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SMEC and Spectrometer Performance

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1.Introduction and scope

This document compares the performance of the SPIRE imaging spectrometer during the PFM1 and PFM3 ground-based test campaigns against the scientific requirements. Special emphasis is given to the spectrometer mechanism.

2.List of requirements that the test programme was designed to evaluate

The SPIRE spectrometer requirements that were evaluated during the PFM1 and PFM3 test campaigns are given in the table below. Also indicated in the table is whether the information regarding the requirement has been updated since SVR1.

Requirement Number	Description	Requirement	Update since SVR-1
IRD-SPEC-R01	Wavelength Range [µm]	SSW: 200-300 SLW: 300-670	Yes
IRD-SPEC-R02	Maximum Resolution [cm^{-1}]	Req: 0.4 Goal: 0.04, resolution element 0.0483, FWHM	Yes
IRD-SPEC-R03	Minimum Resolution [cm^{-1}]	Req: 2 Goal: 4	No
IRD-SPEC-R11	Vignetting	<10% uniformity at a resolution of 0.4cm^{-1}	Yes
IRD-SPEC-R14	Fringe Contrast	>80% at a resolution 0.4cm^{-1}	Yes
IRD-OPTS-R07	Balancing of ports	Beamsplitters shall have $2RT=R^2+T^2$ to within 90% over the band	Yes
IRD-OPTS-R09	In-band straylight	<5% for each band	No
IRD-SMEC-R01	Linear Travel	Req: 14cm total OPD	No
IRD-SMEC-R02	Minimum movement sampling interval	5µm SSW 7.5µm SLW	No
IRD-SMEC-R03	Sampling step control	Interval variable between 5 and 25µm	No
IRD-SMEC-R04	Scan length	Able to start a scan from either side of ZPD	No
IRD-SMEC-R05	Dead-time	<10% at resolution of 0.4cm^{-1}	No
IRD-SMEC-R06	Mirror velocity	Req: 0.1cm/s MPD Goal: 0.2cm/s MPD	No
IRD-SMEC-R07	Velocity control	Selectable from 0 to 0.1cm/s	No
IRD-SMEC-R08	Velocity stability	<10µm/s RMS over the full range of movement	No
IRD-SMEC-R09	Position measurement	0.1µm within +/- 0.32cm of ZPD, 0.3µm elsewhere	No

Table 1: SPIRE Spectrometer Requirements

3.Test results and conclusions

3.1.1 Wavelength Range (IRD-SPEC-R01)

The edges of the SPIRE spectrometer bands (SLW and SSW) are defined as the points where the spectral intensity is one half of its average in-band value. In order to focus on the response of the detectors themselves, the contributions to the measured spectrum from the input sources (CBB and SCAL) were removed (see refs. 7, 9). The edges of the spectrometer wavebands shown in the following table are the average (± 1 σ) for the active pixels in each array.

	SLW		SSW	
	Cut-on (cm^{-1})	Cut-off (cm^{-1})	Cut-on (cm^{-1})	Cut-off (cm^{-1})
Specification	14.64-15.02	33.00-33.67	30.40-31.15	52.08-53.19
PFM1	14.905 ± 0.099	33.068 ± 0.096	31.32 ± 0.28	51.99 ± 0.24
PFM3	14.899 ± 0.091	33.525 ± 0.096	31.37 ± 0.17	51.98 ± 0.20

Table 2: SPIRE Spectrometer Band Edges

While there was a small difference in the measured SLW cut-off, the high-wavenumber (short-wavelength) edge, between the PFM1 and PFM3 test campaigns, in each case the measured band edge agreed with the specifications within measurement uncertainty. As the values in the table above show, both band edges for the SLW array as well as the high-wavenumber (short-wavelength) SSW band edge meet the specifications within measurement uncertainty. With respect to the SSW low-wavenumber (long-wavelength) edge, while it was found to be marginally outside the specification, it still ensures an overlap of 2cm^{-1} between the two detection bands.

3.1.2 Maximum Resolution (IRD-SPEC-R02)

There are many definitions of resolution in the field of spectroscopy. One of the most widely used is the full width at half maximum (FWHM) of the instrumental line shape (ILS) of the spectrometer. This definition is well suited to spectrometers whose ILS are not well defined such as a diffraction grating or a Fabry-Perot interferometer. The Fourier transform spectrometer, however, possesses the best ILS of any spectrometer – in the ideal case this is the well known sinc function. The sinc function possesses secondary oscillations that decay in amplitude at increasing difference frequencies from the line centre. The resolution of an FTS based upon the FWHM criteria gives a slightly higher value than that obtained if all the information in the extended sinc ILS is used in the subsequent data analysis.

The design goal is such that the spectrometer mechanism is that it should have a maximum optical path difference of 12.5cm. The measured maximum optical path difference for the QM SMEC was 12.6cm for the PFM1 and PFM3 test data, meeting the resolution element goal. It is anticipated that the FM SMEC will also meet the resolution element goal, though this will have to be verified in the PFM4 test campaign.

To determine the resolution of the SPIRE spectrometer measurements were made of unresolved line sources. The line source used in the PFM1 tests was an infrared laser, in the PFM3 tests it was a tunable photomixer. Due to time constraints and because the line source can only be focussed on one detector pixel per observation, measurements of the FWHM spectral resolution are only available for limited set of the SLW and SSW pixels.

The PFM1 and PFM3 test results, presented in detail in §7.1, show that the QM SMEC meets the requirement for the maximum spectral resolution requirement (0.4cm^{-1}) within measurement uncertainty. In addition, for the pixels within the unvignetted field of view, the goal for the maximum FWHM resolution (0.0483cm^{-1}) has also been achieved within measurement uncertainty. As is the case for the resolution element, the FWHM resolution will have to be re-examined during the PFM4 test campaign when the FM SMEC is tested.

3.1.3 Minimum Resolution (IRD-SPEC-R03)

The 4cm^{-1} requirement for the minimum resolution of the spectrometer was found not to be practical. Due to the inherent limits on the SLW and SSW bands, a minimum resolution of 2cm^{-1}, while achievable, would result in only 11 in-band points for the SLW array and 12 in-band points for the SSW array. This low number of data points may make it difficult to properly correct for instrumental effects within the band and will lead to difficulty in the interpretation of the measured spectra. As such, it is recommended that the requirement for the minimum resolution of the spectrometer be changed to 1cm^{-1} (see ref. 4).

3.1.4 Vignetting (IRD-SPEC-R11)

Vignetting, the loss of power for off-axis pixels at high optical path differences, was observed in both the PFM1 and PFM3 spectrometer tests. At the required resolution of 0.4cm^{-1}, the baseline of the measured interferograms was found to be uniform to within 2%, meeting the requirement of 10% uniformity. At the maximum spectral resolution for the SPIRE spectrometer, uniformity to within 10% was measured on all of the pixels that lie within the unvignetted field of view as well as on most of the pixels that lie outside this field of view (see refs. 1, 4).

3.1.5 Fringe Contrast (IRD-SPEC-R14)

During the PFM1 test campaign, observations with the laboratory far-infrared laser as the primary source were used to evaluate the fringe contrast requirement. For the reasons mentioned in §3.1.2, the infrared laser was only shone on a subset of the pixels in the SLW and SSW detector arrays. As such, the fringe contrast was measured for those selected pixels only. The selected pixels were the central pixels for each array (C3 for SLW, D4 for SSW) and a set of off-axis pixels (B2 and C2 for SLW, F3 for SSW). A fringe contrast in excess of 90% for the maximum resolution was observed when the SMEC was at its position of maximum travel (see §7.2).

During the PFM3 test campaign, the laboratory photomixer was used to study fringe contrast. As was the case for the infrared laser during PFM1, only a subset of the pixels was directly illuminated with the photomixer. For the PFM3 test campaign, only the central and one outer pixel of the SLW array (SLWC3 and SLWE2, respectively) were targeted by the laboratory photomixer. An average fringe contrast greater than 90% was observed at the maximum spectral resolution on pixel SLWC3. For the outer pixel, SLWE2, which lies outside the unvignetted field of view, the average fringe contrast was observed to be 80% at the maximum resolution.

These results, given in detail in the table in §7.2, show that, for pixels within the unvignetted field of view, the measured fringe contrast derived from both the PFM1 and PFM3 test campaigns exceeds the predicted value of 87% given in ref. 8.

3.1.6 Balancing of Ports (IRD-OPTS-R07)

The PFM tests have shown that while the SCAL sub-system is capable of nulling the emission from the laboratory cold black body (CBB) source, the nulling occurs at different temperatures for pixels in the same detector array (see ref. 7). In addition, the range of temperatures over which spectral nulling was achieved was different for the two detector arrays. As a result, it may be necessary to choose a temperature that, while not optimal for any given pixel, is optimal for one detector array as a whole.

The nulling studies to date have by necessity involved the CBB and not the actual telescope. As such, the final SCAL settings for the optimal spectral nulling will only be found in flight when the Herschel telescope, the temperature and emissivity of which are still unknown, is the other source of emission.

3.1.7 In-band Straylight (IRD-OPTS-R09)

In-band spectral contamination due to straylight has been observed in each test campaign. This straylight has manifested itself as channel fringes. It has been shown that the replacement of the field lenses prior to the PFM3 test campaign led to a reduction in the intensity of the channel fringes, in particular for off-axis pixels (see ref. 9). For the central pixels of each array, the ratio of in-band spectral power from the channel fringes to that from the source was measured to be 3% for SLWC3 and 2% for SSWD4. For the off-axis pixels, the ratio was <2% and <1% for the for SLW and SSW arrays, respectively. In all cases, the in-band spectral power from the straylight is <5% of the source power, meeting the straylight requirement.

3.1.8 Linear Travel (IRD-SMEC-R01)

The range of motion for the SMEC as measured from the PFM1 test campaign was 39.8mm (see ref. 5). Taking into account the factor of four conversion from mechanical to optical path travel due to the Mach-Zehnder design of the SPIRE FTS give a total optical path difference of 15.91cm, exceeding the requirement of 14cm OPD. The position of zero path difference was measured during the PFM1 test campaign to be 8.21mm MPD (3.28cm OPD), leading to a maximum optical path difference of 12.62cm.

3.1.9 Minimum movement sampling interval (IRD-SMEC-R02)

The servo system of the spectrometer mechanism is designed to provide any sampling interval requested. The sampling interval results from a combination of the spectrometer mechanism speed and of the sampling rate of the detectors. The current design is for a detector sampling rate of ~80Hz, for a speed of 0.1cm/s the sampling interval is 12.5µm or 1.25µm for a speed of 0.01cm/s, which meets the requirement for both detector bands.

3.1.10 Sampling step control (IRD-SMEC-R03)

In the nominal continuous scan operating mode of the spectrometer there is no control on the sampling step but only on the speed of the spectrometer mechanism. For the step-and-integrate mode the servo system is able to provide any step value that is an integer number of 1µm. The step-and-integrate mode has not been tested to date, however, so it will be necessary to verify this functionality during the PFM4 test campaign (see ref. 6).

3.1.11 Scan length (IRD-SMEC-R04)

While this functionality has not been specifically tested in any of the PFM test campaigns, there were PFM1 test observations wherein the mechanism began the scan from the position of maximum optical path difference. This therefore demonstrates the ability to start a scan on either side of zero path difference. It may, however, be prudent to specifically test this functionality during the PFM4 test campaign.

3.1.12 Dead-time (IRD-SMEC-R05)

During the PFM1 test campaign, the SMEC was operated with three different PID settings (see ref. 5). For each setting, the dead-time, defined as the time during which the SMEC is accelerating/decelerating at the start and end of each scan was measured.

As to the proportion of the total scan time that is consumed by the dead-time, it is first necessary to compute the total scan time for a given resolution. The *total* scan length required, L, is inversely proportional to the resolution. For the required resolution of 0.4cm^{-1}, an overall scan length of 7.56mm is required. The overall scan time at the nominal scan speed of 0.5mm/s is therefore equal to 15s.

The results presented in the table below confirm that for each of the control settings tested, the performance of the spectrometer mechanism satisfied the requirement of the dead-time being <10% of the total scan time.

PID Settings	Dead-Time [s]	Dead-time [% of scan time for R=0.4cm^{-1}]
Kp=1000, Kd=350, Ki=0	0.41	2.6
Kp=2000, Kd=350, Ki=1000	0.40	2.7
Kp=2000, Kd=700, Ki=1000	0.42	2.7

Table 3: SPIRE Spectrometer dead time for various PID settings

3.1.13 Spectrometer mirror velocity control and stability

This section covers four related requirements:

- Mirror Velocity (IRD-SMEC-R06),
- Velocity control (IRD-SMEC-R07),
- Velocity stability (IRD-SMEC-R08), and
- Position measurement (IRD-SMEC-R09)

During the PFM1 test campaign, the spectrometer mechanism was operated at various speeds in the range from 0.01cm/s to 0.10cm/s (see ref. 5). For each test, both the speed error and position error were determined with the results shown in the table below.

Speed, Mechanical Path Difference [cm/s]	Speed Jitter, RMS [μm/s]	Position Jitter, RMS [nm]
0.01	5.4	63
0.03	5.8	71
0.05	5.5	59
0.07	4.4	37
0.10	5.6	59

Table 4: SPIRE Spectrometer velocity and position stability for various scan speeds

These measurements show that the spectrometer satisfied the mirror velocity and velocity control requirements (IRD-SMEC-R06 and IRD-SMEC-R07, respectively). Moreover, analysis of the spectrometer data for the variable speed observations (see table above) shows that the spectrometer met the velocity stability and position measurement requirements (IRD-SMEC-R08 and IRD-SMEC-R09, respectively).

3.2 List of tests carried out and tests still to be done

The following is a brief summary of the spectrometer related tests that were done during the PFM1 and PFM3 test campaigns:

- High resolution scans with various CBB and SCAL settings as well as with the room/laser/photomixer as the primary source.
- Medium resolution scans with SCAL as the primary source.
- Medium resolution nulling tests were been performed whereby for a given SCAL setting, the CBB temperature was varied so as to try to minimize the interferogram signal.

An issue that arose in both the PFM1 and PFM3 test campaigns was that the detectors quickly began to saturate as the CBB temperature was increased. This saturation limited the amount of information that could be derived from the test results.

Please refer to §5 and to ref. 6 for a list of tests for a list of spectrometer-related tests that are recommended for the upcoming PFM4 test campaign.

4. Open issues and anomalies

Maximum Resolution: The maximum resolution that can be achieved by the spectrometer will be adversely affected by the presence of channel fringes. While a marginal reduction in the amplitude of the channel fringes was observed in PFM3 test campaign data, a detailed data processing algorithm will need to be developed to minimize their impact.

5. Recommendations for further data analysis and tests

The groups at LAM and the Lethbridge have been in consultation and have derived a list of tests for the upcoming PFM4 test campaign, the goals of which is to provide the calibration information for the flight spectrometer and to cover any outstanding spectrometer-related tests. The following is a brief description of the proposed tests (see ref. 6 for a more detailed description of these tests):

- High and medium resolution spectrometer scans with various CBB and SCAL settings.
- High resolution spectrometer scans with the photomixer as the primary source.
- Scans that will test the high, medium, and low resolution spectrometer AOTs.

- Tests that use both the SMEC and the external TFTS to provide external calibration of both the Heidenhain encoder and the LVDT for the SMEC as well as calibration of the obliquity factor (off-axis OPD scale factor) for spectrometer (ref. 10).

6. References

1. "*Vignetting in PFM1 High Resolution Interferograms*", Naylor, D. A., et. al., SPIRE-UOL-REP-002410, 29 April 2005
2. "*Channel fringes in PFM1 High Resolution Interferograms*", Naylor, D. A., et. al., SPIRE-UOL-REP-002418, 2 May 2005
3. "*Phase Study of SPIRE PFM1 Spectrometer Data*", Naylor, D. A., et. al., SPIRE-UOL-REP-002421, 25 May 2005
4. "*Spectrometer Performance Review*", Naylor, D. A., et. al., Presentation for the SPIRE Consortium Meeting, Caltech, 19-21 July 2005
5. "*PFM1 Cold Tests Results*", Baluteau, Jean-Paul, et. al., 3 August 2005
6. "*Calibration Requirements for the SPIRE Spectrometer*", version 2.0, Fulton, Trevor, et. al., 8 September 2006
7. "*PFM1/PFM3 Transmission Analysis*", Fulton, Trevor, 10 August 2006
8. "*SPIRE Design Description*", Griffin, Matt, et. al., SPIRE-RAL-PRJ-000620, 15 May 2003, p. 53
9. "*PFM3 Test Results*", Fulton, Trevor, Presentation to SPIRE SDAG, 10 July 2006
10. "*Dual FTS Proposal*", Spencer, Locke, et. al. 9 September 2006

7.Appendix

7.1 Maximum Resolution (IRD-SPEC-R02)

The results presented in the following table are the measured FWHM resolutions for all of the spectrometer detector pixels tested during the PFM1 and PFM3 test campaigns.

Test Campaign	Pixel	Line Centre (μm)	Line Centre (cm^{-1})	Measured Resolution FWHM (cm^{-1})	R (=λ/Δλ)
PFM1	SSWD4	232.1	42.90	0.0500 ± 0.0020	858
PFM1	SLWC3	433.0	23.10	0.0484 ± 0.0010	478
PFM1	SSWF3	302.5	33.04	0.0489 ± 0.0010	675
PFM1	SSWD4	302.5	33.06	0.0496 ± 0.0010	666
PFM1	SLWC2	302.5	33.06	0.0488 ± 0.0010	677
PFM1	SLWC3	302.5	33.06	0.0494 ± 0.0010	669
PFM1	SLWB2	433.2	23.08	0.0487 ± 0.0010	474
PFM1	SLWC3	433.0	23.10	0.0483 ± 0.0010	478
PFM1	SLWC3	513.4	19.48	0.0480 ± 0.0010	406
PFM3	SLWA1	377.8	26.47	0.0500 ± 0.0010	541
PFM3	SLWB1	377.6	26.48	0.0486 ± 0.0010	545
PFM3	SLWB2	377.5	26.51	0.0484 ± 0.0010	548
PFM3	SLWB4	377.5	26.49	0.0484 ± 0.0010	547
PFM3	SLWC1	377.7	26.47	0.0490 ± 0.0010	540
PFM3	SLWC3	377.0	26.53	0.0484 ± 0.0010	548
PFM3	SLWC4	377.1	26.52	0.0489 ± 0.0010	542
PFM3	SLWD2	377.2	26.51	0.0487 ± 0.0010	544
PFM3	SLWB2	345.6	28.94	0.0486 ± 0.0010	596
PFM3	SLWC4	345.5	28.95	0.0484 ± 0.0010	598
PFM3	SLWE2	311.7	32.08	0.0501 ± 0.0010	640
PFM3	SSWD2	311.5	32.10	0.0484 ± 0.0010	663
PFM3	SSWC3	301.6	33.16	0.0484 ± 0.0010	685
PFM3	SLWC4	301.6	33.16	0.0484 ± 0.0010	685
PFM3	SSWD3	301.6	33.16	0.0484 ± 0.0010	685

Table 5: Measured FWHM resolution for the SPIRE Spectrometer pixels tested during the PFM1 and PFM3 test campaigns

7.2 Fringe Contrast (IRD-SPEC-R14)

The following table presents the measured fringe contrast for the spectrometer detector pixels tested during the PFM1 and PFM3 test campaigns.

Test Campaign	Target Pixel	Line Centre (μm)	Line Centre (cm^{-1})	Fringe Contrast (%) at maximum OPD
PFM1	SSWD4	232.1	42.90	92
PFM1	SLWB2	302.6	33.05	99
PFM1	SLWC3	302.5	33.06	97
PFM1	SSWD4	302.5	33.06	97
PFM1	SSWF3	302.7	33.04	97
PFM1	SLWC3	433.0	23.10	99
PFM1	SLWB2	433.2	23.08	99
PFM1	SLWC2	513.4	19.48	90
PFM1	SLWC3	513.4	19.48	99
PFM3	SLWC3	640.0	15.63	99
PFM3	SLWC3	640.0	15.63	99
PFM3	SLWC3	377.1	26.52	99
PFM3	SLWC3	377.1	26.52	96
PFM3	SLWC3	301.6	33.16	94
PFM3	SLWC3	345.4	28.95	88
PFM3	SLWC3	345.4	28.95	93
PFM3	SLWC3	345.4	28.95	98
PFM3	SLWC3	345.4	28.95	91
PFM3	SLWE2	311.7	32.08	72
PFM3	SLWE2	346.0	28.90	87

Table 6: Measured Fringe Contrast for the SPIRE Spectrometer pixels tested during the PFM1 and PFM3 test campaigns