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Contents

1. Summary of Main Objectives

This document presents the top level requirements and specifications of a Fourier Transform Spectrometer (FTS) to complement SCUBA-2, the new generation array camera for the James Clerk Maxwell Telescope (JCMT).

The key design features are summarised as follows:

1) *Hyperspectral mapping*. Merging the mapping speed improvement of SCUBA-2, with the high resolution of the FTS, will provide an unprecedented hyperspectral imaging ability in the submillimetre.

2) *Dual wavelength operation*. The SCUBA-2 FTS will take advantage of the unique simultaneous dual wavelength capability of the SCUBA-2 system.

3) *Mach-Zehnder Design*. This innovative FTS design provides high efficiency and access to all four ports of the interferometer.

4) *High Spectral sensitivity / Low noise*. The SCUBA-2 detector will provide excellent noise performance, which translates directly to spectral sensitivity for the FTS.

5) *Novel observing modes*. Instantaneous, fully-sampled image plane in SCUBA-2 will provide better image fidelity, and techniques such as the DREAM mode will provide convenient atmospheric correction for each frame in the interferogram.

These features are briefly discussed in the following sections.

2. Instrument Technical Design and Specification

2.1. Mach-Zehnder design

The SCUBA-2 FTS will incorporate a Mach-Zehnder design (ref. http://www.uleth.ca/phy/naylor/pdf/fts99.pdf) which has been demonstrated successfully in the SPIRE instrument (ref. http://www.uleth.ca/phy/naylor/pdf/SPIE_FTS.pdf) and the University of Lethbridge spectrometer in use at the JCMT (ref. http://www.uleth.ca/phy/naylor/pdf/SPIE_Hawaii_MZFTS.pdf). A schematic of this design is shown in Figure 1.

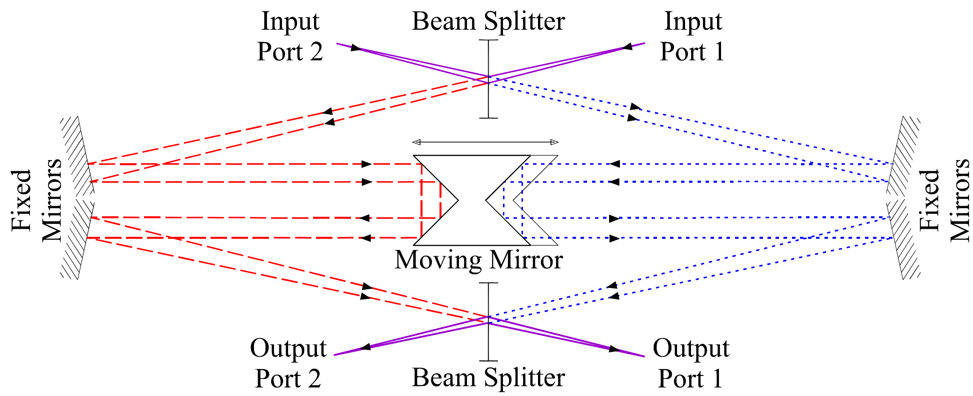

Figure 1. Schematic of a Mach-Zehnder FTS.

The Mach-Zehnder design has the advantage of being insensitive to polarization, while providing high and uniform efficiency over a broad frequency range. The design provides access to two input and two output ports, which allows a reference blackbody calibration source to be viewed at all times with one input, and the astronomical source with the other. Sequential measurements with the blackbody set at two different temperatures allow the resulting spectra to be calibrated on an absolute intensity scale.

As a consequence of the limited mounting options in the now fixed SCUBA-2 feed optics system, the actual layout of the SCUBA-2 FTS is slightly different from what is shown in the schematic above. Conceptual renderings of the FTS layout can be found at: http://research.uleth.ca/scuba2/cad.shtml.

2.2. Overview of main system components: beam splitters, blackbody, linear stage, etc.

The performance of this design depends critically on the beam splitter characteristics. The Cardiff University group has extended their expertise in manufacturing metal mesh resonant filters to the production of beam splitters with 4RT efficiencies above 90% and a factor of 4 in frequency range, as shown in Figure 2. Figure 3 shows a metal mesh beam splitter recently made for the U of L SPIRE test FTS.

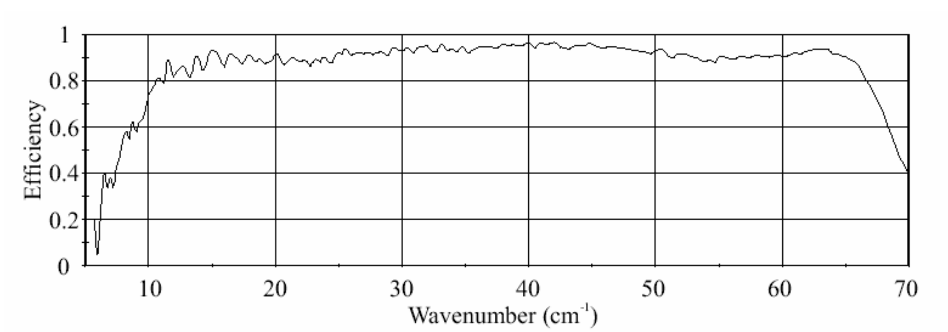

Figure 2. Measured beamsplitter efficiency.

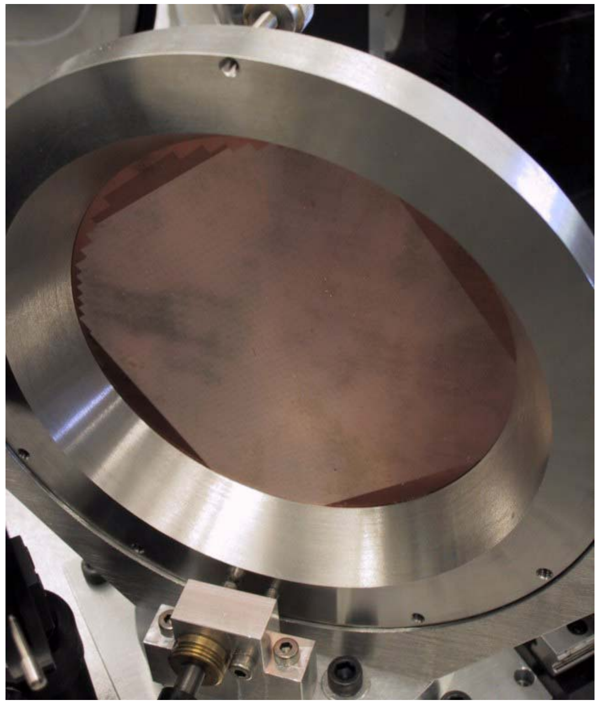

Figure 3. Metal mesh beam splitter.

Intensity calibration will be made possible by a cryogenic, variable temperature blackbody source, which will operate between 77 K and 150 K. A cryogenic blackbody is required in order to minimize the total power loading on the pixels. This blackbody could also be used to null the signal variations produced as the FTS scans through the zero path difference location, which would reduce the burden on the SQUID flux-locked loops.

Central to the operation of the FTS is the linear translation stage, which allows high accuracy velocity and position control of the moving rooftop mirror assembly. An Aerotech brushless direct-drive servo motor based linear stage will be used which features zero backlash, zero windup, low friction, and high acceleration. These stages incorporate absolute encoders which allow sub-micron accuracy and repeatability.

2.3. Sensitivity, performance, etc.

SCUBA-2 will have extended capabilities enabling large-scale projects covering many tens of degrees of sky, along with deep and high-fidelity imaging of selected areas. While SCUBA-2 will offer the JCMT a unique and wide-ranging observing facility in the submillimetre waveband, the FTS will provide hyperspectral imaging capabilities unprecedented in submillimetre astronomy. The FTS 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. The advantages of the SCUBA-2 FTS are summarized as follows:

- Simultaneous broadband, readily adjustable intermediate resolution measurements across both 850 and 450 μm bands.
- Continuum measurements will also be possible.
- The system will produce useful 850 μm data in grade 3 weather.
- The FTS has the best instrumental line shape function of any spectrometer
- Intrinsic wavelength calibration
- Relatively easy intensity calibration

3. Observing Modes and Data Handling

Sky correction will be one of the most challenging aspects of the SCUBA-2 data reduction, and this will also be true for the FTS. The most likely scenario is that the FTS will operate in a step-and-integrate mode, where the optical path difference in the interferometer is incremented in discrete steps, and data is read out only when the mirrors are stationary. This method will allow use of the DREAM mode to correct the frames before they are passed to the FTS processing pipeline. Since the SCUBA-2 filters have extremely high out-of-band rejection, the interferograms may be sampled sparsely and the resulting aliasing of the spectra can be easily removed. This will allow high resolution (0.005 cm^{-1}) spectra to be obtained in an integration time of an hour.
It is not anticipated that the data volumes will present any particular problem for processing. The FTS in itself will not produce a higher data rate than any of the normal SCUBA-2 observing modes. Simulations have shown that current consumer grade PCs can cope with the Fourier transform of data sets corresponding to one sub-array at 0.005 cm^{-1} resolution

4. System Integration and Laboratory Acceptance Tests

4.1. System Integration

The FTS will be fully assembled in the U of L labs, and shipped disassembled to the JAC. The system will have to be reassembled at the JCMT and realigned once installed in the telescope framework. The internal FTS optics can be aligned independently from the pickoff mirrors which feed the beam into the FTS and back to SCUBA-2.

4.2. System tests

The FTS will be fully tested in the U of L labs, although most likely with a single pixel detector. Operation of the mechanical and electronic components will be verified completely before shipping. Tests at the telescope will include image quality tests with the SCUBA-2 array, spectral characterization of all pixels in both bands.

5. **Operational Requirements**

In this section we present a brief summary of the main operational requirements at the telescope and the level of support for the instrument. Details of these and other interfaces can be found in the FTS ICD (SC2/FTS/SYS/002).

5.1. Telescope interfaces

5.1.1. Mechanical interface to telescope.

The FTS will be mounted within the support framework for mirror N1, which sits above the left Nasmyth platform at the level of the elevation bearing. Retractable pickoff mirrors will redirect the astronomical signal though the FTS and back to mirror N1 when the system is in use.

5.1.2. Transport and access systems.

This includes equipment to install and service the instrument.

5.1.3. Connections to JAC computers.

The FTS will use the RTS to coordinate its operation with the SCUBA-2 system. The FTS control PC will accept commands and pass position values pack to the SCUBA-2 data analysis system via an Ethernet connection.

5.1.4. Grounding and power interface (including electrical safety).

The FTS electronics will conform to the JCMT requirements for electrical safety.

5.1.5. Cryogenic interfaces.

This includes the vacuum connections and possibly liquid cryogens for the FTS cryogenic blackbody calibration source.

5.2. Software interfaces:

5.2.1. Observation planning system.

To be subsumed into the JAC Observation Management Project, as a subset of the SCUBA-2 observation planning system.

5.2.2. Data storage and pipeline data reduction.

How to handle the large data rates and data storage. The FTS processing pipeline that transforms interferograms into spectra will be a subset of the overall SCUBA-2 data reduction pipeline.

5.2.3. Hyperspectral image analysis packages.

This will start with the basic SCUBA-2 image analysis software, and will include custom routines to do basic spectral analysis on the final spectral data cubes.

6. Expected Performance

Table 1. SCUBA-2 850 µm system noise parameters with FTS

	0.5 mm PWV	1 mm PWV
Total Power Loading	11.5	12.3
Overall NEP (W/√Hz)	$8.5\cdot10^{-17}$	$8.7\cdot10^{-17}$

Table 2. FTS sensitivity for 450 and 850 µm

	850 µm		450 µm	
FTS optical efficiency[1]	43.7%			
System transmission[2]	23%			
Resolution (MHz)	150	3000	150	3000
Resolution (cm^{-1})	0.005	0.1	0.005	0.1
NEP (W/√Hz)[3]	$8.5\cdot10^{-17}$	$8.5\cdot10^{-17}$	$\sim8\cdot10^{-16}$	$\sim8\cdot10^{-16}$
1-σ ΔT Sensitivity in one hour integration (mK)	2	0.1	~10	~1

By way of illustration, M82 is a nearby, well studied ULIRG, and is the brightest member of that class in the sky. With the estimated sensitivity given in Table 2 and using previous results from the CSO[4] it will be possible to obtain spectroscopic mapping of M82, at the highest spectral resolution of 150 MHz, which will yield a S/N of 500 on the peak of the CO 3-2 line at 345 GHz in an integration time of one hour.

[1] Efficiency for an ideal dual output FTS is 50% at each output.
[2] Transmission from the JCMT dish, through the SCUBA-2 feed optics and FTS, to the detectors.
[3] NEP values at 450 µm have not been fully modeled.
[4] Serebyn E. & Weisstein E.W., *ApJ*, **451**, 238 (1995)