FTS-2: A Submillimetre Astronomical Imaging Fourier Transform Spectrometer

D. A. Naylor and B. G. Gom
Department of Physics, University of Lethbridge, 4401 University Dr., Lethbridge T1K 3M4, Canada
naylor@uleth.ca

Abstract: We present the design of FTS-2, a dual-port imaging Fourier transform spectrometer for use with SCUBA-2 at the James Clerk Maxwell Telescope. The challenging mechanical and optical constraints imposed by the telescope interfaces are discussed.

OCIS codes: (300.6190) Spectrometers; (300.6300) Spectroscopy, Fourier transforms

1. Introduction

SCUBA-2, a new large format submillimeter camera, is currently under development for use at the JCMT [1]. SCUBA-2 features two dc-coupled, monolithic TES filled arrays operating at 450 and 850 µm with a total of ~10,000 bolometers, unlike previous detectors which have used much smaller arrays of discrete bolometers. With its larger format and increased sensitivity, SCUBA-2 promises a factor of 1000 increase in mapping speed compared to its predecessor. Two ancillary instruments, a polarimeter and imaging spectrometer, are also being developed to further extend the capabilities of SCUBA-2. A Fourier Transform Spectrometer (FTS) was selected as the optimal intermediate resolution spectrometer for SCUBA-2. The instrument, named FTS-2, will be primarily a galactic spectrometer (e.g. spectral index mapping of molecular clouds), but will also provide useful information on bright nearby galaxies and planetary atmospheres. FTS-2 thus fills a niche between the dual band SCUBA-2 continuum images and the higher spectral resolution, but smaller images produced by the JCMT heterodyne facility instrument HARP-B.

Since the layout of the JCMT - SCUBA-2 feed optics was well advanced prior to the decision to include a spectrometer, the mechanical, optical, and software design of FTS-2 was significantly more challenging. Previous papers have discussed the conceptual design [2] and observing modes [3] of FTS-2. In this paper we review the current optical design of the instrument as the project enters the CDR phase.

2. Design constraints

Since the JCMT optical and structural framework designs were fixed before the FTS-2 project began, the FTS-2 optical and mechanical designs are highly interdependent and tightly constrained. FTS-2 intercepts the SCUBA-2 optical beam near an intermediate image surface directly outside the telescope elevation bearing opening (see Fig. 1a). However, as an ancillary instrument, FTS-2 must not interfere with the SCUBA-2 beam when the FTS is not in use. Within the interferometer, there are additional design constraints that the beams at the rooftop mirrors must be collimated, there must be pupils located at the rooftop mirrors (at the ZPD location) for symmetry, and the beam waist near the beamsplitters must be minimized in order to reduce the beamsplitter diameters. Design goals for the spectrometer included placing both input ports on the sky, placing both output ports on adjacent detector subarrays, maximizing the useable field of view, and providing variable spectral resolution from 0.1 to 0.006 cm^{-1}.

The optical design problem for FTS-2 is essentially to reproduce the original image and pupil at the outputs of the interferometer, while maintaining unity image magnification, in order to allow the instrument to be placed midway through the existing SCUBA-2 feed optics. The optical design is complicated by the limited available space, the curved image surface at the input, and the ~f/7 input beam. It is impossible to achieve diffraction limited imaging at high spectral resolution over the entire SCUBA-2 field of view. Optimizing the resulting trade-off between FOV and spectral resolution within the constraints imposed by the fixed space envelope was a significant challenge. Optimization of the optical design was done using ZEMAX [4] in collaboration with INO [5], taking into account the physical constraints of the available space envelope.

3. FTS-2 optical design

In order to fit the optics in the available space, a folded, dual-input, dual-output, Mach-Zehnder interferometer design [6] was adopted, as shown in Fig. 1b. Retractable pickoff mirrors are used to divert two quadrants of the telescope intermediate image through the FTS before being returned to mirror N1 in the SCUBA-2 feed optics. Each output port is mapped to one of the subarrays in both of the SCUBA-2 450 µm and 850 µm detector surfaces. Retro-reflecting mirrors are required for the interferometer moving mirrors because of the break in symmetry induced by the vertical folding of the interferometer arms. Discrete mirrors are used instead of a conventional corner cube to conserve height.

A simplified linear schematic of one arm of the interferometer is shown in Fig. 2. In order to mate with the existing SCUBA-2 optics, the telescope intermediate image (the FTS output image) must be reproduced a distance (B) in front of the return mirror equal to the thickness of the corner cube. Similarly, the telescope pupil must also be reproduced at the proper distance (A) relative to the output image.

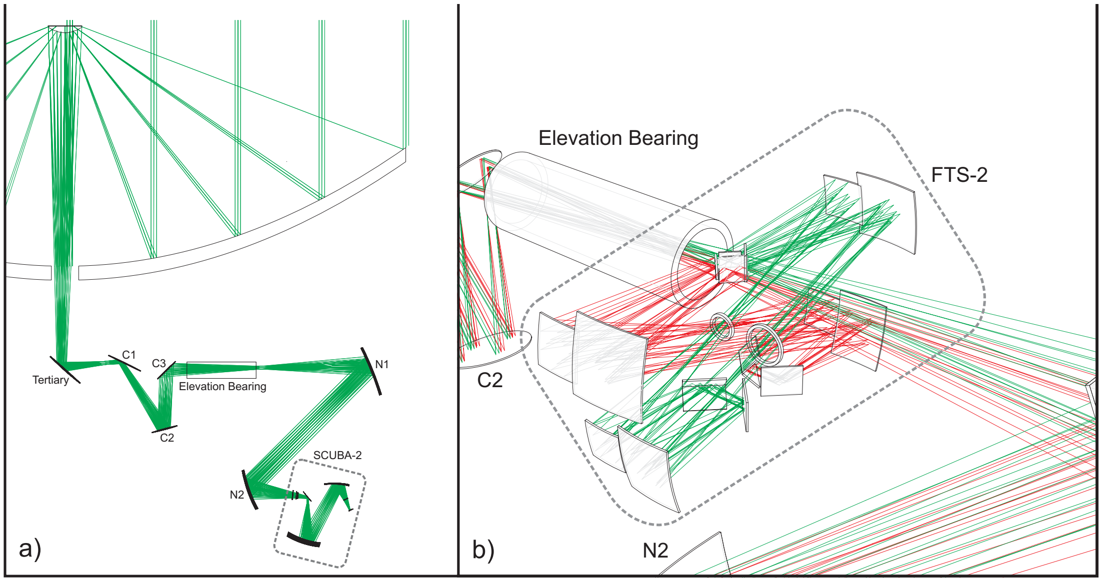

Fig. 1. The left panel (a) shows the SCUBA-2 feed optics on the JCMT. The only available location for the FTS is at the intermediate image surface between the JCMT elevation bearing and mirror N1. The right panel (b) shows the FTS-2 optics (surrounded by dotted line) and rays for both ports of the interferometer.

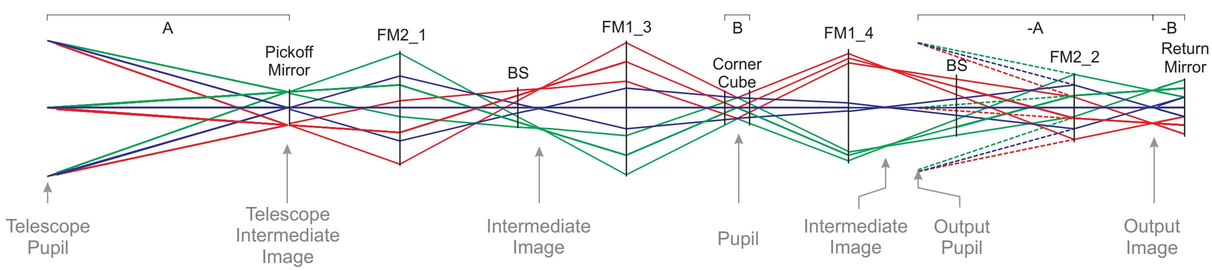

Fig. 2. Simplified linear schematic of one arm of the FTS-2 interferometer.

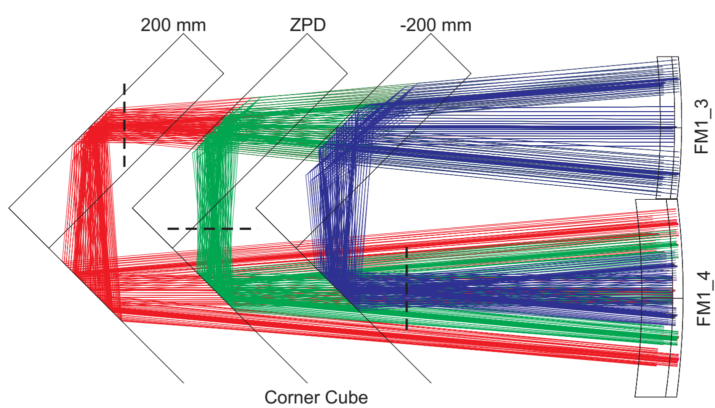

Fig. 3. Pupil location (dotted lines) for one arm of the interferometer at corner cube positions of ZPD and +/- 200 mm relative to ZPD, as seen from above.

Aspherical powered mirrors are used within the FTS to constrain the expanding beam, in a design similar to the one first proposed by Dohlen [7]. For symmetry, a pupil is placed at the apex of the corner cubes when the moving mirrors are at zero path difference (ZPD). However, this pupil drifts as the mirrors translate during a scan (see Fig. 3), and since the following mirrors are aspherical, there is spill-over on subsequent optics and misalignment of the image field points from both arms of the interferometer on the detector. The net effect is increased apodization in the interferograms due to vignetting and increased spot sizes at higher spectral resolution, and is more severe at the periphery of the field of view. At high resolutions, vignetting occurs primarily at the cold stop of the detector, although there is also some vignetting within the second half of the interferometer and at the return mirrors.

Placing the return mirrors as close as possible to the pickoff mirrors reduces the required aperture for the return mirrors, and allows the lower two quadrants of the image to pass through unobstructed to the detector. Placing the return mirrors out of the plane of the output half of the interferometer, however, introduces a small image rotation relative to the non-FTS image, which must be corrected in software.

4. Performance

The maximum field of view of the FTS input ports is ultimately limited by the maximum practical mirror diameters (roughly 400 mm diameter) to approximately 5 arcmin^2. The system maintains diffraction limited spot sizes at intermediate spectral resolution (mirror travel up to ~100 mm). The computed fraction of rays passing through the FTS unvignetted and the interferograms contrast ratio for the central field are given in Table 1, as a function of mirror travel for low, medium, and high spectral resolution. For the outer field points, the corresponding values are given in Table 2.

Table 1. Efficiency of FTS for central field considering vignetting losses as a function of mirror travel.

Travel Distance	Fraction of Rays Passing Through FTS		Interferogram Contrast
	Positive Travel Side	Negative Travel Side	
ZPD	88.99%	88.99%	1.000
±15mm	89.80%	88.07%	0.981
±100mm	95.46%	83.53%	0.875
±200mm	98.27%	80.32%	0.817

Table 2. Efficiency of FTS for outer field considering vignetting losses as a function of mirror travel.

Travel Distance	Fraction of Rays Passing Through FTS		Interferogram Contrast
	Positive Travel Side	Negative Travel Side	
ZPD	90.77%	90.77%	1.000
±15mm	86.69%	91.94%	0.943
±100mm	39.21%	65.68%	0.597
±200mm	3.37%	10.91%	0.309

5. Conclusions

In this paper we have presented the optical design of an imaging FTS for SCUBA-2 which incorporates several unique features. FTS-2 is entering the CDR stage, with delivery to the JCMT anticipated in mid to late 2007. On behalf of the Canadian SCUBA-2 consortium, the authors acknowledge the support of a CFI international access award for Canadian participation in the SCUBA-2 project.

6. References

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