

“AIRBORNE TESTING OF SMALL, FAST, RUGGED FOURIER TRANSFORM
SPECTROMETER FOR GEOLOGIC SURVEY USE*”

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Designs & Prototypes, LTD. has fielded a small, very fast, and rugged rotary Fourier Transform Spectrometer (FTS) which can be used for environmental remote sensing and chemical detection. The continuous rotary scan of the Turbo FT allows operation without the laser reference of conventional FT spectrometers, and it has been demonstrated to deliver 360 spectral scans per second and 1 cm^{-1} resolution, with excellent lineshape. A new "space frame" version of the interferometer, with excellent mechanical and thermal stability, was field tested in an airborne system during the year 2000, with good results. The interferometer for this instrument is palm sized, and weighs 20 oz. It is also totally sealed from the environment, and was mounted, with its drive electronics, into a temperature stabilized enclosure for the field test.

The airborne system was a single pixel configuration, mounted in a fixed wing research aircraft used for geologic surveys. Dual on-board blackbodies allowed regular intervals of in-flight calibration. The calibrated output achieved an NEDT of better than 0.5 degrees K at 300 K. The pixel size was 10 meters by 10 meters at an altitude of 100 meters.

1.0 INTRODUCTION

This paper describes the field testing of the latest version of a new type of rotary scan FTIR spectrometer. A brief description of the evolution of the interferometer design is presented, followed by a summary of field test results obtained during the 2000 calendar year. The field data was obtained aboard a small geophysical research aircraft built and operated by CSIRO and Fugro Airborne Services in Australia.

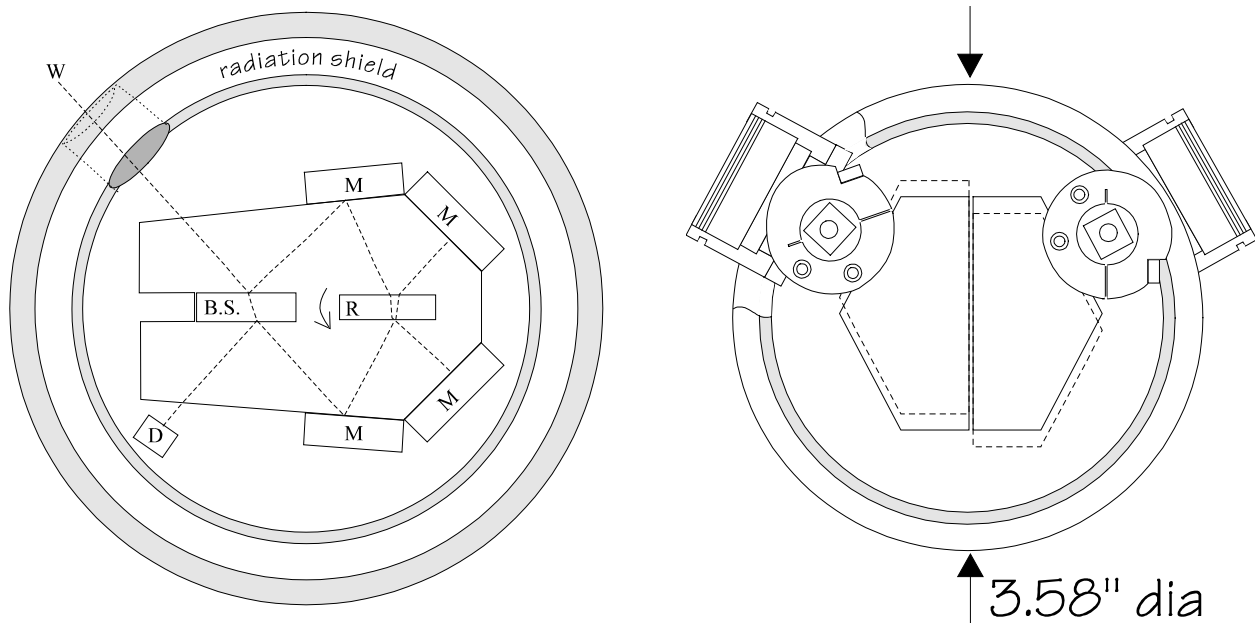
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2.0 HISTORICAL BACKGROUND

Designs & Prototypes has been developing both very small and very high speed Fourier Transform Spectrometers since 1985. There are two basic designs used in our instruments, each one ruggedized for use outside in the environment. One is a linear scan device, the Micro FT, which is optimized for optical throughput. The other is a rotary scan device, the Turbo FT, which is capable of the high scan rates. The linear scan reciprocates, and thus requires a reference laser to provide proper detector sampling. The rotary scan is based on a spinning refractor, and thus can be run laserless. Generally, the linear scan device is used in portable ground truth and atmospheric remote sensing, where high throughput is needed for optimal signal to noise. The rotary interferometer lends itself more to airborne applications where high speed and freezing of motion are required. Both types typically have a 1 inch diameter beam path, and are totally sealed from the outside world by lenses on both input and output ports. Alignment is maintained over time and temperature by careful design of beamsplitter mounting, and use of stress free aligners, which do not have a tendency to “creep” out of adjustment.

In previous years, we have reported on our R&D efforts to explore the characteristics of our very fast scanning FTIR, the Turbo FT. We have demonstrated speeds to 360 scans per second, good lineshape at 1 cm^{-1} resolution without use of a reference laser, and sufficient sensitivity to image amongst elements of multiple detector focal planes. In 2000, a ruggedized Turbo FT interferometer design was subjected to field trials in both an airborne thermal IR (TIR) application, and in a ground based TIR imaging instrument (Dybwad, et al, 2001). There is also an internal R&D effort to develop a Turbo FT in the NIR/SWIR spectral region. This presentation focuses on the airborne TIR instrument, which was installed in a Britanni Norse Trilander aircraft, looking straight down at nadir with a nominal 10 X 10 meter pixel.

We will present an overview of our efforts to make specific Turbo FT versions operational. Detailed measurement results will be presented by the instrument users in other presentations. Some of this overview also involves use of our Micro FT as a ground truth instrument supporting airborne data collection.



3.0 THEORY OF OPERATION: ROTARY SCAN INTERFEROMETER

The rotary interferometer optical schematic is shown in Fig. 1. The rotating refractor R is the only moving part in the interferometer. The incoming beam from the field stop FS is collected by collimating lens LC. Half of that light is reflected from the beamsplitter BS to M, where it then passes through R to ME, which reflects it back through the same path. The other half of the input beam from LC passes through the beamsplitter BS, reflects off M, and goes through R in the other direction, then back from its end mirror ME. The beams recombine at BS, and go on through the focussing lens LF and onto the detector D, where the light is converted to a voltage signal. As the rotor R rotates, the optical path difference (OPD) increases in one path, while it

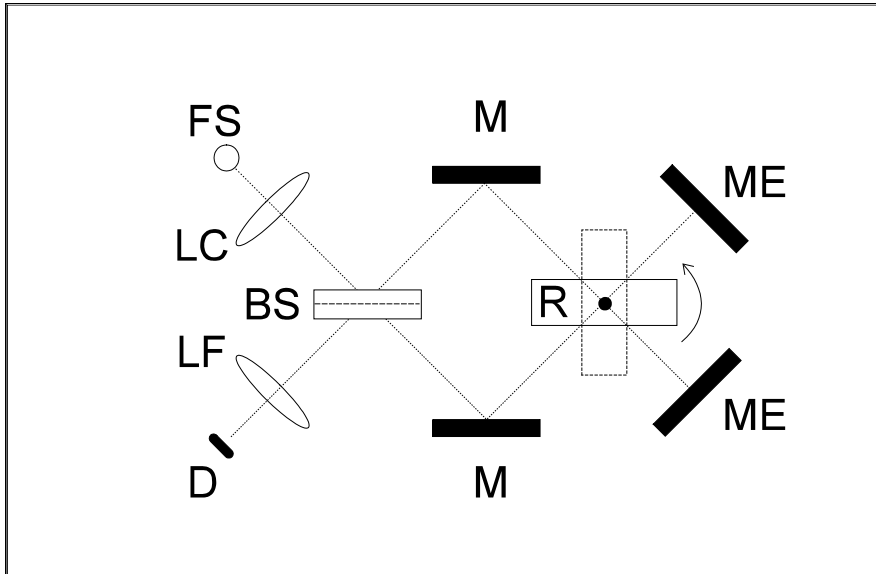


Figure 1. Rotary Interferometer Optical Schematic

decreases in the other. The non-linearities due to the sine of the scan angle subtract, thus decreasing the effects of any non-linear OPD variation. For one revolution of the rotor, there are 4 positions where the OPD is zero, giving 4 scans per revolution.

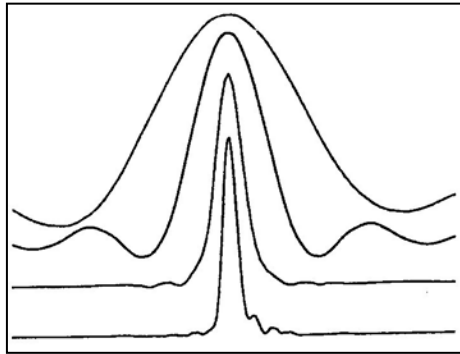
The spectral resolution is a function of the rotor thickness (T), and rotor material index of refraction (n), and the scan angle over which data is taken. For practical purposes, the scan angle is

generally limited to ± 15 degrees maximum. The spectral range is determined by the type of optical material used for the beamsplitter and rotor, with Zinc Selenide (ZnSe) used in the TIR in most cases. Using a photoconductive Mercury Cadmium Telluride (MCT PC) detector with the ZnSe optics, the typical spectral range is 7-14 micrometers.

4.0 LASER LINESHAPE AND HIGH RESOLUTION

The Turbo FT has been tested in previous work to determine the lineshape and resolution limits possible without using a laser reference. The lineshape analysis was performed using a 3.3 micron HeNe laser, expanded to fill the field of view. An optimized rotor material was employed to measure the lineshape at increasing angle of scan. The increasing scan angle of the Turbo FT corresponds to longer path length in a linear FT spectrometer, so increasing scan angle means increased resolution. The plot in Figure 2 shows the lineshape measured at four scan angles from ± 2.2 to ± 17.6 degrees, resulting in resolutions from 10.6 to 1.4 cm^{-1} . The lineshape is very symmetric, with near ideal $(\sin X)/X$ side lobes. The calculated values for resolution are shown as well, indicating good agreement with theoretical values. Most of the non-agreement is likely

due to inaccuracy in the index of refraction value at the operating wavelength. Note that the line width decreases nicely in factors of two as scan angle increases, showing excellent linearity.



<u>Scan Angle</u>	<u>Calculated Res.</u>	<u>Measured Res.</u>
+/- 2.2 deg	7.7 cm^{-1}	10.6 cm^{-1}
+/- 4.4 deg	3.9 cm^{-1}	5.3 cm^{-1}
+/- 8.8 deg	2.0 cm^{-1}	2.7 cm^{-1}
+/- 17.6 deg	1.0 cm^{-1}	1.4 cm^{-1}

Figure 2. Turbo FT Laser Lineshape

The same setup was then used to measure the CO₂ bands of the atmosphere at 4.3 micrometers. These two bands actually consist of a number of sharp lines with approximately 1 cm^{-1} resolution and 1 cm^{-1} separation. The data was taken using the full +/- 17.6 degrees of scan angle, yielding the maximum resolution of 1.4 cm^{-1} . The plot of Figure 3 shows the result, where the individual CO₂ lines are clearly resolved. These two results demonstrate that the Turbo FT can achieve its maximum resolution of 1 cm^{-1} . It should be noted here that this result can be achieved independent of scan speed, which is a limitation common to very fast reciprocating FT spectrometers. At very high speeds, a reciprocating FT spectrometer spends a greater and greater percentage of its time turning around, leaving less time for acquiring data after settling from a turnaround. This is not the case for the Turbo FT.

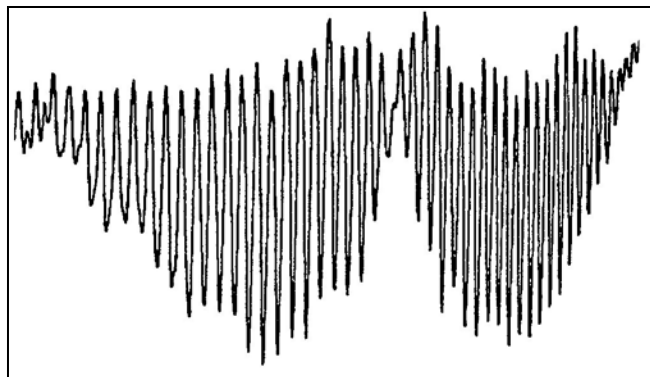


Figure 3. Resolved CO₂ bands at 4.3 micrometers

5.0 MECHANICAL EVOLUTION: ROTARY SCAN INTERFEROMETER

The initial Turbo FT interferometers were built with a flat optical bench, which had the beamsplitter, side mirrors, and end mirrors attached to it. There was a separate dust cover, which also contained the lenses. The dust cover served as a mount for the detector and any input optics required. The side and end mirrors were made of thick diamond turned aluminum, and were permanently affixed to the sides of the bench. The beamsplitter was mechanically mounted to the flat bench through an X-Y adjustable mounting device, and this was used to align the interferometer. The picture in Figure 4 shows the previous generation interferometer layout. The dust cover has been removed to show the mechanical layout. Note the ZnSe rotor on the left side between the four mirrors and the beamsplitter on the right, attached to its adjuster. The input and

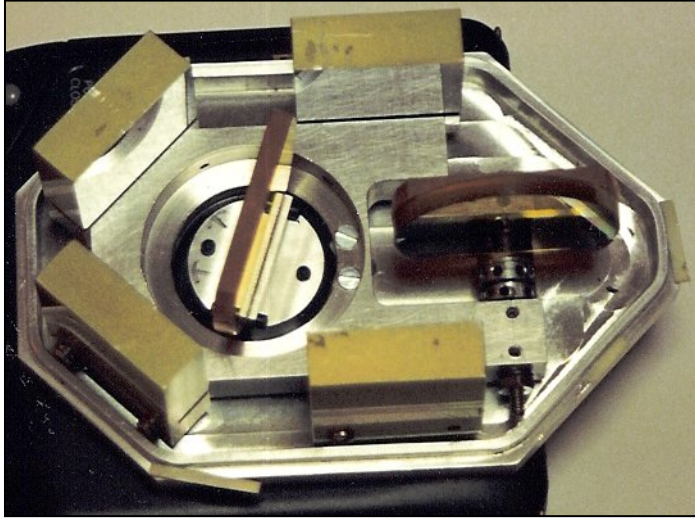


Figure 4. Previous Turbo FT Interferometer Layout

output ports would be on the cover in the upper right and lower right angled sides above and below the beamsplitter.

The current “space frame” 3D design shown in Figure 5 looks more like a “coffin” with a lid. This view is taken with the lid off. The “coffin” enclosure portion is machined from a single block of material. It has integral mirror mounts milled into the sides, and separate beamsplitter and motor mount holes in the bottom. The four mirrors are mounted, with their fine aligners, into circular recesses in the sides of the enclosure. The beamsplitter, in its base, is mounted into its hole in the bottom, as is the motor and rotor assembly. Align-

ment of the interferometer is done using the fine aligners of the mirrors, rather than the beamsplitter.

This new three-dimensional design is much more stable mechanically and thermally than the previous flat bench design. The forces required to misalign the interferometer have increased from ounces to pounds. Thermally, the single piece enclosure also distributes heat more evenly, so that interferometer alignment is maintained satisfactorily over 20 to 30 degrees C. If a larger temperature range is required, or better calibration stability, the instrument is quite small, and can easily be put into a thermally controlled enclosure. Internal power dissipation is very low, requiring only about 0.1 watts for the scan motor. This, too, facilitates temperature control. The new design is simpler to assemble and align, since the adjustment of the beamsplitter and mirrors can now be de-coupled. No dust cover is required in the new design, since the enclosure serves as the cover as well. The detector and input optics can be mounted directly onto hard ports mounted onto the enclosure. These ports are on the right side in Figure 5. The lenses that seal the unit from the environment are mounted inside these ports. This configuration is clearly much more rugged and stable.

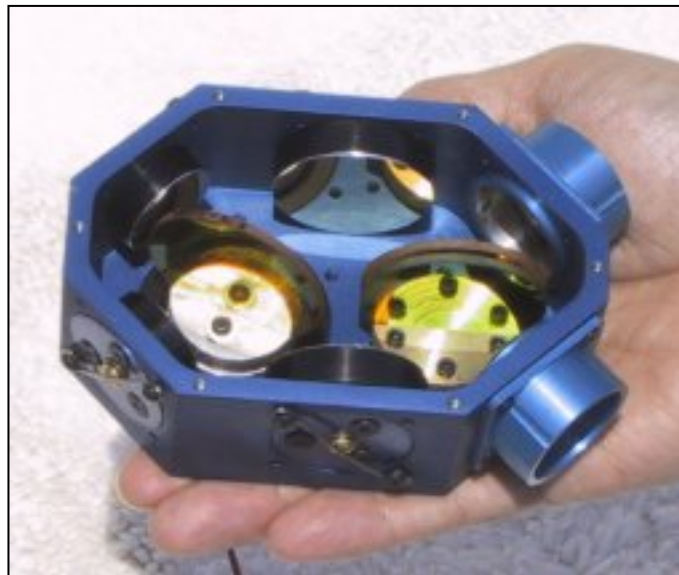


Figure 5. Current 3D Turbo FT “Space Frame”

6.0 AIRBORNE SURVEY INSTRUMENT

An airborne, single pixel instrument called TIPS (Thermal Infrared Profiling Spectrometer) was built and flown in Australia, in a joint effort program between CSIRO Australia and Fugro Airborne Surveys, Pty. Ltd. It is based on the Turbo FT and is flown aboard a small geophysical survey aircraft. This is a very harsh environment, since it is both high vibration and large temperature extremes (up to 50 degrees C). In fact, the temperature extremes are so severe, pre-alignment at the estimated operating temperature of the survey area must sometimes be done before flight.

The interferometer used is based on the latest “space frame” design, and it is mounted into a thermal enclosure, with active heating and cooling, to help maintain calibration. The installation into the aircraft was accomplished by the customers, CSIRO and Fugro Airborne. The spectral range is 8-12 micrometers, at a spectral resolution of 8 cm^{-1} . The nominal operating altitude is 100 meters, giving a nominal pixel size of 10 meters. Commercial off-the-shelf (COTS) hardware was used to acquire data, which was then integrated into an on board data system for analysis and storage. The data was used to differentiate mineral

types, such as quartz, feldspars, garnets, pyroxenes, carbonates, and others. The airborne data was used in conjunction with ground truth data acquired with a D&P Micro FTIR (mFTIR) based thermal emission spectrometer. The results obtained, as shown in Figure 6, clearly show good agreement between ground (mFTIR) and airborne (TIPS) data taken over a kaolinite pit at Lake Toolibin in Western Australia. This data was used to discriminate quartz rich sandy soils from clay-rich soils to map encroachment of saline areas in this agricultural region.

Other results from this instrument show spectral unmixing of mineral types at two other sites in Australia (Hewson, et al., 2001). Mixtures of dolomite, quartz, and talc were extracted and mapped at Mt. Fitton in South Australia. In the Broken Hill mining district, quartz and garnet endmembers were identified. These results were produced by calculating apparent emissivity from the raw sample and calibration data, and using ENVI to separate out the spectral endmembers.

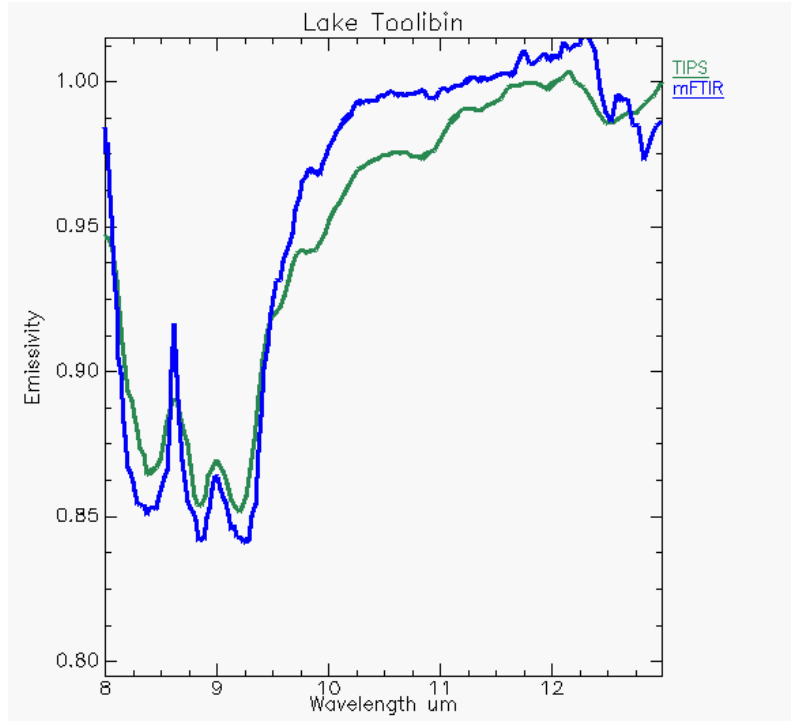


Figure 6. Comparison of ground and airborne data.

The false color image in Figure 7, to the right, shows the same kaolinite pit as the aircraft flew over it from vegetation (at the top of the image) into the exposed kaolinite (dark area from the middle to the bottom of the image). The low emissivity of the kaolinite causes the dark regions of the image. In this image, the flight direction is down the page, and the spectrum from 8 to 12 micrometers is from left to right across the page.

Data from a second site in Western Australia is shown in Figure 8 on the left. This is a quartz ratio plot superimposed on a LANDSAT image. The blue areas represent all pixels having a high abundance of quartz. The quartz spectrum from the airborne sensor is shown in Figure 9.

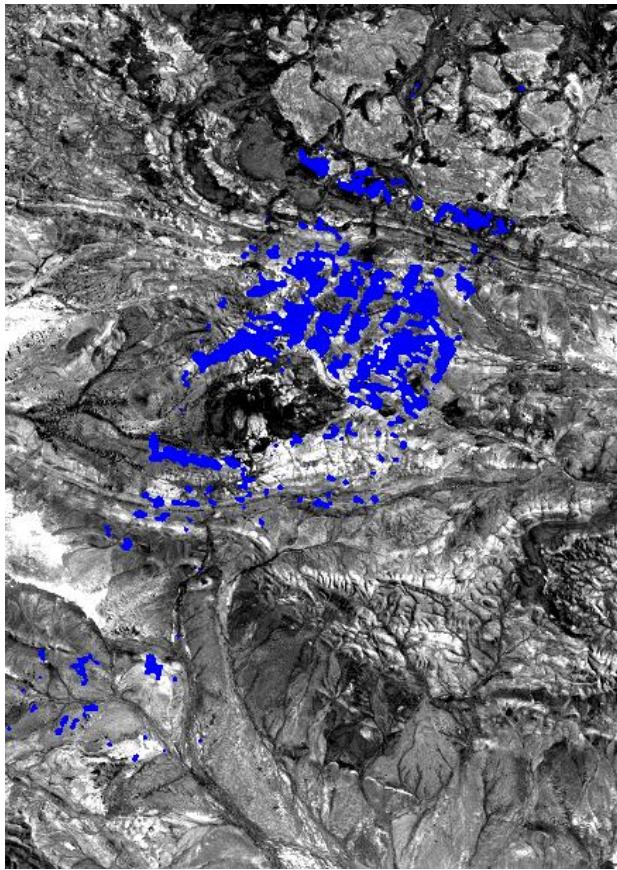
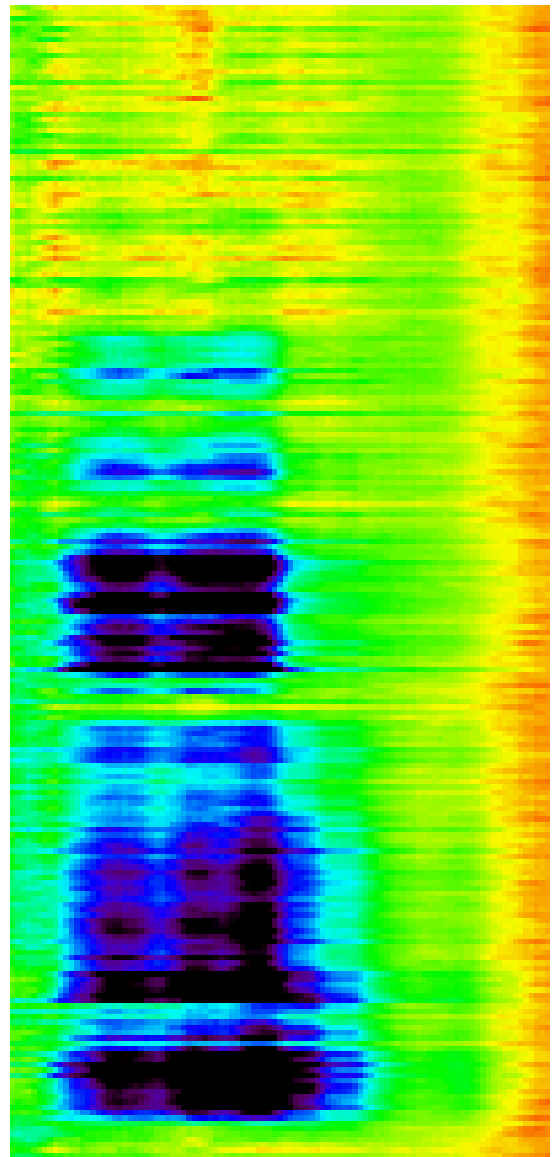


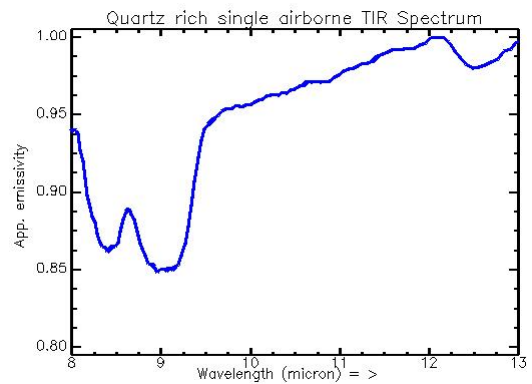
Figure 8. LANDSAT image with quartz ratio

Figure 9. Airborne quartz spectrum.



8um 12 um

Figure 7. False color image kaolinite pit



7.0 FUTURE PLANS

7.1 IMAGING AIRBORNE INSTRUMENT

As noted previously (Dybwad, et al, 2001), a ground based imaging Turbo FT was built and tested in summer 2000. The detector was a 2X8 element PC MCT, and the sensor was fitted with a 6 inch telescope, to image at 1.5 Km. The total size of the field of view at 1.5 Km was just under 20 meters, with each of the 16 pixels measuring 7 X 1.75 meters. In this application, chemical plumes were released from a stack, and remotely sensed to analyze the constituents. This configuration could quite easily be flown on a small aircraft with the appropriate data system to collect and store the increased amount of data.

7.2 NIR/SWIR TURBO INSTRUMENT

With the use of different optics and detectors, a Turbo FT can be built to operate in the NIR/SWIR spectral region from 1-2.5 microns. In this configuration, there are much more stringent alignment and drift requirements for the interferometer, and much higher operating frequencies of detectors and data systems, each by about a factor of 10. This will require new approaches to mounting and adjustment techniques for both the beamsplitter and mirrors. In addition, most all presently available NIR/SWIR detectors have a sharp rolloff in detectivity (D^*) due to their high impedance.

For this reason, it is important to minimize the resolution requirements of a NIR/SWIR system, since that directly affects the frequency content of the IR signal. Fortunately, the resolution of an FT spectrometer goes up quickly in nanometers at the shorter wavelengths; e.g. an 8 cm^{-1} interferometer yields a 3.2 nanometer resolution at 2 micrometers. For 10 nm resolution at 2 micrometers, a 16 or 32 cm^{-1} interferometer may suffice. Further reduction of detector frequency specifications can also be achieved, of course, by scanning more slowly.

8.0 ACKNOWLEDGEMENTS

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9.0 REFERENCES

Dybwad, Dr. Jens Peter and Winthrop Wadsworth, "Field Testing of a Small, Fast, Rugged Fourier Transform Spectrometer in the Air and on the Ground", In *Proceedings of International Symposium on Spectral Sensing Research*, Quebec City, 10-15 June 2001.

Hewson, et al., "Hyperspectral Thermal Infrared Line Profiling for Mapping Surface Mineralogy", In *Proceedings of the Fifth International Airborne Remote Sensing Conference*, San Francisco, CA, 17-20 September 2001.