“FIELD TESTING OF SMALL, FAST, RUGGED FOURIER TRANSFORM SPECTROMETER IN THE AIR AND ON THE GROUND”

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Designs & Protoypes, 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 and in a ground based unit 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 both field tests.

The airborne system was a single pixel configuration, mounted in a fixed wing research aircraft used for geologic surveys. The ground instrument was tripod mounted, and ran in an imaging mode having 16 individual pixels in its focal plane.

INTRODUCTION

This paper describes the field testing of the latest version of a new type of rotary scan FTIR spectrometer. Two specific applications are covered; one is a flight instrument, built and tested in Australia, the other is a tripod mounted ground instrument, built and tested in the U.S. Some background and detail on the design evolution is given, followed by some overall results.

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 if other design considerations are met. 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. Either design can be used in an imaging type spectrometer, but so far only the rotary type has been built for imaging.

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. For instruments that need to maintain a calibrated output, such as a ground truth spectrometer measuring temperature and emissivity, temperature control of the interferometer is used. Most of our portable spectrometers must run on battery power, so all electronic controllers are designed to be 80-90 % efficient. This means most are “switched mode” type controllers, as opposed to the more inefficient linear types. Use of efficient controllers also minimizes heating of the enclosure and interferometer, further easing the calibration drift and heat load on the instrument.

Low power operation is also a fundamental design criterion for the interferometer scan itself. The linear scan device typically runs on 2-4 watts of power, while the rotary runs on 0.1 watts or less, depending on speed. If a laser reference is required, a temperature controlled laser diode is usually used, instead of the more power hungry HeNe laser tube. In general, controlling a laser diode to about 0.1 degree C with a switched mode temperature controller usually takes less power than a HeNe laser tube. For very high accuracy or shorter wavelength regions, a HeNe laser can be substituted.

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} (wavenumber) resolution without use of a reference laser, and sufficient sensitivity to split the signal amongst elements of multiple detector focal planes. In 2000, a ruggedized Turbo FT interferometer design was subjected to field trials in a ground based thermal IR (TIR) imaging instrument, an airborne TIR application, and an R&D effort in the NIR/SWIR spectral region. The ground-based instrument was equipped with a 6 inch Cassegrain telescope with a 0.75 degree total FOV, and a 16 element MCT focal plane. The airborne unit was installed in a Brittani Norse Trilander aircraft, looking straight down at a nominal 10 X 10 meter pixel. A third spectrometer, operating in the NIR/SWIR spectral region, is being prepared for testing. 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.

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. Half of the incoming beam from the field stop FS is collected by collimating lens LC, reflected from the beamsplitter BS, then M1, and passes through R, and reflects back from its end mirror ME1. The other half of the input beam from LC passes through the beamsplitter BS, reflects off M2, and goes through R the other direction, then back from its end mirror ME2. The beams recombine at BS, and go on to the detector D, where they are collected by focussing lens LF, and converted to a voltage signal. As the rotor R rotates, the optical path difference (OPD) increases in one path, while it decreases in the other. The nonlinearities due to the sine of the scan angle subtract, thus decreasing the effects of any nonlinear OPD variation. For one revolution of the rotor, there are 4 positions where the OPD is zero, giving 4 scans per revolution.

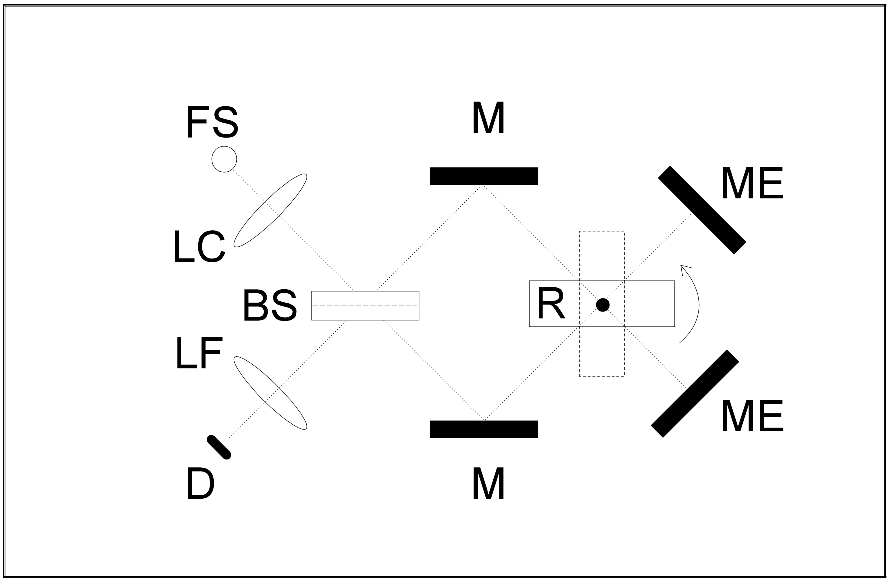

Figure 1. Rotary Interferometer Optical Schematic

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 these optics, the typical spectral range is 7-14 micrometers.

MECHANICAL EVOLUTION: ROTARY SCAN INTERFEROMETER

The initial rotary 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 also served as a mount for the detector and any input optics. The side and end mirrors were thick, and permanently fixed to the side of the bench. The beamsplitter was mechanically fixed to the flat bench through an X-Y adjustable mounting device, and this was used to align the interferometer.

The current “space frame” 3D design looks more like a “coffin” with a lid. The “coffin” portion is machined from a single block of material. It has integral mirror mounts in the sides, and separate beamsplitter and motor mounts in the bottom. Thin mirrors are mounted, with their fine aligners, into circular recesses in the sides of the coffin. The beamsplitter, in its base, is mounted into a hole in the bottom, as is the motor and rotor assembly. Alignment of the interferometer is done using the fine aligners of the mirrors, rather than the beamsplitter.

The new 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 “coffin” distributes heat more evenly, so that interferometer alignment is maintained satisfactorily over 20 to 30 degrees C. If a larger temperature range, or better calibration stability, is required, the instrument is quite small, and can easily be put into a thermally controlled enclosure. Internal power dissipation is also very low, requiring only about 0.1 watts for the scan motor. The new design is simpler to assemble and align, since the alignment of beamsplitter and mirrors can now be decoupled. Also, no dust cover is required in the new design, and the detector and input optics can be mounted directly onto hard ports mounted onto the coffin, using lenses to seal the unit. This configuration is much more rugged and stable.

AIRBORNE SURVEY INSTRUMENT

An airborne, single pixel instrument named 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 the harshest environment of those discussed here, 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 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 wavenumbers. 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. The airborne data was used in conjunction with ground truth data acquired with a D&P Micro FTIR based thermal emission spectrometer. The results obtained, as shown in Figure 2, clearly show good agreement between ground and airborne data

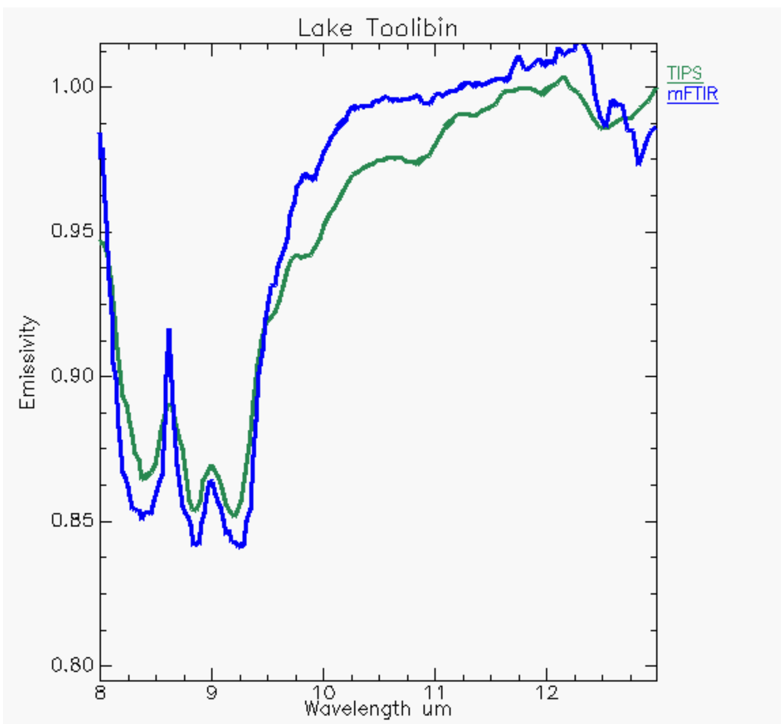

Figure 2. Comparison of ground and airborne data.

taken over a kaolinite pit in Western Australia. The false color image in Figure 3, 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 4 on the left. This is a quartz ratio plot superimposed on a LANDSAT image. The blue areas represents all pixels having a high abundance of quartz. The quartz spectrum from the airborne sensor is shown in Figure 5.

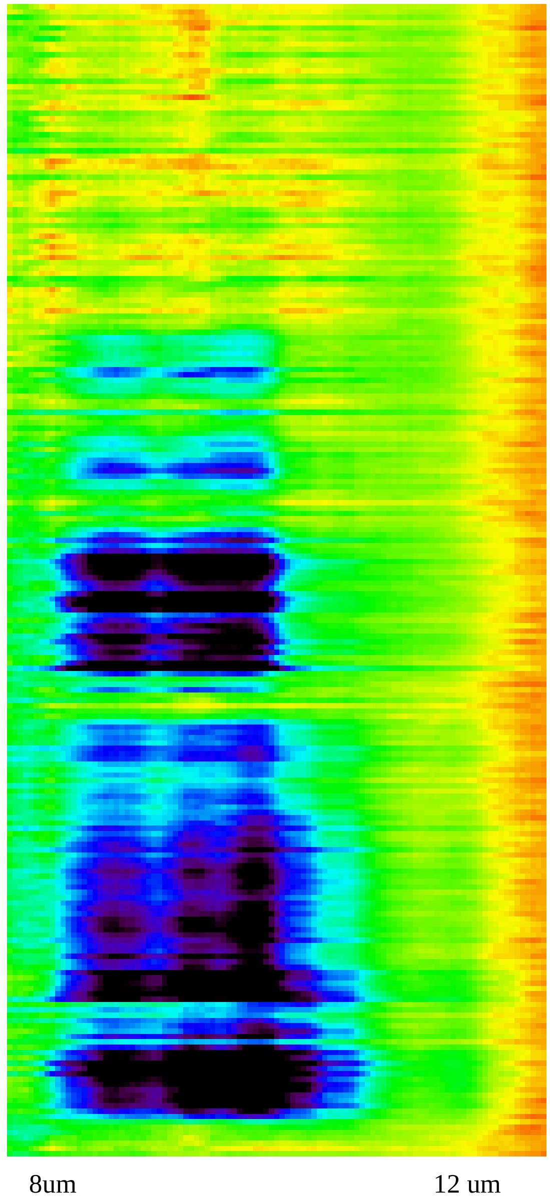

Figure 3. False color image kaolinite pit

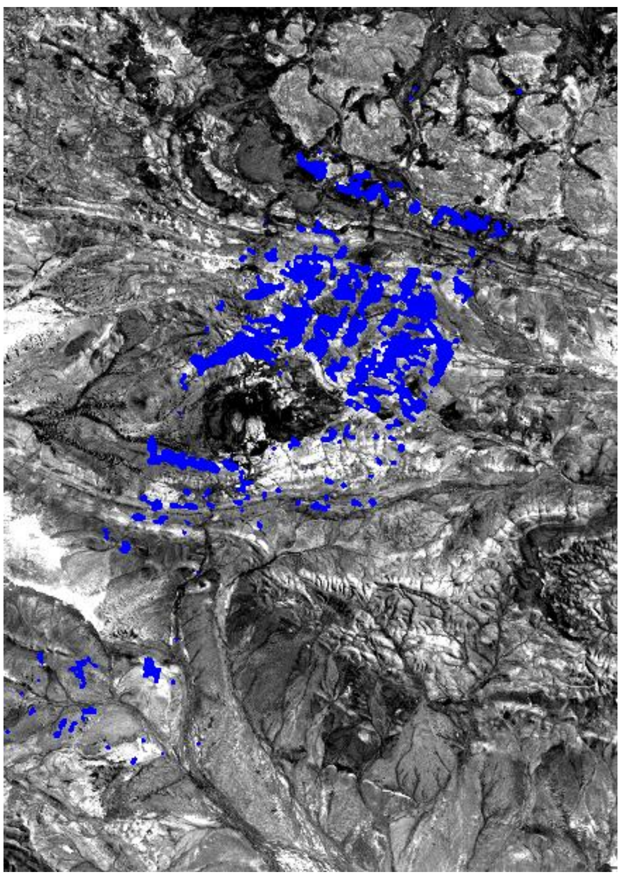

Figure 4. LANDSAT image with quartz ratio

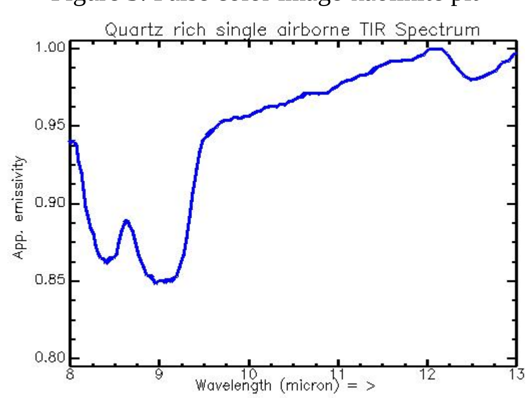

Figure 5. Airborne quartz spectrum.

GROUND BASED IMAGING IINSTRUMENT

A ground based imaging spectrometer was built by Designs & Prototypes, and tested by the Standoff Detection Group at ECBC in summer 2000 for the purpose of remote sensing of gas clouds. A standard “space frame” Turbo FT was fitted with a 2X8 element MCT (PC) detector array and 6 inch telescope. The pixel format is shown below in Figure 6. The pixel size at the detector is 0.2 mm X 0.6 mm each, with a total detector area of about 1.6 mm. The 6 inch telescope field of view was optimized at 0.75 degrees total angle, for the expected cloud size of 20 meters at 1.5 km. Each pixel is then approximately 7 meters high by 1.75 meters wide at 1.5 km. The arrangement of the pixels was horizontal, 8 pixels above 8 pixels. The pixels themselves were rectangular, with a 3 to 1 aspect ratio of height to width. This arrangement was chosen to provide pixels above and below the horizon. In practice, it turned out all pixels were below the horizon because of the geography in the area. The sensor head was built into a temperature controlled thermal enclosure with an active heating/cooling controller. A picture of the inside of the sensor enclosure is shown in Figure 7. The sensor was deployed outside in the elements during the test. The data acquisition and processing computer was built from all COTS components, and was placed inside a facility protected from the elements. There were two 15-foot long cables to connect the sensor to the computer. This instrument detected chemicals in a plume in 3 out of the 16 pixels at a distance of 1.5 km.

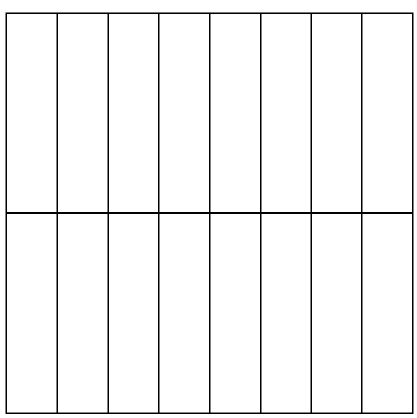

Figure 6. 16 element pixel format

Figure 7. 16 element sensor, cover and telescope off

The instrument ran at around 70 scans per second, with a spectral range of 7-14 micrometers and a spectral resolution of 8 wavenumbers. With these operating parameters, the detector signal frequency at the shortest wavelength is about 80 KHz. The sampling frequency of the data system was 600 KHz, simultaneously on all 16 channels.

A video camera was boresighted with the instrument field of view in the field by members of MESH, Inc., of Oxford, PA. This was done so the operator could aim the sensor from inside the protective enclosure at the site. Some coarse testing of individual pixel FOV was done during the boresighting operation. This testing revealed some signal crosstalk between adjacent pixels, which will be addressed in an improved telescope design.

GROUND TRUTH INSTRUMENT BASED ON MICRO FT

THEORY OF OPERATION: LINEAR SCAN INTERFEROMETER

The linear scan interferometer optical layout is shown in Figure 8. The optical system consists of two prisms, each mounted on very precise slides. One has a beamsplitter coating on its flat side. The scanning action moves one prism in one direction, while simultaneously moving the other prism in the opposite direction. Light enters the interferometer from W, enters the prism, and hits the beamsplitter coating BS on that prism. Half the light reflects, staying within the prism, and reflects back to BS from the mirror coating M on the angled side of the prism. The other half of the light passes through BS, and enters the other prism. It is reflected by the mirror coating M on that prism, then recombines at BS with the other half of the light that was originally reflected off BS. This causes the interference, with half the light returning to the source W, and half passing on to detector D. As the prisms scan back and forth, the path within one prism gets shorter and the path in the opposite prism gets longer, due to the angle of the two mirrors.

The spectral resolution is a function of the index of refraction of the prism material, and the length of the scan.

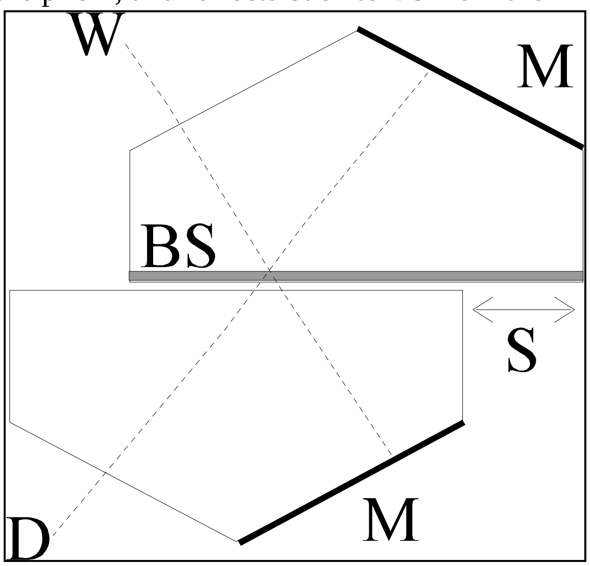

Figure 8. Linear Interferometer Optical Schematic

The ground truth instrument presently being made is called the Model 102. It is a second generation design, and uses the linear scan Micro FT optical head, for maximum throughput. It is a complete spectrometer, including embedded PC computer, in a 14” X 8” X 9” enclosure weighing 15 lbs. Software includes the standard ratio and difference functions, as well as capabilities for measuring absolute radiance and emissivity with the appropriate accessories and data files. The scan speed is usually set at 1 scan per second, with capability to coadd spectra to achieve better signal to noise. Most measurements can be made with 8-16 coadds, and can be made in about 20 seconds, maximum. Typical resolution is 4 cm^{-1}, with options for 2 or 1 cm^{-1} available.

FUTURE ENDEAVORS

GROUND SYSTEM

Future development of the ground based TIR imaging system includes increasing the scan speed, changing the number and/or format of the pixels, and improving the imaging quality of the telescope. This work would involve testing the limits of scan speed out to hundreds of scans per second. This includes many factors, such as detector type (PC vs. PV) and associated bandwidth (>1 MHz); mechanical balancing and servo performance, and very high speed multichannel simultaneous data acquisition and processing hardware. As the number of detector channels and scan speed goes up, the processing power required to provide an operator with meaningful readout and analysis increases dramatically. Also, based on experience measuring clouds in the field, rotating the 2X8 element detector 90 degrees would better match a typically horizontal plume geometry. A more flexible detector arrangement would be to mount a down looking dewar to the interferometer output, and rotate it based on the expected target geometry.

Further software development will also give more feedback to the operator via a real time graphical output of processed data. In addition, several "alarm" wavelengths at known spectral lines will help to find plumes by putting a different color bar in each pixel having a detection at each particular wavelength.

NIR/SWIR INSTRUMENT

The Turbo FT can be outfitted with different optics and detectors to work in the NIR/SWIR spectral region, from about 1-2.5 micrometers. The main challenges at the shorter wavelengths are the much more stringent alignment and drift requirements, and much higher operating frequencies of detectors and data systems. Both of these challenges increase by a factor of 10 when compared to the current TIR operations. Alignment accuracy and drift specifications approach the order of visible wavelengths, requiring new approaches to mounting and adjustment techniques. To compound the challenge further, commonly available NIR/SWIR detectors experience a sharp rolloff in D* due to their high impedance. It is therefore very important to minimize the resolution specifications at these shorter wavelengths, as this directly affects the frequency content of the IR signal. Fortunately, the resolution in nanometers goes up quickly at the shorter wavelengths; e.g. an 8 wavenumber system gives 3.2 nanometers resolution at 2 micrometers. Most applications in the NIR/SWIR require about 10 nanometer resolution, so 16 wavenumbers would be sufficient. Further reduction of detector frequency specifications can be achieved by scanning more slowly, assuming the overall system specifications are still met.

CONCLUSION

From these results, it is clear that the latest incarnation of the Turbo FT spectrometer is capable of operation in harsh environments, without sacrificing much in performance. The greatest improvement has been in the area of thermal and mechanical stability, which is critical in maintaining alignment over temperature and time. Further improvements in optical design will be required to achieve a high quality imaging spectrometer. This, along with higher speed, will be the focus of ongoing work on this technology.

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