# An update on the imaging Fourier transform spectrometer for SCUBA-2

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## ABSTRACT

We present the recent developments and current design and of an imaging Fourier transform spectrometer (IFTS) for use with SCUBA-2, the second generation, wide-field, submillimetre camera currently under development for the James Clerk Maxwell Telescope (JCMT). The spectrometer will offer variable resolution with resolving powers ranging from R ~10 to 5000. The IFTS uses a folded Mach-Zehnder configuration with novel intensity beam dividers and dual input ports for continuous atmospheric cancellation. This system, which is planned for operation in 2006, will provide simultaneous, broadband, intermediate spectral resolution imaging across both the 850 and 450 μm bands. The optics, observing modes, and projected telescope performance of the IFTS are discussed.

**Keywords:** Imaging, Fourier, Transform, Spectrometer, SCUBA-2, Submillimetre

## 1. INTRODUCTION

SCUBA-2 is a highly innovative wide-field camera[1] designed to replace SCUBA and is planned to be operational on the James Clerk Maxwell Telescope in 2006. With approximately 10,000 pixels in two arrays, SCUBA-2 will map the submillimetre sky up to a thousand times faster than SCUBA, to the same signal-to-noise ratio, and will reach the extragalactic confusion limit in only a couple of hours. By combining a spectrometer with the SCUBA-2 detector array it will be possible to obtain, simultaneously, a spectrum from each point on the sky corresponding to individual pixels in the array. The imaging spectrometer will therefore open a third dimension for SCUBA-2 by providing spectral information at each point in the object under study (e.g. galaxy, molecular cloud). While SCUBA-2 will provide unprecedented morphological information about such sources, composition and physical conditions can only be determined through imaging spectral measurements. A Fourier Transform Spectrometer (FTS) has been selected as the optimal instrument to provide medium resolution spectroscopic capabilities to SCUBA-2.

The SCUBA-2 project is funded jointly by the Joint Astronomy Center, Hawaii, and research granting agencies in the UK and Canada. Canadian support is in the form of a Canada Foundation for Innovation (CFI) international access award. In addition to supporting the development costs of SCUBA-2, this award provides funding for two auxiliary instruments: a Fourier transform spectrometer and a polarimeter. To maximize the scientific return, SCUBA-2 must be operational in 2006, well before the tripartite agreement (UK, Canada, and Netherlands) to run the telescope ends in 2009. This is an aggressive schedule, and several aspects of the system are being designed and constructed in parallel with the detector development program.

The SCUBA-2 FTS fills a niche between the SCUBA-2 continuum images and the higher spectral resolution but limited size images produced by HARP-B. Some key areas of application for the FTS are:

- Interstellar Medium - offers both a rich spectrum, with continuum and line components, and a rich field. The IFTS will allow for the spectral index mapping of molecular clouds and in particular identify those sources where a significant contribution to the total band flux arises from line emission.
- Extra galactic objects - although challenging it may be possible to measure the spectral energy distribution (SED) of some higher Z objects using only the 850 μm band.

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- Planetary atmospheres - inventory molecular species and provide information on the physical and dynamical processes of the atmospheres

## 2. INSTRUMENT DESIGN

The design of the SCUBA-2 FTS[2] is based on the Mach-Zehnder design[3] that has been adopted for the SPIRE instrument[4] of the ESA Herschel mission as well as for the University of Lethbridge spectrometer[5] currently operating at the JCMT. Figure 1 shows a schematic of the Mach-Zehnder FTS design. Retractable pickoff mirrors M1 and M2 intercept two 3 arcminute beams from the SCUBA-2 beam as it exits the left telescope elevation bearing tube. The collimated beams are redirected by mirrors M3 and M4 to the first intensity beam divider[3], BS1. As the moving mirror assembly (consisting of two rooftop mirrors, RT, mounted on a linear stage) is moved a distance x, an optical path difference of 4x is introduced between the interferometer arms M5/M7 and M6/M8. The beams are recombined at beam divider BS2, and the two output ports are returned to the SCUBA-2 optical system by mirrors M11 and M12.

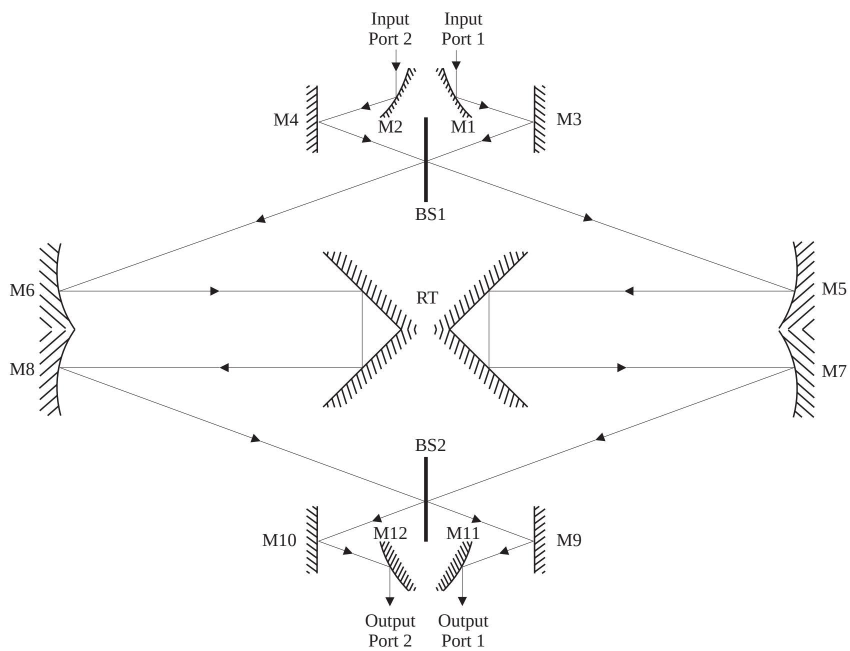


**Figure 1. A schematic of the dual-port Mach-Zehnder FTS design.**

The FTS will be mounted within the support structure for the SCUBA-2 mirror N1, just outside the left elevation bearing of the JCMT, as shown in Figure 2. Retractable pickoff mirrors will redirect the astronomical signal though the FTS and back to mirror N1 when the system is in use, and will be removed from the beam for photometric observations. The FTS will occupy a volume of roughly 2 m x 0.75 m x 1.2 m (w x d x h) and have a mass of approximately 500 kg. The control PC will be mounted at a convenient distance from the FTS instrument, and will communicate with the RTS and SCUBA-2 network via fiber optic links.

The University of Lethbridge group will produce the hardware, electronics and software necessary to implement the instrument at the JCMT. The hardware consists of a damped optical breadboard supporting a series of fixed mirrors and moveable pickoff mirrors, a moving mirror assembly on a linear stage that produces optical path variations between two interferometric beams, and associated framework. The electronics consist of a linear motor controller, electronics interface to the JCMT Real Time Sequencer (RTS) and network, and various limit switches and diagnostic systems, all connected to a control PC. The software consists of control code to accept commands from the JCMT Observatory Control System (OCS) and control the FTS electronics, as well as data analysis software, in the form of a spectral processing engine within the SCUBA-2 data reduction pipeline, that will convert interferogram data into hyperspectral image cubes.

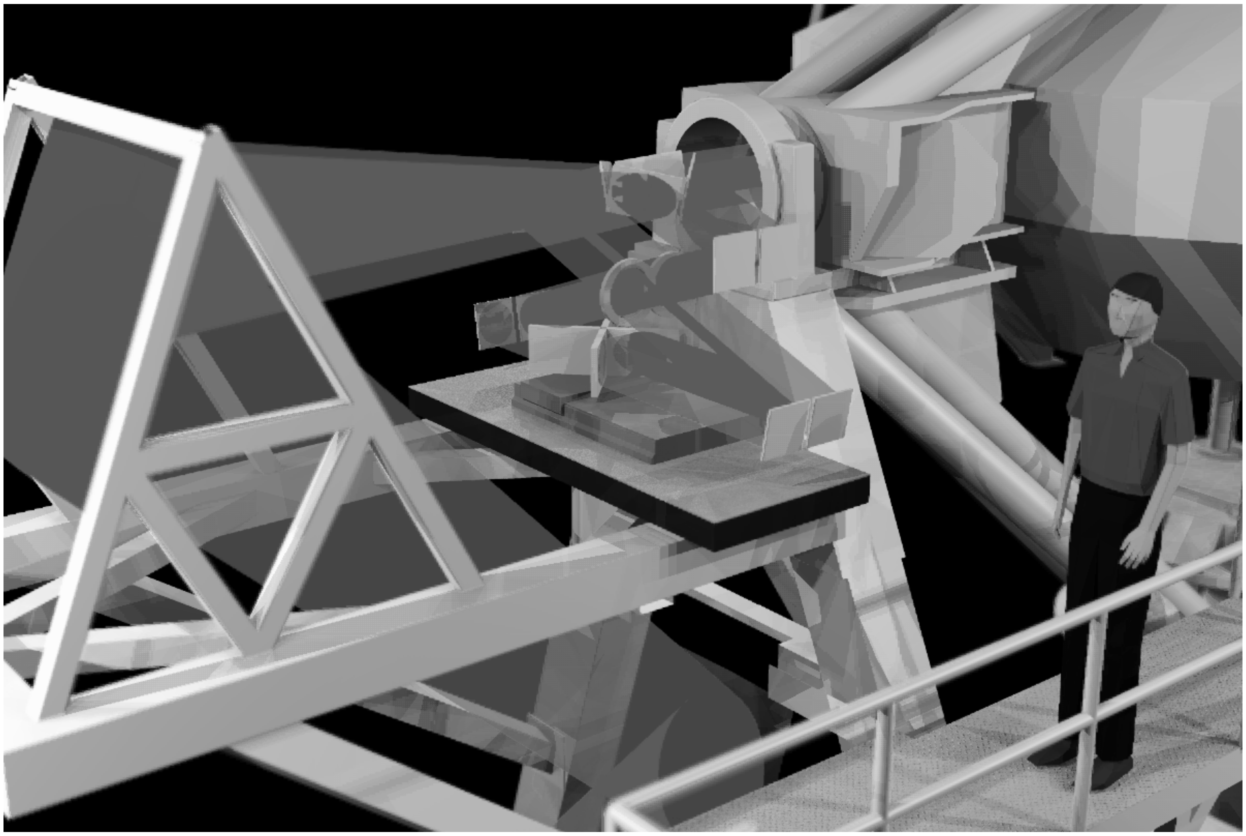

**Figure 2. The SCUBA-2 FTS mounted on the mirror framework outside the left elevation bearing tube.**

The key design features of the SCUBA-2 FTS are summarized as follows:

- Hyperspectral mapping. Merging the mapping speed improvement of SCUBA-2, with the high resolution of the FTS, will provide an unprecedented hyperspectral imaging ability at submillimetre wavelengths.
- Dual wavelength operation. The SCUBA-2 FTS will take advantage of the unique simultaneous dual wavelength capability of the SCUBA-2 system.
- Mach-Zehnder Design. This innovative FTS design provides high efficiency and access to all four ports of the interferometer, allowing two input ports to be placed on the sky simultaneously for atmospheric correction.
- High Spectral sensitivity / Low noise. The SCUBA-2 detector will provide excellent noise performance, which translates directly to spectral sensitivity for an FTS.
- Novel observing modes. The instantaneous, fully-sampled image plane in SCUBA-2 will provide better image fidelity, and placing both FTS input ports on the sky will provide convenient atmospheric correction for each frame in the interferogram.

The FTS has the following interfaces with the JCMT/SCUBA-2 systems:

**Telescope Electrical Interfaces**

Construction of the FTS will require very little custom electronics; the major electronic component is the microcontroller based motion controller for the moving mirror linear stage and for the pickoff mirrors. The motion controller and electronics will be interfaced to a control PC. This PC must be interfaced with the SCUBA-2 network so that the 32 bit stage position is recorded in the header of each frame when an FTS observation is in progress.

**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 from, and pass optical path difference values back to the SCUBA-2 data analysis system via a network connection.

**Software interfaces**
The FTS control PC will take commands from the RTS Client to initiate a scan, and will send commands to the motion controller to move the mirror at the required speed and distance, and return the mirror position to the software pipeline. The control PC will also monitor the various limit switches and FTS housekeeping parameters.

**Observation planning system**
FTS observation planning and management will be subsumed into the JAC Observation Management Project, as a subset of the SCUBA-2 observation planning system.

**Data storage and pipeline data reduction**
The FTS processing pipeline that transforms interferograms into spectra will be a subset of the overall SCUBA-2 data reduction pipeline. Our group will provide the spectral processing pipeline modules to be called by the data reduction pipeline. Data storage will be no different than the normal SCUBA-2 storage, since interferogram and spectral data cubes are simply stacks of normal SCUBA-2 frames. It is not anticipated that the data volumes will present any particular problem for processing. In operation, the FTS 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.

**Hyperspectral image analysis packages**
Spectral analysis code will be provided by our group, which will be based on the basic SCUBA-2 image analysis software and will include custom routines to do basic spectral analysis on the final spectral data cubes.

## 3. OBSERVING MODES

Atmospheric correction[6] will be one of the most challenging aspects of the SCUBA-2 data reduction, and this will also be true for the SCUBA-2 FTS. The baseline operating mode for the SCUBA-2 FTS is the rapid-scan mode with the two input ports of the interferometer viewing adjacent regions of the sky to provide instantaneous cancellation of background atmospheric emission. Individual frames from SCUBA-2 will be acquired as a function of increasing optical retardation in the interferometer and the resulting interferogram data cubes will be analyzed within a specialized FTS processing engine within the SCUBA-2 pipeline. Since the SCUBA-2 data acquisition system is independent of the FTS scanning mechanism, the resulting interferograms will not be sampled uniformly in optical retardation, which will necessitate the use of a non-uniform FFT or an interpolation process in the processing pipeline. Our group is currently developing algorithms to cope with this problem for the SPIRE spectrometer[7].

We are also investigating the potential use of a step-and-integrate operating mode[8]. In this mode, the optical path difference in the interferometer is incremented in discrete steps and data is read out only when the mirrors are stationary, thereby ensuring that the interferogram is sampled on a uniform position grid. This mode could in principle be used with only one input port viewing the source, with atmospheric correction for each frame provided by the proposed DREAM observing mode[9] before the frames are passed to the FTS processing engine. The baseline plan, however, is to use the dual-input cancellation technique.

Since the SCUBA-2 filters will 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 spectra to be obtained in shorter scan times, which will reduce the effects of sky rotation and atmospheric noise. By proper selection of the optical path sampling interval, both the 450 and 850 μm bands can be aliased simultaneously without any loss of information within the bands. In order to test this technique, we have reconfigured our existing FTS[2] to use both the normal rapid-scan and the step-and-integrate modes. Results of these tests are discussed below.

During an observing run at the JCMT in October 2003, we acquired back-to-back observations of the Orion KL region with both the normal rapid-scan and the aliased step-and-integrate modes. The weather during the run was particularly poor, with the best data being taken with 5 mm of precipitable water vapor. Approximately 30 minutes of rapid-scan data and 30 minutes of step-and-integrate data were collected. The rapid-scan data were taken alternately on-source and off-source, with an offset of 2340" in RA. Source and background observations were composed of an 'up' scan and a 'down' scan, referring to the direction of travel of the moving mirror. The time for each of these scans was on average 73 seconds, giving a total time for one pair of on-source/off-source observations of just under 2.5 minutes. In total, there were 24 scans taken (12 pairs of on-source/off-source observations) over ~30 minutes. The corresponding spectra are shown in Figure 3.

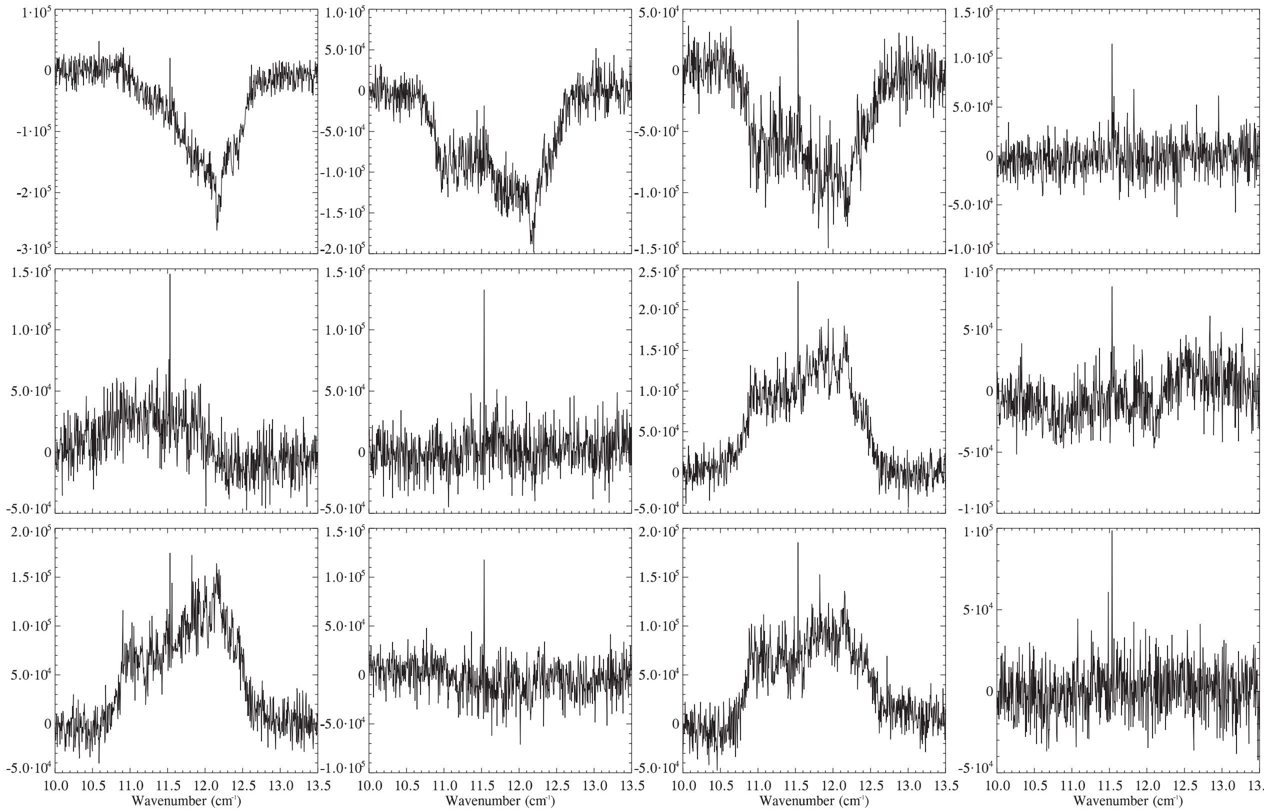


**Figure 3. Difference between 12 pairs of rapid-scan spectra.**

Although the CO line is visible in all the spectra, several spectra exhibit non-physical (flat or negative) continuum levels. This is due to atmospheric variation within the 2 minutes between on-source and off-source scans. This can be minimized by acquiring interferograms as quickly as possible so that the on-source and off-source scans are taken with nearly identical sky background. Unfortunately, since the continuum in the spectrum is determined by the zero path difference (ZPD) region of the interferogram and the scan speed is limited by the detector frequency response, there is a limit to how quickly successive interferograms can be acquired and how well the atmospheric background can be cancelled in the single input rapid-scan mode.

The alternative to increasing the scanning speed is the step-and-integrate mode, where the secondary mirror chops between on and off-source positions and a lock-in amplifier provides the difference signal at each interferogram sample position. This mode has the drawback of taking one second at each sample position due to the limited chopping frequency of the secondary mirror unit, lock-in time constants and overhead delays from point to point moves, so a 5000 point scan with a Nyquist frequency equivalent to the rapid-scan interferogram would take over 80 minutes and would therefore be susceptible to variations in atmospheric transmission (which cannot be corrected). Our technique is to make use of the well-defined bandpass of the filters and sample the interferogram more sparsely by a factor of 4, intentionally 'aliasing' the spectral band into a 0 to 5 cm$^{-1}$ spectral range instead of 0 to 20 cm$^{-1}$. This reduces the scan time to a more reasonable 28 minutes (including system overheads that have not been optimized). Figure 4 shows the resulting spectrum (black trace), shifted back to the proper frequency range, and overlaid with the average of the difference of the three good pairs (out of a total of 12) of rapid-scan data (gray trace).

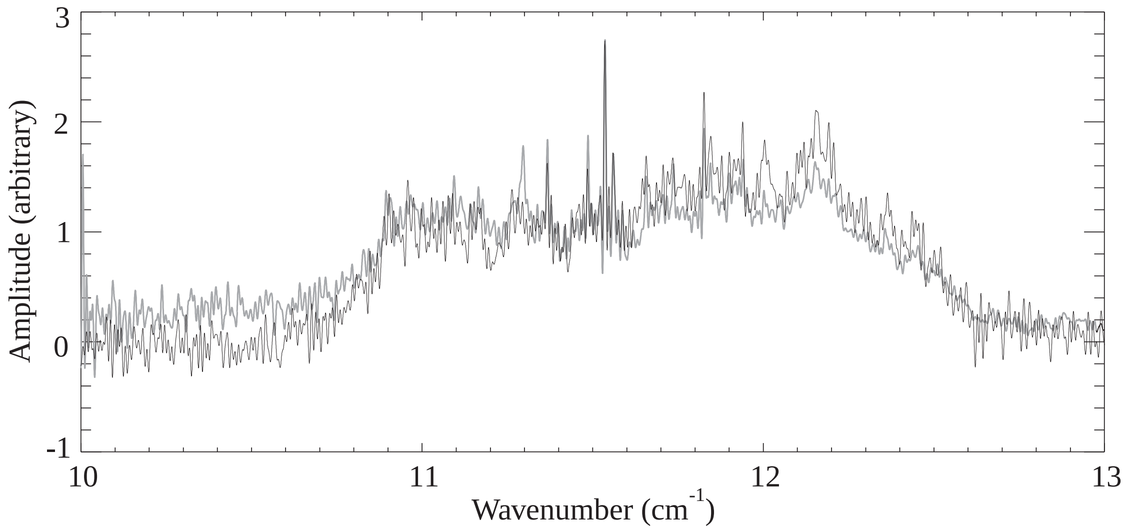


**Figure 4. Step-and-integrate spectrum (black) and averaged rapid-scan spectra (gray).**

It can be seen from the figure that there is good agreement between the two techniques and, as expected, the continuum is better behaved in the step-and-integrate data. There is an improvement in the signal to noise of about a factor of two in the step-and-integrate data, for an equivalent integration time. Figure 5 shows a small spectral region of the step-and-integrate (top), the rapid-scan (middle), and B3 heterodyne spectra (bottom) convolved to the FTS resolution, each offset for clarity.

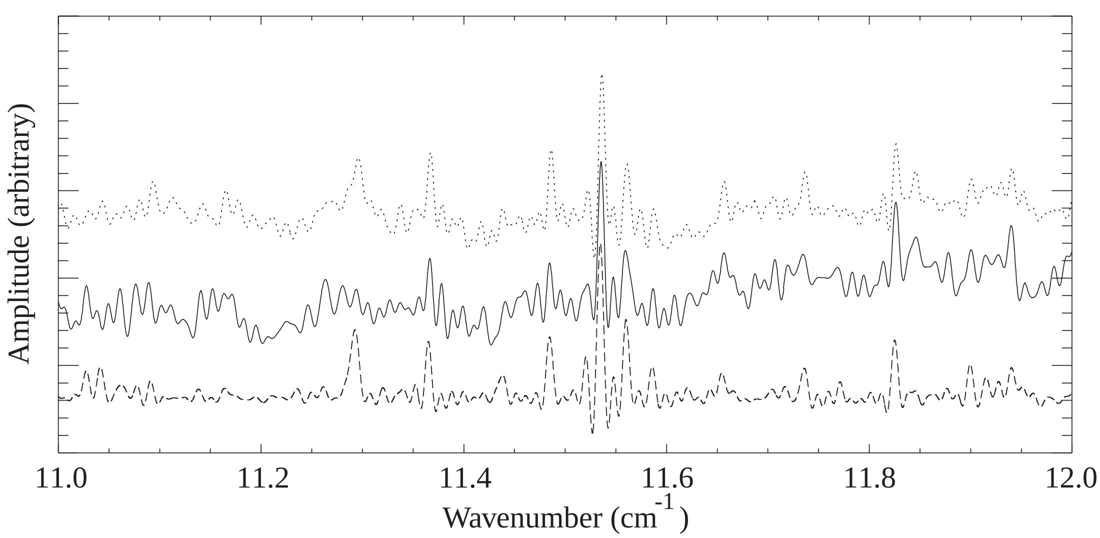


**Figure 5. Step-and-integrate spectrum (top), averaged rapid-scan spectra (middle) and B3 heterodyne spectrum (bottom) convolved to match the FTS resolution, each offset for clarity.**

There was some concern raised in the CoDR about the feasibility of phase-correction with undersampled or 'aliased' interferograms. We have confirmed that there is no intrinsic difficulty in phase correcting the aliased step-and-integrate data, as evidenced by the line shapes in the spectrum given earlier. The ZPD region of a phase-corrected aliased step-and-integrate interferogram is shown in Figure 6, where the symmetry can be clearly seen.

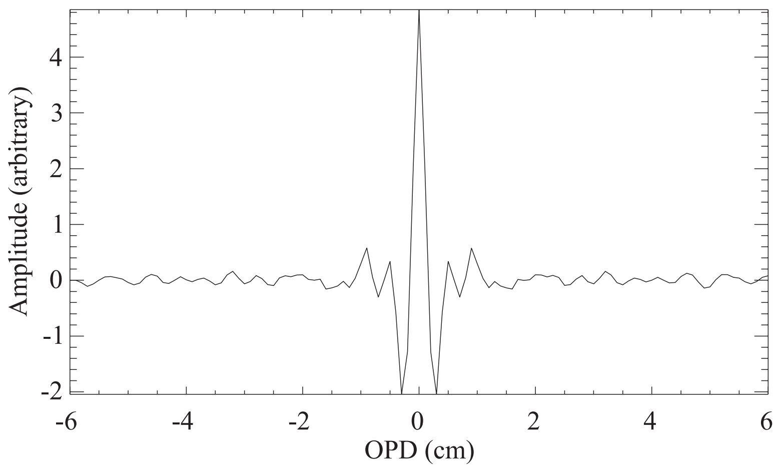


**Figure 6. Phase corrected aliased step-and-integrate interferogram.**

## 4. FTS SPECTRAL ENERGY DISTRIBUTION (SED) MEASUREMENTS

The continuum emission flux ($S_\nu$) as a function of frequency ($\nu$) can be expressed as:

$$S_\nu = \nu^\gamma = \kappa_0 \left( \frac{\nu}{\nu_0} \right)^\beta B_\nu(T)$$

where $\gamma$ is the spectral index, $\beta$ is the dust emissivity index, $\kappa_0$ is the dust emissivity at frequency $\nu_0$, $B_\nu(T)$ is the Planck function, and $T$ is the dust temperature.

Photometric measurements at 850 and 450 µm can provide estimates of γ, but knowledge of the dust temperature is required to determine $\beta$. Estimates of dust emissivity can be obtained by taking a ratio of 850 and 450 µm photometric measurements, but there are difficulties with this method: the JCMT beam at 450 µm has a narrow diffraction limited response of ~7" and an extended pedestal. Comparing photometric data at the two wavebands requires assumptions about the size of the emitting region and its coupling to the telescope. In addition, observations at 450 µm are very sensitive to weather and require the best observing conditions. The main drawback with this method is that small errors in the assumed temperature of the source region translate to large errors in the retrieved $\beta$.

FTS spectra, on the other hand, can be used to determine $\beta$ by fitting to the slope of the continuum within the 850 µm band alone, or by fitting to the slope and magnitude across both bands. When using both bands, one can fit the dust temperature as a free parameter. Figure 7 shows the error in retrieved $\beta$ for a 30 K cloud with $\beta$ = 1.5 as a function of the assumed temperature for the photometric and spectroscopic methods. It is readily seen that the photometric method is much more sensitive to the accuracy of the assumed temperature. The dash-dot trace shows the error in retrieved $\beta$ as a function of the true source temperature, when spectra from both bands are used and the source temperature is fit as a free parameter. It can be seen that the dual band FTS method produces the lowest error levels, except for when the temperature estimates for the photometric method are accurate to better than 1 K. Table 1 lists errors in retrieved $\beta$ associated with the various observation methods for various temperature estimates.

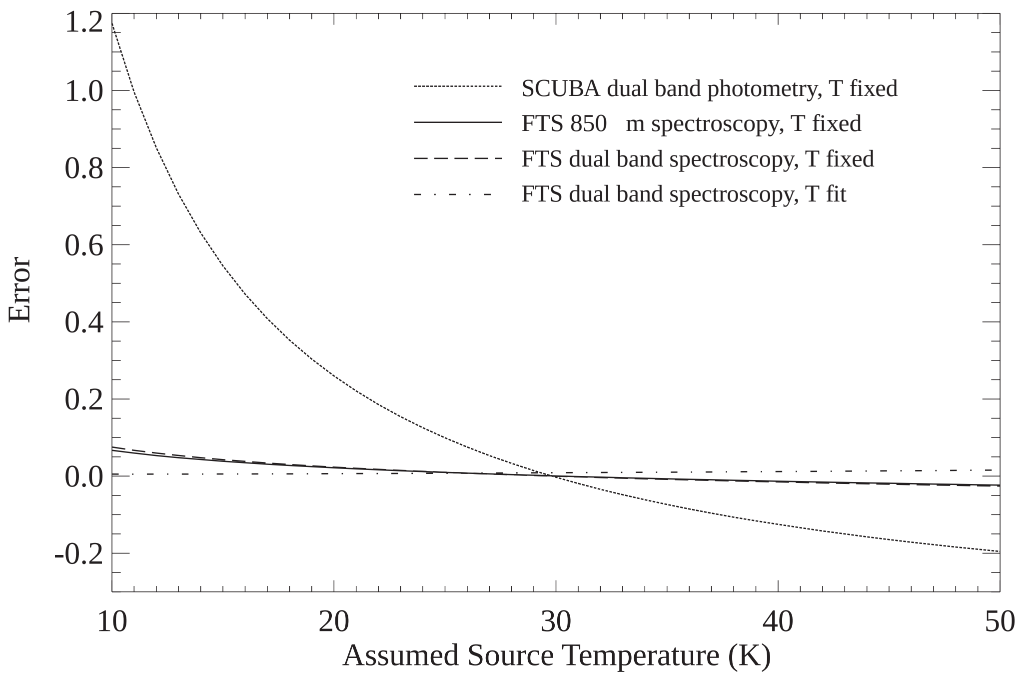


**Figure 7. Error in extracted *β* for a 30 K source as a function of assumed temperature. The dash-dot trace shows the error when using dual band spectroscopy to determine *β* and *T*.**

**Table 1. Comparison of methods to determine SED for a 30 K source with *β* of 1.5 and 2.0.**

| **Actual *β*** | **Measurement** | **Retrieved *β* assuming *T*=30 K** | **Error in *β* assuming *T*=40 K** | **Error in *β* assuming *T*=20 K** |
|---|---|---|---|---|
| 1.5 | Photometry | 1.503 | 0.122 | -0.263 |
| | FTS Dual Band | 1.5002 | 0.0149 | -0.0242 |
| | FTS 850 µm Band | 1.4995 | 0.0136 | -0.0212 |
| 2.0 | Photometry | 2.005 | 0.122 | -0.263 |
| | FTS Dual Band | 2.0003 | 0.0152 | -0.0245 |
| | FTS 850 µm Band | 1.9995 | 0.0136 | -0.0212 |

The advantages of the photometric and spectroscopic methods can be summarized as follows:

850 and 450 µm photometry
- best sensitivity
- requires knowledge of source size and coupling to 850 and 450 µm beams
- requires estimate of temperature to get *β*
- requires difficult 450 µm observations

FTS-2 850 and 450 µm dual band spectroscopy
- less sensitive than photometry
- requires knowledge of source size and coupling to 850 and 450 µm beams
- can use spectra to determine temperature
- requires difficult 450 µm observations

FTS-2 850 µm single band spectroscopy

- less sensitive than photometry
- essentially same beam for all observations
- low dependence on assumed temperature
- does not require 450 µm observations

## 4. PROJECTED PERFORMANCE

The FTS observing time, *t*, required to achieve a per-pixel 1-σ temperature sensitivity of $\Delta T$ (K) is given by[10]:

$$t = \left( \frac{2 \cdot NEP'}{k \cdot \Delta f \cdot \Delta T} \right)^2$$

where $NEP'$ is the system noise equivalent power measured above the atmosphere, *k* is Boltzmann's constant, and $\Delta f$ is the spectral resolution. For the SCUBA-2 FTS, this can be rewritten in terms of mapping time as:

$$t = \frac{3.8 \cdot 10^{31}}{\eta} \left( \frac{A}{FOV} \right) \left( \frac{NEP}{\Delta f \cdot \Delta T} \right)^2 \quad \text{(16-hour nights)}$$

where *A* is the map area, *FOV* is the FTS field of view, *NEP* is the detector noise equivalent power measured at the bolometer, $\eta$ is the observing efficiency and $\Delta f$ is the spectral resolution in MHz. In terms of the noise equivalent flux density, *NEFD*, this becomes:

$$t = \frac{x}{\eta} \left( \frac{A}{FOV} \right) \left( \frac{NEFD}{\Delta f \cdot D} \right)^2 \quad \text{(16-hour nights)}$$

where *D* is the survey depth in mJy, and the other parameters can be found in the table below:

| | **850 µm** | **450 µm** |
|---|---|---|
| $x$ | $8.8 \times 10^4$ | $2.1 \times 10^5$ |
| *NEP* | $7 \times 10^{-17}$ W/√Hz | $5 \times 10^{-16}$ W/√Hz |
| *NEFD* | 25 mJy | 80 mJy |
| $\eta$ | 0.5 | 0.5 |

**Table 2. FTS per-pixel sensitivity for 450 and 850 µm.**

| | **850 µm** | | **450 µm** | |
|---|---|---|---|---|
| FTS optical efficiency | 43.7% | | | |
| System transmission | 23% | | | |
| Resolution (MHz) | 150 | 3000 | 150 | 3000 |
| Resolution (cm-1) | 0.005 | 0.1 | 0.005 | 0.1 |
| NEP (W/√Hz) | $7 \times 10^{-17}$ | | $5 \times 10^{-16}$ | |
| 1-σ ΔT sensitivity in one hour integration (mK) | 16 | 0.8 | 116 | 6 |
| 1-σ Flux sensitivity in one hour integration (mJy) | 280 | 14 | 1382 | 69 |

## 5. CONCLUSIONS

In this paper we have discussed the design, potential observing modes and predicted performance of an imaging Fourier transform spectrometer which is being developed for use with the SCUBA-2 detector system at the James Clerk Maxwell Telescope. The design provides access to both interferometer input ports while maintaining a high and uniform efficiency over a broad spectral range. It is estimated that the per-pixel performance will be at least an order of magnitude better than previous single pixel systems. When coupled with the imaging capability of SCUBA-2, it is anticipated that the imaging FTS will provide an improvement of over 3 orders of magnitude in spectral mapping speed over existing single pixel systems operating at submillimetre wavelengths. The SED measurement capabilities of the FTS will be a powerful addition to the SCUBA-2 instrument.

We anticipate that the optical design will be finalized by October 2004 and that construction of the FTS will begin in early 2005. The FTS will be commissioned after the SCUBA-2 commissioning phase is complete in 2006.


## ACKNOWLEDGEMENTS

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