Before Hyperspectral Ruled the World

Dr. J. Bruce Rafert
Professor of Physics
Department of Physics, North Dakota State University, Fargo, USA

Abstract. We discuss early hyperspectral research and development activities during the 1990's that led to the deployment of aircraft and satellite payloads whose heritage was based on the use of Visible, spatially modulated, imaging Fourier transform spectrometers, beginning with early experiments at the Florida Institute of Technology, through successful launch and deployment of the Visible Fourier Transform Hyperspectral Imager on MightySat II.1 on July 19, 2000. In addition to a brief chronological overview, we also discuss several of the most interesting optical engineering challenges that were addressed over this timeframe, present some as-yet un-exploited features of field-widened (slit less) SMIFTS instruments, and present some images from ground-based, aircraft-based, and satellite based instruments that helped provide the impetus for the proliferation and development of entire new families of instruments and countless new applications for hyperspectral imaging.

Introduction. The past ~50 years has seen what can now in hindsight best be described as the emergence of a new metadiscipline—hyperspectral remote sensing. Taxonomy previously confined for use by a small and restricted number of specialists has now penetrated virtually every scientific and engineering discipline from agriculture through zoology, although routine use of what is now a very mature technology is not yet ubiquitous across all fields.

Figure 1 depicts the growth of the field. The timeframe can be divided into three main intervals: pre-1990 when use of 'hyperspectral' was constant and extremely sparse; the decade of the 1990's when a period of exponential growth occurred, and the post 2000 period with a high linear trajectory to over 10,000 occurrences per year. This paper focusses on just one of many specific technologies (Visible, Fourier Transform Hyperspectral Imaging—VFTHSI) that contributed to the growth of the field during the decade of the 1990's, when numerous investigators and laboratories were experimenting and deploying a wide array of hyperspectral instrument configurations (e.g., dispersive, Fourier Transform, acousto-optical) in a number of band passes (visible, SWIR, LWIR) for an array of applications. In this paper we will trace the development of

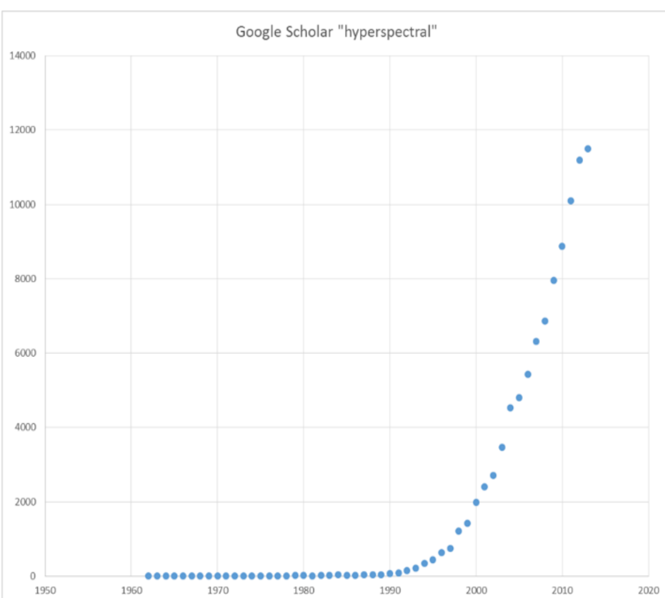


Figure 1. Plot of the number of times/yr that the word 'hyperspectral' appears in a Google Scholar search of the literature since 1950.

just the VFTHSI instrument design heritage—a subset of Spatially Modulated Imaging Fourier Transform Spectrometers (SMIFTS), from initial brass board implementation to orbit. Topics will include a short review of operational features as seen from the perspective of an optical systems engineer, tracking of the design heritage from brass board to orbit, some observational data from several of the instrument variations, and a short summary of unexplored vistas for the future.

VFTHSI Basic Operational Characteristics

Figure 2 depicts the now well-known configuration of a VFTHSI instrument. Shown is a single, polychromatic ray from a target spatial element (x,y). The ray passes through a fore optic (not shown) with focal length and f/ratio such that infinity focus is at the field stop, which serves only as a spatial mask in the x direction (but allows image formation in the y direction). We note that the spatial mask serves primarily to aid in image reconstruction following data reduction, although the wider the spatial mask, the more photons that are admitted to the system—a limiting case being elimination of the field stop entirely. The ray passes through some type of a beam splitter, and hence through the triangle-path or Sagnac interferometer. We also make note that deviations from R=T=0.5 split of the ray by the beam splitter across the entire band pass result in rapid deteoriation of fringe visibility on the detector. The Sagnac has a number of desirable features including extreme ease of configuration and alignment, and is amenable to monolithic solutions to avoid vibration or misalignment issues. The lower right mirror in Figure 2 is shown with an offset s from the triangle orientation which introduces a sheer in the two mutually coherent parallel rays shown exiting the interferometer downward.

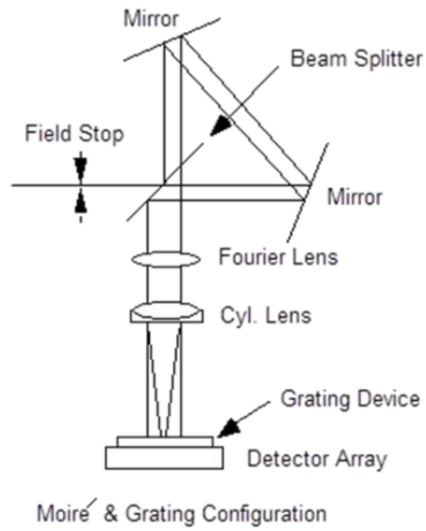


Figure 2. Triangle path interferometer

Those two rays enter a Fourier optic, whose focal length is selected to be the distance back through the interferometer to the field stop. Arbitrary magnification (e.g., size of the aperture function necessary to fully illuminate a CCD of size n by m) can be achieved via selection of f/ratio with the fore optic. A cylinder lens whose focal length is chosen to reimage the target y-dimension onto the visible CCD has no power in the (target) x dimension. The net effect of this optical device for a ray of wavenumber k is that

an Interferogram $I(x)=\int (I_o(k)/2)*[1+\cos(2\pi ks)]dk$ is created on the CCD detector in the (target) x direction, while the target y direction creates a 1-dimensional image orthogonal to the Interferogram on the CCD.

Tracking the Design Heritage from Brass board to Orbit

Our original experiments with the VFTHSI were undertaken on a surplus 2x3 foot brass board at the Florida Institute of Technology—using available surplus beam splitters and surplus optical table components—essentially, nothing more sophisticated than the optics shown in Figure 2. An early version of the brass board was mounted aboard the R1 and R2 telescopes at the Malabar Test Facility, where proof of concept hyper cubes were obtained for space objects (space station MIR) as well as cooperative ground-based targets on the Malabar optical range (readily available video cameras and image intensifiers were used as the CCD sensors for these early experiments). Concurrently, a utility study was undertaken as part of a larger project funded through Darpa with collaborators from the

University of Hawaii and the University of Central Florida (Lucey, 1992). Interestingly, the final report which alluded to 'dozens or hundreds' of potential applications for hyperspectral imaging was received with some skepticism from the sponsor, perhaps feeling that such proliferation of applications of such an seemingly limited technology would never occur.

Early success with such modest hardware quickly led the US Air Force to provide strong development support for more sophisticated instruments. Figure 3 shows the 3-d optical schematic of the Kestrel/Michigan Technological University (MTU) VFTHSI (Otten, 1995; Rafert, 1999). The design heritage of the original prototype is retained, although chromatic correction across the band pass led to a number of refinements in the design. The beam splitter is no longer square, becoming more compact and rectangular (with the larger dimension in the target y direction). Curiously, we found that the Fourier optic could be positioned partially in front of and partially behind the beam splitter—a significant savings in space.

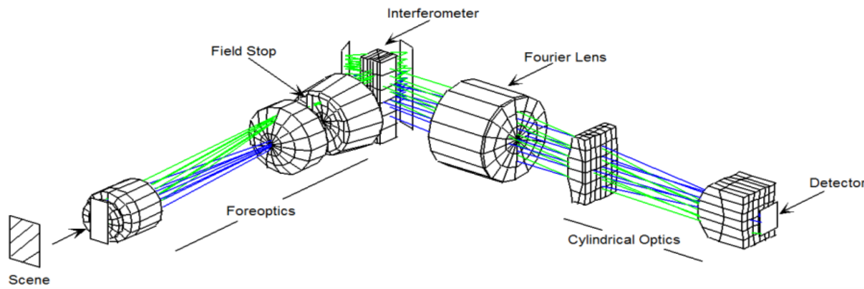


Figure 3 (above). The Kestrel/MTU VFTHSI Raytrace

This updated version of the VFTHSI was built in duplicate—one system was integrated into the Kestrel Cessna shown in Figure 4, while the second (optically identical) was fabricated as a scanning ground based unit at MTU.

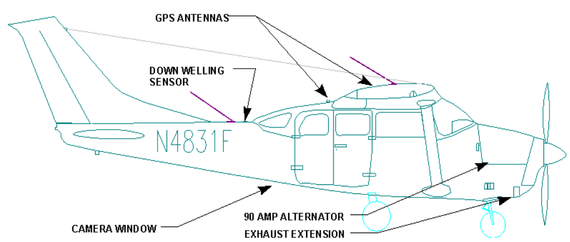


Figure 4 (right). Kestrel Cessna

Figure 5(a) is one flight line of the Kestrel VFTHSI over the MTU campus, while Figure 5(b) depicts spectral profiles for 7 different targets within the scene (the spectral profiles shown here are uncorrected for sensor or atmospheric effects).

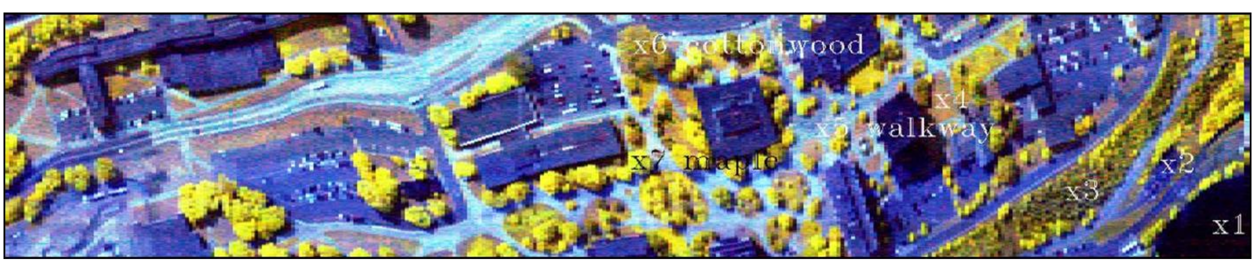
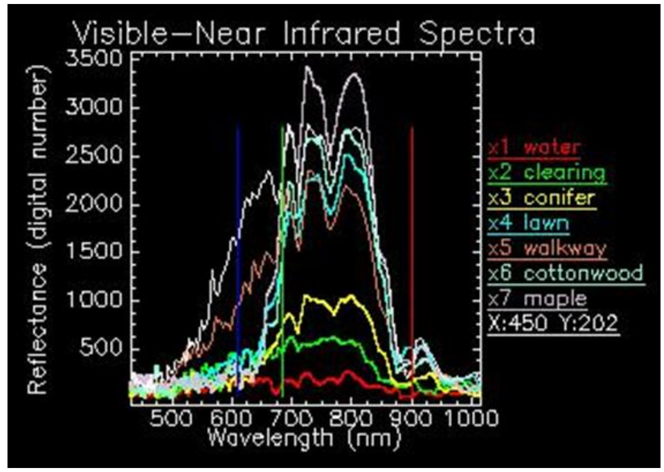
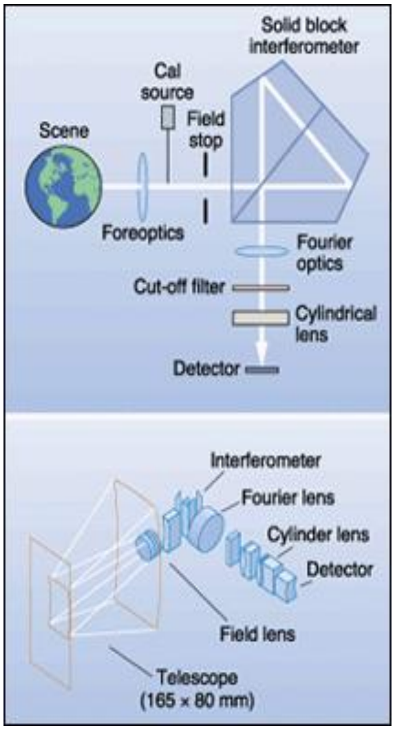


Figure 5(a) (above). The MTU campus as seem with Kestrel VFTHSI.

Figure 5(b) (right, next page). Ray spectral data for representative targets, marked right to left in 5(a) above. Target 1 is a portion of the Portage Lake in the lower right corner; Target 6 is the large cottonwood located in the upper center.

Figure 6 (below) shows a schematic of the version of VFTHSI that was built to fly in space on MightySat II.1 (Otten, 1997; Rafert, 2001). This was the first hyperspectral satellite that returned a hyperspectral image from space. Note the introduction of square reflective fore optics (weight saving), and monolithic components (to address vibration and alignment issues during launch and on-orbit operations.





Summary
There is now little doubt that Hyperspectral remote sensing has 'arrived', and is in the process of becoming a major remote sensing tool. Two particular areas—precision agriculture and transportation infrastructure are in a rapid initial phase of experimentation and adoption. Our current efforts are focused on optimizing hyperspectral remote sensing for use with lightweight (less than 50 pounds) unmanned aircraft systems (UAS) and to provide the relevant training necessary for future practitioners to construct and deploy full solutions.

Acknowledgements
We gratefully acknowledge numerous conversations, collaborations, and the contributions that Joel Blatt, Paul Lucey, Tom Rusk, Glenn Sellar, Eirik Holbert, Harold Newby, Susan Durham, John Otten, Andrew Meigs, Gene Butler, Chris Gittins, Mark North, and Raj Bridgelall have made to the efforts described here, and their many contributions to the field of hyperspectral imaging.

References
Lucey, P.G., Williams, T., Horton, K., Hinck, K., Rafert, J.B., Rusk, E.T., "SMIFTS: A Cryogenically Cooled Infrared Spatially Modulated Imaging Fourier Transform Spectrometer for Remote Sensing Applications", Proceedings of the ISSSR 1, 251, (1992).

Otten, L.J., Butler, E.W., Rafert, J.B., Sellar, R.G., "The design of an airborne Fourier transform visible hyperspectral imaging system for light aircraft environmental remote sensing", Aerosense '95, Orlando, Florida, (1995).

Otten, L.J., Rafert, J.B., Meigs, A., Jones, B., Prinzing, R., Fronterhouse, R., Sellar, R.G., Hodge, P., "The Engineering Model for the MightySat II.1 Hyperspectral Imager", SPIE VOL 3221, pg 412-420, Aerospace Remote Sensing Conference (London), (1997).

Rafert, J.B., Slough, W., Pilant, A., Otten, L.J., Meigs, A., Jones, A., Butler, E., "The Michigan Technological University-Kestrel Airborne Hyperspectral Imaging Campaigns of the Lake Superior Ecosystem", SPIE 44th Annual Meeting #3753-13, (1999).

Rafert, J.B., Otten, L.J., Meigs, A.D., Butler, E.W., "Orbiting Fourier Transform Hyperspectral Sensor", Laser Focus, 21 February, 2001.