SCUBA-2 FTS Project Office
University of Lethbridge
Physics Department
4401 University Drive
Lethbridge, Alberta
CANADA
T1K 3M4

Tel: 1-403-329-2771
Fax: 1-403-329-2057
Email: brad.gom@uleth.ca
WWW: http://research.uleth.ca/scuba2/

Document Title:	**Proposal to the JCMT Board for Approval of a Facility Fourier Transform Spectrometer for SCUBA-2**
Issue:	**Version 1.0**
Date:	**25 October 2003**

Document Prepared By:	B. G. Gom FTS Project Manager	Signature and Date:	Brad Gom	25/10/2003
Document Approved By:	D. A. Naylor FTS Project Lead	Signature and Date:	David A Naylor	25/10/2003
Document Released By:	J. Molnar Canadian Project Manager	Signature and Date:	[illegible]	25/10/2003

Change Record

Issue	Date	Section(s) Affected	Description of Change / Change Request Reference / Remarks
0.1	15/10/2003	All	First draft version
1.0	25/10/2003	All	First release version

Contents

1. Executive summary

SCUBA-2 is a highly innovative wide-field camera designed to replace SCUBA and will 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 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. The imaging spectrometer will therefore open 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, 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 Centre, 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 programme. In order to minimize the pecuniary risk to the funding institutions the project and instrument is subject to a number of reviews. The FTS, which is an ancillary instrument to SCUBA-2, is also subject to a number of reviews. The FTS, which is being developed by Dr Naylor's group at the University of Lethbridge, in close cooperation with the UK ATC, successfully passed its Conceptual Design Review on the 30th July 2003.

The SCUBA-2 FTS design is based on the Mach-Zehnder design that has been adopted for the SPIRE instrument of ESA's Herschel mission and the University of Lethbridge spectrometer currently operating at the JCMT. 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, a cryogenic blackbody calibration source, and associated framework. The Electronics consists 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 of 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.

The FTS will be mounted within the support structure for the SCUBA-2 mirror N1, just outside the left elevation bearing of the JCMT. The control PC will be mounted at a convenient distance to the FTS instrument, and will communicate with the RTS and SCUBA-2 network via fibre optic links.

There are a number of challenges associated with the FTS design. Key amongst these are:

- Designing a system of acceptable size and resolution that will accept approximately a 3'x3' field of view
- Design a processing pipeline that will produce calibrated hyperspectral data cubes as a science product.

These challenges are addressed in the following sections.

Dr Naylor's group has over 40 years combined experience in the design, construction and use of FTSs in astronomical research. Dr Naylor is the Canadian PI on the Herschel/SPIRE project and, as part of Canada's contribution to this project, has recently delivered a FTS, a key component of the ground test equipment for SPIRE, to the Rutherford Appleton Laboratory, Oxford (RAL). At a cost of ~$600,000 this instrument was delivered on time and under budget to RAL, on a very demanding time scale of less than one year. This success relied on extensive project management and hardware/software documentation demanded by the interfaces with ESA.

2. Science Case

This section describes the science case for the development of a medium resolution FTS for SCUBA-2. The scientific aims of the FTS seek to capitalize on the imaging power and sensitivity of the SCUBA-2 camera, and extend its capabilities to include simultaneous medium resolution imaging spectroscopy across the 450 and 850 µm atmospheric windows. 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 FTS. Since the spectral resolution of a FTS can be adjusted instantly, the resolution can be optimized for the scientific problem at hand. Examples of three areas of interest are given below:

2.1. Extragalactic astronomy

One of the most exciting astronomical discoveries in the last two decades has been the class of Ultraluminous Infrared Galaxies (ULIRGs). These are among the most powerful objects in the local Universe with far-IR luminosities exceeding 10^{12} L_O. They are often colliding or merging galaxies, and it is likely that the mergers caused the inordinate far-IR luminosities, by either compressing the natal ISM triggering a global starburst, or by triggering accretion onto a central massive black hole forming an active galactic nucleus (AGN). The extragalactic submillimetre community is engaged in projects that require some understanding of the Spectral Energy Distribution (SED) of the dust emission from ULIRGs. Unfortunately, our knowledge is limited to only a handful of photometric measurements in even the best studied bright sources. In particular, the dust emissivity is determined essentially by fitting a line between fluxes measured with SCUBA at 450 and 850 µm. The problem with this approach is that 450 µm observations are typically difficult to obtain and calibrate, and the 850 µm fluxes have a non-negligible contribution from CO line emission. Also, the assumption used in these fits is that the SED is dominated by a single dust temperature/emissivity, which in many cases is known to be wrong. By using an FTS to measure the SED across the 850 µm band, one can escape many of these issues and determine the emissivity directly.

An early, groundbreaking result from SCUBA was the measurement of 104 nearby Luminous Infrared Galaxies (LIRGs) detected by IRAS. By using the 60, 100, and 850 micron fluxes, along with a simple model for the shape of the dust SEDs, Dunne et al.[1] fit the temperature and dust emissivities of the sources. The SEDs of this Scuba Local Universe and Galaxy Survey (SLUGS) sample are now used in photometric redshift estimators for the more distant ULIRG population ($z > 1$).[2,3] However, it is now clear that using continuum measurements alone can bias the fits. In particular, recent heterodyne observations of this sample by Yao et al.[4] reveal that a significant fraction, ranging from 20 to 50%, of the continuum flux measured by SCUBA in the 850 µm band is, in fact, due to CO 3-2 line emission. There is also increasing evidence that ULIRG SEDs are better fit by using multi-temperature models. This is revealed in part by 450 µm observations of 17 of the SLUGS.[5] At these shorter wavelengths, the strength of the emission is particularly sensitive to the SED model, as it lies near the peak of the thermal emission. Heterodyne observations of these galaxies are useful for charactering their line emission, but their narrow bandwidth means that little can be learned about the shape of the underlying continuum. This is where a low resolution, broadband spectroscopic observation can be particularly useful. With the proposed FTS it will be possible to measure, simultaneously, the slope of the dust emissivity across both the 450 and 850 µm bands. Obtaining this information in both bands is particularly useful since the short wavelength observations, in addition to being substantially more difficult due to the poor atmospheric transmission and stability, are near the thermal peak of the SED, and hence more difficult to interpret.

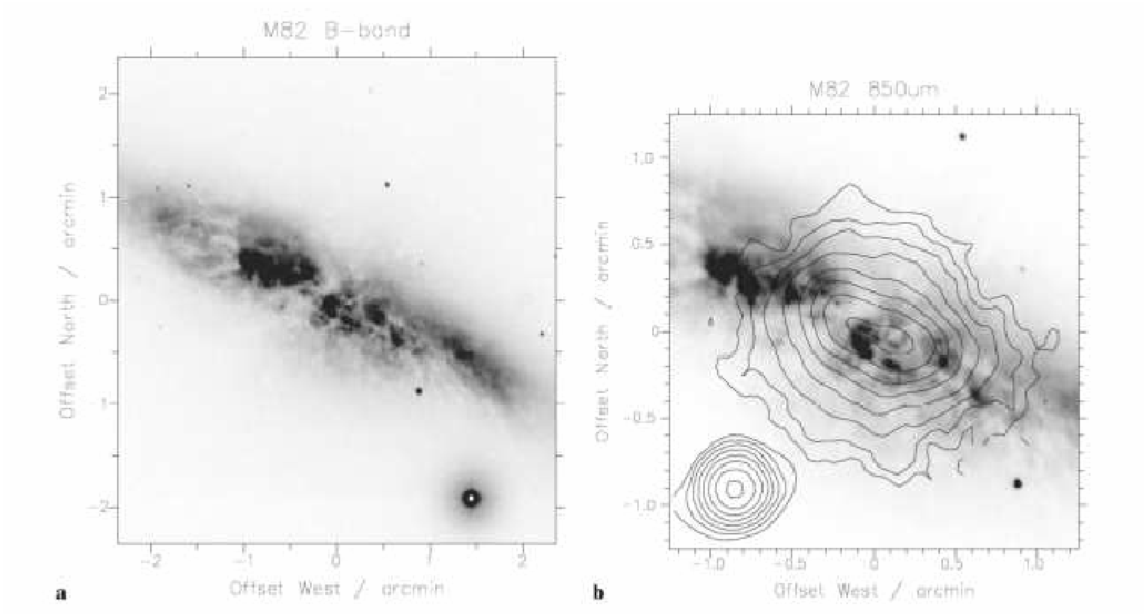


Figure 1. M82 as seen by SCUBA at 850 µm. The panel on the left is the B-band optical image. On the right is a close-up of the central region, with SCUBA contours overlaid. The emission is clearly extended beyond the SCUBA beam, which is shown in the bottom left corner of the panel. (Figure taken from Alton et al. 1999 [6])

By way of illustration, M82 is a nearby, well studied ULIRG, and is the brightest member of that class in the sky (Figure 1). With the estimated sensitivity given in Table 1 and using previous results from the CSO[7], it will be possible to obtain spectroscopic maps 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.

The temperature sensitivity of an FTS, σ, can be determined using the following equation:

$$\sigma = \frac{4 \cdot \mathrm{NEP}}{k \cdot \Delta\upsilon \cdot \sqrt{2 \cdot t}}$$

where k is Boltzmann's constant, Δυ is the spectral resolution in Hz and t is the total integration time:

Table 1. Estimated FTS temperature sensitivities.

	850 µm		450 µm	
Resolution (MHz)	150	3000	150	3000
Resolution (cm^{-1})	0.005	0.1	0.005	0.1
NEP (W/√Hz)	$8.5 \cdot 10^{-17}$	$8.5 \cdot 10^{-17}$	$\sim 8 \cdot 10^{-16}$	$\sim 8 \cdot 10^{-16}$
1-σ ΔT Sensitivity in one hour integration (mK)	≥2	≥0.1	~10	~1

A more ambitious project, and one which may be possible with the proposed FTS[8], is a redshift survey of SCUBA sources. The SHADES/BLAST team estimates that their photometric uncertainty in z will be ~0.5[9]. This uncertainty is equivalent to a 30 GHz resolution element when observing a CO 1-0 line from a galaxy at z = 2! While many interesting SCUBA sources are expected to be at the 10 mJy level, which translates to a temperature of ~0.5 mK, the sensitivities in Table 1 would indicate that observations of such sources at low resolutions of 3 GHz may lie within the capabilities of the proposed system and provide a much better estimate of the redshift. For example, the redshifted CO 7-6 line observed at a spectral resolution of 3 GHz in the 850 µm band would trace redshifts in the range of 1.24 to 1.45 with a resolution of 0.02. Higher CO transitions will trace will higher z regimes. To assess the feasibility of such observations, measurements of the submillimetre fluxes of nearby bright IRAS sources could be compared with FTS measurements of redshifted CO lines and the results extrapolated to high redshift to estimate the applicability of the FTS for this work. The known redshift of M82 has been confirmed via the CO 3-2 line observed with the University of Lethbridge FTS using a far less sensitive single pixel detector.

2.2. Interstellar medium

One of the most important problems in modern astronomy is to understand the formation of stars and planets, which has implications for other branches of astronomy on all scales from galaxy formation to solar system formation. To understand the formation of stars, however, we must first understand the detailed physics and chemistry of the interstellar medium (ISM). The ISM is where the material is collected together to form, first of all, dense clouds, and ultimately stars. There are many processes within these clouds that have a bearing on star formation. These include heating and cooling of the gas and dust, turbulent support and magnetic fields.

Since the general ISM is too hot to collapse to form stars, the cooling of gas clouds is of singular importance to star formation. This cooling process is complex and involves dust grains shielding the dense clouds from the general inter-stellar radiation field (ISRF), as well as cooling radiation from molecules and grains. Disentangling these different processes and understanding their complex interplay and relative importance is a significant problem. The proposed FTS will attack this problem in several ways:

It will provide simultaneous measurements of both the continuum and line emission across the whole atmospheric windows at 450 and 850 μm at every point in ~9 square arcminute field of view at up to 150 MHz spectral resolution, and at the diffraction limited spatial resolution of the JCMT. This will provide a spectrum at every point in the image of a molecular cloud. Individual spectra can be analyzed to determine the total continuum flux and its spectral index, as well as the detection of strong emission lines from the many molecules that are expected to play a role in the radiative balance of the cloud. Such a data cube will provide a unique resource, unmatched by any other facility on any other telescope. The spectral index variation across a cloud yields information on the variation of dust grain properties such as temperature, optical depth and grain emissivity. The latter embodies information on dust grain growth and dust destruction.

For lower resolution spectral energy distribution (SED) observations, the important measure is not the flux at a particular wavelength, but rather the change in the flux across the 850 μm band. For typical thermal dust radiation conditions, the variation is expected to be between ten percent and forty percent, depending on the dust temperature and emissivity. Thus, for meaningful interpretation of the SED, measurements of the relative flux in each spectral element to an accuracy of ~1 percent are required. From the sensitivities given in Table 1, this accuracy should be achievable at a resolving power of 10 in about one hour. Table 2 gives estimated sensitivities for line and continuum observations with the SCUBA-2 FTS.

Table 2. Estimated FTS line and continuum sensitivities.

Observing Time	3-sigma line (150 MHz)	3-sigma SED source (3000 MHz)
2.4 min	50 K km/s	2500 mJy/bm
1 hr	10 K km/s	500 mJy/bm
25 hr	2 K km/s	100 mJy/bm

Over a smaller instantaneous field of view than the SCUBA-2 FTS, HARP-B operating at a resolution of 1 km/s can measure a 2 K km/s line to three-sigma sensitivity in the time it takes the FTS to reach 50 K km/s. Thus, for a known narrow line HARP-B is much more efficient than the FTS. For a broad (~150 MHz) line, however, HARP-B is less efficient by about an order of magnitude. Moreover, the FTS is more effective for continuum measures of the SED.

The SCUBA-2 FTS has an additional advantage in that it offers complete coverage of the ~30 GHz window, observed under the same instrumental settings and atmospheric conditions, compared to only ~2 GHz for HARP-B. Indeed the detection of molecular lines with the FTS will pave the way for high-resolution follow-up observations with instruments such as HARP.

Simultaneous mapping of dust emission and spectral index together with molecular line detection from significant molecules, such as CO, CS, OH, HCN, HCO+, etc., and major isotopomers of these lines, will provide an extremely powerful set of diagnostics of the physics and chemistry of the molecular cloud region being studied. For example, any significant bipolar outflows in the cloud will be visible in the main CO lines. These can be relatively wide and hence contain significant flux that would otherwise contaminate continuum measurements made without a spectrometer.

The variation in relative line strengths from one molecular species to another yields detailed information on the chemistry of a region. The first step in the chemistry of the ISM is believed to be the formation of molecular Hydrogen from atomic Hydrogen on the surfaces of dust grains. Thereafter, the molecular Hydrogen is released back into the gas phase, where it participates in what is now known to be a rich chemistry. In general, ion-neutral reactions proceed faster than neutral-neutral reactions, and the primary reactions are believed to be initiated by cosmic rays (cr):

$\mathrm{H2 + cr \rightarrow H2^{+} + e^{-}}$

$\mathrm{H2^{+} + H2 \rightarrow H3^{+} + H}$

$\mathrm{H3^{+} + O \rightarrow OH^{+} + H2}$

Thereafter, the OH+ drives the oxygen chemistry. A similar sequence occurs for the carbon chemistry. There are now known to be some 120 molecular species that have been identified in space, up to about 13 atoms in size. To build a chemistry that explains their existence a number of chemical models of networks containing some 400 species interacting in about 4000 chemical reactions have been developed. An understanding of these reactions is central to the interpretation of molecular chemistry in the ISM.

Producing a map of such a molecular cloud in one or two molecular line tracers is currently a slow process. Furthermore, the resultant map does not simply trace gas density, since a given species can be formed and destroyed by different chemical reactions in different parts of a cloud, and variations in the intensity of a single spectral line could therefore simply be mapping variations in the chemical processes across a cloud. Furthermore, molecules can be frozen out of the gas phase onto the surfaces of dust grains in regions of high density and low temperature. Thus, in the very regions most likely to form stars, single molecular line tracers can suddenly appear to decrease in column density.

Likewise, the mapping of the continuum emission across a cloud, whilst being a tracer of the dust density, is also complicated by variations in dust grain parameters. Hence, a single waveband SCUBA continuum image traces a combination of density, temperature, grain emissivity and optical depth, all convolved in some fashion that is not easily disentangled. The SCUBA-2 FTS will allow these parameters to be separated from one another by providing a simultaneous line and continuum spectrum across an entire waveband at every point in a molecular cloud. Indeed, recent measurements (Figure 2) obtained with the University of Lethbridge FTS operating with a single detector at the JCMT have shown that Fourier spectroscopy is capable of differentiating continuum and line emission in complex regions like the Orion molecular cloud, although only at discrete locations.

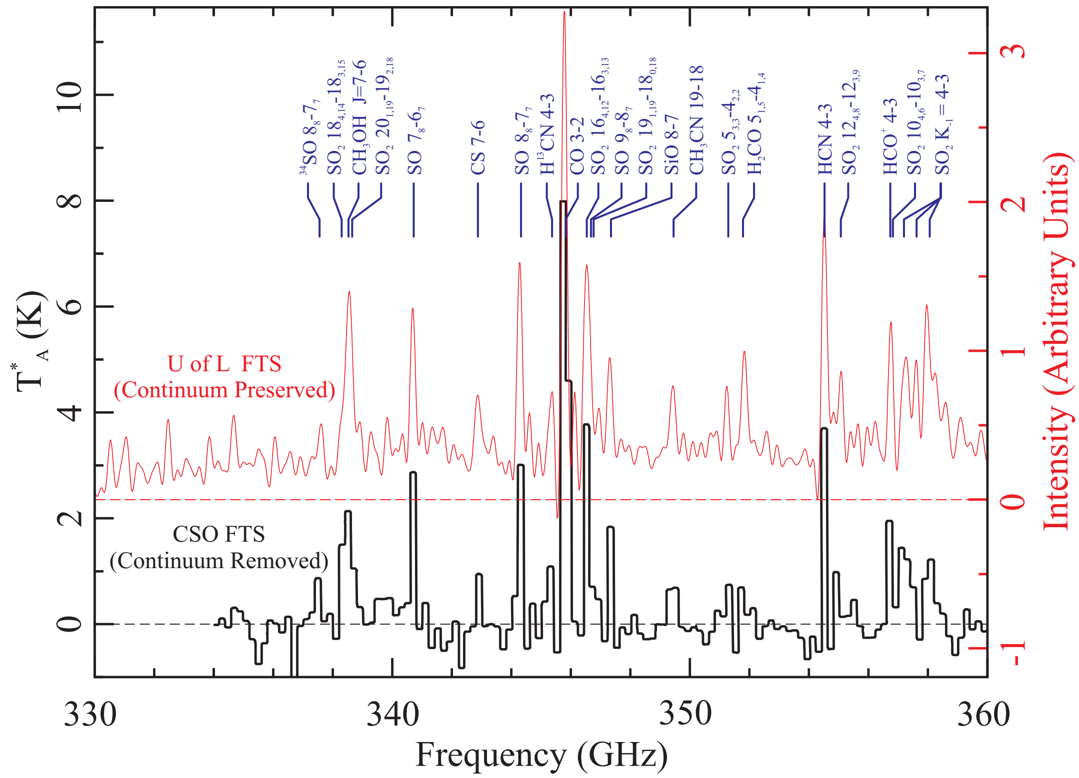


Figure 2. FTS observations of Orion Kl region: Lower trace (left scale) Serabyn and Weisstein[7], upper trace (right scale) Lethbridge FTS spectrum at 850 µm. Note the higher resolution and clear identification of several lines and detection of continuum emission under less than ideal conditions.

The northern part of the Orion A molecular cloud, which has been mapped by SCUBA at 850 and 450 µm with angular resolutions of 14" and 8", respectively, exhibits the greatest known concentration of Class 0 protostars, shock excited molecular hydrogen and CO outflows. The submillimetre images reveal a remarkable chain of compact sources embedded within a narrow, high column density, integral shaped filament that extends the length of the map, with faint extended structure surrounding it. The spectral index determined from the 450 and 850 µm maps is uniform except for the peak ridge sources, the photo-heated edges of HII regions (including the Orion Bar), and the location of the brightest molecular hydrogen shocks.

While some of the compact sources observed in the continuum maps contain extremely young protostars, others may be pre-collapse phase cloud cores. Without corresponding spectral line observations it is virtually impossible to separate pre-collapse and post-collapse cores with the angular resolution provided by SCUBA. The lower spectral indices observed for the compact sources with respect to the filament may indicate a change in the physical conditions, such as lower temperatures or flatter dust emissivity functions within the cores, or they may be indicative of variable contributions from molecular line emission within the SCUBA bands.

Molecular line emission is known to be significant in the Orion KL region of Orion molecular cloud. For example, at 850 µm the peak flux in a 14" beam is 167 Jy, yet the contribution from line emission is between 25 and 50%. While the ^{12}CO 3-2 line is the strongest single line in the 850 µm band, emission from a plethora of weaker SO and SO_2 lines dominates the total line emission. Figure 3 compares heterodyne spectra of the Orion KL and S regions, and shows the differences between these regions. It is clear that spectral index measurements alone cannot be interpreted directly in terms of temperature and dust properties.

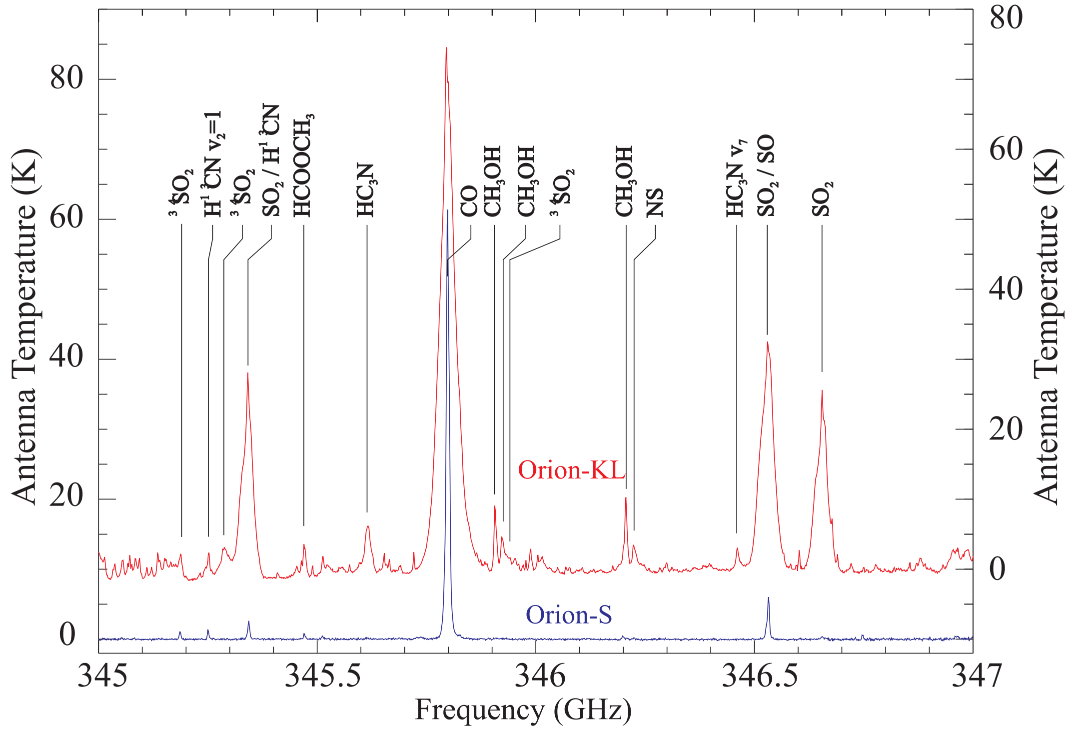


Figure 3. Heterodyne spectra of the Orion KL and S regions taken with Rx B3 on the JCMT.

When the heterodyne spectrum of the KL region shown in Figure 3 is convolved with a sinc function corresponding to the instrumental line shape of the University of Lethbridge FTS of resolution 0.005 cm^{-1} and compared with data obtained with this FTS, as shown in Figure 4, there is seen to be excellent agreement. The SCUBA-2 FTS will provide an improvement of over 4 orders of magnitude in spectral mapping over this system, due to a factor of 10 increase in detector sensitivity and 10^3 in mapping speed.

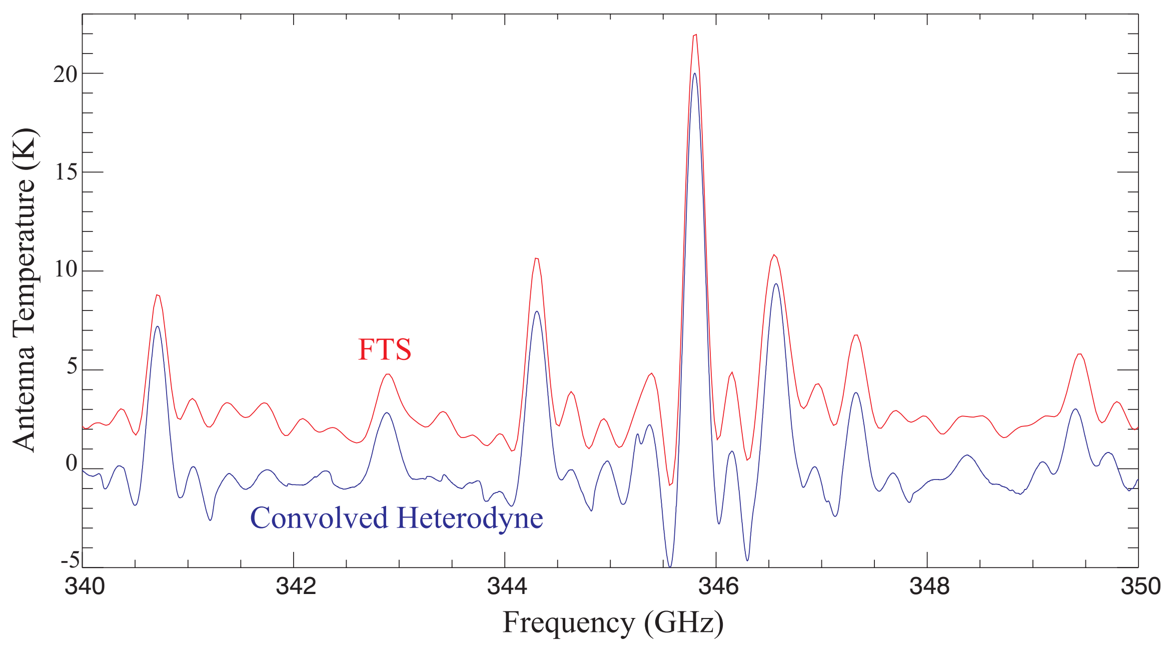


Figure 4. Comparison of FTS and convolved heterodyne spectra offset for clarity.

To date, theoretical modeling of the ISM has outpaced observations. There are complex theoretical chemical codes available that include the reaction rates for a few thousand chemical reactions. There are also radiative transfer codes that can predict the observed molecular line intensities across a molecular cloud for any of several hundred molecular lines. What is now required is a set of large data-cubes covering many lines and the continuum across many different molecular cloud regions to allow a detailed comparison between models and observations, and to differentiate between the many theoretical models that currently exist.

The SCUBA-2 FTS will provide just such a series of datasets. It will allow observers to calculate detailed abundances of many important molecular species as a function of position in the cloud. From these data it will be possible to calculate where specific molecular lines have become optically thick, and where molecular species are being depleted due to chemical reactions. It will also be possible to determine those locations where molecules are being frozen out onto dust grains due to increased density and a decrease in temperature. In short, the SCUBA-2 FTS will give an instantaneous snapshot of the primary physical and chemical parameters across a molecular cloud. This will provide a significant step forward in our understanding of the physical conditions of star forming regions.

2.3. Planetary Atmospheres

The submillimetre region is a particularly rich field of study because it is the region of maximum intensity for the rotational lines of many potential atmospheric constituents. Spectroscopic measurements provide an inventory of molecular species and information on the physical and dynamical processes (e.g. internal heat sources) of the atmosphere. Observations of the giant planets also provide an important database for calibrating astronomical sources. With its broad spectral coverage and intermediate resolution, an FTS is ideally suited to measuring the pressure broadened tropospheric absorption features in planetary atmospheres.

It is evident that current theoretical models do not fully describe the observed spectra of the giant planets at submillimetre and far-infrared wavelengths. For example, reported brightness temperature measurements of Jupiter differ significantly in the region from 350 to 500 µm.[10,11,12] Although these measurements are photometric, attempts have been made to compare the results with theoretical models of the Jovian atmosphere. The principle sources of atmospheric absorption (pressure induced absorption of H_2-H_2, H_2-He; gaseous absorption of NH_3, PH_3, CO and NH_3 cloud particles) are found to be insufficient to explain the observed results. Model spectra of the giant planets at submillimetre wavelengths have revealed a plethora of lines arising from NH_3, PH_3, HCN and CO, and a wide range of non-equilibrium species.[13] The detectability of such molecular species from their rotational transitions has been addressed by Encrenaz.[14]

Recent measurements of the submillimetre spectra of Jupiter and Saturn[15] yielded three results: first, detection of the PH_3 3→2 transition in both planets; second, a tentative detection of the HCI 1→0 transition in Saturn (though not in Jupiter); and third, non-detection of a number other halides, including HBr, LiH, NaH, HCN and HCP (see Figure 5). The detection of HCI is surprising since chlorine is a trace constituent in solar-composition objects. The atmospheres of both planets are highly convective, due to their internal heat sources, and as the gas rises from the hot deep interior and cools, HCl should react with gaseous ammonia (plentiful by comparison) and condense to form solid NH_4Cl particles.[16] This occurs well below detectable levels, at a pressure of ~ 20 bar; the tenuous cloud layer formed by this process is not visible to telescopic observations due to the presence of three thicker overlying layers (H_2O, NH_4SH and NH_3).

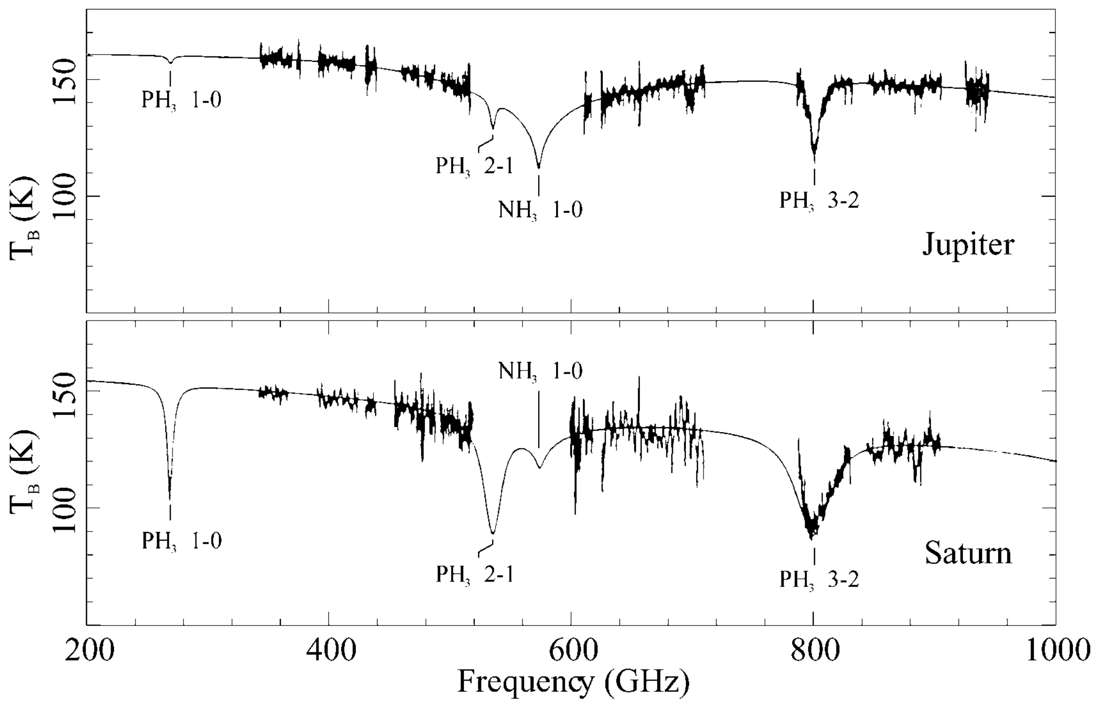


Figure 5. Submillimetre spectra of Jupiter and Saturn[15]

The only mechanism by which HCl could evade condensation and exist in the upper troposphere is if the vertical transport is significantly faster than the chemical equilibration lifetime. This is the same mechanism by which phosphine reaches observable levels and the detection of PH_3 at submillimetre[15] and infrared wavelengths, in both Jupiter and Saturn attest to the strength of the convection. On the other hand, the absence of H_2S at observable levels serves as a counter-example: this gas is more abundant than HCl but condenses thoroughly to NH_4SH and has never been detected. Recent analysis of the Galileo Probe Mass Spectrometer (GPMS) data has resulted in a tentative detection of HCl [17] (although the GPMS sampled a point location on the planet which may be unrepresentative of the global emission). Bezard *et al.* have shown that all of the hydrogen halides are potentially detectable at submillimetre wavelengths.[13]

The increased sensitivity of the SCUBA-2 FTS and small diffraction limited JCMT beam of 7" at 450 µm will allow, for the first time, submillimetre spectral mapping of the Jovian, Saturnian and Martian discs (which have angular sizes of 45", 19" and 16", respectively at opposition) and the study of hemispheric, zonal and polar differences and transport effects. Spectral mapping of Jupiter will also be practical at longer wavelengths where the diffraction limit reaches 14" at 850 µm.

The spectroscopic imaging capability of the FTS will allow for simultaneous observations of planetary satellites. For example, the atmosphere of Titan is expected to have a complex submillimetre spectrum dominated by the poorly characterized N_2-dimer spectrum and HCN absoption. Other potential solar system targets include asteroids, comets and TNO's. Spectral observations of asteroids will be of particular importance in the calibration of future submillimetre space missions such as Herschel.

3. Conceptual Design

This section presents the top-level requirements and specifications for the SCUBA-2 FTS.

3.1. Summary of Main Objectives

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, allowing two input ports to be placed on the sky simultaneously for atmospheric correction.

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 placing both FTS input ports on the sky will provide convenient atmospheric correction for each frame in the interferogram.

These features are briefly discussed in the following sections.

3.2. Instrument Technical Design and Specification

3.2.1. 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 6.

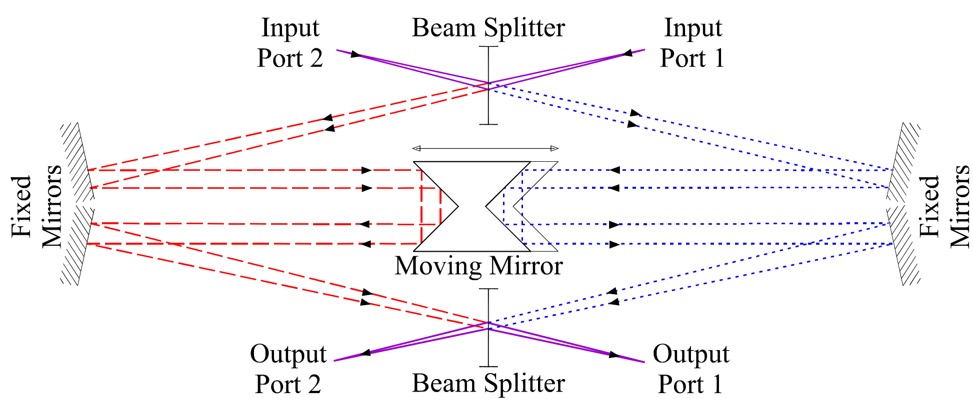


Figure 6. Schematic of a Mach-Zehnder FTS.

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. An alternative configuration allows both input ports to be placed on neighbouring parts of the sky to provide instantaneous atmospheric correction in both bands simultaneously.

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.

3.2.2. Overview of main system components

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 7. Figure 8 shows a metal mesh beam splitter recently made for the University of Lethbridge SPIRE test FTS.

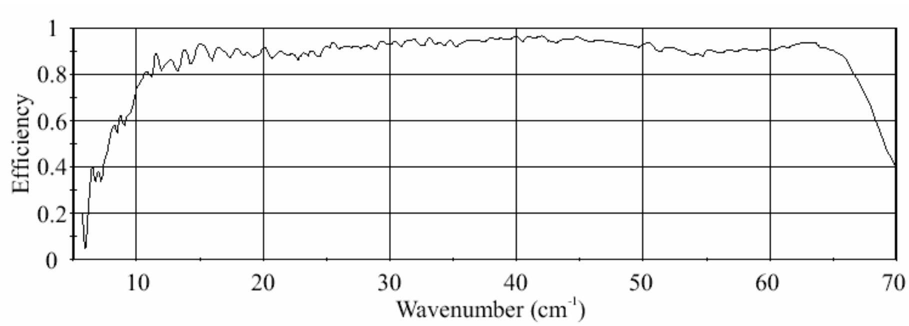


Figure 7. Measured beamsplitter efficiency.

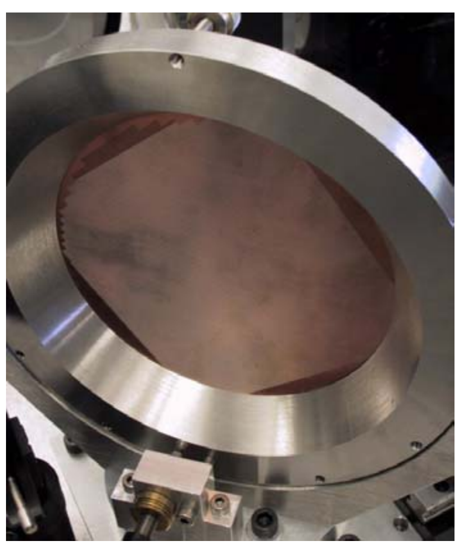


Figure 8. Metal mesh beam splitter.

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. The University of Lethbridge has extensive experience with these stages, which incorporate absolute encoders with sub-micron accuracy and repeatability.

3.2.3. Sensitivity and performance

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.
- 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 making continuum measurements possible.

Sensitivity estimates for the SCUBA-2 FTS are given in Tables 1 and 2.

3.3. 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 SCUBA-2 FTS. The baseline operating mode for the SCUBA-2 FTS is rapid scan with the two input ports of the interferometer viewing adjacent regions of the sky to provide background cancellation of 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 analyzed within a specialized FTS processing engine within the SCUBA-2 pipeline.

We are also investigating the potential use of a step-and-integrate operating mode for the SCUBA-2 FTS exploiting the DREAM mode to correct individual SCUBA-2 frames before they are passed to the FTS processing engine. 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. 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 relatively short integration times[18].

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

3.4. Operational Requirements and Interfaces with SCUBA-2 and JCMT

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).

3.4.4. Telescope Mechanical Interfaces

The FTS will sit within the mounting framework for mirror N1, and will likely encroach on the receiver cabin access walkway. The SCUBA-2 mounting framework will be completely redesigned and rebuilt from the current configuration. It is absolutely essential that the JAC and FTS design teams closely cooperate in mechanical engineering to ensure that the FTS can be installed, aligned, operated and maintained with relative ease. The mass of the FTS is roughly estimated to be 600 kg, and the volume will be approximately 3 m x 1 m x 1.3 m. The JAC should prescribe limits for the inertial forces in all three axes that the FTS could exert on the mount during operation in order to prevent misalignment of mirror N1.

3.4.4.1. 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. This framework will be designed with provisions for the FTS mass and volume.

3.4.4.2. Transport and access systems.

This includes equipment to install and service the instrument. The current Nasmyth platform will be removed to provide space for SCUBA-2, and an access platform or walkway will have to be provided to allow servicing of the FTS.

3.4.5. 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 for the blackbody source 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.

3.4.5.1. 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 an optical or Ethernet connection.

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

The FTS electronics will require mains connections for the control PC, linear stage driver, and control electronics. Grounding connections will be required to comply with the SCUBA-2 instrumental grounding scheme.

3.4.5.3. Vacuum interfaces.

The initial FTS design included a closed cycle cryogenic blackbody source to fill the second input port, which would require vacuum connections to the telescope. A dual-input FTS with both input ports viewing the sky, however, would not require a blackbody source, and therefore no cryogenic or vacuum interfaces. Currently the blackbody is planned as contingency in case the DREAM-FTS mode is realized.

3.4.6. 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.

3.4.6.1. Observation planning system.

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

3.4.6.2. 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. The University of Lethbridge 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.

3.4.6.3. Hyperspectral image analysis packages.

Spectral analysis code will be provided by the University of Lethbridge, 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.

3.5. Expected Performance

Table 3. 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 4. 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

[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, not including beam efficiencies.
[3] NEP values at 450 µm have not been fully modeled.

4. Commissioning Plan

In this section we present details of the steps and tests required during the commissioning phase.

4.1. System Integration

The FTS will be fully assembled in the University of Lethbridge laboratories, 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 that feed the beam(s) into the FTS and back to SCUBA-2. Initial assembly and internal alignment will be performed in daytime, with no impact on observing. Installation in the operating location may also be done with minimal interruption of nighttime observations, with the exception of the final optical alignment of the pickoff mirrors with the SCUBA-2 beam. The University of Lethbridge group has extensive experience in aligning FTSs to the JCMT.

4.2. System tests

The SCUBA-2 FTS will be fully tested in the group's laboratories, although most likely with a single pixel detector. Operation of the all mechanical and electronic components will be verified before shipping. Integration and verification at the telescope will include functional tests of active components, optical alignment to the with the telescope and SCUBA-2, image quality tests of point sources with the SCUBA-2 array and spectral characterization of all spectroscopic pixels in both bands. The University of Lethbridge group has a long history in the development and use of FTSs at the JCMT.

5. Project Management

The SCUBA-2 FTS development will be managed by the local project manager, Mr Brad Gom. The interface with the JAC will be through the Canadian SCUBA-2 project manager, Mr Janos Molnar.

5.1. Responsibilities

The University of Lethbridge will acquire and/or produce all the mechanical and optical components required to build the FTS, as well as the FTS control PC. The optical and mechanical design will be undertaken at the University of Lethbridge. Where possible optics, blackbody, linear stage, optical breadboard, and other components will be purchased from suitable vendors, but inevitably custom mechanical components and mounts will be required; these will be manufactured at the University of Lethbridge.

The University of Lethbridge will provide spares of critical components (beamsplitters, custom electronics boards etc). However, the experience gained from using FTSs at the JCMT for over a decade suggests that the risk of failure of any opto-mechanical component of the FTS is negligible. The University of Lethbridge group will provide preventative maintenance of the SCUBA-2 FTS as required.

Software to control the FTS, as well as the data reduction routines, will be provided by the University of Lethbridge. Provisions must be made so that suitable FTS commands will be delivered to the FTS control PC, and table position values are recorded with each frame. Significant collaboration will be required with the Data Analysis Software group in order to implement FTS processing in the SCUBA-2 software pipeline; this effort has already begun. Details are presented in the FTS software requirements document (SC2/FTS/SYS/003).

It is expected that the JAC will provide allowances in the mechanical support structure of the telescope for the mounting of the FTS and logistical support during the commissioning.

5.2. Dependencies

Information: Optical, mechanical, electronics and software interfaces (ATC, JAC, UBC)
Approval: CSC
Acceptance: Design will be presented to, and acceptance sought from ATC and JAC throughout the development process.
Components: Beamsplitters will be manufactured by Cardiff. The optics will be custom machined by a suitable shop. Most other components are easily acquired from commercial sources.
Infrastructure: Laboratory space and time at University of Lethbridge for initial construction and testing. Use will be made of University of Lethbridge electronics fabrication equipment and personnel.
Funding: Provided by the CFI budget.

5.3. Risks

FTS development risks will be managed by the Canadian SCUBA-2 team, headed by the Canadian SCUBA-2 Project Manager. See the SCUBA-2 Fourier Transform Spectrometer Risk Assessment document (SC2/FTS/PM500/001) for details.

5.4. Major milestones

The following milestones dates are given with the assumption that the current spending freeze for descoping contingency will be lifted by April 2004. Any extra delay in funding beyond this date will result is a corresponding delay in the overall FTS project. The FTS development is organized so that development activities are minimally impacted by the current spending freeze.

In order to ensure seamless collaboration among other teams within the SCUBA-2 development effort, the FTS development process will closely follow the procedures established by the Astronomy Technology Centre in Edinburgh, Scotland and will be accepted by the entire team. See the ATC Project Management Procedures document (189/PMG/01/001) for details.

The following major milestones will be implemented with their corresponding deliverables:

Conceptual Design Review (CoDR) - July 30th, 2003

Deliverables	Owner	Due Date	Status
Operational Concept Document (OCD)	BGG	July 16th, 2003	ok
FTS Requirements Document	BGG	July 16th, 2003	ok
Conceptual layouts	BGG	July 16th, 2003	ok
Initial draft Interface Control Document (ICD)	BGG	July 16th, 2003	ok
Project Cost (part of PMP)	BGG	July 16th, 2003	ok
Project Schedule (part of PMP)	BGG	July 16th, 2003	ok
Risk Assessment and mitigation Plan	BGG	July 16th, 2003	ok

Preliminary Design Review (PDR) - May 2004

Deliverables	Owner	Due Date	Status
Updated OCD			
Updated FTS Requirements Document			
FTS Engineering Specification			
Preliminary Design Drawings			
Design Analysis Reports			
Initial Draft Test Requirements			
SW Architecture Definition			
Preliminary Safety Plans			
Updated ICD			
Updated Project Cost (part of PMP)			

Updated Project Schedule (part of PMP)			
Updated Risk Assessment and Mitigation Plan			
Long lead-time items Procurement Plan			

Critical Design Review (CDR) - October 2004

Deliverables	Owner	Due Date	Status
Updated OCD			
Updated FTS Requirements Document			
Updated FTS Engineering Specification			
Detailed Design Drawings			
Design Analysis and Development test Reports			
SW Integration and Test Plans			
Draft Acceptance Test Procedures and criteria			
Updated Safety Plans			
Updated ICD			
Special tooling and support equipment definitions (special facility requirements)			
Updated Project Cost (part of PMP)			
Updated Project Schedule (part of PMP)			
Updated Risk Assessment and Mitigation Plan			
Vendor Data for critical items			

Build/Test/Rework FTS - October 2005

Deliverables	Owner	Due Date	Status

Acceptance Readiness Review (ARR) - January 2006

Deliverables	Owner	Due Date	Status
Complete set of FTS drawings			
Interface drawings and documents			
Spares list			
Test and Analysis Reports			
Acceptance Test Plan			
Commissioning Plans			
Special tooling and support equipment documentation			
Preliminary operation and maintenance documentation			
Maintenance Manual			
Safety Documentation and Procedures			

Delivery to telescope - March 2006

Deliverables	Owner	Due Date	Status
All tested HW, SW, documentation			
Commissioning tools equipment and documentation			
Support Agreement			

Commissioning - 2-3 months after SCUBA-2 commissioning

Deliverables	Owner	Due Date	Status
To be determined by the PDR and negotiated between University of Lethbridge and JAC			

FTS Support - until SCUBA-2 decommissioning

Deliverables	Owner	Due Date	Status
To be determined by the PDR and negotiated between University of Lethbridge and JAC			

5.5. Project Financials

FTS Development is 100% funded by the Canadian Foundation for Innovation with a budget of CDN$ 996,740. Funding is granted through the Canadian Lead Intitute; the Physics and Astronomy Department of the University of Waterloo. Moneys will be disbursed according to the Inter Institutional Agreement (IIA) between the Lead Institution and the University of Lethbridge per the established schedule.

The current development cost and spending profile corresponds to the above IIA and is a snapshot as of July 2003.

5.5.1. Budget

The FTS project budget is summarized is the following table. Descriptions of the various items are given below, listed according to the CFI budget item numbers.

Items	CFI Items		Year 1 1/4/02 – 31/3/03	Year 2 1/4/03 – 31/3/04	Year 3 1/4/04 – 31/3/05	Year 4 1/3/05 – 31/4/06	Year 5 1/3/06 – 31/8/06	Total	Spent up to date	Remaining
17,16,23	9,8,57	Salaries	42,000	73,260	172,671	177,370	134,939	600,240	65,539	534,700
1 - 9	1,2,10-16	Optics and Hardware (mirrors, stage, laser, etc)	0	0	219,500	0	0	219,500	0	219,500
10	3	Large aperture cold blackbody	0	0	55,000	0	0	55,000	0	55,000
11	4	Control PC	0	4,000	0	0	0	4,000	0	4,000
12	19	Development software (IDL , Optical CAD package)	10,000	0	0	0	0	10,000	5,822	4,178
13	5	Machine shop time : ~3 month	0	0	24,000	0	0	24,000	0	24,000
14	6	Control/data acquistion electronics design and fabrication	0	0	9,000	6,000	0	15,000	0	15,000
15	17	Consumables for laboratory testing (LHe, LN2 etc)	2,000	2,000	2,000	2,000	0	8,000	0	8,000
18	7	Misc.items (eg FTS frame, lifting gear, alignment tools, etc)	0	0	0	0	3,000	3,000	0	3,000
20	18	Travel (ATC, Cardiff, Hawaii, Canadian partners)	10,990	8,802	12,500	12,500	5,208	50,000	11,783	38,217
21	20	Shipping crates for FTS system	0	0	0	0	3,000	3,000	0	3,000
22	21	Shipping FTS to Hawaii	0	0	0	0	5,000	5,000	0	5,000
								Grand Total		
		YEARLY TOTALS	$64,990	$88,062	$494,671	$197,870	$151,147	$996,740	$83,144	$913,596
		Spent so far	$64,284	$18,860						
		Delta	$706	$69,202	$494,671	$197,870	$151,147	$913,596		

Item 1 Aerotech precision translation stage and controller. This is a precision interferometer translation stage (300mm minimum travel) with Heidenhain linear encoder, control electronics and low EMI brushless DC linear motor.

Item 2 Motorized alignment laser assembly system that can be remotely inserted accurately and repeatedly into FTS to check alignment.

Item 3 Large aperture cold blackbody calibration source is required for the second input port of the Mach-Zehnder FTS. This will be based around a standard Infrared Laboratory dewar.

Item 4 Dedicated computer for FTS control and analysis software development

Item 5 Machine shop time to fabricate and mount optical components, construct framework and lifting harness, and some shipping crates. Estimated time 3 months.

Item 6 Electronics shop time to design and build the control interface electronics for the FTS. This requires extracting the Heidenhain encoder signal from the linear stage and time stamping the optical retardation with the JCMT RTS signal.

Item 7 Miscellaneous items related to installing and operating the FTS.

Items 8 and 57 Control software programmer(s). Software scientist responsible for developing the FTS control software, which must interface with the JCMT observatory control software, and the FTS analysis software, which must interface with the SCUBA-2 data product. This is an important position where continuity is critical throughout the project. This person must be knowledgeable about Fourier analysis, fluent in RT Linux, C++ and IDL and be able to work effectively with the FTS project manager as well as JAC and UBC personnel.

Item 9 Project manager and instrument engineer. This person will be the first point of contact with the FTS and assume the responsibility for overseeing the development and testing of the FTS. This will involve working closely with collaborators at ATC, Cardiff and Hawaii and the software scientist in the team. Specific tasks include producing technical drawings and specifications for the overall FTS design and its interface with the JCMT, drawings for all the optical and mechanical components, finding suitable vendors and/or custom manufacturers, overseeing the work in the electronics and machine shops at the University of Lethbridge and preparing monthly progress reports. This person will report to the Canadian project manager and work closely with ATC and Cardiff personnel.

Item 10 Custom Damped optical table to mount interferometric components.

Item 11 Custom large mirror mounts with precision micrometer adjusters.

Item 12 Custom large beamsplitter mounts with precision micrometer adjusters.

Item 13 2 Mylar beamsplitters for optical alignment of the FTS and 2 equal intensity beamsplitters.

Item 14 Large aluminum steering mirrors to direct telescope beam into FTS. These mirrors will be ~0.5m diameter

Item 15 300mm diameter aluminum plane mirrors for FTS, with mounting adaptors. Diamond turned for optical quality finish necessary for alignment

Item 16 300mm diameter aluminum aspherical mirrors for FTS, with mounting adaptors. Diamond turned for optical quality finish necessary for alignment.

Item 17 Lab testing the FTS (@ $2K per year x 4 years). Cryogens, general lab supplies.

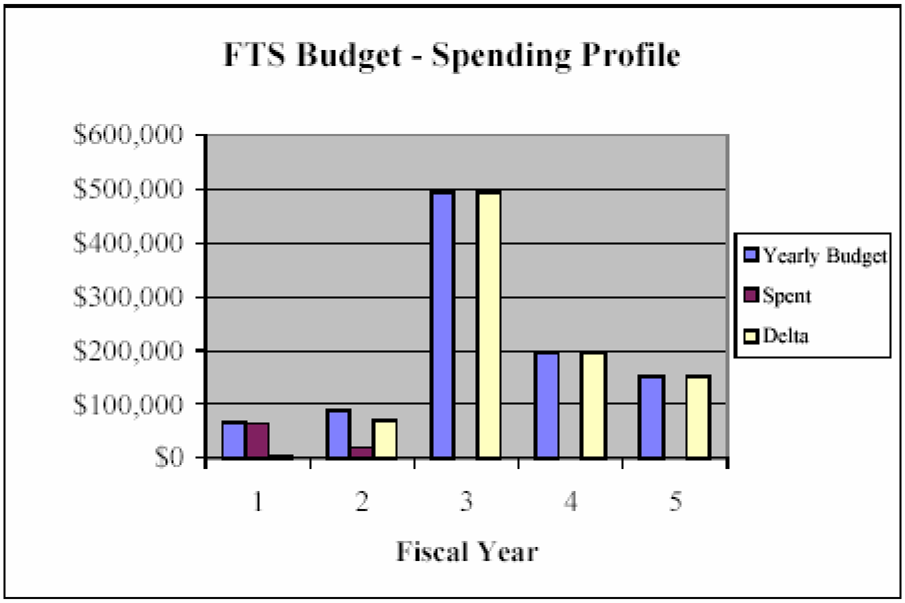
Item 18 Travel (@ $12.5K per year x 4 years). FTS team travel primarily to ATC and Cardiff but also to Hawaii.

Item 19 Development Software: IDL software package and an optical CAD package to produce interface drawings for the ATC

Item 20 Custom shipping crates for the FTS components.

Item 21 Shipping costs of the FTS to Hawaii.

5.5.2. Spending Profile



5.6. Team list

Name	Area of Responsibility	Phone No.	Email address
University of Lethbridge			
Professor David Naylor	Overall responsible for FTS work package	+1 403 329 2426	naylor@uleth.ca
Mr Brad Gom	FTS Project Manager	+1 403 329 2771	brad.gom@uleth.ca
Mr Greg Tompkins	FTS Electronics Technician	+1 403 329 2297	tompkins@uleth.ca
Mr Ian Schofield	FTS Control Software Engineer	+1 403 329 2741	ian.schofield@uleth.ca
TBD	FTS Data Reduction Software Engineer		
Joint Astronomy Centre (JAC), Hawaii +1 808 961 3756			
Professor Gary Davis	Director, JAC/JCMT	+1 808 969 6504	g.davis@jach.hawaii.edu
Dr Nick Rees	Head of JAC Software and Computing Services	+1 808 969 6547	n.rees@jach.hawaii.edu
Ms Frossie Economou	Computing Services Manager, OMP project manager	+1 808 969 6536	f.economou@jach.hawaii.edu
Dr Tim Jenness	High Level Software Manager	+1 808 969 6553	t.jenness@jach.hawaii.edu
Dr Per Friberg	Head of JCMT Instrumentation	+1 808 969 6522	p.friberg@jach.hawaii.edu
Mr Dean Shutt	Chief Engineer	+1 808 969 6542	d.shutt@jach.hawaii.edu

Name	Area of Responsibility	Phone No.	Email address
Mr Tomas Chylek	Mechanical Design Engineer	+1 808 969 6540	t.chylek@jach.hawaii.edu
UK ATC +44 (0) 131 668 8* **			
Mr Trevor Hodson	SCUBA-2 Project Manager	409	t.hodson@roe.ac.uk
Dr Wayne Holland	SCUBA-2 Project Scientist	389	w.holland@roe.ac.uk
Dr Dennis Kelly	SCUBA-2 Software/ System Analysis	369	d.kelly@roe.ac.uk
Dr Mike MacIntosh	SCUBA-2 Systems Engineer	368	m.macintosh@roe.ac.uk
Mrs Lynn Ritchie	SCUBA-2 Project Assistant	442	l.ritchie@roe.ac.uk
University of Wales at Cardiff +44 (0) 292 087 ****			
Professor Peter Ade	Head of Lab	4643	Peter.ade@astro.cf.ac.uk
Canadian SCUBA-2 Consortium (CSC) Steering Committee			
Professor Michel Fich, University of Waterloo	Chair, CSC Steering Committee	+1 519 888 4567 , ext 2725	fich@astro.uwaterloo.ca
Professor Mark Halpern UBC	Head of UBC Engineering Group	+1 604 822 6435	halpern@physics.ubc.ca
Professor Pierre Bastien, Université de Montréal	Responsible for polarimeter module	+1 514 343 5816	bastien@astro.umontreal.ca
Other Canadian Team Members			
Mr Janos Molnar, UBC	Canadian Project Manager	+1 604 822 1938	jmolnar@physics.ubc.ca
Professor Douglas Scott, UBC	Data Reduction and Pipeline SW lead	+1 604 822 2801	dscott@astro.ubc.ca

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