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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 PFM4 and PFM5 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 PFM4 and PFM5 test campaigns are given in the table below. Also indicated in the table is whether the information regarding the requirement has been updated since SVR2.

Requirement Number	Description	Requirement	Update since SVR-2
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	No
IRD-OPTS-R08	Out-of-band radiation	10^{-3} for 40 cm^{-1} to 200 cm^{-1}	No
IRD-OPTS-R09	In-band straylight	<5% for each band	Yes
IRD-OPTS-R10	Off-axis resolution	FWHM < 110% of nominal resolution	Yes
IRD-SMEC-R01	Linear Travel	Req: 14cm total OPD	Yes
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	Yes
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 single-mode 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, and 10). 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})
Test Campaign	14.64-15.02	33.00-33.67	30.40-31.15	52.08-53.19
PFM3	14.899 ± 0.091	33.525 ± 0.096	31.37 ± 0.17	51.98 ± 0.20
PFM4	14.91 ± 0.10	33.535 ± 0.084	31.30 ± 0.35	52.12 ± 0.37
PFM5	14.98 ± 0.13	33.57 ± 0.11	31.32 ± 0.28	52.24 ± 0.31

Table 2: SPIRE Spectrometer Band Edges

As can be seen from the results presented in the above table, the band edges as measured from PFM4 and PFM5 data showed no significant difference from the band edges defined by the PFM3 data. As such, the conclusions with respect to the band edges are the same as those that followed the PFM3 test campaign. That is, the 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), Off-Axis Resolution (IRD-OPTS-R10)

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 resolution of the SPIRE spectrometer was determined by way of observations of unresolved line sources. The line source used in the PFM4 tests of the FM SMEC was an infrared laser. 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 PFM4 test results, presented in detail in §7.1, show that the FM 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 that the measured resolution not exceed 110% of the maximum FWHM resolution ($0.0531cm^{-1}$) has also been achieved within measurement uncertainty.

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 data from each of the PFM test campaigns. 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 PFM4 test campaign, the laboratory infrared laser was used to study fringe contrast. As was the case for the infrared laser during the PFM1 and PFM3 test campaigns, only a subset of the pixels in each spectrometer detector array was directly illuminated with the laser. The results of these tests, given in detail in the table in §7.2, show that, for pixels within the unvignetted field of view, the measured fringe contrast 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 compensating for the emission from the laboratory cold black body (CBB) source, the compensation occurs at different temperatures for pixels in the same detector array (see ref. 7). In addition, the range of temperatures over which spectral compensation 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 two detector arrays as a whole.

The compensation studies to date have by necessity involved the CBB and not the actual telescope. As such, the final SCAL settings for the optimal spectral compensation 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 during each PFM 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 §7.3). Further study of the PFM4 data has shown that for all active pixels with the exception of SLWC3, the ratio of the in-band channel fringe spectral power to that of the source is less than 4%, meeting the <5% requirement. In the case of pixel SLWC3, the central pixel of the SLW array, the ratio was found to be 6%, slightly exceeding the <5% 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 SMEC servo system is designed to provide any step value that is an integer number of 1µm. The step-and-integrate mode was tested during the PFM4 and PFM5 test campaigns and the 1-σ position errors were found to be 0.533µm for each step. While this value exceeds the specification, it was found that this position error did not have a negative impact on the detector noise.

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.

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

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

- Low, Medium, and High resolution scans with various CBB and SCAL settings as well as with the room/laser/photomixer as the primary source.
- Medium resolution compensation tests were been performed whereby for a given CBB setting, the temperatures of SCAL2 and SCAL4 were varied in turn so as to determine the settings that result maximum compensation of the interferogram signal in the ZPD region.
- Tests of the SOF1 and SOF2 AOTs.
- Tests of the Step-and-integrate mode of the SMEC.

Please refer to §5 for a list of tests for a list of spectrometer-related tests that are recommended for the PV phase.

4. Open issues and anomalies

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 PV phase, the goals of which is to provide the calibration information for the SPIRE spectrometer as it will be operated in flight. The following is a brief description of the proposed tests:

Several times during telescope cool-down, at intervals of 10K of the average telescope temperature or perhaps once per week and while the telescope points in a stable manner to a dark region in the sky, the following test should be performed:

- Set SCal temperatures to avoid clipping the interferograms. The exact temperature settings per telescope temperature will be provided based on models/prior experience.
- Let SCal settle while taking medium-resolution scans.
- A set of full resolution scans. This should be a scan across the full length of the mirror stage, i.e. stretching out farther into the short double-sided wing than the currently defined high-resolution scan.
- A series of medium resolution scans while at a set telescope temperature while SCal is cooling.

6. References

1. "*Vignetting in PFM1 High Resolution Interferograms*", Naylor, D. A., et. al., SPIRE-UOL-REP-002410, 29 April 2005
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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. "*PFM4 Test Results*", Fulton, Trevor, Presentation to SPIRE SDAG, 30 November 2006
11. "*Dual FTS Proposal*", Spencer, Locke, et. al. 9 September 2006

7.Appendix

7.1 Maximum Resolution (IRD-SPEC-R02), Off-Axis Resolution (IRD-OPTS-R10)

The results presented in the following tables are the measured FWHM resolutions for the spectrometer detector pixels in the SLW and SSW arrays that were examined during the PFM4 test campaign. The central pixels of each array, where the maximum resolution was achieved, are shown in blue.

Test Campaign	Pixel	Line Centre [μm]	Line Centre (cm^{-1})	Measured Resolution FWHM [cm^{-1}]	R (=λ/Δλ)
PFM4	SLWC3	393.7	25.399	0.0492 ± 0.0094	516
PFM4	SLWC3	393.7	25.398	0.0483 ± 0.0035	526
PFM4	SLWC3	393.7	25.397	0.0484 ± 0.0020	524
PFM4	SLWC5	394.4	25.357	0.049 ± 0.012	520
PFM4	SLWD2	394.0	25.379	0.0491 ± 0.0053	516
PFM4	SLWE2	394.5	25.350	0.0503 ± 0.0019	504
PFM4	SLWE2	394.5	25.349	0.0529 ± 0.0033	479

Test Campaign	Pixel	Line Centre [μm]	Line Centre (cm^{-1})	Measured Resolution FWHM [cm^{-1}]	R (=λ/Δλ)
PFM4	SSWA2	202.6	49.347	0.05500 ± 0.00053	897
PFM4	SSWA2	202.6	49.352	0.0482 ± 0.0014	1024
PFM4	SSWB3	202.5	49.380	0.05094 ± 0.00036	969
PFM4	SSWB3	202.5	49.380	0.04916 ± 0.00015	1004
PFM4	SSWB4	202.6	49.360	0.04905 ± 0.00049	1006
PFM4	SSWC3	202.4	49.416	0.04695 ± 0.00005	1052
PFM4	SSWC3	202.4	49.416	0.05042 ± 0.00078	980
PFM4	SSWC4	202.4	49.404	0.04751 ± 0.00092	1040
PFM4	SSWD3	202.4	49.398	0.04883 ± 0.00051	1012
PFM4	SSWD3	202.4	49.398	0.04680 ± 0.00007	1056
PFM4	SSWD4	202.4	49.412	0.0483 ± 0.0012	1024
PFM4	SSWD4	202.4	49.412	0.0484 ± 0.0012	1016
PFM4	SSWE3	202.4	49.403	0.04877 ± 0.00012	1013
PFM4	SSWE3	202.4	49.404	0.04933 ± 0.00077	1002
PFM4	SSWE6	202.8	49.310	0.0471 ± 0.0052	1048
PFM4	SSWE6	202.8	49.310	0.04962 ± 0.00070	894
PFM4	SSWF3	202.5	49.381	0.04788 ± 0.00027	1031

Table 5: Measured FWHM resolution for the SPIRE Spectrometer pixels tested during the PFM4 test campaign.

7.2 Fringe Contrast (IRD-SPEC-R14)

The following tables presents the measured fringe contrast for the SLW and SSW spectrometer detector pixels tested during the PFM4 test campaign.

Test Campaign	Target Pixel	Line Centre [μm]	Line Centre [cm^{-1}]	Fringe Contrast (%) at maximum OPD
PFM4	SLWC3	393.7	25.399	95
PFM4	SLWC3	393.7	25.398	98
PFM4	SLWC3	393.7	25.397	95
PFM4	SLWC5	394.4	25.357	84
PFM4	SLWD2	394.0	25.379	96
PFM4	SLWE2	394.5	25.350	83
PFM4	SLWE2	394.5	25.349	82

Test Campaign	Target Pixel	Line Centre [μm]	Line Centre [cm^{-1}]	Fringe Contrast (%) at maximum OPD
PFM4	SSWA2	202.6	49.347	97
PFM4	SSWA2	202.6	49.352	98
PFM4	SSWB3	202.5	49.380	97
PFM4	SSWB3	202.5	49.380	96
PFM4	SSWB4	202.6	49.360	99
PFM4	SSWD3	202.4	49.398	95
PFM4	SSWD4	202.4	49.412	97
PFM4	SSWD4	202.4	49.412	90
PFM4	SSWE3	202.4	49.403	99
PFM4	SSWE3	202.4	49.404	88
PFM4	SSWF3	202.5	49.381	85

Table 6: Measured Fringe Contrast for the SPIRE Spectrometer pixels tested during the PFM4 test campaign

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

In-band straylight for the SPIRE spectrometer was defined as those contributions to the measured spectrum that were due to the channel fringes. ound to be 6%, slightly exceeding the <5% straylight requirement. detector pixels tested during the PFM4 test campaign.

Pixel	SQRT(Fringe Power / Source Power) [%]	Pixel	SQRT(Fringe Power / Source Power) [%]
SLWA1	3.10	SSWA1	2.05
SLWA2	1.82	SSWA2	2.08
SLWA3	3.67	SSWA3	2.29
SLWB1	1.55	SSWA4	1.90
SLWB2	2.65	SSWB1	1.51
SLWB4	2.95	SSWB2	1.86
SLWC1	3.78	SSWB3	2.26
SLWC3	6.05	SSWB4	1.85
SLWC4	4.11	SSWB5	2.47
SLWC5	4.91	SSWC1	1.22
SLWD1	1.55	SSWC2	1.67
SLWD2	2.81	SSWC3	1.98
SLWD3	2.82	SSWC4	2.11
SLWD4	2.36	SSWC5	3.39
SLWE1	3.56	SSWC6	2.61
SLWE2	1.73	SSWD1	1.48
SLWE3	3.69	SSWD2	1.51
		SSWD3	1.65
		SSWD4	2.65
		SSWD6	2.20
		SSWE1	1.42
		SSWE2	1.81
		SSWE3	2.15
		SSWE4	2.72
		SSWE5	2.46
		SSWE6	1.98
		SSWF1	1.28
		SSWF2	1.59
		SSWF3	1.95
		SSWF4	2.50
		SSWF5	1.48
		SSWG1	2.16
		SSWG2	1.85
		SSWG3	2.16
		SSWG4	2.66

Table 7: Measured straylight in-band power as a percentage of in-band source power from the PFM4 test campaign