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Relevant Documentation

Document Number	***Title***
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SC2/FTS/SCE/001	FTS-2 Science Case
SC2/FTS/SRE/001	FTS-2 Functional and Performance Requirements
SC2/FTS/SOF/001	FTS-2 Data Reduction Engine
SC2/FTS/SOF/002	FTS-2 to OCS ICD
SC2/FTS/SYS/005	FTS-2 to RTS ICD
SC2/SOF/S200/026	SCUBA-2 FTS and Polarimeter Coordination

Contents

1. Introduction

This document presents the operational concepts for the Fourier Transform Spectrometer (FTS-2) to be used in conjunction with SCUBA-2, the new generation array camera being developed for the James Clerk Maxwell Telescope (JCMT). This spectrometer will take advantage of the extra sensitivity, imaging speed and improved image fidelity of the new SCUBA-2 camera, and will provide the following key features:

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 FTS-2 instrument will take advantage of the unique simultaneous dual wavelength capability of the SCUBA-2 system.
3. *Mach-Zehnder Design*. This innovative FTS design provides high efficiency and access to all four ports of the interferometer.
4. *High Spectral sensitivity / Low noise*. The SCUBA-2 detector will provide excellent noise performance, which translates directly to spectral sensitivity for the FTS.
5. *Novel observing modes*. Instantaneous, fully-sampled image in SCUBA-2 will provide better image fidelity, and techniques such as the DREAM mode may provide an alternative method for atmospheric correction of each frame in the interferogram.

In the simplest type of Fourier spectrometer, the Michelson interferometer (see Figure 1), the incoming beam of light (e.g. from the telescope) is divided into two beams of equal intensity by a beamsplitter. After reflection from a fixed and a moving mirror the beams recombine at the beamsplitter and are brought to a focus on the detector. The signal recorded by the detector as a function of the path difference, or delay, between the recombining beams is known as the interferogram (see Figure 2). The interferogram represents the autocovariance function of the incident radiation. Applying an inverse Fourier cosine transformation of the interferogram yields the spectrum of the source. Thus, while in principle the design of an FTS is quite simple, obtaining the spectrum requires sophisticated mathematical analysis.

The mechanical, optical, and software design of FTS-2 will be much more complicated than that of a standard non-imaging FTS. Also, since the FTS-2 instrument was not included in the initial design of SCUBA-2, the layout of the SCUBA-2 feed optics is not optimal for inclusion of an FTS.

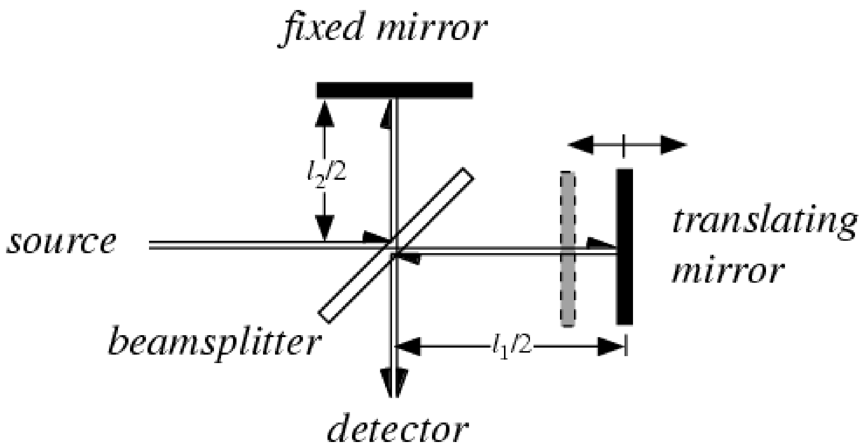

Figure 1. Typical Michelson interferometer. The optical path difference is l_1-l_2.

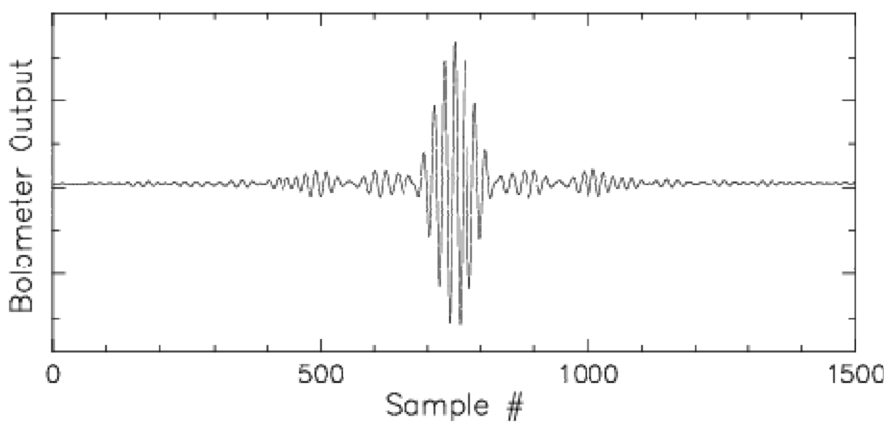

Figure 2. Typical Interferogram showing the Zero Path Difference (ZPD) feature.

2. Science Case

The scientific aims of FTS-2 are 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:

Extragalactic Astronomy. With FTS-2 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 Spectral Energy Distribution (SED), and hence more difficult to interpret. Even when observing only in the 850 µm band, the FTS can provide SED measurements without the problems of line contamination experienced with photometric methods.

Interstellar Medium. FTS-2 will be able to provide a spectrum at every point in the ~9 arcmin^2 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.

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.

A more detailed discussion of the science case can be found in the FTS-2 Science Case document (SC2/FTS/SCE/001).

3. Instrument Design

3.1. Mach-Zehnder design

The design of FTS-2[1] is based on the Mach-Zehnder design[2] that has been adopted for the SPIRE instrument[3] of the ESA Herschel mission as well as for the University of Lethbridge spectrometer[4] which operated at the JCMT until 2004. Figure 3 shows a schematic of the Mach-Zehnder FTS design. Retractable pickoff mirrors M1 and M2 intercept two ~3 arcminute beams from the SCUBA-2 beam as it exits the left telescope elevation bearing tube. The collimated beams are redirected by mirrors M3 and M4 to the first intensity beam divider, BS1. As the moving mirror assembly (consisting of two rooftop mirrors, RT, mounted on a linear stage) is moved a distance *x*, an optical path difference of 4*x* is introduced between the interferometer arms M5/M7 and M6/M8. The beams are recombined at beam divider BS2, and the two output ports are returned to the SCUBA-2 optical system by mirrors M11 and M12.

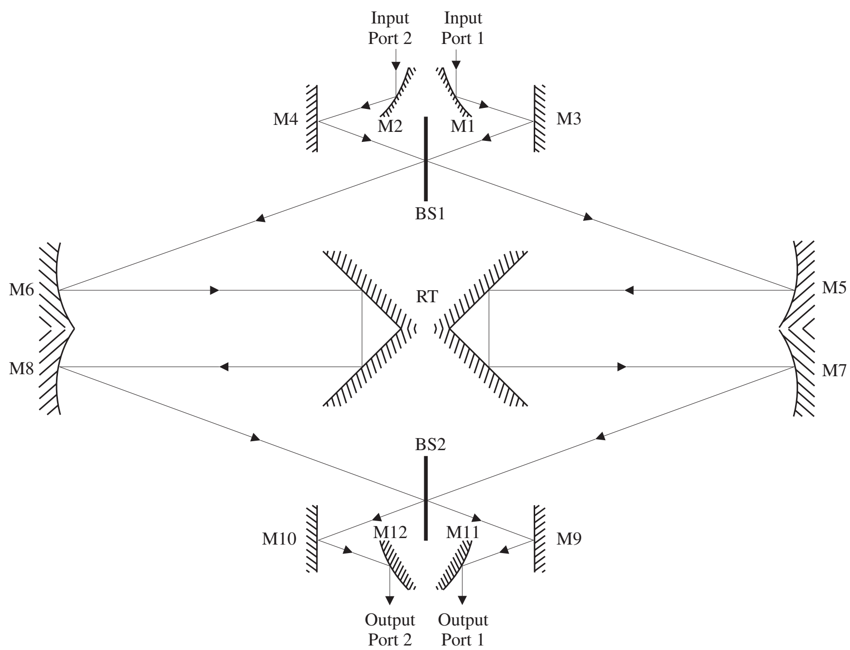

Figure 3. A schematic of the dual-port Mach-Zehnder FTS design.

The FTS will be mounted on the support structure for the SCUBA-2 mirror N1, just outside the left elevation bearing of the JCMT. Retractable pickoff mirrors will redirect the astronomical signal though the FTS and back to mirror N1 when the system is in use, and will be removed from the beam for photometric observations. The FTS will occupy a volume of roughly 2 m x 0.6 m x 1.4 m (w x d x h) and have a mass of approximately 400 kg. The control PC will be mounted at a convenient distance to the FTS instrument, and will communicate with the RTS and SCUBA-2 network. Individual frames from SCUBA-2 will be acquired as a function of increasing optical retardation in the interferometer and the resulting interferogram data cubes will be analyzed within a specialized FTS processing engine within the SCUBA-2 pipeline.

3.2. 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 4. Figure 5 shows a metal mesh beam splitter recently made for the U of L SPIRE test FTS.

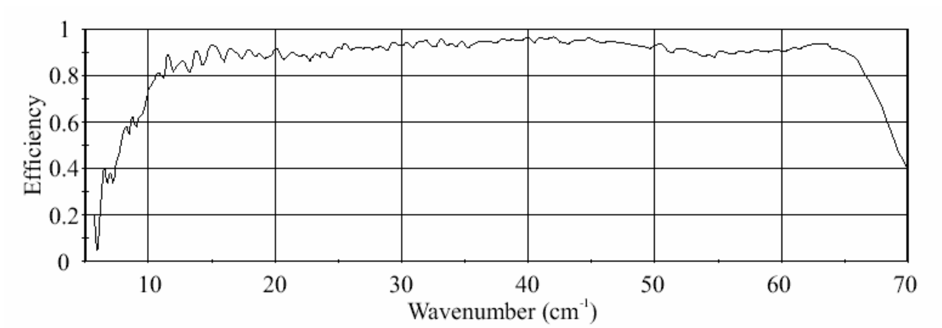

Figure 4. Measured beamsplitter efficiency.

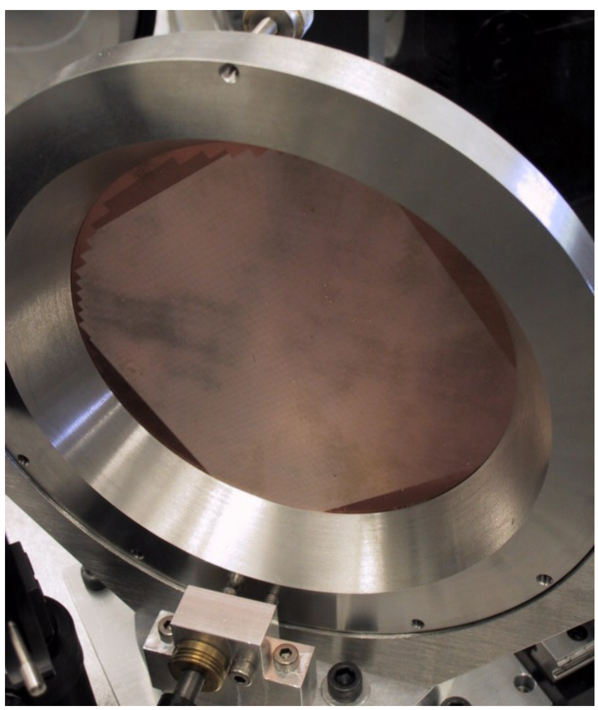

Figure 5. Metal mesh beam splitter.

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 linear motor based translation stage will be used which features zero backlash, zero windup, low friction, and high acceleration. These stages incorporate absolute encoders which allow sub-micron accuracy and repeatability. An Aerotech Soloist® stand-alone motion controller provides real-time position monitoring and high speed servo control of the stage velocity and position.

3.3. Sensitivity, performance, etc.

SCUBA-2 will have extended capabilities enabling large-scale projects covering many tens of degrees of sky, along with deep and high-fidelity imaging of selected areas. While SCUBA-2 will offer the JCMT a unique and wide-ranging observing facility in the submillimetre waveband, the FTS will provide hyperspectral imaging capabilities unprecedented in submillimetre astronomy. The FTS will be primarily a galactic spectrometer (e.g. spectral index mapping of molecular clouds) but will also provide useful information on bright nearby galaxies and planetary atmospheres. The advantages of FTS-2 are summarized as follows:

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

Calculations of the FTS-2 survey speed have been done and are presented in the "FTS-2 Survey Time Estimation" document (SC2/FTS/SYS/006).

4. Observing Modes

The Mach-Zehnder configuration of FTS-2 provides a wide range of operating mode options: The optical layout provides access to both input ports and both output ports, the moving mirror unit can be translated continuously or in discrete steps, and the resolution may be adjusted anywhere between the limits set by the available mirror travel. The choice of observing mode obviously affects the processing required, and certain configurations have advantages over others in different situations. We have attempted to define the minimum set of configurations that will accommodate the widest range of astronomical observations while minimizing the complexity of the data reduction algorithms and observation planning.

4.1. Configuration Options

Dual Input Ports

By placing one input port on the source and the other port on a nearby background location, the interferometer provides instantaneous cancellation of atmospheric emission variations for both bands simultaneously. Proper selection of a background location is crucial to the success of this technique, so the location of the second input port must be carefully considered in the observation planning. Atmospheric emission is the dominant source of radiant loading at submillimetre wavelengths. Moreover, variations in atmospheric emission are particularly problematic for an FTS where, upon Fourier transformation, they introduce spectral features into the resulting spectrum. By utilizing the second input port of the FTS to view an adjacent background sky position variations in atmospheric emission can, to first order be cancelled by the subtractive properties of the FTS. Moreover, this cancellation results in a dramatic reduction in the dynamic range required in the resulting interferogram.

In this mode, the moving mirror may be scanned continuously (Rapid-Scan or RS) or stepped discretely (Step-and-Integrate or SI). With RS, the resulting interferograms will not be sampled uniformly in optical retardation since the SCUBA-2 data acquisition system is independent of the FTS-2 scanning mechanism. This will necessitate the use of a non-uniform FFT or an interpolation process in the processing pipeline. Algorithms to cope with this problem have already been developed for the Herschel SPIRE spectrometer[5].

The dual output ports of the FTS provide complementary data which can further reject common mode noise present in the often hostile telescope environment, resulting in a factor of square root 2 increase in s/n.

Single Input Port

An alternative to the dual-port mode is to block one of the input ports with a stable blackbody and use some other means to correct for atmospheric variations, such as the proposed DREAM observing mode[6], before the frames are passed to the FTS processing engine. This implies a reduced operational efficiency since chopping or jiggling techniques cannot be combined with RS mirror scanning. However, if aliasing is employed and the atmospheric correction technique is effective, then a *gain* in efficiency can be realized since fewer steps will be required in a scan and, since the requirement to complete a scan before the atmosphere changes is relaxed, the integrations at each step can be long relative to the motion delay.

Step-and-Integrate

We are also investigating the potential use of a step-and-integrate operating mode[7]. In this mode, the optical path difference in the interferometer is incremented in discrete steps and data is read out only when the mirrors are stationary, thereby ensuring that the interferogram is sampled on a uniform position grid. This mode could in principle be used with the single-port mode in conjunction with DREAM, however, the baseline plan is to use the Rapid Scan dual-port cancellation technique.

Undersampling

Since the SCUBA-2 filters will have extremely high out-of-band rejection, the interferograms may be sampled sparsely and the resulting aliasing of the spectra can be easily removed. This will allow high resolution spectra to be obtained in shorter scan times, which will reduce the effects of sky rotation and atmospheric noise. By proper selection of the optical path sampling interval, both the 450 and 850 μm bands can be aliased simultaneously without any loss of information within the bands.

Normal Nyquist sampling requires that the interferograms be sampled every 0.02 cm of OPD, but this interval can be increased to 0.1 cm through the use of undersampling, which translates to a factor of 5 increase in acquisition speed. In order to test this technique, we have reconfigured the existing U of L FTS to use both the normal rapid-scan and the step-and-integrate modes. Results of these tests are discussed in the following paper:
http://www.uleth.ca/phy/naylor/pdf/SPIE_Glasgow_SCUBA-2_FTS.pdf

Resolution

The maximum resolution of an FTS is a function of the maximum optical path difference (OPD_{max}) within the interferometer:

$$\Delta\nu \approx \frac{1.21}{2 \cdot OPD_{\max}}$$

The FTS-2 instrument[8] has a continuously variable resolution ranging from $\Delta\nu \sim 0.5$ to 0.006 cm^{-1}.(The translation stage will allow slightly better resolution if some vignetting of the outer pixels can be tolerated) With a fixed detector frame rate, higher resolution comes at the expense of longer acquisition times.

While the FTS-2 resolution can be adjusted arbitrarily over the full range, the baseline plan is to provide only two resolution modes. The maximum resolution will be used for line studies, while a lower resolution of ~0.1 cm^{-1} will be used for SED measurements.

Mapping

Mapping with FTS-2 will be complicated by vignetting effects and calibration issues with off-axis pixels. While correction of these effects should be possible after commissioning tests, mapping of extended regions will be left up to the observer.

4.2. Interferogram Sampling Criteria

Per Friberg pointed out in the PDR that because the SCUBA-2 electronics does not use sample-and-hold circuitry, scanning the FTS during data acquisition (e.g. the Rapid Scan mode) leads to a filtering of the interferogram signal (see: http://research.uleth.ca/scuba2/documents/cdr/Integration_during_Sampling.pdf). The effect of integrating (convolving) the signal over a path length equal to the optical path velocity multiplied by the integration time (5 ms) is equivalent, in the frequency domain, to a low-pass filtering by its Fourier transform given by:

$$H(\sigma) = 2L \; \frac{Sin(2\pi L\sigma)}{2\pi L\sigma}$$

Where $2L$ is the optical path over which the integration takes place and σ is the wavenumber of interest.

In the current design, the optical velocity is 6.6 cm/s for the single band mode (850 µm), which corresponds to an integration length of 6.6 x $5\cdot10^{-3}$ = 0.033 cm. At the highest frequency of 12.5 cm^{-1} in the 850 µm band, the effective signal gain is:

$$H(\sigma) = \frac{Sin(2\pi \cdot 0.0165 \cdot 12.5)}{2\pi \cdot 0.0165 \cdot 12.5} = 0.74$$

For the dual band mode (850 and 450 µm), the optical velocity is 4 cm/s, which corresponds to an integration length of 4 x $5\cdot10^{-3}$ = 0.02 cm. At the highest frequency of 25 cm^{-1} in the 450 µm band, the effective signal gain is:

$$H(\sigma) = \frac{Sin(2\pi \cdot 0.01 \cdot 25)}{2\pi \cdot 0.01 \cdot 25} = 0.64$$

Which agrees with Per's analysis. We can determine the scanning speed which is the best compromise between acquisition time and filtering losses by inverting this equation to determine the optical path velocity required for a given signal gain for the two modes.

For an effective gain of 95% in the interferogram signal at the highest frequency in either mode, $2\pi L\sigma$ must equal 0.55 which is equivalent to optical velocities of 2.8 cm/s and 1.4 cm/s for single and dual band observing modes respectively.

For an effective gain of 90% in the interferogram signal at the highest frequency in either mode then $2\pi L\sigma$ must equal 0.8 at the highest frequency equivalent to optical velocities of 4 cm/s and 2 cm/s, for single and dual band observing modes respectively.

4.3. Baseline Observing Modes

FTS-2 observations can be classified as either SED measurements or spectral line studies. SED measurements only require a few spectral bins across a filter bandpass in order to characterize the continuum curvature, and can be accomplished with low resolution ~0.1 cm^{-1} scans. On the other hand, spectral line studies require the maximum possible resolution. By grouping all observations into these two resolution categories, the processing and observation planning can be simplified.

In the low-resolution SED mode, scans can be double-sided without seriously affecting observing efficiency. With fully double-sided scans, the phase correction processing step is simplified greatly. The baseline plan is to implement the SED mode using the dual-port configuration to provide atmospheric correction. The nominal operating mode will be RS; aliased SI mode combined with DREAM will be investigated during commissioning.

In the high-resolution spectral line mode, scans must be single sided to maximize the use of the linear stage travel and minimize the scan acquisition time. A short double-sided scan will provide phase information for the phase correction algorithm. The dual-port configuration will be used to provide atmospheric correction.

Table 1. Observing mode summary.

Mode	SED	Spectral Line
Resolution	~0.1 cm^{-1}	~0.006 cm^{-1}
Scan type	Double-sided	Single-sided
Phase correction	Simple	Full
Port configuration	Dual-port	Dual-port
Scan mode	RS (SI)	RS

5. Data Handling

5.1. Data rate

The scan speed of the FTS-2 moving mirror, v_{OPD}, is determined by the desired Nyquist frequency, σ_{max}, and the bolometer frequency response, f,:

$$v_{OPD} = \frac{f}{\sigma_{\max}}$$

For dual-band operation, the acquisition time is limited by the 25 cm^{-1} Nyquist for the 450 µm band. If only the 850 µm band is needed, then the acquisition time (and cube size) is reduced due to the lower 15 cm^{-1} Nyquist. A summary of the acquisition times and interferogram lengths is given in Table 2, without taking into account the sampling speed issues identified in section 4.2.

Table 2. Scan parameters for the SED and Spectral Line modes.

	SED		**Spectral Line**	
	Dual Band	**850 µm**	**Dual Band**	**850 µm**
Total Travel (cm OPD)	6+6		100+6	
Velocity (cm/s OPD)	4	6.6	4	6.6
Scan time (s)	3	1.8	26.5	15.9
Frames	605	363	5300	3180

Data rates for the FTS-2 instrument will not exceed those for normal SCUBA-2 observations. In the RS mode, frames will be stored at 200 Hz, and reduced by the pipeline. Depending on the spectral range in the stored spectral cubes, the maximum reduced data volume before averaging will range from 0.25 to 0.5 times the raw data volume.

5.2. Processing speed

Processing of the FTS-2 interferogram cubes will be sufficiently fast to keep up with the data acquisition, but it will not be fast enough to provide fully reduced spectral cubes to the Quick Look (QL) display at a useful rate. The processing engine has been benchmarked on a 3.2 GHz P4 hyperthreaded system running Windows XP with 1 GB RAM, and the results are summarized in Table 3 for a 40x32xN cube. The processing steps are described in the FTS-2 DR Engine document (SC2/FTS/SOF/001). The JAVA processing modules can take advantage of dual processors by splitting the pixels into 2 threads. It should be noted that the CPU speed of the current DR machine is considerably slower than our test platform.

Full processing is too slow for a real-time display, so the processing must be simplified or the number of pixels must be reduced. In the SED mode, the processing can be simplified by using the simple power spectrum for the display (no phase correction). The processing for the Spectral Line mode can be simplified by only processing a small number of pixels in a central region of interest. The QL processing will be tuned to provide a refresh rate of at least 0.1 Hz.

Table 3. Processing engine benchmark results, time expressed in seconds.

	SED		Spectral Line	
	Dual Band	**850 µm**	**Dual Band**	**850 µm**
Interpolation	0.52	0.31	4.83	2.88
Phase correction	1.83	1.03	5.38	3.14
FFT	0.72	0.47	10.67	5.77
Total Execution Time	3.1	1.8	20.9	11.8
Acquisition Time	3	1.8	26.5	15.9

6. System Integration and Laboratory Acceptance Tests

6.1. System Integration

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

6.2. System tests

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

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