

This discussion paper is/has been under review for the journal *Atmospheric Chemistry and Physics (ACP)*. Please refer to the corresponding final paper in *ACP* if available.

Evolution, current capabilities, and future advances in satellite ultra-spectral IR sounding

W. L. Smith Sr.^{1,2}, H. Revercomb¹, G. Bingham³, A. Larar⁴, H. Huang¹, D. Zhou⁴, J. Li¹, X. Liu⁴, and S. Kireev²

¹University of Wisconsin, Madison, Wisconsin, USA

²Hampton University, Hampton, Virginia, USA

³Space Dynamics laboratory, Logan, Utah, USA

⁴NASA Langley Research Center, Hampton, Virginia, USA

Received: 11 December 2008 – Accepted: 1 February 2009 – Published: 10 March 2009

Correspondence to: W. L. Smith Sr. (bill.l.smith@cox.net)

Published by Copernicus Publications on behalf of the European Geosciences Union.

6541

Abstract

Infrared ultra-spectral spectrometers have brought in a new era of satellite remote atmospheric sounding capability. During the 1970's, 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, respectively. The successful development and ground demonstration of the Geostationary Imaging Fourier Transform Spectrometer (GIFTS), during this decade, is now paving the way toward future implementation of the ultra-spectral sounding capability on the international system of geostationary environmental satellites.

1 Introduction

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 res-

6542

olution instruments. The first experimental space demonstration of the technique was conducted from polar orbiting research satellites 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 Environmental Satellite System, NPOESS. Together, MetOp and 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, and 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).

6543

3 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 (~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 (~9000) with higher spectral resolution than the AIRS grating instrument (~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.

6544

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 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 considerably lower cost and in a much smaller volume than the AIRS grating spectrometer.

4 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 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 1990s 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 revolution-

6545

ize 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 Hyper-spectral 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.

6546

5 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 retrieved profiles than can be achieved with multi-spectral radiance data. Figure 2 shows the comparison of weighting functions (i.e., vertical resolving power of individual spectral radiances channels) and vertical resolution functions (i.e., the averaging kernels of retrieved temperature profiles) for both low spectral (15 cm^{-1}) and ultra-spectral (0.5 cm^{-1}) resolution radiance observations with the CO_2 band region. 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 within the CO_2 and H_2O spectral band regions. 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 lower spectral resolution 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

6547

emissivity and cloud spectral properties to be more accurately accounted for in the retrieval process.

Figure 4 shows that high vertical resolution 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). The retrieval technique used was a 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) was used for the profile retrieval process and that there was no adjustment (i.e., so-called “bias correction” or “tuning”) 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. 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 (i.e., due to lack of exact time and space coincidence) is validated by independent retrievals using coincident NAST-I aircraft high spectral resolution radiance observations (Zhou et al., 2007).

6 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-

6548

spectral satellite radiance observations. The location of the IASI footprints and the aircraft flight tracks, along which dropsondes were launched from a BAe-146 aircraft to validate the satellite retrievals, are shown in Fig. 5 superimposed upon a cloud image of the region constructed from observations made with the IASI 10–12 μm infrared camera. A red box delineates a small 2 \times 2 degree (222 km linear dimension) 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 the same physical/statistical retrieval algorithm described earlier for IASI (Sect. 3).

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 ($\sim 1\text{--}2\text{ K}$) 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.

6549

7 The Geostationary Imaging 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 uses two 128 \times 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 \times 512-km) of the Earth within an 11-s time interval. A visible light camera provides continuous imaging of clouds and the Earth's surface at 1-km spatial resolution over the 512-km \times 512-km Field of Regard (FOR) of the GIFTS sensor. Extended Earth coverage is achieved by step scanning the instrument FOR 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, are constructed for each spatial scan. The sampling period ranges 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

6550

for each atmospheric level are then animated to reveal the motion of small-scale thermodynamic and cloud 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. O₃ and CO features observed in their spectral radiance signatures provide a measure of the transport of these pollutant 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 GIFTS spectral bands differ from those of polar orbiting satellite ultra-spectral resolution instruments (i.e., AIRS, IASI, and CrIS) in that GIFTS achieves temperature and water vapor information more efficiently using two, rather than three, distinct spectral bands. One advantage of the GIFTS 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 N₂O and CH₄ absorption. Because 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. 8.

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 better 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

6551

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 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 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 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 better, 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 sounders.

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 a comparison between the GIFTS and AERI spectral radiance measurements across a small spectral region of the 15 μm band. As can be seen, the two spectra

6552

fall on top of each other, illustrating the excellent agreement between the two sets of observations.

Figures 12 and 13 show the results of the vertical temperature and moisture profile retrievals from GIFTS radiance measurements obtained between 5 a.m. and 2 p.m. MDT at Logan, Utah on 13 September 2006. As can be seen both the temporal variability and spatial structure of the atmospheric temperature and moisture are observed by the GIFTS with high sensitivity. The temporal, vertical, and horizontal coherence of the GIFTS imaging spectrometer measurements, as illustrated in these figures, is noteworthy.

8 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 vertical resolution of atmospheric soundings from environmental satellites. After the demonstration of ultra-spectral sounding capability from aircraft, during the middle 1980s, the evolution continued with 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. 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

6553

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 future Global Environmental Observing System of Systems (GEOSS).

Acknowledgements. The evolution of the ultra-spectral sounding capability reported here, is due to the dedicated and persevering efforts of scientists and engineers from a large number of university, government, and industrial institutions. The University of Wisconsin's Cooperative Institute for Meteorological Satellite Studies (CIMSS) and the Space Science and Engineering Center (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 stand out amongst those who have contributed greatly to the evolution of today's ultra-spectral satellite sounding capability.

References

- Bloom, H. J.: The Cross-Track Infrared Sounder (CrIS): A Sensor for Operational Meteorological Remote Sensing, Fourier Spectroscopy, 5–8 February, 2001, OSA 2001 Technical Digest, 76–78, 2001.
- Chahine, M. T., Pagano, T. S., Aumann, H. H., et al.: AIRS: Improving Weather Forecasting and Providing New Data on Greenhouse Gases, *B. Am. Meteorol. Soc.*, 87, 911–926, 2006.
- Aumann, H. H., Chahine, M. T., Gautier, C., et al.: AIRS/AMSU/HSB on the Aqua Mission: Design, Science Objectives, Data Products, and Processing Systems, *IEEE Transactions on Geosci. Remote Sens.*, 41, 253–264, 2003.
- Chalon, G., Cayla, F., and Diebel, D.: IASI: An Advanced Sounder for Operational Meteorology, Proceedings of the 52nd Congress of IAF, Toulouse France, 1–5, 2001.
- Cousins, D. and Smith, W. L.: National Polar-Orbiting Operational Environmental Satellite System (NPOESS) Airborne Sounder Testbed-Interferometer (NAST-I), in Proceedings, SPIE Application of Lidar to Current Atmospheric Topics II, 3127, 323–331, 1997.

6554

- Elwell, J. D., Cantwell, G. W., Scott, D. K., et al.: A geosynchronous imaging Fourier transform spectrometer (GIFTS) for hyperspectral atmospheric remote sensing: instrument overview & preliminary performance results, *Proc. SPIE* 6297, 62970S, 2006.
- Revercomb, H. E., LaPorte, D. D., Smith, W. L., Buijs, H., Murcay, D. G., Murcay, F. J., and Sromovsky, L. A.: High-altitude aircraft measurements of upwelling IR radiance: Prelude to FTIR from geosynchronous satellite. *Mikrochimica Acta (Wien)* II, 438–444, 1988.
- Revercomb, H. E., Smith, W. L., Knuteson, R. O., and Best, F. A.: Advanced sounding systems: The polar orbiting ITS and the ground-based AERI. In: *Technical Proceedings of the International TOVS Study Conference, 7th, Igls, Austria, 10-16 February 1993*. Reading, UK, European Centre for Medium-range Weather Forecasts (ECMWF), 404–415, 1993.
- Revercomb, H. E., Walden, V. P., Tobin, D. C., et al.: Recent results from two new aircraft-based Fourier-transform interferometers: The scanning high-resolution interferometer sounder and the NPOESS atmospheric sounder testbed interferometer. *Proc. 8th Int. Workshop on Atmospheric Science from Space using Fourier Transform Spectrometry (ASSFTS)*, Toulouse, France, 16–24, 1998.
- Smith, W. L., Woolf, H. M., Hayden, C. M., Wark, D. Q., and McMillin, L. M.: The TIROS-N operational vertical sounder, *B. Am. Meteorol. Soc.*, 60, 1177–1187, 1979.
- Smith, W. L., Howell, H. B., and Woolf, H. M.: The use of interferometric radiance measurements for sounding the atmosphere, *J. Atmos. Sci.*, 36, 566–575, 1979.
- Smith, W. L., Suomi, V. E., Menzel, W. P., Woolf, H. M., Sromovsky, L. A., Revercomb, H. E., Hayden, C. M., Erickson, D. N., and Mosher, F. R.: First sounding results from VAS-D, *B. Am. Meteorol. Soc.*, 62, 232–236, 1981.
- Smith, W. L., Revercomb, H. E., Howell, H. B., Woolf, H. M., and LaPorte, D. D.: The High Resolution Interferometer Sounder (HIS). In: *Atmospheric Radiation Progress and Prospects: Beijing International Radiation Symposium, Beijing, China, 26–30 August 1986*, Boston, MA, American Meteorological Society, 1987, 271–281, 1986.
- Smith, W. L., Revercomb, H. E., LaPorte, D. D., Sromovsky, L. A., Silverman, S., Woolf, H. M., Howell, H. B., Knuteson, R. O., and Huang, H.-L.: GHIS – The GOES High resolution Interferometer Sounder. *J. Appl. Meteor.*, 29, 1189–1204, 1990.
- Smith, W. L.: Atmospheric soundings from satellites – false expectation or the key to improved weather prediction? *Royal Meteorological Society, Symons Memorial Lecture*, London, UK, 16 May 1990, *J. Roy. Meteor. Soc.*, 117, 267–297, 1991.
- Smith, W. L., Harrison, F. W., Revercomb, H. E., and Bingham, G. E.: Geostationary Fourier

6555

- Transform Spectrometer (GIFTS) - The New Millennium Earth Observing-3 Mission. *IRS 2000: Current problems in atmospheric radiation. Proceedings of the International Radiation Symposium, St. Petersburg, Russia, 24-29 July 2000*. Hampton, VA, A. Deepak Publishing, 81–84, 2001.
- Smith, W., Zhou, D., Antonelli, P., et al.: Validation of Satellite AIRS Retrievals with Aircraft NAST-I Soundings and Dropsondes – Implications for Future Satellite Sounding Capabilities, *Proceedings of the thirteenth International TOVS Study Conference (ITSC-XIII)*, Ste. Adele, Quebec, 2005.
- Smith, W. L., Zhou, D. K., Larar, A. M., Mango, S. A., Knuteson, H. B., Revercomb, H. E., and Smith Jr., W. L.: The NPOESS Airborne Testbed Interferometer – Remotely Sensed Surface and Atmospheric Conditions during CLAMS, *J. Atmos. Sci.*, 62, 1118–1134, 2005.
- Tobin, David C., Revercomb, H., Moeller, C. C., et al.: Radiometric and spectral validation of Atmospheric Infrared Sounder observations with the aircraft-based Scanning High-Resolution Interferometer Sounder, *J. Geophys. Res.*, 111, D09S02, doi:10.1029/2005JD006094, 2006.
- Taylor, J. P., Smith, W. L., Cuomo, V., Larar, A.M., Zhou, D.K., Serio, C., Maestri, T., Rizzi, R., Newman, S., Antonelli, P., Mango, S., Di Girolamo, P., Esposito, F., Grieco, G., Summa, D., Restieri, R., Masiello, G., Romano, F., Pappalardo, G., Pavese, G., Mona, L., Amodeo, A., and Pisani, G.: EAQUATE: An International Experiment For Hyperspectral Atmospheric Sounding Validation, *B. Am. Meteorol. Soc.*, 89, 203–218, 2008.
- Smith, W., Larar, A., Taylor, J., Revercomb, H., Kireev, S., Zhou, D., Liu, X., Tobin, D., Newman, S., Schlüssel, P., Clough, A., Mango, S., and St. Germain, K.: Joint Airborne IASI Validation Experiment (JAIVEx) - An overview, *Proc. Int. ATOVS Study Conf. XVI, Angra dos Reis, Brazil, CIMSS, University of Wisconsin–Madison*, in press, 2008.
- Zhou, D. K., Smith, W. L., Cuomo, V., Taylor, J. P., Barnett, C. D., Di Girolamo, P., Pappalardo, G., Larar, A. M., Liu, X., Newman, S. M., Lee, C., and Mango, S. A.: Retrieval validation during the European Aqua Thermodynamic Experiment, *Q. J. Roy. Meteorol. Soc.*, 133, 203–215, 2007b.
- Zhou, D. K., Smith, Sr., W. L., Bingham, G. E., Huppi, R. J., Revercomb, H. E., Zollinger, L. J., Elwell, J. D., Larar, A. M., Liu, X., Tansock, J. J., Reisse, R. A., and Hooker, R.: Ground-based measurements with the Geosynchronous Imaging Fourier Transform Spectrometer (GIFTS) engineering demonstration unit – experiment description and first results, *J. Appl. Remote Sens.*, 1, 013528, 14 pp., 2007.

6556

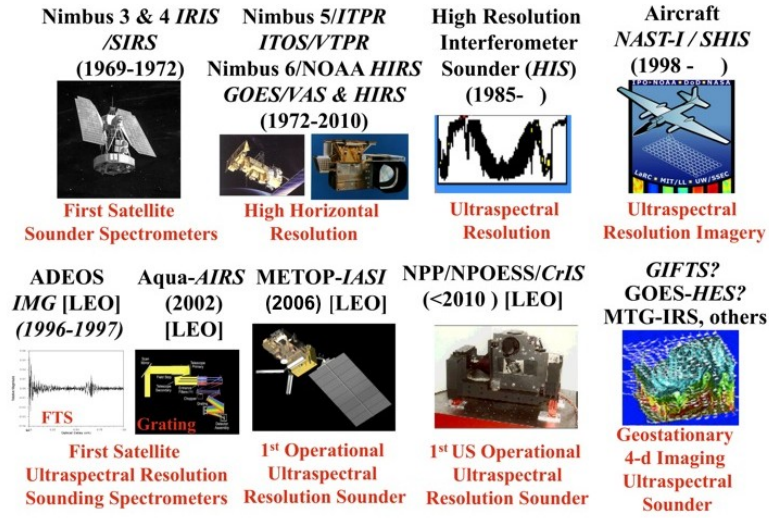


Fig. 1. Evolution of the satellite ultra-spectral resolution sounding capability.

6557

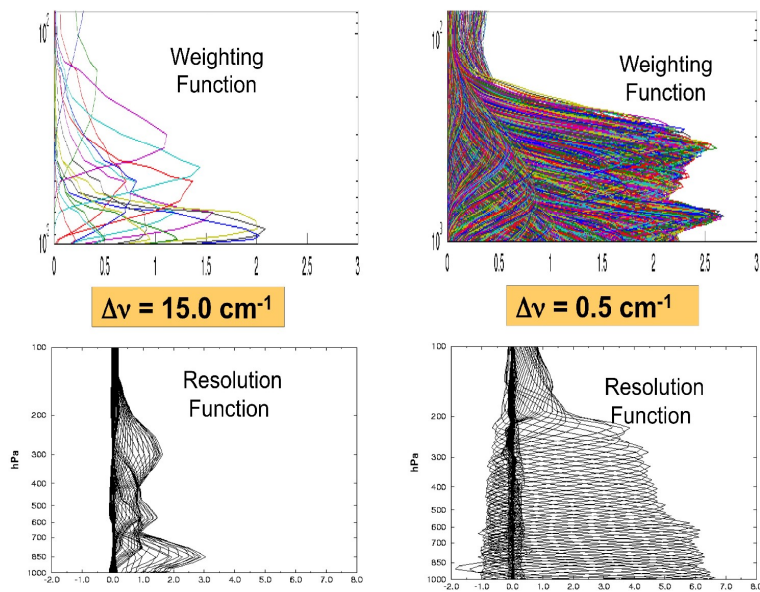


Fig. 2. The weighting functions and vertical profile resolution functions (i.e., averaging kernels) for two different instrument spectral resolutions.

6558

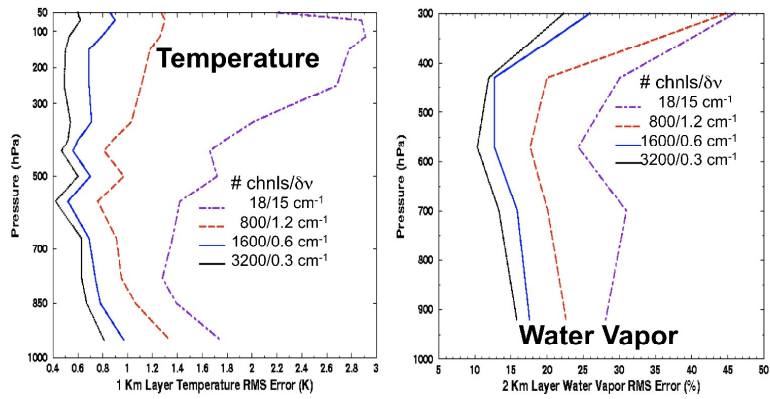


Fig. 3. Sounding RMS error as a function of spectral resolution and associated number of spectral radiance channels.

6559

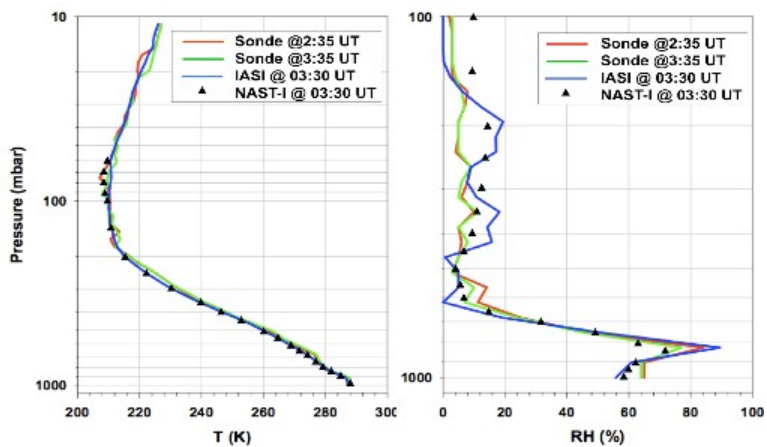


Fig. 4. IASI and NAST-I profile retrievals compared to special radiosondes at Lamont, Oklahoma on 19 April 2007.

6560

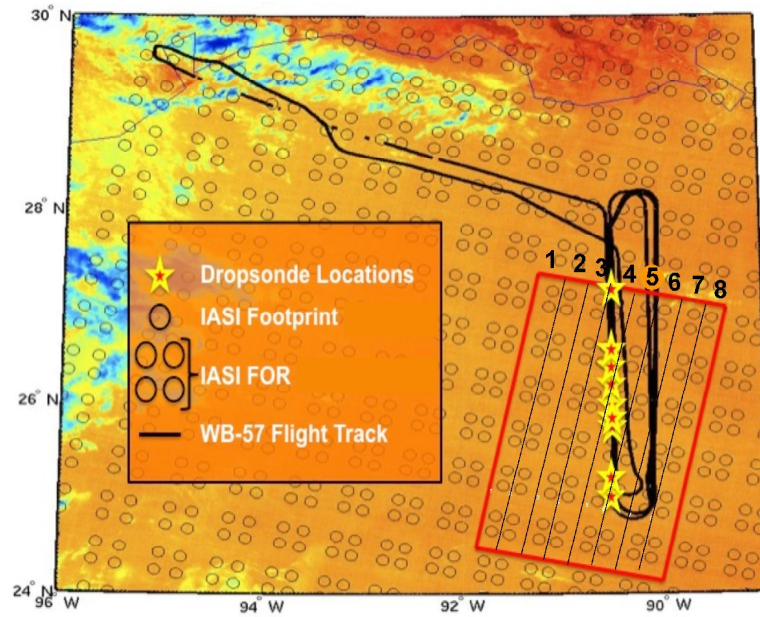


Fig. 5. The location of the IASI footprints, the aircraft flight track, and the dropsonde locations, superimposed upon a 10–12 μm infrared cloud image obtained with the IASI at 15:50 UTC on 29 April 2007. The red box delineates the validation area of interest.

6561

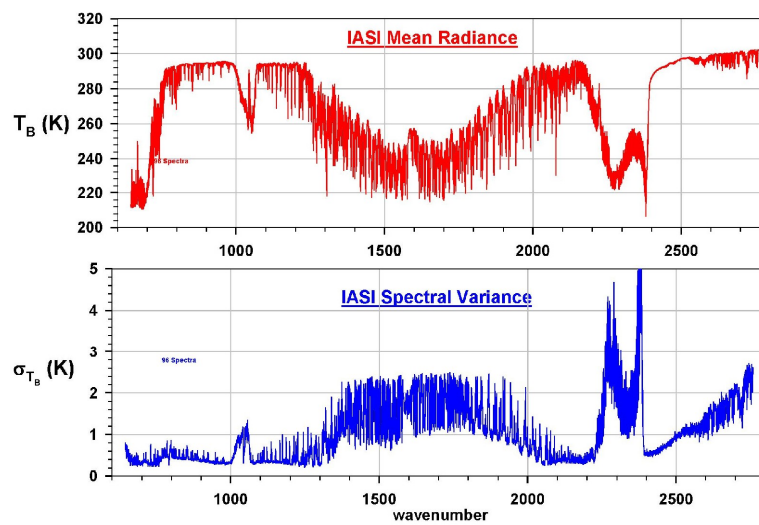


Fig. 6. Mean and standard deviation of the 96 IASI spectra obtained within the validation area (red box) shown in Fig. 5, above.

6562

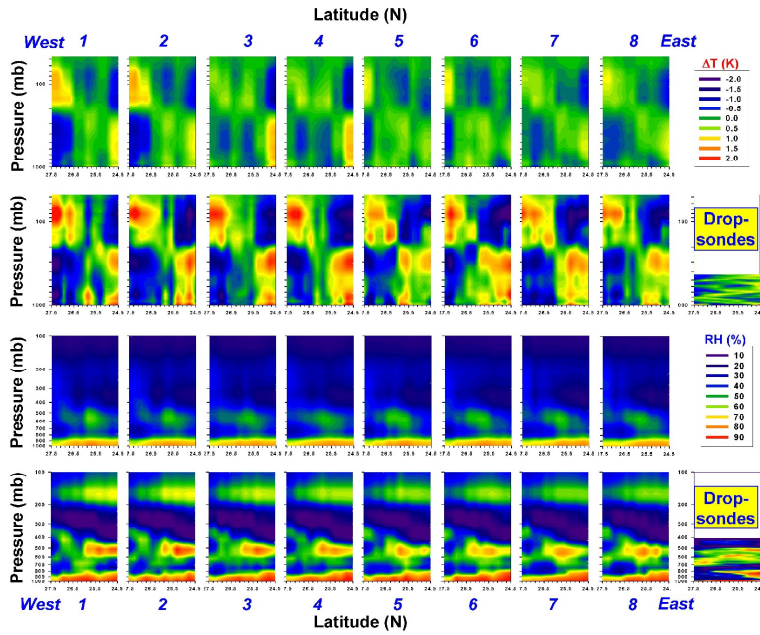


Fig. 7. North-South vertical cross-sections of atmospheric temperature deviation from the mean (upper two panels) and moisture relative humidity (lower two panels) for the eight columns of IASI footprints shown in Fig. 5. The upper panel for each variable corresponds to retrievals from the IASI simulated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

6563

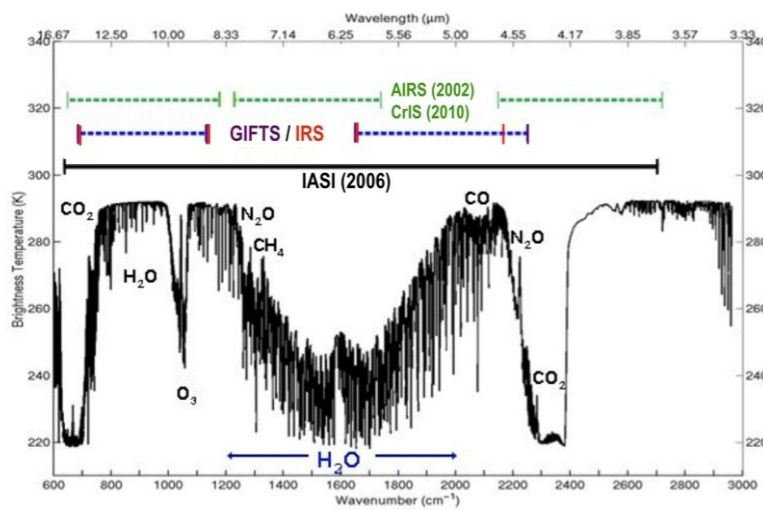


Fig. 8. Spectral coverage of various ultra-spectral sounding instruments.

6564

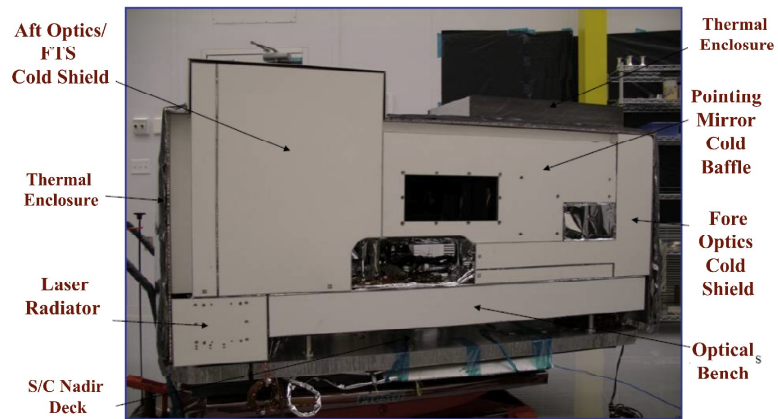


Fig. 9. The completed GIFTS-EDU instrument.

6565

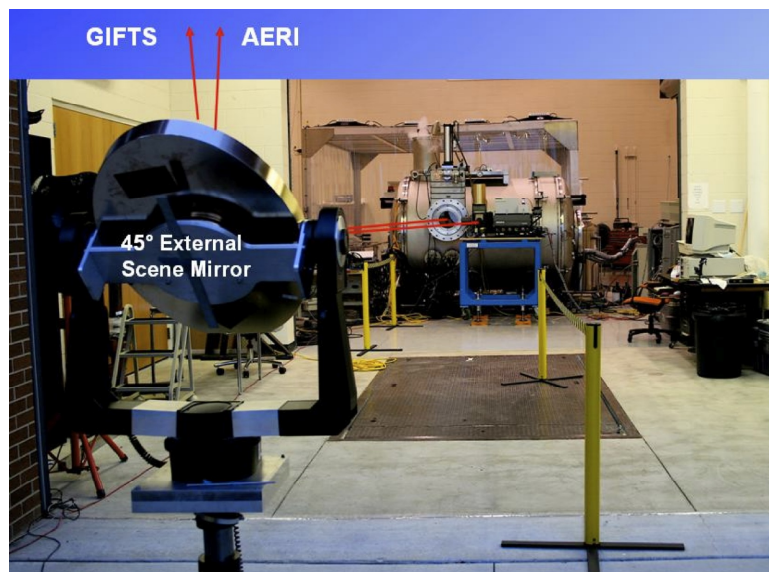


Fig. 10. The experimental configuration of the GIFTS and AERI instruments used for providing simultaneous measurements of the sky radiation from the Space dynamics Laboratory in Logan UT.

6566

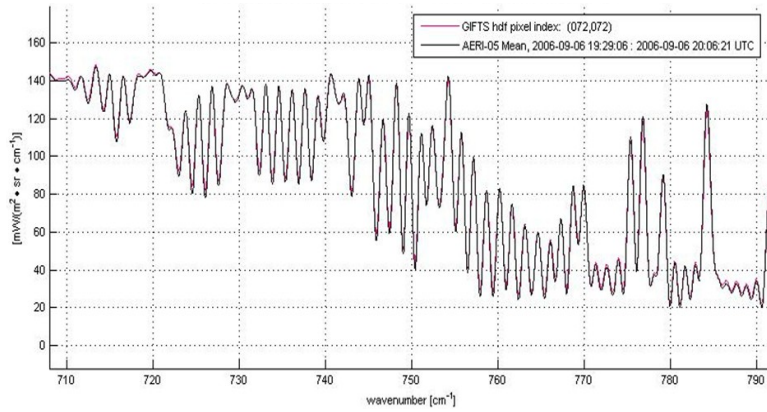


Fig. 11. Comparison of AERI and GIFTS CO₂ region spectra observed at Logan UT on 6 September 2006.

6567

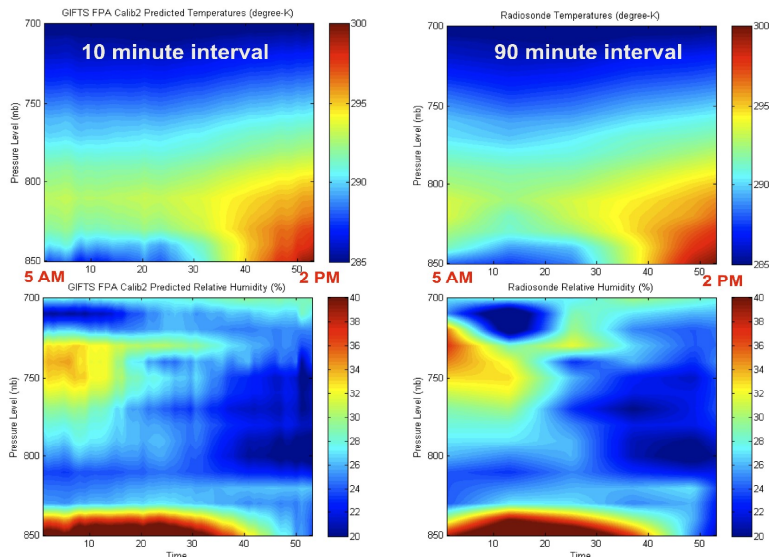


Fig. 12. Comparison of GIFTS retrieved and radiosonde temperature and moisture profiles observed at Logan UT on 13 September 2006.

6568

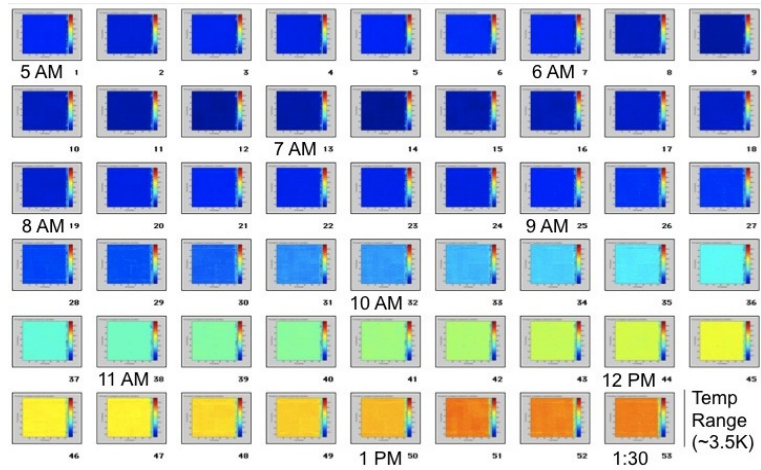


Fig. 13. Consecutive 10 min interval 128×128 detector element frames of 600-m level atmospheric temperature retrieved from GIFTS sky-viewing radiance observations at Logan UT on 13 September 2006.