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BOL

FIRST Bolometer

Title: The FTS option for SPEC-BOL

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I) INTRODUCTION:

Fourier Transform Spectroscopy offers some notable advantages over what might be termed mono-chromating spectroscopy i.e. gratings or Fabry-Perots. The two most often quoted are the so called muliplex advantage - that is all of the spectrum is measured all of the time - and the throughput, or etendue, advantage - i.e. no slit is required. However, when comparisons with grating instruments are made, both these are generally based on instruments in which only one order from the grating is measured using a single detector and the optics are not diffraction limited. In real instruments multiple orders from the grating are measured using arrays of detectors and, in the far infrared (FIR) or sub-millimetre (SMM), the optical system, and therefore the system throughput, is almost always diffraction limited: in this case these advantages are not so readily apparent. In addition, in the situation where a warm telescope is employed, the instrument performance is limited by the background power from the telescope itself in the waveband of interest. A more detailed study using real instrument parameters is thus required to compare the sensitivity of the two types of instrument - this is the subject of section II of the current note.

If a Fourier transform spectrometer (FTS) can be shown to be competitive with an equivalent grating spectrometer, there are still some real practical advantages to using this type of instrument in the FIR and SMM wavebands over and above the "multiplex" and "throughput" advantages usually referred to; these are laid out in section III. There are also some system implications and practical difficulties with this type of instrument - most obviously the mirror drive mechanism. Some notes on this are given in section IV.

Finally the case for an FTS over a grating for the SPEC-BOL is summarised in section V and some open questions discussed.

II) MODEL FTS FOR SPEC-BOL

Figure 1 shows an outline design for an FTS instrument for SPEC BOL. At this stage it is only included to allow a straightforward interpretation of the various parameters that will be included in the performance model. Obviously a more detailed optical layout will be necessary in order to check out the space requirements.

II.i Assumptions for the comparison between the grating and FTS instruments.

The following three subsections give the assumptions that have been used to calculate the performance of the grating and FTS options for the SPEC-BOL. In addition it is assumed that the baseline arrangement will have four temperature stages: 15°K for the fore optics; 4°K for the main optics and the grating or FTS; 2°K for the refocussing optics and bandpass filters and <300°mK for the detectors.

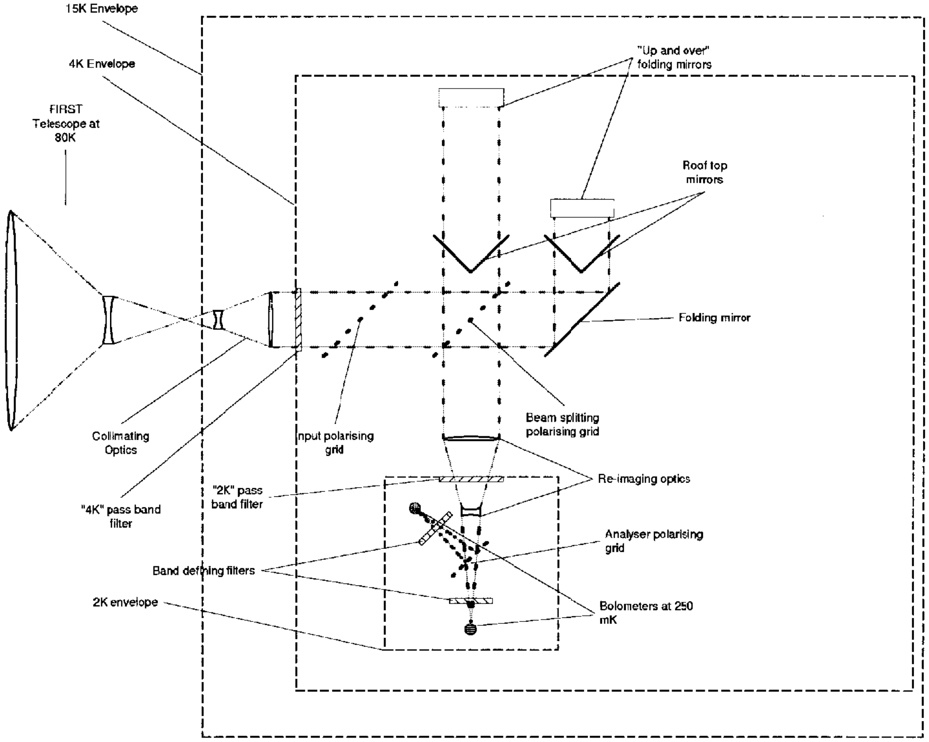

Figure 1: Outline layout for a Martin-Puplett polarising FTS for the FIRST-BOL instrument.

II.i.i General

Telescope	Diameter	3.5 m
	Temperature	80°K
	Emissivity	0.04
	Transmission	0.96
	Point source efficiency	0.7
Bolometers	Quantum efficiency	0.8
	Feed efficiency	1.0
All mirrors	Reflectivity	0.99
	Emissivity	0.01
Throughput	AΩ	λ^2

II.i.ii Grating Specific

Grating 1	Efficiency	0.6	
	Effective emissivity	0.4	
	Diffraction loss	0.2	
Grating 2 (cross dispersed only)	Efficiency	0.3	(Due to polarisation of beam from grating 1)
	Diffraction loss	0.2	
	Effective emissivity	0.4	

Filters:	15 K input filter	$t = 0.9$	
		$\varepsilon = 0.1$	in band
		$\varepsilon =$ TBD	out of band
	2 K blocker HP	$t = 0.9$	
		$\varepsilon = 0.1$	in band
		$\varepsilon =$ TBD	out of band
	2 K blocker LP	$t = 0.9$	
		$\varepsilon = 0.1$	in band
		$\varepsilon =$ TBD	out of band
	2 K bandpass	$t = 0.7$	
		$\varepsilon = 0.1$	in band
		$\varepsilon =$ TBD	out of band
		bandwidth=$\lambda/40$	

Spectral resolution $\lambda/\Delta\lambda = 400$ at 250 μm

Observing overhead	1.5 for single grating A bit less for cross dispersed
Chopping factor	0.45
Number of detectors	40 (two rows of 20) for single grating option TBD for cross-dispersed option

II.i.iii FTS specific

Polarisers:	Input	t = 0.5 (assume 2nd port not used for signals) ε = 0.04
	Beam divider	efficiency = 0.96 ε = 0.04
	Analyser	t = 0.5 (both ports used - one for each band) ε = 0.04
Filters:	15-K blocker	t = 0.9 (0 - 70 cm^{-1}) ε = 0.1
	4 K blocker	t = 0.9 ε = 0.1
	2 K blocker	t = 0.9 ε = 0.1
	2 K bandpass	t = 0.7 ε = 0.1 bandwidth 1 = 25-38 cm^{-1} bandwidth 2 = 38-50 cm^{-1}
Electrical filtering		efficiency = 0.8
<Cos^2> modulation		efficiency = 0.5
2nd input port:	Black body	T (adjustable) = 4°K nominal ε = 1

Other parameters will be as for grating except chopper not needed

II.ii Results of Mathcad calculations of the FTS sensitivity

Using the assumptions detailed above, a Mathcad calculation of the performance of an FTS has been run (see appendix A). To evaluate the sensitivity of the instrument to the raw detector NEPs, values of the NEP of 1,3 and 5x10^{-17} W Hz$^{-1/2}$ were used to calculate the limiting flux density and line strengths in each detector band. Also a sensitivity analysis was carried out into the affect of having only three temperature stages i.e. removing the "4°K" stage, and varying the temperature of the "non-2°K" portion of the instrument. This simulates the situation whereby the spacecraft is able to offer an optical bench at lower than 15°K. Three temperatures were tested: 10, 8 and 6°K.

The results are presented in tables 1 through 3. In the tables the temperature designated as "Nom." represents the nominal situation with a 15°K and a 4°K stage before the 2°K stage.

	Band 1 38-50 cm^{-1} (centre band ~225 μm)				Band 2 25-38 cm^{-1} (centre band ~320 μm)			
Temp ⇒ Detector NEP ⇓	Nom.	10	8	6	Nom.	10	8	6
1x10^{-17}	4.90	4.93	4.83	4.81	4.76	4.85	4.63	4.53
3x10^{-17}	5.66	5.68	5.60	5.58	5.54	5.61	5.42	5.34
5x10^{-17}	6.93	6.95	6.88	6.87	6.83	6.89	6.74	6.67

Table 1. Instrument NEPs in 10^{-17} W Hz$^{-1/2}$ as a function of detector NEP, optical bench temperature and waveband.

	Band 1 38-50 cm^{-1} (centre band ~225 μm)				Band 2 25-38 cm^{-1} (centre band ~320 μm)			
Temp ⇒ Detector NEP ⇓	Nom.	10	8	6	Nom.	10	8	6
1x10^{-17}	0.086	0.085	0.084	0.084	0.118	0.120	0.114	0.112
3x10^{-17}	0.099	0.098	0.097	0.097	0.137	0.139	0.134	0.132
5x10^{-17}	0.121	0.120	0.119	0.119	0.169	0.170	0.166	0.165

Table 2. Limiting flux densities in Jy quoted as 1-sigma in 1-hour as a function of detector NEP, optical bench temperature and waveband.

	Band 1 38-50 cm^{-1} (centre band ~225 μm)				Band 2 25-38 cm^{-1} (centre band ~320 μm)			
Temp ⇒ Detector NEP ⇓	Nom.	10	8	6	Nom.	10	8	6
1x10^{-17}	2.85	2.83	2.79	2.78	2.75	2.80	2.67	2.62

3×10^{-17}	3.29	3.27	3.23	3.23	3.20	3.24	3.13	3.09
5×10^{-17}	4.02	4.01	3.98	3.97	3.95	3.98	3.90	3.86

Table 3. Limiting line strengths in 10^{-18} W m^{-2} quoted as 1-sigma in 1-hour as a function of detector NEP, optical bench temperature and waveband.

The figures given here should be compared to the results of the single grating study (see Mathcad model from Matt) which gave a limiting flux of 0.085 Jy and a limiting line strength of 2.1×10^{-18} W m^{-2} for a full spectral survey and 0.049 Jy and 1.2×10^{-18} W m^{-2} for detection of a line at known wavelength; all these figures are for a wavelength of 300 μm.

III) ADVANTAGES OF AN FTS FOR SPEC-BOL

III.i. Much easier detector NEP requirement.

As shown in section II, the broad instantaneous passband of the FTS compared with the grating instrument, means that the achievable sensitivity is much less dependent on the detector NEP. In fact an increase in detector NEP from 1×10^{-17} to as much as 5×10^{-17} W Hz$^{-1/2}$ only results in a 40% increase in the limiting flux. The basic NEP requirement is thus easier to meet and the instrument is intrinsically less susceptible to changes in the detector NEP caused by changes in operating conditions in orbit. A detector temperature of 300 mK can also now be contemplated, obviating the need for a dilution fridge.

III.ii. Adjustable spectral resolution

The spectral resolution of the FTS is easily adjusted by changing the scan range of the moving mirror. In the case of the BOL, it could be set at an value between ~10 and even up to ~1000, depending on the scientific application and the space and power constraints on the instrument design. This also has the advantage that the limiting detectable continuum flux decreases linearly with the resolving power employed. Thus the same instrument can be used to obtain narrow band photometry on faint objects (R~10 F_{LIM}~ 2-3 mJ) and medium resolution spectroscopy on brighter objects (R~400 F_{LIM} ~90-120 mJ). Note however that this does not affect the limiting detectable line strength.

III.iii. Imaging spectroscopy

For the modest resolution requirement of the BOL, the FTS is compatible with imaging spectroscopy using a compact array at the focal plane.

III.iv. Immunity to stray light and spectral purity

Only radiation that is modulated by the instrument is detected as truly part of the source spectrum. Thus any radiation, either in or out of band, not coming via the instrument but reaching the detector via an unauthorised route contributes to the detector NEP only and does not contaminate the source spectrum. Also any out of band leaks in any of the filtering will be encoded spectrally and not seen as in band spectral features - unlike the situation with the grating instrument.

The broad band nature of the instrument means that most - essentially **all** - of the background limited NEP is contributed by the primary telescope and other sources of straylight would have to be very large indeed to have a significant impact on the overall NEP (see section II table nnn). The instrument is therefore very much less sensitive to the straylight environment than the grating.

III.v. No chopper required

An FTS, operated in continuous scan mode, requires no chopping, giving an increase in observing efficiency and greater reliability.

III.vi. Simplified calibration

The second input port can have an accurately calibrated black body source in it, thus the source spectrum can be constantly referred to a relative calibration standard if required. This makes removal of detector or amplifier drifts very much easier to remove. Also the wavelength calibration is inherent in the measurement technique provided the Fourier transform is sampled correctly. Any phase errors, shifts etc. only affect the derived power at a particular wavelength.

III.vii. Well behaved instrument response function

Given that any phase errors etc. have been dealt with in the Fourier transform, the basic scanning function for an FTS is a SINC function. This has undesirable side lobes in its raw form - however, it can be adjusted by apodisation and has the important property that it has the same FWHM at all wavelengths. Although to first order this is also true for grating instruments within a single order, in practice multiple orders are used and the width also changes with diffraction angle causing small changes within a single order.

III.viii. Wavelength coverage.

The wavelength coverage of an FTS is, within a waveband that can be efficiently transmitted by the polarising grids, governed only by the final filters on the detectors. It is thus easy to extend the wavelength coverage to higher or lower wavelengths. In a grating spectrometer, once the design waveband has been fixed, the wavelength coverage can only be changed by the addition of extra detectors at fixed diffraction angles - this will always prove problematic.

III.ix. Limited variation in sensitivity with wavelength

For both the FTS and grating instruments there will be a variation in sensitivity as a function of wavelength caused by the use of bandpass filtering i.e. the filters will not be perfect top hats. In the case of the grating there is a second variation in sensitivity caused by the changes in efficiency for wavelengths not at the blaze wavelength - this could be as much as a factor of 2 between the blaze wavelength and the edge of the diffraction order. The bandpass filtering for the grating will also have to be much narrower than for the FTS and, therefore, the efficiency variations will have a higher frequency as a function of wavelength causing difficulties in "stitching" an end-to-end spectrum together.

IV OPERATING PARAMETERS AND SYSTEM REQUIREMENTS FOR THE FTS

IV.i Operating parameters

In this section the global operating parameters (scan range, wavelength coverage etc. etc.) are given for a model FTS for the SPEC-BOL. In section IV.ii the implications of these for the drive mechanism are discussed and in section IV.iii the implications of the operating parameters and the drive mechanism on the system requirements (mass, power etc.) are considered.

Wavelength coverage	$\lambda = 200 - 400\ \mu m$ or $25 - 50\ cm^{-1}$
Required resolution	$\lambda/\Delta\lambda = 400$ at $250\ \mu m$ $(40\ cm^{-1})$ $\Rightarrow \Delta\sigma = 0.1\ cm^{-1}$
Optical path difference	$\sigma = 1/(2L) \Rightarrow L = 5\ cm$ assume 6 cm for scan length to allow for measure of zero path difference
Linear travel	(6 cm)/8 = 7.5 mm - or about 1.5 for R = 1000. A factor 8 folding can be achieved with "up and over" folding flats.
Nyqvist sampling rate:	$\Delta x_{max} = 1/(2\sigma_{max})$ $\Rightarrow \Delta x_{max} = 1/(2 \times 38) = 0.013\ cm$ for band 2 $\Rightarrow \Delta x_{max} = 1/(2 \times 50) = 0.010\ cm$ for band 1
Over-sampling factor	3

	$\Rightarrow \Delta x = 43\ \mu m$ band 2 $\Rightarrow \Delta x = 33\ \mu m$ band 1
No. of samples per interferogram	$N_{samp} = (6\ cm)/(43\ \mu m) = 1395$ band 2 $N_{samp} = (6\ cm)/(33\ \mu m) = 1818$ band 1
Audio frequencies	$f = v_{opd}\sigma$ where v_{opd} is the rate of change of the optical path difference.
Max. allowed audio freq.	20 Hz (from assumed detector response) $\Rightarrow v_{opd} = 20/50 = 0.4\ cm\ s^{-1}$ $\Rightarrow v_{mirrors} = v_{opd}/8 = 0.05\ cm\ s^{-1}$
Audio freq. band	$25 - 38\ cm^{-1} \rightarrow 10 - 15$ Hz $38 - 50\ cm^{-1} \rightarrow 15 - 20$ Hz
Time per scan	$t_{scan} = (6\ cm)/(0.4\ cm\ s^{-1}) = 15\ s$
Sampling rate	(1395 samples)/(15 s) = 93 samples s^{-1} - band 2 (1818 samples)/(15 s) = 121 samples s^{-1} - band 1
Number of detectors	40 (two arrays of 20)
Position measurement:	Accuracy required = 1 μm Sampling required = same as detector in band 1
Internal read-out rate:	Band 2: 93 Hz x 20 dets = 1.86 kHz Band 1: 121 Hz x 20 dets = 2.42 kHz Position measurement = 0.12 kHz Total = 4.39 kHz

IV.ii Requirements for the drive mechanism

The major difficulty in implementing an FTS for the BOL will be in building a mechanism working at cryogenic temperatures that will move the mirrors back and forth whilst keeping them parallel with each other. One option would be to adapt the existing ISO grating drive motor to drive a pantagraph arrangement similar to used on SAFIRE. The angular movement required, if the beam on which the mirrors are mounted has a 10 cm half width, will be about ±2.9°. Inspection of the grating mechanism power requirements shows that about 2 mW is needed to drive to ±2.9° (CHECK THIS) with a more of less linear angle vs. power curve in between. The average power consumption over a movement cycle will therefore be 1 mW - an allowance should be made however for the fact that the FTS mirrors are likely to be heavier than the grating.

Another way of estimating the power required is the scale from an existing mechanism. The SAFIRE FTS has mirrors of mass 5 Kg, driven at a velocity 20.3 mm s^{-1} with a power consumption of 13W. If this is scaled to mirrors of total mass 0.8 Kg (10 cm diameter 2 cm thick) with a velocity of 0.5 mm s^{-1}: linearly with mass and by the square of the velocity - then the power consumption for BOL would be 1.25 mW. This is in the same range as for the grating mechanism. Allowing for unforeseen inefficiencies (bearings etc.) the power requirement can be set conservatively at 2 mW for the present purposes, but a more detailed study will be required for the IID input.

IV.iii System Requirements Compared with Grating Option

Mass	Same as grating or less
Volume	Same as grating or less
Thermal dissipation	Dissipation from the mechanism is likely to be higher - first-cut guess 2 mW at 4 K in operation - see above (cf. 0.6 mW for grating) .
Duty Cycle	Operation for 50% of BOL time (1/6 of mission time) Peak ≡ 2 mW (when averaged over 15-sec. interval) Average over mission = 2/6 mW Minimum = 0
Operating modes:	Continuous back and forth scanning Scan time = 15 sec max.; 2 sec. min (narrow band photometry) Pointing fixed for a given scan At least five scans per spatial point on the sky If fully sampled map needed, may need to do raster-(jiggle)-map as for photometer
Numbers of wires:	About same as for grating
Bit rate	4390 x 14 = 61 kbs - note less bits are assumed than required for grating owing to low dynamic range (2).
Telemetry rate:	The low dynamic range also offers scope a larger degree of data compression than in the case of the grating option. If it is assumed that a compression factor of 3 is easy

→ 20 kbs

V SUMMARY OF THE CASE FOR AN FTS AND OPEN QUESTIONS.

Performance models of both a single grating spectrometer and a Fourier transform spectrometer have been constructed using Mathcad. These show, given the same input assumptions, that the FTS will be as sensitive as the grating for full spectral surveys of point sources, but a factor of two less sensitive for detection of a line at known wavelength. It is then a matter of scientific judgement as to which of these modes will have the highest priority for FIRST.

Given that the FTS is competitive in terms of sensitivity, the practical advantages of an FTS over a grating have been outlined in section II above. The major advantage of the FTS is its insensitivity to both changes in the raw detector NEP and changes in the level of straylight. For the grating however, the straylight level would have to be below a few tens of femtowatts - an unprecedented level in sub-millimetre instrumentation - and any change in the detector performance feeds linearly into the achievable sensitivity.

Some practical difficulties and open questions remain to be solved for the FTS:

- Mechanism design and power dissipation - is 2 mW achievable? If so does it meet the system thermal design requirements? How reliable will it be?
- Measurement of the mirror position - are LVDTs sufficient? If not is it feasible to think of system based on a solid-state laser for position measurement?
- How big a field can we accommodate with good fringe contrast?
- What is the optimum scan rate? Is there scope for using signal freq. < 10 Hz?
- Can bolometers with an operating frequency of 20 Hz and NEP of <5x10^{-17} W Hz$^{-1/2}$ be made to work at 300 mK?
- What wavelength range and resolution should we aim for?