

# **Rugged high speed rotary imaging Fourier Transform Spectrometer for industrial use**

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## **ABSTRACT**

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A new rugged rotary Fourier Transform Spectrometer (FTS) has been developed. It can be used for environmental remote sensing and monitoring of chemical processes. Both single pixel and mosaic imaging configurations have been built and tested. The continuous rotary scan of the "Turbo FT" allows operation without the laser reference of a conventional FTS, and it has been demonstrated to deliver 30 to 360 spectral scans per second and  $1\text{ cm}^{-1}$  resolution, with excellent lineshape. A new "space frame" version of the interferometer, with excellent mechanical and thermal stability, was field tested in both airborne and ground systems during the year 2000, with good results. The interferometer for this instrument is palm sized, and weighs 20 oz. It is totally sealed from the environment, and can be mounted, with its drive electronics, into a temperature stabilized enclosure for outside remote sensing applications. For industrial applications, it can be used on-line or off-line, in conjunction with fiber optics, to measure and/or control multiple process lines. With the appropriate optics and detector set, the wavelength range can be adjusted from 1.0 to 25.0 micrometers. The resolution is variable from 1 to  $8\text{ cm}^{-1}$ .

Various processors, data acquisition boards, and software have been used in the development, including the Labview package from National Instruments. Custom software for acquisition, display, and storage is being developed in summer 2001. The data acquisition system can be tailored for the speed and number of pixels required for the application. The current commercially available hardware being used can support up to 16 pixels at up to 100 scans per second.

## **1. INTRODUCTION**

Designs & Prototypes (D&P) specializes in developing new designs of miniature, ruggedized Fourier Transform Spectrometer (FTS) systems. At present, there are two basic designs available at D&P. The Micro FT is a slow scan, reciprocating linear drive module with maximum throughput for its size. It is presently being used in many portable field FTIR spectrometer systems. The Turbo FT is a fast scan, rotary drive unit, being used mostly for aircraft instruments, and for observing fast processes. The rotary configuration (the Turbo FT) is more suited to industrial and process control applications, due mostly to its very high scan rate and simple, rugged design. The optical head is very small and lightweight. In addition, because of the rotary nature of the scan, various techniques can be applied to run the interferometer without the usual reference laser channel required in a laboratory FT spectrometer. The Turbo FT is the subject of this paper.

Since last reported in 1998, significant improvements have been made in our unique rotary scanning Turbo FT interferometer. These improvements are the result of our ongoing work with the U.S. Army Edgewood Chemical and Biological Center (ECBC) at Aberdeen Proving Grounds in Maryland. Their need for very fast scanning (360 scan per second) passive remote sensing chemical agent sensor has driven the Turbo FT to ever higher spectral scan rates. In addition, their sensors to be increasingly more of the imaging type, so as to identify areas of chemical contamination from longer standoff distances. On the commercial side, the same Turbo FT design has been used at lower scan rates in an airborne geophysical survey application. This has proven its use in identifying mineral soil types and assessing environmental change from the air. The same properties that make this instrument uniquely suited to for its use in the field (i.e. small size, low power, rugged design) should make it equally applicable to numerous industrial applications.

## 2. OPTICAL SCHEMATIC AND OPERATION

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, and impinges on the beamsplitter BS. Half of the light reflects to the upper mirror M, and passes through rotor R. It then reflects back from its end mirror ME, and retraces the same path back to BS. The other half of the light from the input beam passes through the beamsplitter BS, reflects off the lower M, and goes through R in the other direction, then back from its end mirror ME. The beams recombine at BS, are collected by focusing lens LF, and go on to 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 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 interferograms per revolution.

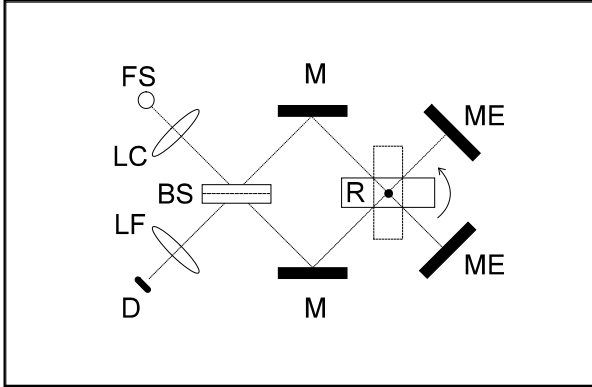


Figure 1. Rotary Interferometer Optical Schematic

The spectral resolution is a function of the rotor thickness (T), 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.

## 3. RECENT MAJOR UPGRADES OF TURBO FT

The major benefits of the Turbo FT over other conventional FTS designs is the extremely high speed operation (hundreds of scans per second), the ability to run without a reference laser, and very small size and low weight. This has been discussed in a previous paper presented in 1998<sup>(1)</sup>. This paper will discuss the major improvements in the Turbo FT since that time. There are two major enhancements made to the Turbo FT over the last three years. The first is a newly designed interferometer optical bench. The second is an improved custom servo and analog processing electronics, coupled to a new data acquisition system allowing more pixels at higher speed.

The previous Turbo FT interferometer employed a flat optical bench for the interferometer. The side and end mirrors were permanently affixed to the sides of this flat bench. The beamsplitter was mounted to the flat bench in an adjustable fixture, and all alignment was done on the beamsplitter. The input and output lenses were mounted in a separate dust cover, which also held the input optics and detector. The scan motor and rotor were attached to the base of the dust cover. This arrangement is shown in Figure 2. The new "space frame" interferometer, in Figure 3, is more of a

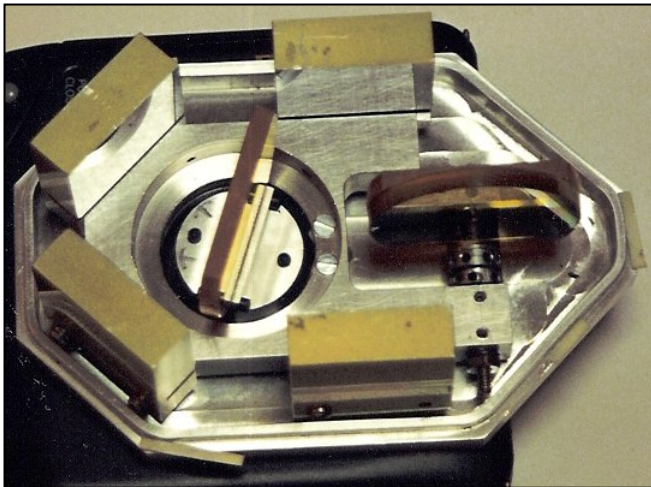


Figure 2. Previous Turbo FT mechanical layout

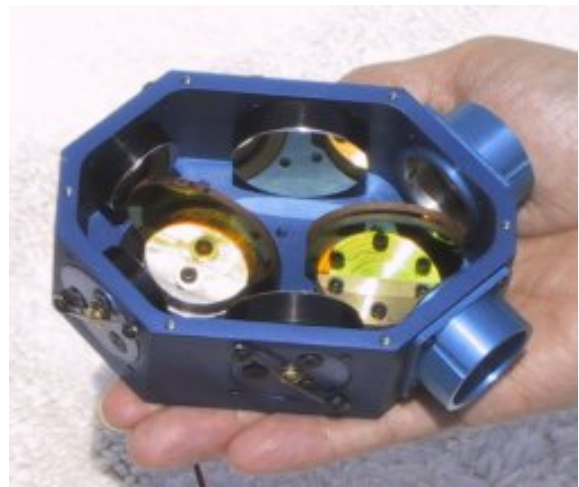


Figure 3. New "space frame" Turbo FT layout.

three dimensional design, consisting of a box type enclosure with a lid. The side and end mirrors are mounted in the sides of the box, with integral aligners on all four mirrors. The beamsplitter is mounted firmly in the bottom of the box, as is the scan motor and rotor. In this design, all alignment is done using the side and end mirrors, resulting in a much more solid beamsplitter mounting. The input and output lenses are mounted in tube type extensions which are mounted directly onto the box structure. The detector and input optics mount directly onto these tube extensions. The lid of the box has no components in it, but it contributes substantially to increased rigidity of the structure when installed. It also seals the unit from the environment. This new configuration is much more solid than the previous arrangement, and holds interferometer alignment much better over time and temperature. Initial testing shows that the external force required to misalign the interferometer has gone from ounces to pounds, and alignment is stable over 20-30 degrees C.

In the area of drive and sampling electronics, a set of electronics boards has replaced the previous method of using a hard disk drive or CD-ROM player to drive the rotor at a constant, repeatable speed. In that scenario, the laserless time sampling would generate an inaccurate wavelength scale if there were disturbances in the rotational speed, or a slow change in speed over time. Also, variable speed operation was not possible without making adjustments to the time sampling. The new scheme uses an optical encoder on a DC servomotor. Thus, not only is speed information fed back to control the rotation, but all sampling and triggering signals are generated off the encoder as well. This means that these signals now track the scan speed as it varies, either from external disturbances or under external variable control. The sampling and triggering of scans is inherently more accurate, which also puts less importance on scan speed accuracy. In an enhanced version of this design, the anti alias filter in the signal channel was also tuned as the speed was changed. With that capability, it is possible to trade off scan speed for signal to noise without having to adjust anything but the speed.

These improvements have significantly enhanced the commercial possibilities for the Turbo FT. The industrial environment is generally full of disturbances from vibration and noise. It also usually involves large temperature excursions as well. Outside remote sensing applications certainly involve temperature extremes, and airborne remote sensing involves both high vibration and large temperature extremes. Hardening the interferometer against these elements makes it more rugged and reliable over sustained use. The external control of speed may be desirable for changing a process line operation from one product, or quality of product, to another. If the instrument adjusts its operating parameters automatically to a single command, less intervention by an operator is required in reconfiguring a process line.

#### **4. IMAGING SPECTROMETER ENHANCEMENTS**

In the previous paper <sup>(1)</sup>, an imaging spectrometer using the Turbo FT interferometer was discussed. The possibility of sharing one spectrometer over a number of targets was suggested. This could be done using fiber optics on a process line, or other methods in other applications. Thus, the cost of an imaging system would be spread amongst a number of processes, perhaps bringing the cost per process to a feasible level for commercial or industrial use. At the time of that paper in 1998, a 3X3-pixel detector was being used, and the system was being run at 32 scans per second. In the interim, new hardware and software have made it possible to run a 16 element detector at 100 scans per second. In addition to a Labview software implementation used back then, there is now a custom Turbo FTIR program for acquiring, processing, and storing data from the 16 channel sensor. A sample output screen from this sensor is shown in Figure 4.

The detector used in this most recent remote sensing application was a 2 row by 8 column mosaic, with rectangular pixels that were 0.2 mm wide X 0.8 mm high. The spectra shown in the figure are all ratios against a stored reference background of coadded spectra. A plastic film was held against a warm source at the pixel 11 position for the sample spectra. All other pixels have no sample, so the ratio is around 1.0. The Turbo FTIR software has a wavelength discriminator in it, which can be used to indicate detection of a threshold crossing on ratio data. Up to four wavelengths can be specified, each with its own threshold levels above and below 1.0. Values below 1.0 are used for absorption peaks, while values above 1.0 are used for emission peaks. In the output spectra shown, there are two detections present, indicated by two different colors illuminated on two quadrants of the pixel number 11 frame. This feature could be used for quality control on a process line, or chemical detection in a plume for a remote sensing application. The process line application might be a wide web product, such as plastic film, or multiple inputs from fiber optic probes

Turbo Imaging System Screen Output – Ratio of Sample/Reference

Plastic film detected in pixel 11 using two wavelengths at 7.255 and 10.05 micrometers;  
Threshold value = 0.7 on both

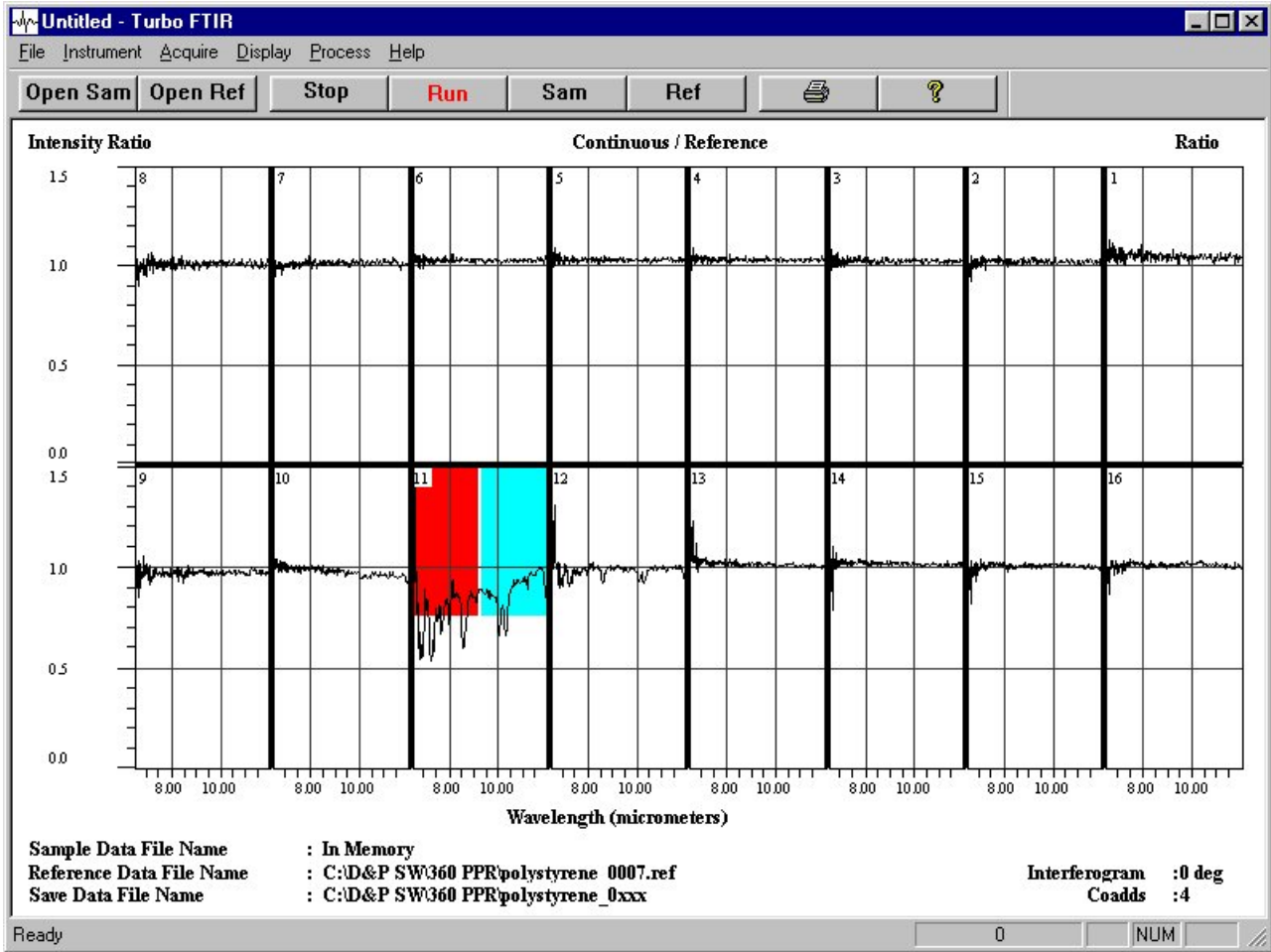


Figure 4. Turbo FTIR screen of imaging FTS system

## 5. AIRBORNE INSTRUMENT RESULTS

The new “space frame” Turbo FT was used in a single pixel airborne remote sensing application in Australia. The purpose of the program was to measure soil types from the air for geophysical research, and characterize them using standard spectral unmixing techniques in the Thermal IR (7-14 micrometer) region. The instrument was a joint effort between D&P and two Australian organizations, CSIRO and Fugro Airborne Pty., Ltd. It was called TIPS (Thermal Infrared Profiling Spectrometer). D&P supplied the interferometer, detector, and data acquisition hardware, while CSIRO and Fugro did all the aircraft installation, flight testing, and data processing. During 2000, various regions of Australia were overflown, and measurements of calibrated ground emissivity were made. Emissivity is an absolute measurement of spectral emission signatures from rocks and soil, which can then be compared against known emissivity spectra to identify soil types. The airborne data was backed up by ground truth measurements made by D&P’s portable, battery powered FTIR emission spectrometer. The test results were supplied by CSIRO and Fugro <sup>(2)</sup>.

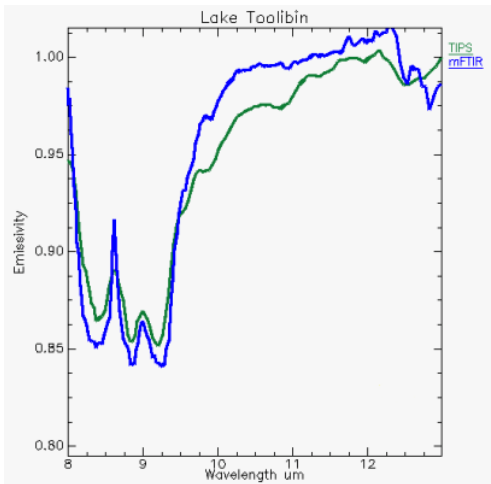


Figure 5. Airborne and ground data plots

mental conditions due to the saline intrusion. Similar results were previously measured by SEBASS.

In their paper <sup>(2)</sup>, the Australians give other results from other sites, such as Mt Fitton and Broken Hill. These are more mineralogical and geological in nature. The maps generated from those areas can delineate minerals such as talc, dolomite, quartz, and tremolite at Mt. Fitton. The Broken Hill region contains various types of garnet, which were detected and mapped by TIPS. The conclusions drawn at the end of the paper point out that the single pixel TIPS instrument is a good supplement to data in the NIR/SWIR spectral regions. They are currently flying a NIR/SWIR instrument called OARS, built in Australia.

The Turbo FT could also be built in the NIR/SWIR spectral region, and supply the same data at very high speed and also high spectral resolution. An  $8 \text{ cm}^{-1}$  resolution FTS gives 3.2 nanometer resolution at 2 micrometers. At shorter wavelengths, the resolution is even higher, e.g. 0.8 nanometers at 1 micrometer. This is easily achieved using the Turbo FT. If higher spectral resolution is needed, 4 and  $2 \text{ cm}^{-1}$  Turbo FT interferometers are easily achievable.

Some test spectra from these flights are shown below. The data was taken in the Lake Toolibin district in southwestern Australia. This region was chosen for testing because of its environmental and agricultural features. It suffers from dryland salinity which is the result of encroaching salinity. The ability to discriminate between quartz and kaolinite soil in the 8-14 micron spectral band allows mapping of sandy versus clay rich soils, which then maps the saline encroachment. In Figure 5, the green trace shows the spectrum of quartz as measured from the air by the TIPS instrument. The blue trace is the ground truth measured by the D&P Micro FTIR (mFTIR). Both have been calibrated using blackbody spectra to generate calibrated radiance spectra, then ratioed against a Planck function at the proper temperature to yield the apparent emissivity spectra shown. Note the good agreement between the two spectra, even though the Micro FT uses a laser reference to generate its wavelength scale, while the Turbo in the aircraft is time sampled using the encoder clock as its reference.

The spectra in Figure 6 show the spectral endmembers of quartz, kaolinite, and mixed soil types used to map the various environ-

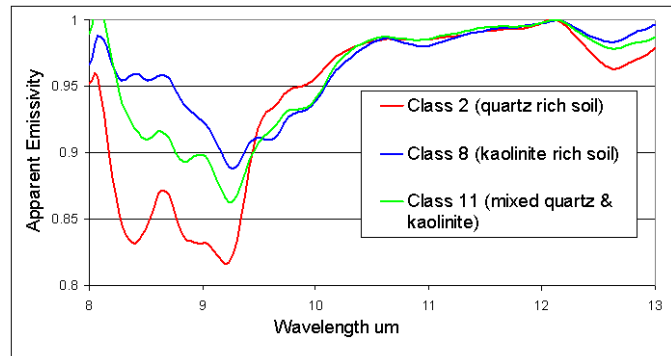


Figure 6. Lake Toolibin spectral endmembers

## 6. ONGOING AND FUTURE DEVELOPMENT

It seems clear from these developments that the next step is to find new ways to exploit both the increased speed and larger number of pixels which have been demonstrated in real world uses of the Turbo FT. In remote sensing, there are few airborne instruments in the Thermal IR (8-12 micrometer) spectral region. Many geologic and mineralogic features are in this region. The commercial appeal to the mining community in the exploration area is quite obvious. An imaging airborne Turbo FT might be the next step for this application. In addition, a NIR/SWIR Turbo FT running in parallel would enhance the value of a dual instrument, supplementing the TIR and allowing better discrimination of soil and mineral types. Environmental applications could also use an imaging version of the airborne Turbo FT.

In the process control area, the imaging nature of a Turbo FT based system might be used to look at a wide web type product, and detect local abnormalities in product as it moves past at high speed. It could also be used in an aperture-sharing mode to monitor several processes at once, as described previously<sup>(1)</sup>. The cost of each line would now be 1/16<sup>th</sup> of the total system cost, instead of 1/9<sup>th</sup> before.

## 7. CONCLUSIONS

The progress of the Turbo FT over the last three years has brought it to the point of commercialization. With the new "space frame" interferometer design, mechanical and thermal drift has been reduced an order of magnitude. With the development of new drive and sampling electronics, better laserless sampling and variable speed operation have been realized. Finally, a good basic Windows software application has been written and tested. These elements can now be combined and expanded upon to open new opportunities in both process line and remote sensing applications.

## 8. ACKNOWLEDGMENTS

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I would also like to acknowledge my co-author and colleague at Designs & Prototypes, LTD, Dr. Jens Peter Dybwad, for his substantial contribution of test results and review of this paper. Dr. Dybwad is the inventor of both the Turbo FT and the Micro FT.

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