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Response of the SPIRE consortium to questions arising from the second FSEC meeting
(Fax from Michel Anderegg of 18 March 1998 – PT-05382)

3 April 1998

1 Funding pressure/simplification of SPIRE

Question: Given the funding pressure, can you identify the simplest instrument which will still fulfil the main science objectives and give an indication as to the relevant cost savings, while keeping the AO model philosophy unchanged?

Related question from Martin Harwit: There are difficulties in constructing a spectrometer for the far infrared that covers both high and low resolution and does not require excessive cooling for the bolometers. Given these difficulties, is there an essential set of capabilities (e.g., high resolution vs. low resolution or vice versa) that is necessary to meet FIRST's most compelling scientific goals? How would singling out this capability affect the SPIRE spectroscopy design?

Since the FIRST Red Book was published in 1993, SPIRE has already undergone considerable evolution to focus the instrument on the main scientific goals of FIRST and to make it as simple as possible. Whilst the instrument is expensive, the projected funding levels in the major contributing nations (UK and France) are not so far away from the cost estimates made by the consortium as to require a major descope. Rather than react to funding difficulties by immediately descoping with serious loss of science, we would prefer to explore the possibilities of procuring the proposed instrument within the overall financial envelope available.

1.1 Photometer

The imaging photometer is essential to the scientific aims of the instrument and of the mission. It is already a simple instrument in terms of its design and cost. We do not propose to simplify it any further or to compromise its performance in the course of any other changes to the instrument design.

1.2 Spectrometer

We contend that a significant imaging spectroscopic capability is essential for SPIRE and for FIRST, and that the proposed FTS is an economical and well optimised solution. Here we address the following issues:

(i) What wavelength range should it cover?
(ii) What range of spectral resolution should it have?
(iii) Should it have an imaging capability?
(iv) Should it be optimised for observations of known lines or for spectral survey observations?
(v) What savings can be made by descoping the FTS, eliminating it or replacing it with something technically simpler, and at what cost to the science?

The importance of various spectroscopic modes is summarised in Appendix A. All of the major scientific issues addressed in the SPIRE proposal will need or greatly benefit from the capability to perform spectroscopy in the full 200-700-μm range. Spectroscopy of a selected sample of galaxies found in the cosmological survey is the only way to measure precisely the spectral energy distribution of these sources. The low resolution ($\lambda/\Delta\lambda$ = 20 – 100) mode is therefore essential for the main cosmological survey and for a number of other key projects for SPIRE. It is essential to determine the dust continuum and to detect any lines if present, thus providing a direct measurement of the redshift. Higher resolution spectroscopy ($\lambda/\Delta\lambda > 100$) is of lower priority, but still extremely valuable, particularly for studies of the ISM and protostellar evolution, and to remove it would be serious loss of science unique to FIRST. The spectral imaging capability will be unique in probing the environments of protostellar condensations found in the photometric survey. It will provide the data which are necessary to understand the changes which occur in the properties of the interstellar gas and dust from the low-density warm interstellar medium to the dense and cold cores from which the stars will form. These transition zones are very poorly understood and the wavelength range covered by the SPIRE spectrometer is ideally suited to measure the bulk of the dust emission together with any changes in its properties, and - at the same time - the major molecular cooling lines (especially water lines) which are expected to be dominant in protostellar environments. None of these projects will be done from the ground (LSA/MMA) or from airborne platforms (SOFIA). Nor will measurement of the dust continuum or of detailed spatial variations of major cooling lines be done by HIFI. For observations of known lines, SOFIA, various ground-based facilities, and PACS and HIFI on board FIRST, will have capabilities which there is no point in trying to match with SPIRE. For survey spectroscopy, and spectroscopy of broad extragalactic lines, SPIRE will be greatly superior to HIFI (see Appendix B).

The scientific priority table in Appendix A gives a good indication of the importance of the imaging capability. It is required for all the programs concerned with observations of nearby objects, and for the whole ISM programme. These are highly valuable programs, and part of the primary goals of the FIRST mission. In addition to these scientific requirements, there are two fundamental reasons to incorporate an imaging capability in the spectrometer.

(i) Background fluctuation

Recent results of deep surveys at 175 µm with ISOPHOT (and many LWS observations) demonstrate that measuring the spectrum with respect to one off-source position may lead to large errors in the background determination. The results of these surveys show that at 175 µm, at the resolution of ISOPHOT (1.5 arcminutes), the background is not homogeneous and the confusion limit is reached at a level of 100 mJy. (The confusion limit is defined as 1 source in every 40 resolution elements). From these measurements, the noise background has been estimated at 20 mJy rms (Jean-Loup Puget, private communication). This means that the determination of the backgtound with a single chopped measurement will be a dangerous exercise. A more complex chopping procedure, with measurements at several different locations, could be implemented, but at the expense of much increased observing time.

(ii) Spectral structure in the 200 – 600µm region

This spectral range is basically *terra incognita* It contains a large number of molecular absorption bands and fine structure emission lines. These spectral features have been modelled, and their intensities can be predicted. However, the global shape of the emission of most astrophysical objects is unknown. As an example, Fig 1 shows the spectral features in the galactic centre region observed by the FIRAS FTS on COBE (kindly provided by M.Y. Gerin and F. Boulanger). This spectrum demonstrates that this wavelength domain can be quite complex. There are a large number of absorption lines and emission lines. More surprisingly, there is a transition from a spectrum dominated by $H_2 0$ molecular absorption bands below 300 µm to a spectrum dominated by C and CO emission above 300 µm. One of the SPIRE goals is therefore to characterise this complete spectral region. This has important implications:

- We definitely need a low resolution spectrometer to measure the spectral distribution of the continuum and the most prominent spectral features. Without this measurement, the interpretation of the photometric surveys will be very difficult.

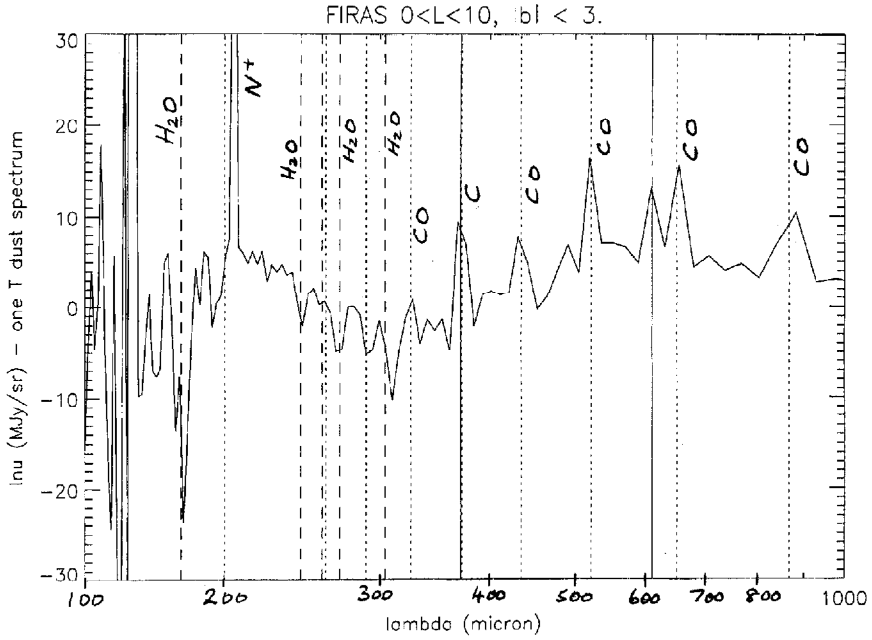

Figure 1: FIRAS FTS observation of the Galactic central regions (l = 0-10°; -3° < b < 3°). The spectrum covers 100 μm to 1 mm with a spectral resolution of 50. The dust continuum has been removed to enhance the visibility of the spectral features. The plain lines correspond to C emission lines, dotted lines to CO and dashed lines to H_2O. There is a clear change in the spectrum around 300 μm. Below, it is dominated by the absorption band of H_2O while at longer wavelengths, it is dominated by emission of C and CO.

- An imaging spectrometer is essential to characterise the variation of the spectral features with the other physical parameters prevailing in the observed regions. Observations of selected areas like interfaces between hot ISM, PDR and HII regions in our Galaxy will provide the necessary templates to determine the spectral variations. These results can be used later to interpret the photometric observations. Without them, the physical interpretation of the SPIRE photometric results will be very uncertain.

There is a very good analogy with the ISOCAM CVF. Without the CVF observations of a few template objects, the interpretation of the broad band imaging surveys for extragalactic sources would have been mostly wrong since the spectral features and the dust continuum did not behave as predicted before the ISO observations. Likewise, LWS medium resolution observations of dust sources revealed that substantial corrections were necessary to broad-band IRAS fluxes.

1.2.1 Scientific requirements for SPIRE spectroscopy

The essential scientific requirements for spectroscopy with SPIRE are:

- Wavelength range : 200 – 400 μm absolutely essential; 400-700-μm highly desirable
- Spectral resolution : 20 – 100 absolutely essential; > 100 very highly desirable; > 1000 not necessary
- Imaging capability : Essential
- Optimisation for complete spectral scans rather than observations of known lines (except for wide extragalactic lines for which direct detection provides better sensitivity than heterodyne receivers)

It was this set of requirements, together with compelling technical considerations outlined below, which led us to choose an FTS. Fabry-Perot and grating instrument options were also studied by the SPIRE consortium before the FTS was adopted. The FTS was chosen on the grounds that it best served the scientific goals **and** was also the least expensive and least risky option. One of the most important factors in the choice was the fact that the FTS allows the essential requirements to be met naturally while at the same time allowing the wavelength range and the spectral resolution to be extended with little or no penalty in cost or complexity of the instrument.

1.2.2 Fabry-Perot option

The Fabry-Perot design (as outlined in the FIRST Red Book) was suited to high resolution imaging spectroscopy of known lines. In the light of the capabilities of other facilities including FIRST HIFI, SOFIA, and various ground-based telescopes, the optimisation of SPIRE for this combination of features is not justified. In addition, the F-P option has numerous practical disadvantages.

1. Very complex instrument construction and operation.
2. Serious concerns over reliability (wheel mechanisms in series).
3. Considerable development effort required on massive low-power mechanisms.
4. Poor overall transmission efficiency and difficulty in covering a wide spectral range.
5. Poor spectral response function: the F-P response function (Airy profile) contains significant amounts of power outside the nominal spectral resolution element - grating or FTS spectrometers are much superior in this respect.
6. Not well-adapted for spectral survey or low-resolution work.
7. Band-pass filters must be located in a filter wheel at 4 K, posing big problems with the temperature stability of the filter wheel and the significant photon noise emitted from the 4-K filters.
8. Extremely stringent stray light rejection requirement, with an instrument optical design (multiple mechanisms, need for band-defining filters well forward of detectors) which is highly vulnerable to this problem.
9. Need to cool the detectors below ^{3}He temperature to meet photon noise limit (and even at 100 mK they will still not be photon noise limited).

1.2.3 Grating option

A grating spectrometer covering the 200-400 μm range was studied in detail by the SPIRE team. It was more attractive than the F-P option from the point of view of cost and complexity, but still suffered from many of the same drawbacks together with some new ones.

1. Vulnerability to stray light and out-of band leaks which can be very problematic with a low-background grating instrument. For instance, at 400 μm, the legitimate power per pixel with R = 400 is only 10 fW for the grating. For R = 40 it is 100 fW – but even this is much lower than has ever been achieved in a working instrument at these wavelengths. Even in low-background photometric testing in the laboratory, we have to take extreme precautions (multiple radiation shields, heavy filtering, elimination of all possible paths for stray light to enter the system) to reduce the background power to a level comparable with this. Achieving the same low background in the much more open configuration of a large spectrometer would be a major challenge.
2. Detectors need to be colder than 300 mK and even then are not photon noise limited (see Appendix C).
3. Not well suited to imaging spectroscopy.
4. Long linear arrays of feed-horns are required, making the cryogenic focal plane engineering much more difficult than for a non-dispersive spectrometer (this is in contrast to the compact 25-mm square arrays for the FTS or the F-P options).
5. Two different detector array types required in the instrument if base-line filled arrays are used for the photometer (order-sorting and stray light rejection considerations preclude the use of filled absorber arrays in the grating option unless an additional filter wheel is incorporated).
6. Spectral coverage limited to 200 – 400μm – a rather narrow range.
7. Not possible to adjust the resolving power.
8. Expensive due to high cost of grating with surface profile optimised for low final optics focal ratio (to keep instrument mass low enough).
9. Difficult compromise between need to have a large aperture to prevent loss of efficiency due to slit diffraction and need for a small aperture to minimise the beamwidth.

1.2.4 Reasons for choice of FTS option

1. Full utilisation of the imaging capabilities of the FIRST telescope, which was not possible with the grating.
2. Spectral resolution easily adjustable and tailored to the scientific requirements of the observation. The FTS is the best option for covering a range of spectral resolutions because (i) the background on the detectors remains constant, so that the arrays and their readout are always properly optimised (the performance at any one spectral resolution is essentially unaffected by the need to accommodate any other); (ii) changing the resolution is simple and straightforward, being effected by changing the length of the moving mirror travel.
3. Full spectral range observed in one observation, making SED and simultaneous multiple line measurements easy (and offering the possibility of unexpected discoveries in this poorly studied spectral region). The SPIRE FTS would be the first (and only) instrument capable of making complete measurements of the submillimetre spectra of astronomical sources.
4. Detectors can be operated at 300 mK, with comfortable margin. This is because the photon noise limited NEP is much higher for the FTS, whose detectors observe broad-band, than for grating or Fabry Perot spectrometers in which they observe in narrow-band mode. A ^{3}He sorption cooler can therefore be adopted for SPIRE - an enormous simplification over the previously base-lined dilution cooler.

5. Competitive sensitivity. If the extremely stringent stray light requirement could be met, then the grating would be more sensitive for observations of known spectral lines. However, there is little difference in the sensitivities of the two options for spectral survey observations, which are of greater scientific priority for SPIRE. In practice, our experience with both FTS and grating spectrometers shows that practical grating instruments at long wavelengths can be very inefficient. In particular, the problem of diffraction losses at long wavelengths proved to be a major drawback for a grating instrument for SPIRE (resulting in high loss of efficiency or else an unfeasibly large instrument).
6. Much lower vulnerability to stray light and out-of band leaks. In the FTS, stray light adds photon noise but does not contaminate the signal unless it is spectrally modulated by the interferometer. Any out-of-band spectral leaks also add photon noise but are spectrally modulated at frequencies outside the signal band, and so do not corrupt the spectrum. These are crucial advantages over the grating instrument, for which the relative contribution of stray light is much greater. For instance, a stray background power of 10 fW would severely degrade the performance of the grating , but for the FTS option it would be insignificant compared to the legitimate thermal background from the telescope (5000 fW).
7. Easy to extend wavelength range from 400 μm up to ~ 700 μm with essentially no penalty in performance over the 200-400μm band for which the instrument is optimised.
8. Easy to achieve R up to 1000 by extending the mirror travel with little penalty in terms of cost or complexity.
9. Lower susceptibility to 1/f noise (telescope temperature fluctuations, pointing jitter etc.). In a rapid scanning FTS, all spectral elements are continually being **spectrally** modulated, so that contrast between lines and adjacent continuum is maintained in the presence of noise at frequencies lower than the signal frequency band. (This issue is discussed in more detail in Appendix D). To achieve this with a grating instrument, spectral modulation must be performed by chopping with the grating. It would not be feasible to modulate any faster than around 1 Hz (compared with 5 Hz minimum for the FTS), and even this would be problematic with a physically large grating needed at such long wavelengths. Furthermore, spectral chopping with the grating potentially involves chopping onto an unknown part of the spectrum.

1.2.5 Options for simplifying the FTS

The FTS should be regarded as a relatively low-cost addition to the photometer, and one which provides a great enhancement of SPIRE's scientific capabilities. Descoping it, or replacing it with some other "simpler" option will not bring about any substantial cost reduction.

A. Decrease the spectral resolution from 1000 to, say, 50 or 100, by reducing the scan length.

- Slightly simpler mirror drive mechanism with lower power dissipation
- No other significant savings
- Overall: hardly any saving at all

B. Decrease the number of pixels

- Lower data rate – less on-board processing required. Savings insignificant unless no. of pixels reduced by a large factor (e.g., keeping only a very basic imaging capability using only a few pixels)
- Small reduction in instrument mass
- Insignificant saving in focal plane array costs: the FTS design is configured to use arrays which are identical to those needed for the photometer
- Overall, small saving in cost at great expense to the science

Conclusion: Descoping the FTS design will save little. All major subsystems will remain, all major development programmes will still be needed, and only marginal cost reductions will be effected.

To save significantly on the cost of SPIRE, a different instrument concept is required. The ground-rules for this would have to be:

- Maintain the detector operation at 300 mK (otherwise it gets *more* expensive and becomes unbuildable anyway).
- Eliminate moving parts if possible (but the spectrometer would need to share the chopper again making the fore optics more complex and possibly compromising the photometer optical design).
- Go for low resolution (R ? 40) spectrophotometry only, losing all of the spectral line detection and imaging spectroscopy capabilities of SPIRE.
- Decrease number of pixels by a large factor, eliminating completely the need for on-board processing.
- As an extreme option, eliminate the spectrometer entirely.

All of these changes involve drastic loss of scientific capabilities, making the instrument potentially far less attractive to the scientific community. Clearly, the most savings could be made by abandoning spectroscopy entirely and just flying the photometer. This would certainly provide significant financial savings: probably on the order of 20-25% in the total cost of the instrument (but nothing like a factor of two).

Various options are being considered in a basic way at the moment within the SPIRE consortium. None of them are particularly simple when it comes to practical implementation. It is not possible to produce a credible alternative low-resolution spectrometer design (or a proper cost estimate) without a serious design study. None of these options would save a very large amount over the FTS design, and none of them would match its scientific capabilities.

1.2.6 Current funding status of SPIRE (more detailed information to be provided later)

UK: A detailed cost review of the SPIRE workpackages allocated to the UK was carried out in January 1998. The assessment involved consideration of the detailed costings submitted by the UK groups, negotiation with the groups to minimise costs, and prioritisation of the proposed work-packages. PPARC's allocation for SPIRE is approximately 20% smaller than the amount needed to fund all of the UK-allocated work-packages.

France: The French participation in SPIRE is funded by CNES and CEA. CNES will support the investment cost of all development activity at LAS, IAS, and DESPA, and only half of the cost of SAp activity, the second half being funded by CEA. Preliminary discussion between CNES, CEA and CNRS took place on February 4th. The overall demand to CNES will exceed by around 10% the preliminary indication of available funding given by CNES (note that CNES requests that a 20% contingency be included at this stage, so that the funding envelope is actually adequate for a 10% level of contingency.) However, the CNES mid-term strategic plan is not yet finalised, and the exact available budget for the FIRST instruments is still under discussion. For CEA, the SPIRE demand fits within the allocation.

US: A proposal from the US team is currently being considered by NASA, and a generally favourable outcome is expected. It is not anticipated that there will be any problem with the funding of the US groups involved in SPIRE. In fact, possibilities for US groups taking on responsibility for some focal plane modules originally allocated to the UK are being considered (the internal calibration sources for the photometer and the FTS).

Italy, Spain, Sweden: Indications are that these countries will be able to carry out the work to which they have committed.

Other possible contributions: It is possible that Canada may be willing to provide the EGSE for SPIRE. This is seen as practical and cost-effective, and not likely to result in significant dilution of the consortium. However, no firm commitments are available as yet. The SPIRE PI and Project Manager will attend a meeting at the Canadian Space Agency in Ottawa in late April to discuss this option.

Summary: The funding problem for SPIRE is not a trivial one, but is at the level of 15-20% rather than 50%. In seeking a solution, there are a number of avenues which should be explored before starting to hack at the science that the instrument and the mission can do. The fundability of SPIRE is highly dependent on several factors including the following.

(i) The mission schedule and implementation. It would seem logical to consider potential descoping of the instruments alongside (rather than prior to) any revision of the schedule or mission implementation.

(ii) ESA's policy towards ICC funding. This is at the root of the problem -- were it not for the additional cost burdens imposed by having to provide the ICC, then the UK and France would be able to fund the instrument hardware and also support operations at an appropriate level. While the planned Operations philosophy may represent the least cost *overall*, it is in danger of seriously damaging the ability of the agencies to fund scientifically powerful instruments and so degrading the quality of the mission.

(iii) ESA's model philosophy and testing requirements. For example, it would save a lot if cold vibration testing were allowed at liquid nitrogen temperature, or if the requirements for provision of the flight spare were reconsidered.

We would like to pose this question to ESA and the Evaluation Committee. Given that achieving the best science (within the total budget) for the astronomical community is the common goal of ESA, the instrument teams and the agencies, would it not be more fruitful to look at ways of minimising the Operations costs (while still doing the same science and delivering the results to the community in a fair manner) rather than seeking to save relatively small amounts of the total mission budget by deleting important scientific capabilities from the focal plane instruments?

2 Management

Question: In your consortium, the responsibilities of the Project Manager are very large and include the monitoring and control of numerous Co-I institutes. In the organogramme provided, he is supported by very few people. Could you review the responsibilities of your Project Manager and define in detail the "project" with an adequate team who will support him.

We accept the concerns that the work-load on the project manager appears heavy and that the proposed management structure does not look to be optimised. The main responsibilities of the PM are to put in place the planning for the project, to monitor its progress and to report to the PI and ESA. Much of this can be performed in a routine fashion by someone with experience of this aspect of project management. The administrative support of SPIRE at RAL will include someone with this experience. We believe that for an effective ("strong") management structure within the consortium, it is essential that the local institute managers all deal with one office and one person when it comes to progress reporting, task and deadline assignments, etc., and that this requirement can only be served by having a single central project office and manager. So monitoring of numerous Co-I institutes is an *essential* role of the PM. But this function should not be seen as a form of heavy policing or micro-management. The PM is supported at the subsystem level by the local project managers, who serve to *reduce* the workload on the PM, not increase it. We note also, that when it comes to hardware delivery, the number of Co-I institutes is not so great (QMW, ROE, MSSL, IC, LAS, CEA, IFSI, Stockholm = 7).

The Project Team: Whilst it may not be obvious on the organogramme, there will be ample support from the core of the consortium, especially the Systems Team and the Project Scientists. A realistic definition of the Project Team would be as follows:

Project Manager: Ken King (at RAL)
Instrument Scientist: Bruce Swinyard (at RAL)
Systems Engineers: Louis Rodriguez at (CEA) - Chair of Systems Team
Colin Cunningham (ROE) - Hardware Systems Engineer
To be appointed - Software Systems Engineer
Project Scientists: Jean-Paul Baluteau (LAS)
Walter Gear (MSSL)
ICC Scientist ICSTM
AIV and Calibration scientists at RAL (to be appointed)
PA/QA experts: RAL (who will support and advise consortium groups)
Project office support (secretarial, financial admin., etc.) at RAL

The PM has at his disposal these people who have the responsibility for the smooth running of the project in their own fields of expertise and activity. In our management structure, the PM and the ICC Development Manager are one and the same. This is partly because the particular individual is highly skilled in both areas. With appropriate administrative support (which is agreed with PPARC), we believe this will work for the benefit of the project.

3 Development Plan

Question: There is a general concern, which applies to all three FIRST instruments, regarding the lack of visibility into planned development activities, particularly over the next two years. Because of the complex division of development work this apparent lack of planning is considered critical. Consequently, you are requested to identify the main development tasks per model, paying particular attention to new technologies and risk areas. A basic plan of these activities with duration and key milestones should then be produced. This initial development planning should then be produced by the end of May. It would later evolve in a Development and Test Plan to be maintained as a controlling document through the B and C/D phases of the project.

Whilst the optical mechanical and thermal design of the instrument is complex, it is essentially "hard work" within the boundaries of known technology. This includes the FTS mechanism and the ^{3}He cooler. The most significant risk we perceive to the instrument development is the evaluation of the filled absorber arrays. The development schedule for this over the next two years (leading to a selection in late 1999) is outlined in Table 2.3 in section 2.5.1 of the SPIRE Scientific and Technical Plan. A risk assessment for the various options is given in Table 2.5 of section 2.7.

A more detailed development plan is being formulated (we note that there is already a considerable amount of information on this in the proposal). Vacation arrangements of various key people preclude a sufficiently detailed first version being produced before the end of April. Some of the milestones will require provision of information by ESA and working meetings of the Commonality Working Group and the GSAG. Various aspects of the instrument development plan depend on agreement with ESA. For example, we will want to make decisions about the spacecraft interfaces and operations before ESA appoints contractors for the spacecraft. Will ESA be willing to place requirements on the contractors based on decisions made by the instrument groups?

Appendix A:SPIRE scientific programmes and required observational capabilities
Appendix B Comparison of spectroscopic capabilities of SPIRE and HIFI
Appendix C:BLIP requirements for SPIRE grating and FTS options
Appendix D: Effect of 1/f (e.g., pointing jitter) noise on FTS performance.

Appendix A: Scientific priorities for SPIRE observing modes

In this appendix, we summarise which observing modes are required for each of the scientific programmes which are described in the SPIRE proposal. To clarify the presentation we have divided the observing modes into three categories.

- Imaging and photometric mode. This is basically covered by the photometer part of SPIRE alone.
- Low resolution spectroscopy. We have used a rather arbitrary definition of spectral resolution between R = 20 and R = 100. This part can be covered by the FTS, or by another dedicated low resolution spectrometer, which would have to be studied and designed.
- High resolution spectroscopy (R = 100 to R = 1000). This could be done with the FTS or, in principle, with the previously envisaged grating spectrometer.

In each of the spectroscopic modes, we have considered the scientific need for an imaging capability.

We define a scale of scientific priority as follows:

- Priority 1: Essential for the program, SPIRE capabilities without competition.
- Priority 2: Useful complement to the first priority observations which cannot be made by other instruments, in space or from Earth.
- Priority 3: Essential for the program, but can be tackled partially by other instruments, either on FIRST or by other observatories in space or on ground.
- Priority 4: Not relevant for the program.

Programme	**Priority**			**Competition**
	Three-channel photometry	Low resolution spectroscopy R= 20 - 100	High resolution spectroscopy R=100 - 1000	
Cosmological Survey				
Characterisation of galaxy evolution for Z = 1 - 4	1 Determination of the SED and rough photometric redshift The definition of the bands might still be optimised	2 A spectroscopic survey can be done on a sample of galaxies selected by photometric redshift Imaging spectroscopy is needed to make an accurate subtraction of the background	4	LSA, or NGST can be used to detect the galaxies. NGST and LSA cannot be used to determine the SED and therefore the bolometric luminosities of the galaxies in this redshift range
Study of high-z dusty galaxies: relation between Ultra- luminous IR galaxies, AGN, QSOs	1	1 A low-resolution spectrum is needed to identify the nature of these objects	4 Objects too faint to be observed at high resolution or with HIFI	LSA can be used for the same purpose, but cannot determine the redshift of galaxies with z < 4, and many interesting lines are in the SPIRE range
Large scale structure at Z = 1 - 4	1	3 The main limitation for this program is the no. of redshift to be measured (>1000 by	4	LSA cannot be used since it cannot provide a direct redshift measurement. NGST is more

		redshift bands)		appropriate for this program.

Programme	**Priority**			**Competition**
	Three-channel photometry	Low resolution spectroscopy R= 20 - 100	High resolution spectroscopy R=100 - 1000	
Galaxies in the local universe				
Interstellar medium in nearby galaxies	**1** Needed to look for faint extensions of dusty disk	**1** Spectroscopy is needed to determine the dust content and its temperature distribution	**1** High resolution spectroscopy is needed to study the molecular content. In the two spectroscopic modes, imaging is needed to disentangle the various components of the galaxies (e.g. arms, interarms, dust lanes)	This program must be complemented by PACS observations
Dust cycling in the extragalactic ISM	**2**	**1** Imaging spectroscopy is essential to assess the temperature of the dust in various environment, e.g. disks and halos of spiral galaxies	**4**	This program must be complemented by PACS observations
Galaxy interaction and nuclear activity	**2**	**1** Imaging spectroscopy is mandatory for this program, to determine the areas of active star formation (see the Antennae mid IR image in the proposal)	**1** Very little is known about the molecular content of strabursts and AGN. The Arp 220 spectrum is dominated by molecular absorption bands	This program must be complemented by PACS observations
Nearby low-metallicity galaxies as models of primeval galaxies	**2**	**1**	**4**	This program must be complemented by PACS observations

Programme	**Priority**			**Competition**
	Three-channel photometry	Low resolution spectroscopy R= 20 - 100	High resolution spectroscopy R=100 - 1000	
Protostars and Young Stellar Objects				
Protostellar surveys in active and quiescent molecular clouds	1 Determination of the luminosity function with emphasis on low luminosity objects	2 Needed to determine the dust emissivity law, and the main cooling lines	3	This program must be complemented by PACS observations LSA may be used to do a complete survey for protostars, depending on its mapping capability. However, it will be useless to determine the SED, and therefore, the luminosity function.
Spectroscopic surveys of YSOs and their outflows	4	2	1 Gas cooling around YSOs Flow - ISM interactions Physics of shocks	Imaging capability is required to separate the regions of normal ISM, shock fronts in the flows and flow matter. HIFI could be used to determine the dynamics of the flow, but will lack imaging capabilities.
Main Sequence and Evolved Stars				
Mass loss from evolved stars	1 Detection of low brightness extended envelopes	2	2	
Dust discs around main sequence stars	1 The main driver for SPIRE is the very large extension of the disks	2	2	Will be done partly by SIRTF. LSA is not suited to look at low surface brightness extended objects

Programme	**Priority**			**Competition**
	Three-channel photometry	Low resolution spectroscopy R= 20 - 100	High resolution spectroscopy R=100 - 1000	
Galactic Interstellar Medium				
Temperature structure and cycling of dust in the ISM	**1** Main interest in large scale dust distribution	**1** Determination of dust emissivity	**4**	Cannot be done by LSA: extended low surface brightness objects Same for HIFI
Spectral imaging of molecules distribution	**4**	**2** Imaging spectroscopy is mandatory for this program	**1**	Partial competition with HIFI, but SPIRE provides Two major advantages: (i) complete spectral coverage; (ii) more accurate calibration of line ratios due to the multiplex nature of the FTS
Cooling of the ISM	**4**	**2**	**1**	Same as above
Solar System				
Giant planets	**4**	**2**	**1** High resolution needed for tropospheric and stratospheric lines	
Mars	**4**	**1** Thermal properties of martian surface	**3** Could be done with HIFI	
Comets	**2**	**1** Needed to determine the properties of cometary dust	**3** Could be done with HIFI	
Small bodies, asteroids and Kuiper Belt objects	**1** Determination of surface properties	**2** Might be used on brightest objects (e.g. Pluto/ Charon)	**4**	This program should be complemented by PACS observations

Appendix B: Comparison of spectroscopic capabilities of SPIRE and HIFI

The following sensitivity figures are given in the HIFI proposal (SPIRE figures also given for comparison):

Band	**1**	**2**	**3**	**4**	**5**	**6a**	**6b**
ν (GHz)	480-640	640-800	800-960	960-1120	1120-1250	1410-1910	2400-2700
λ (μm)	470-625	375-470	310-325	270-310	240-270	212-160	110-125
Line flux limit (5σ, 1 hr, $R=10^4$) (W m^{-2} x 10^{-18})	0.9	1.4	2.0	2.6	3.2	7	14
SPIRE sensitivity (5σ, 1 hr) (W m^{-2} x 10^{-18})	39-64	35-39	35	35	35	35	Not covered by SPIRE

For detection of wide extragalactic lines, we must take into account the following:

(i) A spectral resolution of around 300 (1000 km s^{-1}) is optimum given the need to detect all of the energy in the line.

(ii) The noise temperatures quoted in the HIFI proposal are goals which are lower by a large factor than anything achieved by current technology. It would be more realistic to assume numbers at least a factor of two higher.

In order to compare HIFI with SPIRE for wide extragalactic lines, we should therefore multiply the HIFI line flux limits by at least $(10^4/300)^{1/2}(2) = 11.5$:

Band	**1**	**2**	**3**	**4**	**5**	**6a**	**6b**
ν (GHz)	480-640	640-800	800-960	960-1120	1120-1250	1410-1910	2400-2700
λ (μm)	470-625	375-470	310-325	270-310	240-270	212-160	110-125
Line flux limit (5σ, 1 hr, R=300) (W m^{-2} x 10^{-18})	10	16	23	30	37	81	161
SPIRE sensitivity (5σ, 1 hr) (W m^{-2} x 10^{-18})	39-64	35-39	35	35	35	35	Not covered by SPIRE

It can be seen that, for simple detection of a known line, SPIRE is competitive with HIFI except at the longer wavelengths. In addition

- SPIRE measures the **whole spectrum** over the 445-1500 GHz range **at the same time.** To measure the complete spectrum over the smaller 480-1250 GHz range, HIFI would take (1250-480)/4 = **193** times as long as for a single 4-GHz wide portion.
- SPIRE also measures the continuum at the same time.
- SPIRE also provides instantaneous imaging over a 2 x 2 arcminute field of view.

These advantages mean that for survey spectroscopy and spectral imaging of sources with narrower lines, SPIRE is much faster than HIFI. For galactic sources and nearby galaxies, there will typically be 10 - 30 important lines in the SPIRE range, all measured simultaneously. Obviously, the two instruments are complementary in that SPIRE should carry out imaging survey spectroscopy which can then be followed up by HIFI on brighter sources to measure line profiles.

Appendix C: BLIP requirements for SPIRE grating and FTS options

The lowest achievable NEP with state-of-the art bolometer technology, even at a temperature as low as 100 mK, is around 1 x 10^{-17} W $Hz^{-1/2}$. This cannot be achieved at 300 mK. The best predicted performance of a single-pixel NTD Ge bolometer at 300 mK optimised for the SPIRE grating option speed of response requirement, is 1.4 x 10^{-17} W $Hz^{-1/2}$ (c.f. Jamie Bock's presentation at the QMW Bolometer Arrays Workshop, October 1997). The background limited NEPs for the SPIRE grating option are summarised below for two resolutions: 400 and 40. It can be seen that at R = 400, the system is nowhere near photon noise limited. At R = 40, the BLIP performance could just be achieved over the whole 200-400-μm range. However, this would be pushing bolometer technology to the limit, with no margin on sensitivity or cryogenic performance. Similar considerations apply to a low-resolution F-P spectrometer.

λ (μm)	λ/Δλ	P_{det} (fW)	NEP_{blip} (W Hz^{-1} x 10^{-17}
200	400	36	0.95
	40	360	3.0
300	400	31	0.72
	40	310	2.3
400	400	13	0.42
	40	130	1.3

Conclusion: Assuming that the detectors cannot be cooled below 300 mK, a grating or Fabry-Perot spectrometer for SPIRE cannot be photon noise limited for R ? 40 (with no margin on operating temperature or detector performance).

One of the major practical advantages of the FTS spectrometer is that the BLIP limit is easily achieved at 300 mK. The relevant figures for the SPIRE FTS are summarised below. They are independent of the spectral resolution.

	P_{det} (pW)	NEP_{blip} (W Hz^{-1} x 10^{-17}
Band 1: 200-300 μm	1.8	6.2
Band 2: 300-670 μm	2.7	5.7

Note: These figures assume 0.5Fλ pixels (i.e., filled arrays), which is the worst case (lowest background per pixel) as far as the detector sensitivity requirement is concerned.

The required sensitivity and speed of response can now easily be met at 300 mK, with comfortable margin on operating temperature and detector performance (factor of two in NEP for 20 Hz speed of response).

Appendix D: Effect of 1/f noise on FTS performance

Variations in the FIRST telescope temperature or pointing jitter could lead to low frequency variation in the intensity during a spectral scan of the SPIRE FTS (maximum duration ~ 30 sec.). These effects are expected to be small on the timescale of a SPIRE FTS scan (typ. 30 seconds). This type of error is a much smaller problem for a rapid-scanning FTS instrument than for a grating instrument. The advantage of the rapid-scanning FTS is that it modulates the signal at relatively high frequency and so separates the signal from this low frequency noise. Radiation frequencies are encoded as audio frequencies with a conversion factor determined by the mirror scan speed. In the case of SPIRE, the band of interest (200 – 670 μm) corresponds to 6 – 20 Hz. All of the scientific information is within this band.

In the rapid scanning FTS, the radiant signal is also continuously spectrally modulated so that the contrast between spectral elements is maintained in the presence of low frequency noise. Some recent data from Earth observing far infrared FTS experiments shows how low-frequency noise can be made to have negligible impact on the scientific data, including applications in which it is required to measure weak features against a strong continuum.

In an FTS only half the light reaching the detector is modulated by the interferometer and so low frequency variations result in two components.

a) Additive component

This is a variation of the intensity of the unmodulated light. In a well designed instrument the frequency of the variation is outside that induced by the interferogram scan so after the Fourier transform this noise will appear outside the spectral region of interest. Figure 1 shows an example of this. It is an early spectrum from the SAFIRE far infrared atmospheric spectroscopy instrument on an M55 aircraft platform at 19 km altitude. An interface problem between the aircraft and the instrument roll correction system led to pointing errors causing large signal excursions which are readily apparent in the interferogram. These excursions resulted in large noise peaks (> 10%) at low frequency but have **no impact in the spectral window of interest** near 23 cm^{-1} where the noise is near the photon background limit (0.5%). Clearly, the additive component may be removed in either the spectral or interferogram domains.

Variation of the additive component will only cause significant problems if it occurs at the zero path difference (ZPD) position of the interferogram. This causes a constant offset in the spectrum, essentially a baseline level drift from scan to scan. This will average to zero and will not affect the recovery of weak signals through co-addition of scans (or even in a single scan).

b) Multiplicative component

A variation of the intensity of the light which *has* been modulated by the interferometer leads to a redistribution of power in the spectrum. Intensity is redistributed into sidebands which have a maximum amplitude of $\alpha/2$ where α is the relative amplitude of the variation[1]. This worst case situation is only achieved when the variation is perfectly sinusoidal and continuous throughout the scan; random variations will lead to some smearing of the sidebands. Pointing error variations and similar noise sources are expected to be small, on the order of a few %. So the multiplicative error leads to the creation of very weak sidebands, typically a few percent of the main line intensity. Even if these sidebands are smeared due to the random nature of the error, the main line will hardly be affected: a few percent of the line intensity will be smeared around the base of the line. For weak features, the sidebands will be well below the noise level and hence negligible. For the continuum it will be equivalent to applying a smoothing function, appearing as a variation in baseline level.

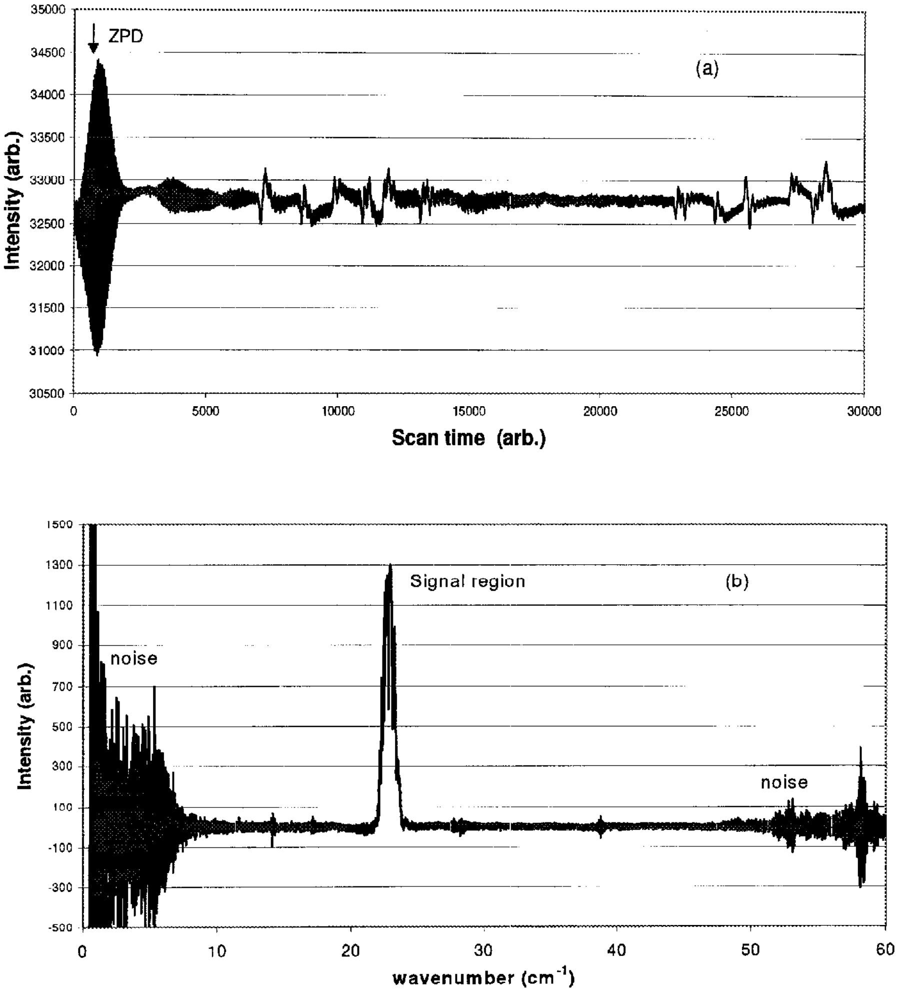

Figure 1: Effect of pointing errors. (a) An interferogram taken on an aircraft platform showing large excursions due to the (uncorrected) roll of the aircraft. (b) The resulting spectrum showing the pointing error noise transformed out of the spectral region of interest.

To illustrate that such baseline level variations (from any cause) do not affect the recovery of small peaks Fig. 2 shows a series of spectra from the IBEX far infrared spectroscopy instrument on a balloon platform (35 km altitude) recorded at nominally the same observation geometry. The peak signal is normalised to unity so the baseline variation apparent between these scans is on the order of 5%, with the single-scan noise level being about 1%. Signals of about 2% amplitude (much smaller than the baseline variation) are clearly detectable in all scans.

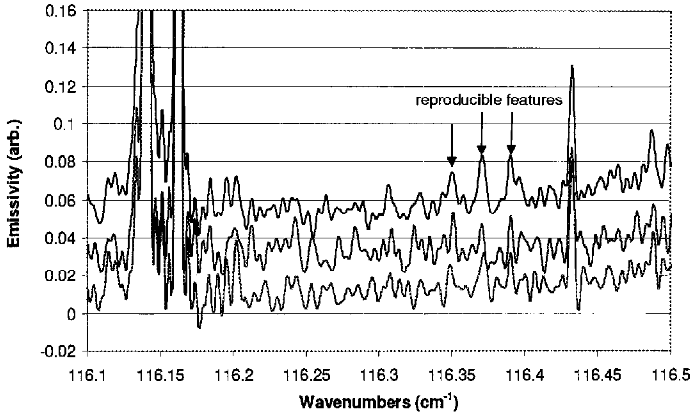

Figure 2: Effect of baseline variations. Instrument instabilities and pointing errors may cause significant baseline drifts but this does not prevent detection of very weak (S/N≈ 2) features.

The multiplicative component will cause significant problems only if there are intense lines in the spectrum and the multiplicative variation is of constant frequency. In this worst case scenario the secondary peaks from the intense features could potentially be mistaken for small peaks in the spectral domain. However the presence of multiplicative component necessarily implies an additive component and so this condition is easily detectable as described above and is correctable to first order.

1. Learner, R C M, A P Thorne, and J W Brault. Ghosts and artefacts in Fourier transform spectrometry. *Appl. Opt.* **35**, 2947, 1996.