Mach-Zehnder Fourier transform spectrometer for astronomical spectroscopy at submillimeter wavelengths

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ABSTRACT

Astronomical spectroscopy at submillimeter wavelengths holds much promise for fields as diverse as the study of planetary atmospheres, molecular clouds and extragalactic sources. Fourier transform spectrometers (FTS) represent an important class of spectrometers well suited to observations that require broad spectral coverage at intermediate spectral resolution. In this paper we present the design and performance of a novel FTS, which has been developed for use at the James Clerk Maxwell Telescope (JCMT). The design uses two broadband intensity beamsplitters in a Mach-Zehnder configuration, which provide access to all four interferometer ports while maintaining a high and uniform efficiency over a broad spectral range. Since the interferometer processes both polarizations it is twice as efficient as the Martin-Puplett interferometer (MPI). As with the MPI, the spatial separation of the two input ports allows a reference blackbody to be viewed at all times in one port, while continually viewing the astronomical source in the other. Furthermore, by minimizing the size of the optical beam at the beamsplitter, the design is well suited to imaging Fourier transform spectroscopy (IFTS) as evidenced by its selection for the SPIRE instrument on Herschel.

Keywords: Mach-Zehnder, Fourier, imaging, spectrometer, submillimeter, astronomy

1. INTRODUCTION

Submillimeter astronomy has experienced rapid growth over the last decade, primarily as a result of the development of sensitive array detector systems and efficient spectrometers. Heterodyne receivers, with their high spectral resolution but limited spectral range, are ideally suited to the study of narrow line emission from, for example, cold molecular clouds. By comparison, Fourier transform spectrometers (FTS), with their inherently broad spectral coverage at intermediate resolution, are well suited to the study of tropospheric lines in planetary atmospheres, the simultaneous measurement of the continuum and line emission in the interstellar medium, and bright extragalactic objects. In these cases the required instantaneous bandwidth exceeds that of heterodyne receivers.

For over a decade we have been conducting astronomical observations from the James Clerk Maxwell Telescope (JCMT) using various FTS. In 1990 an existing Michelson interferometer[1], modified to operate at submillimeter wavelengths, was used to measure the atmospheric transmission above Mauna Kea[2] in order to determine the feasibility of conducting broadband spectroscopic observations from the JCMT. These encouraging results provided the impetus for developing a polarizing FTS[3]. Initially this FTS used the JCMT facility bolometer UKT14[4] as the detecting element. In more recent years a dual-polarization bolometer detector system[5] has been developed for use with the polarizing FTS. Results from these programs include: measurements of the atmospheric transmission throughout the submillimeter spectral region[6], the search for HCN, NH3 and PH3 in the troposphere of Jupiter[7], the detection of CO in the troposphere of Neptune[8], the detection of high-n HI Rydberg transitions in the submillimeter spectrum of the sun[9,10] and measurements of line emission from the Orion molecular cloud[11]. For reference, the atmospheric transmission above Mauna Kea for 0.5 mm precipitable water vapour, corresponding to relatively dry conditions, is shown in figure 1.

In this paper we present the design of a novel FTS, which has been developed for use at the JCMT. The design uses two broadband intensity beamsplitters in a Mach-Zehnder configuration, which provide access to all four interferometer ports while maintaining a high and uniform efficiency over a broad spectral range. The system performance is illustrated by 850 and 450 μm spectra of the Orion molecular cloud core.

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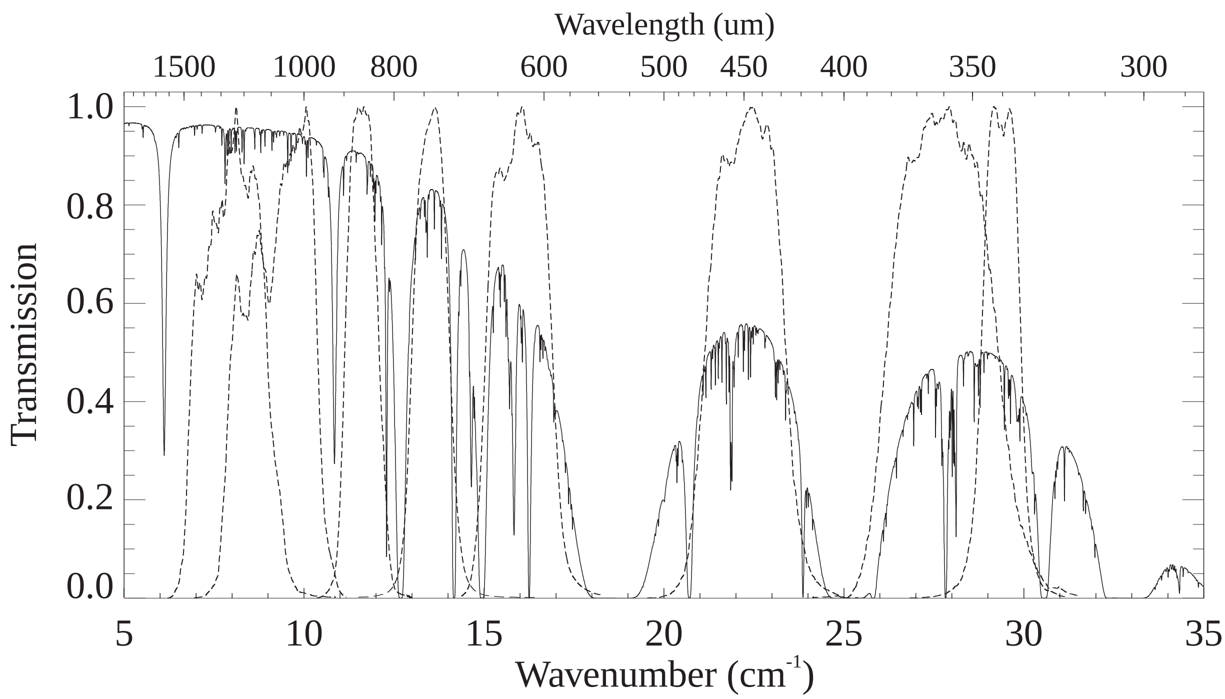

Figure 1. Theoretical atmospheric transmission spectrum modeled for Mauna Kea with 0.5 mm precipitable water vapour. Some of the available filter bands (normalized) are shown with dotted lines.

2. MACH-ZEHNDER FTS

The interferometer is based on the Mach-Zehnder (MZ) design[12, 13] and is shown schematically in figure 2; top and side views of the interferometer in the laboratory are shown in figure 3. The main characteristics of the system are given in Table 1. Extending previous work in the development of far infrared metal mesh filter technology, an intensity beamsplitter with a high and uniform efficiency over a broad spectral range has been developed[14]. 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. By using complementary structures (capacitive and inductive grids) on a thin Mylar support substrate, beamsplitter efficiencies (4RT) exceeding 90% over a range in frequency of a factor of 4 have been achieved. Furthermore, the precise spectral range can be accurately determined by the geometry of the grids and their spacing. One serendipitous feature of these beamsplitters is that they also work effectively at the HeNe laser wavelength (632.8 nm), which greatly simplifies the alignment of the interferometer. The MZ configuration uses two broadband intensity beamsplitters in place of the conventional polarizing beamsplitters of the the Martin-Puplett interferometer[15] (MPI). As with the MPI, the MZ design provides access to the two input and two output ports. However, since the MZ processes both polarizations, it is twice as efficient as the MPI. Furthermore, by using powered mirrors within the arms of the interferometer, the size of the optical beam at the beamsplitter is minimized. This design is therefore well suited to imaging Fourier transform spectroscopy, as evidenced by its selection for the SPIRE instrument on Herschel[16].

2.1 Optical design

The MZ FTS is designed to mount on the right-hand Nasmyth platform of the JCMT as shown in figure 4. As for the SCUBA instrument[17], the normal f/12 focal ratio, which feeds the cabin-mounted receivers, has been extended to ~f/16 by a small shift in the secondary mirror position. This ensures that the telescope beam passes unvignetted from the tertiary mirror, through the elevation bearing to the instrument. The interferometer is assembled on a damped optical breadboard, with optical components housed in high-precision adjustable mounts. All mirrors are uncoated, diamond-turned aluminum. The ~f/16 JCMT beam is brought to a focus at the beamsplitter (BS1) by two flat mirrors (M1 and M2) for each of the two input ports of the MZ FTS. The input mirrors (M1) can be mounted close together to allow for differential measurements of the source and a neighbouring background sky position (~60″) or, in the case of extended objects, the second input mirror can be directed to view an LN_2 calibration source.

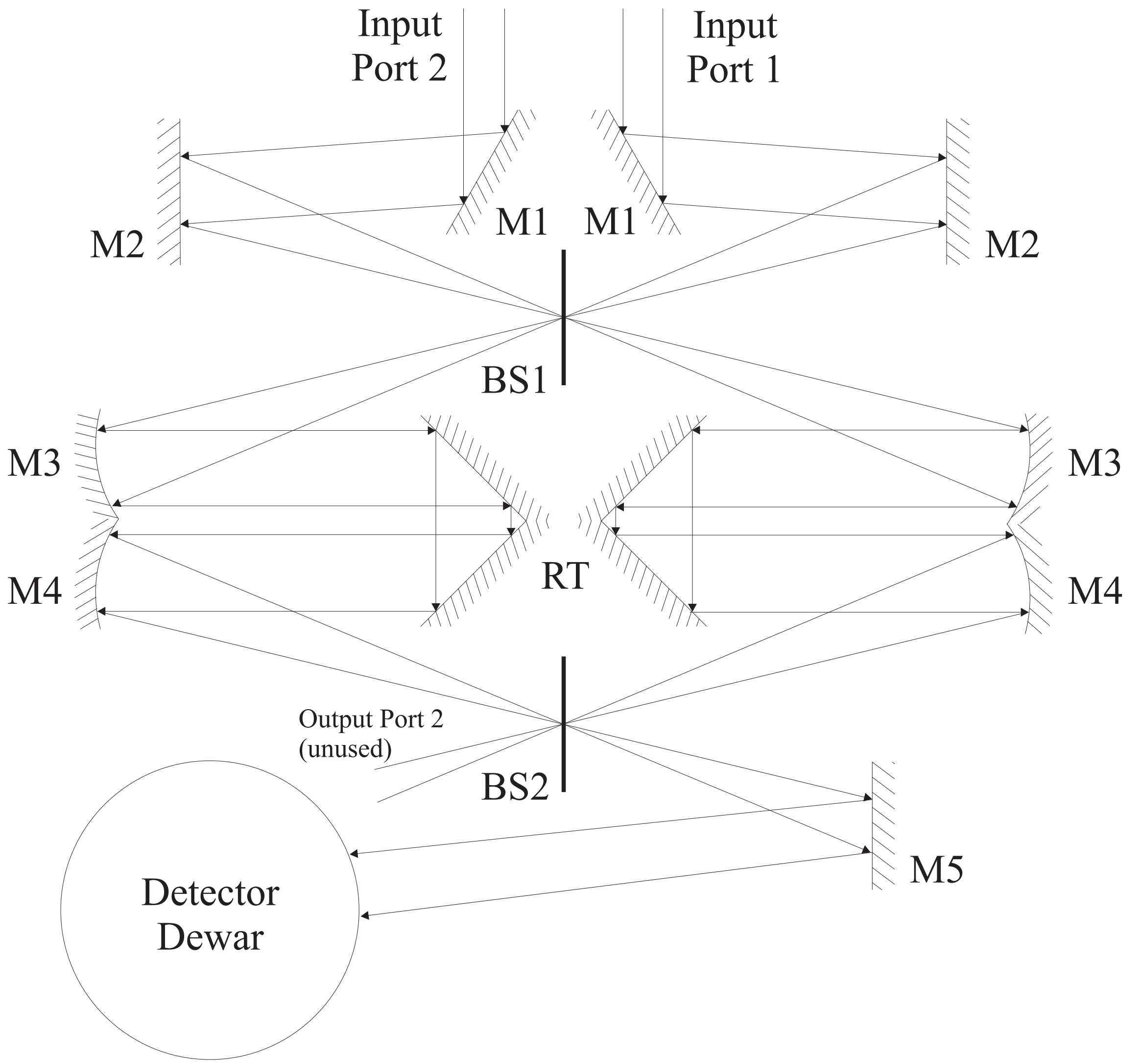

Figure 2. A schematic of the Mach-Zehnder Fourier transform spectrometer.

The reflected and transmitted beams from the beamsplitter are collimated by the spherical concave mirrors M3 (diameter 100mm, focal length 700 mm) and directed to roof-top mirrors (RT) constructed from 150 x 100 mm rectangular mirrors, which are mounted back-to-back on the precision translation stage (Aerotech ATS 20030). The translation stage provides a travel of 300 mm, which provides a maximum optical path difference between the interfering beams of 1.2 m. This optical path difference multiplication factor of four provides a spectral resolution of ~0.005 cm^{-1} (for single-sided interferograms) in a compact instrument. The design is such that the divergence (of solid angle Ω) within the interferometer does not compromise the maximum attainable resolving power, $R \sim 10^4$, constrained by the Jacquinot criterion (ΩR [2Π). The roof-top mirrors provide a horizontal shear to the input beams which then follow a symmetrical path, via the focusing mirrors M4, beamsplitter BS2, and flat mirror M5, to the detector dewar[5]. Since our detector was originally designed for use with the f/35 focus of the JCMT, the focal length of mirrors M4 is 1400 mm to provide the appropriate image magnification (in the present instrument only one of the output ports is used). The detector dewar contains a six-position filter wheel, whose filters are matched to the atmospheric windows (figure 1), and a variable cold field stop to match the diffraction-limited beamwidth of the telescope, which varies from ~7″ at 350 μm to ~14″ at 850 μm.

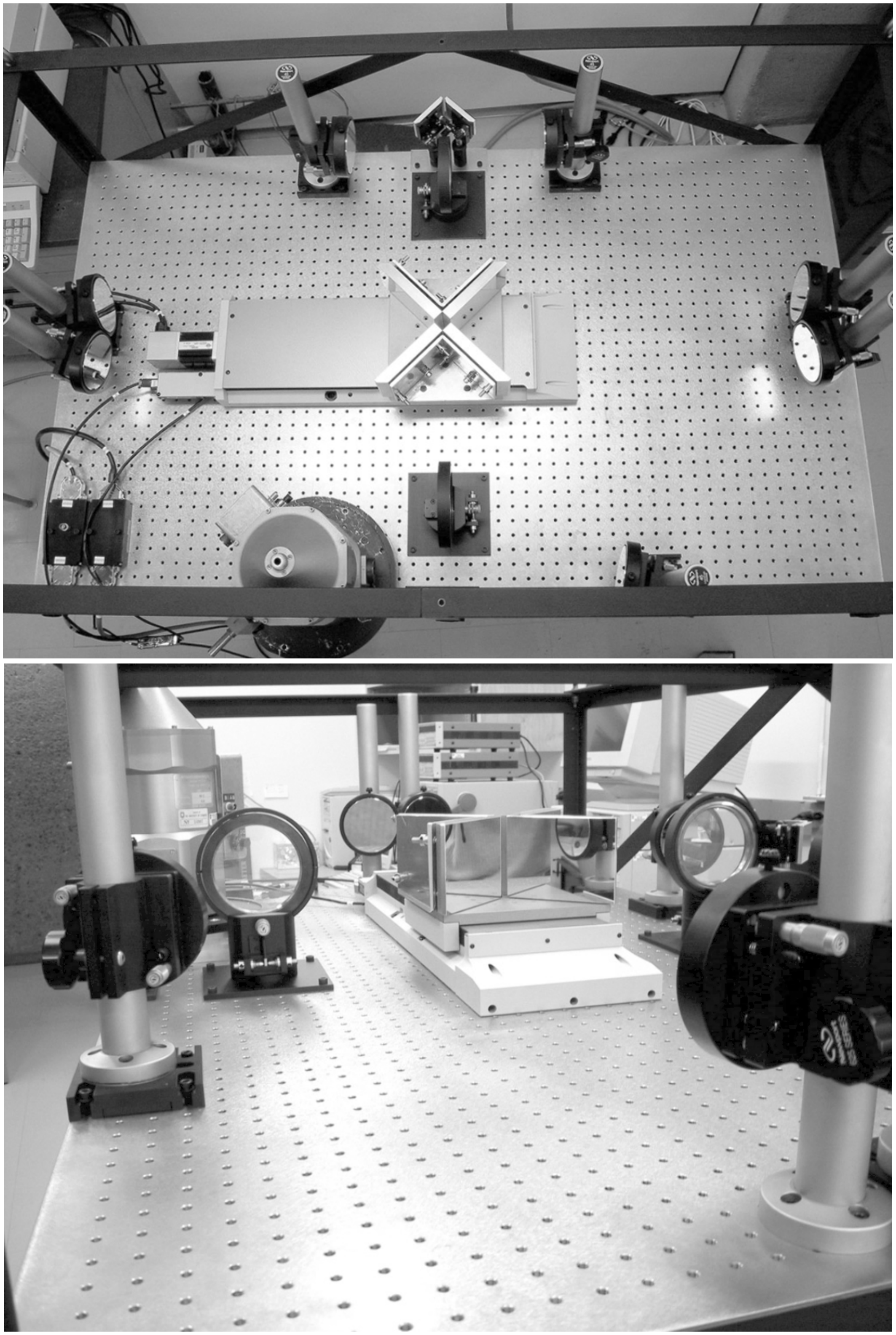

Figure 3. Top and side views of the MZ FTS in the laboratory.

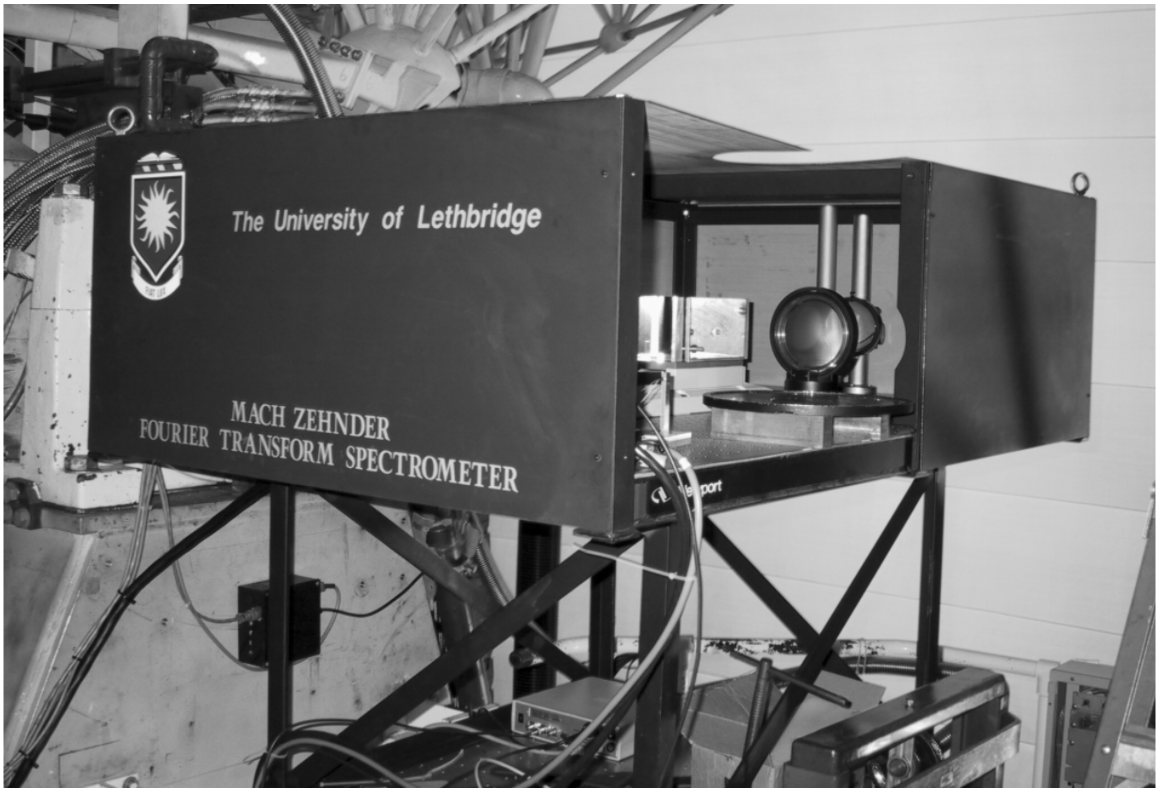

Figure 4. MZ FTS shown in position at the right-hand Nasmyth focus of JCMT.

2.2 Electronic design

The electronics has two primary modules, interferometer control and data acquisition, and is controlled by a PC running RTLinux 3.0 (Finite State Machine Labs, Inc.; www.fsmlabs.com), a real-time variant of the Linux operating system. The control PC is located at the Nasmyth focus and communicates, over a local area network (LAN) with the command laptop in the control room. A system block diagram is shown in figure 5.

2.2.1 Interferometer control

The interferometer control module controls the motion of the translation stage and provides sample pulses for the interferogram. The position, velocity and acceleration of the stage are controlled by an intelligent programmable controller (Aerotech Unidex100 (U100)), which uses PID feedback from an integral shaft encoder and an auxiliary linear encoder to control the brushless DC servo motor (chosen for its low EMI). The interferogram is sampled at equal optical path intervals by means of pulses generated by the Heidenhain linear encoder. This encoder has a line spacing of 4μm and a unique index point for absolute position referencing. The raw encoder pulses are input to a divide-by-eight counter, to generate pulses every 32 μm of linear motion. When account is taken of the four-fold optical path factor, this yields a Nyquist frequency of 39.0625 cm^{-1}, which satisfies all wavelength ranges of interest (figure 1).

2.2.2 Data acquisition

The data acquisition module digitizes the detector signal upon receipt of a sample pulse generated by the control electronics. The detector system[5] employs a fully differential electronic design, which virtually eliminates common mode electrical noise picked up from the often hostile telescope environment. A low-noise preamplifier (gain of 10^4) feeds one of the four analog inputs of dual, 4-channel, 24-bit ΔΣ analog-to-digital converters (ADC) featuring software programmable gain (CS5534, Cirrus Logic Inc.; http://www.cirrus.com). The other inputs of the ADCs monitor meteorological and housekeeping parameters (e.g., pressure, temperature(s), detector DC bias). A single 5V supply powers the digital logic, low-noise linear sub-regulators (Linear Technology LT1763) provide power for the analog circuitry, and chopper-stabilized buffer amplifiers are used to reduce front-end noise.

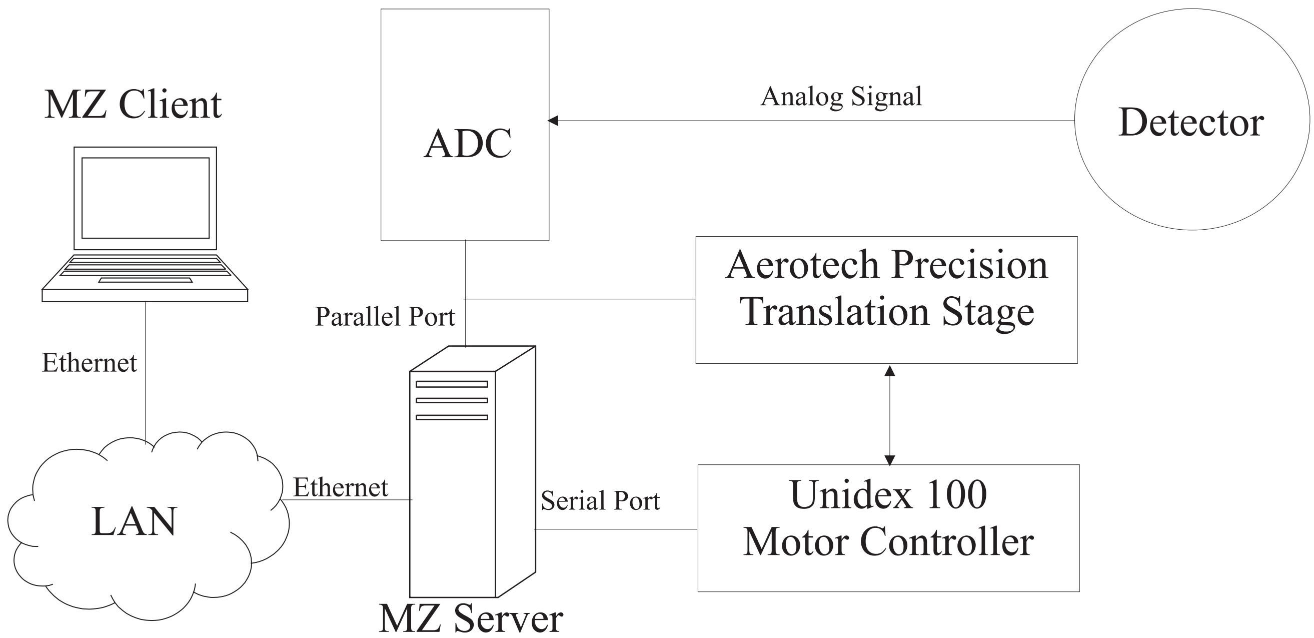

Figure 5. MZ FTS system block diagram.

The ΔΣ ADC communicates with the control PC via the parallel port, which is opto-isolated as a noise reduction measure. The control PC is interrupt-driven; upon receipt of a sample pulse a conversion sequence is initiated. At the end of conversion the ΔΣ ADC electronics uses the same external interrupt line to notify the control PC that data are ready. The ΔΣ ADC has an adjustable sample rate, inversely proportional to the digitized resolution, which is matched to the time response of the bolometer detector, this in turn sets the limit on the speed of the translation stage and thus the minimum time per scan. Currently the speed of the translation stage is set at 4.5 mm/s, which allows full resolution spectra to be obtained in ~1 minute. At this speed sample pulses are generated every ~7 ms and the integration time of the ΔΣ ADC is set at ~5.8 ms, which yields 17-bits noise-free resolution.

Interferometer	Mach-Zehnder, double input, double output
Translation stage	Aerotech ATS 20030-M-40P-LN30
Linear encoder	Heidenhain 250 lines per mm
Motor controller	Aerotech U100Z-A-40-F1.8
Scan mode	Rapid scan, maximum scan time 20 to 60 s
Spectral Bands	350, 450, 750, 850 μm
Resolution	0.005 cm^{-1}, 150 MHz
Accuracy	0.0002 cm^{-1}, 6 MHz
Beamsplitter	Intensity beamdividers
Detector	Composite NTD bolometer, 0.3 K
Beam Width	7” to 14” (FWHM)
NET (per resolution element of 150MHz)	~1K @ 850 μm, 1σ per 200s integration ~4K @ 350-450 μm, 1σ per 200s integration

Table 1. A summary of the MZ FTS characteristics

2.3 Real-time Software

The MZ FTS real-time software is divided into two parts: RTLinux-based server software (MZserver) running on the control PC located at the right-hand Nasmyth, and IDL[18]-based client software (MZclient) typically running on a laptop in the JCMT control room (figure 5). The two computers are connected on the JCMT local area network (LAN).

2.3.1 Server software

The MZserver controls the motion of the translation stage by issuing high-level commands to the intelligent U100 programmable motion control unit via an RS232 serial interface. This involves scanning the translation stage a specific distance defined by the requested spectral resolution. The U100 controller automatically controls the positioning of the translation stage through velocity-shaped motion profiling, reporting status and errors to the control PC. The MZserver periodically polls the U100 to determine when a commanded motion has completed. The MZserver controls data acquisition by issuing conversion commands to, and reading digitized data from, the ΔΣ ADC via an opto-isolated parallel port.

A key feature of the MZserver software is the use of an efficient Interrupt Service Routine (ISR) running on RTLinux, which guarantees rapid service of external interrupts. The interrupt latency of the ISR (i.e., time between getting an interrupt and entering the ISR) is not affected by excess load on the system. Computationally intensive programs can be run simultaneously on the system without compromising data collection. A heavily loaded system will, however, have difficulties spooling the collected data back to the MZclient program. The ISR can be triggered by either a start or end of conversion request. Once a start of conversion request (i.e., sample pulse) is received, a command sequence is sent to the ΔΣ ADC to initiate a conversion and the ISR is immediately exited. Upon receipt of an end of conversion request (generated by the ΔΣ ADC), a command sequence is sent to the ΔΣ ADC to read the digitized data, which is stored in a shared memory space that can be accessed by other programs. Sample pulses are generated every ~7 ms, the sample command takes ~70 μs, the conversion itself takes ~5.8 ms, and reading the digitized data takes ~200 μs. Since over 95% of the time is taken up by the conversion process, the use of a two level ISR allows the control PC to service other tasks such as spooling data back to the MZclient via the LAN, saving the data to a local hard drive, or responding to web requests.

2.3.2 Client software

The IDL client software, typically run from a laptop in the JCMT control room, provides the graphical user interface to the MZ FTS, controls the scanning sequence, plots incoming data, performs a real-time FFT, and saves data to files. At the beginning of an observation, the user selects various instrumental parameters (e.g. filter band, aperture, spectral resolution, number of scans, file name, title etc.) by means of a windows-style menu (shown in figure 6). The parameters are sent via the TCP socket connection to the MZserver when the scan sequence is initiated.

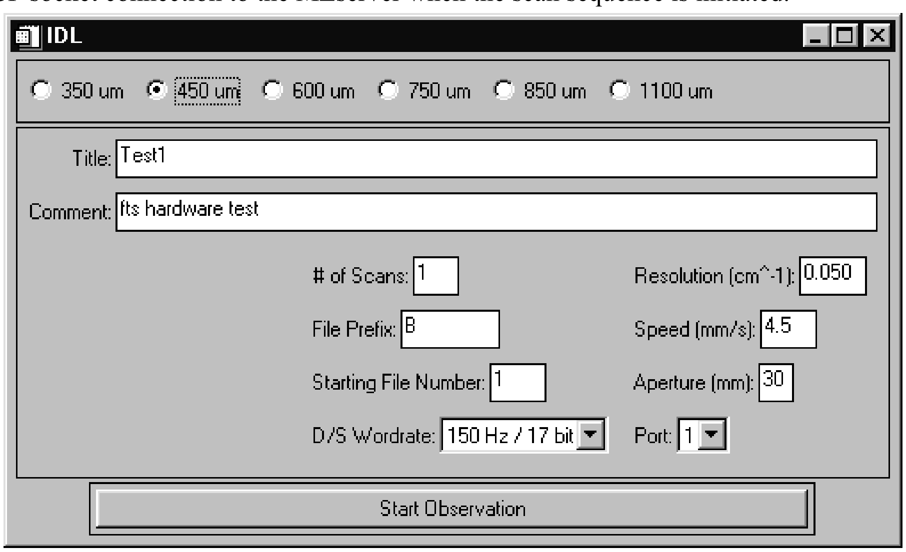

Figure 6. Scan sequence parameter menu.

The MZclient display is shown in figure 7. There are four windows showing, clockwise from the top left, the unity gain interferogram, the zero path difference (ZPD) region, the FFT, and the 8x gain interferogram. All plots are updated in real time as the data is collected, and can be zoomed, panned, or rescaled on the fly. The FFT can be displayed in terms of electrical frequency (Hz) or wavenumber (cm^{-1}), the former scale being useful for diagnosing electrical interference problems. The FFT display can also be disabled, or the plot refresh rate decreased, to increase performance on slower computers. Telescope and atmospheric parameters such as atmospheric opacity (CSO Tau), seeing, source, and airmass are collected from the JCMT notice board at the beginning of each scan and are displayed at the top of the screen. The scan completion time is also indicated for convenience, as well as some basic file parameters for logbook entry.

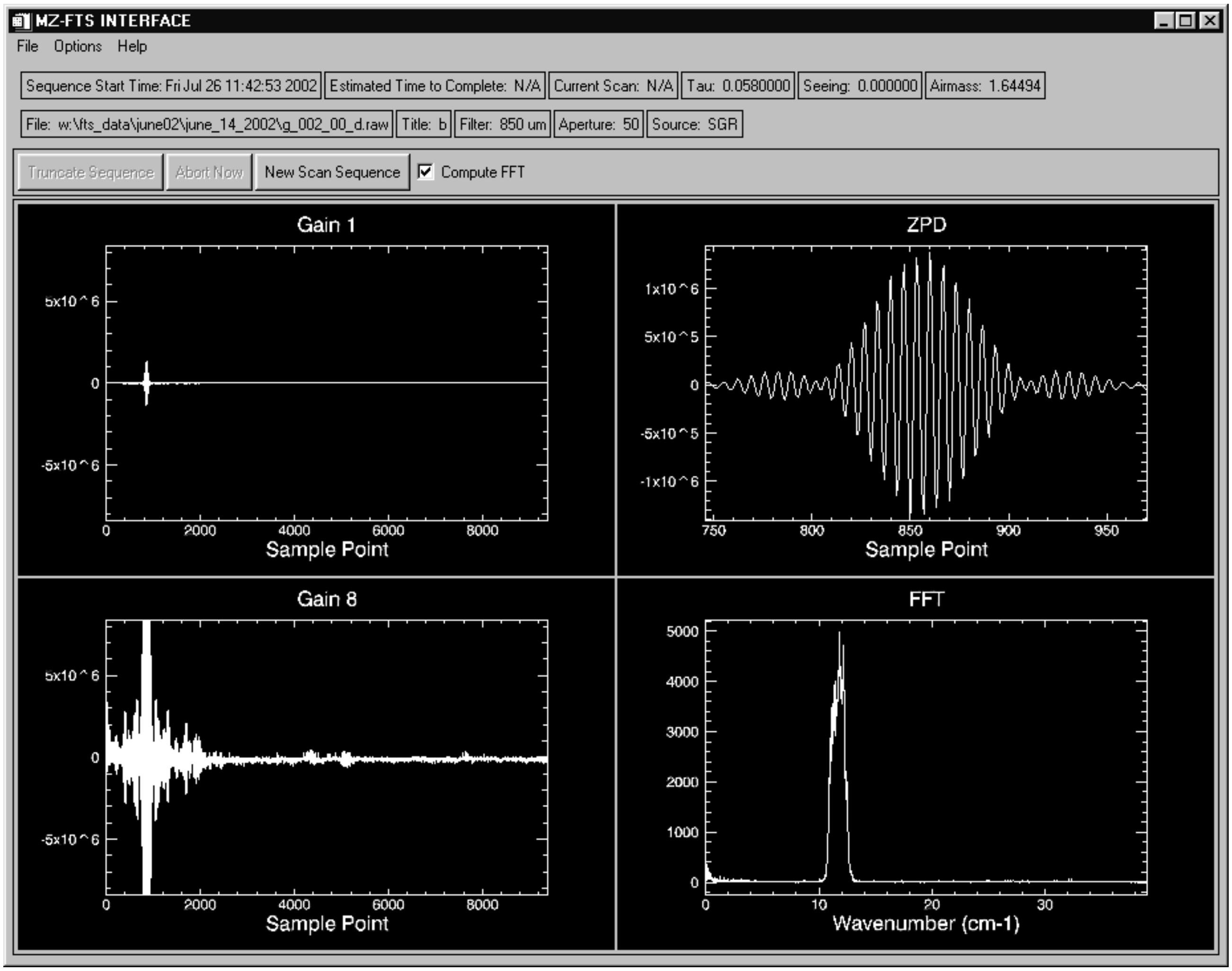

Figure 7. The MZclient display window.

As the FTS is scanning, the plots for the upward and downward scans are overlaid in alternating colors. In addition, previous data files can be loaded and displayed for reference. The observer can abort a scan or scan sequence at any time. Collected data are saved to a file with a unique name at the end of each scan, along with a header block containing system and observing parameters such as: azimuth, elevation, Ra, Dec, CSO Tau, seeing, airmass, atmospheric pressure and temperature, wind speed and direction, scan resolution, Nyquist frequency, sample points, table speed, scan time and duration, title, source, filter, and aperture. These header blocks provide a comprehensive log of the parameters which are required for subsequent data analysis. The files are written identically on the MZserver computer for backup purposes. The files are saved in a compact binary format, and further processing is done in separate IDL offline data pipeline software.

2.4 Processing software

Processing pipeline software, written in IDL, converts the raw interferograms into spectra and records all processing parameters. The first step in this pipeline is to inspect each interferogram for the effects of ubiquitous cosmic rays (which contaminate roughly 1 in every 10 interferograms) and for rapid changes in atmospheric opacity. Interferograms of low quality are deleted at this stage; those affected by cosmic rays can generally be recovered by the interactive removal of the associated noise spikes. The next step is to apply standard FTS analysis techniques[6]. Since the optical elements in the spectrometer and detector produce negligible dispersion over the narrow spectral ranges of interest, in most cases a linear phase correction function is computed (by weighting phase values obtained from a short, double-sided interferogram by the amplitude of the corresponding spectral point) and convolved with the edited interferogram, to produce a phase-corrected interferogram. However, the software also allows for the application of non-linear phase correction and a variety of apodizing functions for both the edited interferogram and the derived phase correction function. The final step is to Fourier transform the phase corrected interferograms; the resulting spectra can be saved in Galactic Grams format (www.galactic.com), or an internal IDL format for further processing.

The pipeline also allows for spectral processing. Each spectrum is first corrected for airmass and atmospheric transmission, the latter being calculated from the recorded CSO Tau zenith opacity values (logged in the MZ FTS header file) and an atmospheric model. Astronomical and background spectra can then be averaged, differenced and ratioed as required. Spectra obtained using a blackbody operating at two temperatures provide intensity calibration. The pipeline also allows the user to reject noisy spectra and remove residual baseline artifacts using spline fitting routines.

3. RESULTS

We illustrate the performance of the MZ FTS by presenting some preliminary spectroscopic observations of the Orion molecular cloud obtained at the JCMT. The proximity of the Orion molecular cloud provides a unique opportunity for studying star formation. SCUBA images have revealed a remarkable variety of structures including candidate pre-stellar cores, cores containing Class 0 protostars, shocks and PDR fronts[19]. Spectral index maps obtained from the ratio of the 450 and 850 μm images yield values in the range $2< \beta <4.5$ (where S_ν ;ν^β). While structure in the submillimeter spectral index map is thought to be dominated by dust emissivity and temperature variations, a significant contribution to the total measured flux may arise from molecular line emission that falls within the SCUBA band-passes.

Figure 8 shows recent MZ FTS spectra of the Orion KL region compared with earlier work at the CSO[20]. Our spectra show the classical *sinc* line-shape of a FTS measuring unresolved molecular lines, and represent a significant increase in sensitivity over the CSO spectra; more importantly, while up to fourth order polynomial baselines have been removed from the CSO spectra (reflecting calibration uncertainties), our spectra show a well-behaved continuum. Line and continuum emission components are clearly seen in both the 850 and 450 μm bands with many lines being readily identified. Although the ^{12}CO(3-2) and ^{12}CO(6-5) lines are the strongest single lines, emission from a plethora of weaker SO and SO_2 lines dominates the total line flux. It is therefore clear that temperature and dust properties cannot be derived solely from SCUBA maps. For example, in the Orion KL 850 μm spectrum the contribution from line emission is found to account for 33% of the total flux. We are in the process of analyzing these spectra to determine the temperatures and column densities of the detected molecular species using the rotation diagram technique[21], and to extract the underlying continuum emission component.

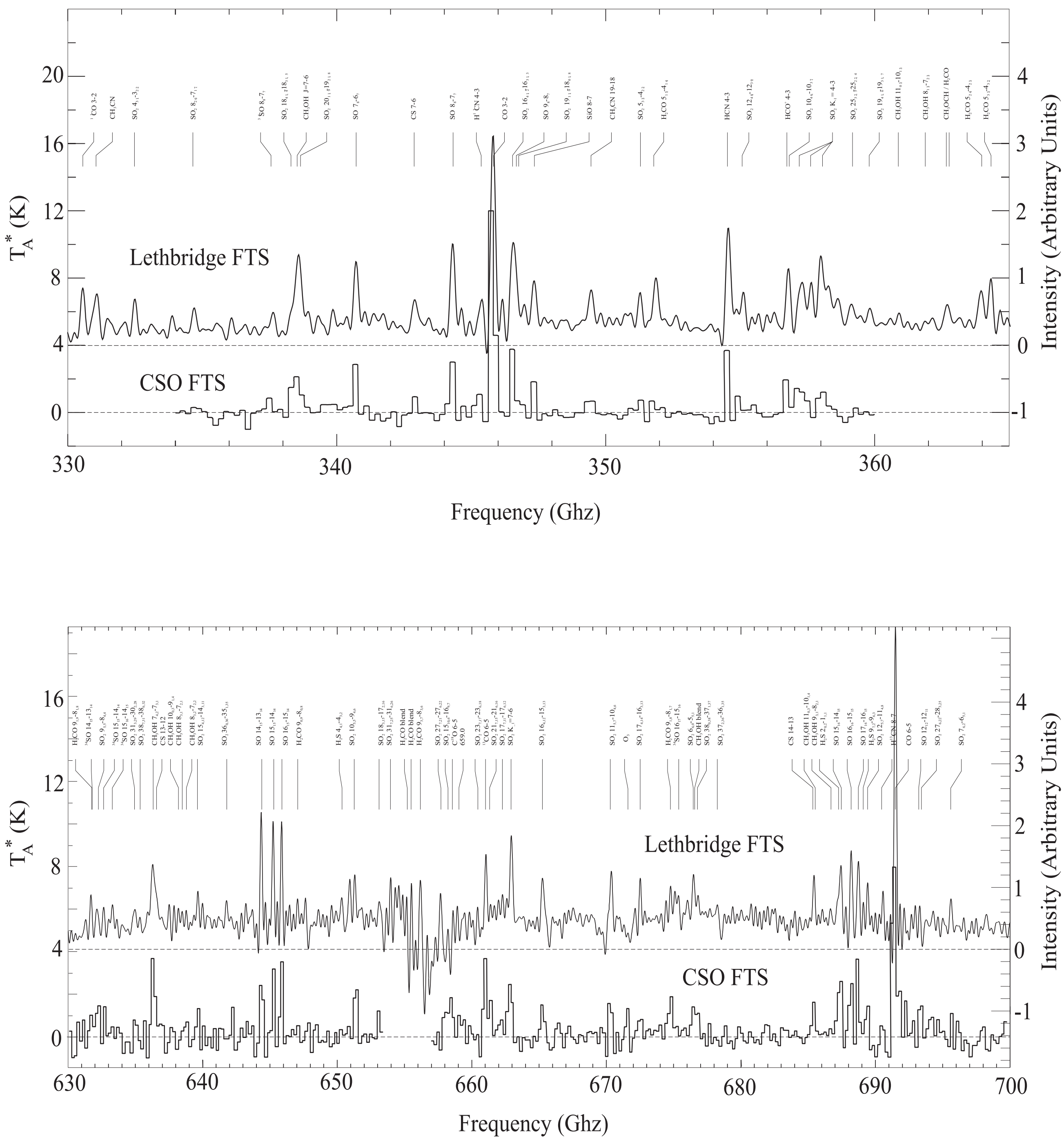

Figure 8. 850 μm (upper plot) and 450 μm (lower plot) spectra of the Orion KL region. The upper traces in each plot show the MZ FTS spectra in which the continuum emission component is preserved. The lower traces show FTS spectra obtained at the CSO in which the baseline has been removed.

4. SUMMARY

In this paper we have presented the design and performance of a Mach-Zehnder Fourier transform spectrometer which has been developed for use at the James Clerk Maxwell Telescope. The design provides access to all four interferometer ports while maintaining a high and uniform efficiency over a broad spectral range. Since the interferometer processes both polarizations, it is twice as efficient as the Martin-Puplett interferometer. Moreover, by using powered mirrors within the arms of the interferometer, the size of the optical beam at the beamsplitter is minimized. Since the size of the beamsplitter is one of the limiting factors in any FTS, this design is well suited to imaging Fourier transform spectroscopy, and is currently being evaluated as a potential spectrometer for use with the planned SCUBA-2 camera. Preliminary results show that the MZ FTS is capable of simultaneously detecting the continuum and line emission components from the Orion molecular cloud core. We are planning to use the MZ FTS to measure the Spectral Energy Distribution across the 850 μm band for an ensemble of sources in the Orion molecular cloud.

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