14.6 GIFTS – Hyperspectral Imaging and Sounding from Geostationary Orbit

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1. INTRODUCTION

The Geosynchronous Imaging Fourier Transform Spectrometer (GIFTS) combines advanced technologies to observe surface thermal properties and atmospheric weather and chemistry variables in four dimensions. Large area format Focal Plane detector Arrays (LFPAs) provide near instantaneous large area coverage with high horizontal resolution. A Fourier Transform Spectrometer (FTS) enables atmospheric radiance spectra to be observed simultaneously for all LFPA detector elements, thereby providing high vertical resolution temperature and moisture sounding information. The fourth dimension, time, is provided by the geosynchronous satellite platform, which enables near continuous imaging of the atmosphere's three-dimensional structure. GIFTS will provide: (1) a direct measure of moisture flux and altitude-resolved water vapor and cloud tracer winds throughout the troposphere, (2) an observation of the time varying atmospheric thermodynamics associated with storm system development, and (3) the transport of tropospheric pollutant gases (i.e., CO and O_3). The GIFTS instrument will be completed in late 2005 to support a 2006 to 2008 launch opportunity. GIFTS will conduct the "proof of concept" mission for the Hyperspectral imaging and sounding systems to fly on future operational geosynchronous satellites.

This paper provides an overview of the GIFTS measurement concept. The high altitude aircraft NPOESS Airborne Sounder Test-bed Interferometer (NAST-I) radiance spectra, and Aqua satellite AIRS radiance measurements are used to demonstrate the retrieval algorithms to be used for processing the data as well as to empirically validate the imaging and sounding product accuracies expected from the GIFTS. Wind profiles obtained from a time sequence of NAST-I water vapor retrieval images, observed from the NASA ER-2 flying off the Pacific coast, are validated using Doppler LIDAR winds, obtained simultaneously from a Navy Twin Otter aircraft.

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2. 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 routine operation. The intent is to use the GIFTS weather product imagery in support of Navy operations and the sounding data as input to global numerical weather forecast models. The GIFTS will be an important geostationary satellite augmentation of NASA's Earth Observing System (EOS) system.

3. MEASUREMENT CONCEPT

The GIFTS uses large area format focal plane array (LFPA) infrared (IR) detectors (128 × 128) in a Fourier Transform Spectrometer (FTS) mounted on a geosynchronous satellite to gather high-spectral resolution (0.6 cm^{-1}) and high-spatial resolution (4-km footprint) Earth infrared radiance spectra over a large geographical area (512-km × 512-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 different 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. O_3 and 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 (Fields of Regard) with a linear dimension in excess of 500-km, depending upon view angle, anywhere on the visible disk. The Field of Regard (FOR) dwell period will range between 0.125 and 11.0 seconds, depending on the data application (i.e., imaging or sounding). In order to achieve the required spectral radiance measurements, the GIFTS uses two detector arrays within a Michelson interferometer to cover the spectral bands, 685 to 1130 cm^{-1} and 1650 to 2250 cm^{-1}. The length of the interferometer scan can be varied in orbit to achieve a wide range of spectral resolutions. The Michelson interferometer, or FTS, approach for geosyncronous 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 the resolution of small scale atmospheric water vapor and cloud tracers for wind profiling.

4. RETRIEVAL APPROACH

Retrievals of temperature and moisture soundings from the GIFTS will be obtained using the eigenvector regression retrieval method as applied to high-spectral resolution interferometer 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 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. RETRIEVAL CONCEPT VALIDATION

The GIFTS temperature, moisture, and wind sounding retrieval concept has been validated using two different high spectral resolution radiance measurement instruments: the National Polar-orbiting Operational Environmental Satellite System (NPOESS) Airborne Sounding Testbed-Interferometer (NAST-I) and the Atmospheric Infrared Radiation Sounder (AIRS) flying aboard the Aqua satellite. DropSondes (DS) from aircraft are used to provide in-situ validation of the NAST-I and AIRS temperature profiles and Doppler Wind LIDAR (DWL) measurements are used to validate tracer wind profile extractions from a multiple time sequence of water vapor profile imagery.

AIRS. The Aqua satellite AIRS instrument is the first US 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 250-K target-temperature, ranges from 0.1 K in the 4.2-µm lower tropospheric sounding wavelengths to 0.5 K in the 15-µm upper tropospheric and stratospheric sounding spectral region. The AIRS Instrument provides spectral coverage in the 3.74 µm to 4.61 µm, 6.20 µm to 8.22 µm, and 8.8 µm to 15.4 µm 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. The AIRS ground resolutions at nadir are about 15 km and 2.5 km for the infrared and visible channel measurements, respectively, and the swath width is approximately 1650 km from the Aqua altitude of 705 km.

NAST-I. The 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 µm, 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 Aqua-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 (0.25 cm^{-1}) 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. 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 within a 40 km swath width is achieved, thereby providing three-dimensional hyperspectral images of radiance and derived geophysical products.

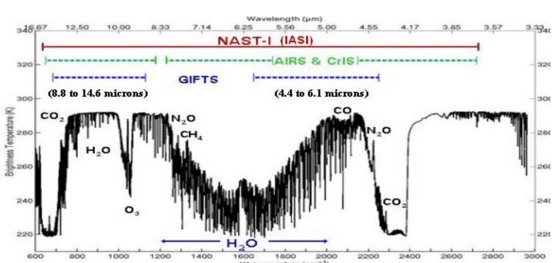

Figure 1. The NAST-I spectral coverage compared to that of advanced satellite sounders.

Dropsondes. A dropsonde system, developed by the National Center for Atmospheric Research, has been deployed on the NOAA Gulfstream IV aircraft and used to validate the remotely sensed temperature and moisture profiles obtained with AIRS and NAST-I. The GPS dropsondes provide an accuracy of 0.2 C and 5 % for temperature and humidity measurements, respectively. The wind profile beneath the aircraft is also measured with an accuracy of 1 knot.

Doppler Wind LIDAR (DWL) system. A 2 µm coherent detection Doppler LIDAR system has been used to validate the GIFTS wind measurement concept. The DWL is mounted on the Navy Twin Otter aircraft and has a side door mounted 10 cm two axis scan mirror. The accuracy of a 1 minute average wind vector is better than 1 knot.

6. Example Results

Water Vapor. 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.

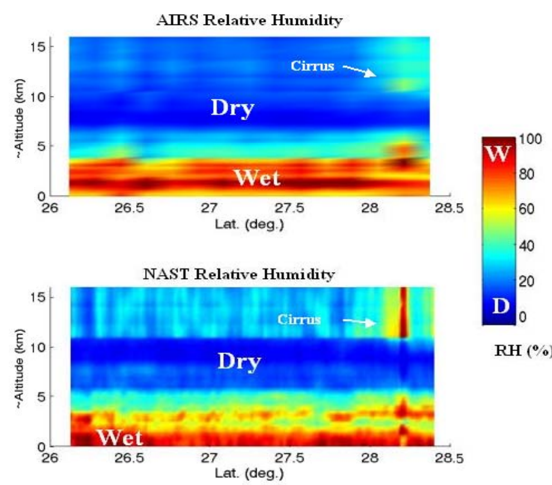

Figure 2. Comparisons between vertical cross sections of relative humidity retrieved from AIRS and NAST-I radiance spectra.

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 GIFTS spatial and water vapor absorption region spectral resolution are comparable to those provided by the NAST-I which are both significantly higher than those provided by the AIRS. As can be seen from figure 2, the GIFTS resolution is extremely important for the resolution of fine scale water vapor features that can be used as tracers of the wind velocity distribution.

Temperature. Figure 3 shows a comparison of a cross section of atmospheric temperature, deviation from its level mean value, as retrieved from 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 NAST-I radiance data compare well with data from dropsondes released from the NOAA G-4 aircraft at an altitude of 13 km. 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 aircraft retrieval cross-section shows higher horizontal resolution than the dropsonde cross section because it is derived from a large number of closely spaced (~3 km) retrievals, whereas the dropsonde cross-section is based on only three profiles, 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 NAST-I profiles is almost identical to the mean of the dropsonde observations.

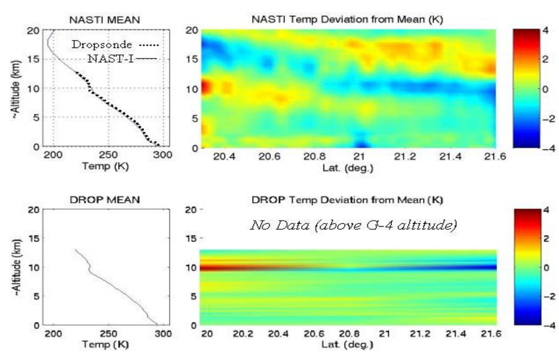

Figure 3. Comparison between cross sections of temperature (deviation from the level mean value) for NAST-I retrievals and dropsonde observations near Hawaii on March 3, 2003.

Wind Velocity. An ER-2 NAST-I flight off the coast of California on 11 February, 2003, was coordinated with and under flight of the Navy Twin Otter aircraft carrying the DWL for the purpose of validating the GIFTS wind measurement concept. The flight tracks are shown in figure 4.

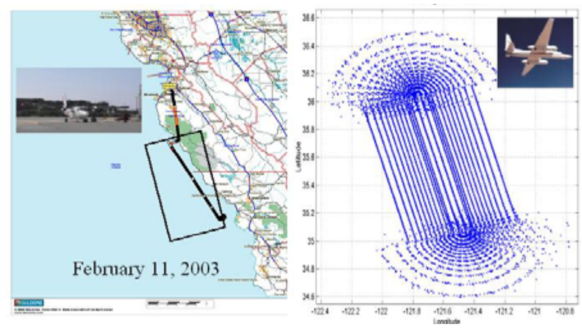

Figure 4. A racetrack ER-2 aircraft flight pattern was flown over the region is shown in the right hand portion of the figure. This flight pattern provided multiple overpasses of the same region, and allowed sequential moisture fields to be derived for winds production. The flight path of the Navy Twin Otter carrying the DWL is shown in the left hand portion of the figure.

Utilizing the approach and methodology discussed by Velden et. al., (this preprint), wind fields were derived from the NAST-I moisture analyses. Since there were nine successive overpasses of the same domain, 3 sets of winds (each using 3 sequential analyses centered at 21, 22 and 23 GMT) were attempted. Examples of the resulting wind fields are shown in Figure 5 for several selected pressure levels. As can be seen, even though the domain is spatially limited by the overflight scan angles, coherent vectors are produced.

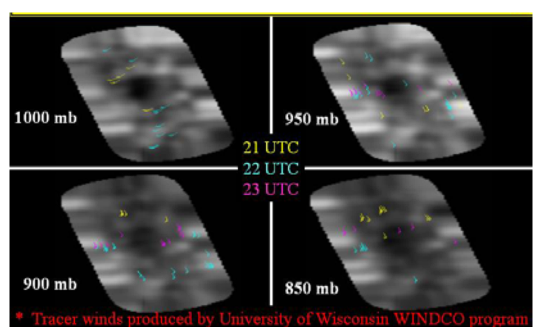

Figure 5. Tracer winds produced by UW-CIMSS algorithms from NAST-I moisture analyses.

In order to validate the quality of the winds shown in Fig. 5, wind profiles from the coincident DWL observations were used as a comparison. Figure 6 shows that the agreement is good with maximum differences being less than 3 m/sec.

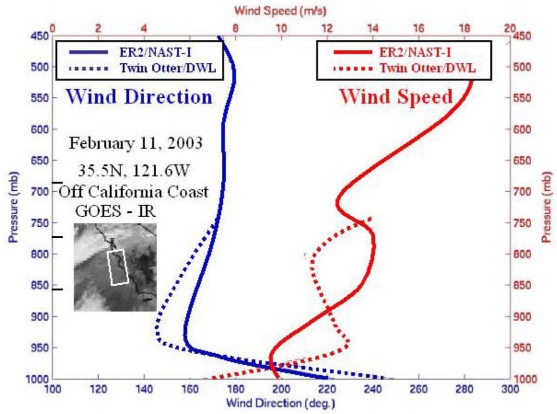

Figure 6. Comparison between water vapor tracer wind profiles derived from NAST-I data and coincident measurements with a Doppler wind LIDAR system.

7. Summary

The GIFTS hyperspectral imaging spectrometer will provide high spatial resolution temperature, moisture, and wind profiles. The GIFTS sounding concept and algorithms have been validated using Aqua satellite AIRS data and airborne NAST-I high spectral resolution radiance measurements. Comparisons of retrieved profiles with dropsondes and Doppler wind LIDAR measurements indicate that the desired accuracy of 1K, 15%, and 3m/sec accuracy can be achieved for temperature, moisture, and wind profiles, respectively, with a 1 – 2 km vertical resolution throughout the troposphere. Validation of the actual GIFTS hardware/software system awaits the launch of the EO-3 satellite mission.

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