PACS Science Requirements Document

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1 Introduction

1.1 The FIRST Mission

The Far Infrared and Submillimetre Telescope FIRST is ESA's cornerstone mission designed to study the universe in a largely unexplored wavelength regime, with an anticipated launch year 2007. A passively cooled 3.5m telescope provides the opportunity for high spatial resolution, sensitive observations over the range from 60 to 670μm.

Main scientific drivers of the FIRST mission include

- Investigations of the distant universe, studying the history of star formation and activity in galaxies through extensive surveys and dedicated follow-up observations.
- Studies of the origins of stars through photometric and spectroscopic surveys of star forming regions and pre-stellar condensations.
- Physics and chemistry of the interstellar medium.
- Solar system studies.

The instrument complement selected for FIRST to achieve these goals includes a 60-200μm camera/spectrometer (PACS), a 200-670μm camera/low resolution spectrometer (SPIRE) and a heterodyne high resolution spectrometer (HIFI). Many scientific projects regard FIRST as a unified facility and will in fact impose requirements on several instruments. In the remainder of this document, however, we will focus on the requirements set on the PACS instrument, tacitly assuming that e.g. sensitive longer wavelength maps are available through SPIRE or highest resolution spectra can be obtained through HIFI.

By its combination of sensitivity, wavelength range, and spatial resolution, FIRST is unique among related projects. Such projects to be considered in the definition of the FIRST science case include IRAS, KAO, ISO, SCUBA (past) and SIRTF, SOFIA, ASTRO-F, PLANCK, ALMA, NGST (future).

1.2 PACS

The basic concept of PACS is to provide

- Efficient imaging and photometry in several wavelength bands within the 60-200μm range, fully exploiting the telescope's imaging performance.

- Spectroscopy and spectroscopic mapping, with the possibility to cover at spectral resolution about 1000 to 2000 the entire 60-210μm wavelength range or short segments.

The following discussion of scientific goals is intended to cover some of the highest priority scientific goals and discuss the ensuing requirements on the PACS instrument and its observing modes. It is not a comprehensive discussion of 'PACS science' and omits other scientific projects that can be carried out using similar observing modes.

2 Scientific goals

2.1 Extragalactic surveys: Galaxy formation in the early universe

Recent progress in quantifying the cosmic infrared background and first inroads by ISO and SCUBA into detecting its constituents highlight the importance of deep far-infrared and submillimeter surveys for understanding galaxy evolution and the cosmic history of star formation and AGN activity.

One key wavelength range for such surveys is around 150-200μm. These wavelengths sample the peak of the far-infrared emission of actively star forming galaxies at redshifts 1 to 2. This is the redshift range where most of the cosmic star formation happened and where most of the metals were formed. The basic strategy to be employed with PACS is to detect large numbers of galaxies from this population, and later try to determine their nature and redshift. These observations will resolve the majority of the cosmic far-infrared background into discrete sources.

From a technical point of view, the same range is also interesting in that it includes the wavelength for which the FIRST confusion limit can just be reached in practical integration times. Longer wavelength surveys more quickly run into the confusion limit set by their larger beams and the number counts, while shorter wavelength surveys are unconfused but will miss many higher redshift targets.

Interpretation of a single wavelength survey is limited since the nature and redshift of the sources detected are *a priori* unknown. More complete spectral energy distribution (SED) measurements can constrain both redshift and nature of the source, although with ambiguities due to variance of intrinsic SEDs. For this reason, extragalactic surveys with PACS should also include a wavelength in the 60 to 100μm region. Determination of SEDs is also **the** area of natural synergy between SPIRE and PACS. This could either take the form of dual-band PACS surveys and SPIRE surveys being obtained sequentially for the same fields, or of single/dual-band PACS surveys obtained simultaneously with SPIRE in parallel mode. The scientific and technical tradeoff between the two options is not yet fully clear.

The resulting requirements are that PACS should be able to:

- Survey a 'large' region at a wavelength near 170μm to the confusion limit. 170μm is a compromise between the push for longer wavelengths in order to get higher redshift sources and the push to shorter wavelengths induced by the wish to beat confusion. It also provides an adequate combination with the 250μm+ SPIRE bands. The FIRST confusion limit ("5σ") at this wavelength is predicted to be below or near 10mJy by different models.
- Simultaneously survey at a shorter wavelength to provide SED information, with the goal of covering the same area to the same depth as at 170μm. It is not realistic to reach the confusion limit at shorter wavelengths. Meaningful SED information (e.g. discrimination of lower

z sources) requires sensitivity at least comparable to the 170μm one. With similar detector sensitivities and pixel sizes that are proportional to wavelength, this requires larger arrays at short wavelengths if SED information should not be restricted to brighter sources.

- Provide large sample sizes (at least thousands of objects) required in order to detect rare objects and provide sufficient statistics even after binning objects into redshift, color etc. groups. While the attainable sample size obviously improves further with any sensitivity or array size improvement, the 1 hour 5σ detection limit of 5mJy for a 2' by 3' FOV given in the PACS proposal will result in detection of several thousand galaxies in a confusion limited survey of 1000 hours, consistent with the requirement.
- Map contiguous regions without gaps or significant depth variations. This may need special care for the observing procedures in case of butted arrays. Uniform coverage is especially important for clustering analysis of the detected galaxy populations.
- Preserve the image quality provided by the FIRST telescope (diffraction limited at 150μm (goal 85μm). PSF width variations of more than 20% (TBC) over the FOV would start degrading the confusion limit that can be achieved and affect combination of individual frames.
- If technically feasible, provide a non-chopping scanning mode for surveys. While the default mode for PACS observations will be chopping/nodding, this is clearly not desirable near the confusion limit. The unavoidable loss of large-scale smooth emission is acceptable for distant extragalactic sources.
- Provide the best possible positional accuracy. The identification of faint far-infrared galaxies is nontrivial and positional errors of several arcseconds can already be detrimental. As the short wavelength camera of FIRST, PACS can provide the best positions, even taking into account plausible SEDs for redshifted galaxies. For good detections, the PACS internal positional error should be less than 1 arcsec, in order to be an insignificant contribution to the the total FIRST/PACS pointing accuracy.

PACS follow-up observations on galaxies detected by PACS or SPIRE surveys are covered by the requirements listed below.

2.2 Galaxies

Many processes in forming and evolving galaxies occur in dust-obscured environments that are best studied in the mid- and far-infrared continuum and line emission. The infrared SEDs already echo the physical conditions in their interstellar medium and the contribution of star formation and AGN. Line emission provides more quantitative constraints on various phases of the ISM and on the contribution of starbursts and AGN. Targets for detailed galaxy studies include local galaxies, high redshift galaxies from PACS/SPIRE/PLANCK surveys, and other distant galaxies.

PACS should be able to take photometry at about two photometric points per octave in order to provide sufficiently detailed SEDs. Mapping extended dust emission shall be possible. Dust mapping on the largest spatial scales is the domain of SIRTF, but PACS will be able to trace for the first time the different warm/cold dust components on the scale of different sub-galactic components (arms, interarm regions, star forming complexes etc.).

Key far-infrared diagnostic emission lines in the PACS range start with [O I] 63μm and reach out to [N II] 205μm, i.e. local galaxy studies suggest a minimum wavelength range 60 to 210μm. The density of bright lines in this range is small. Typical intrinsic line widths are 200 to 1000km/s.

For higher redshift galaxies, starburst/AGN discrimination via measurements of low versus high excitation lines is a key project. The longest wavelength high energy line suited for this analysis is [O IV] 26μm. The short end of the PACS spectroscopy range thus directly determines the accessible redshift range, e.g. z>1.3 for a 60μm cut.

Sensitivities of 5mJy (5σ, 1 hour) will allow construction of meaningful samples for many types of galaxies. The ultimate sensitivity limit for photometry at longer PACS wavelengths is of course set again by confusion. Better detector sensitivity would cut the time within which this limit can be reached, and provide a real sensitivity increase at short wavelengths.

The brightest emission lines in very bright z=1-2 galaxies will reach $10^{-19} \ldots 10^{-18}$W/m^2, more if gravitationally lensed. Bright emission lines in local galaxies will reach surface brightness above 10^{-5} erg s^{-1} cm^{-2} sr^{-1}, i.e. above 10^{-17}W cm^{-2} for a $\sim$10arcsec spectroscopic pixel. This will allow mapping of bright lines and detection of faint lines.

These considerations imply that PACS should be able to

- Provide simultaneous dual-band photometry at 170μm and one shorter wavelength, and the possibility to obtain photometry in total for three different bands in the 60 to 200μm range. An example meeting the requirements would be central wavelengths of 75, 110, and 170μm. A smaller shortest wavelength would be desirable (but not required) for SED characterization and AGN/starburst discrimination.
- Reach an absolute photometric accuracy of 20% (goal 10%) and an internal reproducibility of 5% (goal 3%) (e.g. for AGN variability studies).
- Use the spatial multiplexing of the PACS arrays to obtain photometric information also for the maximum possible field of a few beams around the nominal target. This may not be fully possible for observations with external constraints on chopper throw.
- Obtain continuous maps over larger regions.
- Provide spectroscopy of individual lines anywhere in the 60 to 210μm range, covering instantaneously a range of 1000-2000km/s with a resolution element of 150-300km/s. The detection limit should reach 10^{-18}W m^{-2} in practical times to achieve the mentioned goals.
- Provide the possibility to obtain complete 60-210μm spectra at this resolution for brighter sources.
- Obtain spectral line maps. Spatial multiplexing increases mapping speed and ensures correct spectroscopy even for slightly mistargeted sources, as might occur due to inaccurate (far-infrared!) positions or FIRST pointing errors. These advantages are considered more important than those of increased spectral multiplexing (i.e. increased instantaneous wavelength range).

2.3 Star formation and the interstellar medium

Star formation research traditionally has been a domain of infrared and (sub)mm astronomy. All young stellar objects emit mainly in the wavelength range of FIRST – protoclusters, Class 0, I, and optically visible Class II sources have peaks of their SED in the PACS range. Given the PACS sensitivity, surveys of nearby star forming regions will allow the detection of a large number of pre-stellar condensations, protostars and young stars of various classes. These sources as well as regions of star formation in general are subject of detailed spectroscopic studies with PACS.

Confusion due to cirrus is a major limitation of surveys in these high background regions. Several mJy RMS (at 170μm) can be easily encountered. This emphasizes again the advantage of the smaller PACS beams. The higher confusion noise suggests that these surveys will typically be shallower than the extragalactic ones. The detailed survey layout is to be determined and could focus on high density regions as well as cover larger areas in an unbiased way, but obviously PACS shall be capable to integrate to the (local) confusion limit in order to detect lowest mass star or brown dwarf progenitors. The spatial scale of nearby star forming regions ranges from several arcmin for cores to several degrees for entire complexes. Unlike the situation for the extragalactic surveys where maps at the confusion limit are dominated by sources from a modest brightness interval, strong contrasts are to be expected in surveys of star forming regions.

Dust emission in protostellar objects, young stars, and star forming regions covers a wide range of dust temperatures extending from $\sim$15K for pre-stellar cores to $\sim$80K for Herbig AeBe stars with corresponding SED peaks at $\sim$200 and $\sim$60μm, respectively. For follow-up photometry of known objects and objects detected in PACS/SPIRE surveys, it will be essential to include these wavelengths. The high spatial resolution possible at shorter wavelengths is also needed to establish structure and temperature profiles of pre-stellar clumps.

Radiation and outflows from young stars excite the surrounding interstellar medium. Spectroscopy of the envelopes of young stars and the interstellar medium in both star forming regions and more diffuse environments is the key tool to study the interaction between the forming star and the surrounding cloud. A wide range of molecular (CO, OH, HD, H_2O, etc.), atomic and ionic species is observable in the PACS wavelength range. In many cases analysis of photodissociated or shocked regions is involved, for which the [O I] 63μm line is crucial. At the long end, the [N II] 205μm transition provides a diagnostic of the ionized medium.

Many of the targets of galactic spectroscopy with PACS are expected to be very complex in spatial structure, multiple, clustered, or extended. In addition, some spectroscopic followup may be on infrared targets with positional inaccuracies that are a significant part of, or larger than, the FIRST/PACS diffraction limit (e.g. from IRAS, Planck etc.). The need to understand complex sources clearly requires to address this problem with imaging spectroscopy rather than an enlarged aperture.

To achieve these scientific aims, PACS has to be able to

- Survey at 170μm large areas (up to square degrees, either contiguous or in patches preselected from other observations) to a depth somewhat shallower than for the extragalactic surveys (5σ, ten mJy to a few tens of mJy)
- Simultaneously cover a shorter wavelength, with the goal of reaching the same depth over the same area. In a situation limited by cirrus confusion, deeper integrations may in fact be chosen to take advantage of the lower confusion limit in the shorter band.
- Preserve the image quality of the FIRST telescope. The PSF width should not vary by more than 20% (TBC) over the field of view. Especially for crowded cluster cores, the intended lowering of the FIRST telescope diffraction limited wavelength to the goal of 85μm or below will directly

boost the quality of the data at these wavelengths. PACS has to be able to preserve diffraction limited beams at these wavelengths. Limiting the strength of PSF wings and sidelobes due to optical effects or crosstalk is important because of the presence of strong contrasts.

- Provide SED photometry for three points spread across the 60–200μm range. For study of the warmest sources, it is desirable (but not required) to include a photometric point below 60μm to get below the peak of the SED. Photometry should at least include a small field of a few beams around the nominal target.
- Cover a wavelength range of at least 60-210μm in spectroscopy mode, allowing both single line and range spectroscopy.
- Provide spectroscopy for a FOV of several beams instantaneously for observations of complex targets and efficient mapping
- Spectroscopically observe bright sources (details TBD)

2.4 Stars

Early and late type stars and their envelopes present a rich far-infrared spectrum of both molecules and features to be studied by PACS spectroscopy. Broad band imaging at the spatial resolution of PACS allows one to resolve debris disks around young stars with planetary systems in formation. Dust envelopes and shells of nearby evolved stars can be resolved as well in order to better understand mass loss and the latest phases of stars. Requirements are that PACS should be able to

- Spectroscopically observe bright sources (maximum about 10000Jy at 60μm) **Note:** In case this goal induces design conflicts with faint source observations, faint sources must have absolute priority.
- For studies of features in bright sources rapidly cover (spectrophotometrically) the full 60-210μm wavelength range, at the expense of high resolution fidelity

2.5 Solar system objects

Far-infrared broad-band imaging of solar system objects with PACS will focus on fainter comets, asteroids, and trans-neptunian objects. A possible exception is the use of outer planets or asteroids for calibration purposes.

Far-infrared spectroscopy is a powerful tool for the study of physics and chemistry of comets and planetary atmospheres, and will continue to be pursued with facilities like SOFIA and FIRST/HIFI. Nevertheless, there will be observations e.g. on fainter objects and at wavelengths blocked by the earth's atmosphere where PACS excels.

Implications are that PACS should be able to

- Obtain all types of observations (photometry, line spectroscopy, range spectroscopy, chopping/nodding) also on (moving) solar system targets. This is primarily a requirement on the FIRST pointing system but also on PACS observing modes.

- Observe bright sources. Goals are that PACS should be able to obtain observations of Uranus in imaging mode for calibration. All outer planets should be observable in spectroscopy mode (Extended sources, brightness temperature ≈140K for Jupiter/Saturn, Mars is even warmer but smaller). **Note:** In case this goal induces design conflicts with faint source observations, faint sources must have absolute priority.

3 Required performance and observing modes

3.1 Summary of performance figures

The most salient requirements on performance can be summarized as:

- Broad-band imaging sensitivity: 5mJy 5σ 1 hour, simultaneously at 170μm and one shorter wavelength.

- Array field of view: At least 5 sq. arcmin at 170μm. Goal is to have the same FOV at shorter wavelengths.

- Three filters, e.g. 75,110,170μm.

Several science aspects would benefit from the shortest wavelength being lower, e.g. 60μm, or an additional filter below 60μm. This is considered a desirable option but not a requirement.

- Preservation of telescope image quality

- PACS-internal position error less than 1 arcsec

The main scientific driver here are the surveys, in particular the requirement to detect and identify thousands of high z galaxies. Mapping speed is driven by the combination of sensitivity and FOV. Large arrays are a must, since the broad-band imaging sensitivity per pixel is effectively limited by the telescope background. This leaves little opportunity for per-pixel sensitivity improvement through optimization of PACS. PACS science clearly needs the 'goal' rather than 'requirement' performance of the satellite pointing.

- Photometric accuracy: 20% (goal 10%), reproducibility 5% (goal 3%)

- Photometric dynamic range: up to the maximum consistent with faint source observations - if possible thousands of Jy. The faint end is determined by the noise level reachable in a several hours of integration.

- Spectroscopic sensitivity: a few times 10^{-18} W/m^2 5σ 1 hour

- Resolution: 150-300km/s

- Instantaneous wavelength coverage: 1000-2000km/s

- Spectroscopic wavelength range: At least 60 to 210μm

- Spatial multiplexing also in spectroscopic mode

- Spectroscopic dynamic range: up to the maximum consistent with faint source observations - if possible tens of thousands of Jy. The faint end is determined by the noise level reachable in a long integration of up to 10 hours.

3.2 Observing modes

This section collects the scientific requirements on the observing modes of PACS. The term 'AOT' (astronomical observing template) is used for an observing mode. All observing modes will be strongly driven by the need to eliminate the large telescope background.

3.2.1 Photometry

The basic photometric mode of PACS will be one of dual-band photometry simultaneously using the short and long wavelength arrays. The AOT has to provide suppression of the large telescope background. Likely, the FOV will be chopped using the internal chopper and residual background gradients will be subtracted by regular nodding of the telescope.

The chopper throw should be selectable between just a few beam diameters (probably giving the best correction for single compact sources) to several arcminutes (to be able to chop to a reference position outside a somewhat extended source). Effectively this transfers to a throw selectable between 0 and $>$ 3arcmin.

The PACS arrays will fully sample the PSF, the result of PACS photometry will hence be not only two values but two small images. In order to sample the PSF to its wings and provide spatial information on moderately extended sources, the size of these images should be maximized. In case of butted arrays, this may invoke a complex interplay between selected chop throw, array gaps, and possible contiguous image size.

Arrays may have dead pixels or in case of butted arrays even 'missing' rows and columns. Some small step (few arcsec) rastering mechanism (from chopper or spacecraft) has to exist to provide contiguous coverage of the FOV if desired.

Parameters specified by the observer for such an AOT will thus *include* (there may be others)

- Target position
- Filter selection in blue channel
- Expected source flux
- Chopper throw
- Chopper avoidance regions (TBC)
- Required integration time
- Rastering parameters if applicable

3.2.2 Photometric Mapping

Blind surveys and many maps of known sources will cover regions substantially larger than the PACS FOV. The basic requirement is to map them deeply, rapidly, uniformly, and with preservation of a maximum range of spatial frequencies. Telescope background and source confusion cause a number of complications that likely require different solutions for different scientific projects and will need careful in-orbit testing and optimization. The following is a list of approaches to be pursued in parallel and constraints on them.

1. Mosaic from raster of chopped FOVs: The most straightforward solution is to execute the procedure used for photometry in a suitable spatial raster, with parameters optimized for uniform coverage. Possible drawbacks are matching of individual FOVs and difficulties to carry forward corrections when reconstructing unchopped maps.
2. Chopped line scans: Uniformity of chopped maps can be improved by spatial scanning of the telescope at a constant rate while chopping.
3. Unchopped line scans (fast scans): In a confusion-limited situation, chopping is highly undesirable and leads to an increase in effective confusion limit. Staring observations require an unrealistic flatfielding accuracy. A solution that is attractive for e.g. deep surveys is fast, unchopped linear scanning. This will work if the frequencies to which the desired spatial frequencies of the targets are transformed at the adopted scan speed can be sampled by the on-board data processing *and* do not suffer too high levels of noise due to either detector/readout 1/f type noise or telescope thermal drifts. Such a mode is a high priority from the point of view of surveys. Details like, e.g., selecting the slew direction angle relative to the array orientation may need careful consideration.

All these options will affect retrieval of low spatial frequency (many arcmin) information, either through buildup of inaccuracies in reconstruction of chopped maps, or through low frequency noise and drifts in unchopped scans. This loss of information has to be minimized.

3.2.3 Spectroscopy

Spectroscopy requirements can be naturally grouped into two modes:

1. Line spectra and spectral maps: A limited number of relatively narrow emission/absorption lines is to be observed for either a single spectroscopic FOV or for a larger map. Background subtraction can be achieved either through standard chopping/nodding (preferable for faint/compact sources) or through rapid 'frequency-switching' of the grating mechanism (preferable for mapping strong, highly extended line emission - note that this mode eliminates continuum information). Both modes shall be possible. For the frequency switching mode, a tradeoff between a simple switch and a repetitive fast scan has to be made.

   The pixel size in spectroscopy mode undersamples the PSF especially at short wavelengths. In some cases it will be necessary to retrieve some more spatial detail by rastering in sub-pixel steps.

   Parameters specified by the observer for a chopped line spectroscopy observation will thus *include* (there may be others)

   - Target position, raster parameters if applicable
   - Intended central wavelength(s)
   - Intended width of wavelength range(s)
   - Expected source flux(es)

- Chopper throw
- Chopper avoidance regions (TBC)
- Required integration time(s)

Parameters specified by the observer for a frequency-switched line spectroscopy observation will thus *include* (there may be others)

- Target position, raster parameters if applicable
- Intended line wavelength(s)
- Intended offset wavelength(s) for frequency switch
- Expected source flux(es)
- Required integration time(s)

2. Range spectra: This mode covers the need for larger wavelength ranges and full spectra, optionally at decreased resolution/faster speed. Parameters will *include*:

   - Target position, raster parameters if applicable
   - Intended wavelength range(s)
   - Expected source flux
   - Resolution/speed parameters
   - Chopper throw
   - Chopper avoidance regions (TBC)
   - Required integration time

4 Document change log

Version	Date	Initials	Comment
0.0	06 Jun 2000	DL	Early draft
0.1	19 Jun 2000	DL	Comments of HF,PA,AP
1.0	27 Oct 2000	DL	Comments up to PACS Science Team Meeting 1