Performance and Application of a Very High-Speed 2-12 μm Ultraspectral FTIR Imager

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ABSTRACT

As an offshoot of hyperspectral imaging, which typically acquires tens to slightly more than 100 spectral bands, ultraspectral imaging, with typically more than 1000 bands, provides the ability to use molecular or atomic lines to identify surface or airborne contaminants. Surface Optics Corporation has developed a very high-speed Fourier Transform Infrared (FTIR) imaging system. This system operates from 2 μm to 12 μm, collecting 128 x 128 images at up to 10,000 frames-per-second. The high-speed infrared imager is able to synchronize to almost any FTIR that provides at least mirror direction and laser clock signals. FTIRs rarely produce a constant scan speed, due to the need to physically move a mirror or other optical device to introduce an optical path difference between two beams. The imager is able to track scan speed jitter, as well as changes in position of the zero path difference (ZPD) position, and perform real-time averaging if desired. Total acquisition time is dependent on the return stroke speed of the FTIR, but 16 cm^{-1} (1024 point) spectral imagery can be generated in less than 1/5 second , with 2 cm^{-1} (8192 point) spectral imagery taking proportionately longer. The imager is currently configured with X-Y position stages to investigate surface chemistry of varied objects. Details of the optical design, focal plane array, and electronics that allow this high-speed FTIR imager to function are presented. Results of using the imager for several applications are also presented.

Keywords: Ultraspectral imaging, SWIR, MWIR, LWIR, FTIR, high-speed, continuous scan

1. ULTRASPECTRAL FTIR IMAGING

Although no clear delineation exists between multispectral imaging, hyperspectral imaging, and ultraspectral imaging, the typical range of spectral images is 2 to 10 for multispectral, 10 to around 100 for hyperspectral, and hundreds to thousands of bands for ultraspectral. Ultraspectral imaging provides such high spectral resolution that individual molecular absorption lines can be resolved. Such high spectral resolution lends itself to applications where small spectral differences exist among objects, or where ability to effectively tune bands of interest is required. Surface Optics Corporation has previously presented basic information on development of Fourier Transfrom Infrared (FTIR) ultraspectral imaging systems. Current embodiment of this system allows operation with almost any continuous scan Fourier Transform spectrometer.

2. SYSTEM ARCHITECTURE

The design parameters for the SWIR-LWIR FTIR Ultraspectral imager developed at Surface Optics are

- Very broad band operation: 2 - 12 μm

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- Variable spectral resolution: 32 cm^{-1} - 2 cm^{-1}
- Total transformed spectral points per pixel (no zero-filling): 256 to 4096
- Spatial Format : 128 x 128
- Spatial Resolution at the sample: 40 μm or 60 μm
- Large Sample coverage: automated positioning and image "quilting" to view samples larger than the 5 mm x 5 mm view of a single image
- Imager frame rate: up to 10 KHz to enable use with continuous scan FTIRs
- Laser clock synchronization: Frame-to-frame lock to each laser clock crossing
- Cube collection speed: Up to 5 cubes-per-second at 16 cm^{-1} resolution (FTIR dependent)
- Averaging: real-time with automatic correction for scan-to-scan ZPD jitter

Key to operation of this FTIR imager is its ability to operate with continuous scan FTIRs. Before development of the camera system used in this imager (in 2001), only step-scan spectrometers could be used with FTIR imaging. With a mirror scan speed of 0.63 cm/s and sampling every laser clock positive edge (every .63 μm of mirror optical path difference travel), required imager frame rate is 10 KHz. Step scan systems can operate with much slower framing imagers, but suffer from a variety of problems including thermal instability, mirror positioning errors, long collection times, and high FTIR cost. By operating with a reasonable continuous scan speed, these limitations are overcome.

The system developed by Surface Optics is currently an inspection tool, used to inspect panels or other surfaces for contaminants, coating imperfections, or other such problems. The system can also be used in double-pass transmission for investigating internal properties of IR transmissive samples. A side view of the complete system is shown in figure 1.

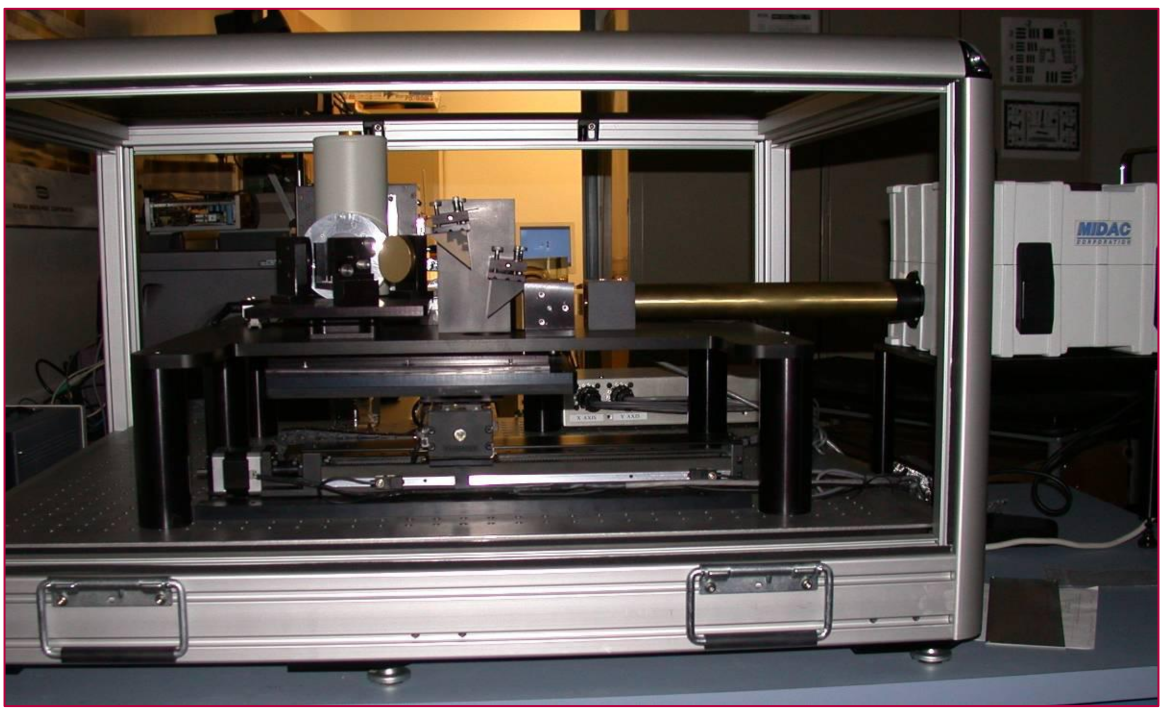

Figure 1: Complete continuous scan FTIR inspection system

In the above figure, the FTIR is located at the extreme right of the image. Modulated light is brought to the sample via the gold light pipe. The imaging optics and camera are at the right center of the image. Two dimensional positioning stages reside under the optical table. The major components of the system are illustrated in the mechanical drawing of figure 2.

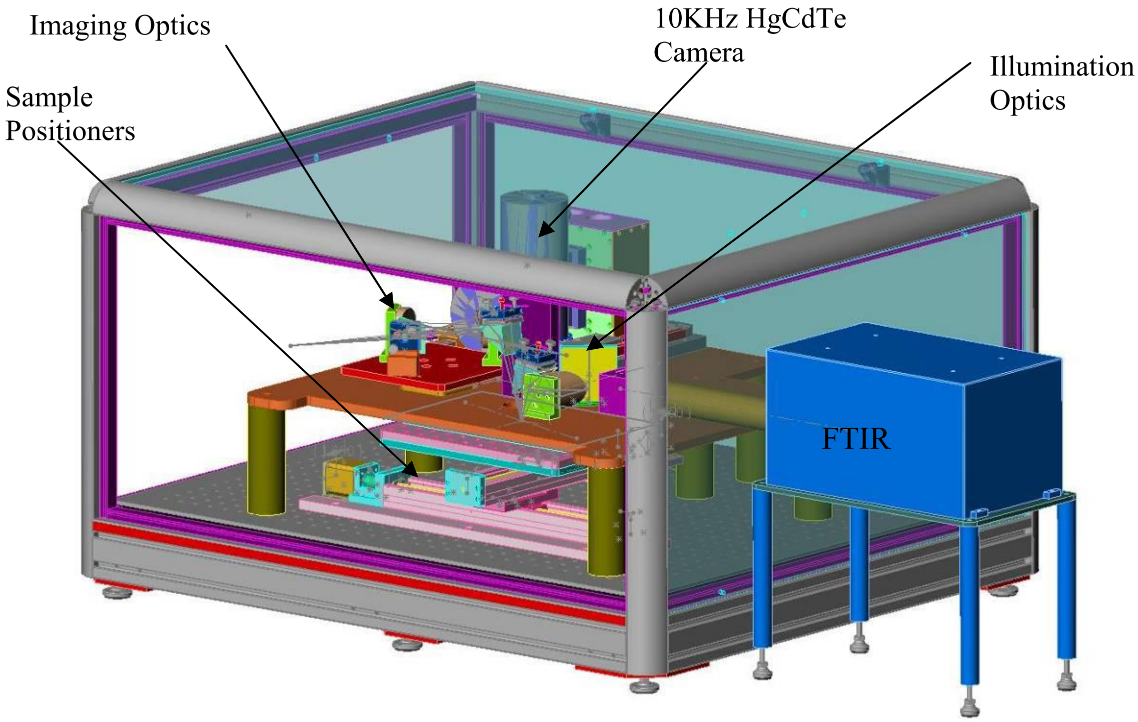

Figure 2: Mechanical system drawing highlights the major components

2.1 OPTICAL DESIGN

Optical design of this imaging system is straightforward. After exiting the light pipe, light from the FTIR illuminates the sample via an off-axis parabola designed to provide a relatively uniform illumination area of 5 mm x 5 mm, the area imaged by the camera. Light reflected by the sample is re-imaged onto the focal plane via a pair of low-angle off-axis parabolas, configured to eliminate coma. Figure 3 illustrates this configuration

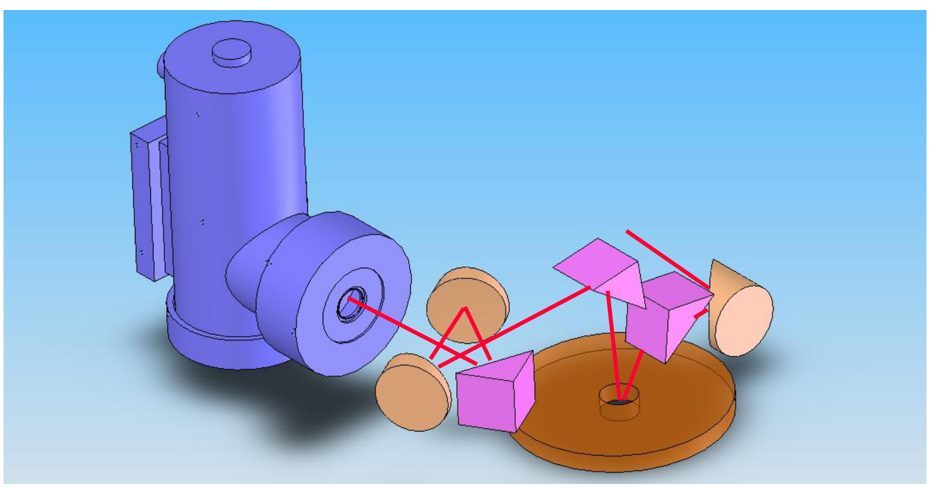

Figure 3: Optical design of the system uses three powered optics, and two plano optics

Figure 4 presents an overhead view of the optical system. The two off-axis parabolas configured for low-aberration imaging are clearly visible just below and to the left of the center of the image. By using parabolas of different focal length, the magnification of the system can be changed. Although currently being used at 1:1 magnification, magnifications of 1.5:1, 2:1, or even 3:1 are achievable. The opposite is also true. The image can be de-magnified to provide larger sample coverage at reduced spatial resolution.

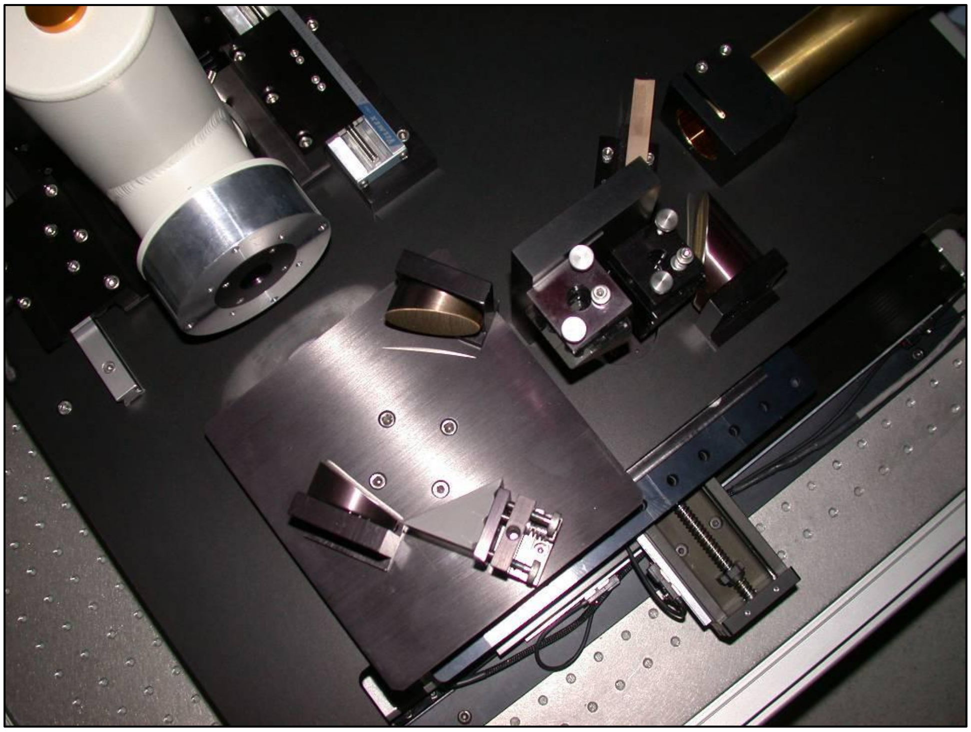

Figure 4: Top view of the optical system shows all major optical components

Although the configuration of the off-axis parabolas does eliminate any coma, it still creates some spherical aberration. When using the system without stopping down the illumination, i.e., using the system at its full F/4 relative aperture, the images are crisper at the center of the field than at the edges. This is illustrated in figure 5.

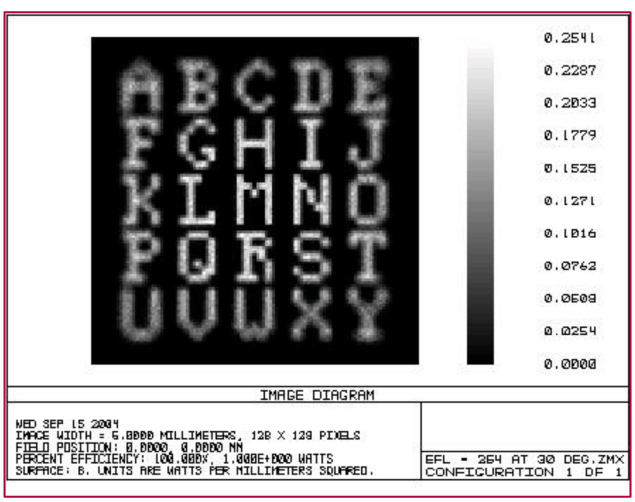

Figure 5: Dual off-axis parabola imaging does introduce some spherical aberration

For most samples, however, the full illumination aperture is not necessary to achieve high signal-to-noise. Hence, stopping down the illumination enhances the spatial resolution at the corners of the field

2.2 IMAGING ARRAY AND ELECTRONICS DESIGN

As previously mentioned, key to operation of this system is the very high frame rate Mercury-Cadmium-Telluride (HgCdTe) focal plane. Developed by Rockwell Scientific (RSC), this FPA provides 128 x 128 spatial resolution. To achieve frame rates of 10 KHz, a pixel rate of over 160 million-pixels-per-second is necessary. With a quantization of 16 bits, this amounts to a data rate of 1/3 Gbyte-per-second. The Rockwell array provides 32 output ports to achieve such a tremendous pixel rate without requiring an unacceptably high pixel clock rate. Using HgCdTe provides high quantum efficiency from less than 2 µm to 12 µm. Note that the laser clock sets the Nyquist lower spectral limit to twice the laser wavelength, or 1.27 µm. The focal plane also provides very low noise readout, and variable well depth to accommodate varying reflectance samples. Figure 6 shows the focal plane resident behind a cold shield in the Dewar.

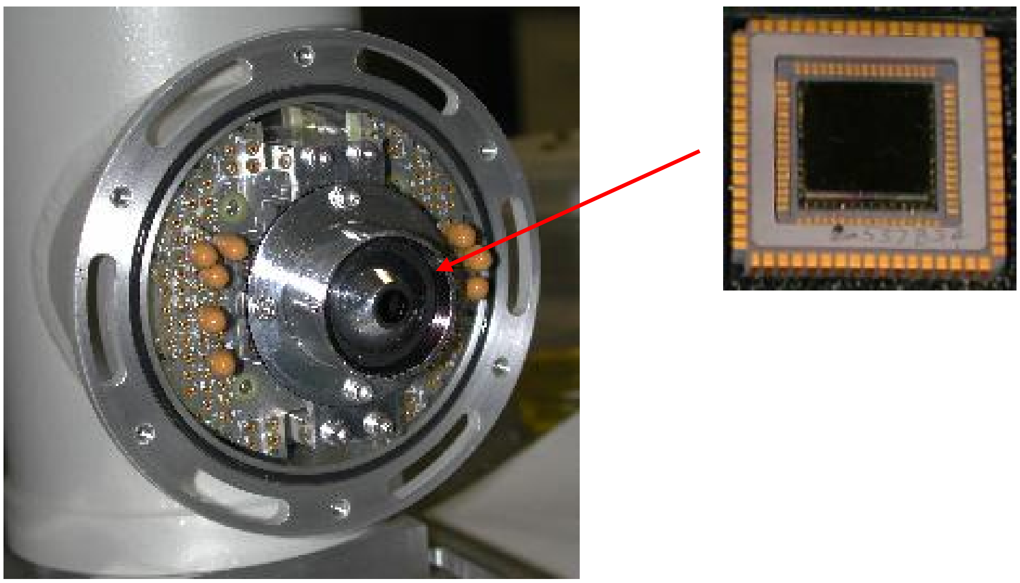

Figure 6: Located in a pour-fill Dewar, Rockwell's 128 x 128 HgCdTe FPA is the heart of the system

To allow this very high speed FPA to operate with a Fourier Transform spectrometer, Surface Optics designed a set of custom readout electronics. Key Features of this board set are:

- 32 input channels provide high-speed imaging capability
- Arbitrary analog offsets can be applied to each pixel to maximize dynamic range
- Pixel data is digitized to 16-bits, providing very good intra-scene dynamic range
- Electronics synchronize image generation and readout to every FTIR laser clock
- An onboard 2 GB buffer accepts interferogram imagery for real-time imaging
- Since mirror turnaround introduces small jitter into ZPD position, the system automatically tracks and corrects ZPD jitter for real-time data averaging
- Real-time averaging is selectable from 1 to 256 scans
- Gain can be changed between frames during a scan to maximize SNR throughout the interferogram
- Resolution is tailorable from 32 cm^{-1} to 2 cm^{-1}

The ability to track scan-to-scan changes in ZPD (the location of the center burst resulting from zero path difference) is key to performing real-time averaging. Without this feature, single scans would need to be read by the control software, ZPD located, and scans averaged. Even with the fastest PCs available, this process, including data transfer from the imager, is more than 20 times slower than performing the averaging in real time at the camera. Figure 7 shows the four board of the custom SOC electronics.

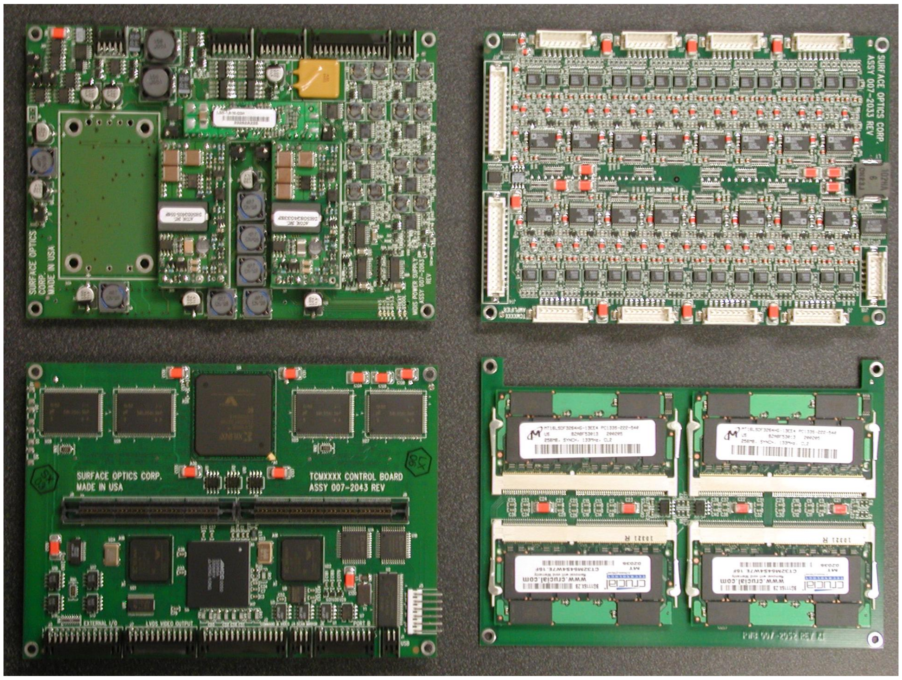

Figure 7: A four-board modules provides 32 input channels and all functions necessary to interface to the Rockwell FPA for FTIR imaging

3. PERFORMANCE AND APPLICATIONS

After development of the FTIR imager, system performance was evaluated. Spatial resolution was found to be as predicted by design analysis, with higher corner spatial resolution available by stopping down the illumination (or received) beam. Ability to synchronize to the laser clock during an entire scan without any loss was also demonstrated. Note that this ability has been demonstrated both with high-end Nicolet FTIRs, and with less stable, less expensive spectrometers. Real-time averaging in the presence of ZPD location jitter has also been demonstrated, from 1 to 256 averages. Figure 8 shows example imagery. In this figure, the image at the left is a photograph of the surface, the middle image is at 1034 cm^{-1} (9.67 μm) and the right image is at 1475 cm^{-1} (6.78 μm), showing the different chemistries present in the sample.

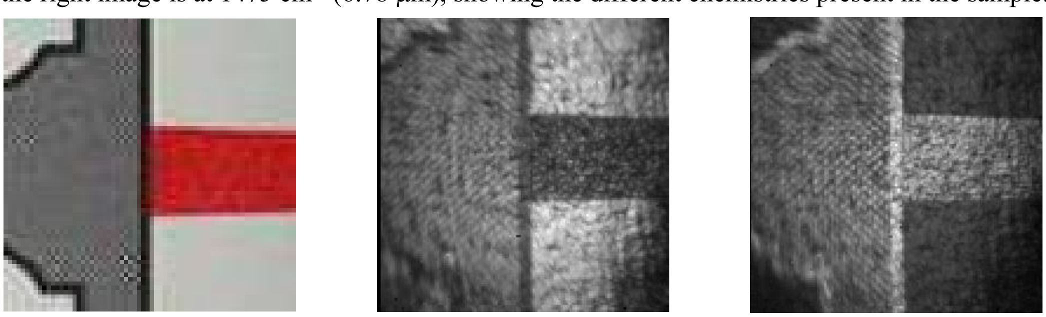

Figure 8: Photograph (left) and images at 9.67 μm (center) and 6.78 μm (right) show system capability

Figure 9 shows the quality of the data produced by the system. The interferogram and its transformed spectrum from one of the pixels in the above sample are shown. Taken in only 30 seconds, this 8 wavenumber resolution data shows a 2000-to-1 peak signal to RMS noise ratio. This is by far the fastest FTIR imaging system currently available providing this data quality.

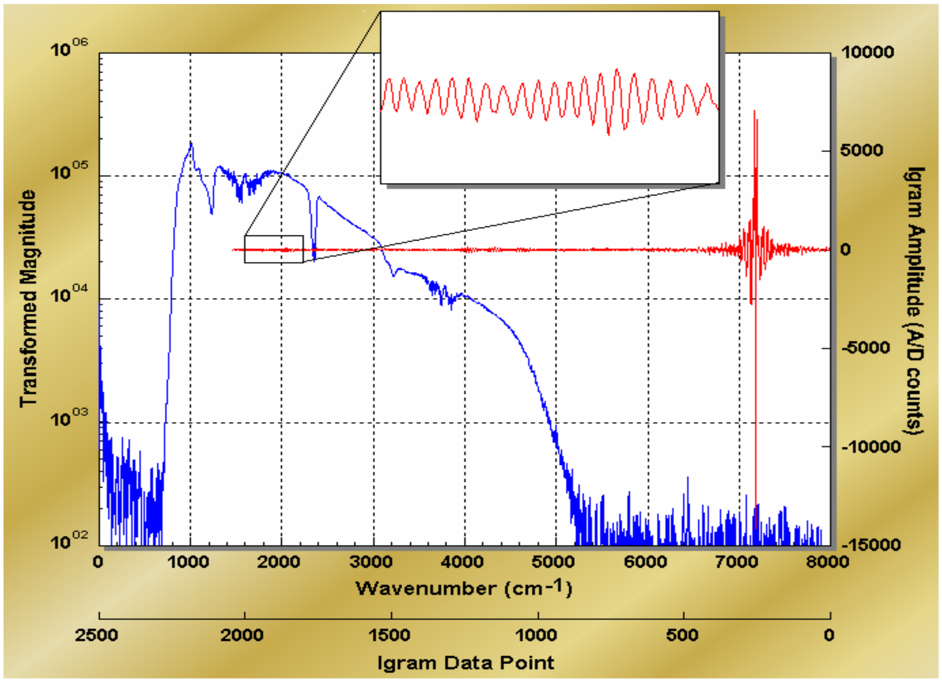

Figure 9: Example 8 cm^{-1} interferogram and its transformed spectrum, showing quality of data

The 2 µm (5000 cm^{-1}) cutoff of the system is apparent in the above figure. Note that this cutoff is a result of the Germanium window used in the Dewar. Were this window to be changed, data could be taken with reasonable SNR down to the Nyquist limit of the system, 1.27 µm (7900 cm^{-1}). Also note the very clean nature of the interferogram, showing a very flat baseline and high SNR modulation, even at the extreme edge. Some commercial spot FTIRs fail to produce such artifact-free interferograms.

Since spectra produced by this imager are so rich, ability to find and uniquely identify material is far greater than other multispectral or hyperspectral imaging systems. Surface Optics has explored several different applications for this system, including finding surface contamination and other surface imperfections. Figure 10 shows the ability of the system to see surface contaminants that are indiscernible when viewed broad-band.

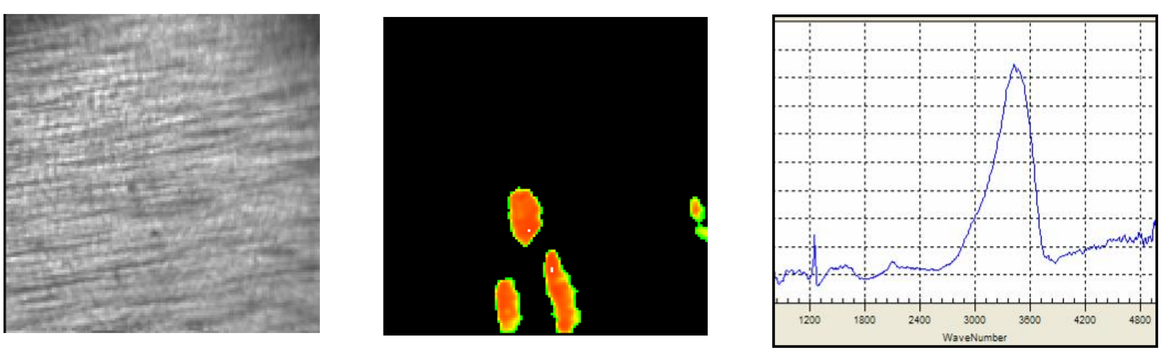

Figure 10: Broadband imagery (left) fails to reveal surface contaminants, clearly visible after spectral processing (center). Contaminant spectrum is shown at right

The above imagery represents a single spatial frame, or 5 mm x 5 mm. Figure 11 shows the ability of the system to scan much larger areas. Here, oils left from a fingerprint are clearly visible. Also shown in the image is the absorptance spectrum associated with the fingerprint oil. The hydrocarbon absorption spectrum around 3000 cm^{-1} is highlighted. The displayed image represents a 50 mm x 20 mm (10 x 4 frame) quilted surface scan. Note that the displayed image is only part of the total scan of 60 mm x 60 mm.

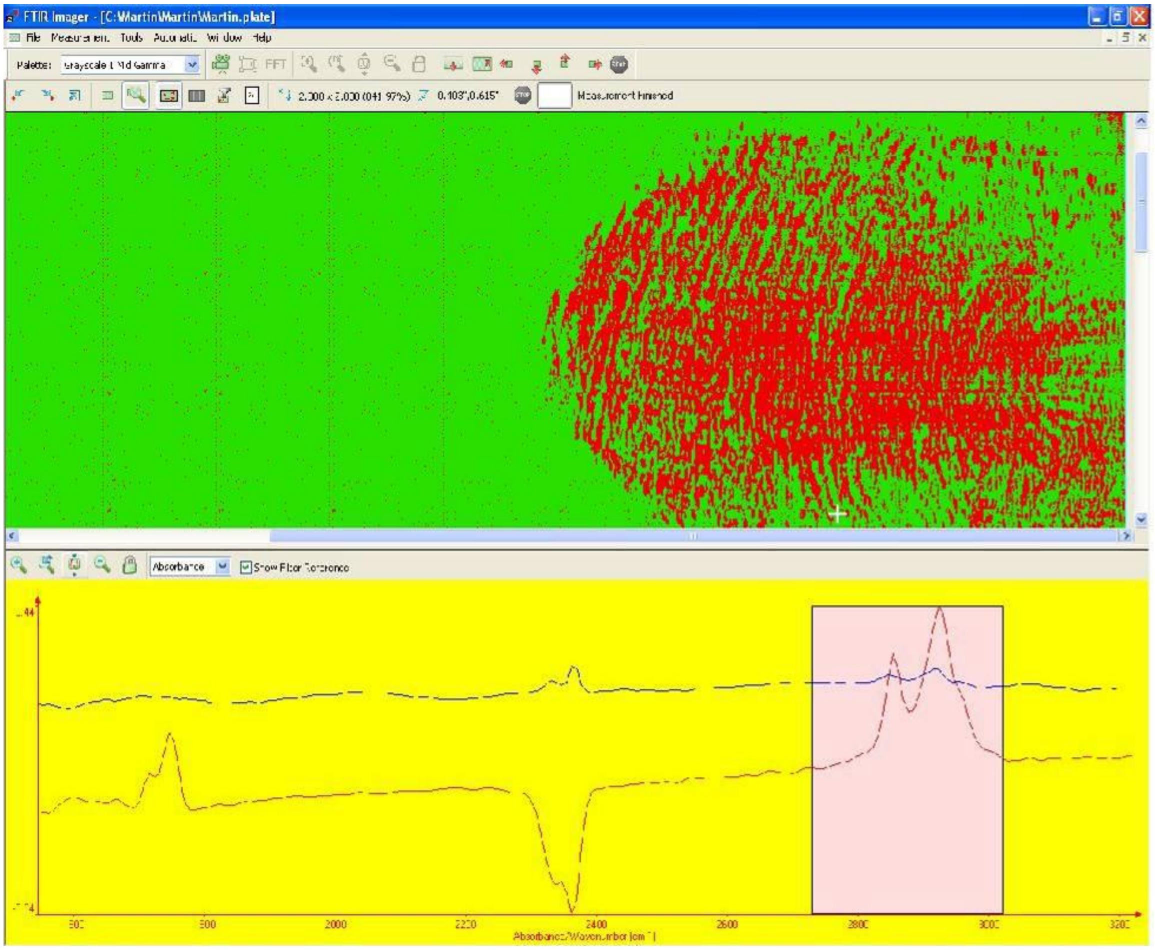

Figure 11: Example large area surface scan, revealing fingerprint through hydrocarbon absorption

4. SUMMARY

Surface Optics Corporation has developed a very-high speed FTIR-based ultraspectral imager. Key operating features, including ability to synchronize frame-to-frame to the FTIR laser clock, average interferograms while accommodating ZPD jitter, and framing at 10KHz, have been described. Some of the challenges of design and development have also been discussed. Optical and radiometric performance of the system has been shown. Finally, some applications appropriate for the system have been discussed.