sources with chopper (cf. req. 2.3.3).
- [3] In-flight: Comparison of signal pattern of arrays from illumination with internal calibration source with that of scan with point-like celestial source (only for illuminated pixels) (inhomogeneity of telescope background?)

Estimated time needed

Calibration Analysis Procedure (CAP)

see req. 2.3.3. for the analysis of chopper scan sequences, req. 4.3.10. for the analysis of flat-field spectrometer external sources and req. 3.2.8 for the photometer full system flat-field.

Output, products

Status/version

Second draft version, minor upgrade

```
$Revision: 1.3 $
$Date: 2003/09/26 15:23:11 $
```

Req. 2.5.3. Time constants: heat-up and cool down times of PACS calibration sources

Objectives

The heater sources of the internal calibrators need to be heated up and to stabilize before they remain in a more or less steady state during the PACS operational period. For any upward adjustment a temperature control circuit applies a ballistic heating pulse followed by a stabilization period. Since there is no active cooling, the thermal time constant of the heater source, determined by the heat capacity of the heater and its coupling to the FPU thermal bath, determines the cool-down time. These time constants should be known for operational procedures and mission planning constraints.

Fulfilling or fulfilled by

Priority

C

When performed / frequency

- [1] As part of the component tests during on-ground module characterization (currently done at CSL including the calibration source control loops and at MPE without control loop)
- [2] During ILT tests (nominal switch on and off procedures)
- [3] In-flight during commissioning (no view outside the instrument necessary).

Required accuracy

The temperature read-out of the control circuit needs to be as accurate as 10^{-4} of the heater temperature to verify the required stability of the source (see req. 2.5.1)

Inputs, prerequisites

Calibration of the temperature sensor

Sources

Calibration Implementation Procedure (CIP)

The read-out of the temperature sensor is monitored for heating pulses of certain temperatures including stabilization times and cool-down times after switch-off.

Estimated time needed

Calibration Analysis Procedure (CAP)

The read-outs of the temperature sensor of the heating loop are plotted with time.

1 switch-on time constant is determined for temperature reaching 5% of the final temperature.

2 stabilization time constant is determined for temperature stability being within $\pm 10^{-4}$ of steady state temperature.

3 cool-down time constant is determined for temperature reaching stable value close to bath temperature.

Output, products

Status/version

First draft version, 15-02-02

Req. 2.5.4. Emissivity of PACS calibration sources

Objectives

The calibration sources shall simulate the thermal emission from the Herschel telescope. The emission spectrum of the telescope is assumed to correspond to a gray-body. Because of the wide wavelength range of 2 octaves and the simultaneous use of short and long wavelength arrays, the calibration sources must mimic the colour and temperature of the telescope, i.e. they should also be gray. Due to the current uncertainty of the telescope emissivity of a factor of 2, the effective emissivity of the sources must be configurable and be adjusted during AIV activities once the telescope emissivity will be better known.

Fulfilling or fulfilled by

Priority

A

When performed / frequency

- [1] As part of the on-ground module characterization
- [2] During AIV tests (configuration of final emissivity)

Required accuracy

The emissivity of the sources has to compensate a different optical path. The range of anticipated telescope emissivity is $\varepsilon_{\rm tel} \sim 2\,\%...8\,\%$. The effective emissivity of the sources shall be configurable between $0.04 < \varepsilon < 0.16$.

Inputs, prerequisites

Heating current vs. temperature relation of the emitter.

Sources

Calibrated BB (inside cryostat) with temperatures typical fpr telescope (50...100 K) coupled into the sky beam.

Calibration Implementation Procedure (CIP)

The emissivity of a radiator of temperature T is defined as the ratio of the radiance of this radiator to the radiance of a BB source of the same temperature. For all three PACS filters this ratio should be determined for a range of temperatures to establish $\varepsilon(\lambda$,T) and perform and verify the final adjustment, once the telescope emissivity will be better defined.
Emissivity measurements of the first PACS calibration sources have been performed and lead to an emissivity value of $19\pm4\,\%$ (specification between 4 and 16 %!). Adjustments with respect to the emissivity have been made (by KT) and model predictions gave now an emissivity value of about 10 %. Detailed measurements can be done in the CQM test cryostat together with the OGSE black bodies and well-characterized filters and attenuators.

Estimated time needed

Calibration Analysis Procedure (CAP)

ILT test of the emissivity: similar to the analysis given in PACS-ME-TR-010 on the “Emissivity of PACS calibration source baseline model”.

Output, products

Adjustment of sources to telescope emissivity

Status/version

First draft version,

```
$Revision: 1.2 $
$Date: 2003/09/26 15:23:39 $
```

2.6 Telescope Pointing Quality

Req. 2.6.1 Absolute Pointing Error

Objectives

Herschel pointing requirements as specified in section 5.12.2 of the IID-A are crucial for success of PACS observations, and PACS as the highest spatial resolution instrument is key for testing whether they are met. IID-A section 5.12 also gives the definitions of APE, PDE, RPE, AME.

The purpose of this requirement is to verify that the separation between (instantaneous) actual direction and commanded direction for pointed observations is within the IID-A requirements/goals. The same measurements will verify the a posteriori AME for pointed observations. This specification covers 'fine pointing' (cf. First Scientific Pointing Modes Document), 'raster pointing' which is a sequence of fine pointings, as well as 'position switching' and 'nodding' (also sequences of fine pointings).

Fulfilling or fulfilled by

Most of the analysis can be done one the basis of other data, taken e.g. for photometric calibration, and on the basis of science observations. Any observation of a bright (point) source with position known to subarcsecond accuracy is suited. Dedicated observations are likely needed very early as part of commissioning, related to establishing the central pointing position.

Priority

A — Identification of objects, and even Herschel observations with HIFI are impossible without good pointing.

When performed / frequency

Dedicated observations in commissioning or early PV. Data analysis of other observations all over the mission.

Required accuracy

The satellite 1σ AME goal is $<$=1.2". Using the blue bolometer channel, a random error of $\sim$0.5" of an individual measurement corresponds to $\sim$beam/14 or pixel/7 which should be realistically achievable despite systematic effects. Assuming positions can be derived to FWHM/2(S/N), measurements need a S/N well above 7 to be of any use. In the following we require S/N$>$20. Adding in quadrature 0.5" measurement error and 0.5" error of the catalogue source position gives $\sim$0.7" accuracy of an individual measurment which would constrain the goal APE at the 2σ level and the required APE (3.1") at higher significance.

Inputs, prerequisites

Assumes the central pointing position has been established i.e. a pointing sends on average the source "to the center of the array" for a standard chop. Note close relation to section 3.1. If data are taken in others than the "standard chop", FOV distortions etc. have to be known.

Sources

Bright point sources with position known to better than 0.5". Faint haloes don't matter. Assuming 1σ 1mJy in 1h, a S/N of 20, and an integration time of 1min, sources should be brighter than $\approx$160mJy in the blue PACS channel.

This assumes that systematic effects like flatfield are already under control. For the very first measurements, yet brighter objects should be chosen.

Calibration Implementation Procedure (CIP)

Standard chopped/nodded photometric AOT

Standard data compression

Estimated time needed

Overhead and slew dominated, at least several minutes per source.

Calibration Analysis Procedure (CAP)

Measure centroid on chopped image and derive difference from the nominal position. Apply correction if a ‘good’ source was observed with commanded position close to but other than the best available one (e.g. in a sloppy GT/OT program). Build up a large database of offsets, derive statistics, look for systematics.

Output, products

Status/version

Draft

```
$Revision: 1.3 $
$Date: 2002/12/11 16:11:15 $
```

Req. 2.6.2 Relative Pointing Error

Objectives

Verify that the the telescope RPE is indeed as low as specified. The IID-A specifies for pointed mode a 1min RPE of $<=$0.3", i.e. within a minute the actual pointing will scatter by this amount (1σ) around its average direction. This is acceptable for all PACS observations. This specification covers 'fine pointing' (cf. First Scientific Pointing Modes Document), 'raster pointing' which is a sequence of fine pointings, as well as 'position switching' and 'nodding' (also sequences of fine pointings).

Fulfilling or fulfilled by

Self-Standing

Priority

A - This priority refers to verifying that the RPE is not in fact much larger than specified. Accurately measuring the RPE at the specified level is neither simple nor very important.

When performed / frequency

Early in PV or commissioning, repeated later if reasons for change

Required accuracy

Verifying a 0.3" scatter implies measuring source positions to below 1/10 of a blue pixel. Systematic effects (e.g. uniformity of pixels, req. 1.1.3) may become important. High S/N in short integrations is needed.

Inputs, prerequisites

Sources

Observe a very bright point source. If we want S/N$>$100 in a 1s chopper plateau, we need about 6Jy or more. A faint halo does not matter.

Calibration Implementation Procedure (CIP)

Do a chopped/nodded observation but perhaps nod less often than normal to not introduce errors from the nod offset. It is unlikely that a science observation will stare long enough at a very bright source.

Standard data compression

Estimated time needed

15 minutes on source?

Calibration Analysis Procedure (CAP)

Derive source centroids for each chopper plateau and look at scatter and drifts.

Output, products

Status/version

Draft

```
$Revision: 1.4 $
$Date: 2002/12/18 09:45:08 $
```

Req. 2.6.3 Absolute Pointing Error - Scan mode

Objectives

Almost certainly, PACS will use line scanning in some of its mapping modes. The basic pointing mode differs from 'fine pointing', as do the IID-A pointing requirements. The goal for the a posteriori AME is 1.2"+0.02*w with w the scanspeed in arcsecond/second. In order to not put the modulation frequency of point sources below the bolometer frequency cutoff, the scanspeed can be at most of the order 10-60 arcsec/sec. We assume in the following that we have to verify an accuracy of the order 1.2" to 2.4".

Fulfilling or fulfilled by

Self-Standing Observation. Perhaps later supplemented by analysis of galactic surveys.

Priority

A – Identification of objects from maps needs good pointing

When performed / frequency

Performance Verification

Required accuracy

We require a source to be detected at S/N$>$20 after a single pass over the array which will last of the order 5-30 seconds.

Inputs, prerequisites

Distortions have to be characterized first.

Sources

A field of TBD size (e.g. 30' long but relatively narrow) is needed which has a significant number of bright sources with accurate position. Given the accuracy request, these have to be above $\approx$400mJy in the blue channel. A technical note is in preparation (D.Lutz, B.Ali) describing attempts to identify such fields which may turn out to be elusive.

If no such field can be identified, we will have to combine very simple checks crossing a single source with a more crude scheme that tests reproducibility rather than absolute error: a field with heavy and bright (but a priori unknown) structure is repeatedly scanned with different parameters, and results compared.

Calibration Implementation Procedure (CIP)

Do a line scanning map with standard AOT

Standard data compression

Estimated time needed

TBD, will be significant

Calibration Analysis Procedure (CAP)

Measure positions from map and compare to known intrinsic positions. N.B.: This is an IA software test as well...

Output, products

Status/version

Draft.

`$Revision: 1.4 $`

$Date: 2002/12/18 10:00:52 $

Req. 2.6.4 Relative Pointing Error - Scan mode

Objectives

The IID-A goal for the RPE in scanning mode is 0.8”. This jitter is difficult to verify since it is superposed on the smooth scan motion, and mixed with effects of field of view distortion. Possibly, the cross-scan jitter is better to constrain than the in-scan jitter.

Fulfilling or fulfilled by

Data analysis only, of scanning observations taken to map field of view distortion (3.1.3), and other scanning observations crossing very bright sources

Priority

B

When performed / frequency

Performance Verification and later

Required accuracy

Inputs, prerequisites

Reconstructed pointing history of satellite during the scan, at appropriate time resolution. Deviations from a smooth motion in the PACS data should be due to jitter or PACS optical distortion, not due to speed up/down of the Satellite...

Sources

Calibration Implementation Procedure (CIP)

Estimated time needed

Calibration Analysis Procedure (CAP)

Measure position of source on array (array coordinates) as a function of reconstructed satellite pointing position while array is crossed by a bright point source, and determine deviations of the measured positions from a simple trend corresponding to the satellite pointing. These are due to field of view distortions and pointing jitter. Use physical knowledge of the instrument (sect. 2.4) to identify components of this deviation that are likely optical distortions (e.g. a quadratic(?) trend all over the array), and use what ever remains to put limits on, or measure the, pointing jitter RPE.

Output, products

Status/version

Draft.

```
$Revision: 1.3 $
$Date: 2002/12/18 10:00:52 $
```

Chapter 3

Full System Calibration Photometer

3.1 Spatial Calibration

The requirements described below address the spatial calibration of the photometer section of PACS under the following assumptions and definitions:

Coordinate systems used are

- Subarray coordinates i,p,q: A coordinate system for each subarray i trivially assigning the center of each pixel with a ”clean” coordinate like p,q=(4,5). This is the system in which we will actually measure source centroids.
- Array coordinates u,v: A coordinate system in the focal plane (offsets in mm) in which the centers/corners of all pixels of all subarrays are known.
- Telescope coordinates y,z: This is an ”on the sky” coordinate system centered on the optical axis of Herschel. Its coordinate axes are defined by the spacecraft y and z axis, coordinates are in arcseconds.
- Sky coordinates RA,DEC: RA, DEC around the commanded position of the Herschel spacecraft (This position is not usually identical to the source coordinates, because of chopping!).

Coordinate conversions between these various systems include the following elements:

- Subarray — Array: Considers gaps between subarray matrices and possible misalignments of the array assembly. Related calibrations are addressed in requirements 1.1.15 and 3.1.3.
- Array — Telescope: It would be desirable (and easier to calibrate) to decompose this into a simple angular shift due to chopping and an optical distortion. According to optical modelling (Norbah el Quais and Muhammar al Poglitsch, priv. comm.) this is not possible for PACS/Herschel: Distortion is a clear function of chopper position. The transformation from array coordinates to telescope coordinates is a complicated function f(u,v,chopperposition). This includes the plate scale and rotation of the arrays wrt the spacecraft y,z axes, but also all the optical distortions introduced by PACS. This transformation is addressed in Requirement 3.1.3. Nevertheless, a less extensive 0th order characterization of the chopper effects, establishing a chop direction wrt the spacecraft yz coordinates, and an angle vs. encoder readout characteristic curve is foreseen in 3.1.2.
- Telescope — Sky: This includes the normal trigonometrical conversions due to position on sky and telescope roll angle, but also the offset between commanded and actual pointing (sect. 2.6). For an individual measurement, this implies an uncertainty of the order of the APE or AME in this conversion step. Needs for calibration initiated by this step are: Definition of the PACS photometer optical axis/central pointing position (3.1.1) and characterisation of APE/AME (sect. 2.6).

These transformations are written here in the sequence from detector to sky corresponding to the calibrations that will be applied to science data. Inverse transformations will be needed for other purposes.

A detailed astrometric error budget remains to be done. In the following, we assume that for a high S/N source errors other than the pointing accuracy shall be minimized in order to not dominate over the pointing AME (goal 1.2”). Assuming we have a chain of factors influencing the total error, this is taken care of below in a preliminary way by assuming 0”.5 for one step. This may turn out to be overambitious for certain steps, but the preferred approach is to selectively relax individual requirements if detailed analysis shows this to be necessary, rather than starting with an overall generous budget.

Req. 3.1.1 Photometer Central Pointing Position

Objectives

Establish the relation between a defined spot on the bolometer arrays, for a defined chopper position, and the satellite pointing, so that commanding the satellite to the position of an object sends that object on that spot on the array if the chopper is in the specified position. (Sometimes also called ‘focal plane mapping’)

There are conflicting needs on where to put this spot. From a mapping point of view, one would place this at the center of symmetry of the PACS arrays which is a gap, however. From the point of view of photometric obervations and to make it actually calibratable, one will choose a point giving simultaneously good data for both blue and red channel. In the following, we adopt the concept of a ‘standard chop’ which is a moderate throw chopped observation, around a defined chopper readout, chosen to put an object alternatingly on two positions on two of the inner blue arrays, symmetric to the minor axis of symmetry of the detector assembly. We choose an offset from the major axis of symmetry of the detector assembly such that positive/negative beam are at the centers of these inner blue subarrays (TBC). We define the central pointing position as the center of gravity measured between the positive and negative chopped image. `Note: if we then add nodding or position switching, do we want to do it the classical way or do we want to shift to the other side of the major axis?`

Fulfilling or fulfilled by

Self-Standing

Priority

A — You can’t observe without it. ILT version is C.

When performed / frequency

ILT pre-exercise version. Result is sensitive to relative movements between test cryostat cold part and warm setup on the outside of the cryostat, and to accuracy of mask mounting.

In orbit very early in commissioning. Later, this is regularly verified by APE checks. which would show systematic drifts if the central position changes.

Required accuracy

There are two different accuracies involved: a) Accuracy with which the central point matches the desired one. This is probably not very critical, perhaps half a blue pixel or so. b) Accuracy to which this position is known. This is central to any further astrometry and needs to be very accurate, 0.5” TBC

Inputs, prerequisites

The ’defined chopper position’ has to be known first. This should be close to the PACS instrument optical axis and should be established in a separate requirement, e.g. looking for the center of symmetry between the two internal calibration sources. See requirement 2.3.1.

Sources

ILT: punched hole mask with one hole of 2-4arcsec diameter

In orbit: Bright point sources. The random position error of an individual measurement should be well below the AME goal. Assuming 1min 20σ in the blue channel, at least 160mJy are suggested.

Calibration Implementation Procedure (CIP)

ILT: Set up OGSE with punched mask on xy stage and hot plate behind. Be sure to select the appropriate attenuation filter for the bolometer channel used. After switching on everything, locating the source and (if necessary) focussing the xy stage do a chopped observation with throw 54 (TBC) arcsec. Iterate measuring beam centroids and offsetting xy stage until mean of positive and negative beam is on the desired spot.

In orbit: Do a chopped observation with throw 54 (TBC) arcsec. If the source centroid can be measured already in chopped data, this is fine. If nodding is needed, beware that the two positive beams may not match in position in a standard nodding scheme. Position switching to some other point may then be better. The original misalignment between instrument line of sight and star tracker can be as large as 0.3 degree (H-P-1-ASPI-RP-0312 Issue 1 6.5.3.4.3). If this number holds, then plan very first observation as a sufficently large raster.

Estimated time needed

In orbit: Individual measurements are overhead dominated and will take just a few minutes. Note, however, that at least $(APE/0.5'')^2$ measurements are needed. Time can be saved by sharing with e.g. photometric calibrations.

Calibration Analysis Procedure (CAP)

ILT: Measure centroids of positive and negative beam. If their mean is off the desired spot, offset xy-stage accordingly and repeat. Note final setting of zy stage for later use.

In orbit: Measure centroids of positive and negative beam and determine mean. If this is far off the desired point, trigger change of attitude control parameters. if it is near desired point, save results for later averaging/trend analysis

Output, products

Updates to satellite attitude control parameters, accurate knowledge of reference position on array.

Status/version

Updated for possible large initial in-orbit misalignment

```
$Revision: 1.3 $
$Date: 2003/07/25 08:59:55 $
```

Req. 3.1.2 Relation between Chopper Position and Angular Displacement on Sky

Objectives

To establish a relation between commanded chopper position (in chopper readout units) and the displacement of the FOV on sky, in direction and amplitude.

Optical distortions make this relation strictly valid only for a given point on the arrays.

Fulfilling or fulfilled by

Self-Standing, but data also useful for 3.1.3. ILT pre-tests may be very closely related to 3.1.3

Priority

A

When performed / frequency

PV, pre-tests in ILT

Required accuracy

Amplitude: 1” for a standard chop, extrapolation to other situations by 3.1.3

Direction: to $<$1 degree, as determined by errors of the four centroid measurements ($\sim$0.5” each) and chop throw (1-2’). This is well above the uncertainty of the satellite roll angle (3’, IID-A sect. 5.12, this is the quantity called ”around line of sight”)

Inputs, prerequisites

Relation between chopper readout and chopper tilt (lab measurement, req. 2.3.1) and PACS optical model for nominal transfer into displacement on sky.

Definition of the chopping zero point (with respect to the internal blackbodies) requirement 2.3.1.

Sources

- [1] ILT: Punched hole masks outside test optics and hot plate, combined with modelling of test optics. Hole sizes approx 4arcsec (0.72mm). Relative positions of hole centers known to 0.5arcsec (0.09mm) or better.
- [2] In Orbit: Double point sources (some faint halo does not matter), with $>$160mJy each in the blue (75μm) channel, separations up to 3.5 arcmin, and position angle close to the chopping direction at the time of the observation. Chop direction is parallel to the spacecraft Y-direction. Both separation and position angle have to be accurately known at the time of the observation `Well? Does this exist?`

Calibration Implementation Procedure (CIP)

- [1] If contrast with background and flatfielding is good enough to measure good positions without background subtraction: Use a mask with many holes in a $\sim$20arcsec spaced grid. Step chopper from one end of its range to the other (partly) using smallest possible chopper increment. Dwell a few seconds per step. If contrast is not good enough, use double hole mask and chopping procedure similar to the one in orbit.
- [2] Two possible methods, both making sense only if PA of double star is at the time of the observation close to the chop direction: (a) Do a normal chopped observation, placing the negative beam of star 1 close to (but not exactly on) the positive beam of star 2. Repeat for different stars / chop throws. If possible don’t nod or nod orthogonal to chop direction, to avoid effects of pointing inaccuracies on the centroids measured. (b) Do a symmetric triple chop which has, for the chopper in center position, the middle between the double source placed in the center of a blue

subarray. Then alternatingly 'triple-chop' the two sources to this center by moving 1/2 of the double star distance in either direction.

Standard data compression

Estimated time needed

For [1] a few minutes to an hour depending on sampling density. For [2] overhead dominated both in lab and in orbit, a few minutes per source plus setup times.

Calibration Analysis Procedure (CAP)

- [1] Note that ILT measurements can only give a consistency check for the PACS optical model since their scale is based on the test optics model, and relative orientations may be slightly different. Compare the difference of the positions measured for the images of a single hole at different chopper positions with the scale that is projected onto the array at a single chopper position, by the combination of mask metrology and test optics model.
- [2] (a) subtract on and off and apply flatfield. If all four beams are on array: Compare offset between star 1 positive and negative beam and offset of the positive beams of the two stars. If separation and chop throw are large such that only the (nearby) positive beam of one star and negative beam of the other star are registered: Convert offset of these into on-sky offset (an approximate plate scale/orientation is fine for this as long as offset is small) and subtract from true separation of double star to get chopper throw and direction. Note that this interacts with FOV distortions if the offset is too large! (b) Subtract central 'off' chop position from the two different 'on' ones and apply flatfield. Measure centroids of the two sources. If identical, then the chop throw betwen the two ends of the triangular chop corresponds exactly to the speration. If slighlty different (e.g. due to not perfect position angle match to chop direction), apply correction based on this offset and an approximate plate scale/orientation.

Output, products

Chop direction, chop throw for chopping between two chopper readouts

Status/version

Substantially revised and now coordinated with 2.3.1

```
$Revision: 1.4 $
$Date: 2003/02/14 09:18:19 $
```

Req. 3.1.3 Photometer Field of View Distortion

Objectives

Determine the optical distortions introduced by the PACS instrument optics and the telescope optics. The optical distortions depend on position on the array as well as chopper position, i.e. the chopper introduces more than a trivial translation.

It is assumed (TBC) that distortions are measured in blue channel and only verified in red channel, .i.e, that they are intrinsically the same but more readily measured with smaller beams.

Fulfilling or fulfilled by

Self-standing. Some relation to 3.1.2

Priority

A – if completely uncorrected the distortions will dislocate sources and smear them in averaged maps.

When performed / frequency

ILT

PV

Required accuracy

Directly affects astrometry. 0.5” (TBC).

Inputs, prerequisites

Optical modelling giving an indication of magnitude and shape of effects. For the bolometer, the distortions are suggested to be a smooth function of source and chopper position.

It is assumed that detector misalignments are measured at room temperature as described in requirement 1.1.15, so that the transformation from centroids measured on a subarray to array coordinates for the entire focal plane is possible. The possibility of differential contractions when cooling the bolometer assembly urges to recheck these numbers at operating temperature, however.

`We may need another requirement to measure distortions introduced by test optics? Or is modelling enough?`

Sources

ILT: Use a back-illuminated punched hole mask with many accurately known hole positions in front of test optics. Choose hole pattern for good coverage of the FOV but avoiding confusion, especially if chop is used. Move the mask on the X-Y stage to further improve the sampling and provide information to check the relative geometry of the subarrays. Alternatively/additionally: do linear scans of a single hole (or few hole) punched mask parallel to major and minor axes of the array assembly, at various offsets (detailed design/tradeoff of such a procedure TBD).

In-Orbit: We need clusters of FIR point sources (>160mJy) spread over a few arcmin, with accurate positions known. Replacing this by mapping a single source will be inaccurate since the APE enters every individual measurement, rather than cancelling out as for measuring offsets between sources of a cluster.

In-orbit: very bright point sources for linear scan across array

Calibration Implementation Procedure (CIP)

Blue channel: Mostly use 75μm filter for best spatial resolution and then do a quick verification for other filter.

ILT: The back-illuminated holes might have a relatively large contrast over the background, compared to astronomical sources. If the flatfield accuracy allows, staring observations with densely punched masks may be possible. Otherwise use chopping and a less busy mask designed to avoid confusion by the chopping. Use the chopper to sample not only the central part of the FOV but also the edges used for large chop throws. Move the mask with x-y stage to improve sampling, and to provide information to recheck relative alignment of subarrays (1.1.15).

In orbit: A number of chopped observations of suitable clusters, variously offset and with varying chopper throw.

In orbit: Do linear scans of a very bright point source parallel to array major and minor axis, at several offsets and for several chopper positions/throws. The absolute positions measured will be uncertain by the AME and hence of limited use, but the curvature of the track measured for a linear scan will constrain the optical distortions.

Standard data compression

Estimated time needed

TBD: complex but feasible in ILT, possibly very long in orbit.

Calibration Analysis Procedure (CAP)

ILT: Measure centroids and transform from subarray to array coordinate system (cf checks below). Compare to input positions in telescope coordinates and fit to a parametric model of y,z = f(array u, array v, chopper position) with choice of parameters based on modelling.

Check for inadequacies that might occur because of changes of the subarray alignment between room temperature and operating temperature. Overall contraction is of the order 1% so that differential contractions might perhaps be noticeable over the entire array. Specifically check ”transitions” of the same source across subarray gaps. Adjust subarray-array transformation if necessary and iterate with derivation of distortion correction.

Distortions introduced by test optics itself have to be known from modelling and testing(?). Transfer the distortions measured using test optics and PACS to the situation for telescope and PACS using the difference between the models the two respective situations (Req. 2.4.1).

In-Orbit: For cluster observations measure centroids and transform to array coordinate system. No dedicated attempt to recheck subarray-array alignment. The comparison to inputs will likely be a pretty complex system of equations including also the inaccurate absolute pointings of the individual observations

For line scans measure cross-scan deformation of track and compare to ground test results and model. Beware of possible effects of spacecraft jitter (Req. 2.6.4).

Output, products

Calibration file between array and telescope coordinates.

Verification or update of calibration file between subarray and array coordinates.

Status/version

Early incomplete draft

```
$Revision: 1.3 $
$Date: 2003/02/12 14:06:39 $
```

Req. 3.1.4 Photometer Point Spread Function

Objectives

Determine the Point Spread Function of the Photometer for the three filters, possibly for both 'hot' and 'cold' sources to account for color terms in the fairly wide bands. Do this for several positions in the chopped FOV to test smearing/distortion. At least near center of FOV, also exercise small sub-pixel offsets.

Preliminary tests can be done during ILT, but the difference between telescope and test optics and the complexity of the test optics setup (reflections in filters or dewar window?) preclude a direct transfer of results. In particular, the Herschel telescope is not required to be diffraction limited for the PACS blue channel, although the goal is to be close to diffraction limited. This uncertain situation will not be adequately reproduced in ILT.

There is a possibility that the bolometer "blind pixels" used to compensate drifts see some light from a very bright point source near to the appropriate edge of the subarray. This would offset signals for part of the detectors in the respective subarray (Req. 1.1.17). Observations to determine PSF and Ghosts should be set up to test for this effect as well.

Fulfilling or fulfilled by

Self-Standing, but partly benefitting from analysis of photometric calibrations etc. Observations will fulfill 3.1.5 and partly 1.1.17.

Priority

A

When performed / frequency

PV and later. Pre-tests in ILT

Required accuracy

S/N $>$ 300 in the peak in order to have decent S/N down to faint wings

Inputs, prerequisites

Library of model PSFs at least for central part of FOV and for various sub-pixel positions. Req. 7.x?

Sources

Bright point sources without far-infrared halo. One also has to take care to not integrate into the structure of the background, long integrations don't make sense. At 170μm, e.g., we expect one background source of $\sim$30mJy in a 2 by 2 arcmin region. We hence have to go to very bright sources to get the dynamic range and still be confident that some maximum is a PSF structure and not a source. 10Jy should give a dynamic range of 300 wrt the mentioned chance background source. Still to be estimated: Effect of cirrus structure on measuring faint wings on the arcmin scale. This may urge for yet brighter sources. Suitable sources might be asteroids moving through clean fields, or stars selected to most likely not have dust shells. Cold point sources: distant infrared galaxies (but low S/N and little dynamic range wrt background, hence good for a FWHM at best), and/or distant solar system objects like KBOs.

ILT: mask with one or very few very small holes. The hole size is a tradeoff between PSF smearing and contrast. A useful start may be 2arcsec.

Calibration Implementation Procedure (CIP)

ILT: Set up OGSE with punched mask on xy stage and hot plate behind. Be sure to select the appropriate attenuation filter for the bolometer channel used. The total procedure has several steps some of which may be skipped depending on what was done before:

- Switch on PACS and OGSE, wait for stabilization of internal calibrators etc.

- Locate the source on the PACS array and center it properly.
- Do a focus sequence for the z coordinate of the xy stage.
- Measure PSFs for a number of locations of the source. The basic procedure is a chopped measurement, with added observations of the internal calibrators to allow a posteriori improvements of flatfielding.
- Estimate systematic errors by doing the same observation with a hole-free mask.

Be sure to also maneuver the point source close to the edge of a subarray where the blind pixels are located, to test for the effect discussed in req. 1.1.17. Many variations of the basic procedure are conceivable to test for PSF variations with large scale or sub-pixel position changes, chop throw, hole size, and to test for focus differences blue vs. red array or with position of the xy stage.

In orbit: Chopped observation and/or small maps. Use various chop throws and positions to sample PSF over the entire FOV. Position switch outside FOV to minimize disturbances by negative beam.

From a sub-pixel raster or using proper motion of asteroids ensure that PSFs are obtained for various positions of the peak within a pixel.

Standard data compression

Estimated time needed

ILT: individual measurement short of the order 1 minute. Significant setup overheads or wishes for large rasters can easily produce overall times of a few hours, though.

In orbit: Short, overhead driven integration times. One should stay on source for a few min to also include smearing by pointing jitter. Doing this for 3 filters * 2 source types * n positions in FOV and doing some sub-pixel stepping for part of the positions may give considerable overall times, though.

Calibration Analysis Procedure (CAP)

Subtract background, apply flatfield, and derive a library of normalized PSFs for various locations in FOV, compare to model expectations.

In ILT additional steps of QLA monitoring for locating the source, evaluating the focus sequence, and estimating systematic problems in background

Output, products

PSF library and associated products like FWHM tables and pixel efficiency factors

Status/version

Draft modified after first ILT CIP thinking

```
$Revision: 1.3 $
$Date: 2002/12/18 10:29:03 $
```

Req. 3.1.5 Photometer Ghosts

Objectives

Test for presence of ghosts (=false sources or structures due to internal reflections) in photometer images.

Fulfilling or fulfilled by

Analysis of data taken for PSF determination (TBC), and science data

Priority

B

When performed / frequency

PV and later, pre-tests in ILT

Required accuracy

TBD small fraction

Inputs, prerequisites

Sources

Bright point sources, as isolated as possible

Calibration Implementation Procedure (CIP)

Observe a point source with different positions on array, and different chop throws.

Estimated time needed

Calibration Analysis Procedure (CAP)

Look for signals that neither stay at the same astrometric position (as real background sources would do) nor move with the point source (as PSF structures do). The discrimination between PSF features and ghosts is somewhat fuzzy...

Test optics (ILT) differs from in-orbit setup.

Output, products

Status/version

Early incomplete draft

```
$Revision: 1.3 $
$Date: 2003/02/12 14:07:19 $
```

Req. 3.1.6 Photometer Straylight

Objectives

Determine signals measured by the PACS photometer that are due to bright sources of radiation outside the field of view. Note that such radiation of significant strength may remain undetected in chopped observations if it is only weakly dependent on chop position, and that the bolometers give relative fluxes subject to drifts rather than absolute fluxes. Sources to be considered include

- Very bright compact sources (late type stars, Planets) within a few arcmin of the FOV (possibility of compact reflections?)
- ???

A signal that could be called 'straylight' is caused by chopping in the presence of telescope temperature gradients, and is being fought by nodding or position switching. Trend analysis of this signal is covered in requirement 3.2.x????

Fulfilling or fulfilled by

self-standing

Priority

B

When performed / frequency

PV and later, pre-tests in ILT?

Required accuracy

Inputs, prerequisites

Modelling of Herschel straylight properties to guide search

Sources

Mars, Jupiter, late type stars

Calibration Implementation Procedure (CIP)

Two possibilities: a) chopped observations at some predefined position relative to the bright source. Probably suggested for a range of positions where radiation is still near the PACS aperture b) unchopped fast line scan passing over or near the bright source, aiming to detect a temporary signal excess at a level that can be discriminated from background/sensitivity drifts.

To be verified to which extent ILT hole masks can be used to try out possibility a). Note that test optics setup is complex and different from telescope.

Estimated time needed

Calibration Analysis Procedure (CAP)

Output, products

Status/version

Early incomplete draft

`$Revision: 1.3 $`

$Date: 2003/02/12 14:05:03 $

3.2 Photometric calibration

Req. 3.2.1 Derive photometer nominal responsivity

Objectives

To obtain, for the complete instrument, the relation between a voltage output readout and the absolute sky brightness. This is different from the objective of Req. 1.1.2 where what we calibrate is the relation between the power falling onto the detector and the voltage output readout. This is one of the most important calibration item of the whole system.

Fulfilling or fulfilled by

This is the full system version of requirement 1.1.2 “Nominal responsivity”, at ILT and subsequent phases, the two requirements are not distinguishable and req. 3.2.1 fulfills req. 1.1.2.

At the current stage, this requirement is fulfilled by req. 3.2.3 “Calibrate the photometer’s non-linearity”.

Priority

A.

When performed / frequency

ILT and later phases.

Required accuracy

The photometric accuracy: 5% (TBC)

Inputs, prerequisites

The nominal detector responsivity as we have to understand how the detector’s responsivity relates to the full system one.

Sources

Internal calibrations sources, well controlled black-bodies (for the ground tests) as well as celestial standards.

Calibration Implementation Procedure (CIP)

Estimated time needed

Calibration Analysis Procedure (CAP)

Output, products

A table of conversion factors from readout units to sky brightness.

Status/version

```
$Revision: 1.5 $
$Date: 2003/03/07 14:34:16 $
```

Req. 3.2.2 Monitor nominal responsivity variations with time

Objectives

Previous bolometer-based detectors have exhibited responsivity variations for a number of reasons, some or all of which can be expected to affect the PACS bolometers. Proper monitoring of variations in the PACS bolometer response requires that we first identify the relevant causes of these variations and the pertinent time-scales on which these variations manifest themself. Since response variations directly impact photometric calibration, these variations must be suitably characterized and corrected to reach photometric accuracy goals.

For ground-based bolometer instruments (*e.g.* SCUBA) the variations in background sky dominate responsivity variations. For Herschel, thermal emission from the telescope's primary mirror is the dominant "sky". The absolute level of telescope emission is expected to remain constant to less than one percent (TBC) and is, therefore, not a significant source of variation for bolometer responsivity. Variations in the level of astrophysical background sources, for example, zodiacal light intensity as a function of time, are also insignificant compared to telescope background level.

However, sky variations that are potentially significant causes of responsivity changes can originate either as variations in the amount of stray light (change of emission from inside the cryostat), and spatially, rather than temporally, as non-uniformity of coating on the primary mirror surface. Stray light variations may come from Herschel's position angle and, possibly, as time since last cooling cycle. While the bolometer thermal bath is expected to reach thermal equilibrium quickly, other surfaces within the cryostat may reach this equilibrium at different time-scales, hence, leading to possible variations in the stray-light level. Non-uniform coating on primary mirror leads to non-uniform emissivity. However, this particular requirement is not concerned with spatially induced response variations. Instead, see requirement XXX.

The variations in the bath temperature of the bolometer are potentially another significant contributor to responsivity variations. One source of this type of variation is variation in the efficiency of the coolant pumping leading to variations in system temperature. [*Note from author: We need an estimate of the max fluctuations from the cryo-folks as well as time scale of these fluctuations*].

Variations in responsivity may also originate from the bolometer electronic components: (i) Systematic or random variation in the bias voltage supply, (ii) variations in the thermal conductance, (iii) gain drifts and (iv) random events such as impact by charged particles and/or solar storms.

Given the above mentioned possible causes, the time-scales of interest are:

- At switch-on of the instrument.
- Time since cooler recycling.
- Orbital position of the telescope.
- Life-time of the instrument.
- After a charged particle impact.

Unfortunately, not all of the time-scales can be predicted for these causes ahead of time.

It is important to distinguish this requirement from Requirement number 3.2.1 – measuring the full system responsivity. Requirement 3.2.1 is concerned with bolometer responsivity over the full rdynamical range of fluxes, and uses a more sohpisticated (and time consuming) CIP that is not needed to monitor responsivity changes with time. Instead time variations of responsivity will be measured at a "nominal" (see CIP below) flux level by assuming that any responsivity changes above and below the nominal flux are also determined by changes in the nominal level.

Fulfilling or fulfilled by

This is the full system version of req. 1.1.4 "Monitor nominal responsivity variations with time". At ILT and subsequent phases, the two requirements are not distinguishable and in fact, req. 3.2.2 fulfills req. 1.1.4.

Priority

B.

When performed / frequency

An accounting of previous bolometer instruments yields the following time-scales for responsivity monitoring:

- SCUBA – Every minute (goal). Sky variations dominate response variations.
- SHARC – Hourly. Sky variations dominate response variations. They have noted evidence for a second factor, but have not identified what it is.
- Boomerang – Every 18 minutes.
- PLANCK – At multiple times during each scan. However, they are aided by the presence of the cosmic microwave background in the low-frequency instrument and by FIRAS data in the high frequency band.
- CSO – Every minute using an independent sky monitoring set-up.

The above discussion has attempted to provide an estimate of what time-scales are relevant (give the set of probably causes) and what other similar instruments have used (though their causes may be different from PACS). In some cases, particular those that originate in the electronic, the time-scales can not be determined accurately without actual measurements. Hence, the author recommends the following basic philosophy: "monitor as often as practical, characterize any observed response variations, and either ease-up or speed-up as dictated by the data."

The following time-table is thus recommended for in-flight monitoring:

1. Measure at every switch-on.
2. Measure before every switch-off.
3. Measure after a (TBD) selected glitch events.
4. Measure every (TBD) minutes for the first hour (TBC).
5. Measure hourly between switch-on and switch-off.

Note that during ILT a number of ground based artifacts may lead to responsivity variations that will not be present in the complete instrument and thus may require more frequent monitoring.

Required accuracy

$<$ 5% (goal). This accuracy is driven by the final photometric accuracy we are aiming at.

Inputs, prerequisites

The nominal value of the full system responsivity. The range of variations observed at the detector level to be able to design sensible calibration measurements.

Sources

- in-flight: celestial sources and internal calibrators.
- ground & flight: EGSE blackbodies and the internal calibrators.

Calibration Implementation Procedure (CIP)

The telescope background dominates the total flux seen by the detector and is present in all PACS's images. It is therefore, a natural "nominal" value at which responsivity variations will be measured. There are three methods available for repeatedly measuring the PACS's bolometer responsivity:

1. By using the telescope background itself.
2. By using the internal calibrators.
3. By using Astrophysical sources (in-flight) or EGSE blackbodies (during ILT).

It is not clear at this point that all three methods are feasible or even necessary. However, as mentioned above, we intend to monitor the responsivity "as often as practical" until more accurate variability time-scales have been established.

1. By using the telescope background itself. The idea is to monitor the heater voltage of the blind pixels with time. Assuming that the telescope background does not vary signifcantly compared to required photometric accuracy, any changes in the blind pixel heater voltage can be assumed to be caused by responsivity changes. This method has the advantage that it is potentially available at the highest possible time resolution, i.e. for every single bolometer frame. However, the stability of telescope background must be established independently. Additonally, the stability of blind pixel heaters must be established independently. The procedure is simply to set the blind pixel heater to cancel the telescope background.

2. By using the internal calibrators. In this case, the internal calibrators are set to produce approximately the same number of photons as are being produced by the telescope background. The required photometery accuracy is less than 5%. Therefore the total signal (over the integration period) must have signal-to-noise ratio of 20 or higher. The measurement is repeated with the time-resolution identified above. Once the calibartors stabilize at the nominal flux level, the procedure is to chop between the two internal calibrators for a (TBD) amount of time such that the final signal-to-noise ratio is higher than 20.

3. By using the ESGE blackbodies or astrophysical sources. During ILT, two additional calibrators are available. No specific setting is required for the EGSE calibrators as long as the "nominal" level is one of the settings used during measurements. This will allow this CIP to be harmoneously integrated with other similar CIPs. As for the 2nd method above, signal-to-noise ratio of 20 or higher are required to meet the photometry accuracy goals. The time-resolution is identified above. An advantage of using both the EGSE and internal blackbodies will be to isolate any responsivity variations as either "inside" or "outside" the cryostate. The procedure is to chop between the two EGSE calibrators for a (TBD) amount of time such that the final signal-to-noise ratio is higher than 20.

The additional calibrators are replaced by astrophysical sources during flight. However, inflight measurements levy additional overheads in the form of telescope slew and settle times. Therefore, it may not be possible to use this method as frequently.

Estimated time needed

The time needed to achieve signal-to-noise ratio of at least 20.

Calibration Analysis Procedure (CAP)

Since we have defined the nominal flux level (see above), the process of isolating responsivity variations is tremendously simplified. By definition, the responsivity is a product of detector efficiency and the input flux divided by the bolometer readout voltage. The detector efficiency is constant, and by keeping the input flux level constant as well, one only needs to monitor the variations in the readout voltage. This is simply the median value of the frame.

The responsivity measurements at each time-step are plotted versus time to identify and characterise any observed variations with time.

Output, products

Responsivity correction factors as a function of elapsed time since determined events.

Status/version

Revised for draft 6 of the PCD.

Req. 3.2.3 Calibrate the photometer's non linearity

Objectives

For large flux dynamics, the bolometer arrays are highly non-linear (the higher the flux level, the smaller the measured signal for a given input). We need to make sure this non-linearity is well calibrated although we will try to operate in regions of flux where a linear approximation is correct. This non-linearity calibration will have to be used when observing very bright sources (possibly planets) and even some of primary calibrators (Uranus inputs as much power on the array than the background).

Fulfilling or fulfilled by

This is the full system version of req. 1.1.13 "Calibrate the detector non-linearity". At ILT and subsequent phases the two requirements are not distinguishable from one another and in fact req. 3.2.3 fulfills req. 1.1.13.

The proposed CIP also fulfills req. 3.2.1 "Derive photometer nominal responsivity", req. 3.2.4 "Establish the linearity of the full system", and is also used in req. 3.2.8 "Measure the photometer full system flat-field" although for this last requirement it needs to be expanded.

Priority

A. We need to establish the non-linear behavior of the photometer before we determine the operating flux dynamics.

When performed / frequency

At ILT and subsequent phases, for all instrument models that have detectors. This needs to be done again in space, possibly more than once as a health monitoring activity.

Required accuracy

Driven by the global photometric accuracy we wish to achieve.

Inputs, prerequisites

The detector non-linearity curve as established at the module level tests

Sources

A set of sources with well-known fluxes covering a representative dynamical range (generally small), as well as a set of background levels covering a very wide dynamical range.

Calibration Implementation Procedure (CIP)

Set the readout mode to double correlated differential measurement, i.e. blind pixels signal and reference voltage are subtracted before the signal is downlinked.

The power sources are the external black-bodies (i.e. not those inside the instrument).

We currently assume that there is a way to make a number (> 5) of small ($dP/P < $ TBD) power steps around a nominal power.

Elemental procedure (this is the core of the test).

procedure `make_small_power_steps`

- select mean level of input power (P_b, such as in background) and set the power source accordingly.
- set the blind pixels heater so that it cancels this input power (i.e. readout voltage is 0).
- for a series of small (TBD) power increments $j.dP$, obtain a series of readouts on the detector (j is an integer

varying betwen $-N$ and $+N$, including 0 to obtain a readout corresponding to the optimal setting of the blind pixels). We call the measured voltage $V(P_b, j.dP)$.

- **optional step**: for a series of large (TBD) increments $k.\Delta P$, obtain a series of readouts on the detector (k is again an integer varying between $-M$ and $+M$, and we have $DP >> dP$ and $N >> M$). We call the measured voltage $V(P_b, k.\Delta P)$.

end of procedure `make_small_power_steps`

For non-linearity, linearity and responsivity calibrations, the principle is to repeat `make_small_power_steps` while using different the values of the background power around the nominal background power. The idea of the optional step is to make sure that the linearization curve is unique and does not depend on the actual value of the background. This optional step does not need to be performed when only the linearity or responsivity calibrations are to be derived.

Estimated time needed

Calibration Analysis Procedure (CAP)

For each measurement $V(P_b, j.dP)$ or $V(P_b, k.\Delta P)$, we use the average readout over a predefined region of the array (the same as is used to normalize the Flat-Field).

With the $V(P_b, j.dP)$ readouts, we can compute a responsivity R in two ways: either as $R = V(P_b, j.dP)/j.dP$ which assumes that indeed the readout when $j = 0$ is 0, or as: $R = [V(P_b, j.dP) - V(P_b, 0)]/j.dP$ where we use the actual measurement obtained when the input power is the reference power. This may be better if there is a large scatter in the offset measured on the seeing pixels (there is a ratio of 8 seeing pixels to 1 blind pixel, so the offset compensation offered by the blind pixel may not be perfect). Thus we fulfill the requirement to measure the responsivity.

By identifying on which part of the interval explored by j we obtain the same value of R (within the measurement uncertainties) we establish the intervals around the different values of P_b where the linear approximation is valid.

For each of these intervals we thus have a responsivity R, per values of P_b.

By plotting the different values of R as a function of P_b, we calibrate the non-linearity of the system. We can then use the $V(P_b, k.\Delta P)$ measurements to check that the responsivity values we obtain for incident powers far from the background power are indeed compatible with the curve $R = f(P_b)$ we have just obtained.

Output, products

For each pixel a relative linearisation curve. These curves are normalized to give 1 for the range of fluxes we will have selected as the operating range.

Status/version

```
$Revision: 1.5 $
$Date: 2003/03/07 14:31:03 $
```

Req. 3.2.4 Establish the linearity of the full system

Objectives

Although the detector is globally non-linear, for small flux changes around a mean value, it can be considered as linear. In principle we will work under this linearity assumption. We will therefore verify that for the expected range of observed fluxes, the detector indeed behaves linearly.

Fulfilling or fulfilled by

This is the full system version of req. 1.1.14 "Establish the detector linearity". At ILT and subsequent phases, the two requirements are not distinguishable from one another. In fact, req. 3.2.4 fulfills requirement 1.1.14.

At the current stage, this requirement is fulfilled by the CIP and CAP of req. 3.2.3 "Calibrate the photometer's non-linearity".

Priority

A. Basic element in the definition of operating modes

When performed / frequency

ILT and subsequent phases.

Required accuracy

Driven by the required photometric accuracy so typically better than 5%.

Inputs, prerequisites

- Knowledge of the expected range of sky backgrounds.
- Definition of the operating background level.
- Results from the detector linearity measurements.

Sources

Sources with well controlled fluxes falling in the interval defined as the operational one, over a background corresponding to the operational one.

Calibration Implementation Procedure (CIP)

Estimated time needed

Calibration Analysis Procedure (CAP)

Output, products

Certification that the detector is linear within the operating range.

Status/version

```
$Revision: 1.2 $
$Date: 2003/03/07 14:32:36 $
```

Req. 3.2.5 Relative system response and colour corrections

Objectives

The relative system response is essential to correctly tie our calibration sources to the flux of the observation target which will generally have a very different spectral shape. Unfortunately the relative system response is difficult to measure so this will mostly consist of checking on sources with well-known SED that the relative system response we build from the module level test is correct.

Note that during ground-based test, a low resolution full system relative response measurement will be possible.

Fulfilling or fulfilled by

Self-standing

Priority

B. To a first approximation we can assume that the relative system response can be build correctly from its individually measured components, and check that at low resolution during the ground-based tests.

When performed / frequency

ILT and subsequent phases.

Required accuracy

Driven by the requested photometric accuracy.

Inputs, prerequisites

Individual relative responses from all sub-components (filters, bolometers, etc).

Sources

Sources with well-known spectral energy distributions.

Calibration Implementation Procedure (CIP)

We will use the tuneable laser facility (TUFIR, not available for the CQM tests). In the OGSE set-up, when we want to have all pixels illuminated by the laser, we have to go through an integrating sphere. Accounting for radiation coming from the entrance window, as well as from the room background, computation show that the laser flux to background radiation is probably much smaller than 1. Furthermore the background is not calibrated and its spectral shape is unknown. We thus need to make measurements by pairs: one with the laser on and one with the laser of. We will set the laser to its maximum power to get the highest contrast.

From the description of TUFIR (found in **PACS Cryo Test Equipment and OGSE specification - PACS-ME-DS-002**) we find that there is a calibrated reference detector to which the laser beam can be sent. We will use this detector to measure the laser power at each step.

For each band of the PACS photometer

For a set of wavelength adequately covering the band

set the tuneable laser wavelength to this wavelength
set the laser power to its maximum value
measure the laser power with the reference detector
observe this source through the integrating sphere till we have a signal-to-noise ratio of 10.
switch the laser off or turn it away from the entrance window without closing the window (so that we have the same background level

observe this background for the same amount of time

end of loop on wavelength

end of loop on photometer bands

Estimated time needed

Calibration Analysis Procedure (CAP)

The response function is automatically created by the ratio of the measured flux to the incoming flux. By comparing with the detector relative response function we will evidence the modification brought by the optical chain. Color-correction terms can then be computed on demand according to the input spectrum.

Output, products

Tables with the relative full system response for all bands.

Status/version

Draft version. CIP and CAP filled for version 6 of the PCD.

Req. 3.2.6 Noise and minimum detectable flux

Objectives

Derive the Noise Equivalent Power for the full system photometer. Compare with the bolometer NEP and understands the difference. One may wish to use alternate readout mode for the detector to avoid differentiating on board as in some cases this may help disentangling different sources of noise.

In order to derive the minimum detectable flux, noise measurement will probably have to be performed using all the available observing strategies available to PACS.

Fulfilling or fulfilled by

This is the full system version of requirement 1.1.12 “Measure the bolometers NEP”. At ILT and subsequent phases, the two requirements can no longer be distinguished from one another and in fact req. 3.2.6 fulfills req. 1.1.12.

Priority

A. Defines what is achievable with PACS and how to reach a given flux limit.

When performed / frequency

ILT and subsequent phases.

Required accuracy

Driven by the global photometric accuracy we are aiming at.

Inputs, prerequisites

The bolometer NEP to be able to notice any strong departure from it.

Sources

A constant illumination source to minimize all possible sources of variation. The internal sources should be adequate given their very strong temperature stability specifications.

Calibration Implementation Procedure (CIP)

There is a high probability that the minimum detectable flux depends highly on the observing strategy so one will have to repeat the noise measurement using all strategies available to PACS.

Estimated time needed

Calibration Analysis Procedure (CAP)

Output, products

NEP and minimum detectable flux as a function of the observing strategy.

Status/version

Draft version, revised after the December 01 meeting.

Req. 3.2.7 Pseudo-noise, photometer

Objectives

To determine and characterize the pseudo-noise, due for instance to timing jitter of the readout process, timing jitter between the chopper motion and the readout, settling time for the chopper at each of its positions, digitization noise, the effect of data compression.

Fulfilling or fulfilled by

Self-standing mostly although some pseudo-noise sources can be investigated using other calibration measurements (for instance the undifferentiated, uncompressed data stream that we extract to investigate offset drifts can be used to study the effect of data compression).

Priority

B. Expected to be small contribution due to the very small time constants of the bolometer.

When performed / frequency

ILT and subsequent phases.

Required accuracy

The pseudo-noise is required to be at a level of less than 20% of the system noise.

Inputs, prerequisites

None.

Sources

A well calibrated constant source so as to minimize all possible sources of signal variation and noise.

Calibration Implementation Procedure (CIP)

TBD.

Estimated time needed

Calibration Analysis Procedure (CAP)

Output, products

Level of the pseudo-noise contribution as a function of the observing strategy. Possibly limitations on the use of some observing modes.

Status/version

Draft version, added after the December 01 meeting.

Req. 3.2.8 Measure the photometer full system flat-field

Objectives

Each pixel will have different gain from its neighbor (detector flat-field), and transmission of the system may not be spatially homogenous (optical flat-field). This needs to be calibrated to obtain accurate photometry. Distinguishing between the detector and optical component is generally impossible, unless the detector component has been measured before independantly, and is relatively constant. Note that the detector comes with a gain specification of an 8% *rms* fluctuation over a whole 16×16 matrix.

One will also need to monitor changes in the flat-field, as we cannot exclude that it changes with time.

There are two ways of deriving the flat field which have different sources of error. The confrontation of the both results is usefull.

- Assuming that the small power change induces an increase or decrease by a constant ratio of the illumination on all the array, the flat field is proportional to the difference of 2 images $V(P_b, j\ \mathrm{d}P)$ and $V(P_b, j'\ \mathrm{d}P)$ (see req. 3.2.3). All independent pairs of measurement can provide a flat field image. After normalization by the central area of the detector, they are averaged together to form the flat field correction. A pair of images should be taken within a same calibration source of different temperature to avoid the possible difference of the illumination pattern between two calibraion souces. Nevertheless, this method is sensitive to the possible difference of the illumination pattern between 2 different temperatures of a same calibration source.

- Compute the responsivity for each pixels without averaging over the central area used for the flat field normalization. This provides a responsivity map. Then the normalized map gives a flat field and the normalization factor represents the responsivity. This method is sesnsitive to the error on the input flux estimate.

Fulfilling or fulfilled by

This is fullfilled by the photometric calibration on internal sources in req. 3.2.1, req. 3.2.3 and req. 3.2.4.

Priority

A. Essential for map reconstruction.

When performed / frequency

ILT and subsequent phases.

Required accuracy

Better than a few percent. Impacts on the achieved photometric accuracy.

Inputs, prerequisites

An a priory knowledge of the flat-field may be helpful depending on the adopted measurement strategy.

Sources

Depends on the adopted measurement strategy, but most likely the internal calibration sources.

Calibration Implementation Procedure (CIP)

A first method was to observe one of the internal reference sources and change its flux level. This will not work as we will not want to change the temperature of the internal source. A second method is to find a reasonably flat region of sky but at the PACS wavelengths, this is unlikely to happen. A third solution is to measure the flat-field in highly redundant observations. For this method a first guess of the flat-field is usefull. A fourth method exists: if we know the illumination pattern of the internal source with sufficient precision, then we can use the flux calibration to also measure the flat-field.

Finally, we can use a variable temperature black-body at ILT to calibrate the illumination pattern of the internal sources and then use that to flat-field the detector. Note that distortion may have to be taken into accound in that case.

The flat field is a by-product of the responsivity measurements described in req. 3.2.3 which uses a set of sub-procedure defined by **make_small_power_steps**. The optional steps are not used for the derivation of the flat field. If the OGSE allows it, a slight scan of PACS chopper may also be used to correct for the possible irregularity of the OGSE black body sources.

Estimated time needed

Calibration Analysis Procedure (CAP)

The data are reduced in the standard way. First method:

- Compute the difference D for every pairs of different temperatures of the same calibration source $D(j,j') = V(P_b, j\ \mathrm{d}P) - V(P_b, j'\ \mathrm{d}P)$.
- Normalize these differences $F(j,j') = D(j,j')/M(D(j,j'))$, where $M(D(j,j'))$ is the median value of the central part of the detector array.
- Compute an avearged flat field $F = (\sum F(j,j'))/N$, where N is the number of pairs
- Do the same for the other calibration source
- Check the consistency and if positive, make the average of these 2 results to improve

Second method:

- Derive the responsivity map following the CAP of req. 3.2.3, but without averaging over the central area of the detector
- Compute the normalization factor as the median value of the central area of the detector. This gives a set of responsivity values.
- Normalize the responsivity map which provide a flat field

Output, products

Images of the flat-field.

Status/version

```
$Revision: 1.3 $
$Date: 2003/06/18 09:48:37 $
```

Req. 3.2.9 Telescope background and its stability

Objectives

The emission from the telescope will be the major flux source in all PACS observation, driving quite a number of choices in the instrumental set-up or observing strategy. As far as possible we need to characterize the amplitude of temperature gradients and structures that can be seen in the PACS field of view as well as the temporal stability of these patterns. The result of these investigation may lead to simplification of observing modes.

There could be some problem distinguishing telescope signal from stray-light so this is why the CIP is quite complex.

Fulfilling or fulfilled by

Self-standing

Priority

A. Needed to validate/modify our observing strategies.

When performed / frequency

In-flight as only there will we have a reasonable “model” of the telescope.

Required accuracy

Driven by the required photometric accuracy.

Inputs, prerequisites

None.

Sources

The telescope.

Calibration Implementation Procedure (CIP)

Explore a not too complex region of the sky with all possible chopping throws. Repeat that observation with a slightly offset pointing. Features that move on the resulting maps should be in the sky while residual gradients and structures that appear identical on all maps are in the telescope background.

To distinguish between telescope background and stray-light, one may want to repeat the measurement with a bright source in the field.

Repeat regularly if the telescope temperature is changing (telescope temperature is provided in the housekeeping data).

Estimated time needed

Calibration Analysis Procedure (CAP)

Output, products

Prescription on the best observing strategy.

Status/version

Draft version, revised after the December 01 meeting.

3.3 Mutual influence

Req. 3.3.1 Investigate the influence of SPIRE in the partner mode

Objectives

Though it is not decided whether there will or will not be a partner mode where both PACS and SPIRE and on, we have to prepare for this and study the possible influence of SPIRE on the PACS photometer.

Fulfilling or fulfilled by

Self-standing

Priority

C. Partner mode is not decided yet.

When performed / frequency

In flight or possibly when all three instruments are integrated on the spacecraft.

Required accuracy

Driven by the required photometric accuracy aimed at for the partner mode (probably relaxed from that aimed at for the prime mode).

Inputs, prerequisites

None

Sources

Standards (could be the internal sources)

Calibration Implementation Procedure (CIP)

Perform a typical noise measurement to check that we measure the same noise level as in prime mode.

Estimated time needed

Calibration Analysis Procedure (CAP)

Output, products

Validation of the Partner mode.

Status/version

Draft version, added after the December 01 meeting.

Chapter 4

Full System Calibration Spectrometer

This Chapter describes the calibration requirements on the spectrometer from the point of view of a “full system” rather than the more “modular” point of view in Chapter 1.

The requirements cover tests to be done both during ILT and in-orbit.

The main topics addressed in the following sections are the spatial-, spectral and photometric calibration of the spectrometer.

4.1 Spatial Calibration

The basic calibration strategy is similar to the one for the photometer. Larger and fewer pixels relax some of the constraints and accuracy requirements, but slicer diffraction effects, grating alignment, and wavelength dependence induce additional complexity. The 5*5 spatial pixels of the spectroscopic arrays may look simple but are arranged in the complex chain of slicer, spectrometer, and detector assembly. Using the naming conventions of 3.1, the 'array' coordinates are in principle defined by the slicer. The real detector arrays have to be aligned with respect to to the slicer/spectrometer output, misalignments cause effects more complex than a simple rotation/shift. Measurements of central pointing position (4.1.1), FOV distortions (4.1.2) and PSF/ghosts (4.1.3/4.1.4) are sensitive to such misalignments in that chain as well as to the more global effects referred to in their names.

At this point, it is not clear to which extent on-array chopping will be used for spectroscopy of faint point sources. This is clearly desirable from the S/N point of view but only 5*5 pixels are available. Spatial calibrations should be set up to not exclude this option.

Req. 4.1.1 Spectrometer Central Pointing Position and Grating Alignment

Objectives

Establish the relation between the spectrometer central pixel, for a defined chopper position, and the satellite pointing, so that commanding the satellite to the position of an object places the object on the central pixel if the chopper is in the specified position.

In that process, also verify the relative alignment of blue and red spectrometer array and the grating alignment.

Establish the boresight between photometer and spectrometer section of PACS

Fulfilling or fulfilled by

Self-Standing

Priority

A

When performed / frequency

Early in commissioning or PV.

Related procedure in ILT, only to verify alignment.

Required accuracy

One fifth of a spectrometer pixel. Unlike for the photometer, the requirement is *not* split into a more sloppy requirement on the placement of the nominal position, and a strict requirement on the accuracy of the knowledge. For the few and somewhat undersampling spectrometer pixels it shall be possible to put sources into a single pixel as good as possible, to optimize S/N.

Inputs, prerequisites

The ‘defined chopper position’ has to be known first (Req. 2.3.1).

It is assumed that the Photometer central pointing position (3.1.1) is established first, providing a first estimate for the location of the smaller spectrometer FOV on the basis of the boresight from the instrument design (for ILT) and checked by ILT measurement (for in-orbit). This will not be true for the first CQM ILT (no bolometer available). This will require a variant of 2.3.1 to be done on the spectrometer first, and more extensive source searching and focussing of the OGSE xy stage for the spectrometer.

Sources

ILT: single punched hole, size $\sim$5arcsec to get reasonable contrast

In-orbit: Bright point sources, very faint haloes don’t matter. Assuming a 5σ one hour sensitivity of $\approx$0.3Jy, we need sources brighter than 10Jy to get S/N 20 in 1 minute.

Calibration Implementation Procedure (CIP)

In-orbit: Do chopped observations symmetric to the center of the FOV and position switch to outside the FOV. Use several chop throws between $\sim$15” and $\sim$30” around the ’defined chopper position’ to obtain several different positions of beams, with both beams inside the array and well separated.

After center in chop direction has already been well established, repeat with several few arcsecond offsets in cross-chop direction to improve cross-chop centering.

After center has been established in both directions, observe a source such that it is centered at a corner of the central pixel. At this point also repeat for at least five grating settings spread over the grating, always setting blue order sorter to record useful data in both channel simultaneously. Use a four pixel 'quadrant sensor' to probe for small spatial shifts with wavelength.

Combine with observations of the internal calibrators that can be linked to flatfields.

ILT: For a nominal wavelength, maneuver xy stage with single punched hole to bring center of symmetry of chop to central pixel. If necessary, do a z focus sequence of the xy stage. Then observe at at least five wavelengths spread over the grating range to check alignment. Repeat with 'source' centered on a pixel corner to sense small spatial shifts between different wavelength settings using a 'quadrant decetor' of the spatially undersampled spectrometer pixels. It is assumed that the photometer central pointing position is obtained during the same cryocycle to minimize the effect of differential contractions of the test cryostat, and if possible 'in one go' to minimize misalignments of the xy stage.

Combine with observations of the internal calibrators that can be linked to flatfields.

CQM-ILT: with only part of the detector modules available, don't use a chop with positive and negative beam symmetric to the central pixel. Rather, place the positive beam first on the central pixel of the small contiguous field, and then on a pixel corner. Observe several wavelengths for each array/grating order.

Standard science data compression

Estimated time needed

In orbit: One 'elementary' observation will take just $<\sim$2 minutes, but then assuming several wavelengths, several chop throws, and several cross-chop offsets 1 to several hours for a target may be obtained. Several repetitions.

ILT: real measurement of the order 0.5 hour, initial source searching and focus may impose significant overheads (several hours) for CQM ILT.

Calibration Analysis Procedure (CAP)

ILT: after maneuvering (with QLA help) hole to being properly centered at a TBD nominal wavelength, measure and compare centroids for the 16 spectral pixels, for other spectrometer channel and for a set of wavelengths to verify alignment.

Determine boresight wrt photometer channel by comparison to results of 3.1.1, obtained during same cryocycle.

In orbit: Subtract position switched data and measure centroid of positive and negative beam (note undersampling!). Using the various chop throws and cross-chop offsets, derive a center of symmetry consistent with all data at this wavelength.

For a TBD nominal wavelength: If center of symmetry differs from center of central pixel, change satellite attitude control parameters so that future observation will be properly centered

Compare centroids for red vs. blue array and for various grating settings to quantify possible misalignments.

Check for trends within the 16 spectral pixels that might indicate misalignment of the spectrometer array.

Output, products

Status/version

Updated to synchronize with first CIP draft

```
$Revision: 1.3 $
$Date: 2003/04/17 09:32:55 $
```

Req. 4.1.2 Spectrometer Field of View Distortion

Objectives

Determine the optical distortions introduced by the PACS instrument optics and the telescope optics. The optical distortions depend on position on the array as well as chopper position, i.e. the chopper introduces more than a trivial translation.

It is expected that diffraction inside the slicer modulates the relation between input position and measured centroid on a pixel scale, and creates a wavelength dependent astigmatism, both at measurable levels.

The transformation from array to telescope coordinates is hence a function of two spatial dimensions, chopper position, and wavelength.

Fulfilling or fulfilled by

Self-Standing

Priority

A

When performed / frequency

ILT. CQM ILT has only partial spectrometer arrays, thus limiting the range of meaningful settings

Late PV or later (do not do too early since satellite a posteriori pointing information is used)

Required accuracy

1/5 of a spectrometer pixel.

Inputs, prerequisites

Optical modelling giving an indication of magnitude and shape of effects. Preliminary modelling suggests that diffraction effects in the slicer induce both a wavelength dependency of distortion and (in one spatial direction) a modulation of the relation between input position and and measured centroid.

Sources

ILT: Single punched hole. Diffraction effects in slicer should not be smeared out by a too large source. Try hole sizes as in PSF measurement (4.1.3), for example 2 arcsec.

In orbit: Very bright point source $>\sim$100Jy for instantaneous good S/N

Calibration Implementation Procedure (CIP)

For both ILT and in Orbit: While chopping, scan the source along lines parallel to both array axes and at several offsets.

Repeat for a few chop throws

Repeat for a few wavelengths

Standard science data compression

In CQM ILT only reduced version with a cross-scan across the central pixel of the contiguous 3*3 pixel block. Only one wavelength per grating order, e.g. 175μm in first order which gives valid wavelengths also in the other orders.

Estimated time needed

TBD, pretty long

Short CQM-ILT version about 1/2 hour plus setup times

Calibration Analysis Procedure (CAP)

Compare input coordinates (ILT: test optics X/Y scaled to sky using test optics model, in orbit: A posteriori satellite pointing) to measured centroids. Depending on test optics implementation (Can the hole be continuously scanned? Is the X-Y position recorded online?) this may take several flavours.

Check whether results indicate a misalignment of the individual components of the spectrometer array or of the slicer/spectrometer/array assembly.

Fit a parametric model.

This includes deriving or putting a limit on rotation of ‘array’ (=slicer) wrt spacecraft coordinates. Chop direction is taken from photometer (3.1.2).

Output, products

Calibration file between array and telescope coordinates

Alignment check

Information on sub-pixel modulation.

Status/version

Updated for consistency with first CIP draft.

```
$Revision: 1.3 $
$Date: 2003/05/28 08:54:33 $
```

Req. 4.1.3 Spectrometer Point Spread Function

Objectives

Determine the Point Spread Function of the Spectrometer for several wavelengths spread over the PACS wavelength range. Do this for a small sub-pixel raster near the center of the FOV and for a default chop throw. Do spot checks in other parts of the FOV and for other chop throws.

Check for shifts or optical crosstalk suggesting misalignment of the spectrometer arrays.

Fulfilling or fulfilled by

Self-Standing, but partly benefitting from analysis of photometric calibrations

Priority

B

When performed / frequency

PV and later. Pre-tests in ILT. CQM ILT has only partial spectrometer arrays, thus limiting the range of meaningful settings.

Required accuracy

S/N$>$ 100 in the peak.

Inputs, prerequisites

4.1.1 has to be done first.

PSF Models?

Sources

In orbits: Bright point sources without far-infrared halo. Requesting S/N $>$100 in 1 min implies $>$50Jy. Suitable sources might be asteroids moving through clean fields, or stars selected to most likely not have dust shells.

ILT: Back-illuminated punched hole masks

Calibration Implementation Procedure (CIP)

ILT: Chopped observation using punched hole at various positions in FOV. Use a diameter of $\sim$1/4 of the expected FWHM, but no smaller than 2arcsec. Full version: 7*7 raster covering the central pixel for 3 wavelengths each in each grating order, plus spot checks at other chop throws and other spatial positions. CQM ILT: One wavelength for each grating order (e.g. 175μm in 1st order which gives valid wavelengths in other orders as well), no spot checks.

In orbit: Chopped observations, position switch outside FOV to minimize disturbance by negative beam. Do for several positions in central pixel.

Standard science data compression

Estimated time needed

Individual measurement short, but with several wavelenghts and sub-pixel stepping a few hours can be spent easily.

Calibration Analysis Procedure (CAP)

Subtract background, apply flat-field and derive a library of normalized PSFs.

Check for weird behaviour (e.g. PSF shift or PSF deformation between the 16 spectral planes) that might indicate misalignment of the spectrometer array.

Output, products

PSF library and associated products (FWHM etc.)

Status/version

Updated for consistency with first CIP draft

```
$Revision: 1.4 $
$Date: 2003/05/28 08:55:09 $
```

Req. 4.1.4 Spectrometer Ghosts

Objectives

Test for presence of ghosts (=false sources or structures due to internal reflections) in spectrometer data.

Fulfilling or fulfilled by

Analysis of data taken for PSF determination (TBC), and science data

Priority

B

When performed / frequency

PV and later, pre-tests in ILT

Required accuracy

TBD very small fraction

Inputs, prerequisites

Sources

Bright point sources, as isolated as possible

Calibration Implementation Procedure (CIP)

Observe a point source with different positions on array, and different chop throws.

Estimated time needed

Calibration Analysis Procedure (CAP)

Look for signals that neither stay at the same astrometric position (as real background sources would do) nor move with the point source (as PSF structures do). The discrimination between PSF features and ghosts is somewhat fuzzy...

Test optics (ILT) differs from in-orbit setup.

Output, products

Status/version

Draft.

```
$Revision: 1.2 $
$Date: 2002/12/11 17:23:52 $
```

Req. 4.1.5 Spectrometer Straylight

Objectives

Determine signals measured by the PACS spectrometer that are due to bright sources of radiation outside the field of view. Note that such radiation of significant strength may remain undetected in chopped observations if it is only weakly dependent on chop position. Spectral structure in the source that causes straylight may help discriminating straylight from other backgrounds. Sources to be considered include

- Very bright compact sources (late type stars, Planets) within a few arcmin of the FOV (possibility of compact reflections?)
- ???

A signal that could be called 'straylight' is caused by chopping in the presence of telescope temperature gradients, and is being fought by nodding or position switching. Trend analysis of this signal is covered in requirement 4.3.x????

Fulfilling or fulfilled by

self-standing

Priority

B. Pre-test in ILT: C

When performed / frequency

PV and later, pre-tests in ILT

Required accuracy

Inputs, prerequisites

Modelling of Herschel straylight properties to guide search

Sources

Mars, Jupiter, late type stars

Calibration Implementation Procedure (CIP)

Two possibilities: a) chopped observations at some predefined position relative to the bright source. Probably suggested for a range of positions where radiation is still near the PACS aperture b) unchopped fast line scan passing over or near the bright source, aiming to detect a temporary signal excess at a level that can be discriminated from background/sensitivity drifts.

ILT hole masks can be used to try out possiblity a). Note that test optics setup is complex and different from telescope, results have to be interpreted with caution. Using a chopped observation and a large (5-10arcsec) hole in front of the external hot plate, do a finely sampled cross scan over the full x and the full y range, centered on the FOV, and a more coarse rectangular grid over the full range of the xy stage. Choose a wavelength giving simultaneous data in both channels.

If there is sufficient test time at TUFIR, do the same ILT procedure with hole illuminated by TUFIR line source. This should help better discriminating straylight (line) from background variations on the mask (continuum). Obviously, this can be done only for one line at a time.

Estimated time needed

ILT: About one hour

Calibration Analysis Procedure (CAP)

ILT: Subtract on-off, apply flatfield, and look for unusual signals.

Output, products

Status/version

Mention TUFIR

```
$Revision: 1.4 $
$Date: 2003/07/25 14:09:46 $
```

4.2 Spectral Calibration

This section addresses the requirements related to the spectral calibration of the spectrometer.

The requirements cover the wavelength calibration, instrumental profile, spectral purity and spectral ghosts.

In all cases a full characterisation is essential during ILT tests, with only refinements and verification of the calibration forseen in the mission.

Req. 4.2.1 Grating Wavelength calibration

Objectives

Determine the relation between the grating angle and the central wavelength of the grating response. This has to be done for different sky pixels as the central wavelength is shifted as function of pixel. The amplitude of the shift is related to the grating angle.

Fulfilling or fulfilled by

Fulfilling 2.2.1 & 4.2.2

Priority

A, fundamental

When performed / frequency

a) ILT

b) PV Phase

c) Routine Phase to monitor possible shifts. For the monitoring only the central pixel has to be observed and only a few lines have to be measured.

Required accuracy

Peak position to within 10-20% of a spectral resolution element.

Inputs, prerequisites

For the water vapour cell wavelength calibration during ILTs a line list is needed with central wavelengths. The available HITRAN database (http://cfa-www.harvard.edu/HITRAN/) provides a line list for the 4 most abundant water isotopes which is stored in the ancilliary data base: TBC.

Sources

During ILTs:
Assuming that the CQM@MPE scenario will apply, the reference calibration source is a water vapour absorption cell in front of a hot plate. As an alternative medium CO gas can be used. The nominal working conditions and parameters of the water cell are specified in the PACS-ME-DS-002 document.

In orbit:

Sources with well identified emission lines which are not blended. These are PNs, HII regions or late type stars with water lines. Instrumental fringes found through the calibration may also be used. An extended source with strong well-known emission lines would be useful to study efficiently (otherwise a compact source has to be rastered) the shift of the central wavelength as function of pixel.

Calibration Implementation Procedure (CIP)

Perform a full grating scan to measure the water vapour absorption cell absorption line spectrum (external calibration source aligned with the PACS cryostat). The wavelength calibration is based on the study of line center position as a function of grating throw. Line centers are identified on pixels of the detector frequency domain. The extended radiation of the absorption vapour cell is assumed to be homogeneous and isotropic [Requirements, specifications: TBC] at the exit pupil of the cell providing a homogeneous illumination of the detector pixels in the spatial domain. The most appropriate reference source setup (hot-plate temperature, pressure of vapour, absorption path length, stabilization times length...etc:

TBD) is determined during short spectral calibration (CQM-T03). Concerning the detectors, the whole Ge:Ga setup shall be nominal, the procedure should allow to set only the reset interval at run time. In case of saturation the switch to an other capacitor has to be done. An optimization of reset interval and/or integration capacitor shall be considered when switching between grating orders. The measurement sequence is done in range spectroscopy mode (2×3 scans, change of diffraction order in between). A full wavelength range scan shall be performed where the typical grating step size may be of the order of $20''$ to obtain a sampling on each pixel of around 1/5 FWHM. Using the WEBGEN [1] water absorption spectrum simulator one can obtain that the typical FWHM for a strong isolated line is ≤ 0.05 μm. Assuming a resolving power of 2000 @ 100 μm the whole profile is covering $\sim 1 - 8$ spectral pixels instantanously. With sampling of 1/5 FWHM the line profile is represented by $\sim 5 - 30$ data points (@ 3σ assuming a Gaussian profile, $\Gamma = 2.35\sigma$) when scanning the line over the detector pixel. This resolution provides a statistical uncertainty in the determination of the line center of 0.001 - 0.06 microns (from 60 to 200 μm). In order to discriminate between spectral features and characteristics of detectors, filters, windows and the vapour cell itself, two separate grating sequences are required: one with vapour and one without. The ratio of filled/empty cell measurements can provide a rough transmittance baseline. For a characterization of the instrumental profile both up and down grating sequences are required.

Estimated time needed

$\geq$ 7200 sec

Calibration Analysis Procedure (CAP)

The calibration analysis can be made offline. An input data set is required where each pixel signal in V/s is provided with grating position and time, also the grating scan direction must be indicated. Another input dataset is the model line list for the 4 most abundant isotopes taken from the HITRAN database. First fit baseline to define the background continuum. The accuracy of automatised baseline fitting is critical, especially in regions of weak absorption, and the method of using the ratio of filled- and empty-cell measurements certainly does not achieve the necessary precision (TBC). A higher precision fitting method shall be used where absorption free features are recognized from the HITRAN list and the fitting algorithm is restricted to use these selected good window regimes. Accurate continuum estimation is needed in order to fulfill req. 2.2.1. Generate H_2O spectra at all PACS wavelengths for comparison with real data. A key input for an already existing IDL routine is the HITRAN list with the extracted lines. This will allow for easy identification of the individual lines or line patterns using a robust fitting algorithm. For test purposes a simulated spectrum may be produced by "observing" a modeled "vapour cell sky" with the PACS instrument simulator. Register the grating positions for the peaks and the identified wavelengths. Try to fit higher order polynomials for functional description of wavelength calibration. Analyse up- and down-scans separately to identify possible deviations. Eventual deviations might be plotted against the grating throw.

Output, products

Calibration file containing the wavelength vs grating angle positions. This will be necessary for each pixel. Alternative: functional description for each pixel: $\lambda =$f(grat_pos).

Status/version

Draft version

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$Revision: 1.5 $
$Date: 2003/05/06 09:50:33 $
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[1]http://nitrogen3.atmosp.physics.utoronto.ca/webgen_lab_in.html

Req. 4.2.2 Grating Instrumental Profile

Objectives

The instrumental profile is defined as the instrument response when scanning over a line which is intrinsically much narrower, i.e. unresolved, than the profile itself. The characterisation will be done by determining the FWHM level and also the 5% level of the peak to assess the impact of the wings.

Fulfilling or fulfilled by

Priority

A

When performed / frequency

a) ILT

b) PV Phase

c) Later refinements in the mission can be done on the analysis of a larger sample of observations, selected from scientific measurements (see ISOLWS analysis).

Required accuracy

The expected uncertainty of the IP's FWHM is 5%.

The achievable accuracy is very much dependent on the intrinsic line shapes of the calibrator lines. If a modeled profile only poorly represents the real intrinsic line shape, then the deconvolved IP will not show the real IP of the spectrometer. While the vapour cell reference emitter has relatively broad absorption lines, the TUFIR provides much narrower profiles - almost monochromatic lines - and therefore diminishes this bias. If only theoretical assumptions are available for the intrinsic profiles (the WEBGEN spectrum with freely chosen profile pattern), the IP is representative only in terms of its linewidth instead of the overall profile. Only if the spectrum of the vapour cell source were known with higher resolution than the PACS instrumental one, this would lead to a well determined line profile. Instrumental broadening and noise in this reference spectrum can be ignored when determining the IP of the PACS spectrometer with substantially lower resolution.

Emission lines have another advantage, if straylight has to be taken into account. Straylight may fill absorption features leading to unrealistic profiles close to the line center. To properly account for straylight, one needs to measure the IP over the entire wavelength interval of the system. Degradation of the spectrum might be caused also due to the presence of ghosts. Spectral ghosts (which are usually due to periodic ruling errors) scale in strength as the square of the grating order. Therefore ghosts can be produced not only in the vicinity but also far from the parent lines leading to uncertain spectral features and influencing the IP reconstruction accuracy in certain wavelength regimes.

From a computational point of view an uncertainty in the IP is introduced due to the approximation made in discretizing the convolution. This uncertainty in the derived IP scales as $1/\sqrt{N}$, where N is the number of spectral lines containing IP information.

When AOT type calibration measurements performed (FM and PV phase) the grating step size and scanning speed must be variable. Since the step sizes will be more around $\geq$20" it has an impact on the accuracy of the IP reconstruction procedure. Tcl scripts must have to allow the tuning of these parameters.

Inputs, prerequisites

Calibration measurements required to be completed before:

1) Req. 2.4.5, (In order to get as narrow a profile as possible a perfectly focused spectrometer needed)

2) Req. 2.4.4 & req. 4.1.5 (Straylight). Not available for CQM!

3) Req. 4.1.4 & req 4.2.4 (Spectral/spectrometer ghosts). Not available for CQM!

Sources

a) CQM-ILT: List of WEBGEN generated model spectrum lines of the water vapour applying nominal cell conditions ($p = 20$ mbar, $T_{\rm cell} = 298$ K, $l_{\rm absorption\ path} = 0.3$ m, $T_{\rm hot\ plate} = 450$ K, # of H_2O isotopes: 10, line shape: Voigt, line model: HITRAN '96). The number of scanned lines might be increased to establish better the wavelength - resolving power relation.

   1) 1st order (57-72 μm): 59.35, 65.16, 71.07 [μm]
   2) 2nd order (72-105 μm): 76.42, 92.81, 98.5 [μm]
   3) 3rd order (105-210 μm): 121.74, 160.51, 187.11 [μm]

b) PV Phase: List of astronomical sources with isolated lines which are narrow in comparison to the profile from ILT measurements. PN and HII regions are expected to provide these. Also the water lines observed in objects W Hydra. CO lines.

Calibration Implementation Procedure (CIP)

Perform individual grating scans in line spectroscopy mode to measure the specified 9 absorption lines (see list under "Sources") in the water vapour spectrum. Both up and down grating sequences are required. The extended radiation of the absorption vapour cell is assumed to be homogeneous and isotropic [Requirements, specifications: TBC] at the exit pupil of the cell providing a homogeneous illumination of all 25 detector pixels in the spatial domain. The most appropriate reference source setup (hot-plate temperature, pressure of vapour, absorption path length, stabilization times length... etc: TBD) should be determined during the short spectral calibration (CQM-T03). Concerning the detectors, the whole Ge:Ga setup shall be nominal, the procedure should allow to set only the reset interval at run time. In case of saturation the switch to another capacitor has to be done. An optimization of the reset interval and/or integration capacitor set-up shall be considered when switching between grating orders. The lines are to be measured down to the smallest grating step of $10''$ with sufficient wavelength coverage to observe the wings at 5% of the peak level and determine the continuum. Using the WEBGEN [2] water absorption spectrum simulator, one obtains a typical FWHM for a strong isolated line of ≤ 0.05 μm. Assuming a resolving power of 2000 @ 100 μm the whole profile is covering $\sim 1-8$ spectral pixels instantanously. With the finest grating step of $10''$ a sampling of 1/10 FWHM is achieved. In this case the line profile is represented by $\sim 10-60$ data points (@ 3σ assuming a Gaussian profile, $\Gamma = 2.35\sigma$) when scanning the line over the detector pixels. In this calculation the instrumental broadening has not been taken into account, as a consequence, during measurements the number of data points over the line profile has to be higher. This spectral sampling enables the application of the goodness-of-fit parameter estimation technique described in the CAP. For the selected lines we assume a S/N < 1000. The integration time and grating dwell time is calculated in the following way: TBD.

Estimated time needed

$\geq$ 1000 sec

Calibration Analysis Procedure (CAP)

The recorded spectra $g(x)$ may be represented as

$$g(x) = \int_{-\infty}^{\infty} f(x')\phi(x-x')dx',$$

where the kernel $\phi(x-x')$ describes the unknown IP and $f(x)$ is the true underlying function of the intrinsic line profile (x represents the pixel position in the spectral domain). From the recorded spectrum $g(x)$, $\phi(x)$ has to be determined.

[2] http://nitrogen3.atmosp.physics.utoronto.ca/webgen_lab_in.html

One way is to invert the above equation by using discrete Fourier or wavelet functions. However, these deconvolution techniques are imperfect: lines in these representations are smoothed, leading to a broader IP. An alternative method is therefore proposed: an analytic form of the IP is selected and the high resolution line spectrum $f(x)$ is convolved with this kernel according to the discretized form of the expression above,

$$g_i = \sum_{j=i-p}^{i+p} f_j \phi_{i-j},$$

where i represents the pixel's mid-position, j is the oversampled position and p is the half-size of the kernel. Since the IP generally falls below 5% of its peak intensity a few pixels away from the line center, we may assume ϕ_{i-j} is zero when $|i-j| > p$. This synthetic spectrum is then rebinned to match the pixel locations in the observed spectrum and modified by a linear term to fit the baseline and the line peaks (valleys). By iteration of this procedure the IP parameters can be optimized using maximum-likelihood, χ^2 or other standard parameter estimation techniques. The derived parameters of $\phi(x)$ should be adopted at 95% confidence level. A fairly general $\phi(x)$ function (e.g. gaussian) should be used initially, when the basic form of the IP is unknown. If neither TUFIR nor high resolution measured water vapour spectra were available, then the WEBGEN generated profile should be applied to approximate $f(x)$ during the ILT phase. Profile asymmetries could be recognized, if the above fitting procedure were done separately for the blue and red wings relative to the line center. Profiles obtained in the 25 spatial channels must be compared. Wavelength/order dependence of the IP must be followed up. If absorption lines are not as deep as expected, then a straylight correction has to be applied (TBD). `(Note: the SWS IPs have a Gaussian shape up to accuracies of a few percent. The only systematic differences from a Gaussian profile are a slight shoulder on the blue side of the base of the profile and a depression on the red side as compared to a purely Gaussian profile which varies with the position in the slit.)`

Output, products

Calibration file containing the instrumental profiles (if needed for different wavelength regimes (TBD) or at least for the different orders). Wavelength dependent resolving power of the spectrometer (a convolution of the IP and pixel size).

Status/version

Draft version

```
$Revision: 1.3 $
$Date: 2003/04/01 15:20:47 $
```

Req. 4.2.3 Spectral Purity

Objectives

To measure any contamination of the spectrum by light from outside the nominal grating order. This will be done by measuring strong lines in the wavelength range covered by the detector response but outside the nominal grating order.

Fulfilling or fulfilled by

Self-standing

Priority

B

When performed / frequency

- ILT
- PV Phase

Required accuracy

The accuracy of the impurity characterization procedure is noise limited, the noise rms should be derived during the test sequence.

Inputs, prerequisites

- PV phase: Sources with bright pronounced emission lines and a relatively low continuum level, ideally no line forest e.g. PNe lines (TBC).
- ILT: CAPs required to be completed before: req. 4.1.5 & req. 4.2.4

Sources

- ILT: TUFIR
- PV phase: Bright line-sources (possibly one already well measured with LWS). If observability constrains allow use the same targets as proposed for req. 4.2.1 & req. 4.2.2.

Calibration Implementation Procedure (CIP)

During ILT the spectral impurity should be investigated in the following order sorting filter - TUFIR wavelength combinations:

Configuration	λ_{TUFIR} [μm]	Order-sorting filter in the Blue channel	Blue Array Expected wavelength if impurity occurs	Red Array Expected wavelength if impurity occurs
(a)	144-160	2^{nd}	$1/2\lambda_{\mathrm{TUFIR}}$	$(\lambda_{\mathrm{TUFIR}})$
(b)	72-108	3^{rd}	$2/3\lambda_{\mathrm{TUFIR}}$, $(82.5 \leq \lambda_{\mathrm{TUFIR}} < 108)$	$2\lambda_{\mathrm{TUFIR}}$
(c)	35-72	2^{nd}	$3/2\lambda_{\mathrm{TUFIR}}$, $(48 \leq \lambda_{\mathrm{TUFIR}} < 72)$	$3\lambda_{\mathrm{TUFIR}}$
(d)	41.25-55	3^{rd}	$4/3\lambda_{\mathrm{TUFIR}}$	$4\lambda_{\mathrm{TUFIR}}$ & $3\lambda_{\mathrm{TUFIR}}$

In these configurations TUFIR can produce lines outside the range of the selected grating order due to the spectral response of the detector. The only exception is configuration (a) where the illuminating line can be detected directly in the red channel. In case of spectral impurity a TUFIR line can contaminate the selected spectral order, the goal is to find wavelengths where the intensity of the unwanted line is above the 3σ noise level. The settings for the configurations in the table above are determined by the following factors: (i) operational regime of the PACS grating in terms of the angle of the incident light (which can be expressed by the grating throw, too), (ii) grating equation, (iii) nominal wavelength range of the order-sorting filters (iv) the sensitivity ranges of the PACS Ge:Ga arrays. The relative spectral response drops to zero at ~ 35 μm for both the stressed and low-stressed detectors defining a blue cutoff, while the long wavelength cutoff is assumed to be at ~ 160 μm for the blue detector and ~ 250 μm for the red one (the latter one is not relevant for the configuration design since lies outside the nominal grating angle range).

The grating equation is given by $m\lambda = d(\sin\alpha + \sin\beta)$, where m is the diffraction order, d is the grating constant, α is the grating angle of incidence and β is the diffraction angle with respect to the grating normal direction. In the Littrow condition which applies to the PACS design the incident and diffracted rays are (nearly) in auto-collimation (i.e. $\alpha \approx \beta \approx \omega$), ω is the groove angle on the incident facet. Applying this condition, the grating equation is simplified to: $m\lambda/2d = sin\alpha$ (see e.g. Fig. 6.2-10 in PACS-ME-GR-002).

In a first, rough approach the check for spectral purity shall be performed for a few selected wavelengths distributed over the wavelength regimes of the different configurations as indicated in the first table. Applying the grating equation the respective wavelengths of the proposed TUFIR lines for the different configurations are calculated and summarized in the following table:

	α [degrees]	30	35	38	40	42	45	50	55	60	65
	Grating throw [degrees]	18	13	10	8	6	3	-2	-7	-12	-17
(a)	λ_{TUFIR} [μm]	–	–	144.8	151.2	157.4	–	–	–	–	–
(b)	λ_{TUFIR} [μm]	–	–	72.4	75.6	78.7	83.2	90.1	96.4	101.9	106.6
(c)	λ_{TUFIR} [μm]	39.2	45.0	–	50.4	–	55.5	60.1	64.2	67.9	71.1
(d)	λ_{TUFIR} [μm]	–	–	–	–	–	41.6	45.1	48.2	50.1	53.3

When a given TUFIR line is tuned, then the PACS grating throw shall be set according to the values in the second row of the table above (TBC) and the order-sorting filter is chosen as described in the first table. This sequence is done in line spectroscopy mode. Note that the narrow TUFIR lines are always in the regime of the spectrometer's instantaneous coverage. The TUFIR laser beam should be targeted on the mid-pixel of the 5×5 spectrometer FOV and the grating throw should be set such that the line center during all measurements illuminates the 8^{th} spectral pixel.

If on-the-fly data reduction is available and in case of unwanted line detection three further steps are needed for a detailed impurity characterization: (i) a detailed TUFIR scan with a step of 0.2 μm (TBC) should be performed in addition. This procedure is completed when the impurity line intensity drops below the noise level. During these TUFIR scans the grating should be operated in line spectroscopy mode and the actual grating position should be calculated from the grating equation (what might be implemented into the test procedure). In order to determine the unwanted impurity line intensity with regard to the TUFIR line intensity ($I_{\mathrm{I}}/I_{\mathrm{TUFIR}}$): (ii) the I_{TUFIR} should be measured using the appropriate order-sorting filter in the spectral regime determined by measurement (i). In case of impurity identification the spatial dependence should be followed up: (iii) at least the four spatial corner pixels of the spectrometer FOV should be measured in addition. A grating line scan should be performed around the wavelength where the impurity intensity shows a maximum in step (ii). For these sequences, the point source displacement is supported by the test equipment.

Contamination by higher orders ($m > 4$) is assumed to be negligible due to the decreasing grating efficiency, while the zeroth order falls far from the diffracted orders in the Littrow condition. If TUFIR wavelength tuning takes longer time than the order-switching procedure of the PACS spectrometer, then measurements of different configurations should be executed in a common block. In order to get the background noise rms a series of background measurements must be performed at the beginning and at the end of the test sequence. During these background sequences the experimental set-up is the same, but TUFIR is switched off. In this configuration PACS can measure all components contributing to the background. Other test conditions and setup should be nominal. The TUFIR radiation [Requirements, specifications: TBC] is expected to be point like at the exit pupil of the half-transmitting laser mirror. During the test sequences the illuminating TUFIR flux should be chosen as maximum as possible, but avoid detector saturation. The whole Ge:Ga setup shall be nominal, the procedure should allow to set only the reset interval at run time. In case of saturation the switch to another capacitor has to be done. An optimization of the reset interval and/or integration capacitor set-up shall be considered when switching between grating orders.

During PV phase perform a grating scan around dedicated lines (TBD) within the wavelength regimes of configurations a-d.

Estimated time needed

Calibration Analysis Procedure (CAP)

Spectral purity can be expressed quantitatively as the ratio of the in-band light passed through the spectrometer to that light transmitted from outside the selected spectral band. After the determination of the noise rms and removal of the background level obtained by the background sequences, peaks above the 3σ level should be searched for.

An impurity of the system might occur due to straylight, imperfect ruling of the grating substrate (when $m\lambda/d \neq \mathrm{const}$) and contamination by the vignetted orders. The last effect might be significant only if the transmission of the order sorting filter does not drop to zero at the nominal cut-off wavelengths. According to the filter performance requirements the out-of-band suppression of the filters multiplied by the detector suppression factor lies between $\sim 10^{-4}$ and $\sim 10^{-3}$. The grating efficiency for 2^{nd} order is 50-70% providing an additional attenuation. This leads to the assumption that in case of nominal conditions the contaminating out-of-band lines must be very strong (TBD) and the occuring impurity is substantially related to parasitic light passing through the dichroic and/or order-sorting filters.

Output, products

List of unexpected lines above the 3σ noise level in all identified configurations with the corresponding TUFIR wavelength and their relative strength to the original lines.

Status/version

second draft

```
$Revision: 1.3 $
$Date: 2003/06/11 18:56:31 $
```

Req. 4.2.4 Spectral Ghosts

Objectives

To check to which extent ghosts are present at various distances to the principal maximum by making a very detailed scan of a source with bright lines or TUFIR lines during ILT.

Fulfilling or fulfilled by

Priority

A

When performed / frequency

- ILT
- PV Phase

Required accuracy

Ghosts should be detected down to the noise level, the noise rms should be derived during the test sequence.

Inputs, prerequisites

Identification of astronomical sources with well identified bright lines and the list of these lines.

Sources

- On ground during ILT tests a grating scan on the TUFIR source will be performed. Check for inter-order lines with respect to the illuminating TUFIR line.
- In orbit: Scan a source with a well known spectrum of lines. Look for lines not present in the true spectrum. Sources already well studied with LWS (so that the lines are identified) should be good targets.

Calibration Implementation Procedure (CIP)

Full grating scan in three orders with high resolution. TUFIR will be tuned over the full wavelength regime in all three orders with steps of $\delta\lambda \sim 3$ μm in the 3rd order, $\delta\lambda \sim 5$ μm in the 2nd order and $\delta\lambda \sim 10$ μm in the 1st order leading to 23 settings in the entire wavelength regime. For a given TUFIR wavelength a grating range scan must be performed over $\pm\Delta\lambda/5$ (TBC), where $\Delta\lambda$ represents the nominal bandwidth for each order (leading to $\pm 21.0, 6.6$ and 3.4 microns in the $m = 1, 2, 3$ orders). The TUFIR laser beam should be targeted on the mid-pixel of the 5×5 spectrometer FOV. In case of ghost identification in the central pixel position and if on-the-fly data reduction is applicable then at least the four spatial corner pixels of the spectrometer FOV should be measured in addition. In this case the point source displacement is supported by the test equipment. Focal plane chopper positions different from zero might also be used for a detailed ghost follow-up (TBC). Concerning the detectors, the whole Ge:Ga setup shall be nominal, the procedure should allow to set only the reset interval at run time. In case of saturation the switch to another capacitor has to be done. An optimization of the reset interval and/or integration capacitor shall be considered when switching between grating orders. The measurement sequence is done in range spectroscopy mode (2×3 scans with up- and down sequences, change of diffraction order in between) where the typical grating step size may be of the order of $20''$ to obtain a sampling on each pixel of around 1/5 FWHM of the TUFIR lines (TBC). The illuminating TUFIR flux should be chosen as the maximum one possible, just to avoid detector saturation. In order to get background noise rms a series of background measurements must be performed at the beginning and at the end of the test sequence. During these background sequences the experimental set-up is the same but TUFIR is switched off. In this configuration PACS can measure all components contributing to the background. Other test conditions and setup should be nominal.

Estimated time needed

Calibration Analysis Procedure (CAP)

Ruled gratings exhibit ghosts due to ruling errors on the grating substrate. This parasite light is focused in the dispersion plane, while stray light is almost randomly scattered and not focused. Generally, ghosts should follow the grating equation, but for spatial frequencies other than $1/d$ and m (the diffraction order) holds not to be integer. The analysis is straightforward: search for narrow (line-type) spectral features above the noise level. After the determination of the noise rms and removal of the background from the background sequences, peaks should be searched for above the 3σ (TBC) level. The goal is to find the ghost intensity relative to the parent line, record the displacement of the ghost intensity maximum from the parent line center and try to specify the type of the grating error. Rowland ghosts - due to longer-term periodicities (much larger than the groove spacing) - are located closely and symmetrically on both sides of the parent diffracted line. The separation of the Rowland ghosts from the parent line depends on the period of the ruling error, and they intensity depends on the amplitude of this error. The displacement from the parent line at λ shall be expressed by $\delta\lambda = \pm\lambda/d * D_p$, where d is the groove density and D_p represents the pitch of the ruling engine. Additional ghosts might be located at integer multiples of $\delta\lambda$. Applying this equation with the PACS grating constraints (TBC) we get $\delta\lambda = n*$ (TBD) as a prediction for the location of Rowland ghosts with respect to the parent line. The relative Rowland gost intensity in Littrow condition is approximated by $I_{RG}/I_P = d^2m^2e^2\pi^2$, where I_{RG} is the ghost intensity, I_P is the parent line intensity, d is the groove density, m is the order and e represents the error in the position of grooves. Adopting the PACS grating values according to the specifications $d = 8.5$ mm^{-1} and $e = 0.3$ μm, in $m = 2$ order one can get $I_{RG}/I_P \simeq 2.6 * 10^{-4}$. Note that ghost intensity in the order of 10^{-4} is typical for high quality gratings. The measured I_{RG}/I_P ratios should be checked by the above expression. When more periodic deviations are present in the groove spacing, interference of the ghost diffraction patterns can generate spurious lines far from the parent line - these are the so called Lyman ghosts. Lyman ghosts are usually caused by short-term periodicities (in the order of few times the groove spacing) and are located in fractional-order positions. These positions are determined by the number of grooves per period e.g. an error every five grooves corresponds to a fraction order of $1/5$. Random (rather than periodic) irregularities in groove placement leads to a faint background between orders, rather than sharp ghosts (grass effect) but this unwanted light feature is interpreted as a component of straylight and supposed to be traced in req. 4.1.5.

Output, products

List of parasitic peaks as a function of TUFIR wavelength and grating position.

Status/version

Second draft version, complete upgrade

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$Revision: 1.3 $
$Date: 2003/06/11 18:56:03 $
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4.3 Photometric Calibration

This section addresses the requirements related to the photometric calibration of the spectrometer.

The main topics are the absolute flux calibration and the reproducibility of the internal reference sources, the relative spectral response function, and the flat-field. These requirements involve extensive ground tests for a first characterisation.

Other topics are the instrumental polarisation and the stability of the telescope background which can only be addressed by in-orbit measurements.

Req. 4.3.1 Absolute flux calibration internal sources, spectrometer

Objectives

Determine the absolute flux calibration of the spectrometer using the PACS calibration sources together with the OGSE black bodies (during ILT) and together with celestial standards (in orbit); Prepare the grounds for photometric calibration within AOTs.

Fulfilling or fulfilled by

Related to
Req. 4.3.3 Absolute flux calibration external sources, spectrometer;
Req. 4.3.8 Relative spectral response function, spectrometer;

Priority

A

When performed / frequency

ILT: calibrate the PACS calibration sources against the OGSE black bodies. Monitoring during ILT tests.
PV phase: calibrate the PACS internal calibrators against celestial standards.
Routine phase: monitoring.

Required accuracy

20% (10% goal) [instrument requirements document]

Inputs, prerequisites

Basic detector, filter, grating and chopper characterisation; Nominal PACS calibraton sources and OGSE black body performance; Nominal optical and grating alignment; No straylight influences; Nominal spatial and spectral calibration.

Sources

Both OGSE black-bodies during ILT. Their spectral shape and intensity should be known to a percentage significantly smaller than the 20% (10% goal) for the accuracy on the absolute flux calibration itself.

Celestial standards with absolute flux calibrated spectra of various flux-levels in PV and later phases.

Calibration Implementation Procedure (CIP)

The absolute flux calibration should be performed on several short scans distributed homogeneously over the full scan range. The absolute calibration of the full wavelength range will be established together with the RSRF (Req. 4.3.8). This will then allow to make frequent and fast photometric performance checks in orbit with only small and fast grating movements to reach the short reference scan regions. Short scans might also be part of the spectrometer AOTs (details TBD). The applicability of fixed grating measurements for photometric checks has to be checked in comparison with short scans and the full RSRF measurements. The homogeneity of the PACS calibration sources should be checked independently by small modifications of the absolute chopper position (req. 2.5.2 Spatial stability of PACS calibration sources).

ILT CIP:

1. Switch-on/Setup spectrometer
2. Short chopped grating scans on OGSE BBs and PACS internal sources (1-3 (TBD) short scans per grating order)
3. Fixed grating position measurements on OGSE BBs and PACS internal sources, repeat step 2, several chopper cycles on OGSE BBs and on PACS internal sources, key wavelength (TBD): 195, 155, 115, 95, 80 and 65 micron

4. The measurements at fixed grating positions (step 3) should be repeated with different chopper positions on the PACS internal calibrators to check homogeneity of the sources (related to Req. 2.5.2)

Note: During ILT, the internal reference sources are only calibrated against extended cryo black bodies, no point-source absolute calibration will be done on ground.

In-orbit CIP: Observe the source. Perform flat-fielding. Perform wavelength calibration, including spectral distortion. Divide the resulting spectral scans by the RSRF to get the true shape fo the observed spectrum. Divide the absolute flux calibrated spectrum of the celestial standard by this spectrum to get the conversion from physical units to observed units. Note: more details can be found in PTD_4.3.1.

Estimated time needed

Depends on the input values, scan lengths, number of scans, up/down scans, number of chopper cycles, readouts, S/N, ... considerations. Due to the limitations in test time, only the most important part of the absolute flux calibration of the spectrometer can be done within this requirement.

Calibration Analysis Procedure (CAP)

The measured signals are products of black body emission, filter transmission, grating efficiency, spill-over factors and detector efficiency. The signal differences from the OGSE BBs have to be calculated for each temperature setting. Note: more details can be found in PTD_4.3.1.

Output, products

A relation between internal source signal levels and reference flux scale set by the OGSE cryo black bodies (during ILT) and the celestial standard sources (in-orbit) at grating/band key wavelengths and, together with the RSRF, at all wavelengths. Note: The OGSE cryo-BBs are extended sources, celestial standards are point-sources!

Status/version

Third draft version

```
$Revision: 1.7 $
$Date: 2003/04/11 15:23:50 $
```

Req. 4.3.2 Reproducibility internal sources, spectrometer

Objectives

Verify the reproducibility of the spectrometer signal ("slopes") using the internal calibrators. This should be performed on different timescales. The slopes to be compared should be derived from the raw data with a uniform setup concerning the datareduction.

Fulfilling or fulfilled by

Related to 4.3.1, 4.3.4.

Priority

C

When performed / frequency

During ILT and PV. Monitoring during routine phase.

Required accuracy

5% (3% goal) [instrument requirements document]

Inputs, prerequisites

Sources

OGSE black-bodies during ILT.

Sources

Calibration Implementation Procedure (CIP)

Repeat a series of measurments as described under 4.3.1 with identical setups. For CQM the implementation of the CIP is chosen to be directly coupled to that of 4.3.4. as there there will be chopped measurements on both PACS and OGSE BBs.

Estimated time needed

Calibration Analysis Procedure (CAP)

Analyse sequences of absolute flux calibration measurements.

Output, products

Status/version

First draft version

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$Revision: 1.7 $
$Date: 2003/04/04 14:05:40 $
```

Req. 4.3.3 Absolute flux calibration external sources, spectrometer

Objectives

Determine the absolute flux calibration of the spectrometer using external sources (only relevant in orbit). During ILT this requirement is fulfilled by req. 4.3.1.

Fulfilling or fulfilled by

Related to
Req. 4.3.1 Absolute flux calibration internal sources, spectrometer;
Req. 4.3.8 Relative spectral response function, spectrometer;

Priority

A

When performed / frequency

During PV phase. Monitoring during routine phase.

Required accuracy

20% (10% goal) [instrument requirements document]

Inputs, prerequisites

Needs flat-field, wavelength calibration (taking into account spectral distortion), RSRF, straylight characterisation, PACS calibration source characterisation (spatial, spectral and time stability).

Sources

Celestial standards with absolute flux calibrated spectra of various flux-levels in PV and later phases. Spectral features of the celestial standards have to be well known. A mixture of different types of celestial standards will allow to identify unknown features in certain object classes.

Calibration Implementation Procedure (CIP)

The absolute flux calibration should be performed on several short scans distributed homogeneously over the full scan range, using celestial standards with well estblished spectral energy distributions. The absolute calibration of the full wavelength range will be established together with the RSRF (Req. 4.3.8). Absolute flux calibration requires celestial sources which cover a wide range in flux densities at the given wavelengths of the short scans. This is strongly connected to req. 4.3.5 Linearity with flux. Regular flux reproducibility checks on celestial standards are part of req. 4.3.4.

Observe the source. Perform flat-fielding. Perform wavelength calibration, including spectral distortion. Divide the resulting spectral scans by the RSRF to get the true shape of the observed spectrum. Divide the absolute flux calibrated spectrum of the celestial standard by this sprectrum to get the conversion from physical units to observed units.

Estimated time needed

Depends on the input values, scan lengths, number of scans, up/down scans, number of chopper cycles, readouts, S/N, ... considerations.

Calibration Analysis Procedure (CAP)

The measured signals are products of the celestial source spectrum, filter transmissions, grating efficiency, spill-over factors and detector efficiency. Note: During ILT, this requirement is covered by req. 4.3.1 (see also PTD_4.3.1.)

Output, products

A relation between PACS calibration source signals and signals from the celestial standard at grating/band key wavelengths and, together with the RSRF, at all wavelengths. Note: The celestial standards are mainly point-sources, while during ILT only extended sources (cryo-BBs) are used.

Status/version

Second draft version

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$Revision: 1.6 $
$Date: 2003/04/11 15:24:04 $
```

Req. 4.3.4 Flux reproducibility external sources, spectrometer

Objectives

Verify the continuum and line flux reproducibility of the spectrometer using external sources.

Fulfilling or fulfilled by

Related to 4.3.3

Priority

C

When performed / frequency

During ILT and PV. Monitoring during routine phase.

Required accuracy

5% (3% goal) [instrument requirements document]

Inputs, prerequisites

Needs wavelength calibration.

Sources

OGSE black-bodies during ILT, celestial standards in PV phase.

Calibration Implementation Procedure (CIP)

The reproducibility test in CQM is performed by scanning small wavelength ranges with both detectors. We select scans that overlap with the short scans observed for the absolute flux calibration (req. 4.3.1.). The measurements should be repeated 10 times. Most likely this could be combined with the test measurements of 4.3.1. The present description only concerns the reproducibility of measuring a continuum source and does not concern line fluxes.

Short chopped grating scans on OGSE BBs and PACS internal sources (1 scan per detector).

a) red array, 1st order
Temperatures of OGSE BBs to $T_{BB1} = (20 - x)K$ and $T_{BB2} = (20 + x)K$, with 'x': a few K (TBD), to produce a well-characterised signal, but avoid transients
- grating scan (up and down) 150 to 153 micron, switching between both OGSE BBs (OGSE chopper), several read-outs per chopper plateau, several chopper cycles per grating position
- grating scan (up and down) 150 to 153 micron, switching between both PACS calibrators (PACS chopper), several read-outs per chopper plateau, several chopper cycles per grating position
Repeat the above sequence nine times.

b) blue array, 2nd order
Temperatures of BBs to $T_{BB1} = (32 - x)K$ and $T_{BB2} = (32 + x)K$
- repeat sequence with grating scan (up and down) 90 to 93 micron for a total of 10 measurements

Estimated time needed

Calibration Analysis Procedure (CAP)

The measured signals are products of black body emission, filter transmission, grating efficiency, spill-over factors and detector efficiency. The signal differences from the OGSE BBs have to be calculated for each temperature setting.

- Comparison and averaging of up- and down-scans per reference scan range (filter-order combination) for sequences on internal calibrators and sequences on cryo-black-bodies.
- Reproduceability has to be checked by comparing averaged up and down scans and comparing the up scans and the down scans seperately. This should be done for the ‘naked’ signals obtained from the internal PACS BBs and OGSE BBs and also for ‘calibrated’ signals for which the signal obtained by measuring the OGSE BBs is calibrated by using the measurement from the closest measurement in time on the PACS internal sources. Comparison is performed by determining the spread of signals per wavelength position (and visualised by plotting sigma as function of wavelength).

Output, products

Status/version

Second draft version

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$Revision: 1.7 $
$Date: 2003/04/07 08:36:45 $
```

Req. 4.3.5 Linearity with flux

Objectives

Determine the scaling relation for detector responsivity as function of incident flux (source + background).

Fulfilling or fulfilled by

Priority

A

When performed / frequency

ILT, in PV with some repetition (once in 3 months) during the further mission.

Required accuracy

Inputs, prerequisites

Outcome of requirements 1.2.3. (Dynamic range per selected capacitor) and 1.2.11. (linearity of CRE readout).

Sources

OGSE Black bodies for the ILT.

In orbit; Possibly it is difficult to control sufficiently the internal sources and would these only be of limited or no use to study a wide flux range. The alternative is to measure astronomical sources with a wide range in flux densities. What range and how fine grid of fluxes will be related to the final set up of the capacitors (see req 1.2.4).

Calibration Implementation Procedure (CIP)

For ILT:
Measurement has to be done for the blue and red detectors. For each channel a key wavelength is selected and considered representative for the whole channel. At the key wavelengths the flux of the OGSE blackbodies will be measured at a range of temperatures. Most astronomical targets that will be measured have fluxes which are only a small fraction of the expected telescope background flux.

In principle linearity is measured by measuring the responsivity as function of input flux. A first test is to start from the background level and see how responsivity changes as function of increasing flux.

OGSE3: Two internal cryogenic blackbodies are available, which can be set at different temperatures between 20 and 100K ("PACS Cryo Test Equipment and OGSE Specification", PACS-ME-DS-002). We are still waiting for answers on the OGSE black bodies, but I assume that the accuracy of the temperature determination is 15mK.

As the emissivities of the OGSE black bodies cannot be adjusted we need to use a certain black body temperature to obtain an input power per pixel corresponding to that of the telescope background (emissivity=0.04, T=80 K assumed). Wait for sufficient stabilization of the BBs and the signal. Measure the BBs at different (increasing) temperatures (this should correspond to telescope + a source of 1, 2, 5, 10, 20, 50, 100, 200, 500, 1000, 2000, 5000, 1000 Jy).

This has to be done for the blue and red detector. Red: starting temperature of BB1 at 25K, select grating position corresponding to 130 μm. Blue: starting temperature of BB1 at 30K, select grating position corresponding to 100 μm.

Estimated time needed

Calibration Analysis Procedure (CAP)

The output of the measurements are data cubes (25 spatial pixels, 16 wavelength pixels).

```
---25 spatial pixels--- 1
```

```
---------------------- 6
.                      w
.                      a
---------------------- v
---------------------- e
```

Determine the flux from the BB (Jy / pixel) for each wavelength and divide the measured signal (flat-fielded) per pixel by that flux. Plot the responsivities as function of input flux.

Output, products

Status/version

Second draft version

```
$Revision: 1.3 $
$Date: 2003/04/04 16:49:59 $
```

Req. 4.3.6 Minimum detectable flux, spectrometer

Objectives

Determine the minimum detectable line (and continuum) flux with the spectrometer. This determination is made empirically. Thus, it provides estimates for the signal-to-noise ratios (SNR) that PACS users can expect in the presence of all sources of noise (whether accounted for in theory-based estimates of SNR or not).

Knowledge about two relationships is required: (i) the SNR vs flux relationship, and (ii) the SNR vs total observation time relationship. The minimum detectable flux for a given observing duration is simply the corresponding flux value for an adopted threshold criterion (SNR) for detection. The second relationship extends this flux limit to other observing times.

Fulfilling or fulfilled by

Self-standing

Priority

C

When performed / frequency

ILT, PV phase, begining of routine phase. Understanding will grow during mission.

Required accuracy

TBD

Inputs, prerequisites

We require knowledge about the input flux. And, knowledge of various detector characteristics, identified below, is needed:

- Detector responsivity.
- Detector spectral response.
- Spectrometer band-pass.

Sources

For in-flight measurement, no special sources are needed; Input data from objects observed during PV and routine phase are likely sufficient.

During the ILT, a line emission source (e.g. lamps), if available, is required to determine the minimum detectable line flux. The EGSE or intercal calibration sources are sufficient for determining the minimum detectable continuum flux.

Calibration Implementation Procedure (CIP)

We adopt a detection with SNR equal to 10 as a criterion for minimal detectivity. A SNR threshold of 10 is preferable because it avoids various statistical biases (e.g. Eddington bias) that are found in the lower, but more widely used, threshold of 5.

It is quite likely that the CIPs already implemented for other calibration activities will generate the data needed to adequately characterize the two relationships identified above. For example, the CIP used to determine detector non-linearity will likely be useful here as well. Specifically, the following data are needed:

- Measurements made for a fixed integration time but for various input flux levels.

- Measurements made for a fixed input flux level but for various integration time.

The number of such measurements depends on the detector non-linearity, if any. In theory, one expects a linear relationship between flux and SNR on a log-log plot:

$$SNR \propto \sqrt{Flux},$$

Thus,

$$\mathrm{Log}_{10}(SNR) \propto 0.5 \times \mathrm{Log}_{10}(Flux)$$

Equation 16.4.14 by Schroeder (D. J. 1987, in *Astronomical Optics*, San Diego: Academic Press, Inc., pg. 324) describes this relationship in more detail. For our purposes, Schroeder's equation can be reduced to:

$$\mathrm{Log}_{10}(Flux) = A + B \times \mathrm{Log}_{10}(SNR)$$

Thus, in theory, one needs only two pairs of (flux,SNR) data points to determine the two unknown constants (A, and B) to fully characterize this relationship. However, the (expected, TBD) presence of fringes in the spectra and any other non-linearities (transients, for instance) will significanly alter this linear relationship. The good news is that complicated theoretical models for fringes or transients, etc. are not necessary for our purposes. We need only to characterize the flux vs SNR relationship empirically at the low-flux end. Using prior experience as a starting point, we assume that the actual relationship is likely to be a combination of a linear and a non-linear component. And, further assume that the non-linear component is adequately fit by a model with 3 parameters. A total of 5 data points (flux,SNR) are, thus, minimally required to do an initial characeterization. The results from this exercise will determine if our assumptions and, hence, the gathered data, are sufficient. This discussion applies to both continuum and line measurements, as described in the CAP below.

The relationship between SNR vs total integration time is mathematically similar to the one for SNR vs flux. Hence, the same arguments can be applied here and we require 5 independent data pairs of (SNR,time) to do an initial characeterization.

Estimated time needed

TBD

Calibration Analysis Procedure (CAP)

For a given input flux the SNR is calculated from the data as follows:

Continuum measurements: The error is simply the standard-deviation of the continuum level. This is determined either from a small section of the continuum where simple line (linear)-fitting is sufficient, or over the whole continuum if the continuum can be adequately modeled (eg. via a black body).

Line measurements: For weak lines (for which this CIP is sought), the error on the measured equivalent width is calculated by adding in quadrature the error of each pixel included in the spectral band-bass. This is given by (see, for example, Ramirez et al. 1997, AJ, 113, 1411):

$$\sigma_{line} = \sqrt{2N} \ \times \ \sigma \ \times \mathrm{dispersion}$$

where, N is the number of pixels contained within the defined feature band, and σ is the error per pixel in the continuum measurement. This formula assumes that the rms in the line itself is approximately equal to the rms of the continuum level. This is a valid approach for weak lines in background dominated case because photon noise dominates the magnitude of the error.

Thus, the SNR for a equivalent width, EW, is given by:

$$\mathrm{SNR(line)} = \frac{EW}{\sigma_{line}}$$

The above formulae are used to obtain the SNR vs flux (or time) relationshiop for all points for which the data are available. These are then fitted by an appropriate model to obtain the full SNR vs flux (or time) relationship. The minimal detectable flux value is then, simply, the flux corresponding to SNR of 10.

Output, products

An estimate for the minimum detectable line flux.
An estimate for the minimum detectable continuum flux.

Status/version

Sixth draft version

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$Revision: 1.6 $
$Date: 2003/05/12 20:56:23 $
```

Req. 4.3.7 Pseudo-noise, spectrometer

Objectives

This requirement aims at charactering sources of noise not directly related to the noise in the electronics. Sources of this so called "pseudo-noise" could be due to:

- **A** timing jitter in the readout,
- **B** timing jitter between the chopper and the readout,
- **C** digitization noise,
- **D** the effect of data compression,
- **E** mechanical noise of grating movement.

Fulfilling or fulfilled by

Priority

C

When performed / frequency

During ILT when applicable. Verification in PV phase.

Required accuracy

The pseudo-noise is required to be at a level of less than 20% of the system noise.

Inputs, prerequisites

Sources

Calibration Implementation Procedure (CIP)

(A) Unclear how this could be determined.
(B) Unclear how this could be determined.
(C) Unclear how this could be determined.

(D) The effect of data compression can be verified by performing a TBD analysis on compressed and uncompresed data taken under various conditions in terms of point source over background flux and observing modes.

(E) Unclear how this could be determined.

Estimated time needed

Calibration Analysis Procedure (CAP)

Output, products

Status/version

First draft version

```
$Revision: 1.5 $
$Date: 2002/09/20 09:03:34 $
```

Req. 4.3.8 Relative spectral response function, spectrometer

Objectives

Determine the Relative Spectral Response Function (RSRF), and characterize the fringes present in the RSRF.

In principle, the (relative) spectral response function is the product of the (relative) spectral response functions of all components involved, namely, detector, grating, filters, PACS optics, telescope optics. By determining all these RSRFs the full system RSRF could be determined. It seems unlikely however that measurements on *all* individual components will be available and so only the system RSRF will be determined.

Fulfilling or fulfilled by

Priority

A

When performed / frequency

ILT, PV, monitoring in routine phase

Required accuracy

TBD

Inputs, prerequisites

The grating needs to be wavelength calibrated (Req. 4.2.1).

Sources

On-ground: Black bodies In-orbit: Sources with well determined spectral shapes (not necessarily absolute flux calibrated).

Calibration Implementation Procedure (CIP)

The test on the QM and FM will be done by measuring a full scan of an OGSE blackbody at certain temperatures. This blackbody is assumed to be perfectly flat. In order to measure the RSRF more like it is expected to be measured in-orbit, we also determine the RSRF from a chopped measurement on the two OGSE blackbodies. A full scan chopped measurement on the PACS internal calibration sources is made in order to allow a direct comparison with the in orbit measurement of the RSRF. The latter measurement should also be used to check for fringes. If these occur, we could use this as a reference to update the wavelength calibration of the RSRF when an improved wavelength calibration would become available in orbit. At this (ILT) stage, no measurement on simulated point sources is included. The goal would be to see the effect of the slicing on the flux measured of a point source. It is not clear whether a realistic enough point source can be made to check the cuts made in the PSF by the slicer.

OGSE3: Two internal cryogenic blackbodies are available, which can be set at different temperatures between 20 and 100K ("PACS Cryo Test Equipment and OGSE Specification", PACS-ME-DS-002).

A) Measurement on 1 cryogenic BB

As the emissivities of the OGSE black bodies cannot be adjusted we need to use a set of black body temperatures to obtain an input power per pixel corresponding to that of the telescope background (emissivity=0.04, T=80 K assumed), which is estimated as 3.3e-15 W/pixel at 210 micron (using, and scaling, from table 10.2-3 in PACS-ME-GR-002). We choose 5 temperature settings from 20 to 40 K and select apropriate wavelength ranges in which up and down scans are performed.

Based on "PACS Spectral Calibration Requirements for ILT" (PACS-ME-PL-003, appendix), one can expect a S/N of 50 at this flux level for only 1 reset interval of 16 ms per grating position. Four ramps should be measured per grating position.

One other aspect that should be investigated is the dependency of the RSRF on chopper position. The above measurement should be repeated with small scans (few micron) at a number of grating angles for chopper positions at +/- 1'.

B) Chopped measurements on 2 OGSE BB and the 2 internal calibration sources. In this measurement the OGSE and PACS internal black bodies are both used and set at temperatures which are different by a few K (TBD) to produce a well-characterised signal, but avoid transients. The same temperature and wavelength ranges as in A) are used.

Estimated time needed

40 degrees/18" = 8000 steps per full scan.
Reset interval 16ms, transition time 32ms.

To get all wavelengths: 2x 8000x 96ms= 51 minutes without overheads of switch-on procedures, and 1h of stabilization of external BB + TBD stabilization time for the different temperature settings.

Calibration Analysis Procedure (CAP)

The output of the measurements are data cubes (25 spatial pixels, 16 wavelength pixels), for each step.

```
---25 spatial pixels--- 1
----------------------- 6
.                       w
.                       a
----------------------- v
----------------------- e
```

For the non-chopped measurement: Determine the flux from the BB (Jy / pixel) for each wavelength and divide the measured signal (flat-fielded) per pixel by that flux. Compare and average the up and down scan.

For the chopped measurement: Determine the differences from the BB for each wavelength and divide the difference signal (flat-fielded) per pixel by that flux. Compare and average the up and down scan. It may be worthwhile still to determine two RSRFs from both measurements (on BB1 and BB2 resp.) and compare this which the RSRF derived from the difference.

Output, products

Status/version

Draft version. Changed objectives and inputs. The CIP and CAP contain summaries of detailed input to commanding group.

```
$Revision: 1.5 $
$Date: 2002/12/17 17:45:01 $
```

Req. 4.3.9 Flat-field spectrometer internal sources

Objectives

This requirement aims at characterising the pixel-to-pixel variations in gain due to differences in their responsivity (detector flat field) and illumination (optical flat field), using the internal calibrators. In a full-system the two types of flat field can not be distinguished.

Fulfilling or fulfilled by

For QM and FM fulfilled by 4.3.8. Selfstanding for modular detector level tests.

Priority

A

When performed / frequency

During ILT, PV and routine phase.

Required accuracy

TBD percentage. Impact on achievable accuracy in flux determination.

Inputs, prerequisites

QM/FM: Optical distortion map must be known (PACS and test optics). Level of homogeneity and isotropy of the internal and external blackbodies must be known.

Sources

On-ground: Black bodies

Calibration Implementation Procedure (CIP)

ILT detectors only: determine the responsivity of all pixels under various bias and input power conditions. The suitably averaged responsivities give the detector flatfield.

OGSE3: Two internal cryogenic blackbodies are available, which can be put at different temperatures between 20 and 100K (PACS Cryo Test Equipment and OGSE Specification, PACS-ME-DS-002). Contrary to the PACS internal calibrators the emisivity can not be varied (ϵ = 1).

To obtain similar power on the pixels as expected from the telescope background, the OGSE blackbodies need to be operated at considerable lower temperatures than the nominal 80K expected for the telescope. Calculations (by MG) show that at 70 μm the OGSE blackbodies need to be operated at 36 K, at 110 μm at 28 K, at 170 μm at 22 K, and at 210 μm at 19-20 K, to obtain the same fluxes as a blackbody with T = 80 K and ϵ = 0.04.

The test can proceed as outlined in 4.3.8.

Estimated time needed

see 4.3.8 for QM/FM tests.

Calibration Analysis Procedure (CAP)

The output of the measurements datacubes (25 spatial pixels, 16 wavelength pixels), for each step.

```
---25 spatial pixels--- 1
----------------------- 6
.                       w
```

```
.                       a
----------------------- v
----------------------- e
```

If the BB were uniform and there were no distortions, and all pixels had the same sensitivity, then each pixel in every row would have the same output (assuming that the flux levels are far above dark current). Different rows would have different output which would follow the input flux BB(T, lambda). The latter effect is small (FOR ONE GIVEN GRATING POSITION), $<0.1\%$.

In a perfect world, the flat field would then be the output map divided by the average over the 25x16 pixels, for each grating position.

In the real world, one had to apply the distortion map for all pixels and all grating positions first.

By comparing the FF obtained from the internal and external sources one obtains information on the combined effect of: distortions from the test optics, time variations.

Output, products

Flatfield for every grating position (or wavelength, if the wavelength calibration is available).

Status/version

```
$Revision: 1.7 $
$Date: 2002/12/20 02:34:03 $
```

Req. 4.3.10 Flat-field spectrometer external sources

Objectives

This requirement aims at characterising the pixel-to-pixel variations in gain due to differences in their responsivity (detector flat field) and illumination (optical flat field), using external sources. In a full-system the two types of flat field can not be distinguished.

Fulfilling or fulfilled by

Related to 4.3.9

Priority

A, but possibly to time consuming in OGSE test.

When performed / frequency

During ILT, PV and routine phase.

Required accuracy

TBD percentage. Impact on achievable accuracy in flux determination.

Inputs, prerequisites

Sources

ILT detectors only: determine the responsivity of all pixels under various bias and input power conditions.

ILT full system: Accurately movable external blackbody, with constant flux; or movable punched-hole mask illuminated by external blackbody with constant flux.

In-orbit: bright point sources.

Calibration Implementation Procedure (CIP)

ISSUES (7-apr-03):

-If 4 arcsec is the diffraction limit, what makes a real good point source: 4,3,2,1 arcsec ?

-Unclear in december 2002: what about the patterns in the punched hole mask? Update March 03: still no decision on this.

-Stability of OGSE setup wrt. hot plate and its environment.

OGSE set-up.

The 'crude' idea (and in the ideal case) is to measure a point source of constant flux at all pixels. Since the input flux is assumed constant, the suitably normalised image of output flux constitutes the flat-field. This idea follows the only practical implementation of this requirement in orbit.

Problems involved are, (1) the optical distortions (both PACS internal, and in the OGSE optics), (2) the point source nature of the OGSE black-bodies, (3) the brightness of the black-bodies w.r.t. the background signal (provided by the hot plate).

The diffraction limit, 1.22*wavelength/diameter, varies from 4.3 arcsec at 60 micron to 14 arcsec at 200 micron. Any source with a size smaller than this may be considered a point source.

DL's note from 26-nov-2002 (e-mail 27-nov-2002) regarding the "contrast of observations with punched masks in PACS ILT" illustrates another issue and that is that the ratio of signal-to-background (S/B) is a strong function of wavelength, temperature and size of the punched mask. For example, a hole size of 0.36mm diameter corresponds to 2 arcsec. At 60 micron this maybe considered a point source. For a temperature of the source of 500 K behind the punched hole, and a background of 300K, this corresponds to S/B = 0.074. At 170 micron this has dropped to S/B = 0.010. This implies that in a grating scan with increasing wavelength, one has to change, either the integration time, the size of the hole, or the temperature of the hot source, in order to get the same S/N determination for all wavelengths.

Since very likely the exact differences between different punched hole sizes are not well known, and the temperature control of the hot source is not very accurate (and likely variable in time), it is a-priori suggested to perform the observations for a fixed temperature, and fixed punched hole size.

step 1) choose a hole size of 0.18mm (1 arcsec), to ensure a point source behaviour at all wavelengths.

step 2) choose the highest temperature of the hot source (750K following "PACS cryo test equipment and OGSE specification", PACS-ME-DS-002), to maximise the contrast.

Following DL prescription, MG has calculated the following S/B for this set-up: 60 micron (0.061), 110 micron (0.015), 170 micron (0.0058), 210 micron (0.0037). Increasing the hole by a factor of 2 will increase the contrast by a factor of 4.

As one would like to determine the flat field (speak signal) with an accuracy of typically 1%, this implies a S/N of 100 on the signal, which means a S/N of 27000 on the continuum (at 210 mircon), or 1600 at 60 micron. This is likely not achievable, and does not even take into account the noise introduced by the background subtraction (when chopping). Nevertheless, it indicates that this test should be carried out in such a way as too achieve the highest S/N.

I have calculated the power on the detector from P = signal * area * pixel * trans1 * trans2, where signal = integral(BB(750)-BB(300)) is the integral of the BB-curve over the bandwidth; area = telescope surface area; pixel = pixel size in sr; trans1 = overall transmission in PACS (assumed 0.15 for spectrocopy); trans2 = factor to take into account OGSE optics.

trans2 = 0.01 since there is a 100x attenuation on the LHe shield. Additionally, there is a filter wheel, but this is kept in the "open" position.

For 9.4 arcsec pixels, MG then obtains, at 60 micron (2.9 10^{-13} W/pixel), 110 micron (4.9 10^{-14}), 170 micron (1.3 10^{-14}), 210 micron (6.2 10^{-15}).

Based on "PACS Spectral Calibration Requirements for ILT" (PACS-ME-PL-003, appendix), one can expect a S/N of 5000 for a flux level of 1.(-11) W for 1 reset interval of 16 ms. From this assumption, the estimated fluxlevels, and the desired S/N ratios, it then follows that per grating position one would need 4, 350, 9000, 47000 reset intervals of 16 ms at 60, 100, 170, 210 micron.

At this point one comes to the conclusion that this test is not feasible do perform on the ground, as it will take prohibitively long. Even with 4 reset intervals and transition time of 32ms, a full blue and red grating scan with 2×8000 steps takes 26 minutes. This would have to be repeated for the 5×5 spatial pixels.

The alternative would be to the test in the blue only. As a rough indication, as scan between 60 and 75 micron (say 2000 grating steps), with a median of, say, 40 reset intervals, repeated 25 times, would take 25 * 2000 * 672 ms = 9.3 hours.

Another alterative would be to use a pattern of holes. Its unclear what is available in this repsect. It would speed up the test considerably.

set-up:

-set size hole

-set temperature of hot source

-no Chop (?)

-set filter to open (in the filterwheel marked MD1 in the OGSE3 set-up)

-focus (manually)

-command x-y-stage to the position that corresponds to the centre of, say, the upper left spatial pixel.

-do the (partial) grating scan, with the appropriate number of read-outs. (nr. of. readouts = 4$\times$ (lambda/60)**8.8 in the blue)

-command the x-y-stage to the next spatial pixel, etc.

In-orbit: TBW

Estimated time needed

several hours minimum.

Calibration Analysis Procedure (CAP)

Output, products

Status/version

```
$Revision: 1.7 $
$Date: 2003/04/07 09:05:26 $
```

Req. 4.3.11 Stability telescope background for spectrometer

Objectives

The emission of the telescope will in almost all PACS observations be the dominant source of background flux. The structure in, and the time variation of, the telescope emission is therefore of crucial importance in the finally achievable minimum flux levels, and observing strategies.

Investigate the S/N dependence as a function of chopper mode, chopper frequency and chopper throw.

Investigate for fixed chopper parameters, the influence of the S/N on secondary parameters (for example, the pointing of the telescope relative to the Sun).

Fulfilling or fulfilled by

Priority

A

When performed / frequency

PV phase, as a realistic telescope backgound is available only then.

Required accuracy

TBD.

Inputs, prerequisites

Sources

Calibration Implementation Procedure (CIP)

Choose fields with low sky backgound and a few sources that will have line emission. Choose a combination of chop throw and mode. Observe this field and then again off-setted by a few spatial pixels. “Things” that move belong to the sky, structures that do not move belong to the telescope background.

Estimated time needed

Calibration Analysis Procedure (CAP)

Output, products

Status/version

First draft version

Req. 4.3.12 Instrumental polarization spectrometer

Objectives

Determine the instrumental polarization of the spectrometer. The grating is strongly polarized and this is a strong function of wavelength.

Fulfilling or fulfilled by

Priority

C, as we do not expect to observe strongly polarized sources.

When performed / frequency

In-orbit

Required accuracy

Inputs, prerequisites

Sources

Calibration Implementation Procedure (CIP)

Any observations should be differential in time to use the fact that the focal plane has rotated.

Estimated time needed

Calibration Analysis Procedure (CAP)

Output, products

Status/version

First draft version

Chapter 5

Optimized Observing Strategies for AOTs and Scientific Validation of AOTs

In order to achieve the highest possible calibration accuracy it is not only necessary to properly characterize all instrumental effects and establish the transfer relation between instrumental units and astrophysical flux units, but also to apply the optimal observing strategy in order to minimize systematic effects, enhance the source-to-background or line-to-continuum contrast and increase the S/N ratio. The observing strategy may also depend on the nature of the source (brightness, spatial extension or structure). Another issue is the frequency of internal reference calibrations to cope with instrumental drifts.

We therefore include here this special section in order to ensure that sufficient testing of observing modes is performed (beside simulations) prior to release of Astronomical Observation Templates AOTs. These test cases will also serve for their scientific validation.

5.1 Photometer AOTs

Considerations for designing photometer AOTs depending on the size of the source are described in the document Preparing AOTs for the PACS photometer.

Req. 5.1.1 Optimized Observing Strategy for Photometry of Small Sources

Objectives

Optimize the observing strategy for sources smaller than the array coping with the <1 filling factor of the array pixels, the contribution by 1/f noise, chopper offsets and responsivity drifts.

Fulfilling or fulfilled by

Priority

A

When performed / frequency

1) During ILT tests
2) During Performance Verification and Science Validation Phase

Required accuracy

Optimize achievable calibration accuracy depending on source brightness

Inputs, prerequisites

Detector geometries, detector stabilities, simulated sky backgrounds

Sources

Compact, point-like sources with various source-to-background contrasts

Calibration Implementation Procedure (CIP)

Estimated time needed

Calibration Analysis Procedure (CAP)

Output, products

Status/version

```
$Revision: 1.1 $
$Date: 2003/06/18 19:07:10 $
```

5.2 Spectrometer AOTs

PACS spectrometer related aspects and AOT scenarios are described in the document PACS Spectrometer Related Aspects. One main driver of the AOT design is the distinction between line and range spectroscopy mode.

Req. 5.2.1 Optimized Observing Strategy for Line Spectroscopy

Objectives

Optimize the observing strategy for line spectroscopy coping with line-to-continuum contrast, spectral resolution, chopper offsets and responsivity drifts.

Fulfilling or fulfilled by

Priority

A

When performed / frequency

1) During ILT tests
2) During Performance Verification and Science Validation Phase

Required accuracy

Optimize achievable calibration accuracy depending on line-to-continuum contrast and line width.

Inputs, prerequisites

Grating performance, detector stabilities

Sources

Line sources (absorption and emission) with various line-to-continuum contrasts and line widths.

Calibration Implementation Procedure (CIP)

Estimated time needed

Calibration Analysis Procedure (CAP)

Output, products

Status/version

```
$Revision: 1.1 $
$Date: 2003/06/18 19:07:10 $
```

Req. 5.2.2 Optimized Observing Strategy for Range Spectroscopy

Objectives

Optimize the observing strategy for range spectroscopy coping with source-to-background contrast, line-to-continuum contrast, spectral resolution, chopper offsets and responsivity drifts.

Fulfilling or fulfilled by

Priority

A

When performed / frequency

1) During ILT tests
2) During Performance Verification and Science Validation Phase

Required accuracy

Optimize achievable calibration accuracy depending on source-to-background contrast, line-to-continuum contrast and line width.

Inputs, prerequisites

Grating performance, detector stabilities

Sources

Continuum sources (point-like and extended) and line sources (absorption and emission) with various line-to-continuum contrasts and line widths.

Calibration Implementation Procedure (CIP)

Estimated time needed

Calibration Analysis Procedure (CAP)

Output, products

Status/version

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$Revision: 1.1 $
$Date: 2003/06/18 19:07:10 $
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Chapter 6

Cross-Calibration

This Chapter addresses the cross-calibration possibilities of PACS with itself (photometry versus spectroscopy mode), with SPIRE and HIFI, and with other ground or space observations.

6.1 PACS internal cross-calibration

The purpose of PACS internal cross-calibration between photometric and spectroscopic cameras is to ensure that observations of a source using the different PACS modes are internally consistent. If the results do not agree then the calibration procedure for each mode must be re-examined to identify the causes of inconsistencies and to trigger/recommend further work and propose solutions.

As part of the full system calibration of both the bolometers and the spectrometers, the basic data needed for carrying out cross-calibration will already be available.

In the following we provide a brief and general overview of how broad-band filter fluxes are compared with spectrum. Detailed discussion can be found in, for example, Golay (1974) and Blommaert (1999).

The comparison between flux measurements from a broad-band filter and a spectrum requires: (1) A measurement of the broad-band flux of a filter expressed in (TBD) units (e.g. flux density) at a given reference wavelength, and (2) A measurement of the source SED within the filter range integrated over this wavelength range and converted to the same units as for the broad-band filter.

To properly compare the flux between broad-band filters and spectra, the reference wavelength at which this comparison is to be made must be defined first. Ideally, this reference wavelength should be the isophotal wavelength (Golay 1974). However, as was the case for ISO, pragmatic reasons will dictate that an “easy to remember value” near the center of the filter transmission profile, and close to the isophotal wavelength is likely to be used as a reference wavelength. In the subsequent discussions, $\lambda_{\rm ref}$, is the adopted nominal wavelength of the filter.

For the photometer the flux density, $E(\lambda_{\rm ref})$ is given by:

$$E(\lambda_{\rm ref}) = \frac{E(obs)}{K(\lambda_{\rm ref})}$$

Where $E(obs)$ is the calibrated flux density for the source, and $K(\lambda_{\rm ref})$ is the color correction. For the IRAS approximation, i.e., $E(\lambda) \propto \frac{1}{\lambda}$,

The color correction, $K(\lambda_{\rm ref}$, is given by:

$$K(\lambda_{\rm ref}) = \frac{\int \frac{E(\lambda)}{E(\lambda_{\rm ref}} \frac{\lambda}{\lambda_{\rm ref}} S(\lambda) d\lambda}{\int \; S(\lambda) d\lambda}$$

Where, $S(\lambda)$ is the full system responsivity.

For the spectrometer, the inband flux is calculated simply as:

$$E(\lambda_{\rm ref}) = \int_{\lambda_1}^{\lambda^2} S(\lambda) F(\lambda) d\lambda$$

Req. 6.1.1 Compare point-source fluxes between spectrometer and bolometer

Objectives

Compare flux measurements of the same sources between the spectrometers and the bolometer arrays.

Fulfilling or fulfilled by

fulfilled by reqs. 3.2.5 (photometer) and 4.3.3 (spectrometer)

Priority

B

When performed / frequency

After full-system spectrometer and bolometer calibration. The CAP should be repeated after every significant change in either the spectrometer or bolometer calibration.

Required accuracy

Set by the spectrometer and bolometer calibration accuracy. Since this is a comparison, the measured values are expected to be similar within the derived errors.

Inputs, prerequisites

Calibration source SEDs and morphology
PACS Filter profiles/color corrections
PACS Beam profiles
Instrument/spectrometer profiles
Corrections for spatial distortion

Sources

Flux calibration standards (i.e. point sources delivering constant power within the prescribed accuracy) are required. These standards should include bright and faint sources, as well as “red” and “blue” sources. The same standard must be observed with both the spectrometer and the bolometer arrays for proper flux calibration.

Calibration Implementation Procedure (CIP)

The spectral scan has to cover the bandwidth of the photometer filter.

Estimated time needed

no extra time

Calibration Analysis Procedure (CAP)

Output, products

Status/version

```
$Revision: 1.1 $
$Date: 2003/02/07 10:21:33 $
```

6.2 Herschel internal cross-calibration

6.3 Cross-calibration against instruments of other observatories

Chapter 7

Telescope

7.1 Optical Quality

7.2 Thermal background

7.3 Straylight Suppression

Chapter 8

Space Weather Effects (Statistics and Trends)

Chapter 9

Interferences

This chapter considers (unexpected) interferences of HIFI, SPIRE or the PACS bolometer on the nominal spectrometer operation, and of HIFI, SPIRE or the PACS spectrometer on the nominal bolometer operation. Also the thermal self-emission of the spectrometer itself is considered.

Tests during EQM should be performed to investigate this.

9.1 Photometer

9.2 Spectrometer

Req. 9.2.1 Influence SPIRE on photoconductors

Objectives

Investigate the possible influence of previous SPIRE operations (either during a previous operational day, or the same operational day when the PACS and SPIRE photometers are operated together in parallel mode) on the operation of the PACS photoconductors, in terms of increased noise, dark current, etc.

Fulfilling or fulfilled by

Related to requirements x.x where noise properties are determined

Priority

C. Any influence is expected to be small. Revision of priority possibly if this turns out not to be the case during EQM test.

When performed / frequency

First possibility to test this is during EQM test. Should be repeated in PV phase. First indications of any possible influence due to thermal memory effects could come from a thermal model of telescope+cryostat+three instruments.

Required accuracy

Inputs, prerequisites

Sources

Not applicable.

Calibration Implementation Procedure (CIP)

Analysis of noise determinations (and possibly other TBD quantities) as a function of time after the switch-off of the SPIRE photometer or the SPIRE spectrometer and the switch-on of the PACS photoconductors, respectively, in the case of parallel mode, the switch-off of SPIRE and the PACS photometers, and the switch-on of the PACS photoconductors. SPIRE (and the PACS bolometer) should be operated in such a way as to produce the highest heat dissipation expected under normal operating conditions.

Estimated time needed

Calibration Analysis Procedure (CAP)

Output, products

Status/version

First draft version

Req. 9.2.2 Influence HIFI on photoconductors

Objectives

Investigate the possible influence of previous HIFI operations (either during a previous operational day, or the same operational day) on the operation of the photoconductors, in terms of increased noise, dark current, etc.

Fulfilling or fulfilled by

Related to requirements x.x where noise properties are determined

Priority

C. Any influence is expected to be small. Revision of priority possibly if this turns out not to be the case.

When performed / frequency

First possibility to test this is during EQM test. Should be repeated in PV phase. First indications of any possible influence due to thermal memory effects could come from a thermal model of telescope+cryostat+three instruments.

Required accuracy

Inputs, prerequisites

Sources

Not applicable.

Calibration Implementation Procedure (CIP)

Analysis of noise determinations (and possibly other TBD quantities) as a function of time after switch-off of HIFI and the switch-on of the PACS photoconductors.

Estimated time needed

Calibration Analysis Procedure (CAP)

Output, products

Status/version

First draft version

Req. 9.2.3 Influence bolometer on photoconductors

Objectives

Investigate the possible influence of previous PACS bolometer operations (either during a previous operational day, or the same operational day) on the operation of the photoconductors, in terms of increased noise, dark current, etc.

Fulfilling or fulfilled by

Related to requirements x.x where noise properties are determined

Priority

C. Any influence is expected to be small. Revision of priority possibly if this turns out not to be the case.

When performed / frequency

During ILT test. Repeat during EQM test. Should be repeated in PV phase. First indications of any possible influence due to thermal memory effects could come from a thermal model of telescope+cryostat+three instruments.

Required accuracy

Inputs, prerequisites

Sources

Not applicable.

Calibration Implementation Procedure (CIP)

Analysis of noise determinations (and possibly other TBD quantities) as a function of time after switch-off of HIFI and the switch-on of the PACS photoconductors.

Estimated time needed

Calibration Analysis Procedure (CAP)

Output, products

Status/version

First draft version

Req. 9.2.4 Thermal self-emission of the spectrometer

Objectives

Check for thermal self-emission of spectrometer components including in the cryo harness. Investigate the effect of filter wheel and grating movements on the dark currents and the sensitivity of the detectors. The effect on the dark may be less important as it is normally canceled out by the differential measurements.

Fulfilling or fulfilled by

Self-standing

Priority

When performed / frequency

EQM, PV

Required accuracy

Inputs, prerequisites

Sources

Calibration Implementation Procedure (CIP)

Dark current:

Turning the filter wheel:
Keep the grating in a fixed position and let the wheel turn. Small steps as well as full turns should be made. Staring measurement at the dark (cold internal calibrator). This measurement should be sufficiently long to get a stabilized signal (this may be a long time for low signals). If it is possible to stop the wheel movement at a "blocked" filter position one could use that position to get a better dark (only for the blue detector).

Moving the grating:
Keep the filter fixed (possibly in a position which blocks the light towards the blue detector) and move the grating with 1) few steps and 2) a significantly longer scan. Staring measurement at the dark (cold internal calibrator). This measurement should be sufficiently long to get a stabilized signal (this may be a long time for low signals).

Sensitivity:

Similar as above but now observing the heated internal source.

If the above effects turn out to be important, further measurements should be performed for typical observations for every AOT that will be offered to the community.

Estimated time needed

Calibration Analysis Procedure (CAP)

Plot the dark current or measured signal as a funtion of observing time. Perform trend analysis.

Output, products

Status/version

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$Revision: 1.6 $
$Date: 2002/09/20 08:27:58 $
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