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Geosynchronous Imaging Fourier Transform Spectrometer (GIFTS) Engineering Demonstration Unit (EDU) overview and performance summary

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1. ABSTRACT

The Geosynchronous Imaging Fourier Transform Spectrometer (GIFTS), developed for the NASA New Millennium Program (NMP) Earth Observing-3 (EO-3) mission, has recently completed a series of uplooking atmospheric measurements. The GIFTS development demonstrates a series of new sensor and data processing technologies that can significantly expand geostationary meteorological observational capability. The resulting increase in forecasting accuracy and atmospheric model development utilizing this hyperspectral data is demonstrated by the uplooking data. The GIFTS sensor is an imaging FTS with programmable spectral resolution and spatial scene selection, allowing spectral resolution and area coverage to be traded in near-real time. Due to funding limitations, the GIFTS sensor module was completed as an engineering demonstration unit that can be upgraded to flight quality. This paper reviews the GIFTS system design considerations and the technology utilized to enable a nearly two order performance increase over the existing GOES sounder and shows its capability. While not designed as an operational sensor, GIFTS EDU provides a flexible and accurate testbed for the new products the hyperspectral era will bring. Efforts to find funding to upgrade and demonstrate this amazing sensor in space are continuing.

Keywords: Geosynchronous, Fourier transform spectrometer (FTS), Michelson interferometer, hyperspectral, climate

2. INTRODUCTION

Efforts to increase the spectral and spatial resolution of satellite based atmospheric sounding instruments began more than twenty-five years ago when it became obvious that the spectral resolution limitations of filter based instruments limited profile recovery accuracy and resolution. For example, the United States has launched the Advanced InfraRed Sounder (AIRS), which is providing high resolution infrared data aboard the EOS Aqua platform (<http://aqua.gsfc.nasa.gov/>), with similar capability provided for trace gases by the TES sensor (<http://aura.gsfc.nasa.gov/tes/>). Operationally, the NPOESS series satellites will carry the Crosstrack Infrared Sounder (CrIS), which will use a Michelson interferometer to provide AIRS quality data in a much smaller and less expensive package. Similar advances are being developed by other countries to replace their research and operational sensors. These sensors build on previous applications of interferometers in aircraft and space applications¹⁻⁷.

The Geosynchronous Imaging Fourier Transform Spectrometer (GIFTS), built by the Space Dynamics Laboratory of Utah State University, was a NASA New Millennium Program (NMP) sponsored instrument designed to validate the technologies required to provide at least an order of magnitude improvement in the next generation measurement capabilities from geosynchronous orbit. NMP was managed by NASA's Jet Propulsion Laboratory, and the GIFTS

project was managed by the NASA Langley Research Center (LaRC). GIFTS is a revolutionary new instrument, capable of providing from geosynchronous orbit the high spatial density temperature, moisture and trace gas profiles with the high vertical and temporal resolution typical of low Earth orbit sensors. GIFTS implements the atmospheric remote sensing desires that were explored earlier in the GHIS⁸ program, but provides the vast improvements in spatial coverage and sensitivity achievable using the parallel spatial measurement advantages of an imaging interferometer.

The GIFTS sensor was originally intended to fly on NASA's Earth Observing-3 geosynchronous satellite in a mission jointly sponsored by NASA, NOAA, the US Navy and Air Force. However, funding limitations forced the program to terminate flight qualification activities and to complete the instrument as an engineering demonstration unit (EDU). The GIFTS EDU was completed and thermal-vacuum tested and characterized using prototype electronics and some other components. This paper provides an overview of the as-built GIFTS EDU and summarizes the sensor's performance.

The GIFTS design achieves the mass and performance technology advances by combining several technologies. Large-area (128 x 128 pixel) format focal plane arrays (FPAs) enable frequent high spatial resolution coverage over large areas, while the Fourier Transform Spectrometer (FTS) provides simultaneous high spectral resolution. The imaging interferometer concept is not new. A patent on the idea was awarded to A.E Potter in 1972⁹. A fieldable system was developed by SDL and utilized to collect upper atmosphere data from balloons in the mid through late 1970s¹⁰. With the advent of large area FPAs and high capacity electronics and microprocessors, SDL expanded the concept from the 4x4 detector system used in the 1970s into the GIFTS design. Other spectral imaging systems utilizing FPA detectors have been published previously^{11, 12}.

The fundamental advantage of the GIFTS concept is demonstrated by the spectral images shown in Figure 1. During thermal-vacuum testing of the GIFTS EDU the instrument was configured to view down-welling radiance of the sky and Moon. The images in Figure 1 are all from a single data cube collected in ~11 seconds. Figure 1a shows the moon in the visible spectrum, as collected by the visible imager. Figures 1b and 1c show spectral slices at 9.2 cm⁻¹ resolution in transparent and opaque regions of the atmosphere, respectively. Figure 1d shows the full long-wave (LWIR) and short/mid-wave (SMWIR) spectrum at 0.57 cm⁻¹ resolution for two different pixels in the image, one viewing the moon, and one viewing clear sky. The test configuration for collection of the data shown in Figure 1 included a 12-meter horizontal path through warm atmosphere, which explains the detailed line structure in the opaque region of the 6.3 micron water vapor region, as well as emissions from a ZnSe window and a 45-degree turning mirror. The figure illustrates the power of the GIFTS concept: high-resolution spectral information at each spatial location in the image.

1.1. Measurement objectives

The GIFTS measurement concept can improve temperature, water vapor and trace gas sounding and IR imaging from geosynchronous orbit in several areas: faster area coverage, higher spatial and spectral resolution, with lower mass and volume. Sensing the atmosphere of the Earth disk at high spatial resolution requires a high data collection rate. An advantage of the GIFTS Michelson interferometer is the ability to trade off spectral resolution for coverage area to support varying requirements, as summarized in Table 1. GIFTS resolution can be programmed on a scan by scan basis in powers of 2.

Table 1. Example GIFTS spectral resolutions and their associated area coverage rates.

Mode	Resolution		Coverage	
	Spectral	OPD	Area	Time*
Collection Modes	0.57-36 cm ⁻¹	0.014-0.872 cm	512 km sq.	1 to 11 sec
Regional Imaging	36 cm ⁻¹	0.014 cm	6,000 km sq.	3 min
Global Sounding	18 cm ⁻¹	0.027 cm	10,000 km sq.	7 min
Regional Sounding & Chemistry	0.57 cm ⁻¹	0.872 cm	6,000 km sq.	25 min
Self Validation**	0.57 cm ⁻¹	0.872 cm	10,000 km sq.	60 min
*Assumes a constant data rate associated with a Michelson mirror scan velocity of 0.17 cm/sec and 1-second telescope pointing step time.				
**Provides radiometric precision better than 0.1K over all wavelengths				

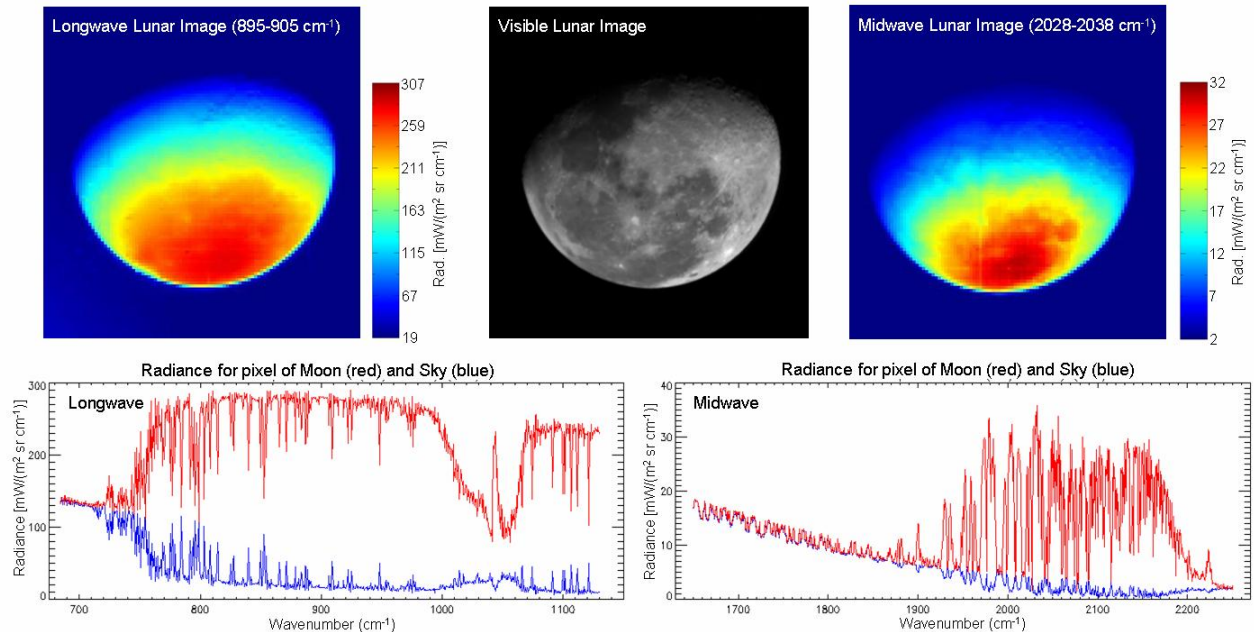


Fig. 1. Results from a single interferometer scan of the moon, viewed in the visible, mid-wave IR, and long-wave IR. Also the spectral intensities of two selected pixels from the IR images, one viewing the moon, the other the clear sky background.

1.2. GIFTS wind profile measurement concept

In addition to providing state-of-the-science temperature, water vapor, and trace gas soundings, GIFTS was designed to allow further processing of the data to provide wind profiles. It has been demonstrated by model simulation and aircraft based instruments⁷ that clear air vertical profiles of wind velocity can be achieved by tracking the movement of small-scale, non-condensed moisture features observed as a function of altitude. This measurement cannot be made by low Earth orbit observational satellites. Viewing from a geosynchronous satellite, the instrument can repeatedly sample regions of convective instability to develop fine scale image motion displacements and derive the wind profile. GIFTS's high spectral and spatial resolution capability supports this goal. The high spectral resolution (0.57 cm^{-1}) measurement mode provides infrared radiance over a large area ($512 \times 512 \text{ km}$) of the Earth at 11-second intervals. A visible-band camera is included in the system to provide cloud images at 1-km spatial resolution for each IR view. Extended Earth coverage is achieved by stepping the instrument FOV across the desired area of the Earth. The radiance measured at each time step are transformed to high vertical resolution (1-2 km) temperature and water vapor mixing ratio profiles using profile retrieval algorithms similar to those proven by AIRS. These profiles are obtained on a 4-km grid and then converted to relative humidity profiles to track moisture movement. Details of the GIFTS mission concept are provided by Smith⁸.

2. GIFTS EDU PRELIMINARY PERFORMANCE RESULTS

As of May 2006, data collection for characterization and calibration of the GIFTS EDU has just been completed. Approximately 30 TBytes of calibration data were collected, using a large number of source configurations. Data were collected to characterize parameters such as offsets, linearity, spectral radiance responsivity (SRR), instrument line shape and position, point response functions, distortion, noise equivalent spectral radiance (NESR), and medium- and long-term repeatabilities. Analysis of this large volume of data is just beginning, with the detailed results expected to be provided over the next several months.

2.1. Preliminary performance results vs. requirements

Quick-look analysis during calibration data collection, as well as analysis of data collected during earlier engineering tests, is very promising. Table 2 summarizes the principal requirements of the GIFTS EDU, as well as the current state of knowledge of the instrument performance.

Table 2. Summary of GIFTS EDU requirements and expected performance.

Parameter	GIFTS EDU Requirement Synopsis	GIFTS EDU Goal Synopsis*	Expected Values & Notes
LWIR NESR	<0.4 mW/(m ² ·sr·cm ⁻¹) for wavenumbers >700 cm ⁻¹ ; 1.2 cm ⁻¹ resolution; scenes <276 K, 2x2 pixel	<0.4 mW/(m ² ·sr·cm ⁻¹) for wavenumbers >700 cm ⁻¹ , 0.57 cm ⁻¹ resolution scenes < 276 K; single pixel	Meets requirement Meets goal over most of spectral range
SMWIR NESR	<0.06 mW/(m ² ·sr·cm ⁻¹) for 1.2 cm ⁻¹ resolution, scenes <260 K, 2x2 pixel	<0.06 mW/(m ² ·sr·cm ⁻¹) for 0.57 cm ⁻¹ resolution, scenes <260 K; single pixel	Meets requirement Meets goal over most of spectral range
LWIR Dynamic Range	197K to 309K		Meets requirement
SMWIR Dynamic Range	204K to 286K		Meets requirement
LWIR Operability	>50%	>75%	>95%, meets goal
SMWIR Operability	>60%	>85%	>95%, meets goal
Ensquared energy at 11 μm	>0.55	>0.67	Meets requirement
LWIR Calibration error	<1K (3σ) for scenes between 197K and 309K		Expect to meet requirement; analysis in progress
SMWIR Calibration Error	<1K (3σ) for scenes between 204K to 286K		Expect to meet requirement; analysis in progress
LWIR Calibration Reproducibility	<0.4K (3σ) over 24 hours for scenes >190K	<0.2K (3σ) over 24 hours for scenes >190K	Expect to meet requirement; analysis in progress
SMWIR Calibration Reproducibility	<0.4K (3σ) over 24 hours for scenes >240K	<0.2K (3σ) over 24 hours for scenes >240K	Expect to meet requirement; analysis in progress
Line position uncertainty	<10 ppm (3σ)	<5 ppm (3σ)	Expect to meet goal; analysis in progress
Line position stability	<2 ppm (3σ) over 1 hour	<1 ppm (3σ) over 1 hour	Expect to meet goal; analysis in progress

*In most cases the GIFTS EDU goals are equivalent to the flight GIFTS requirements

Pixels with nominal responsivities and noise from each FPA were selected for the SRR and NESR comparisons. Fig. 2 shows histograms of the integrated responsivity and noise for each FPA and the pixels selected for the comparisons. Pixels are indexed using the convention (*column, row*) where pixel (0,0) is in the upper left corner of the FPA.

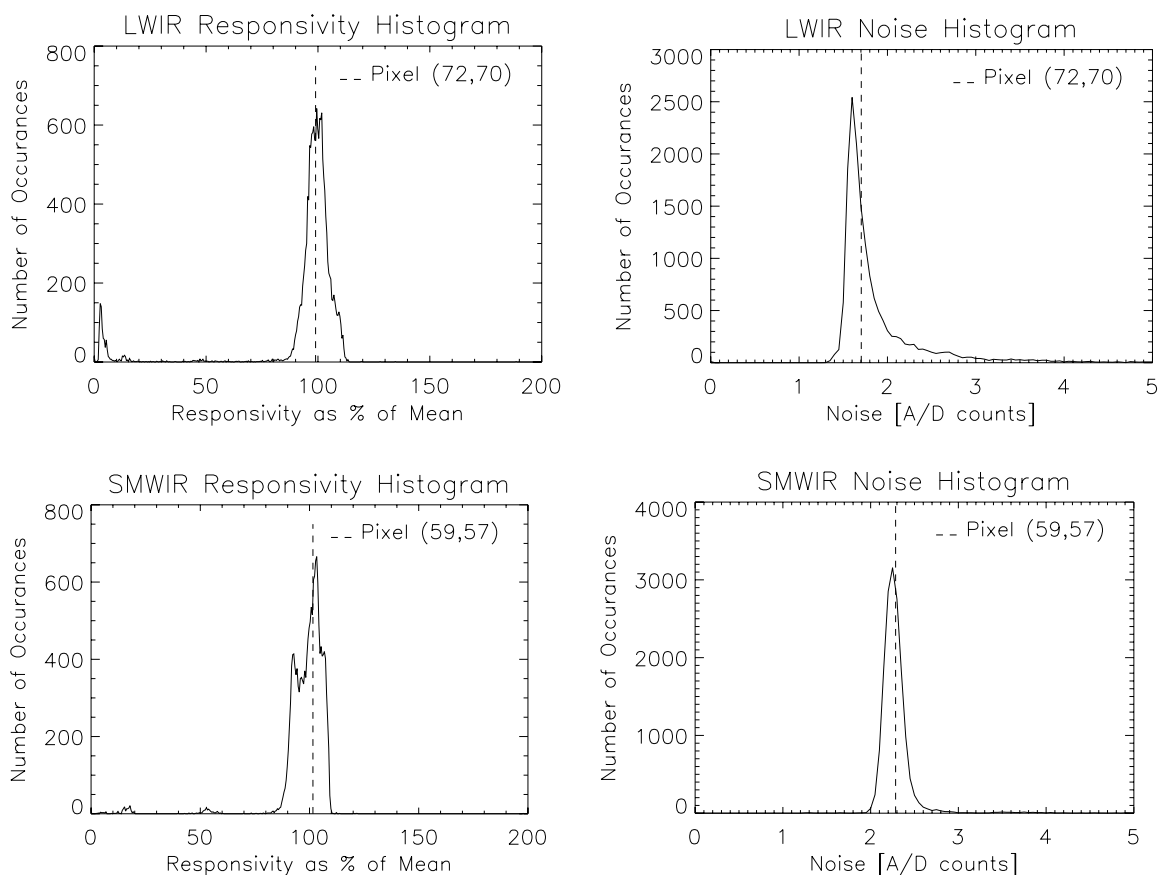


Fig. 2. Histograms of the GIFTS EDU integrated responsivity and noise from the LWIR and SMWIR FPAs. Pixel (72,70) from the LWIR FPA and pixel (59,57) from the SMWIR FPA, which were used for SRR and NESR comparisons, are shown to be nominal pixels in both responsivity and noise.

Fig. 3 compares the modeled and measured NESR, which is a measure of the spectral radiance uncertainty associated with a single GIFTS measurement. The measured NESR estimates were calculated as follows. The spectral standard deviation of several individual phase corrected spectra was computed as an estimate of the spectral noise associated with a single measurement. The spectral noise estimates for the LWIR and SMWIR bands were computed from spectra taken while viewing the HAES-15 at source temperatures of 276 K and 260 K, respectively, because these are the temperatures at which the GIFTS EDU NESR requirements are specified. The spectral noise estimate was then converted to radiance units by dividing it by the SRR. The modeled NESR was generated by computing modeled interferograms, including noise, using Planck functions at the specified source temperatures as model inputs. The modeled interferograms were then processed with identical processing steps used to compute the measured NESR. The NESRs shown in Fig. 3 were smoothed by a moving average function approximately 20 cm^{-1} wide.

Fig. 3 shows excellent agreement between the modeled and actual NESR results. The GIFTS EDU NESR requirements and objectives are also shown in Fig. 3. The measured NESR is well below the EDU requirement for both bands and near the EDU objective for the entire SMWIR band and most of the LWIR band. The EDU NESR objective is the original flight specification. As shown in Fig. 3, the GIFTS EDU has already demonstrated NESR levels that are at or near the levels required for a flight unit to provide the radiometric uncertainty required for atmospheric sounding. We are confident that from the experience gained with the GIFTS EDU, improvements can be made that will result in even better NESR performance for a flight instrument.

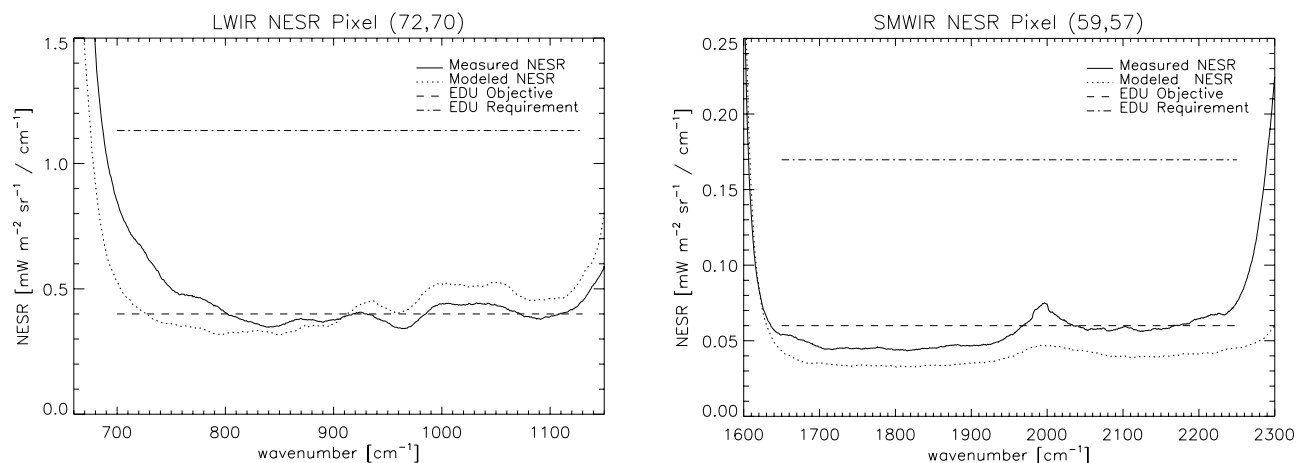


Fig. 3. Comparison of GIFTS EDU measured and modeled NESR for nominal pixels from the LWIR and SMWIR FPAs.

Fig. 4 shows the modeled and preliminary measured instrument line shape (ILS). A CO₂ laser was used to produce the data for the measured ILS. To calculate the measured ILS several interferograms from an LWIR pixel were zero padded by a factor of 32 prior to Fourier transformation and the spectral average of the individual phase corrected spectra was computed. The spectrum was then peak normalized. No wavenumber scale correction was applied. To compute the modeled ILS, interferograms were generated using the sensor response model with an input spectrum consisting of a single spectral line calculated such that the modeled and measured lines are in the same position. The simulated interferograms were processed with the same processing steps used to compute the measured ILS. In this case the measured and modeled results are nearly identical.

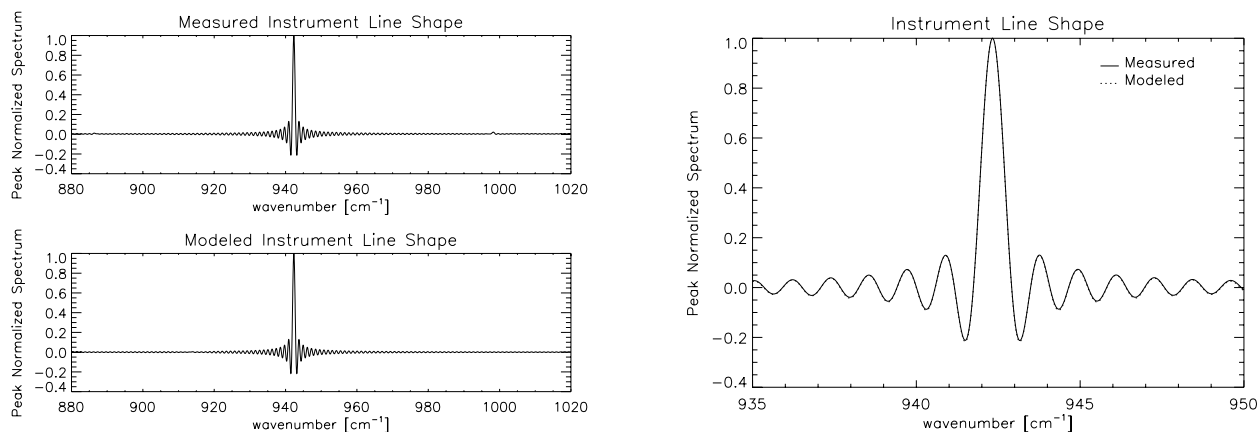


Fig. 4. Comparison of GIFTS EDU measured and modeled instrument line shapes.

Fig. 5 shows actual and modeled apparent spectral line shifts across the SMWIR FPA. In an imaging FTS there is an apparent shift in the position of a spectral line across the FPA that is caused by beams traveling through the interferometer at different angles. Once the apparent shifts have been measured, correction can take place for the spectral line positions. The actual line shifts across the FPA were calculated by analysis from measurements taken in the four corners and center of the FPA. The modeled line shifts were calculated by simulating GIFTS interferograms for an input spectrum consisting of a single spectral line and computing the ratio of the apparent to the true position of the spectral line for each pixel in the FPA. The actual results are in excellent agreement with the predicted results. The actual center of the interferometer is approximately 6.2 pixels above the center of the SMWIR FPA. Finally, the natural variation of the spectral scale over the detector array has been verified using preliminary views of the sky that provided a source with spectral line structure to fill the GIFTS EDU field of regard (FOR). It is expected that the spectral scale spacing is proportional to the cosine of the mean angle that the beam to each pixel passes through the interferometer. This variation

for GIFTS EDU has little effect on the ILS (<0.05 K effects if uncorrected) and is effectively accounted for by spectral calibration. However, verifying this behavior is a good test of the imaging FTS optics and geometry. The measured and modeled variations over the detector array shown in Fig. 5 differ only by fractions of a pixel and offer good verification of expected behavior. Small residual differences are accounted for by the spectral calibration performed for each pixel.

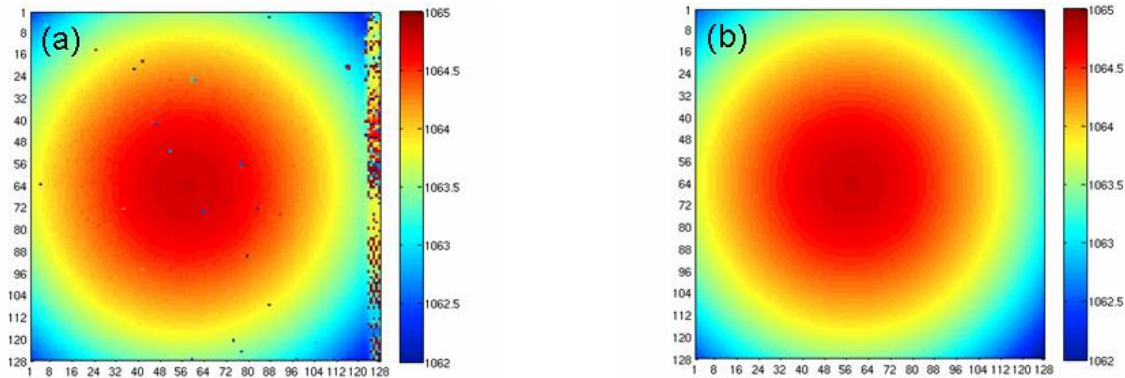


Fig. 5. The measured and modeled variations over the detector array differ only by fractions of a pixel. Effective metrology laser wavelength in nm deduced from spectral line positions in 2 May 2006 sky viewing spectra compared to a simple model expectation. The agreement is excellent.

2.2. Absolute Radiometric and Spectral Calibration

The absolute radiometric calibration of GIFTS is established on orbit based on observations of two reference blackbody sources and space^{13, 14}. Unlike the normal practice of providing a large external blackbody, the GIFTS approach uses two very high emissivity and nearly isothermal blackbodies inside the telescope optical train. The calibration references are viewed using a small flip-in mirror that images the instrument pupil in the blackbodies. The un-calibrated transmission of the telescope optics in front of the blackbodies and of the flip-in mirror are measured before launch and it has been shown that on-orbit transmission changes can be tracked. The potential disadvantage of not directly calibrating the whole instrument with two reference sources is overcome by being able to make the source uncertainties extremely small. The performance of the GIFTS EDU blackbodies exceeded the tight design requirements as shown in the table included in

Fig. 6.

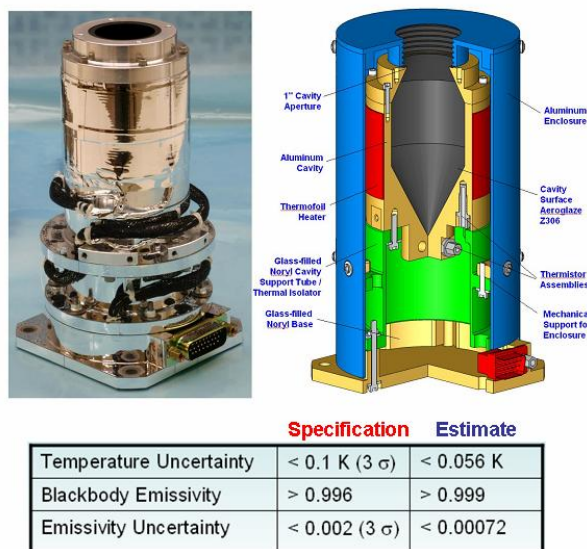


Fig. 6. GIFTS onboard reference sources are high emissivity (>0.999) cavity blackbodies with very low temperature and emissivity uncertainty (< 0.056 K, <0.00072 emissivity, 3-sigma).

The expected 3-sigma absolute calibration uncertainty for GIFTS as a function of scene temperature that results from the use of these blackbody references and space views is shown in Fig. 7. The GIFTS is expected to outperform the calibration possible from using an external source with larger emissivity and temperature uncertainty. These estimates do not include contributions from non-linearity that need further analyses for accurate definition.

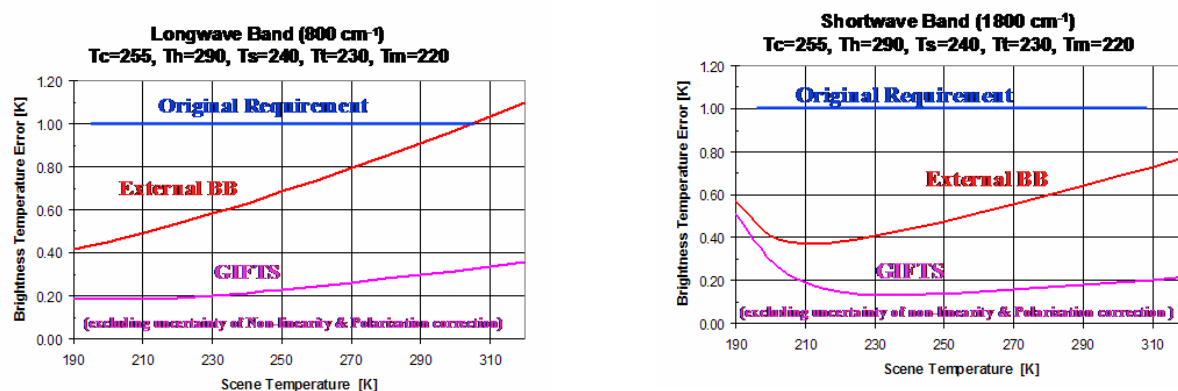


Fig. 7. Absolute calibration uncertainty (3-sigma) estimates for GIFTS as a function of scene brightness temperature.

The spectral calibration of GIFTS is especially sound. Because the atmosphere itself provides an excellent reference, realizing a highly accurate calibration depends on making the instrument stable over reasonable intervals during which it is practical to establish the spectral calibration from atmospheric spectra. For the GIFTS FTS approach, this can be accomplished by just stabilizing the metrology laser. Thermal stabilization of the whole spectrometer, as is necessary with a grating approach, is not necessary. Fortunately, the GIFTS has been able to incorporate a very spectrally stable and long-lived metrology laser.

The GIFTS 1.064 μm diode laser was provided by Tesat in Germany. It is stable to better than ± 50 MHz over 24 hours, which translates to better than ± 0.2 ppm over 24 hours. This should allow a highly accurate spectral calibration to be realized over the full mission of GIFTS (its reliability is quoted as 0.97 over 7 years).

Sky viewing validation with of the GIFTS EDU vs. UW-SSEC AERI

The GIFTS EDU was successfully validated by a parallel data collection from looking outside of its test chamber to view real world targets. One of the key tests was to view the zenith sky through a large 45-degree mirror located outside the building for radiance validation. Viewed from below, the atmospheric spectral line structure is very similar to that seen when viewing downward from space^{15, 16}.

The configuration for the uplooking GIFTS-AERI comparison is shown in Fig. 8. The GIFTS EDU is located inside the T/V test chamber, viewing out horizontally through the chamber ZnSe window to the mirror. The high emissivity reference Blackbody used for EDU calibration testing (HAES 15) was used to calibrate the full system, including the chamber window. Measurements of the atmospheric state were also made to provide the basis for calculating the expected radiance spectrum. These measurements include radiosonde, ceilometer, and surface based temperature, water vapor, and wind.

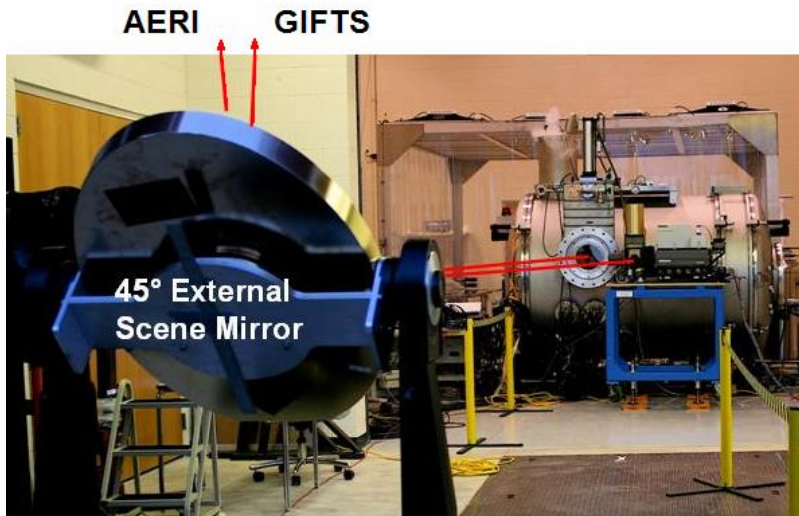
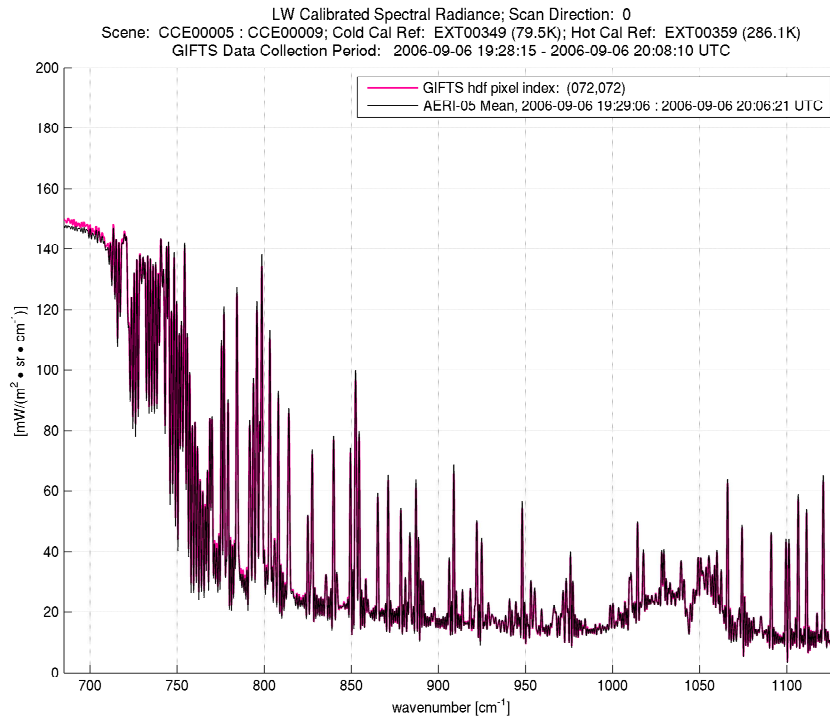


Fig. 8. Configuration for GIFTS EDU sky viewing test, showing the GIFTS thermal-vacuum chamber in the background, an AERI placed just in front of the chamber (sitting on cart visible as a blue rectangle), and the line of sight for each (red lines) shown reflecting off the 45-degree mirror in the foreground that provides a view to zenith. In this view the AERI is to the right of GIFTS. They both have their FOV centered on the mirror. Looking up from the mirror, the AERI is looking to the left of GIFTS.

As a radiance reference, an Atmospheric Emitted Radiance Interferometer (AERI)^{17, 18} was located very close to the GIFTS chamber window with a view to zenith through the same 45-degree mirror (AERI and GIFTS each viewed about 1.5° off zenith). The AERI provides just one 32 mrad view to zenith, while the GIFTS provides about 16,000 views, each with a 0.11 mrad field of view. The AERI provides a well known reference with a calibration accuracy of better than 1% of ambient radiance (3-sigma). AERI instruments were developed by the UW-SSEC for the DOE Atmospheric Radiation Measurement (ARM) Program and have been providing data to the ARM science team for over a decade.

Examples of the comparison of GIFTS EDU calibrated spectra to AERI spectra are shown in Figures 8-9. The spectra have been interpolated to a common wavenumber scale and resolution to show the detailed line shapes, a process that can be performed rigorously given the Nyquist sampling inherent in FTS observations. These comparisons are preliminary, but are very encouraging. Even without implementing a correction for non-linearity the spectral integrity of the data is very evident.

(a) Longwave band



(b) Midwave band

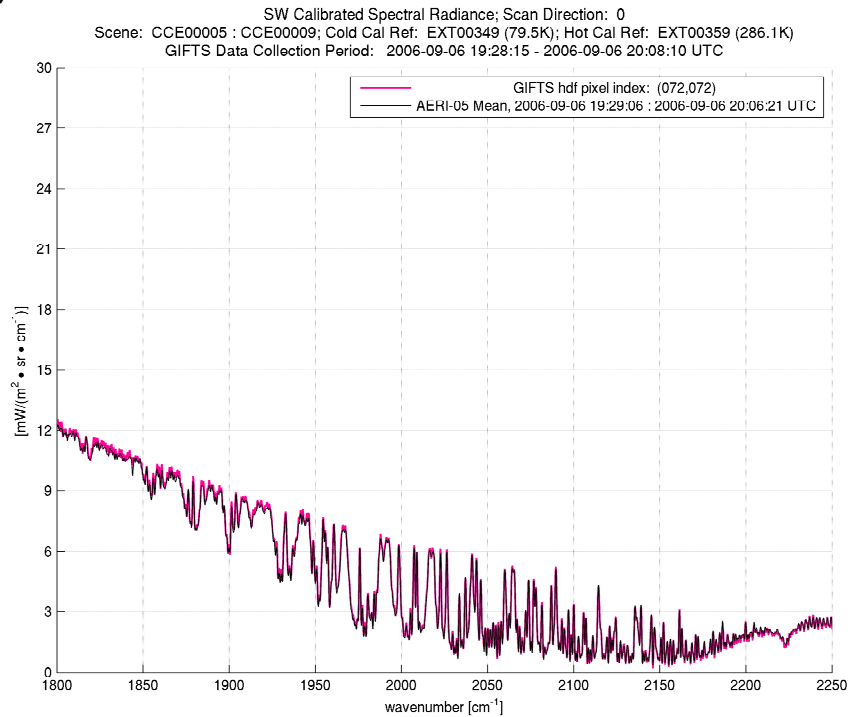


Fig. 9. Comparison of GIFTS LW band zenith spectrum (red) to AERI spectrum (black) from data collected on 6 September 2006. This comparison is for just one of the GIFTS pixels, and does not yet include the linearity correction.

The GIFTS proof of concept is being successfully demonstrated with collection of data from the ground-based measurements and the thermal-vacuum performance and calibration tests. Extensive and detailed data analyses are ongoing. Full analysis of the collected data provides the necessary information to refine the design of the sensor system and allow construction of a high-performance, low-risk flight instrument in the near future.

3. CONCLUSION

The GIFTS instrument combines new sensor and data processing technologies to demonstrate the capability to collect the geophysical measurements that contribute to revolutionary improvements in meteorological observations and forecasting. The GIFTS measurement concept uses two large-area format focal plane detector arrays in an FTS mounted on a geosynchronous satellite. The GIFTS sensor provides the simultaneous gathering of high spectral resolution (0.57 cm^{-1}) and high spatial resolution ($4 \times 4 \text{ km}$ geometric footprint) Earth infrared radiance over a large area ($512 \times 512 \text{ km}$) of the Earth within an 11-second time interval. A visible camera provides imaging of clouds at a $1 \times 1 \text{ km}$ geometric footprint. Extended Earth coverage is achieved by step-scanning the instrument field of view across any desired portion of the visible Earth.

The radiance observed from geosynchronous altitude at each time step can be transformed to high vertical resolution (1-2 km) temperature and water vapor mixing ratio profiles using rapid profile retrieval algorithms. Images of the horizontal distribution of relative humidity for atmospheric levels vertically separated by approximately 2 km can then be constructed for each spatial scan. Successive images of clouds and the relative humidity variations for each atmospheric level can be animated to reveal the motion of small-scale thermodynamic features of the atmosphere. The net result of such data would be a dense grid of temperature, moisture, and wind profiles that can be used for atmospheric analyses and operational weather prediction. Feature tracking can be performed for mixing ratio profiles of O_3 and CO , providing a direct measure of the transport of these pollutant and greenhouse gases. The unique combination of the FTS, the large area format detector array (i.e., an imaging interferometer) and the geosynchronous satellite observation platform enable the revolutionary tracer wind profiles and trace gas transport remote sensing measurements required for our next generation forecast model inputs.

The GIFTS EDU effort has successfully brought together a number of advanced technologies to create a functional and reliable sensor. The successful completion of the GIFTS EDU characterization and calibration phase has provided solid evidence that the imaging FTS approach can meet the requirements needed for meteorological observational capability and forecasting accuracy using atmospheric imaging and hyperspectral sounding methods. The capability of the GIFTS system to accurately determine atmospheric spectral emission simultaneously for large blocks of the atmosphere has been demonstrated by comparison with the UW-AERI system. By collecting a full suite of 16,384 IFOVs in parallel, the GIFTS approach can rapidly measure the visible globe.

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