SCUBA-2 imaging Fourier transform spectrometer

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ABSTRACT

We present the conceptual design 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). 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 spectrometer will offer variable resolution with resolving powers ranging from R ~10 to 5000. When operated at low resolution, the IFTS will provide continuum measurements, well suited to spectral index mapping of molecular clouds, as well as bright nearby galaxies. The IFTS uses a folded Mach-Zehnder configuration and novel intensity beamdividers. The preliminary design, projected telescope performance and scientific impact of the IFTS are discussed. The preliminary design, novel observing modes, projected telescope performance and scientific impact 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 the highly successful SCUBA camera[2] on the James Clerk Maxwell Telescope (JCMT). With ~ 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 and to 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; opening a third dimension in astronomical observations 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, their composition and physical conditions can only be determined through imaging spectral measurements. An imaging Fourier transform spectrometer (IFTS) has been selected as the optimal design to provide medium resolution spectroscopic capabilities to SCUBA-2.

The scientific aims of the IFTS seek to capitalize on the imaging power and sensitivity of the SCUBA-2 camera, and extend its capabilities to include medium resolution imaging spectroscopy across the 450 and 850 µm atmospheric windows simultaneously. New kinds of targets and surveys that are currently not feasible with single pixel spectrometers will become possible with the introduction of the SCUBA-2 IFTS, including:

- Interstellar Medium - offers both a rich spectrum, with continuum and line components, and a rich field. The IFTS fills a niche between the SCUBA-2 continuum images and the higher spectral resolution, but limited size images, provided by heterodyne array receivers (e.g. HARP). The IFTS will provide 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.
- The Spectral Energy Distribution (SED) of the dust emission from Ultra-Luminous Infra-Red Galaxies (ULIRGs). Using the IFTS to measure the SED across the 850 µm band relaxes the current reliance on the generally lower quality 450 µm data to obtain the SED. Again the IFTS will also provide a means of estimating any contribution from line emission to the total band flux.
- Planetary atmospheres - inventory molecular species and provide information on the physical and dynamical processes of the atmospheres (e.g. internal heat sources). Spectral mapping of the Jovian, Saturnian and Martian discs to study hemispheric, zonal and polar differences and transport effects.

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- Super novae remnants - large scale mapping of super nova remnants and interaction with the interstellar medium.
- High red-shift objects - initial estimates indicate that it may be possible to determine the red shift through careful measurements of the slope of the continuum across the 850 μm band.

2. CHOICE OF SPECTROMETER TYPE

Several spectrometer designs were initially considered to provide the SCUBA-2 camera with a spectroscopic capability. These included a cooled grating spectrometer, internal and external cooled Fabry-Perot interferometers and an ambient Fourier transform spectrometer.

The grating spectrometer solution was rejected due to its poor throughput, large grating size and poor instrumental line shape function (of particular concern was the potential for scattering from bright emission lines resulting in poor photometric accuracy). While a grating would be useful as a high red shift spectrometer, it is not well matched to the SCUBA-2 detectors, which must handle the relatively high radiant load from the full 850 and 450 μm bands and are thus far from optimum when de-loaded. Moreover, the grating would produce one spatial and one spectral dimension on the SCUBA-2 arrays which would require non-standard operating and analysis modes.

The Fabry-Perot interferometer (FP) provides high throughput, intermediate to high resolution imaging spectroscopy over relatively narrow spectral ranges. Ideally, a cryogenic FP (which typically consists of two FPs in a tandem configuration) should be mounted within the SCUBA-2 cryostat. This, however, was rejected due to serious concerns of having an active component within SCUBA-2 cryostat immediately behind the entrance window. Moreover, in this configuration an FP can provide imaging in only one wave band at a time. Dual wave band operation would require two FPs located after the dichroic within the SCUBA-2 cryostat. There is insufficient space to even consider this option. From a raw sensitivity standpoint the FP solution is attractive, but, as with the grating, it is not well matched to the SCUBA-2 detectors (which must handle the high radiant load from the 850 and 450 μm bands). Moreover, walk-off of multiply reflected beams due to the speed of the optical beam at the cryostat entrance window would have to be addressed The potential for additional sources of emission and/or failures coupled with the increased complexity from mechanical, optical and cryogenic standpoints, ruled out an internal FP.

An external, cryogenically cooled FP solution would be easier to implement, however, it is still a complex mechanical, optical and cryogenic system and requires two ambient cryostat windows that would themselves be sources of radiant loading. Moreover, the limited space between entrance window of the SCUBA-2 cryostat and the final telescope feed mirror (~ 0.5 m), and the speed of the optical beam at this location, are problematic. Furthermore, from an analysis perspective, the FP has the worst instrumental line shape function of the three proposed spectrometers, wavelength and intensity calibration is non-trivial, and stitching together spectra to provide broad spectral coverage is fraught with difficulty and would render the FP useful only for line emission observations. Moreover, only one wave band can be observed at a time (no simultaneous 850/450 μm spectral mapping). The external FP solution was therefore also rejected.

A Fourier transform spectrometer (FTS) provides high throughput, variable resolution (R from ~ 10 to 5000) imaging spectroscopy over a wide spectral range. Furthermore, an externally mounted FTS provides simultaneous imaging spectroscopic measurements over both the 850 and 450 μm bands. In the Mach-Zehnder configuration the FTS provides ready access to the two input and the two output ports of the interferometer. Importantly, calculations show that the radiant loading from using the FTS with the second input port viewing the sky, or a cold calibration load, is only slightly greater than when using SCUBA-2 alone; this means that placing an ambient FTS before SCUBA-2 does not significantly degrade its performance. The mechanical and optical design of an FTS is simpler than the FP (this simplicity is balanced somewhat by the more complex mathematical analysis required to recover the spectrum). The FTS also has intrinsic wavelength calibration, relatively easy intensity calibration, and the best instrumental line shape function of any spectrometer (and one which can be tailored in post processing). Finally, the FTS is well matched to the SCUBA-2 detectors which have been designed to accommodate the radiant loading from the full 850 and 450 μm bands.

An FTS was therefore selected to provide SCUBA-2 with an imaging spectroscopic capability. The key design features of the FTS are summarized below:

- Mach-Zehnder design: This innovative FTS design provides high efficiency and access to all four ports of the interferometer. With this design, both ports could view the sky, or one port could view a cold load.
- Dual wavelength operation: The SCUBA-2 FTS will take advantage of the unique simultaneous dual wavelength capability of the SCUBA-2 system.
- Variable spectral resolution: The resolving power of the FTS can be selected instantly within a range of 10 to 5000.
- Novel observing modes: The instantaneous, fully-sampled image plane in SCUBA-2 will provide better image fidelity. The potential exists for exploiting the DREAM observing mode to provide atmospheric correction for each frame in the interferogram.
- Hyperspectral mapping: Combining the increased sensitivity of SCUBA-2 with the resolution of the FTS, will provide an unprecedented hyperspectral imaging capability in the submillimetre.

3. INSTRUMENT CONCEPT

The instrument design builds upon our extensive experience in the use of Fourier transform spectrometers at Mauna Kea and, more recently, our role as the lead Canadian institution in ESA's Herschel/SPIRE project which employs an imaging FTS of similar design to that proposed here. Since the internal design of the SCUBA-2 detector and its feed optics was already well advanced at the beginning of the spectrometer development, the mechanical and optical design of the FTS has to accommodate a sub-optimal input beam and mounting location. Details of these design issues are given in the following sections.

3.1 Optical

The SCUBA-2 FTS will incorporate a Mach-Zehnder design[3] which has been selected for the SPIRE instrument and successfully demonstrated in the University of Lethbridge Fourier transform spectrometer currently in use at the JCMT[4]. A schematic of this design is shown in Figure 1.

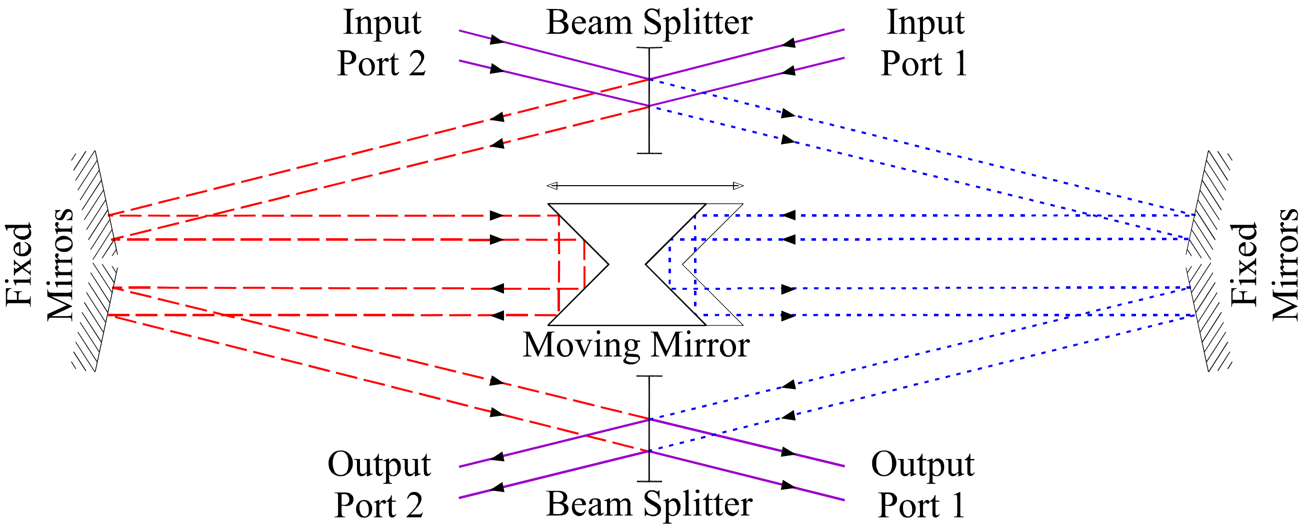

Figure 1. Schematic of a Mach-Zehnder FTS.

The Mach-Zehnder design has the advantage of being insensitive to polarization, while providing high and uniform efficiency over a broad wavelength range. The design provides access to the two input and two output ports of the interferometer. These ports could in principle view adjacent regions of the sky providing a differential measurement, or a reference blackbody calibration source could be viewed at all times with one port while the other views the astronomical source. In the latter configuration, sequential measurements with the blackbody set at two different temperatures allow the resulting spectra to be calibrated on an absolute intensity scale.

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. This beamsplitter uses two metal meshes in a Fabry-Perot configuration designed to meet the 50% transmission and 50% reflection criteria of an ideal intensity beamsplitter. One serendipitous feature of these beamsplitters is that they also function sufficiently well at optical wavelengths that a laser can be used to check the alignment of the interferometer.

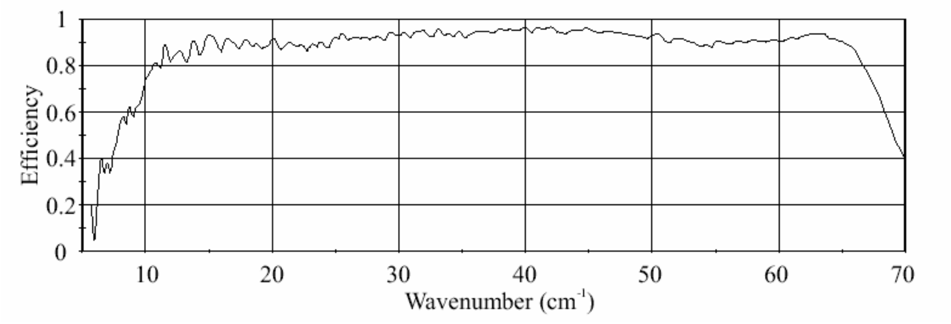

Figure 2. Measured beamsplitter efficiency.

The FTS design is based upon that of the SPIRE instrument[5] of ESA's Herschel mission. This design uses powered mirrors, in a symmetrical configuration, within the arms of the interferometer to minimize the size of the optical beam at the beamsplitter. The beamsplitter is often the most expensive component of an FTS and thus the aperture defining element. The interferometer will be assembled on a damped optical breadboard, with optical components housed in high-precision adjustable mounts. Stationary mirrors will be made from uncoated, diamond turned aluminium, the moving mirrors will be made as light as possible, possibly fabricated from carbon fibre substrates.

3.2 Mechanical

A distinguishing feature of the spectrometer is its large size, which is driven by the size of the SCUBA-2 input beam. It is not practical to build a spectrometer to process the entire SCUBA-2 field. Indeed the maximum field will be determined by the size of the beamsplitter. A conceptual layout of the FTS on the JCMT is shown in Figure 3.

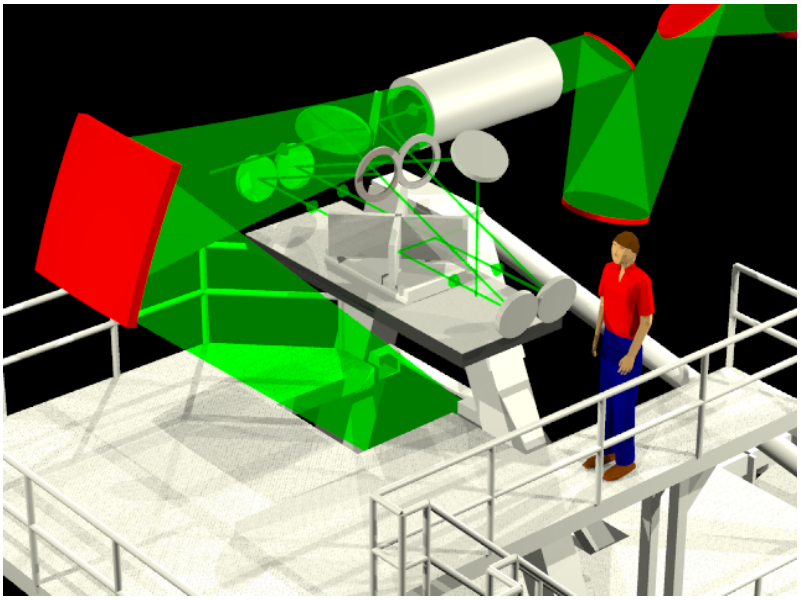

Figure 3. Conceptual model of the FTS mounting location near the left elevation bearing of the JCMT. The thin lines in the FTS represent the center of the beam.

The FTS will be mounted to the telescope framework just outside of the left elevation bearing where the SCUBA-2 beam forms an intermediate image before being redirected downwards to the detector system. The entire FTS will be protected by a cover to prevent the accumulation of dust. The mass of the FTS system will be roughly 500 kg, and the volume envelope will be approximately 3 m x 1 m x 1.3 m (LxWxH). Operation of the FTS will consist of moving the pickoff mirrors into the SCUBA-2 beam, scanning the moving mirror assembly to acquire interferogram data, and then retracting the pickoff mirrors once FTS observations are complete.

Central to the operation of the FTS is the precision linear translation stage, which allows high accuracy velocity and position control of the moving rooftop mirror assembly. An Aerotech[6] ALS5000WB brushless direct-drive linear motor translation stage has been selected which features zero backlash, zero windup, low friction, and high acceleration. These stages incorporate absolute encoders with interpolation electronics that allows sub-micron resolution.

3.3 Electronics

Motion control and position readout for the moving mirror assembly will be performed with an Aerotech motion controller unit. This unit will read the absolute Heidenhain position encoder and monitor the various limit switches. The motion controller and blackbody temperature controller will be interfaced to a control PC. This PC will 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.

In the design where the second input port views a calibration source, intensity calibration will be made possible by a cryogenic, variable temperature blackbody, 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 and reduce the burden on the SQUID flux-locked loops. The FTS system with a 73K blackbody does not raise the radiant loading on the pixels excessively, and, because of contingencies built into the detector design, even an ambient blackbody would fall within the designed detector loading capability of 30 pW under good weather conditions. While an ambient blackbody provides additional loading, at the level of the contingency, it will be useful for the testing phase of the FTS.

3.4 Software

Fourier spectrometers have the advantage of relatively simple optical and mechanical design, but the disadvantage of requiring complex data reduction software. Imaging FTS systems present an increased processing burden. The following sections describe the required control and data reduction software for the FTS.

The University of Lethbridge group has extensive experience designing control and analysis software for Fourier spectrometers, and most of the software required for the SCUBA-2 FTS will be based on a generic processing toolkit under development at the University of Lethbridge for the SPIRE project. A dedicated control PC will handle all FTS I/O and instrument control, while the data reduction software will run within the SCUBA-2 data reduction pipeline. The FTS control PC will take commands from the JCMT Observatory Control System (OCS) 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. Synchronization to the data acquisition system will be orchestrated by the JCMT Real Time Sequencer (RTS). The control PC will also monitor the various limit switches and FTS housekeeping parameters.

A display provided to the observer in the JCMT control room will include the following information:

- Status of the instrument; e.g. position of the pickoff mirrors, position and velocity of the moving mirror, blackbody temperature, time remaining, spectral resolution, error conditions, etc.
- A real-time image of the array; e.g. a frame from the standard SCUBA-2 quick look display sampled at the zero path difference (ZPD) location to show the broadband image.
- A means to display the last interferograms from a few representative pixels, as well as the corresponding spectra, for data quality assessment.

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 the highest spectral resolution (i.e. 0.005 cm^{-1} or 150MHz).

A data reduction pipeline for the FTS will be provided by the University of Lethbridge which takes as inputs the sequence of images in sky coordinates and the associated sequence of optical path difference (OPD) values, and produces a spectral data cube as output. The spectral data cube will be a stack of frames identical to normal SCUBA-2 frames, except that the frame header will contain a wavenumber or frequency index.

For single pixel FTS systems, manual inspection is feasible for interferogram processing. When faced with thousands of pixels, however, an automated data reduction pipeline is essential. The SCUBA-2 FTS pipeline will be based on a generic FTS processing pipeline under development at the University of Lethbridge for the SPIRE project, and must run within the main SCUBA-2 pipeline. A list of the main processing modules includes:

- Interferogram Processing
    - Quality inspection – The interferograms must be filtered automatically to remove or flag obvious bad scans, such as where the atmospheric correction fails, etc.
    - Glitch detection / removal (if necessary) – The SCUBA-2 pre-processing algorithms are designed to remove cosmic ray spikes, but spurious glitches must be filtered automatically from the data stream. Bad pixels, or saturated signal levels must also be handled.
    - Gain / atmosphere correction (if necessary) – If the system gain changes, or atmospheric transmission changes significantly during a long scan, the processing pipeline must correct the resulting signal variation.
    - Apodization – With an FTS the opportunity exits to modify the instrumental line shape post processing by the use of apodization functions. The goal of apodization is to reduce the side-lobes at the expense of lowering the spectral resolution.
- Fourier processing
    - Phase correction – Small sampling errors can result in phase distortions in the final spectra. In the case of linear phase errors, the OPD scale of measured interferograms must be shifted slightly so that data starts exactly at the zero OPD location. Non-linear phase errors require more sophisticated treatment.
    - Fourier Transform – A fast Fourier transform algorithm will be implemented to transform the interferograms into spectra in near real time so that one night's observations can be reduced well before the following night starts.
    - Wavelength correction – Different pixels will have slightly different wavelength scales due to the optics of the FTS, which must be corrected by interpolation onto the proper frequency grid.
- Spectral Processing
    - Quality inspection – The observer will be able to inspect individual spectra in the reduced data cubes to verify that the processing pipeline and instrument are configured properly. Failure of the phase correction routine is generally catastrophic and readily detected.
    - Spectral Math (averaging, differencing, etc) – The observer will specify a script that will perform basic operations on a set of observations. Filter characteristics will be corrected for by subtracting background spectra from the source spectra. It will also be possible to average a set of spectra, and stitch data cubes together to produce larger area data sets.

4. OBSERVING MODES

Typically, an FTS is used in 'continuous scan' mode, where the moving mirror assembly is scanned at a constant velocity, and the detector samples the interferogram on a uniform OPD grid. This requires that the sampling be triggered by the mirror position. In the case that the samples are acquired on a non-uniform grid, extra processing involving the Fourier transform of irregularly sampled data is required. A common alternative method is the 'step-and-integrate' mode, where the moving mirror assembly is moved in discrete steps and held stationary at each position while the detector integrates. Both of these modes are options for the SCUBA-2 FTS, and are discussed below:

4.1 Continuous Scan Mode

With SCUBA-2, raw frames are read out at a fixed (200 Hz) rate independent of the FTS, and mirror positions are therefore recorded synchronously with the detector frames. In reality no translation stage can move at constant velocity and so the resulting interferograms will not be uniformly sampled and the data will have to be processed using a non-uniform FT algorithm.

A complication of the SCUBA-2 detectors is that rapid changes in the interferogram intensity near the ZPD position of the FTS can cause the SQUID amplifiers to lose lock. One solution to this problem is to view the astronomical source through one port while viewing a cold load in the other; the temperature of the cold load being chosen so as to minimize the difference between the fluxes reaching each port. It is, however difficult to design a cold load that will simultaneously match the radiant loading in both the 850 and 450 μm bands. Moreover, unlike the SPIRE IFTS, which has only to cancel the stable background radiation from the Herschel telescope, SCUBA-2 must deal with the emission from the atmosphere which is particularly variable in the 450 μm band. A second solution is to have both input ports view different sky positions. The resulting modulation depth, which is related to the difference between the radiant flux observed in each port, will be minimized automatically as both inputs will view essentially the same telescope and atmosphere. In the case that the modulation near ZPD is still beyond the capabilities of the SQUID amplifiers, the stage scanning speed can be reduced in the vicinity of the ZPD position to accommodate the large dynamic range of the signal at this location.

When operating with both input ports viewing the sky the FTS measures the difference between the radiation reaching each port and thus cancels variations due to atmospheric emission, however, variations in atmospheric transmission cannot be corrected for. The goal of the continuous scan mode is to acquire an interferogram as quickly as possible so that the atmospheric transmission is nearly constant throughout the scan. The SCUBA-2 FTS will have a full resolution scan time of ~30 seconds and a lowest resolution scan time in the order of a second, which will significantly reduce susceptibility to sky noise.

4.2 Step-and-integrate Mode

In the step-and-integrate mode, the optical path difference in an interferometer is incremented in discrete steps, and data is read out only when the mirrors are stationary. This mode is used when some additional means is available for modulating the signal, such as chopping the secondary mirror so that a single pixel system alternately views source and background. Imaging detector systems must use more complex signal modulation schemes.

The proposed modulation scheme for SCUBA-2 is the DREAM mode[7], in which the telescope secondary mirror unit performs a jiggle pattern for atmospheric correction; this mode has the potential of producing atmosphere and sky rotation corrected images, which would allow the SCUBA-2 FTS to use a step-and-integrate mode where the moving mirror is held stationary at discrete intervals of OPD while the DREAM jiggle pattern takes place. Provided that the DREAM mode can be implemented, the FTS scan duration will be less affected by the stability of the atmosphere, and the integration time at each position can be made to be long relative to the time to move the mirrors in order to increase observing efficiency. It should be noted that when using the DREAM mode, the second input port must view a stable cold load.

The DREAM mode has the disadvantage of only producing corrected images at a ~ 1 Hz rate, which is prohibitively slow since high resolution scans would take nearly 1.5 hours. Since the SCUBA-2 filters have extremely high out-of-band rejection, however, the interferograms may be sampled more sparsely than the normal DC band limited Nyquist sampling rate, and the resulting aliasing of the spectra can be easily removed. This will allow high resolution spectra (0.005 cm^{-1}) to be obtained in an integration time of ~ 20 minutes, and low resolution spectra (0.1 cm^{-1}) in ~ 1 minute.

From information theory the highest frequency component that can be unambiguously recovered is determined by the Nyquist sampling theorem:

$$\Delta x \le \frac{1}{2 \cdot \sigma_n}$$

where Δx (cm) is the OPD sampling interval and σ_n is known as the Nyquist frequency (cm^{-1}). Implicit in this relation is the assumption that there are signal components spanning the interval from 0 to the Nyquist frequency. With a band limited signal, the minimum OPD sampling interval can be determined from the Shannon sampling theorem:

$$\Delta x \le \frac{1}{2 \cdot (\sigma_{\max} - \sigma_{\min})}$$

where $\sigma_{\min}$ and $\sigma_{\max}$ are the limits of the signal band.

Figures 4a and 4b show the interferograms for the 850 and 450 μm SCUBA-2 spectral bands and the sample points needed to recover these spectra as given by the DC band limited Nyquist criteria for the 450 μm band (Δx = 0.02 cm OPD, σ_n = 25 cm^{-1}). The spectra shown in Figure 4c represent the atmospheric transmission at Mauna Kea multiplied by the SCUBA-2 filter transmissions. Although the 850 μm filter is narrower and has a lower upper pass band limit than the 450 μm filter, it is the 450 μm filter that sets the design limit because both signals are sampled simultaneously. Based on the width on the 450 μm filter and the Shannon sampling theorem, the maximum sampling interval for the SCUBA-2 system is 0.1 cm OPD which results in a Nyquist frequency of 5cm^{-1}.

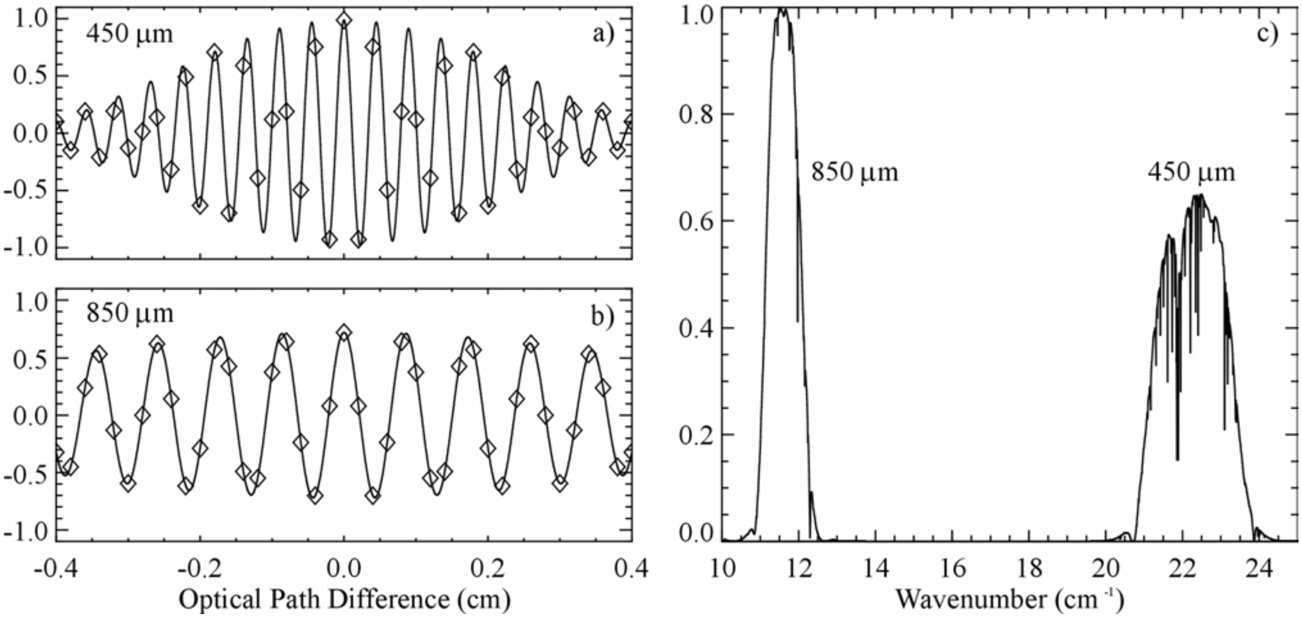

Figure 4. a) Interferograms for the 450 and 850 μm (b) spectral bands, symbols represent the DC band limited Nyquist sampling intervals. c) The 450 and 850 μm filter bands showing atmospheric transmission features.

Increasing the sampling interval from that determined by the DC band limited Nyquist frequency, results in aliasing of the signal spectrum. Figure 5a shows the aliasing that occurs when sampling the 450 μm signal at OPD intervals of Δx = 0.025 cm OPD, corresponding to a Nyquist frequency of σ_n = 20 cm^{-1}. The original spectrum is folded about the Nyquist frequency and appears reversed. The spectral integrity is maintained, however, since the 450 μm optical filter has rejected those frequencies outside the pass band, and the original spectrum folds into a region with zero signal. To illustrate the dangers of aliasing, Figure 5b shows the case where the sampling interval Δx = 0.2 cm OPD, corresponding to a Nyquist frequency of σ_n = 2.5 cm^{-1}. Here, part of the original spectrum folds back upon itself, resulting in a distortion of the spectrum that is impossible to correct.

Since the FTS observes both the 850 and 450 μm bands simultaneously, the challenge is to find a sampling interval that will alias both bands such that neither loses spectral integrity. By selecting a sampling interval of Δx = 0.1 cm OPD, corresponding to a Nyquist frequency of σ_n = 5 cm^{-1}, spectra from both bands can be retrieved, as shown in Figure 6b. Figure 6a shows the corresponding ‘under-sampled’ interferogram for the 450 μm band. This technique provides at least a factor of five reduction in the required sampling rate over a DC band limited measurement, which translates to a factor of 5 decrease in scan time for the step-and-integrate mode. This is only possible due to the high out-of-band rejection of the SCUBA-2 filters.

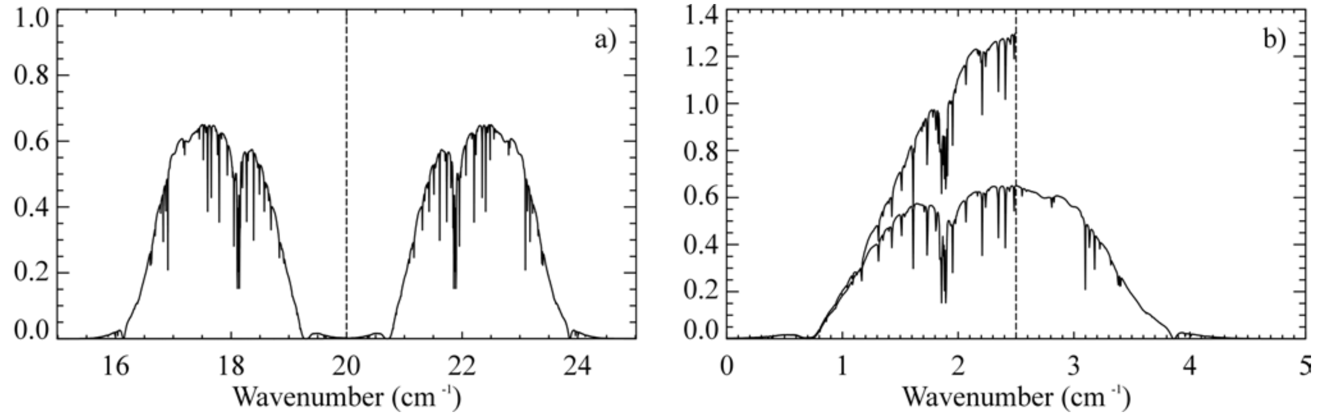

Figure 5. a) Aliasing of the 450 µm spectrum when sampled with a 20 cm^{-1} Nyquist; original spectrum is on the right, aliased spectrum is on the left. b) Example of a poor choice of sampling interval, resulting in part of the band being aliased back onto itself (upper spectrum). Nyquist frequencies are shown as dotted lines.

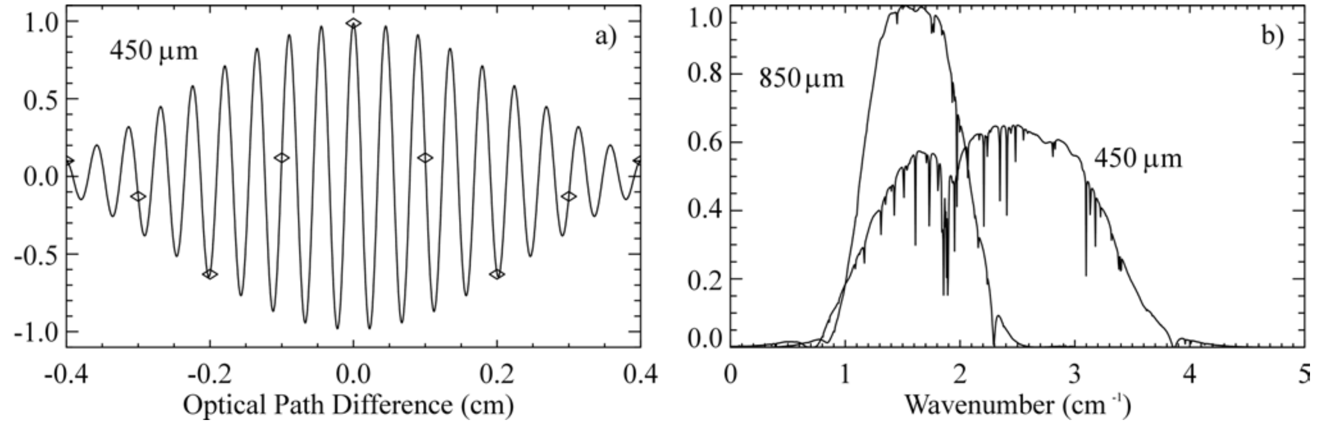

Figure 6. a) 450 µm interferogram; symbols represent the sampling interval corresponding to a Nyquist of 5 cm^{-1}. b) Fully resolved 450 and 850 µm spectra sampled with the same 5 cm^{-1} Nyquist.

5. PREDICTED PERFORMANCE

The performance of the SCUBA-2 FTS can be estimated by comparison with results obtained with a single pixel Mach-Zehnder FTS[4] currently operating at the JCMT. The starting point in this analysis is to calculate the NEP of the SCUBA-2 detectors. Detailed radiative transfer modeling of the Mauna Kea atmosphere, JCMT telescope, SCUBA-2 and FTS optics provides detector power loading levels from which NEP values can be determined. Table 1 shows these estimates for excellent and good atmospheric conditions corresponding to 0.5 and 1 mm precipitable water vapour (PWV), respectively. These NEP values are over an order of magnitude better than current single pixel systems.

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

	0.5 mm PWV	1 mm PWV
Total Power Loading (pW)	11.5	12.3
Overall NEP (W/√Hz)	$8.5 \cdot 10^{-17}$	$8.7 \cdot 10^{-17}$

The effective field-of-view that the FTS can process will be determined primarily by the beamsplitter aperture, and will require more detailed optical modeling. It is expected that at a minimum it should be possible to place two 3 x 3 arc minute fields on the sky in the dual input port mode. In the step-and-integrate mode, where only one port views the sky, it should be possible process a single 4 x 4 arc minute field. The resolution of the FTS can be varied between 0.005 and 0.1 cm^{-1}; Table 2 gives the corresponding scan times for the continuous scan and step-and-integrate observing modes.

Table 2. FTS operational parameters.

	Continuous Scan		Step-and-integrate	
Resolution (cm^{-1})	0.005	0.1	0.005	0.1
Resolution (MHz)	150	3000	150	3000
Scan Time (sec)	30	1	1200	60
Estimated Field of View (arc minutes)	~ 3 x 3		~ 4 x 4	

Given the NEP values in Table 1 and the estimated efficiency of the FTS, the spectral sensitivity can be readily calculated[8] for the 850 μm band. The variability of atmospheric transmission and emission in the 450 μm band makes sensitivity estimates less predictable. The estimated 1-σ uncertainty in temperature expressed in mK, for an integration time of one hour, as a function of resolution and wavelength, is given in Table 3.

Table 3. FTS sensitivity for 450 and 850 μm.

	850 μm		450 μm	
FTS optical efficiency[i]	43.7%			
System transmission[ii]	23%			
Resolution (MHz)	150	3000	150	3000
Resolution (cm^{-1})	0.005	0.1	0.005	0.1
NEP (W/√Hz)[iii]	$8.5\cdot10^{-17}$	$8.5\cdot10^{-17}$	$\sim4\cdot10^{-16}$	$\sim4\cdot10^{-16}$
1-σ ΔT sensitivity in one hour integration (mK)	2	0.1	~10	~0.5

6. CONCLUSIONS

In this paper we have presented the conceptual design 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. By using powered mirrors within the arms of the interferometer, the size of the optical beam at the beamsplitter is minimized. 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 instrument design recently successfully passed a conceptual design review, and the project will now proceed with detailed optical modelling.

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[i] Efficiency for an ideal dual output FTS is 50% at each output.

[ii] Transmission from the JCMT membrane and dish, through the SCUBA-2 feed optics and FTS, to the detectors.

[iii] NEP values at 450 μm have not been fully modeled.

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