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Technical Note: Evolution, current capabilities, and future advance in satellite nadir viewing ultra-spectral IR sounding of the lower atmosphere

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Abstract. Infrared ultra-spectral spectrometers have brought in a new era in satellite remote atmospheric sounding capability. During the 1970s, after the implementation of the first satellite sounding instruments, it became evident that much higher vertical resolution sounding information was needed to be able to forecast life and property threatening localized severe weather. The demonstration of the ultra-spectral radiance measurement technology required to achieve higher vertical resolution began in 1985, with the aircraft flights of the High resolution Interferometer Sounder (HIS) instrument. The development of satellite instruments designed to have a HIS-like measurement capability was initiated in the late 1980's. Today, after more than a decade of development time, the Atmospheric Infrared Sounder (AIRS) and the Infrared Atmospheric Sounding Interferometer (IASI) are now operating successfully from the Aqua and MetOp polar orbiting satellites. The successful development and ground demonstration of the Geostationary Imaging Fourier Transform Spectrometer (GIFTS), during this decade, is now paving the way toward the implementation of the ultra-spectral sounding capability on the international system of geostationary environmental satellites. This note reviews the evolution of the satellite ultra-spectral sounding systems, shows examples of current polar satellite sounding capability, and discusses future advances planned for geostationary orbit.

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1 Introduction

Satellite radiance measurement capability has evolved from the multi-spectral and hyper-spectral imaging and sounding capabilities first demonstrated during the 1960's into the ultra-spectral sounding capability that exists today. Whereas multi-spectral radiometers observe the radiance within a small number of spectral channels (e.g., 2–50) with a spectral resolving power ($\nu/\delta\nu$) of about 100, hyper-spectral and ultra-spectral spectrometers obtain a large number of spectral radiance channels (100–10 000) with resolving powers ranging from 1000 to 10 000, respectively. The ultra-spectral resolution sounding spectrometer evolved from the need to obtain much higher vertical resolution atmospheric soundings from space-based Earth radiance measurements than could be obtained using lower resolution multi-spectral radiometers. In particular, this evolution was driven by the need to produce a sounding vertical resolution, which was consistent with the high horizontal and temporal resolution achievable from geostationary orbit as needed for forecasting localized severe weather. The evolution began with the development of a series of aircraft instruments to demonstrate the higher vertical resolution sounding capability of ultra-spectral resolution instruments. The first experimental space demonstration of the technique was conducted from the Aqua polar orbiting research satellite in order to obtain global atmospheric chemistry and thermodynamic state data. The operational polar orbiting satellite implementation has already been initiated with the European MetOp-A satellite and this is soon to be followed by the US National Polar-orbiting Operational Satellite System, NPOESS. Together, MetOp and

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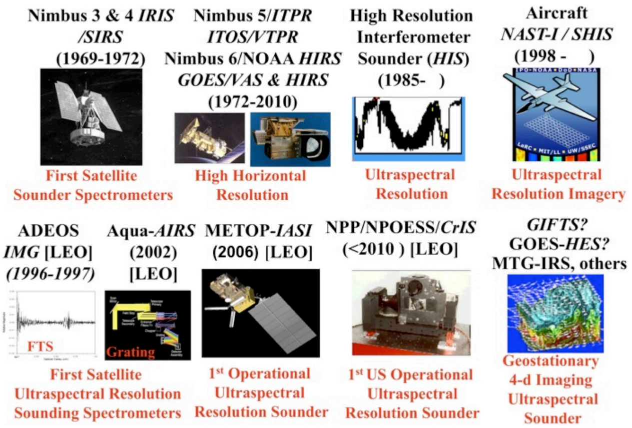

Fig. 1. Evolution of the satellite ultra-spectral resolution sounding capability.

NPOESS will better satisfy the demands for global high vertical resolution sounding data as needed for improved extended range numerical weather prediction. The evolution towards the ultimate goal of a global system of geostationary ultra-spectral sounders has progressed through the successful ground demonstration of the GIFTS (Geostationary Imaging Fourier Transform Spectrometer). Although the GIFTS awaits a space demonstration, Europe is proceeding with the development of an operational GIFTS-like instrument to fly aboard the METEOSAT Third Generation (MTG) of geostationary satellites.

In this paper, the evolution, current capability, and future advances in the ultra-spectral IR sounding program are discussed. The impact of ultra-spectral IR sounding measurements on atmospheric science and operational meteorology is illustrated through the presentation of experimental results.

2 Evolution overview

As shown in Fig. 1, the evolution of ultra-spectral infrared remote sounding systems useful for obtaining high vertical resolution sounding observations began during the mid-1980s with the first flights of the NASA ER-2 High resolution Interferometer Sounder (HIS) (Smith et al., 1979, 1987; Revercomb et al., 1988). The HIS demonstrated the Michelson interferometer technology and data processing techniques that could be employed on future Earth orbiting geostationary and polar orbiting satellites. The primary objective of HIS was to obtain high vertical resolution atmospheric temperature and moisture profiles needed for improving regional and global scale weather forecasts (Smith, 1991).

2.1 Polar satellite

The success of the HIS had a great impact on the design of the Atmospheric Infrared Sounder (AIRS) (Chahine et al., 2006) for the Earth Observing System (EOS) Polar Platform, eventually called the Aqua satellite. Since the HIS interferometer spectrometer had several thousand independent spectral channels to provide the high vertical resolution soundings, as a result of the very high system signal to noise that results from using such a large number of noise independent data in the profile retrieval process, the EOS AIRS was also specified to possess a similar number of spectral channels. Two designs were proposed, an interferometer like HIS and a large focal plane detector linear array ($\sim$2500 detector elements) grating spectrometer (Aumann et al., 2003) in which each detector element corresponded to an independent spectral element of the infrared spectrum. Because of the advanced technology (e.g., the large focal plane detector arrays, a mechanical cooler for maintaining the detector arrays at the required 60 K operating temperature, and the high data rate detector readout system) required for the grating approach, NASA decided to advance remote sensing technology through the selection of this approach for the AIRS. The AIRS was successfully launched into orbit on 2 May 2002.

Also motivated by the successful HIS experience, Japan built and successfully launched into polar orbit, during 1997, the Interferometric Monitor for Greenhouse gases (IMG), which provided the first space demonstration of the ultra-spectral sounding capability. Europe also developed an advanced sounder for both atmospheric chemistry, as well as meteorological, applications for its operational polar orbiting METOP satellite. It chose an interferometer design, with a spectral coverage and resolution similar to the HIS, because it could achieve many more spectral channels ($\sim$9000) with higher spectral resolution than the Atmospheric Infrared Sounder (AIRS) grating instrument ($\sim$2–10 times higher, depending upon wavenumber, using current "state of the art" detector technology). The Infrared Atmospheric Sounding Interferometer (IASI) (Chalon et al., 2001) was successfully launched into polar orbit aboard the METOP-2 satellite on 19 October 2006. The United States also chose a Michelson interferometer, based upon the University of Wisconsin's Interferometer Thermal Sounder (ITS) design, for its future National Polar–orbiting Operational Environmental Satellite System (NPOESS). The NPOESS instrument, called the Cross-track Scanning Infrared Sounder (CrIS) (Bloom, 2001), achieved a spectral resolution, spectral coverage, and number of spectral channels similar to AIRS but was produced with readily available detectors and a passive cooler at lower cost and in a smaller volume than the AIRS grating spectrometer.

2.2 Geostationary satellite

The original motivation for the HIS advanced sounder development was to provide a vertical sounding resolution that was more compatible with the spatial and temporal resolution achievable from geostationary orbit than that provided

Table 1. Characteristics of satellite advanced infrared sounders.

Name	AIRS	IASI	CrIS	IRFS-2	IRS
Orbit	705 km	833 km	824 km	850 km	Geostationary
Instrument type	Grating	FTS	FTS	FTS	FTS
Agency	NASA	EUMETSAT	IPO	RSA	EUMETSAT
Spectral range (cm^{-1})	649–1135 1217–1613 2169–2674	Contiguous 645–2760	650–1095 1210–1750 2155–2550	Contiguous 665–2000	685–1130 1650–2250
Unapodized spectral resolving power ($\nu/\delta\nu$)	1200	2000–4000	1000–1800	2000–4000	2000–4000
Field of view (km)	13	12	14	35	4
Sampling density per 50 km square	9	4	9	1	144
Power (W)	225	200	86	50	300
Mass (kg)	140	230	81	50	200
Platform	Aqua	METOP-1,2,3	NPP NPOESS C1	METEOR	Geostationary
Launch date	2002	2006, 2011, 2017	2011 (NPP) 2013 (C1)	2011	2017

by the VISSR Atmospheric Sounder (VAS) (Smith et al., 1981) filter wheel sounder being flown on GOES, beginning with the GOES-D. The spacecraft version of the HIS was proposed to fly on the first 3-axis stabilized geostationary satellite, GOES-I. However, NOAA felt that combining the high spectral resolution interferometer, together with the 3-axis geostationary satellite, was taking too great a risk for an operational satellite. Instead, NOAA decided to fly a filter wheel instrument, similar to the NOAA satellite High resolution Infrared Sounder (HIRS) (Smith et al., 1979), which could be upgraded to a Geostationary-High resolution Interferometer Sounder (G-HIS) (Smith et al., 1990) for flight on GOES-N. A prototype of G-HIS was built during the early 90s and tested successfully in the Thermal Vacuum (T/V) chamber, but NOAA decided not to move ahead with the program because of its increased cost and the perceived risk of flying this new technology on an operational satellite. Instead, an ultra-spectral imaging interferometer concept, made possible by the rapidly developing large area format focal plane detector array technology, emerged from NASA's Advanced Geostationary Studies (AGS) program. An instrument concept, called the Geostationary Imaging Fourier Transform Spectrometer (GIFTS) (Smith et al., 2001), which promised to revolutionize geostationary atmospheric sounding and imagery observations, was proposed and selected for NASA's Earth Observing three (EO-3) satellite to fly as a New Millennium Program (NMP) technology demonstration mission. The program was a partnership between three agencies. NASA was to fund the building of the GIFTS instrument while the Navy was suppose to fund the building of the spacecraft and provide a launch through the Air Force Space Test Program (STP). NOAA was to provide the ground receiving and data processing system required for the demonstration of the GIFTS operational utility. The GIFTS observations would revolutionize weather forecast capability by providing: (1) wind profiles in addition to thermodynamic profiles to improve hurricane landfall forecasts, (2) water vapor fluxes and high spatial and temporal resolution atmospheric stability measurements to enable precise location and timing of severe convective storm and associated tornado development, and (3) ultra-high density temperature, water vapor, and wind profiles for assimilation into advanced Numerical Weather Prediction (NWP) models. Unfortunately the EO-3 mission was cancelled after the GIFTS spacecraft was de-manifested from the STP launch schedule as a result of a Navy budget shortfall. However, NASA and NOAA decided to continue the development of GIFTS and to demonstrate this new technology and its remote sensing capability through ground-based thermal vacuum tests and ground-based atmospheric measurements. These demonstrations served as risk reduction for the next generation Hyperspectral Environmental Suite (HES), originally planned to fly on the GOES-R series of spacecraft beginning in 2014. The GIFTS Engineering Demonstration Unit (EDU) (Elwell et al., 2006) was completed and tested during 2005 and 2006, ending with a very successful sky measurement experiment (Zhou et al., 2007) that demonstrated the high precision and absolute accuracy of the GIFTS radiance spectra, as well as the GIFTS four-dimensional atmospheric sensing capability. GIFTS now waits for a space flight mission opportunity.

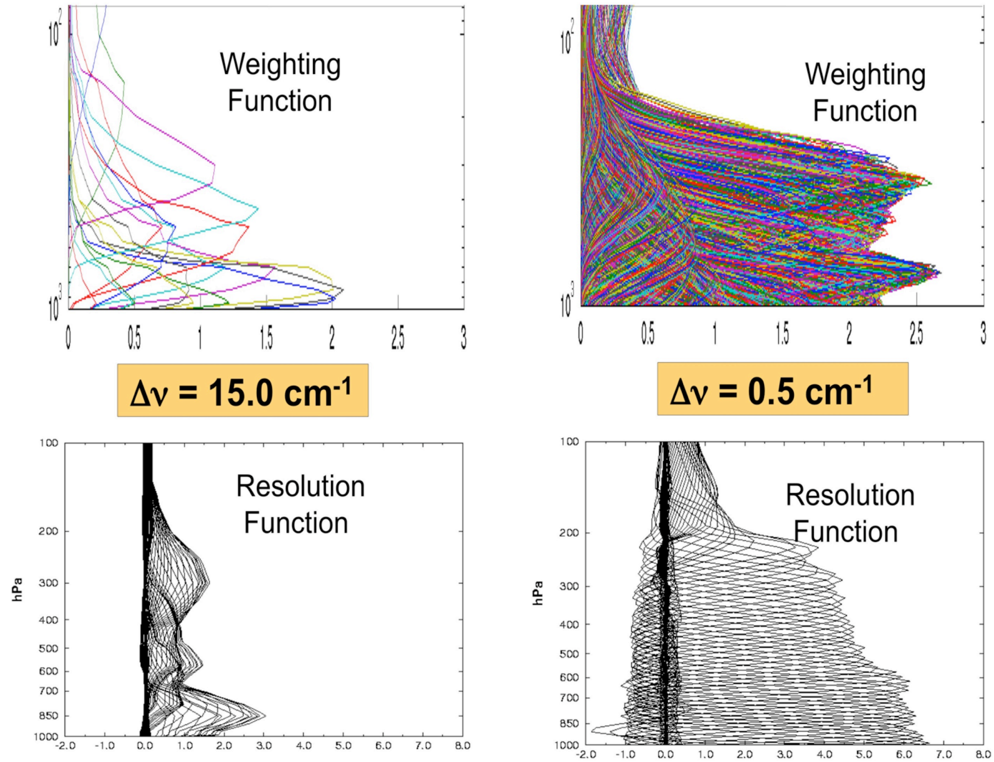

Fig. 2. The weighting functions and vertical profile resolution functions (i.e., averaging kernals) for two different instrument spectral resolutions.

2.3 Satellite advanced sounder characteristics

Table 1 shows the characteristics of the currently orbiting and planned polar and geostationary satellite ultra-spectral sounding instruments. As can be seen, all the instruments possess a spectral resolving power ($\nu/\delta\nu$) greater than 1000 over the spectral range of about 1500 cm^{-1}, or greater. The polar orbiting satellite instruments have fields of view ranging from 12–35 km, whereas the geostationary satellite instrument (i.e., the IRS based on the GIFTS design) has a footprint size of about 4 km, with the actual spatial resolution being limited by diffraction.

3 Ultra-spectral resolution sounding concept

The ultra-spectral resolution concept is to measure a large portion of the infrared spectrum of Earth-atmospheric radiance to space in order to obtain a very large number of noise independent spectral channels of radiance for inferring atmospheric profiles of temperature, water vapor, and trace gases. The high spectral resolution and large number of spectral channels both serve to optimize the vertical resolving power of the measurements. Having thousands of measurements, as opposed to tens of measurements, provides an order of magnitude improvement in signal to noise and this enables a much more precise inversion of the integral radiative transfer equation. The result is improved accuracy and higher vertical resolution of the retrieved profiles than can be achieved with multi-spectral radiance data. Figure 2 shows the comparison of the weighting functions (i.e., vertical resolving power of individual spectral radiances) and the vertical resolution functions (i.e., the averaging kernals of retrieved temperature profiles) for both low spectral (15 cm^{-1}) and ultra-spectral (0.5 cm^{-1}) resolution radiance observations. As can be seen, although the vertical resolution of individual spectral channels is enhanced by 25%, or less, the vertical sounding resolution is enhanced by a factor of two to three (i.e., 200–300%), as a result of the greatly increased system signal to noise of the ultra-spectral resolution system, assumed to have individual spectral channel noise levels comparable to the multi-spectral resolution system.

Figure 3 shows the improvement in sounding accuracy as a result of the improvement in vertical sounding resolution as the number of spectral channels increase. Here the vertical resolution of both the sounding retrievals and the radiosonde observations used for validation have been averaged over 1-km for temperature and 2-km for moisture vertical layers in order to portray the vertical resolution desired from advanced ultra-spectral sounding systems. As can be seen the improvement in the sounding accuracy is nearly proportional to the square root of the number of channels. The improvement of ultra-spectral measurements over low spectral resolution

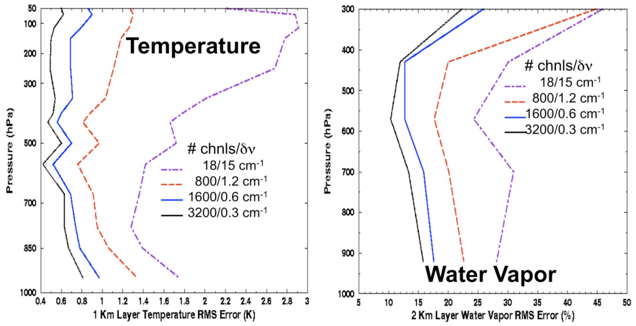

Fig. 3. Sounding RMS error as a function of spectral resolution and associated number of spectral radiance channels.

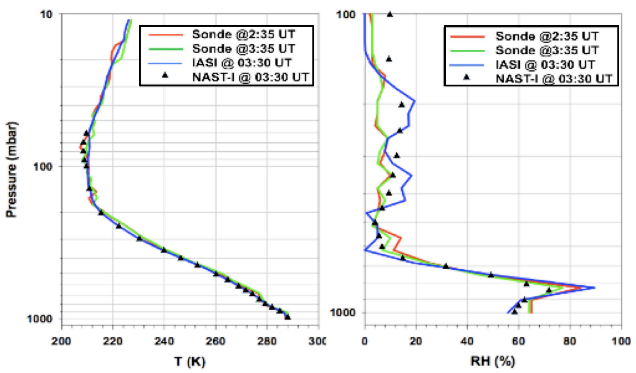

Fig. 4. IASI and NAST-I profile retrievals compared to special radiosondes at Lamont Oklahoma on 19 April 2007.

observations shown here is probably an underestimate of that achieved with real observations. This is because ultra-spectral resolution enables more precise spectral and radiometric calibration, reduces the impact of forward model errors, and enables the Earth's surface emissivity and cloud spectral properties to be more accurately accounted for in the retrieval process.

Figure 4 shows that the desired high vertical resolution (i.e., 1-km for temperature and 2-km for moisture) is realized with actual ultra-spectral radiance measurements. Shown are IASI profile retrievals obtained over the Department of Energy (DoE) Atmospheric Radiation Measurement (ARM) site at Lamont Oklahoma. The ultra-spectral radiance measurements were provided on 19 April 2007 by the IASI aboard the MetOp-A satellite orbiting over Lamont during the Joint IASI Airborne Validation Experiment (JAIVEx) (Smith et al., 2008, Zhou et al., 2009). The retrieval technique used was the one-dimensional variational inverse solution of the radiative transfer equation for the atmospheric profiles. An Empirical Orthogonal Function (EOF), usually referred to as "eigenvector", regression solution based on forward model simulated radiances was used as the initial profile for the iterated inverse solution. It is important to note that the Line-By-Line Radiative Transfer Model (LBLRTM)

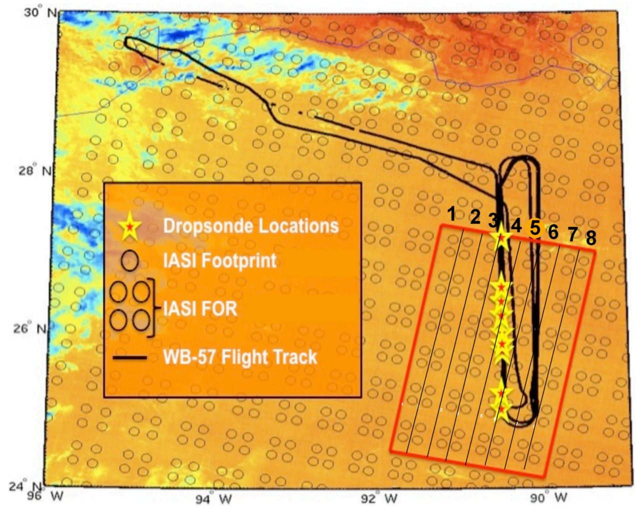

Fig. 5. The location of the IASI footprints, the aircraft flight track, and the dropsonde locations, superimposed upon a 10–12 μm infrared cloud image obtained with the IASI at 15:50 UTC on 29 April 2007. The red box delineates the validation area of interest.

was used for the profile retrieval process and that there was no adjustment (i.e., so-called "bias correction") made to the radiances in order to achieve these solutions. For validation, two special radiosondes were launched; the first one-hour before and the second at the satellite overpass time. The purpose of the two radiosondes is to get near simultaneous validation for both the lower and upper atmosphere through time interpolation of the measurements from the two radiosondes (Tobin et al., 2006a, b). For Fig. 4, the significant level radiosonde observations have been interpolated to levels used for the IASI sounding retrievals. Important to note here is the ability of the IASI retrieval to resolve important vertical temperature and moisture structure of the atmosphere. The small deviation of the IASI retrieved upper tropospheric temperature and moisture from the radiosonde observations is validated by independent retrievals using coincident NAST-I aircraft high spectral resolution radiance observations (Zhou et al., 2007).

4 JAIVEx mesoscale sounding structure comparison example

The IASI data obtained during JAIVEx on 29 April 2007 was used to validate the ability to resolve mesoscale spatial structure of humidity and temperature fields from ultra-spectral satellite radiance observations. The location of the IASI footprints and the flight track, along which dropsondes were launched from a BAe-146 aircraft to validate the satellite retrievals, are shown in Fig. 5 superimposed upon an cloud image of the region constructed from observations made with the IASI 10–12 μm infrared camera. A red box delineates a small 2×2 degree (222 km linear dimension)

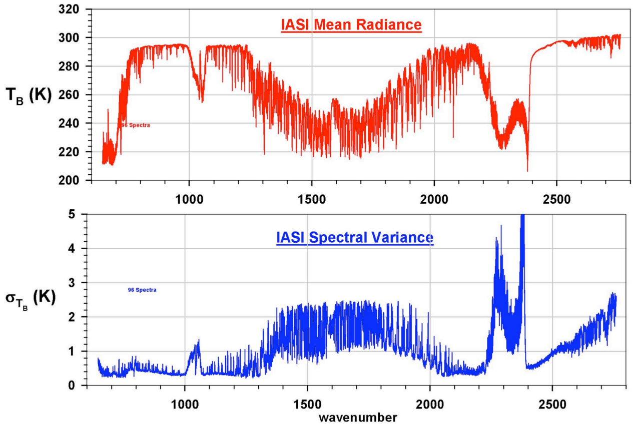

Fig. 6. Mean and standard deviation of the 96 IASI spectra obtained within the validation area (the red box) shown in Fig. 5, above.

area of interest. As can be seen from the infrared image, the area of interest was entirely free of cloud so that the variability of the IASI radiance measurements (shown in Fig. 6) for this area are entirely due to the surface and atmospheric temperature and moisture spatial structure. In order to assess the improvement in ultra-spectral spatial structure information above that obtained with multi-spectral radiometers, the IASI spectra were degraded spectrally to the resolution of the Advanced Baseline Imager (ABI) instrument to fly on the forthcoming GOES-R satellite. Profile retrievals were then performed with the IASI simulated ABI radiances using exactly the same physical/statistical retrieval algorithm described earlier for the IASI (section 3), the only difference being the Jacobian matrix used and the number of radiance observations and their associated expected error input to the retrieval process.

Figure 7 shows eight North-South vertical cross-sections of atmospheric temperature deviation from the mean profile (upper two panels) and moisture relative humidity (lower two panels) for the eight columns of IASI footprints shown in Fig. 5. The upper panel for each variable corresponds to retrievals from IASI simulated multi-spectral (ABI) radiance observations, whereas the bottom panel corresponds to retrievals obtained from full spectral resolution IASI radiances. One can see that even though there is small brightness temperature variation (~1–2 K) across this 200 km region (see Fig. 6), there is a significant amount of spatially coherent mesoscale temperature and moisture structure retrieved from the IASI radiance measurements, as validated by the dropsonde observations. The higher vertical resolving power of the ultra-spectral measurement IASI retrievals over those achievable with multi-spectral (i.e., the simulated ABI) radiance data is illustrated by this example. For temperature, the spatial variability shown by the IASI retrievals appears to be close to the dropsonde noise level, whereas for relative humidity there is close correspondence of the dropsonde spatial features with the IASI retrievals.

The JAIVEx case study result provides qualitative comparison of the IASI retrievals and the dropsonde data. A meaningful quantitative comparison is difficult to achieve for the small region sampled because the differences between the vertical resolution, vertical extent, geographical location, and observation time of the dropsonde and satellite sounding measurements.

5 The Geostationary Fourier Transform Spectrometer (GIFTS)

The Geostationary Fourier Transform Spectrometer (GIFTS) is the first ultra-spectral imaging instrument conceived to produce revolutionary improvements in severe weather prediction. GIFTS combines a number of advanced technologies to observe atmospheric weather and chemistry variables in four dimensions. The GIFTS instrument was developed by a team of scientists and engineers from the NASA Langley Research Center (NASA/LaRC), Utah State University Space Dynamics Laboratory (USU-SDL) and University of Wisconsin Space Science and Engineering Center (UW-SSEC). NASA's New Millennium Program (NMP) provided financial support for the GIFTS. NOAA's National Environmental Satellite Data and Information Service (NESDIS) contributed to the development of the ground data processing system and the completion of the GIFTS instrument as an Engineering Demonstration Unit (EDU). The GIFTS was designed to use two 128×128 Large area format Focal Plane infrared (IR) detector arrays (LFPAs) 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 an 11-s time interval. A visible light camera is designed to provide continuous imaging of clouds and the Earth's surface at 1-km spatial resolution over the 512 km Field of Regard (FOR) of the GIFTS sensor. Extended Earth coverage is to be 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 to be transformed to high vertical resolution (1–2 km) temperature and water vapor mixing ratio profiles using rapid profile retrieval algorithms. These profiles are to be 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, are to be constructed for each spatial scan. The sampling period would range from minutes to an hour, depending upon the spectral resolution and the area coverage selected for the measurement. Successive images of clouds and the relative humidity for each atmospheric level are then to be 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

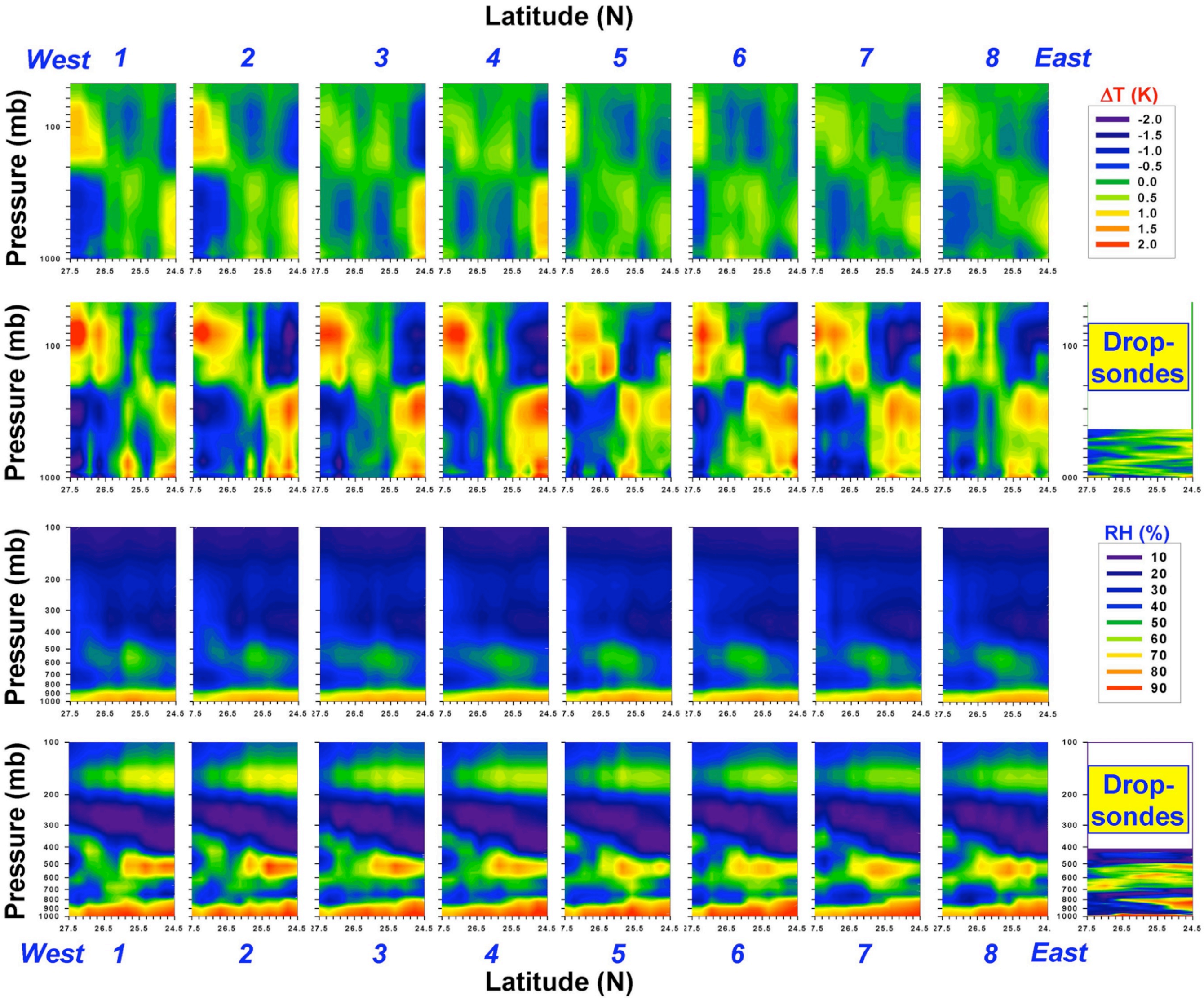

Fig. 7. North-South vertical cross-sections of atmospheric temperature deviation from the mean (upper two panels) and moisture relative humidity (lower two panels) for the eight columns of IASI footprints shown in Fig. 5. The upper panel for each variable corresponds to retrievals from the IASI simulated multi-spectral (ABI) radiance observations, whereas the bottom panel corresponds to retrievals obtained from full spectral resolution IASI radiances.

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 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 GIFTS revolutionary wind profile and trace gas transport remote sensing measurements.

The wind profile estimation technique has been demonstrated using a time sequence of three dimension water vapor images produced with NASA ER-2 NAST-I data. The accuracy of the resulting wind profiles have been validated to be 4 m/s or less, depending upon altitude, using Doppler Wind Lidar (DWL) observation made from a Twin Otter aircraft (G. D. Emmitt, personal communication, 2003) which was flown beneath the ER-2 (Smith et al., 2006).

The GIFTS spectral bands differ from those of polar orbiting satellite ultra-spectral resolution instruments (i.e., AIRS, IASI, and CrIS) in that achieves its' temperature and water vapor information more efficiently using two, rather than three, distinct spectral bands. One advantage of the GIFTS

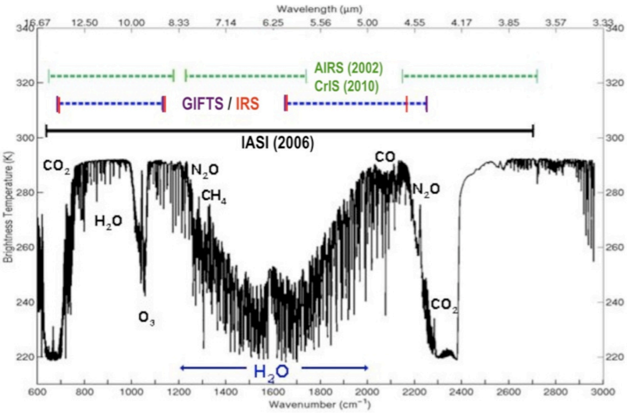

Fig. 8. Spectral coverage of various ultra-spectral sounding instruments.

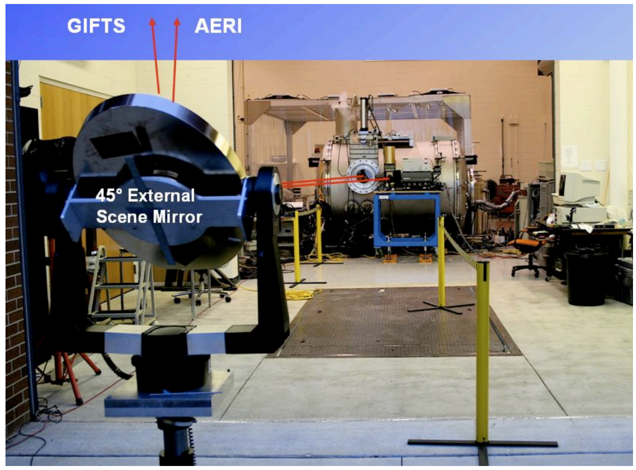

Fig. 10. The experimental configuration of the GIFTS and AERI instruments used for providing simultaneous measurements of the sky radiation from the Space dynamics Laboratory in Logan UT.

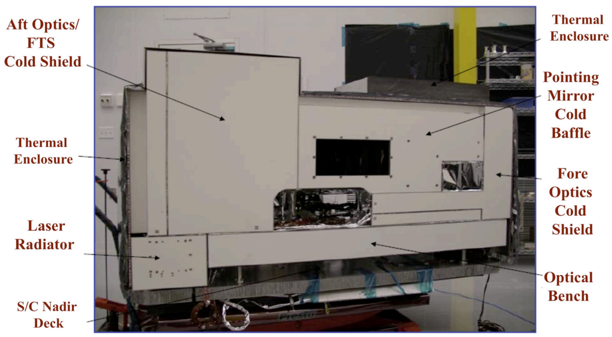

Fig. 9. The completed GIFTS-EDU instrument.

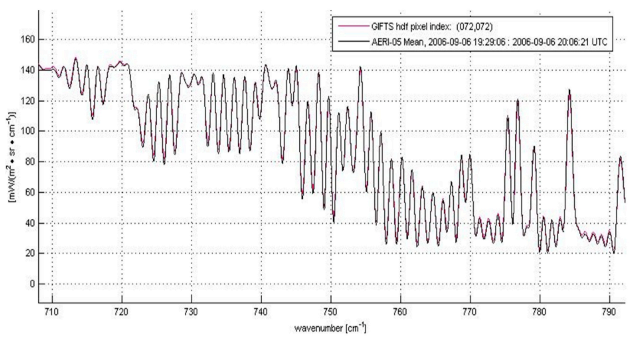

Fig. 11. Comparison of AERI and GIFTS CO_2 region spectra observed at Logan UT on 6 September 2006.

spectral coverage over that of the AIRS or CrIS is that the shortwave side of the 6.3 μm water vapor absorption band, rather than the long-wave side of this band, is observed thereby avoiding the otherwise reduced sensitivity to lower level water vapor structure produced by spectrally overlapping atmospheric N_2O and CH_4 absorption. Because of the efficiency of using two, rather than three bands, to achieve the desired temperature and water vapor profile information, the European ultra-spectral resolution Infrared Radiation Sounder (IRS) to fly on the METEOSAT Third Generation (MTG) satellite series has been designed to have a spectral coverage similar to the GIFTS, as shown in Fig. 6.

The revolutionary sounding advantage of GIFTS is its' ability to produce more than 80 000 closely spaced (4 km) atmospheric soundings every minute. These soundings can be used to track moisture features as a function of altitude thereby producing a dense coverage of vertically resolved atmospheric wind vectors. The wind profiles observed in the environment of a tropical storm or hurricane can be used to predict the track and landfall position and time of these life-threatening weather systems. At the same time, high temporal frequency temperature and moisture profile data are needed to predict the location and onset time of tornado producing convective thunderstorms. With GIFTS observations, the development of these storms can be observed from rapidly changing stability observations up to an hour, or more, before the storm becomes visible from satellite cloud imagery or from Radar. Thus, unlike satellite imagery and Radar, the GIFTS would enable geographically focused severe storm warnings, before the storm has formed.

An Engineering Demonstration Unit of the GIFTS (GIFTS-EDU) was completed and demonstrated through a series of thermal vacuum chamber tests and atmospheric and lunar measurement experiments. Figure 9 shows the completed GIFTS-EDU instrument. The imaging FTS produces the interferograms for spectral separation of scene radiation reaching the detector arrays. To limit the background signal, the GIFTS instrument is cryogenically cooled by the first stage to $<$150 K. The high data rates generated by the

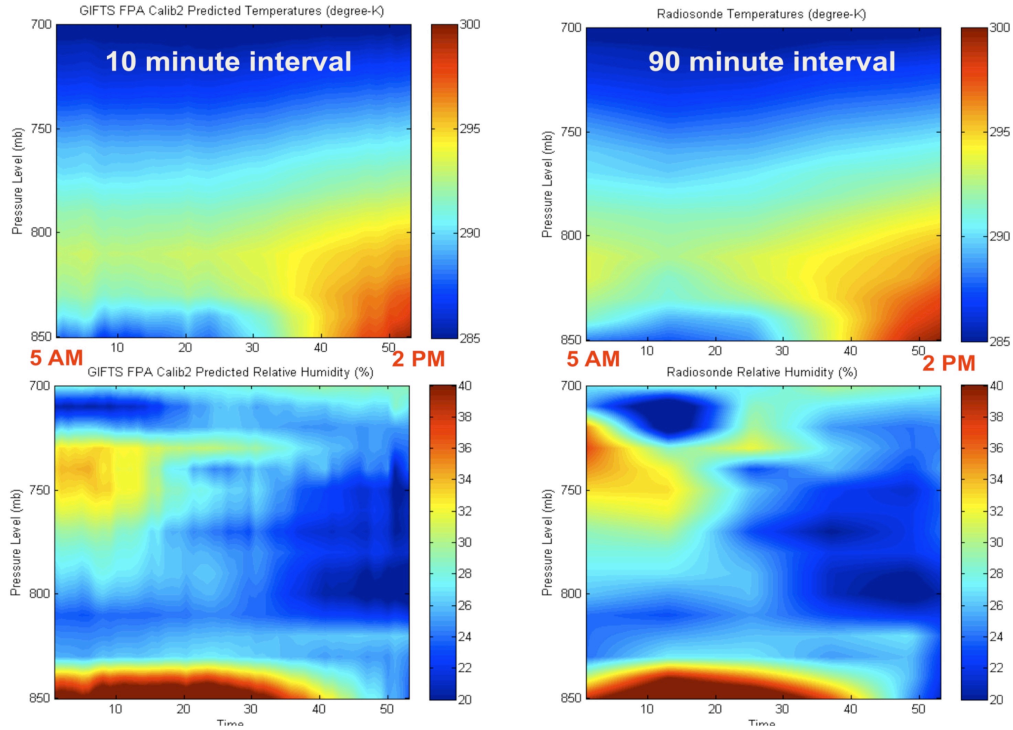

Fig. 12. Comparison of GIFTS retrieved and radiosonde temperature and moisture profiles observed at Logan UT on 13 September 2006.

ultra-sensitive large area format focal plane mercury cadmium telluride photovoltaic detector arrays, cooled to 60 K, are reduced by loss-less compression techniques and then passed to the telemetry system by low-power, low-volume, next-generation electronic components.

The thermal vacuum tests of the GIFTS showed that IASI-like radiometric performance could be achieved with a geographical coverage about 5 times faster, a spectral resolution about 20 times greater, and an area resolution of 4 times better than the current GOES sounder. This two orders of magnitude improvement is certain to bring revolutionary improvements in the environmental observation and forecast applications of geostationary satellite sounding observations.

Environmental measurement tests of the GIFTS were conducted during September 2006 (Zhou et al., 2007). As illustrated in Fig. 10, a University of Wisconsin AERI (Atmospheric Emitted Radiance Interferometer) instrument, considered to be the ultra-spectral radiometric standard, was placed next to the GIFTS thermal vacuum chamber in order to provide radiance spectra to validate the GIFTS measurements. Figure 11 shows the very first in-the-field comparison between the GIFTS and the AERI spectral radiance measurements across a small spectral region of the 15 μm band. As can be seen, the two spectra fall on top of each other at the resolution of this graphical display, illustrating good agreement between the two sets of observations. A more revealing difference spectrum is not shown here because small quantitative differences result from the fact that the GIFTS observations are influenced by the window of the GIFTS thermal vacuum chamber, which was not accounted for in this first order comparison shown with the accuracy needed for a detailed quantitative difference evaluation. In fact, for obtaining the meteorological results from the GIFTS ground-based experiment shown below, the AERI measurements were used to account for the influence of the thermal vacuum chamber window on the calibration of the GIFTS spectral radiance observations (Tian et al., 2008a, b).

Figures 12 and 13 show results of the vertical temperature and moisture profile retrievals from GIFTS radiance measurements obtained between 05:00 a.m. and 02:00 p.m. MDT at Logan Utah on 13 September 2006. Shown in Fig. 12 are comparisons of vertical-time cross-sections of temperature and water vapor retrieved from 10-min interval GIFTS radiances and radiosonde observations made at a 90-min interval. As shown, the diurnal variation features observed by the radiosonde are captured very well by the GIFTS radiance observations. Figure 13 shows the 600-m level temperature variability as retrieved from the radiances for each of the individual elements of the GIFTS focal plane detector array. Since the linear dimension of the area viewed by GIFTS at the 600-m level is only 8 m, one would not expect much real variation in temperature and moisture across the field of regard of the GIFTS instrument. This display is shown merely to convey the relative accuracy of the radiances obtained for the detector elements forming the GIFTS $124 \times 124 = 16\,384$ detector element array. In summary, the horizontal, vertical,

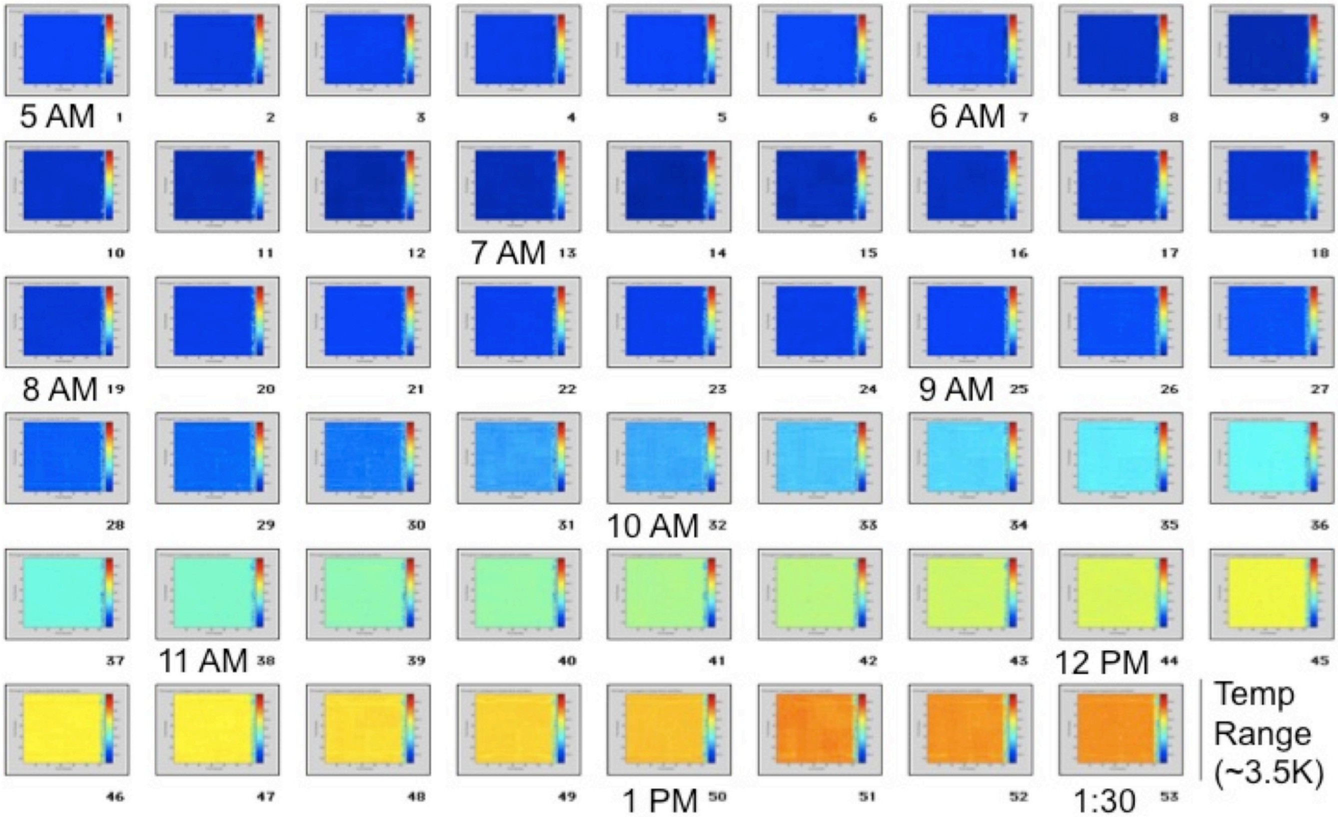

Fig. 13. Consecutive 10 min interval 128×128 detector element frames of 600-m level (800 hPa) atmospheric temperature retrieved from GIFTS sky-viewing radiance observations at Logan UT on 13 September 2006.

and temporal consistency of the GIFTS imaging spectrometer measurements, as illustrated in the above figures, is noteworthy.

6 Summary and conclusions

An evolution of the ultra-spectral resolution sounding capability has taken place over the last three decades for the purpose of improving the vertical resolution of atmospheric soundings from environmental satellites. After the demonstration of the ultra-spectral sounding capability from aircraft, during the middle 1980s, the evolution continued with the development of ultra-spectral resolution satellite instruments for the purpose of improving global atmospheric soundings. This improved sounding expectation was recently realized through the implementation of the AIRS and IASI spectrometers aboard the Aqua and MetOp polar orbiting satellites.

However, the original goal of providing revolutionary improvements in severe weather forecasts is expected to be achieved through the implementation of imaging ultra-spectral resolution interferometer spectrometers aboard geostationary spacecraft. The development and ground demonstration of the Geostationary Imaging Fourier Transform Spectrometer (GIFTS) was an important and highly successful step in the development of the required detector and ultra-high speed data readout technology required for the geostationary satellite application. Recently, the EUMETSAT obtained approval from its governing council to proceed with the development of a GIFTS-like instrument for its METEOSAT Third Generation (MTG) satellites. Other members of the international geostationary environmental satellite community are expected to follow EUMETSAT, in order to achieve a high temporal resolution ultra-spectral sounding capability on a worldwide basis. Once implemented, the global GIFTS-like geostationary satellite spectrometers, combined with the joint European and US polar orbiting satellite system of ultra-spectral resolution infrared instruments (i.e., IASI and CrIS), will be the most significant sounding component of the Global Environmental Observing System of Systems GEOSS).

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(SSEC) initiated and continue to lead the ultra-spectral sounding evolution. The contributions from scientists and engineers from the NOAA/NESDIS, NASA/LaRC, NASA/JPL, Utah State University/SDL, EUMETSAT, Centre National d'Etudes Spatiales (CNES), ABB/BOMEM, ITT, BAE, Raytheon/SBRC, and Alcatel standout amongst those who have contributed greatly to the evolution of today's ultra-spectral satellite sounding capability. IASI has been developed and built under the responsibility of the Centre National d'Etudes Spatiales (CNES, France). It is flown onboard the Metop satellites as part of the EUMETSAT Polar System. The IASI data are received through the EUMETCast near real time data distribution service.

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