PACS

Instrument Requirements Document

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DISTRIBUTION RECORD

Issue / Revision	Issue 1					
Distribution Date						

Intern			Extern		
Department	Name	Qty	Company	Name	Qty
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DOCUMENT CHANGE RECORD

Issue / Rev.	Date	Change Notice Number	Modified Pages or Paragraphs	Remarks / Nature of Change
draft	13.9.00			

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1 Scope of this Document

The PACS Instrument Requirements Document (PIRD) is a compilation of high-level requirements on the design, performance, and operation of the PACS instrument on FIRST. These requirements are direct consequences of the scientific requirements as defined in the PACS Science Requirements Document (PSRD).

All requirements on a subsystem/component level reflect the requirements described in this document. However, in a system as complex as the PACS instrument, subsystem requirements often cannot be derived independently of each other as often several of them are factored into a high-level requirement. In these cases, a “reasonable” balance of requirements on the respective subsystems/components has to be found with the goal to maximize the overall feasibility in fulfilling the top level requirement.

In this document, the term requirement indicates a figure or condition which must be met in order to not compromise the scientific case for the FIRST mission as described in the FIRST Science Management Plan and the PIRD. A goal, in contrast, indicates a figure or condition which seems technically feasible with moderate extra effort and which enhances the capabilities of the instrument significantly in a way to strengthen the scientific outcome of the mission .

2 System Level Requirements

2.1 Basic Instrument Modes

Over the wavelength range to be covered by PACS, the instrument has to be able to operate in two fundamental modes: *broadband photometry* and *medium resolution spectroscopy*. There is no scientific requirement, however, that both basic instrument modes be available at the same time. Therefore, the requirements on the two modes can be treated almost independently of each other. There is one mutual requirement: there must be no adverse interference from one channel of the instrument in its inactive state to the respective other channel in its active state.

2.2 Photometry Requirements

2.2.1 Wavelength Range and Filter Bands

The scientific objectives of FIRST require a wavelength coverage of 60 – 200µm, divided into 3 photometric bands. Based on the center wavelengths suggested in the PSRD we define the following bands:

Band designation	Center wavelength	Filter band
Red photometer	170µm	130 – 210µm
Blue photometer 1	110µm	90 – 130µm
Blue photometer 2	75µm	60 – 90 µm

The red band and one out of the two blue bands, each, have to be available for simultaneous observation. The edge steepness (10%/90% transmission) of the filter bands has to be 20% of the respective center wavelength in order to get sufficient band definition for the required accuracy in photometric SED determination. The out-of-band transmission of the filters must be less than 3% in the adjacent photometric bands. Detection of light from sources at all shorter wavelengths must be suppressed to a level of less than 10% (goal: 3%) of the respective in-band emission of these sources by the combination of detector responsivity and filter transmission.

2.2.2 Field of View and Pixel Scale

The PSRD requires a minimum field of view of 5 arcmin^2 for the red band and of 1.5 arcmin^2 for the blue bands. However, an equal field of view for both bands is a highly desirable goal because a reduced field of view in the blue bands will either lead to incomplete photometric coverage over major parts of the large surveys or to reduced sensitivity in the blue bands for a survey strategy with complete area coverage. Reaching the goal instead of the requirement will be almost mandatory.

Since PACS will be used for both large-scale survey observations and pointed observations of compact objects, the aspect ratio of the field of view has to be optimized for both types of observations. Pointed observations will be mostly combined with chopping/nodding; this observing mode is most efficient if the active field of view is elongated along the chop direction to allow on-array chopping, i.e., the object and an equally large reference field are observed simultaneously. Therefore, a rectangular field of view with an aspect ratio of 2:1 is best suited for this application while it does not reduce the observing efficiency for large-scale surveys compared to e.g. a square field of view.

The pixel scale has to be chosen such that images at the natural angular resolution of the FIRST telescope can be obtained with minimum complexity in operation and data reduction. Filled arrays scaled to the Rayleigh criterion (1.2 λ/D $\pm$5% projected angular separation of pixels, where λ is the band center wavelength and D is the telescope diameter) are most efficient in that respect. Since the telescope will not provide diffraction-limited performance at wavelengths below 85 µm, we only require one pixel scale for both blue bands.

	Array FOV: Requirement [arcmin] / [pixels]	Array FOV: Goal [arcmin] / [pixels]
Red band	1.8 x 2.8 / 16 x 25	1.75 x 3.5 / 16 x 32
Blue bands	0.9 x 1.4 / 16 x 25	1.75 x 3.5 / 32 x 64

If detectors are assembled from sub-arrays they have to be packed as closely as possible. Gaps (rows or columns) are required to be integer multiples of one pixel in width to facilitate image extraction. The maximum allowed width is 2 pixels, with 0 pixels as a goal.

2.2.3 Image Quality

Three classes of errors introduced by the instrument optics are considered in this category: image blur, image distortion, and positioning errors.

Image blur must not increase the width of the point spread function as given by the FIRST telescope by more than 10% (goal: 5%) or increase the time needed to detect a point source with a given flux by more than 20% compared to an aberration-free optical system.

Image distortion over the full field of view has to be no more than ±1 pixel, and it has to be known to within 1/4 of a pixel to allow image reconstruction from multiple pointings.

The misalignment of the two arrays with respect to each other, projected on the sky, must be less than one blue pixel. The positions of both arrays, relative to each other and relative to the satellite reference frame, must be known to <1/3 of a blue pixel.

2.2.4 Stray Light

"Stray light" can be caused by scattering/reflection on surfaces/edges or by diffraction. It can originate from celestial sources within or outside the nominal field of view or from self emission of the satellite including the focal plane instruments.

In order to reach the sensitivity requirement, stray light which leads to a homogeneous and constant illumination of the detectors must be less than 10% of the background level given by the self emission of the telescope system.

Inhomogeneous stray light is of particular concern since it could introduce fake structure into the extracted images (ghost images). The necessary dynamic range within an observed field puts defines the upper limit for such stray light. We require that stray light originating from celestial sources and caused by the PACS optics must be less than 50% of the actual telescope point spread function for radial distances from the source where the telescope point spread function is greater than 0.5% of the peak value, and less than 0.25% of the peak value elsewhere.

2.2.5 Dynamic Range

PACS photometry must allow detection of sources from a few mJy up to >1000 Jy (goal: 3000 Jy). However, degradation of the sensitivity at high flux levels by a factor (t.b.d.) is acceptable. The required dynamic range within one observation (or field of view) is mainly driven by the Galactic surveys with a large spread in surface brightness. We require that PACS can realize a contrast of 1:500 within the same field of view for angular source separations where the contrast is not limited by the point spread function of the telescope.

2.2.6 Observing Modes

The photometric observing modes are defined by combinations of *instrument modes* and (satellite) *pointing modes*. The basic instrument modes are single band photometry, where only one array is used to observe one of the three PACS wavelength bands, and dual band photometry, where both arrays are used simultaneously to observe the red band together with one of the two blue bands. Either instrument mode has to work with any of the pointing modes:

2.2.6.1 *Pointed observations* (fixed or raster pointings) which will be combined with two- or three-point chopping, with or without nodding. The chopper throw can be either fixed for the duration of the observation or (periodically) variable for improved flatfielding

2.2.6.2 *Line scans* where the satellite is slewed across the sky at a (constant) rate. The motion of the field across the detector arrays must not degrade the angular resolution of the extracted images by more than 20% of the width of the peak of the telescope point spread function. The stability of the system must allow detection of large-scale structures up to at least 5 arcmin. As a goal, this shall be possible without use of the PACS chopper. As a requirement, the large scale structure limit must be attainable with the available slew rate of the satellite and without loss of the higher spatial frequencies, as defined above, but with additional use of the chopper in e.g. “freeze-frame” mode as described in the chopper section.

2.2.6.3 *Chopped line scans* where the satellite is slewing across the sky while the chopper is operating with a fixed throw

2.2.7 Post-Detection Bandwidth

The signal chain (detector, readout, analog/digital electronics, telemetry) must be able to handle the bandwidth generated by the observing modes. Chopping is required up to a maximum frequency of 5 Hz. Detection is only required at the respective chop frequency. With (unchopped) line scans, spatial frequencies in the object space are transformed into time-domain frequencies in the signal chain such that a continuous frequency band has to be recorded. We thus require (see 1.1.6.2) a useful frequency range of 0.5 – 5 Hz, with 0.05 – 5 Hz as a goal.

2.2.8 Sensitivity

The PSRD requires a photometric point source sensitivity of 5 mJy (5σ detection) after 1 hour of integration. This value must be reached including the noise added by chopping onto a reference position. Goal is 3 mJy (5σ, 1h).

Any secondary sources of (pseudo)noise must be at a level of less than 20% of the system noise goal. This concerns aspects like timing jitter in the readout or between the readout and the chopper, digitization noise, and data compression/reduction.

2.2.9 Calibration and Photometric Accuracy

Calibration of the PACS photometry channels includes parameters which can only be verified with ground support equipment and which thus have to be guaranteed over the entire lifetime of the satellite, and parameters which can or must be calibrated or updated during the mission.

Pre-calibrated parameters and their maximum allowed calibration errors are listed below.

Parameter	Tolerance (requirement)	Tolerance (goal)
Relative spectral responsivity	10%	3%
Field distortion	1/4 pixel	1/8 pixel.
Relative pointing between photometric bands	1/4 pixel	1/8 pixel
Instrument point spread function	t.b.d.	t.b.d.

Calibration during the mission must include the parameters listed below.

Parameter	Tolerance (requirement)	Tolerance (goal)
Relative pointing between photometric bands	1/4 pixel	1/8 pixel
System point spread function	t.b.d.	t.b.d.
Absolute photometric calibration	20%	10%
Internal photometric calibration (reproducibility)	5%	3%
Flatfielding with internal calibrators	t.b.d. ppm of telescope background	t.b.d. ppm of telescope background
Flatfielding against celestial sources	t.b.d. ppm of telescope background	t.b.d. ppm of telescope background

Calibration on the internal sources must be possible with minimum overhead (t.b.d.) to allow frequent, short-duration calibration measurements within the astronomical observing sequence. The frequency of such calibration measurements depends on the system stability (satellite + instrument). The design of the instrument and its operation must allow for sufficient flexibility to adjust the frequency and duration of these measurements for optimum observing efficiency.

2.3 Spectroscopy Requirements

2.3.1 Wavelength Coverage and Spectral Resolution

The PACS spectrometer must operate over the wavelength range from 60 – 210 μm with a spectral resolving power of 1000 – 2000. It has to instantaneously cover a velocity range of 1000 – 2000 km/s around any selected center wavelength. This precludes spectrometer implementations that don't provide spectral multiplexing. The spectrometer must also allow spectral scans over the entire wavelength range or parts of it.

2.3.2 Field of View, Pixel Scale, and Spectrometer Implementation

Uncertainties in the positions of many submm/FIR point sources detected previously require, for efficient follow-up observations with PACS, a field of view of not much less than 1 arcmin^2. Reaching the required sensitivity (see 2.3.8) in a background-noise limited situation does not allow source dilution to beam sizes much greater than the diffraction limit. Spatial multiplexing is thus mandated. This also enables the mapping efficiency needed for detailed spectral line images of extended sources. We require a pixel size, projected on the sky, of

9”x9” ±10%, and a field of view of 5x5 pixels. This will allow (near-)diffraction limited imaging at the longer wavelengths and observations with comparable angular resolution over the entire wavelength range.

The required sensitivity (see 2.3.8) can only be reached at a background level so low that Fourier transform spectroscopy is ruled out. The only remaining implementation can thus be an integral-field grating spectrometer.

2.3.3 Image Quality

The spectrometer optics must not introduce image blur which increases the width of the point spread function as given by the FIRST telescope by more than 10% (goal: 5%) or increase the time needed to detect a point source with a given flux by more than 20% compared to an aberration-free optical system.

Image distortion over the full field of view has to be no more than ±1 pixel, and it has to be known to within 1/4 of a pixel to allow image reconstruction from multiple pointings.

The spatial alignment of spectral subbands with respect to each other, projected on the sky, must be better than 1/4 pixel.

2.3.4 Stray Light

Stray light control in the spectrometer adds one aspect which is not present in the photometer: The in-beam background power reaching a detector pixel is about a factor of 1000 lower than in photometry mode, defined by the spectral resolution of the instrument, while almost the entire background bandwidth – which is rejected by the spectrometer – has to be prevented from reaching the detectors.

In order to reach the sensitivity requirement, stray light which leads to a homogeneous and constant illumination of the detectors must be less than 20% of the background level given by the self emission of the telescope system within the resolution bandwidth of the spectrometer.

Inhomogeneous stray light is of particular concern since it could introduce fake structure into the extracted images and/or spectra. We require that stray light originating from celestial sources and caused by the PACS optics must be less than 30% of the actual telescope point spread function for radial distances from the source where the telescope point spread function is greater than 0.5% of the peak value, and less than 0.25% of the peak value elsewhere.

Ghost lines, i.e. aliases of spectral lines at far-off wavelengths, must be at a level of 1% maximum to allow reliable observation of weak spectral lines in the presence of strong lines. The grating errors must be specified accordingly.

2.3.5 Dynamic Range

PACS spectroscopy must allow detection of sources ranging from ~10^{-18}W/Hz$^{1/2}$ line flux to 10000 Jy continuum emission. However, the dynamic range in the power incident on a detector pixel is much less because the lower limit is set by the telescope/instrument background which is equivalent to 1500 – 2000 Jy. Degradation of the sensitivity at substantially higher flux levels by a factor (t.b.d.) is acceptable. The required dynamic range within one observation (or field of view) is mainly defined by the telescope point spread function (spatially) and the diffraction limit for the instrument function (spectrally).

Since PACS detects more spectral resolution elements than spatial resolution elements, the maximum number of 8 spectral elements (FWHM) require a contrast of 1:(t.b.d) over the array.

2.3.6 Observing Modes

The spectroscopic observing modes are defined by combinations of *instrument modes* and (satellite) *pointing modes*. The basic instrument modes are *line spectroscopy* where a fixed wavelength and its immediate neighborhood as defined by the instantaneous bandwidth of the spectrometer are observed, and *range spectroscopy* where the spectrometer has to be scanned over a freely defined wavelength range.

Both instrument modes will - by default - be used in combination with the PACS chopper. For spectral line maps of very extended sources, line spectroscopy has to be possible without spatial chopping but with wavelength switching. Wavelength switching requires an amplitude of up to 3 spectral resolution elements (t.b.c.). Wavelength switching must be possible with a frequency of up to 3 Hz and a duty cycle of >80% (t.b.c.).

Either instrument mode has to work with fixed or raster pointing, with or without satellite nodding.

2.3.7 Post-Detection Bandwidth

The necessary post-detection bandwidth depends only on the chopping/switching frequency which is determined by the system stability. We require a bandwidth of 5 Hz, with 10Hz as a goal.

2.3.8 Sensitivity

The PSRD calls for a spectroscopic point source sensitivity of a few 10^{-18}W/Hz$^{1/2}$ (5σ detection) within 1 h of integration; it also points out the importance to reach a limiting sensitivity of ~10^{-18}W/Hz$^{1/2}$ (5σ) within practicable observing times. We require a system sensitivity, including the noise added by chopping, averaged over the PACS wavelength range, of 3×10^{-18}W/Hz$^{1/2}$, with 2×10^{-18}W/Hz$^{1/2}$ as a goal (5σ; 1h).

Any secondary sources of (pseudo)noise must be at a level of less than 20% of the system noise goal. This concerns aspects like timing jitter in the readout or between the readout and the chopper, digitization noise, and data compression/reduction.

2.3.9 Calibration and Photometric Accuracy

Calibration of the PACS spectroscopy channels includes parameters which can only be verified with ground support equipment and which thus have to be guaranteed over the entire lifetime of the satellite, and parameters which can or must be calibrated or updated during the mission.

Pre-calibrated parameters and their maximum allowed calibration errors are listed below.

Parameter	Tolerance (requirement)	Tolerance (goal)
Relative spectral responsivity	10%	3%
Field distortion	1/4 pixel	1/8 pixel.
Relative pointing between spectroscopic bands	1/4 pixel	1/8 pixel
Instrument point spread function	t.b.d.	t.b.d.
Instrument spectral profile	t.b.d.	t.b.d.
Wavelength calibration	1/4 resolution elements	1/8 resolution elements

Calibration during the mission must include the parameters listed below.

Parameter	Tolerance (requirement)	Tolerance (goal)
Relative pointing between spectroscopic bands	1/4 pixel	1/8 pixel
System point spread function	t.b.d.	t.b.d.
System spectral profile	t.b.d.	t.b.d.
Absolute photometric calibration	20%	10%
Internal photometric calibration (reproducibility)	5%	3%
Flatfielding with internal calibrators	t.b.d.ppm of telescope background	t.b.d. ppm of telescope background
Flatfielding against celestial sources	t.b.d.ppm of telescope background	t.b.d. ppm of telescope background

Calibration on the internal sources must be possible with minimum overhead (t.b.d.) to allow frequent, short-duration calibration measurements within the astronomical observing sequence. The frequency of such calibration measurements depends on the system stability (satellite + instrument). The design of the instrument and its operation must allow for sufficient flexibility to adjust the frequency and duration of these measurements for optimum observing efficiency.

2.4 Operational Requirements

Most top level requirements are addressed in the PACS Instrument Operating Modes Document (PACS-ME-PL-005). A few operation-related instrument requirements are added here.

2.4.1 Maximum Uninterrupted Operating Interval

PACS must be able to observe in any of its modes for 24 h (goal: 48h) without longer periods of interruption for instrument maintenance, like cooler recycling, extended calibrations of any kind, or tasks in the data processing system.

2.4.2 Availability of and Switching between Instrument Modes

There is no requirement that photometry and spectroscopy be available during the same observing cycle of 24 h. However, switching between these modes on a daily basis must be possible without loss of observing time.

The submodes available in spectroscopy or photometry mode, in contrast, have to be accessible with a delay of no more than (t.b.d.) seconds.

3 Subsystem Level Requirements

Although not the primary objective of this document, some requirements on a subsystem level need to be defined because they are mutually dependent and cannot be independently derived from system level requirements.

3.1 Sensitivity-Related Subsystem Requirements

The system sensitivity depends on a number of factors: background noise from the far-infrared emission of the telescope/satellite and the instrument itself, losses in the optical train (absorption, scattering, diffraction), detector quantum efficiency, detector/readout noise, and random background modulation caused by the instrument. In order to reach the required system sensitivity, an "error budget" has been set up which is not unique, but which tries to distribute the challenge in a sensible way on different components. It is based on a mathematical instrument model of PACS where these parameters enter into the system performance. We have then looked for solutions which don't pose unrealistic requirements on any of these parameters. Properties of the FIRST telescope have been modeled in to our best present knowledge.

3.1.1 Photometry

The top level requirements on the relevant FPU components in the photometry channels are listed below.

	Optics transmission	Filter transmission	Temperature photometer optics [K]	Detector quantum efficiency	Detector/ readout noise [$W/Hz^{1/2}$]
Requirement	0.75	0.4	5.5	0.45	$1x10^{-16}$
Goal	0.85	0.5	4.3	0.8	$5x10^{-17}$

3.1.2 Spectroscopy

The top level requirements on the relevant FPU components in the spectroscopy channels are listed below.

	Optics transmission	Filter transmission	Grating efficiency	Temperature photometer optics [K]	Detector quantum efficiency	Detector/ readout noise [W/Hz$^{1/2}$]
Requirement	0.55	0.4	0.65	5.5	0.3	5x10^{-18}
Goal	0.65	0.5	0.75	4.3	0.45	5x10^{-18}

3.2 Chopper

The PACS chopper is used in all instrument modes for observation and/or calibration. It has to be able to chop (square wave) between freely definable points with an absolute accuracy and repeatability to better than 1/4 of a blue photometer pixel. The maximum amplitude for observing must be greater than ±1 times the longer dimension of the maximum field of view of the photometer to allow for three-point chopping with full separation of the 3 projections of the field of view on the sky. This must be possible with a duty-cycle of 80% at 8 Hz (goal: 10 Hz) chop frequency. For calibration on the internal sources, the amplitude must be greater than ±2 times the longer dimension of the maximum field of view of the photometer.

In addition to square-wave modulation, the chopper must also enable a “freeze-frame” mode for line scan photometry in case the bandwidth of the detectors doesn’t reach the goal. In this case, the chopper will have to compensate the continuous slew of the satellite for ~1/4 (t.b.c.) of a second with an accuracy of 1/2 (goal:1/4) of a blue photometer pixel, in order to prevent image blurring along the slew direction, and then jump by a t.b.d. integer multiple of a blue photometer pixel. The resulting wave form is a sawtooth modulation. The transition at the end of each sawtooth has to occur in accordance with the requirements for square wave modulation.

More detailed requirements are addressed in the PACS Chopper Specification Document (PACS-ME-SP-001).

3.3 Timing/Synchronization Requirements

There are several subsystems, notably the chopper and the readout electronics of the photoconductor and bolometer arrays, whose timing is critical because timing jitter will introduce a random modulation of the telescope offset, i.e., the difference in telescope background between two chopped positions. This pseudo-noise has to be negligible compared to the system noise as given by the background noise and the detector noise. The timing requirements that ensure this are compiled in the PACS Timing Requirements Document.

4 Related Documents

Documents which have entered into this document or are directly derived from it are listed below.

PACS Science Requirements Document
PACS Instrument Operating Modes
PACS Optical Performance Requirements
PACS Filter Requirements
PACS Ge Detector Module Specifications
PACS CRE Specifications
PACS Bolometer Specifications
PACS Timing Requirements
PACS Chopper Specifications