University of Toronto's balloon-borne Fourier transform spectrometer

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A commercial ABB-Bomem DA5 Fourier transform spectrometer (FTS) was refitted with new software and electronics to create a FTS that is appropriate for both ground-based and balloon-based measurements. Nearly all the electronics were replaced, and new control software was written that allows the instrument to run remotely, provides access to all housekeeping information, and permits considerable freedom in data processing approaches. A "delta" tracker was used for fine tracking of the sun over a small tracking range, using the main gondola pointing system for coarse azimuth tracking. This facilitated a simple, effective method of instrument integration onto the payload. The new design reduced the mass of the FTS from 90 to 55 kg and reduced the power consumption from 145 to 65 W. © *2006 American Institute of Physics.* [DOI: 10.1063/1.2338289]

I. INTRODUCTION

The University of Toronto's Fourier transform spectrometer (U of T FTS) was originally purchased in the 1980s by the Meteorological Service of Canada (MSC) from what is now known as ABB-Bomem, a company that produced an excellent optical design for its research-grade FTSs. Briefly, in the U of T FTS, light from a source is split into two paths: one whose length remains constant and the second whose length modulates. These two beams recombine to produce an interference pattern (an interferogram) as a function of the optical path difference between the two beams. The U of T FTS samples the interference pattern produced while the scan mirror is traveling down the spectrometer. The sampling rate is determined by the speed of the traveling mirror (in our case, typically around 0.5 cm/s) and the frequency of the metrology laser used to determine equally spaced sampling positions (we use a HeNe laser at 15 798 cm^{-1}). The main advantage of ABB-Bomem's design is their dynamic alignment (DA) system, which compensates for the unwanted but inevitable angular instability ("wobble") of the scanning mirror by adjusting the stationary mirror. The DA system on ABB-Bomem FTS instruments is robust, reliable, and repeatable. A schematic of an ABB-Bomem DA-series FTS is shown in the interferometer box in Fig. 1.

The instrument control software provided by ABB-Bomem was embedded in the control computer for the instrument. The software allows the user to manually control the main functions of the FTS in a simple and repeatable way. This, however, was not appropriate for our balloon application, which requires that interferograms be recorded during solar occultation (sunrise and/or sunset) with limited telemetry uplink and downlink. For this application, it is necessary to control the instrument remotely and have a robust automatic mode where, should the communications between the payload and the ground station fail, the instrument will still perform usefully. It is also necessary to constantly monitor "housekeeping" data: voltages, temperatures, and other important instrument status information, such as the alignment signals and the laser intensity.

In order to achieve these objectives, the computer and most of the other electronics had to be replaced. The electronics, discussed in Sec. II, were generally replaced with modern off-the-shelf parts, which were smaller and drew less power than their predecessors. New control software was written in LABVIEW, which controls the instrument, stores the interferograms and housekeeping data on board, receives commands through an RS-232 link, and sends both interferograms and housekeeping data down to the ground station for monitoring during the flight. Spectra are produced with separate analysis software written in MATLAB. The software will be discussed in Sec. III.

FTS instruments, when performing solar occultation measurements, require very accurate solar pointing (better than 5% of a solar diameter: <0.5 mrad, or <0.03° in both zenith and azimuth) and so integration (alignment) with the payload becomes critical, even with a sufficiently accurate gondola pointing system. The balloon payload, upon which the U of T FTS flies, has a pointing system described by Quine *et al.* in Ref. 1. This pointing system can achieve 3° in azimuth, so a small suntracker was used to perform high-precision solar pointing. The suntracker used for the flight will be discussed in Sec. IV.

The U of T FTS flew on the middle atmosphere nitrogen

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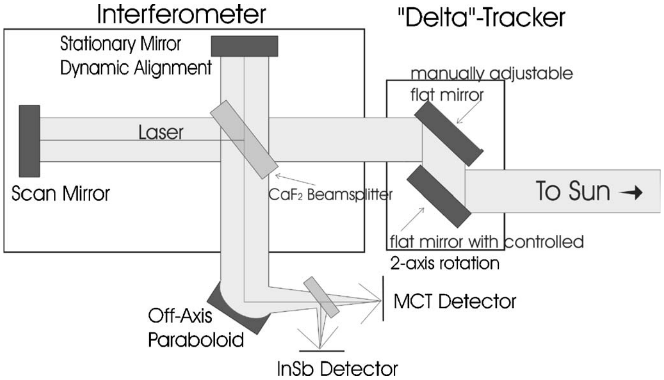

FIG. 1. Schematic of the U of T FTS. The interferometer box, on the left, shows a typical optical layout for an ABB-Bomem interferometer.

trend assessment (MANTRA) 2004 payload. The MANTRA mission, described by Strong *et al.* in Ref. 2, is comprised of four high-altitude balloon flights flown every second year since 1998. The flights are supported by a suite of ground-based measurements in Vanscoy, Saskatchewan, Canada (52°N, 107°W). Both ground-based and balloon-based spectra will be shown and discussed in Sec. V. The scientific goal in flying the FTS was to measure a suite of atmospheric trace gases, including CO_2, O_3, HCl, N_2O, and CH_4. For this application, the FTS spectral range spanned 1200–5000 cm^{-1} (5–8 μm) with a maximum optical path difference of 50 cm. Interferograms are recorded on two detectors: an indium antimonide (InSb) detector and a mercury cadmium telluride (MCT) detector. The main spectrometer beam splitter is made of calcium fluoride (CaF_2). A schematic of the configuration of the FTS for the MANTRA 2004 campaign is shown in Fig. 1.

II. ELECTRONICS

There are three main components of an ABB-Bomem FTS that must be controlled to produce a working interferometer: the scanning motor, the dynamic alignment, and the data collection. The software, embedded in a read-only memory chip, controls eight electronics boards: a microprocessor, through which the other boards are controlled, the sampling board, which controls the data collection by two analog-to-digital converters, a speed and search control board that controls both the scan motor and the dynamic alignment, and three miscellaneous electronics boards.

Because new software was required, the old computer and all its associated boards were removed and replaced. The only board that was kept unchanged was the speed and search control board. The microprocessor and embedded computer were replaced by a 500 MHz EPIA computer and LABVIEW software (discussed in Sec. III with technical details in the Appendix). The sampling boards were replaced by a Schmidt trigger filter to condition the laser signal, which was then counted by a 32 bit digital counter. The housekeeping information was recorded on a 12 bit analog-to-digital converter module produced by LabJack (see the Appendix), which also contains the 32 bit counter channel used for the laser sampling.

The original analog-to-digital (A/D) converters had built-in electronics to perform a gain change after a certain (programmable) number of fringes. A gain change is necessary because a 16 bit analog-to-digital converter does not have the dynamic range to capture an interferogram with a signal-to-noise ratio (SNR) in spectral space of greater than 150 (Ref. 3, pp. 65–67). The largest signal occurs at the zero path difference (ZPD), and a gain change after that point is necessary to accurately measure the rest of the interferogram, which is typically orders of magnitude smaller. The analog-to-digital converters that digitized the detector intensity information were replaced by an eight-channel, 16 bit A/D board from the Measurement Computing Corporation (see the Appendix), on which four independent channels were used to record high-gain and low-gain signals simultaneously for the two detectors. Section III details the importance of the ability to record the high- and low-gain channels simultaneously.

III. SOFTWARE

The control software was written in LABVIEW, and the analysis software was written in MATLAB, in order to take advantage of the strengths of both languages. LABVIEW has a strong instrument control package and an extensive hardware driver library and MATLAB is ideal for matrix calculations, statistical analysis, and graphing. Information about the MATLAB language is contained in the Appendix.

The LABVIEW software integrates three components of the instrument: the scan motor, which is controlled through digital commands to the dynamic alignment electronics (speed and search control), the data acquisition system, and the housekeeping record. The software contains an automated scheduler, so that an experiment can be run without user intervention. The scheduler can record data during preset time intervals: for example, it can measure during both sunrise and sunset without recording data in between. The software is run on a fanless 500 MHz EPIA motherboard with a compact flash card hard drive running WINDOWS embedded (the details can be found in the Appendix). In the future, this will be replaced by a stripped-down version of WINDOWS XP, which can be more easily modified.

The software also contains uplink and downlink capabilities through three RS-232 connections (one 300 baud uplink shared by all instruments on the payload, one dedicated 9600 baud housekeeping downlink and one dedicated 115 kbaud data downlink), so that the instrument can be controlled remotely. The housekeeping downlink includes a "centerburst" from the instrument (a short section of the raw data around ZPD that indicates the data quality), so that the data can be monitored in near real time. The 115 kbaud data line is not fast enough to downlink an entire interferogram in real time. Complete binary interferograms (for two channels on both detectors) are 6 Mbytes each and are recorded every 50 s, giving a data rate of 960 kbaud. It is therefore wise to both downlink the data during the flight (which will take a few hours) and also store the data on-board for retrieval after the payload has landed. This ensures that in the unlikely event that the payload is destroyed upon landing, the data will have been safely recorded on the ground, but if a problem arises with the telemetry system, the complete data set can be retrieved after the flight. Should both events occur, data loss is inevitable.

An occultation takes approximately 30 min, and adding on 15 min before and after the occultation to ensure that the entire occultation is measured gives a data volume of ~430 Mbytes per occultation. The flight time line allows measurements through two occultations, and so, at minimum, a 1 Gbyte hard drive is needed to record the data from one flight. The data were recorded on a 2 Gbyte flash card, separate from that of the operating system, so a new flash card could be inserted before each flight without regenerating the operating system.

This software has many advantages for this application. First, all instrument housekeeping information is recorded and easily accessible. All postprocessing can therefore be done with full knowledge of the state of the instrument. Access to housekeeping data is particularly important during a balloon flight, when ambient temperatures can dip to as low as −60 °C, and where direct sunlight can cause temperatures to rise as high as 80 °C. Since the electronics have only radiative and conductive coolings, monitoring the temperatures during a flight can indicate when an instrument must be turned off to avoid overheating. The instrument heaters are thermostatically controlled to avoid excessively low temperatures.

The software allows for postprocessing flexibility. It is preferable to do no processing of the data on board the balloon so that the data can be processed in any manner desired after the flight. Processing on-board has typically been used in the past to reduce data volume, because on-board storage capacity was limited.[4] Today, this is not an issue. 8 Gbyte flash cards are available, and a pressurized laptop hard drive is a viable alternative.

In this system, as described in Sec. II, both a high-gain and a low-gain channel for each detector are stored on-board, and so it is not necessary to institute a midinterferogram gain change, thereby eliminating the need for this on-board processing procedure. In fact, there is no on-board processing of any kind (FFTs, apodization, digital filtering, etc.). The raw data are both transmitted down to the ground and stored on the hard drive for processing after the flight.

The MATLAB data analysis software decodes the binary data from the LABVIEW program, performs a Forman phase correction to symmetrize the interferograms,[5] and computes a fast Fourier transform to produce an atmospheric spectrum.

IV. DELTA TRACKER

There are three methods of tracking the sun on-board a balloon platform. The first method is to have no gondola control and use a dedicated sunseeker that tracks the sun 360° in azimuth and between −10° and +90° in elevation for each solar-pointing instrument. Integrating the instruments onto the payload is trivial in this case, because the sunseeker does not depend on the orientation of the gondola to track the sun. One problem with this method is that if the payload happens to be oriented in such a way that the gondola's structure or another instrument blocks the sun to the sunseeker, there is no way to recover. A second problem is the potential for interference between different sunseekers. Multiple heavy suntrackers may unbalance the payload as they move their mirrors, causing a problem with gondola stability and reducing pointing accuracy. Finally, these sunseekers also tend to be heavy,[4] costly, and consume a lot of power.

The second method is to control the gondola itself, with azimuth control and a pointing table for elevation control, such as the system described by Quine *et al.*[1] The instruments can then be coupled to the pointing table to receive their solar beams. In practice, however, this has two main drawbacks. The first is that the gondola pointing control, particularly the azimuthal control, is rarely sufficiently accurate for FTS occultation measurements. The second drawback is that even if the azimuthal control were good enough, we would need precise alignment with the pointing system. On the MANTRA 2004 payload, there were five instruments that measured solar absorption by occultation. The solar alignment of such instruments on a gondola structure is a notoriously difficult problem, especially from a logistic point of view. Gondolas are not built to optical precision and so alignment must occur outdoors on a clear day. (Some rough alignment can be done with a lamp source, but all final positions must be determined using the sun.) Each instrument ideally needs at least a few hours with the gondola without other instruments on board, during a day when the skies are clear, creating significant delays in flight preparation.

In light of the drawbacks inherent in these two methods, we decided to use a third, composite method of solar tracking also used by Hawat *et al.*[6,7] We depend on some azimuthal control from the main gondola pointing system and use a small suntracker that has a tracking range covering a small range of azimuthal and elevation angles. Because the small tracker adjusts relative to the main system, it is referred to as a "delta" tracker. The advantage of this third method is that the delta trackers are small, low mass, and draw little power, while still allowing a much simpler method of aligning the instrument with the payload. The instrument is first aligned to the delta tracker off the payload, and then the instrument is integrated onto the payload facing the solar-pointing side of the gondola without any further adjustment, since the delta tracker will take care of any small differences between the instrument and the gondola pointing system.

The delta tracker used with the U of T FTS has a ±10° tracking range in both azimuth and elevation. This is a sufficient tracking range for balloon-based measurements, because from a 40 km float height, elevation angles from just above 0° in elevation, down to −6°, are measured. The delta tracker is a very simple, two-mirror design, with the first mirror allowed to rotate in two axes by two chart-recorder pen motors, and the second 45° mirror is adjustable to align the optical axis with the FTS. A positional sensor output was fed into a simple circuit which controlled the pen motors. The tracker was mounted to the input of the FTS (see Fig. 1). Since the azimuthal control on the payload should be accurate to 3°,[1] the delta tracker is well suited to this job.

On the ground, two additional mirrors need to be placed

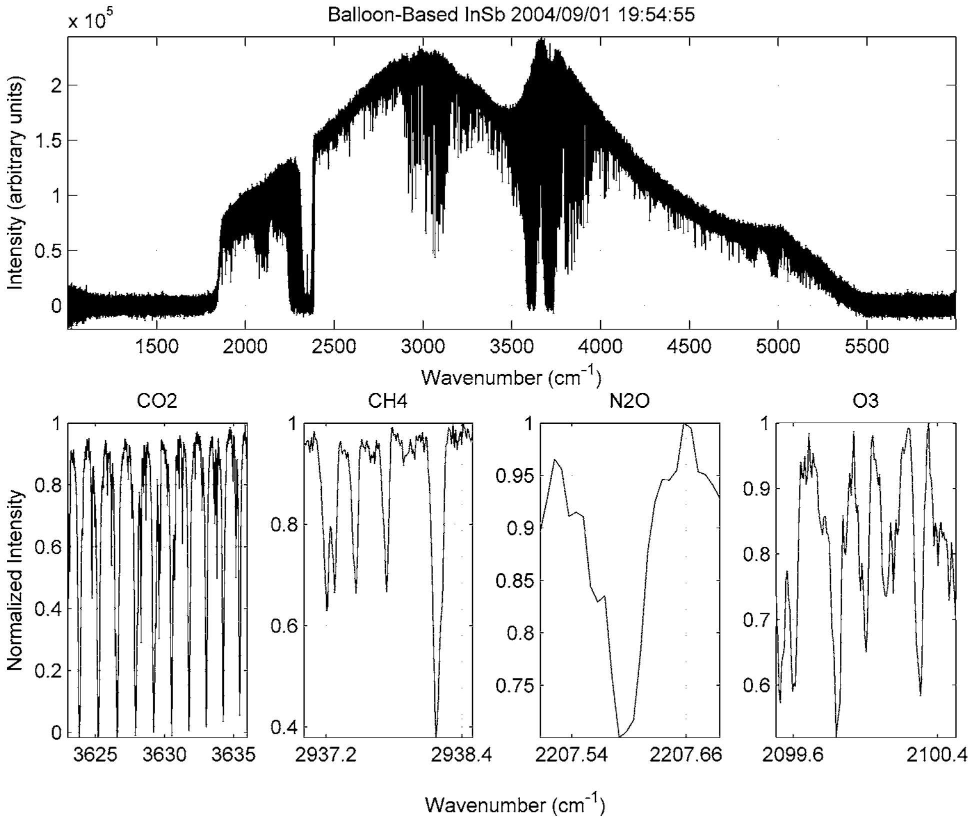

FIG. 2. InSb Spectrum from the MANTRA 2004 flight. The top panel shows the entire spectrum, while the lower four panels show microwindows from which we retrieve CO_2, CH_4, N_2O, and O_3, respectively.

in front of the delta tracker because the sun reaches elevation angles above 45°, and, ideally, we would wish to have a system that is in exactly the same configuration for both ground and balloon-based measurements. This will give us complete confidence that the alignment of the instrument on the ground will be unchanged on the payload. Therefore, in future designs of the delta tracker, a larger tracking range will be used so that we do not need additional optics to use the instrument on the ground. The delta tracker would remain small and dependent on the main gondola's pointing system for its coarse azimuth control on the balloon.

V. RESULTS AND DISCUSSION

The new design of the FTS worked well. The integration of the FTS onto the payload was smooth. The instrument was simply lifted into place after being aligned and tested on the ground, and because the delta tracker was attached to the FTS, no precise alignment was necessary with the payload.

The new control software was put to the test during the MANTRA 2004 balloon flight, where shortly after launch, all uplink commanding was lost to the payload, and the data downlink line was inaccessible. As a consequence of the commanding loss, the main gondola pointing system failed, and the payload slowly spun during sunset. However, the housekeeping downlink was intact and the U of T FTS was automatically set in its scheduler mode. The housekeeping data were useful during the flight, giving constant information about the status of the instrument, and even information about the direction in which the payload was facing, by noting increases in temperatures at various positions along the instrument as the sunlight was incident upon the different sensors. The voltages, temperatures, and laser status were monitored constantly, and the instrument performed well in the low-pressure environment. The automated scheduler began recording data just before sunset, and the spectra it recorded are shown in Figs. 2 and 3. Unfortunately, because the payload was spinning during sunset, the spectra in the figures are two of only four solar spectra recorded. However, had the delta tracker not been used, and had the instrument depended solely on the main gondola pointing system for solar tracking, no spectra would have been recorded at all.

A fortunate result of the work done on this FTS is that both the power consumption and the mass of the instrument were significantly reduced. The power was reduced from 145 to 65 W and the mass was reduced from 90 to 55 kg. This has obvious advantages for the balloon application, since the balloon's ultimate float altitude is dependent on the mass of the payload. The instruments are powered by lithium battery packs, which are heavy and have a limited lifetime, and a lower power consumption will lengthen the lifetime and decrease the added mass. Additionally, a lower power instrument generates less heat that must be removed through conduction and radiation.

The FTS made solar absorption measurements on the ground in the time leading up to the MANTRA 2004 flight. Figures 4 and 5 show the spectra and atmospheric trace gas "microwindows" for the ground-based data. Microwindows are small regions of the spectrum that contain absorption lines of the molecule of interest and as few interfering species as possible. Comparing flight spectra in Figs. 2 and 3 with the ground-based spectra in Figs. 4 and 5, one can see striking differences. The most obvious difference is the overall shape of the spectra. There is much less absorption in the

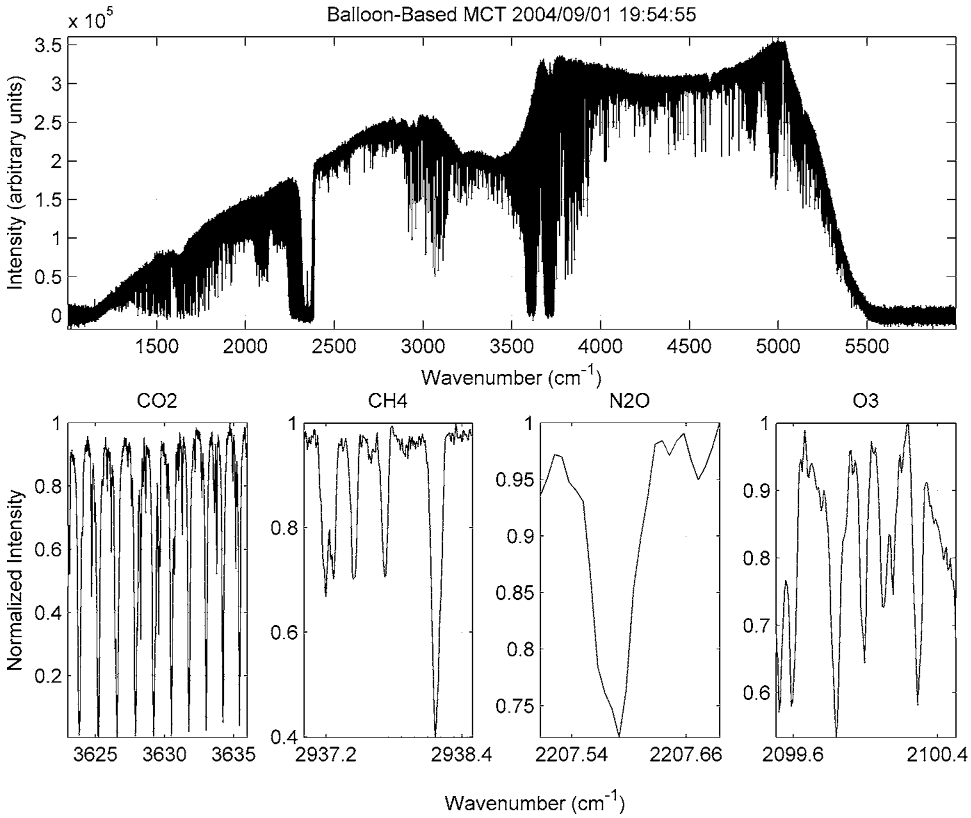

FIG. 3. MCT spectrum from the MANTRA 2004 flight. The top panel shows the entire spectrum, while the lower four panels show microwindows from which we retrieve CO_2, CH_4, N_2O, and O_3, respectively.

balloon spectra, simply due to the lack of water vapor and other tropospheric trace gases in the optical path.

To compare spectral signatures of trace gases, some common microwindows for CO_2, HCl, CH_4, N_2O, and O_3 are shown in the lower panels of Figs. 2–5. Since, in general, molecules cannot be measured in the same microwindows on the ground and from a balloon (since most of the spectral lines present in the balloon spectra are saturated in the ground-based spectra, or obscured by water vapor), microwindows cannot be directly compared. But the microwindows

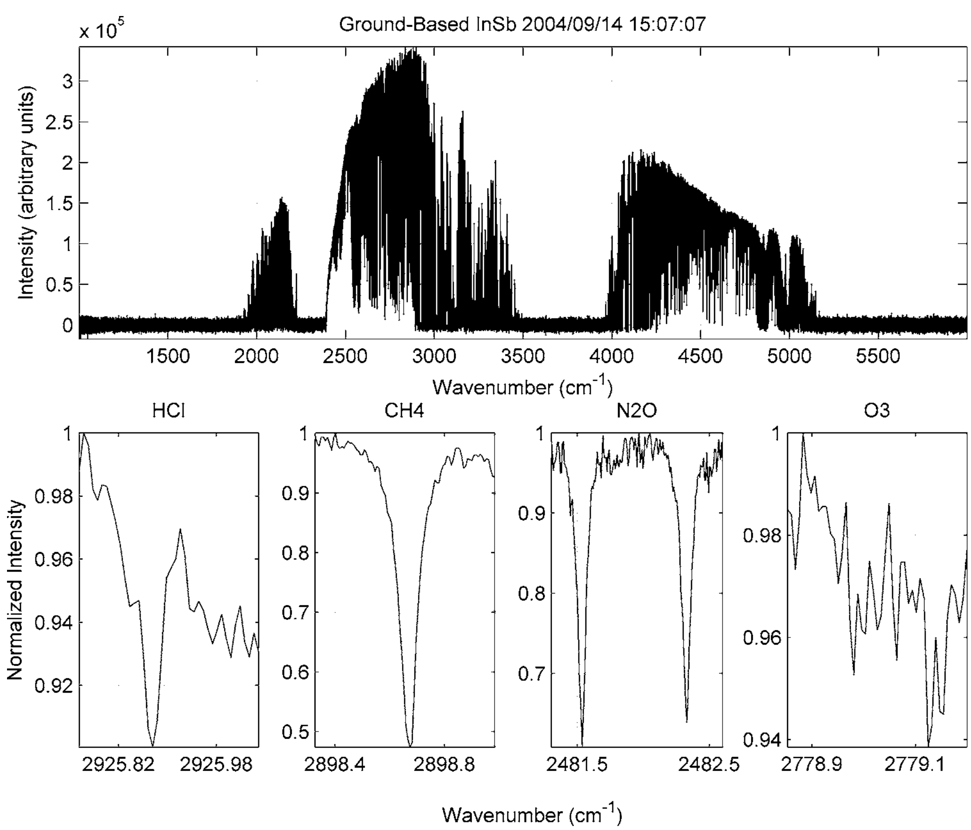

FIG. 4. InSb Spectrum from the MANTRA 2004 ground-based campaign. The top panel shows the entire spectrum, while the lower four panels show microwindows from which we retrieve HCl, CH_4, N_2O, and O_3, respectively.

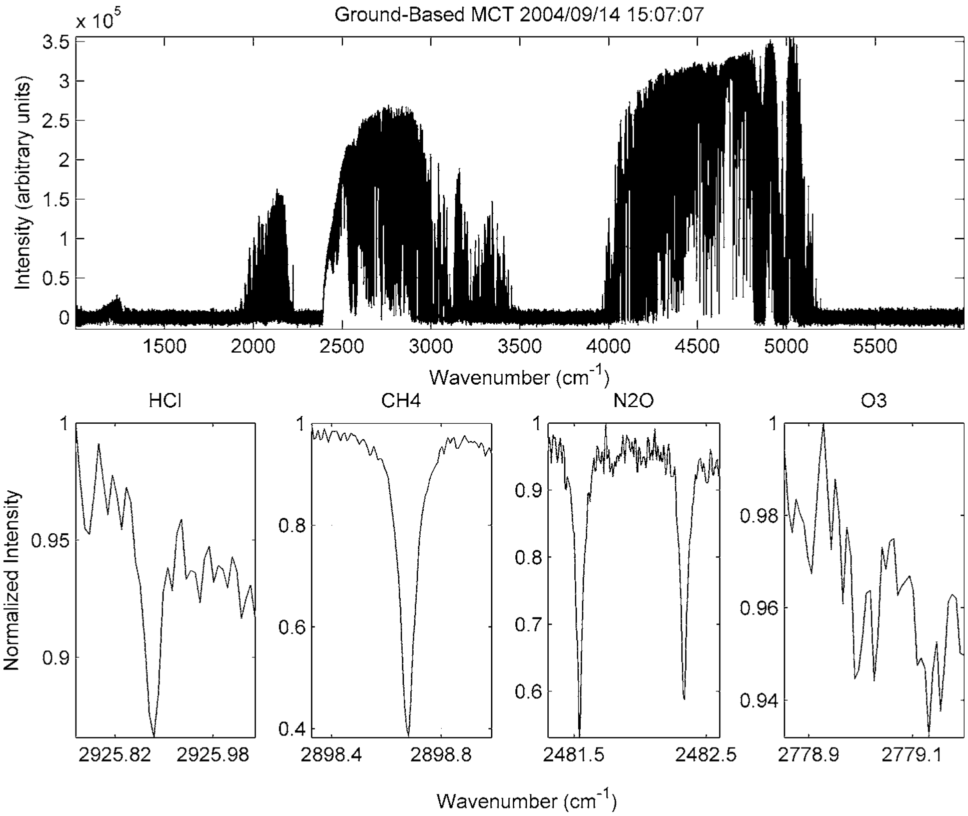

FIG. 5. MCT Spectrum from the MANTRA 2004 ground-based campaign. The top panel shows the entire spectrum, while the lower four panels show microwindows from which we retrieve HCl, CH_4, N_2O, and O_3, respectively.

that are shown indicate the comparable resolutions and noise levels between the two viewing geometries. This indicates that the instrument suffered few alignment problems from the change in environment, even though the ambient temperatures had changed over 80 °C.

In preparation for the flight, a neutral density filter (metal mesh) was placed in front of the input to the FTS, in anticipation of the higher solar signals that would be found at high altitudes as compared with the ground-based signals. One feature to note is that the noise levels appear to be the same in the ground-based spectra and the balloon-based spectra. Since there are many more photons reaching the detectors when the instrument is on the balloon, we would expect an increase in the photon noise for the balloon-based spectra. Because we do not see an increase in noise between the two spectra for the same detector, we can conclude that the spectral noise is not photon limited, and that there is another, larger noise source in the FTS. This will be the subject of further investigation.

Detector alignment for a FTS needs to be precise in order to achieve the maximum resolution.[8] The alignment procedures involve ensuring that the detector element or aperture is centered on the focus of the recombined beam (see Fig. 1). Detector alignment and instrument line shape (ILS) can be verified by measuring a low-pressure cell containing a known amount of a gas (such as HBr or N_2O) with software described by Hase *et al.* in Ref. 9. HBr is an appropriate gas for this purpose because the levels of HBr that exist in the atmosphere[10] are many orders of magnitude lower than the detection limit of the U of T FTS. Because of this, either a blackbody or the sun can be used as a source for HBr cell measurements. Once the detectors are aligned, the ILS remains constant for a few months,[9] unless the instrument is moved. Balloon-based FTS instruments, then, pose a unique problem. Balloon launches can be rough and may jar the instrumentation, and so some more thought needs to be put into monitoring the detector alignment throughout this process. Even if we measure the ILS before and after a flight, we have no knowledge of the ILS during the flight, unless the ILS is identical before and after (which is unlikely). One option is to measure the ILS on board by attaching a well-characterized low-pressure HBr cell to the interferometer, so we can constantly monitor the ILS while ensuring that we do not interfere with the atmospheric measurements. The ILS for the MCT detector for this instrument, recorded in September 2005, is shown in Fig. 6. The resolution is what is expected (around 0.02 cm^{-1}), and there is a phase error indicated by the asymmetry. This error should not affect the retrieved gas amounts from the instrument, since the ILS is included or modeled in the forward model for many commonly used retrieval algorithms, including SFIT2 which uses a forward model developed for the atmospheric trace molecule spectroscopy (ATMOS) experiment[11] and profile fit (PROFFIT), which uses the Karlsruhe optimized and precise radiative transfer algorithm (KOPRA) forward model.[12,13] The InSb ILS is not shown due to ongoing InSb detector alignment modifications.

The U of T FTS demonstrated its ability to function well in both ground-based and balloon-based environments after extensive electronics changes and minimal hardware modifications. It was flown successfully and acquired data even with compromised telemetry and pointing. The changes made to the FTS were relatively inexpensive and are robust

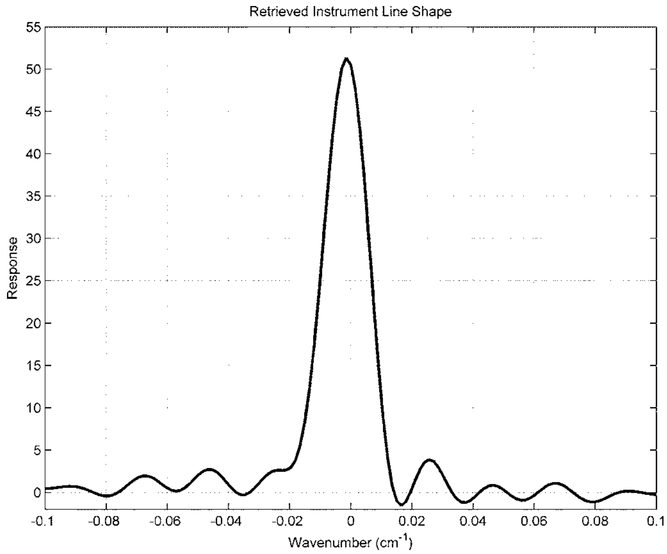

FIG. 6. MCT instrument line shape.

enough to be modified for any desired measurement sequence and most ABB-Bomem DA-series instruments.

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APPENDIX: DETAILED HARDWARE INFORMATION

The LABVIEW graphical programming language: National Instruments Corporation (http://www.ni.com/labview).

The MATLAB technical computing language: The MathWorks, Inc. (http://www.mathworks.com).

The 16 bit A/D converter used for detector data acquisition. Measurement Computing Corporation (MCC) model USB-1608FS (http://www.measurementcomputing.com).

The LabJack A/D converter model U12 OEM (http://www.labjack.com).

The EPIA motherboard: VIA EPIA mini-ITX mainboard (http://www.via.com.tw/en/products/mainboards).

The compact flash cards used as hard drives for the EPIA mainboard: Lexar 2GB Professional Series 40X CompactFlash Card with Write Acceleration (http://www.lexar.com).

WINDOWS XP embedded operating system: (http://msdn.microsoft.com/embedded/windowsxpembedded).

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