

## Appendix 1: Hyper-spectral Atmospheric Sounding

### Hyper-spectral Atmospheric Sounding

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#### ABSTRACT

**Abstract.** The Geosynchronous Imaging Fourier Transform Spectrometer (GIFTS) is the first hyper-spectral remote sounding system to be orbited aboard a geosynchronous satellite. The GIFTS is designed to obtain revolutionary observations of the four dimensional atmospheric temperature, moisture, and wind structure as well as the distribution of the atmospheric trace gases, CO and O<sub>3</sub>. Although GIFTS will not be orbited until 2006-2008, a glimpse at its measurement capabilities has been obtained by analyzing data from the National Polar-orbiting Operational Environmental Satellite System (NPOESS) Airborne Sounder Test-bed- Interferometer (NAST-I) and Aqua satellite Atmospheric Infrared Sounder (AIRS). In this paper we review the GIFTS experiment and empirically assess measurement expectations based on meteorological profiles retrieved from the NAST aircraft and Aqua satellite AIRS spectral radiances.

#### 1. INTRODUCTION

**Background:** The Geosynchronous Imaging Fourier Transform Spectrometer (GIFTS) was selected for NASA's New Millennium Program (NMP) Earth Observing-3 (EO-3) mission. The GIFTS combines new and emerging sensor and data processing technologies to make geophysical measurements that will contribute to earth science, as well as lead to revolutionary improvements in meteorological observations and forecasting. This mission will validate the GIFTS measurement concept for altitude-resolved "water vapor winds" and demonstrate revolutionary technologies for future research and operational systems. The infusion of GIFTS technologies into operational instrumentation is critical for optimizing the next generation geostationary weather and climate observing system.

The GIFTS program is made possible by a NASA, NOAA, and Department of Defense partnership to share costs for instrument development, launch services, validation of sensor capability, and ground data reception and processing of the sounding data. The current plan is to complete the GIFTS instrument in late 2005 to support a 2006 to 2008 launch opportunity. The GIFTS satellite and its associated launch date

remain to be finalized. The first 12 months of operation will be conducted by NASA to satisfy the technology and measurement concept validation phase of the NMP EO-3 mission. During this time period, NOAA will also conduct, in near real-time, a demonstration of operational forecast utility of the GIFTS data. This first year period of operation is important for supporting the infusion of GIFTS technology and data processing techniques into the future operational GOES-R system. After the validation and demonstration phase, the GIFTS operation will be transferred to a geographical position dictated by the satellite provider for another 5-7 years of routine operation. The intent is to use the GIFTS data for Earth Observing System (EOS) scientific research and operational weather forecasting.

## **2. Instrument and Measurement Concept**

The GIFTS uses large area format focal plane array (LFPA) infrared (IR) detectors ( $128 \times 128$ ) in a Fourier Transform Spectrometer (FTS) mounted on a geosynchronous satellite to gather high-spectral resolution ( $0.6 \text{ cm}^{-1}$ ) and high-spatial resolution (4-km footprint) Earth infrared radiance spectra over a large geographical area ( $512\text{-km} \times 512\text{-km}$ ) of the Earth within a 10-second time interval. A low light level visible camera provides quasi-continuous imaging of clouds and surface at 1-km footprint spatial resolution. Extended Earth coverage is achieved by step scanning the instrument field of view in a contiguous fashion across any desired portion of the visible Earth. The radiance spectra observed at each time step are transformed to high vertical resolution (1-2 km) temperature and water vapor mixing ratio profiles using rapid profile retrieval algorithms. These profiles are obtained on a 4-km grid and then converted to relative humidity profiles. Images of the horizontal distribution of relative humidity for atmospheric levels, vertically separated by approximately 2 km, will be constructed for each spatial scan. The sampling period will range from minutes to an hour, depending upon spectral resolution and area coverage selected for the measurement. Successive images of clouds and the relative humidity for each atmospheric level are then animated to reveal the motion of small-scale thermodynamic features of the atmosphere, providing a measure of the wind velocity distribution as a function of altitude. The net result is a dense grid of temperature, moisture, and wind profiles which can be used for atmospheric analyses and operational weather prediction.  $\text{O}_3$  and  $\text{CO}$  features observed in their spectral radiance signatures provide a measure of the transport of these pollutant and greenhouse gases. It is the unique combination of the Fourier transform spectrometer and

the large area format detector array (i.e., an imaging interferometer), and the geosynchronous satellite platform, that enables the revolutionary wind profile and trace gas transport remote sensing measurements. The imaging FTS produces the interferometric patterns for spectral separation of scene radiation reaching the detector arrays. To limit the background signal, the FTS is cooled by the first stage of a cryocooler to <150 K, while the detector arrays are cooled to <60K to maximize sensitivity. The high data rates generated by the focal plane arrays (FPAs) are reduced by loss-less data compression techniques and then passed to the telemetry system by low-power, low-volume, and next-generation electronic components. GIFTS will view areas of the Earth with a linear dimension of about 500-km, anywhere on the visible disk, for a period between 0.125 and 11.0 sec, depending on the data application (i.e., imaging or sounding). GIFTS uses two detector arrays within a Michelson interferometer to cover the spectral bands, 685 to 1130  $\text{cm}^{-1}$  and 1650 to 2250  $\text{cm}^{-1}$ , and achieve a wide range of spectral resolutions. These spectral characteristics are optimized to achieve all technological/scientific validation objectives of GIFTS, as well as the sounding accuracy desired for a future operational sounding system. The Michelson interferometer, or FTS, approach for geosynchronous satellite applications allows spectral resolution to be easily traded for greater area coverage or higher temporal resolution. The 4-km footprint size of the IR LFPAs enable sounding to the ground, under most broken-to-scattered cloud situations, and resolving small scale atmospheric water vapor and cloud features required for wind profiling.

### **3. AIRS and NAST-I**

*AIRS.* The AIRS instrument is the first spaceborne spectrometer designed to meet the 1-K/1-km sounding accuracy objective by measuring the infrared spectrum quasi-continuously from 3.7 to 15.4 microns with high spectral resolution ( $\nu/\delta\nu = 1200/1$ ). The sensitivity requirements, expressed as Noise Equivalent Differential Temperature (NEdT), referred to a 250-K target-temperature ranges, from 0.1 K in the 4.2- $\mu\text{m}$  lower tropospheric sounding wavelengths to 0.5 K in the 15- $\mu\text{m}$  upper tropospheric and stratospheric sounding spectral region. Table 1, below, summarizes the AIRS measurement characteristics. The AIRS Instrument provides spectral coverage in the 3.74  $\mu\text{m}$  to 4.61  $\mu\text{m}$ , 6.20  $\mu\text{m}$  to 8.22  $\mu\text{m}$ , and 8.8  $\mu\text{m}$  to 15.4  $\mu\text{m}$  infrared wavebands at a nominal spectral resolution of  $\nu/\delta\nu = 1200$ , with 2378 IR spectral samples and four visible/near-infrared (VIS/NIR) channels between 0.41 and 0.94 microns. Spatial

coverage and views of cold space and hot calibration targets are provided by a 360-degree rotation of the scan mirror every 2.67 seconds

Table 1. AIRS Measurement Characteristics

Data Rate	1.27 Mbits per second
Spectral Range	IR: 3.74 – 15.4 microns VIS/NIR: 0.4 – 1.1 microns
Instrument Field of View	IR: 1.1 degree (13.5 km at nadir from 705 km altitude) VIS/NIR: 0.2 degree (2.3 km from 705 km altitude)
Swath Width	99 degree (1650 km from 705 km orbit altitude)
Scan Sampling	IR: 90 x 1 x 1.1 degree VIS/NIR: 720 x 8 x 0.2 degree

*NAST-I*. The National Polar-orbiting Operational Environmental Satellite System (NPOESS) Airborne Sounding Testbed-Interferometer (NAST-I) was developed by the NPOESS Integrated Program Office (IPO) to be flown on high altitude aircraft and provide experimental observations especially needed for finalizing specifications and testing proposed designs and data processing algorithms for the Cross-track Infrared Sounder (CrIS) which will fly on NPOESS. As shown in Figure 1, the NAST-I has a spectral range of 3.6–16.1  $\mu\text{m}$ , without gaps, and covers the spectral ranges and resolutions of all current and planned advanced high spectral resolution infrared spectrometers to fly on polar orbiting and geostationary weather satellites, including the EOS-AIRS, METOP-IASI (Infrared Atmospheric Sounding Interferometer), the NPP (NPOESS Preparatory Project)/NPOESS-CrIS (Cross-track Infrared Sounder), and the EO-3/GIFTS. The NAST-I spectral resolution is equal to, in the case of IASI, or higher than all current and planned advanced sounding instruments. Thus, the NAST-I data can be used to simulate the radiometric observations to be achieved from these advanced sounding instruments. Moreover, the forward radiative transfer models and product retrieval algorithms planned for these satellite systems can be validated prior to launch. Finally, NAST-I can be used for the fundamental purpose of post-launch calibration and validation of sensors and data products for the advanced satellite sounding systems. The NAST-I spatially scans the Earth and atmosphere from an aircraft, such as the high-altitude NASA ER-2 research airplane or the Northrop-Grumman Proteus aircraft. From an aircraft altitude of 20 km, 2.6 km spatial resolution is achieved, thereby providing three-dimensional hyperspectral images of radiance and derived geophysical products.

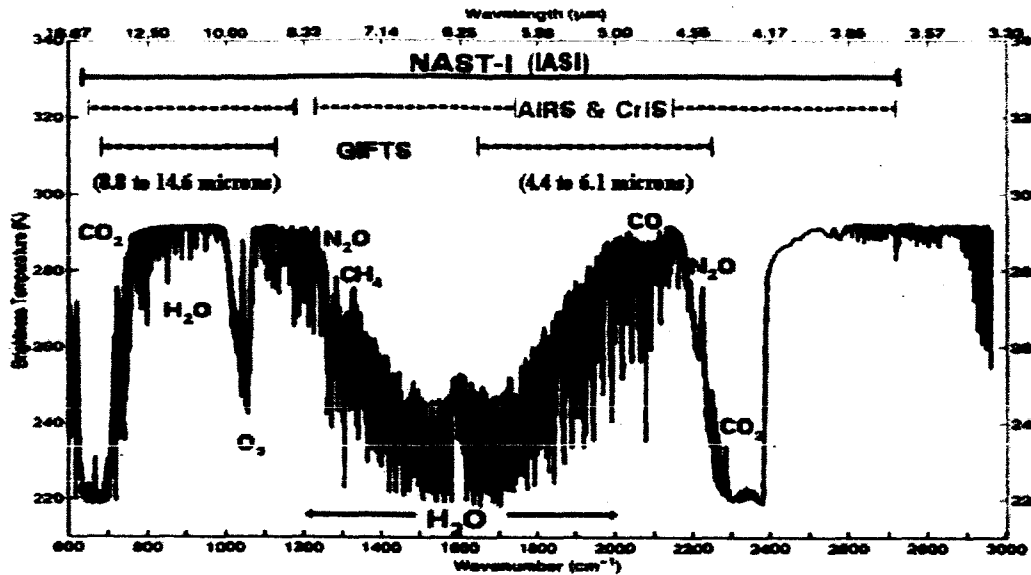


Figure 1. The NAST-I spectral coverage compared to that of advanced satellite sounders.

NAST-I provides a vertical resolution of 1–2 kilometers for atmospheric temperature and water vapor, so that distinct number of layers observed depends upon aircraft altitude. As the aircraft passes over the Earth, NAST-I scans an area at the Earth's surface collecting data on the properties of the Earth's surface and atmosphere beneath the aircraft. These data provide a wide variety of surface and atmospheric sounding and cloud products in support of scientific studies as well as provide a means to validate radiative transfer models and inverse algorithms to be used with sounding instruments, such as the EOS AIRS, NPOESS CrIS, and the NMP GIFTS.

#### 4. Retrieval Approach and Accuracy

Temperature and moisture sounding capability of a high spectral resolution infrared sounder, such as the GIFTS, has been assessed with the Aqua satellite AIRS spectrometer and the NAST-I interferometer sounder during several field campaigns. The retrieval results to be shown were obtained using the eigenvector regression retrieval method as applied to high-spectral resolution radiance data. In this technique, a training sample of historical radiosonde data is used to simulate radiance spectra for the NAST-I instrument. In the simulation, the radiosonde temperature and humidity structure is used to diagnose the cloud top level. For the spectral radiance calculations, each radiosonde, which possesses a cloud, is treated as both a clear sky and as an opaque cloud condition profile. The opaque sky condition profile is created by representing the radiosonde temperature

and moisture profile below the cloud as isothermal, at the cloud top temperature, and as saturated. This profile adjustment enables the retrieval system to obtain a clear sky equivalent temperature and moisture profile, from a radiative transfer point of view, regardless of the cloud condition. If the sky is cloud free, then the correct atmospheric profile will be obtained from aircraft level down to the Earth's surface. If an opaque cloud exists, the correct atmospheric profiles will be retrieved down to cloud top with a saturated isothermal profile, at cloud top temperature, being retrieved below the cloud top down to the Earth's surface. If a semi-transparent or broken cloud cover exists, then the correct profile will be retrieved down to the cloud top level with a less than saturated moisture profile and a temperature profile intermediate to the true profile and the cloud top temperature, being retrieved below the cloud, the proportion of isothermal and saturation being dependent on the cloud opacity and fractional coverage. The surface emissivity spectrum for each radiosonde profile is randomly selected from a set of laboratory measured emissivity spectra for a wide variety of surface types. Trace gas species, such as ozone and carbon monoxide, were specified using a statistical representation based on correlations of these gases with temperature and humidity conditions specified by the radiosonde data.

Radiance eigenvectors are computed and regressions equations are derived which relate the radiosonde temperature and water vapor values to the radiance eigenvector amplitudes. The regression coefficients are determined for different numbers of eigenvectors used to represent the radiance spectra. The appropriate number of eigenvectors to be used for the retrieval is determined from a small representative spatial sample of radiance observations. The optimum number of eigenvectors for the retrieval is defined as that number which minimizes the spatial RMS difference between the radiance spectra calculated from the retrievals and the observed radiance spectra from which those retrievals were produced. This number generally ranges between 15 and 50, depending upon the variance associated with the particular data set used (higher natural variance requires a larger number of eigenvectors to represent the information content of the radiance spectra). The regression equations for the "optimal" number of radiance eigenvectors are then applied to the spectral radiance measurements for the entire spatial domain and time period being analyzed. Since the radiative transfer calculations and

eigenvector decomposition analysis are done “off-line”, the routine retrieval production is extremely fast.

Both theoretical and experimental validations indicate that the AIRS and NAST-I temperature and water vapor profiles, for clear air conditions (i.e., clear atmospheric columns or above clouds), have an accuracy near 1 K, for the atmospheric temperature, and <15 %, for atmospheric relative humidity, when averaged over 1 km thick vertical layers.

## 5. Example Results

Figure 2 below shows a vertical cross section of AIRS and NAST-I relative humidity retrievals for 26 July 2002 off the east coast of Florida during an Aqua satellite overpass of the Proteus aircraft flight track.

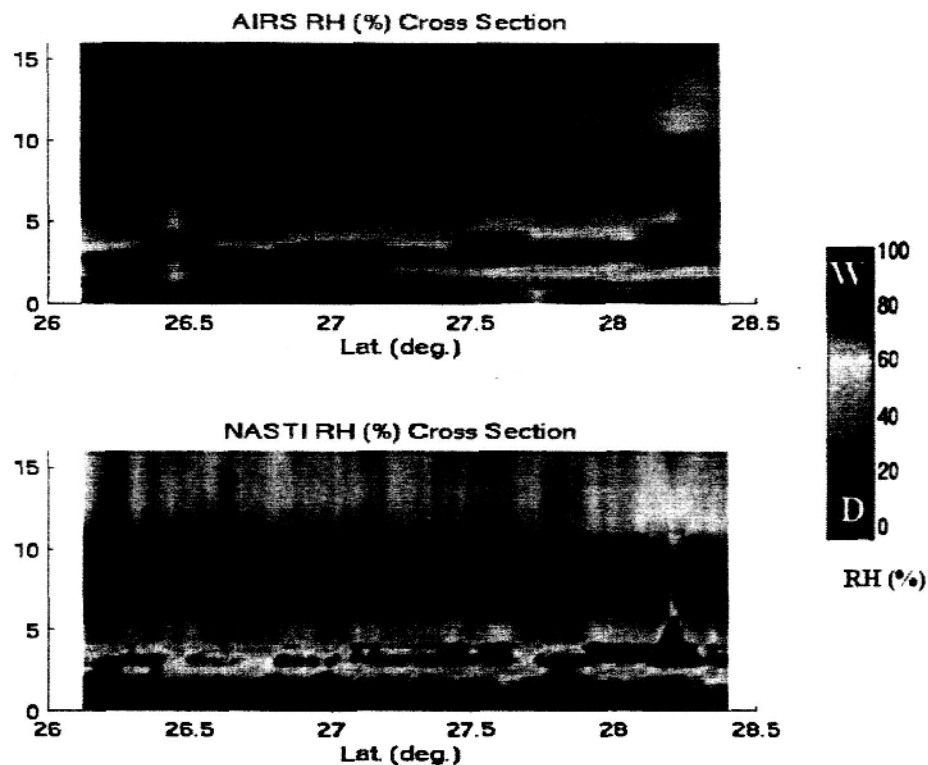


Figure 2: Comparisons between vertical cross sections of atmospheric relative humidity retrieved from AIRS and NAST-I radiance spectra. “W” and “D” denote Wet and Dry values.

Small scale differences in the water vapor cross sections can be seen as a result of the spectral and spatial resolution differences between the two instruments. The difference in the sensitivity to the water vapor above the 10 km level is due to the large difference between the spectral resolution for the two instruments (i.e.,  $\sim 1.25 \text{ cm}^{-1}$  for AIRS vs  $0.25 \text{ cm}^{-1}$  for NAST) which causes a difference in their abilities resolve emission

contributions, which originate from the high troposphere, from the centers of strong water vapor absorption lines.

Figure 3 shows a comparison of a cross section of atmospheric temperature, deviation from its level mean value, as retrieved from Aqua satellite AIRS and NAST-I radiances, observed from the ER-2 aircraft at the 20 km level, on March 3, 2003 near Hawaii. As can be seen, the fine scale vertical temperature profile features retrieved from the AIRS and NAST-I radiance data

compare well with data from dropsondes released from the NOAA G-4 aircraft at an altitude of 13 km. (Note that for this illustration the NAST-I spatial resolution has been reduced to that of AIRS, i.e., 15 km, and that the AIRS retrievals were produced from  $3 \times 3$  averages of spectra about their central nadir positions in order to minimize the effects of measurement noise on the retrieval of fine scale vertical temperature structure.) The vertical resolution difference in the temperature reversal feature in the 9-10 km layer is expected due to the lower vertical resolution of the retrievals compared to the in-situ dropsonde measurements. The satellite and aircraft retrieval cross-section shows somewhat higher horizontal resolution features than inherent in the dropsonde cross section because they are derived from ten relatively closely spaced (~15 km) retrievals, whereas the dropsonde cross-section is based on only three profiles (with about a 75 km separation distance), one at each end, and one in the middle, of the cross section shown in Figure 3. It is particularly noteworthy that the cross section mean of the AIRS and NAST-I profiles is almost identical to the mean of the dropsonde observations.

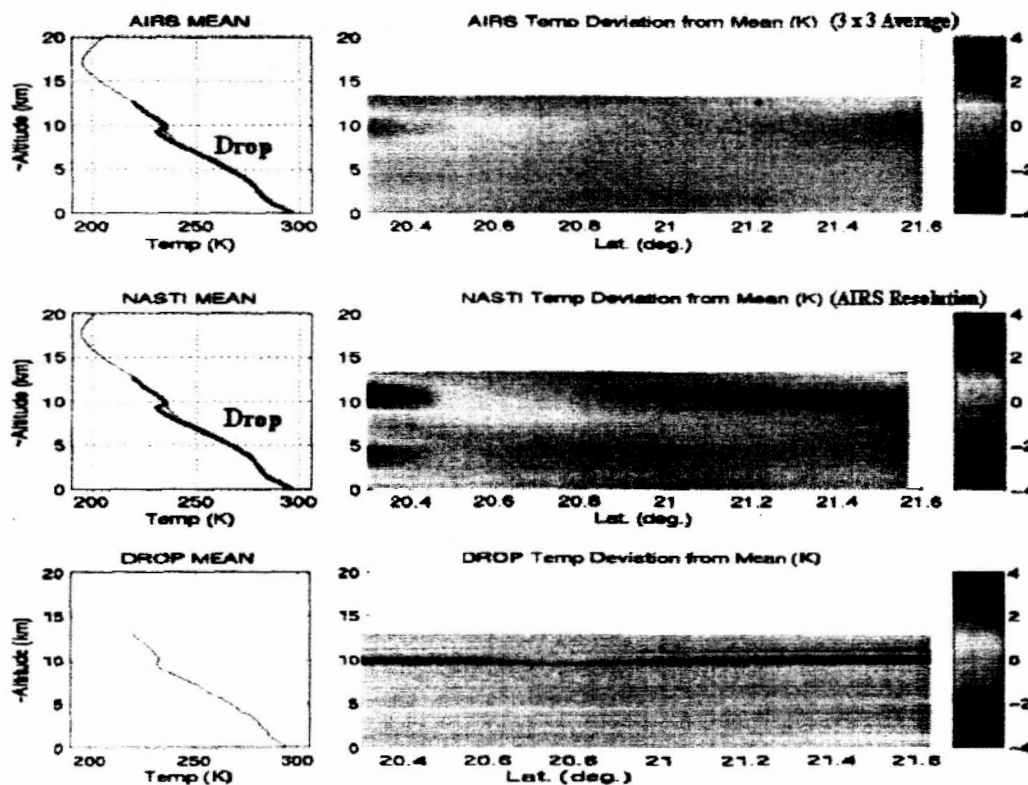


Figure 3. Comparison between cross sections of temperature (deviation from the level mean value) for AIRS and NAST retrievals, at AIRS spatial resolution, and dropsonde



observations near Hawaii on March 3, 2003. Red and Blue areas are relatively warm and cold areas, respectively.

## 6. Summary

GIFTS hyperspectral instrument will provide high spatial and temporal resolution temperature and moisture soundings from geosynchronous orbit from which wind profiles can be determined. The initial sounding retrieval technique to be applied to GIFTS data has been demonstrated and validated through its application to polar orbiting satellite AIRS spectrometer and high altitude aircraft NAST interferometer sounding radiance spectra. Full exploitation of the GIFTS will rely on the assimilation of its continuous data stream in numerical weather prediction models.

## 7. Bibliography

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