SPIRE Science Verification Review

RAL

January 26, 27 2006

SMEC and Spectrometer Performance

Document Number: SPIRE-RAL-REP-002566

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Date: 16 January 2006

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1. Introduction and scope

This document describes the spectrometer as a system, with special emphasis on the mechanism.

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

The spectrometer requirements that were evaluated during the two PFM test campaigns are given in the table below:

Requirement Number	Description	Requirement
IRD-SPEC-R01	Wavelength Range [um]	SSW: 200-300 SLW: 300-670
IRD-SPEC-R02	Maximum Resolution [cm^{-1}]	Req: 0.4 Goal: 0.04
IRD-SPEC-R03	Minimum Resolution [cm^{-1}]	Req: 2 Goal: 4
IRD-SPEC-R11	Vignetting	<10% uniformity at a resolution of 0.4cm^{-1}
IRD-SPEC-R14	Fringe Contrast	>80% at a resolution 0.4cm^{-1}
IRD-OPTS-R07	Balancing of ports	Beamsplitters shall have $2RT=R^2+T^2$ to within 90% over the band
IRD-OPTS-R09	In-band straylight	<5% for each band
IRD-SMEC-R01	Linear Travel	Req: 14cm total OPD
IRD-SMEC-R02	Minimum movement sampling interval	5um SSW 7.5um SLW
IRD-SMEC-R03	Sampling step control	Interval variable between 5 and 25 um
IRD-SMEC-R04	Scan length	Able to start a scan from either side of ZPD
IRD-SMEC-R05	Dead-time	<10% at resolution of 0.4cm^{-1}
IRD-SMEC-R06	Mirror velocity	Req: 0.1 cm/s MPD Goal: 0.2 cm/s MPD
IRD-SMEC-R07	Velocity control	Selectable from 0 to 0.1cm/s
IRD-SMEC-R08	Velocity stability	<10um/s RMS over the full range of movement
IRD-SMEC-R09	Position measurement	0.1um within +/- 0.32cm of ZPD, 0.3um elsewhere

3. Test results and conclusions

3.1.1 Wavelength Range (IRD-SPEC-R01)

For the spectrometer bands (SLW and SSW), the band edges were defined as the point where the spectral intensity was half of its average in-band value. In order to focus on the response of the detectors themselves, the measured spectra were first corrected for the input sources (i.e. the spectra of the CBB and of SCAL).

The test measurements used for the determination of the wavelength ranges were as follows:

- PFM1: CBB = 9.5K, SCAL off (4.9K) for SLW band, CBB = 13K, SCAL off (4.9K) for SSW band.
- PFM2: CBB = 14.02K, SCAL off (6.1K) for SLW band, CBB = 14.02K, SCAL off (6.1K) for SSW band.

The edges of the spectrometer wavebands shown in the table below are the average (± average deviation) 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})
Specs	14.64-15.02	33.00-33.67	30.40-31.15	52.08-53.19
PFM1	14.97 ± 0.22	33.07 ± 0.24	31.34 ± 0.44	52.34 ± 0.24
PFM2	14.95 ± 0.16	33.03 ± 0.24	31.29 ± 0.64	52.02 ± 0.46

NB: Some further analysis is TBD in order to reduce the uncertainties associated with the wavebands shown in the table above.

3.1.2 Maximum Resolution (IRD-SPEC-R02)

The maximum resolution was derived from PFM1 measurements where the laboratory laser was the primary source. A cardinal sine (sinc) function was fit to the spectrum of the measured laser line and the resolution was determined by the full width at half maximum of the fitted sinc function. The measured resolution for the four PFM1 test measurements is given in the table below.

Line Centre (μm)	Line Centre (cm^{-1})	Measured Resolution (cm^{-1})	R (=?/? ?)
513.080	19.490	0.048 ± 0.003	405
432.631	23.114	0.048 ± 0.001	478
302.278	33.082	0.049 ± 0.002	681
232.939	42.892	0.049 ± 0.001	881

The results presented in the table above show that while the maximum resolution requirement of 0.4cm^{-1} has been met, the goal of 0.04cm^{-1} is nearly met. It is worth noting however, that the measured spectral resolutions given in the table above agree with what is expected for the mechanical travel that was available during the PFM1 and PFM2 test campaigns. Please see §3.1.8 and §4 for a further discussion on the linear travel of the spectrometer mechanism and its impact on the maximum resolution.

3.1.3 Minimum Resolution (IRD-SPEC-R03)

For the minimum resolution of the spectrometer it was found that the requirement was not 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 points may make it difficult to properly correct for instrumental effects within the band and may lead to erroneous interpretation of the results. 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, or the loss of power for off-axis pixels at high optical path differences, was observed in both the PFM1 and PFM2 spectrometer tests. The requirement that there be a <10% uniformity in the magnitude of the baseline of interferogram for a resolution of 0.4cm^{-1} was met as a uniformity of <1% was achieved for this resolution (see refs. 1, 4). In addition, for the maximum resolution (0.04cm^{-1}), a uniformity < 10% was achieved on most pixels.

3.1.5 Fringe Contrast (IRD-SPEC-R14)

Fringe contrast was defined as the difference between the maximum and minimum signal of the phase-corrected interferogram relative to the difference in the region of the position of zero path difference. Tests where the laboratory laser was used as the primary source were used for the analysis with respect to this requirement. As such, fringe contrast measurements were made only for those pixels upon which the laser radiation was shone. These pixels were the central pixels for each array (C3 for SLW, D4 for SSW) and an off-axis pixel in each array (B2 for SLW, F3 for SSW). For these pixels, a fringe contrast >95% for the maximum resolution was observed (see ref. 4).

3.1.6 Balancing of Ports (IRD-OPTS-R07)

The PFM1 & PFM2 tests showed the SCAL sub-units behave normally and that the emitted radiation is as was expected from a blackbody at the measured SCAL temperature and for the expected emissivity. As for a derivation of optimal nulling, this will require a good knowledge of the actual temperature and emissivity of the Herschel telescope; information that is not presently available. The optimal nulling will be done in flight when this required information will be provided.

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

From the Instrument Requirements Document, this requirement is defined as "The background power falling on the detectors with the optical beam blocked shall be no more than 5% of the in-band background power from the telescope for each band (SLW, SSW)". As far as I am aware, no such measurement was during wither the PFM1 or PFM2 test campaigns. Therefore, the performance of the spectrometer with respect to this requirement is still TBD.

3.1.8 Linear Travel (IRD-SMEC-R01)

The range of motion for the SMEC as measured from the PFM1 test campaign was 39.778mm (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. In addition, the position of zero path difference was measured to be 8.21mm during the PFM1 test campaign. Thus, with respect to the position of zero path difference, the optical path difference for the spectrometer mechanism was measured to be 12.6cm. See §4 for a further discussion of the factors limiting the travel of the spectrometer mechanism for the PFM1 and PFM2 test campaigns and what is to be expected during the PFM3 test campaign.

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).

3.1.10 Sampling step control (IRD-SMEC-R03)

In the Scanning mode of operation (the nominal mode) 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 was not tested during PFM1 and PFM2 test campaigns, however, so it will be necessary to verify this functionality during the PFM3 test campaign (see ref. 6).

3.1.11 Scan length (IRD-SMEC-R04)

While this functionality was not specifically tested in either the PFM1 or PFM2 test campaigns, there were examples of 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, though it may be prudent to specifically test this functionality during the PFM3 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 for 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.

For a given resolution, R, the *total* scan length required, L, in units of mechanical path difference is given by:

$$L = \frac{1.21}{2R} \times \frac{2}{4}$$

where the factor of 4 in the denominator comes from the conversion from optical path difference to mechanical path difference and the factor of 2 in the numerator arises because the mirror must be scanned an equal path on either side of the position of zero path difference. For the required resolution of $0.4cm^{-1}$, this results in an overall scan length of 7.56mm. The overall scan time at the nominal scan speed of 0.5mm/s is therefore equal to 15s.

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

The results presented in the table above 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.

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 tested at a various speeds in the range from 0.01cm/s to 0.10 cm/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

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 PFM2 test campaigns:

- High resolution scans with various CBB and SCAL settings as well as with the room/laser as the primary source.
- Medium resolution scans with SCAL as the primary source.
- For the majority of the tests, the SMEC was driven at nominal speed (~450µm/s).
- 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 the PFM1 test campaign 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 PFM3 test campaign.

4. Open issues and anomalies

Linear Travel: The maximum linear travel of the spectrometer mechanism was measured to be 39.778mm for the PFM1 and PFM2 test campaigns due to the mechanical constraints of that version of the SMEC (see ref. 5). Consequently, the maximum spectral resolution that was achieved during the PFM1 and PFM2 test campaigns did not meet the resolution goal of $0.04cm^{-1}$ (see §3.1.2). The mechanical constraints from the PFM1 and PFM2 tests have been identified and will be corrected for the PFM3 test campaign version of the spectrometer mechanism in such a manner that the design goal of a $0.04cm^{-1}$ for the spectral resolution will be met.

Phase change from PFM1 to PFM2: A slowing of the detector response was observed in the results of the PFM2 observations. Further observations need to be made to determine if this change in behaviour was due to testing conditions particular to the PFM2 test campaign. Also, more work to be done on this issue to precisely determine by what amount the detector time constants changed and whether the first-order model used in the analysis should be replaced with a second-order model.

Channel fringes: Channel fringe features were observed in the interferograms from both the PFM1 and PFM2 test campaigns. The most likely source of these fringes is the field lenses in the BDAs. It is expected that the anti-reflection coating on the new field lenses will reduce the channel fringes.

5. Recommendations for further data analysis and tests

The groups at LAM and the University of Lethbridge have been in consultation and have derived a list of tests for the upcoming PFM3 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 document describing these tests is given by ref. 6.

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*", Fulton, Trevor, et. al., 10 January 2006