View metadata, citation and similar papers at core.ac.uk
brought to you by CORE
provided by NASA Technical Reports Server

Ground-based measurement experiment and first results with geosynchronous-imaging Fourier transform spectrometer engineering demonstration unit

Daniel K. Zhou,[a] William L. Smith,[b,c] Gail E. Bingham,[d] Ronald J. Huppi,[e] Henry E. Revercomb,[b] Lorin J. Zollinger,[d] Allen M. Larar,[a] Xu Liu,[a] Joseph J. Tansock,[d] Robert A. Reisse,[a] and Ronald Hooker[f]

[a]NASA Langley Research Center, Hampton, VA 23681, USA
Daniel.K.Zhou@nasa.gov, Allen.M.Larar@nasa.gov, Xu.Liu-1@nasa.gov, Robert.A.Reisse@nasa.gov
[b]University of Wisconsin – Madison, WI 53706, USA
Bill.L.Smith@cox.net, Hank.Revercomb@ssec.wisc.edu
[c]Hampton University, Hampton, VA 23668, USA
Bill.L.Smith@cox.net
[d]Space Dynamics Laboratory, Utah State University, Logan, UT 84341, USA
Gail.Bingham@sdl.usu.edu, Lorin.Zollinger@sdl.usu.edu, Joe.Tansock@sdl.usu.edu
[e]Ronald J. Huppi, Consultant, 6 Fairlane Terrace, Winchester, MA 01890, USA
Ron.Huppi@pobox.com
[f]NASA Headquarters, Washington, DC 20546, USA
Ron.Hooker@nasa.gov

Abstract. The geosynchronous-imaging Fourier transform spectrometer (GIFTS) engineering demonstration unit (EDU) is an imaging infrared spectrometer designed for atmospheric soundings. It measures the infrared spectrum in two spectral bands (14.6 to 8.8 μm, 6.0 to 4.4 μm) using two 128×128 detector arrays with a spectral resolution of 0.57 cm^{-1} with a scan duration of ~11 seconds. From a geosynchronous orbit, the instrument will have the capability of taking successive measurements of such data to scan desired regions of the globe, from which atmospheric status, cloud parameters, wind field profiles, and other derived products can be retrieved. The GIFTS EDU provides a flexible and accurate testbed for the new challenges of the emerging hyperspectral era. The EDU ground-based measurement experiment, held in Logan, Utah during September 2006, demonstrated its extensive capabilities and potential for geosynchronous and other applications (e.g., Earth observing environmental measurements). This paper addresses the experiment objectives and overall performance of the sensor system with a focus on the GIFTS EDU imaging capability and proof of the GIFTS measurement concept.

Keywords: Michelson interferometer, Fourier transform spectrometer (FTS), image, remote sensing, satellite.

1 INTRODUCTION

Severe weather (e.g., hurricanes, tornadoes, floods, ice storms, etc.) impacts our daily lives. An accurate weather forecast is needed now more than ever for planning daily activities and for optimizing the preparation for the onset of life-threatening and property-damaging weather (e.g., a hurricane landfall). The improvement of weather prediction requires high resolution temporal and spatial measurements of temperature, moisture, and wind profiles. High density and timely thermodynamic profile measurements are needed to forecast where and when severe convective storms will form before they are visible on radar or in satellite cloud imagery. Quasi-continuous measurements of the moisture flux are needed for timely forecasts of storm intensity changes. Atmospheric wind profiles are needed to predict the storm's trajectory, and in the case of tropical storms and hurricanes, their landfall location and time. Based on these considerations, the GIFTS measurement concept [1] has been developed within the reach of new technologies for improving weather prediction accuracy.

Current and future planned satellite sensors, such as the Atmospheric InfraRed Sounder (AIRS) on the AQUA satellite since May 2002 [http://disc.sci.gsfc.nasa.gov/AIRS], the Interferometer Atmospheric Sounding Instrument (IASI) on the METOP satellite launched in October 2006 [http://smsc.cnes.fr/IASI], and the Cross-track Infrared Sounder (CrIS) on the future NPP (2008) and NPOESS (2012) satellites [http://www.ipo.noaa.gov/], are attempting to fulfill the observational needs for accurate weather prediction. Valuable data obtained from the AIRS measurements have already shown the benefits of hyperspectral data. The GIFTS measurement concept [http://gifts-d.larc.nasa.gov/index.html] takes advantage of the geostationary satellite, an imaging Fourier transform spectrometer with large Longwave Infrared (LWIR) and Short/Midwave Infrared (SMWIR) focal plane detector arrays, and a near-infrared, band-filtered camera to revolutionize the spatial, spectral, and temporal observation of atmospheric conditions [2,3]. The imaging FTS concept was initially developed in the early 1970's. A patent on the imaging concept idea was awarded to A. E. Potter in 1972 [4]. A fieldable system was developed by Stewart Radiance Laboratory (SRL) and utilized to collect atmospheric and earth background data from balloons in 1970's [5]. Other spectral imaging system utilizing focal plane array (FPA) detectors have been published previously [6,7].

The GIFTS EDU utilizes the advantages of cryogenic FTS technology developed by SRL and Space Dynamics Laboratory (SDL) to improve sensitivity and calibration stability [8]. The EDU has undergone a series of thermal vacuum tests followed by an extensive calibration phase. The success of the GIFTS EDU is not only critical to the GIFTS program itself but also for a demonstration of the new technologies (e.g., large area format LWIR FPA and high speed detector readout electronics, mini-pulse tube cooler, lightweight carbon composite optics, long lifetime precision laser, etc.) incorporated in the EDU. NASA and NOAA funded the completion and calibration of the GIFTS EDU as an important risk reduction effort for future programs. After all thermal vacuum tests and calibration experiments were completed in the summer 2006, a ground-based GIFTS EDU measurement experiment was conducted during September 2006 to collect the real atmospheric, lunar, and mountain-sky data needed to characterize and demonstrate the sensor system. This experiment is critical in demonstrating the capabilities of the instrument, its calibration, and its associated data processing procedures including the retrieval of scientific products. An overview of this experiment is presented with some preliminary analyses to illustrate that a successful experiment has been achieved and to reveal the GIFTS sensor system and measurement concept.

2 GIFTS EDU INSTRUMENTATION

The original flight instrument consisted of two subsystems: the sensor module built by SDL containing all the optics and control and data acquisition electronics, and the control module which was to be built by NASA Langley Research Center containing spacecraft interface electronics and payload control. Some elements were eliminated for the EDU. A detailed description of the GIFTS EDU instrumentation is provided by Elwell et al. [9]. The major components of the GIFTS engineering demonstration unit are shown in Figure 1. A diagram of the optical system is shown in Figure 2. The pointing mirror and off-axis telescope (M1, M2, and M3) are made of high thermal conductivity silicon carbide to minimize solar radiation effects and reduce mass. The telescope baffle cover, which would provide a contamination seal for the optics during launch, orbital insertion and extended thruster firings, was not implemented in the EDU. The two-axis scene selection mirror, although not implemented in the EDU, is specified to provide a field-of-regard (FOR) of ±12.9° in both the cross and vertical Earth directions, allowing clear space views on all sides of the globe. Information on other sub-systems, such as Laser metrology, Fourier transform spectrometer (FTS), telescope and relay optics, aft optics/electronics, mechanical cooler, visible camera, and on-board calibration sources, are described and found in Elwell et al. [9]. The GIFTS sensor is an imaging FTS with programmable spectral resolution and spatial scene selection. The GIFTS measurement concept can improve atmospheric-thermodynamic parameter sounding and/or imaging from geosynchronous orbit in several areas, such as faster area coverage and higher spatial and spectral resolution, to meet GIFTS scientific measurement objectives [3,10]. The GIFTS EDU calibration involves characterizing the sensor in several domains including the sensor's radiometric, spectral, spatial, temporal, and polarization responsivities [11]. Two primary calibration sources were used during calibration of the GIFTS EDU: the second multifunction infrared calibrator (MIC2) and the 15-inch High Accuracy Extended Source (HAES-15) [12-14]. These sources can be attached to the GIFTS thermal vacuum test chamber and, when attached, share a common vacuum. Details are documented elsewhere [14,15].

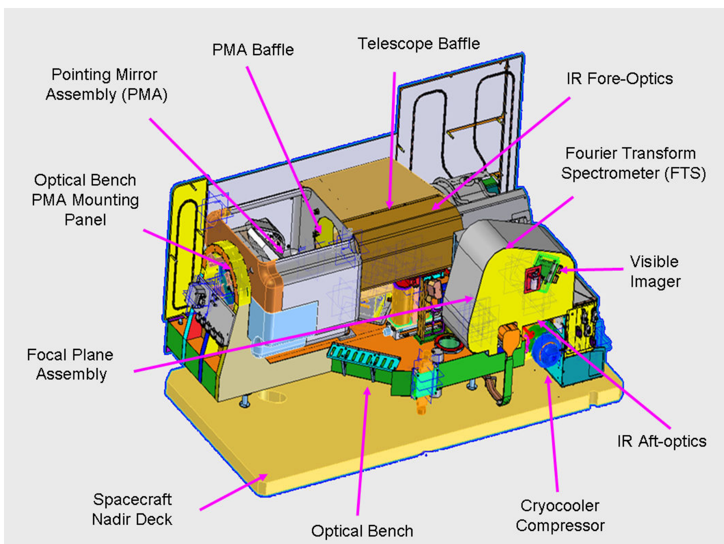


Fig. 1. Major GIFTS EDU components.

Engineering and calibration testing produced data that was used to assess sensor performance. These results indicated that EDU requirements have been achieved [10,15]. Specifically, the spectral performance is consistent with expectations based on the design and performance predictions of the sensor; an overall end-to-end analysis on the spectral calibration was made by Tobin et al. [16] for all pixels of both the LWIR and SMWIR detector bands. The GIFTS EDU noise performance, as measured during thermal vacuum testing, was analyzed by Cantwell et al. [15] and Taylor et al. [17] indicating that threshold performance has been realized, and the goal performance (or better) has been achieved over much of the LWIR and SMWIR spectral bands.

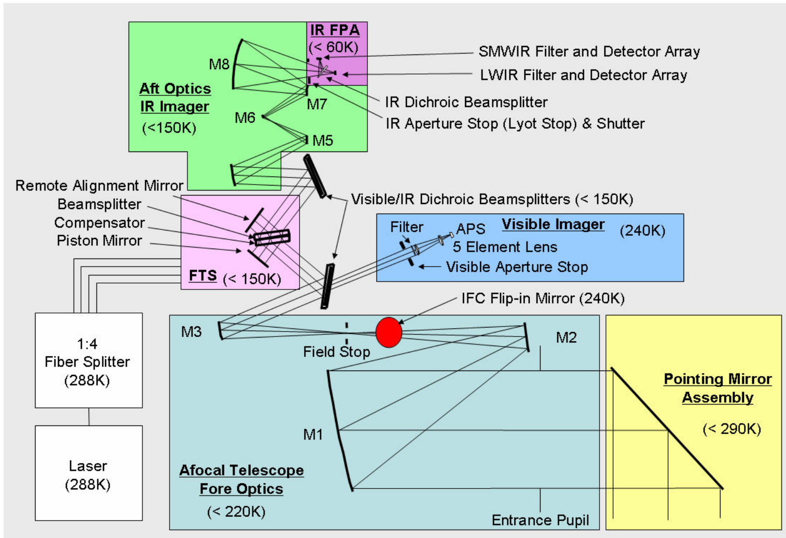


Fig. 2. A conceptual optical system ray trace for the GIFTS sensor.

3 GIFTS EDU GROUND-BASED MEASUREMENT EXPERIMENT

The primary objectives of this experiment are to assess instrumental performance, to produce measured spectral radiance data utilizing the GIFTS EDU, to retrieve atmospheric conditions from the radiance data, and to validate the GIFTS EDU data products at all stages with ancillary data collected coincidently. A secondary objective was to demonstrate the capability of monitoring atmospheric spatial and temporal variations, an important aspect of the GIFTS measurement concept. In addition, a series of events was planned to characterize the sensor system such as the presence and levels of vibration and optical jitter, and their affect on system performance and data products.

3.1 Experiment objectives and setup

A series of 8 science and engineering data collection events was carefully planned to achieve the previously defined objectives of this experiment. The events included a Cross-Check Event (CCE), a Moon Viewing Event (MVE), a Moon Tracking Event (MTE), an Atmospheric Variation Event (AVE), an Outgas Monitoring Event (OME), a Moon-tracking and Sky-viewing Event (MSE), a Vibration Test Event (VTE), and a Jitter Test Event (JTE). Each event had its own objectives that are briefly described in Table 1. For each event, also shown are dates indicating when each experiment was performed. All of these planned events were successfully performed. Quick look displays for the GIFTS EDU and two Atmospheric Emitted Radiance Interferometer (AERI) instruments provided on-site scientists and engineers real time feed back to ensure the success of the experiment.

In order to provide absolute calibration cross checks for validation of the GIFTS EDU measurements of downwelling atmospheric radiance, the University of Wisconsin's AERIbago was brought to the SDL to obtain comparative measurements with the AERI that have proven track records for the application [18,19]. Details of the complete AERIbago measurement capabilities can be found on the web http://cimss.ssec.wisc.edu/AERIbago. The AERIbago is a mobile laboratory containing a suite of meteorological instrumentation including an AERI, a Global Positioning System (GPS), a Vaisala GPS capable RS-92 rawinsonde launch capability, a Vaisala surface meteorological station, and a Vaisala ceilometer. Two AERI instruments operated simultaneously during the GIFTS EDU ground-based measurement experiment: (1) one aligned with the GIFTS EDU field of view to less than approximately 3 degrees constant offset to view the sky using the same external pointing mirror used by the GIFTS EDU, and (2) one which does not use this external pointing mirror to directly view skyward toward the zenith direction as viewed by the GIFTS EDU via the external scene mirror. The AERI has about the same field of view as the field of regard of the GIFTS EDU and can be used to account for the effects of the thermal vacuum chamber window and external scene pointing mirror on the absolute radiometric calibration of the GIFTS EDU. Figure 3 illustrates the setup of the GIFTS EDU chamber, AERIbago, AERI-05, and the external scene mirror.

Table 1. GIFTS EDU ground-base experiment events, major objectives, and data collection dates.

Event	Major Objectives	Date Performed
CCE	To compare the two sets of AERI measurements permitting a characterization of the spectral reflectance properties of the scene mirror. The external scene mirror aligned AERI-05 and GIFTS EDU measurements provide comparative data that are used to assess the spectral transmittance properties of the GIFTS EDU thermal vacuum chamber window (ZnSe) and optical path characteristics between the window and the GIFTS EDU external scene mirror.	5 Sept. 2006 6 Sept. 2006 25 Sept. 2006
MVE	To obtain high quality images of the Moon throughout GIFTS EDU spectral channels while the Moon moves across the GIFTS EDU field of regard with a spectral resolution of 9.2 cm^{-1}, and to demonstrate GIFTS imaging capability.	12 Sept. 2006
MTE	To obtain high quality images of the Moon throughout GIFTS EDU spectral channels (with a high spectral resolution of 0.57 cm^{-1}) while tracking the Moon with the GIFTS EDU field of regard, and to demonstrate GIFTS imaging capability.	11 Sept. 2006
AVE	To capture atmospheric temporal variation during dawn and/or dusk to monitor atmospheric diurnal variation when the atmospheric temperature gradient is often most obvious. The sensor performance (e.g., noise level) and capability (e.g., spectral coverage and resolution) are revealed through the temperature and moisture retrievals.	13 Sept. 2006
OME	To monitor both temporal and spatial variations of the atmosphere with the GIFTS EDU when Sulfur Hexafluoride (SF_6) gas is released in the near field.	18 Sept. 2006
MSE	To collect sky and moon data in the variable integration, variable frame mode of operation (i.e., Laser reference controlled, OPD position and interval sampling), to improve data sampling and understand how well simple integration time/offset normalization and linearity correction algorithms work for two different scenes with different spectral content and different levels in the dynamic range for reducing sampling error/noise due to vibration induced velocity variations of the interferometer scanning mirror.	13 Sept. 2006
VTE	To determine the differences in the spectral data and noise characteristics with and without known vibration sources and demonstrate that excellent performance of the interferometer is achieved under typical, but limited, vibration conditions of known levels.	18 Sept. 2006 25 Sept. 2006
JTE	To determine the optical and pointing jitter characteristics of the sensor and to demonstrate imaging capability. The objectives are to determine effects of discrete frequency jitters on the spectra and the overall affects of jitter in the spatial image at sharp edges in a stable scene.	28 Sept. 2006 29 Sept. 2006

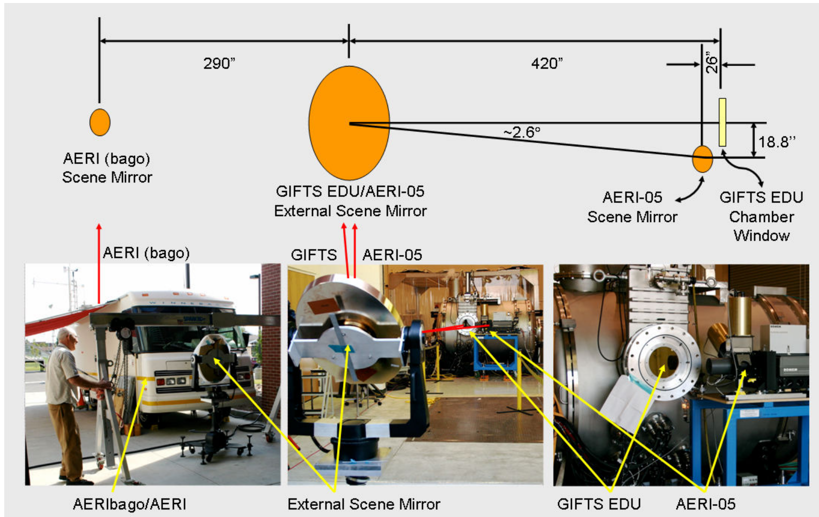


Fig. 3. GIFTS EDU ground-based measurement experiment setup (not to scale) illustrating that GIFTS EDU, AERI-05, and AERI (bago) are lined up as close as possible to measure the same atmospheric conditions.

Prior to the science data collection, the GIFTS EDU was checked out and made ready to collect quantified science data. Since this was a ground-based experiment, a Zinc Selenide (ZnSe) window was used to keep the GIFTS EDU under a space-simulated thermal vacuum condition in a chamber. This window is not needed when GIFTS is in space. Calibration data of the FTS sensor viewing through the ZnSe window were collected and analyzed prior to the science data collection events; these data are to be used to calibrate GIFTS including the window and understand the window effects on the sensor performance relevant to the science data. A very important part of the preparation was to obtain the absolute spectral radiance responsivity for each detector pixel for application to measured atmospheric spatial scenes. This was accomplished by interfacing and sealing the precision HAES, extended black body calibration sources to the window and performing measurements at several blackbody temperatures allowing comparison of HAES data to GIFTS EDU internal calibration source measurements. The comparison provides a basis for deriving spectral responsivity corrections for the internal source calibrations to account for optical path component differences between internal and external calibration sources. AERIbago facilities (including the radiosonde launch system) were checked out after arrival at the measurement site in Logan, Utah. AERI stand-alone measurements (under thin cirrus cloud conditions) coordinated with a radiosonde launch were conducted to verify the readiness of the AERIbago, the AERI-05, and the radiosonde launch systems. Both AERI radiances were compared with radiosonde-simulated radiances.

3.2 Radiometric inter-comparison

Observations with both GIFTS EDU and AERI-05 were obtained during the Cross Check Event with the atmosphere as a source similar to measurements from space. Preliminary radiometric inter-comparison between the GIFTS and AERI was made by Revercomb et al. [20]. Figure 4 shows an example of some initial results obtained from the field measurements with GIFTS LWIR band. The GIFTS observed near-zenith radiance spectrum (red) is compared to the near-zenith AERI radiance spectrum (black) as observed simultaneously on 6 September 2006. The spectra have been interpolated and performed rigorously given the Nyquist sampling inherent in FTS observations to show the detailed line shapes. This comparison is just for one of the GIFTS pixels, and is considered to be preliminary without the implementation of correction for detector/digital readout nonlinearity. The AERI provides just one 32 mrad view to zenith, while the GIFTS provides 16,384 views, each with a 0.11 mrad field of view. AERI provides a well known radiance reference with a calibration accuracy of better than 1% of ambient radiance (3-sigma) [18,19]. This initial radiometric inter-comparison and good agreement between the spectral data from GIFTS EDU and the AERI-05 sensors is clearly shown and encouraging. Similar results from the SMWIR band were also obtained [20]. The results demonstrate that the instrument, as designed and fabricated, meets the demanding radiometric and spectral measurement requirements. The spectral integrity and the excellent sensitivity at high spatial and temporal resolution of the GIFTS data are evident.

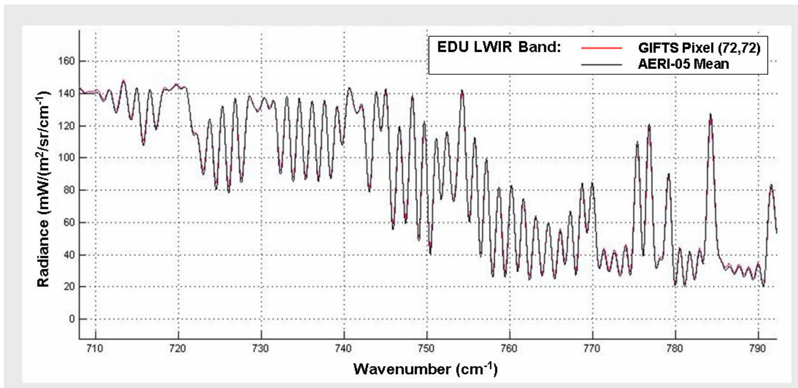
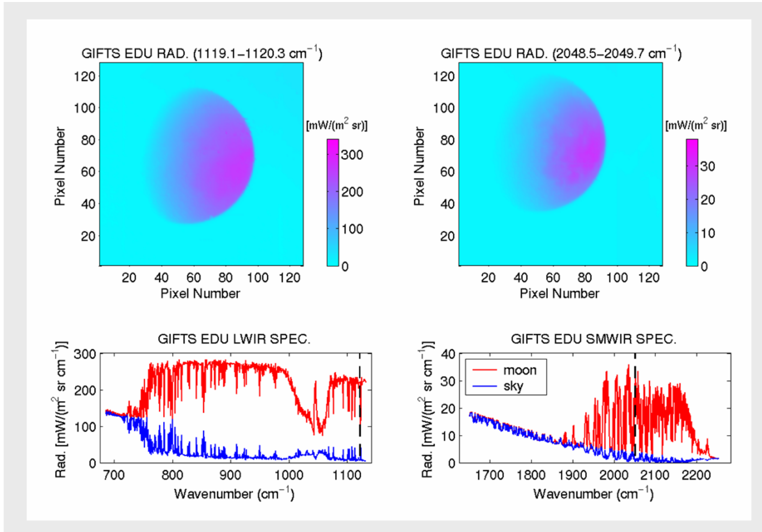


Fig. 4. Comparison of GIFTS zenith spectrum (red) to AERI-05 (black) from a Cross-Check Event on 6 September 2006 (after Revercomb et al. [20]; see text).

3.3 Spectral imaging capability

One of the fundamental advantages of the GIFTS concept is illustrated by the spectral images shown in Video 1, an example of the lunar/atmospheric images obtained with two GIFTS infrared detector arrays indicating that the lunar/atmosphere image is a function of wavenumber. Lunar and sky measurements were obtained during the GIFTS ground-based measurement experiment; the Moon Tracking Event (MTE) was conducted on 11 September 2006.

The major objective was to obtain high quality images of the moon throughout GIFTS EDU spectral channels at the highest spectral resolution of 0.57 cm^{-1} while tracking the moon so as to demonstrate the GIFTS hyperspectral resolution imaging capability (Table 1). The measurements occurred at approximately 4:52 a.m. Mountain Daylight Time (MDT), 11 September 2006, in North Logan, Utah. The radiance spectra observed by detector elements viewing the warm lunar surface (e.g., the red spectrum) are similar in spectral character to those that will be obtained by GIFTS viewing the Earth from orbit. The radiance spectra observed by detector elements viewing the cold space background (e.g., the blue spectrum) are inverted relative to those observed by GIFTS viewing the warm lunar surface background (i.e., the red spectrum). In spectral regions where the atmosphere is a very strong absorber/emitter, one sees little difference between the lunar and cold space background views. It is worthwhile to mention that the video uses only one data cube. In other words, a three-dimensional (3-d) variation (i.e., 2-d in spatial and 1-d in spectral variation) of atmosphere and lunar surface was captured with one scan (~11 seconds). The power of the GIFTS concept of hyperspectral information at each spatial location in the image is illustrated.



Video 1. Illustrations of lunar and atmospheric measurements provided by the GIFTS EDU on 11 September 2006 – a demonstration of the GIFTS imaging spectrometer measurement ability (AVI, 109 MB).

3.4 Image-tracking capability

Furthermore, GIFTS is a geostationary imaging spectrometer, providing radiance observations in four dimensions (i.e., 2-d in horizontal-spatial, 1-d in spectral variation, and 1-d in temporal variation). The revolutionary aspect of GIFTS is that it provides access to the vertical dimension of the wind field with more accurate altitude assignment than possible with current systems [1-3]. With the 4th dimension of temporal variation, the vertical profiles of wind velocity can be achieved by tracking the movement of small-scale, non-condensed moisture features retrieved with first 3-d atmospheric variations. An algorithm to derive altitude-resolved atmospheric motion vectors (AMV) is being developed and evaluated using simulated GIFTS instrument data [21]. A detailed description of this algorithm is found in Velden et al. [22]. As the GIFTS is designed for geosynchronous orbit, the field of view from the ground to monitor moisture variation is limited. To demonstrate GIFTS 4-d observation ability with the GIFTS EDU on the ground, an experiment called Outgas Monitoring Event (OME) is designed to monitor both temporal and spatial variations of the atmosphere with the GIFTS EDU when Sulfur Hexafluoride (SF_6) gas is released in the near field.

The experiment was conducted on 18 September 2006, at approximately 5:30 p.m. MDT. The SF_6 gas was released at a flow rate of 5 Liters/min from a quarter inch pipe. The GIFTS EDU was at a distance of ~70 ft from the pipe where the GIFTS field of view about 1×1 ft^2 was provided. The spectral signature of SF_6 gas emission was clearly evident as detected by both GIFTS and AERI. Figure 5 shows the spectra collected by two different GIFTS LWIR pixels at the same time (i.e., scan 7 of Video 2). The difference shows the atmospheric variation from pixel to pixel (i.e., location to location) contributed mainly by the non-uniform distribution of SF_6 emissions in the GIFTS FOV with a minor contribution from a non-uniform atmospheric thermal distribution.

During this experiment, a set of 35-consective scans with a high spectral resolution (0.57 cm^{-1}; with a scan duration of ~11 sec.), SF_6 gas was released from the top of the images shown in Video 2 during scans 6-30. The spatial, spectral, and temporal distributions of SF_6 infrared emissions were evidently captured by the GIFTS EDU demonstrating GIFTS observation concepts such as moisture traced wind measurements. Video 2 shows the spatial and temporal distribution of SF_6 infrared emissions integrated in a spectral region of 925-951 cm^{-1}.

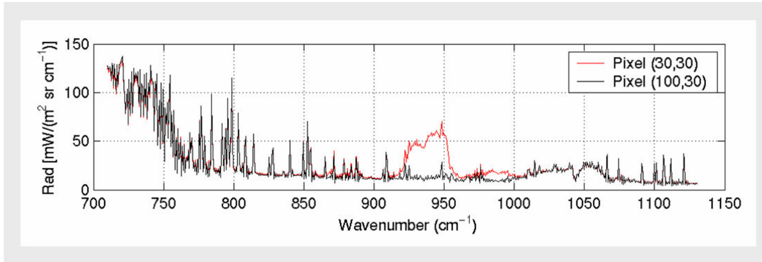
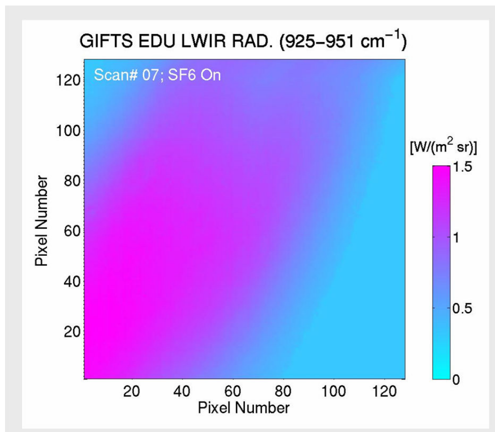


Fig. 5. Non-uniform distribution of SF_6 emissions indicated mainly in the spectral region of 900-1100 cm^{-1} was captured by the GIFTS EDU with a minor contribution from a non-uniform atmospheric thermal distribution.



Video 2. Illustrations of SF_6 outgas measurements provided by the GIFTS EDU on 18 September 2006 – a demonstration of the GIFTS image tracking ability (AVI, 5.8 MB).

4 CONCLUSION

The GIFTS new technologies have been integrated into the GIFTS EDU. The GIFTS EDU ground-based measurement experiment was carefully planned and successfully conducted. The GIFTS measurement capabilities and proof of concept were successfully demonstrated with the data collected during ground-based measurements and the thermal-vacuum performance and calibration tests. Preliminary analyses of atmospheric science data validate the GIFTS design and capability to provide science data from a space-borne system. Further data analyses will improve our understanding of the measurement characteristics of the GIFTS EDU so as to provide information needed to optimize the sensor design and allow the construction of a high-performance, low-risk, and space flight GIFTS instrument. It also provides a great risk reduction effort for any other instruments similar to GIFTS EDU.

Acknowledgments

The GIFTS EDU, built and calibrated by the Space Dynamics Laboratory of Utah State University, was a NASA New Millennium Program (NMP) sponsored instrument designed to validate the new technologies. NMP was managed by NASA's Jet Propulsion Laboratory and the GIFTS project was managed by NASA Langley Research Center. The ground-based experiment was supported by the NASA Headquarters and NASA Langley Research Center. The authors acknowledge support from NASA Headquarters Earth Science Division Deputy Director Dr. Bryant Cramer. The authors express their sincere thanks to the GIFTS team members from various organizations. The personnel who contributed to this project are too numerous to mention by name, nonetheless their personal contributions are greatly appreciated.

Reference

[1] W. L. Smith, F. W. Harrison, H. E. Revercomb, and G. E. Bingham, "Geostationary Imaging Fourier Transform Spectrometer (GIFTS) – The New Millennium Earth Observing-3 Mission," in *Current Problems in Atmospheric Radiation*, M. L. Smith, and Y. M Timofeyev, Eds., *Proc. of IRS 2000*, A Deepak Publishing, Hampton, Virginia, 81-84 (2001).

[2] W. L. Smith, Sr., H. E. Revercomb, D. K. Zhou, H. L. Huang, "Hyperspectral sounding – a revolutionary advance in atmospheric remote sensing," in Multispectral and Hyperspectral Remote Sensing Instruments and Applications II, A. M. Larar, M. Suzuki, Q. Tong, Eds., *Proc. SPIE* **5655**, 1-11, (2005) [doi:10.1117/12.578783].

[3] W. L. Smith, and co-authors, "Geosynchronous Imaging Fourier Transform Spectrometer (GIFTS): science applications," in Multispectral, Hyperspectral, and Ultraspectral Remote Sensing Technology, Techniques, and Applications, W. L. Smith, Sr., A. M. Larar, T. Aoki, R. Rattan, Eds., *Proc. SPIE* **6405**, 64050E (2006) [doi:10.1117/12.696726].

[4] A. E. Potter, Jr., "Multispectral imaging system," U.S. Patent No. 3702735, 14 November 1972.

[5] R. J. Huppi, R. B. Shipley, and E. R. Huppi, "Balloonborne Fourier spectrometer using a focal plane detector array," in Multiplex and/or high-throughput spectroscopy, J. P. Kennealy, F. P. del Greco, G. E. Caledonia, W. T. Rawlins, Eds., *Proc. SPIE* **191**, 26-32 (1979).

[6] M. P. Fetrow, and R. J. Huppi, "Experimental and modeling investigation of a 3-5 μm imaging spectrometer," in Imaging Spectrometry of the Terrestrial Environment, G. Vane, Ed., *Proc. SPIE* **1937,** 225-233 (1993) [doi:10.1117/12.157059].

[7] C. L. Bennett, M. R. Carter, D. J. Fields, "Hyperspectral imaging in the infrared using LIFTIRS," in Infrared Technology XXI, B. F. Andresen, M. Strojnik, Eds., *Proc. SPIE* **2552**, 274-283 (1995) [doi:10.1117/12.218227].

[8] R. J. Huppi, A. J. Steed, and E. R. Huppi, "Cryogenically cooled Fourier transform spectrometers," in International Conference on Fourier Transform Infrared Spectroscopy, H. S. Bellingham, Ed., *Proc. SPIE* **289,** 345-354 (1981).

[9] J. D. Elwell, and co-authors, "A Geosynchronous Imaging Fourier Transform Spectrometer (GIFTS) for Hyperspectral Atmospheric Remote Sensing: Instrument Overview & Preliminary Performance Results," in Infrared Spaceborne Remote Sensing XIV, M. Strojnik, Ed., *Proc. SPIE* **6297**, 62970S (2006) [doi:10.1117/12.684135].

[10] G. E. Bingham, and co-authors, "Geosynchronous Imaging Fourier Transform Spectrometer (GIFTS) Engineering Demonstration Unit (EDU) overview and performance summary," in Multispectral, Hyperspectral, and Ultraspectral Remote Sensing Technology, Techniques, and Applications, W. L. Smith, Sr., A. M. Larar,

T. Aoki, R. Rattan, Eds., *Proc. SPIE* **6405**, 64050F (2006) [doi:10.1117/12.696861].
[11] Wyatt, C. L., *Radiometric Calibration: Theory and Methods*, chp. 1, Academic Press, New York, 1978.
[12] GIFTS SM EDU Instrument Calibration Plan, Technical Report SDL/01-005, Space Dynamics Laboratory, 2006.
[13] SPIRIT III Ground Calibration Equipment Characterization Report, Technical Report SDL/94-073, Space Dynamics Laboratory, 1995.
[14] HAES-15 Design and Performance Report, Technical Report SDL/03-217, Draft, Space Dynamics Laboratory, 2003.
[15] G. W. Cantwell, and co-authors, "Modeled vs. actual performance of the Geosynchronous Imaging Fourier Transform Spectrometer (GIFTS)," in Infrared Spaceborne Remote Sensing XIV, M. Strojnik, Ed., *Proc. SPIE* **6297**, 62970T (2006) [doi:10.1117/12.684136].
[16] D. C. Tobin, and co-authors, "Geosynchronous Imaging Fourier Transform Spectrometer (GIFTS) thermal vacuum testing: aspects of spectral characterization," in Multispectral, Hyperspectral, and Ultraspectral Remote Sensing Technology, Techniques, and Applications, W. L. Smith, Sr., A. M. Larar, T. Aoki, R. Rattan, Eds., *Proc. SPIE* **6405**, 64050G (2006) [doi:10.1117/12.694662].
[17] J. K. Taylor, and co-authors, "The Geosynchronous Imaging Fourier Transform Spectrometer (GIFTS): Noise performance," in Multispectral, Hyperspectral, and Ultraspectral Remote Sensing Technology, Techniques, and Applications, W. L. Smith, Sr., A. M. Larar, T. Aoki, R. Rattan, Eds., *Proc. SPIE* **6405**, 64050J (2006) [doi:10.1117/12.698024].
[18] R. O. Knuteson, and co-authors, "Atmospheric Emitted Radiance Interferometer (AERI): Part I: Instrument Design," *J. Atmos. Oceanic Technol*., **21**, 1763-1776 (2004) [doi:10.1175/JTECH-1662.1].
[19] R. O. Knuteson, and co-authors, "Atmospheric Emitted Radiance Interferometer (AERI): Part II: Instrument Performance," *J. Atmos. Oceanic Technol.*, **21**, 1777-1789 (2004) [doi:10.1175/JTECH-1663.1].
[20] H. E. Revercomb, and co-authors, "GIFTS radiance validation from ground-based sky-viewing comparisons to AERI," in *Fourier Transform Spectroscopy/Hyperspectral Imaging and Sounding of the Environment on CD-ROM* (the Optical Society of America, Washington, DC, 2007), FTuA5 (2007).
[21] C. Velden, G. Dengel, R. Dengel, A. H. Huang, D. Stettner, H. Revercomb, R. Knuteson, and W. Smith, Sr., "Determination of wind vectors by tracking features on sequential moisture analyses derived from hyperspectral IR satellite soundings," preprints, *13th AMS Conf. on Satellite Meteor. And Ocean., Amer. Meteor. Soc*. (2004).
[22] C. Velden, and co-authors, "Recent innovations in deriving tropospheric winds from meteorological satellites," *Bull. Am. Meteorol. Soc.*, **86**, 205-223 (2005) [doi:10.1175/BAMS-86-2-205].

Daniel K. Zhou is a Physical Scientist at NASA Langley Research Center. He received his Ph.D. in Physics from Utah State University in 1992. His current research interests includes meteorological and trace gas profile retrieval, cloud and thermodynamic parameters simultaneous retrieval from ultraspectral infrared measurements, as well as retrieved parameter analyses and validation. Dr. Zhou has been working on numerous programs, such as CIRRIS-1A, SPIRIT III, SABER, NAST-I, AIRS, GIFTS, and IASI. Dr. Zhou has comprehensive experience in remote sensing and published numerous scientific articles. He is a member of American Geophysical Union.

William L. Smith is a Distinguished Professor at the Hampton University and Senior Scientist and Professor Emeritus at the University of Wisconsin – Madison. He is an active satellite and airborne experimentalist. He has been Principal Investigator of three highly successful Nimbus research satellite experiments and several aircraft instruments. Most notably, Dr. Smith pioneered the hyperspectral resolution sounding technique that is being used for current and future polar satellite advanced infrared sounding systems (e.g., the METOP IASI and NPP/NPOESS CrIS). Currently, Dr. Smith is the Principal Investigator of the GIFTS completed as an EDU and prototype for future geostationary satellite operational sounding sensors. Dr. Smith is also the Principal Investigator of the high altitude NAST-I, which flies aboard the NASA ER-2 and WB-57 aircraft, as well as the Northrop-Grumman Proteus aircraft.

Gail E. Bingham is the Chief Scientist of the Space Dynamics Laboratory, Utah State University in Logan, Utah. He received his Ph.D. in Micrometeorology from Cornell University in 1972. He has conducted research in atmospheric physics, remote sensing instrument development and environmental science at the U.S. Army Ballistics Research Laboratory, Laurence Livermore National Laboratory and Utah State University. In 2001, he was awarded the Utah Governor's Medal for Science and Technology. In addition to his leadership duties at SDL, he currently leads a program to assess the Emission and Dispersion of Gases and Particulates from Agricultural Operations; is the instrument Co-I for the NASA FIRST sensor; the Instrument Co-I on the GIFTS; and is the CrIS Instrument Scientist for the NPOESS IPO Algorithms Division.

Ronald J. Huppi is an adjunct Research Associate Professor in the Electrical and Computer Engineering Department at USU and a Sole Proprietor Electro-Optical Engineering and Science Consultant with specialized expertise in remote sensing instrumentation development, measurements, and analysis. Since 1967, he has designed and developed numerous IR radiometric and spectrometric sensor systems and applied them to science applications including extensive atmospheric research involving design, development, and application of very advanced FTS systems. He managed an engineering and science team at Stewart Radiance Laboratory and developed and operated the first successful rocket-borne cryogenic FTS system followed by others developed for multiple measurement platforms. He conceived and developed imaging interferometer concepts and demonstrated the technology with a balloon-borne unit in the 1970's and with an Imaging Interferometer Demonstrator unit from 1993-2004. The Demonstrator unit provided much of the basic technology and many of the concepts incorporated in the GIFTS program.

Henry E. Revercomb is the Director of the University of Wisconsin-Madison, Space Science and Engineering Center. He received his PhD in theoretical physics from the University of Wisconsin-Madison in 1972 and has conducted atmospheric studies that include radiation measurements of the earth and other planets since 1974. He has led several projects related to radiometrically accurate, high spectral resolution observations of the atmosphere, including (1) UW participation in GIFTS, (2) NASA AIRS Science Team, (3) NASA Aura validation team, (4) NASA NPP Science Team and PEATE development, (5) NPOESS CrIS OAT and IPO Government Studies, (6) Scanning HIS aircraft instrument development and use, (7) High Spectral Resolution FTS Observations for the DOE ARM Program, leading to development and use of the Atmospheric Emitted Radiance Interferometer.

Lorin J. Zollinger is a program manager with the Space Dynamics Laboratory at Utah State University. He received his BS in Electrical Engineering from Utah State University in 1971. He joined SDL in 1979 as a research engineer and has been responsible for electronic design and development, system engineering, and mission planning of the CIRRIS-1 and CIRRIS-

1A payloads. He has lead and directed several IR remote sensing programs during the past 20 years including the SPIRIT II, SPAS III, SABER, and GIFTS programs.

Allen M. Larar is a Senior Research Scientist in the Chemistry and Dynamics Branch of the Science Directorate at NASA Langley Research Center. He received his Ph.D. in Atmospheric and Space Sciences from the University of Michigan in 1993. His research interests concentrate on atmospheric radiative transfer and remote sensing of trace species, and he has had extensive involvement in most aspects regarding the development and implementation of advanced, passive remote sensors of the Earth's atmosphere. He is involved in several remote sensing programs developing or currently employing advanced Michelson and Fabry-Perot interferometer systems.

Xu Liu is a Physical Scientist at NASA Langley Research Center. He received his Ph.D. degree from University of Denver in 1989. His research activities include atmospheric remote sensing using high spectral resolution instruments from different platforms (balloon, aircraft, and satellite). His research expertise includes atmospheric and surface property retrievals, instrument trade studies, data analysis, fast forward model and inversion algorithm development. He has worked with data from AMSU, AIRS, IASI, and NAST-I instruments. He also worked extensively on algorithm development for the NPOESS CrIS instrument

Joseph J. Tansock is a senior calibration engineer with the Space Dynamics Laboratory at Utah State University where he specializes in IR sensor calibration. He received a BS in physics and applied mathematics from Weber State University in 1988 and an MS in instrumentation physics from the University of Utah in 1992. He has been with Space Dynamics Laboratory since 1991 where he has been responsible for numerous IR Sensor calibration efforts and the development of calibration equipment. He has been the CALCON conference chairperson from 2000 to 2005. Prior to 1992, Mr. Tansock was a flight equipment test and analysis engineer with Rockwell International. His research interests include IR sensor calibration, IR sensor development, data analyses and system engineering.

Robert A. Reisse: biography not available.

Ronald Hooker is a Program Executive in the Science Mission Directorate at NASA Headquarters, where he is responsible for development of Earth Science spaceflight missions. Prior to arriving at NASA in 2003, he worked extensively on geostationary weather satellite programs for NOAA. He received the BS and MS in electrical engineering from the University of Delaware and Johns Hopkins University, respectively, and is currently completing doctoral degree requirements at the George Washington University. His research interests include analytical and numerical techniques in electromagnetic scattering applied to remote sensing.