ADVANCED SOUNDING SYSTEMS: THE POLAR ORBITING ITS AND THE GROUND-BASED AERI

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1. INTRODUCTION

A practical instrument design for substantially improving the TOVS sounding system is available, and the soundness of the approach has been proven with ground-based systems. The Interferometer Thermal Sounder (ITS) is a high spectral resolution advanced temperature and water vapor sounder, which is no larger than the current HIRS 3. It was designed for EUMETSAT by the High-resolution Interferometer Sounder (HIS) team (University of Wisconsin, Santa Barbara Research Center, and Bomem, Inc.), with the objective of achieving the simplest possible design for operational satellite sounding. No fundamental technological developments are needed to implement the ITS. In fact, ground-based instrumentation with a similar design concept is being installed for zenith viewing with 24-hour, unattended operation at the Southern Great Plains site for the Atmospheric Radiation Measurement (ARM) program. An outgrowth of the HIS program, the Atmospheric Emitted Radiance Interferometer (AERI) has been developed with support from the US DOE and has been used successfully in several field experiments. A future network of ground-based sounding instruments would provide a strong complement to the ITS for significantly advancing our ability to remotely sense the state of the atmosphere.

2. ITS: INTERFEROMETER THERMAL SOUNDER

The ITS was developed for operational implementation on the European Polar Satellite (EPS) in response to a recognition that higher vertical resolution soundings are important for improving global forecast models (UW/SBRC, 1991). Because of the role for ITS in the operational system, the instrument was designed to also be compatible with the NOAA polar platforms and to make use of mature, proven technology.

2.1 Sampling Characteristics and Radiometric Performance

The ITS will measure Earth emitted radiance at the high spectral resolution and the broad spectral coverage needed to provide high vertical resolution temperature and water vapor profiles. A sample ITS spectrum illustrating the resolution (resolving power of about 1000) and coverage from three separate spectral bands is shown in Figure 1. The unapodized resolution is 0.625 cm^{-1} for the longwave band I, 1.25 cm^{-1} for band II, and 2.5 cm^{-1} for the shortwave band III.

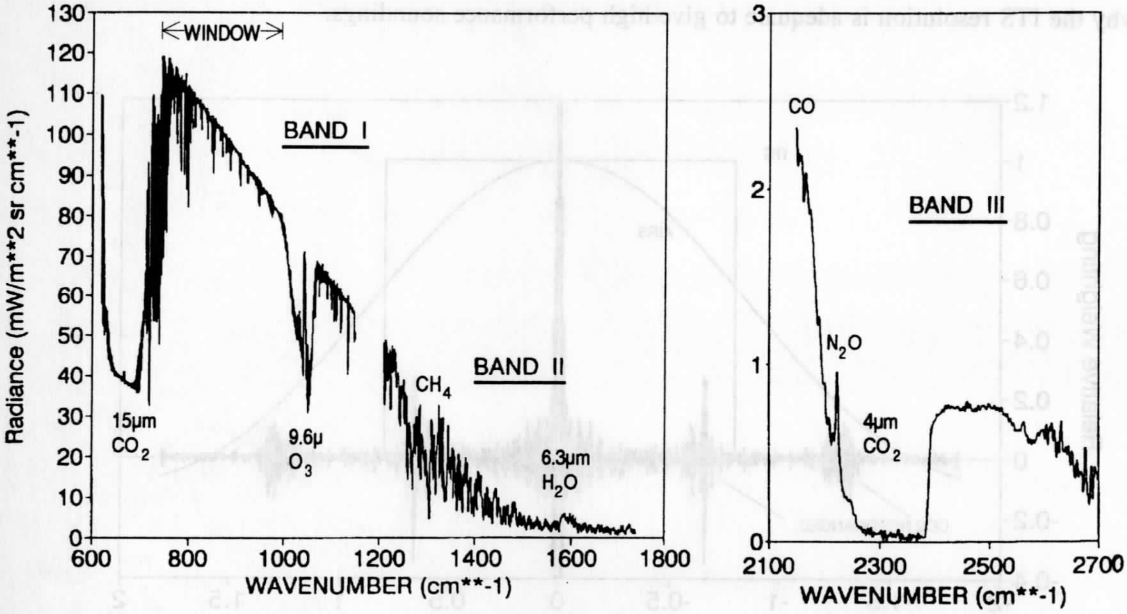


Figure 1. Sample atmospheric spectrum illustrating the ITS spectral bands. The spectrum is derived from a HIS observations from the NASA ER-2 over the Pacific Ocean on 14 April 1986.

The requirements for the ITS have been refined to optimize its efficiency in performing the operational task. Simulation studies show that essentially all of the sounding advantage offered by high spectral resolution IR measurements can be realized with resolutions two times lower than previously specified for HIS applications (W.L. Smith in UW/SBRC, 1991). The resolution in the region of the 15 micron carbon dioxide band is crucial. As Figure 1 shows, the ITS resolution is high enough to distinguish individual absorption lines, and to, thereby, substantially reduce the vertical smearing associated with low resolution measurements.

The spectral resolution for temperature and humidity sounding from the ITS is approximately equivalent to that of the Atmospheric Infrared Sounder (AIRS) grating instrument being developed as a facility instrument for the Earth Observing System (resolving power of 1200). Because of the different spectral resolution function shapes, the unapodized spectral resolution of a Fourier Transform instrument is roughly equivalent to the same resolution of a grating instrument for this application. A comparison of the weighting of the high spectral resolution information in a radiance spectrum by the ITS and by the AIRS is illustrated in Figure 2. The Fourier transform of a spectrum of the 15 micron CO_2 band, showing the high resolution CO_2 resonance regions caused by the equal spacing of the primary lines, indicates where the high resolution information is concentrated. While the AIRS samples about 20% of the second CO_2 resonance region near 1.3 cm which the ITS misses entirely, the ITS gets 100% of the larger first CO_2 resonance region near 0.65 cm that the AIRS weights only about 70%. This helps explain why the ITS resolution is adequate to give high performance soundings.

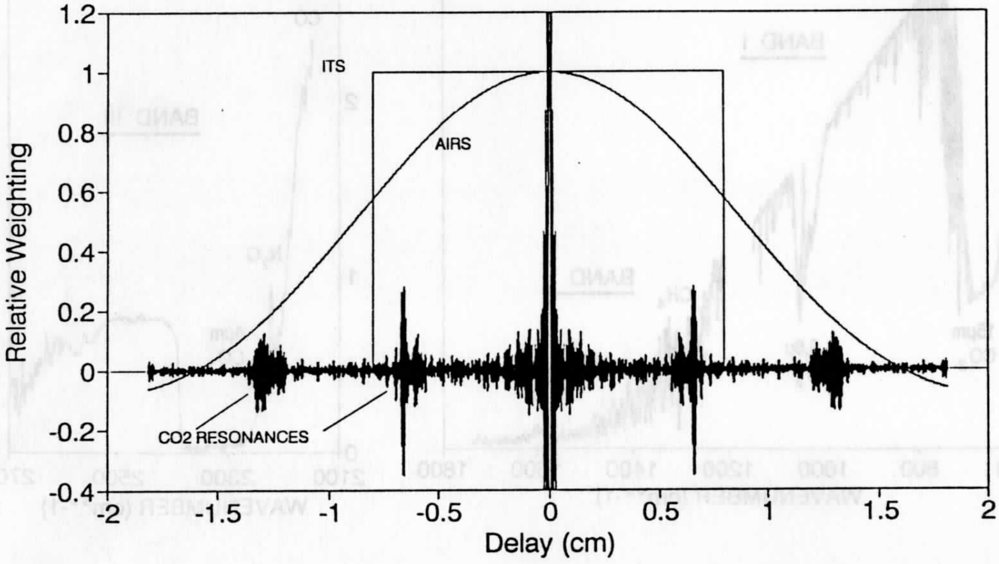


Figure 2. Fourier transform of a radiance spectrum for the 15 micron CO_2 band (600-800 cm^{-1}) compared to the transform of the spectral resolution functions for ITS and for AIRS. The weighting of the high resolution information in the CO_2 resonance regions is different, but roughly equivalent.

Simulated spectra from ITS and AIRS for the single most important region for temperature sounding are shown in Figure 3. Note that the peak-to-peak amplitudes of the lines are actually larger for the unapodized ITS spectrum than for the AIRS spectrum and that the water vapor contamination in this region is not significantly larger for the unapodized ITS spectrum than for the AIRS spectrum. The side-lobes of the ITS spectral resolution function do not substantially change the "spectral purity" of the ITS spectrum in this region, because of the low resolution influence of the water vapor continuum.

The ITS spatial resolution and coverage are illustrated in Figure 4. A 3x3 array of 10 km fields of view sample a 50x50 km region during each of 30 cross-track dwell times. The 10 km spot size offers good cloud clearing opportunities, and the array size and cross-track scan timing are chosen to facilitate common processing with data from the advanced microwave instruments.

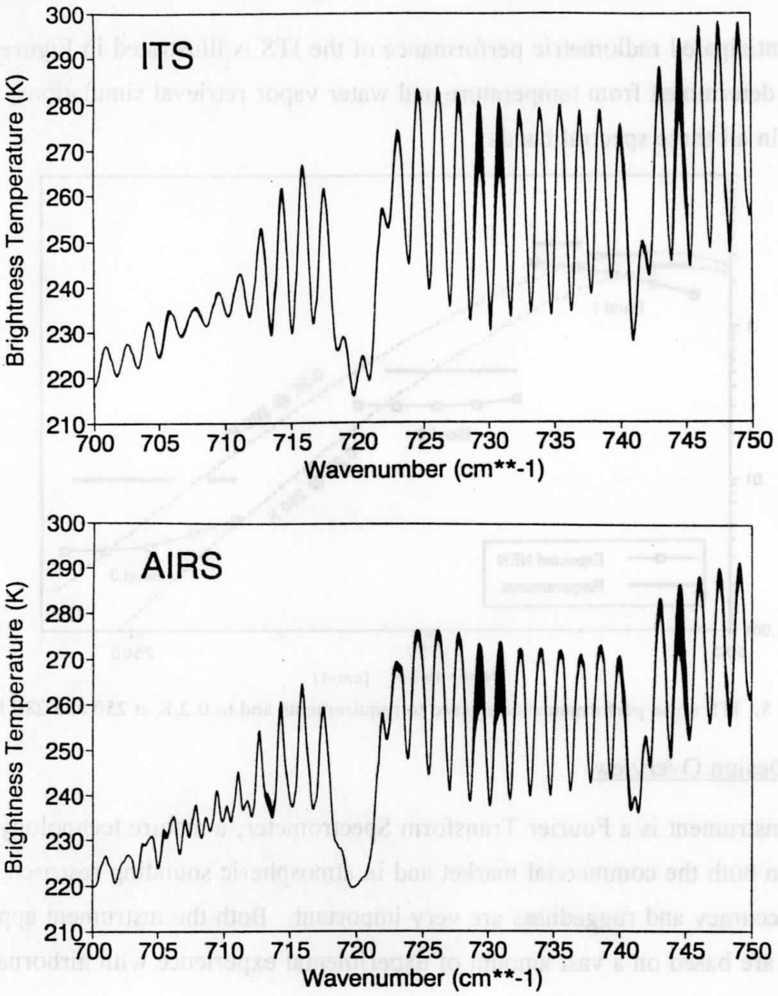
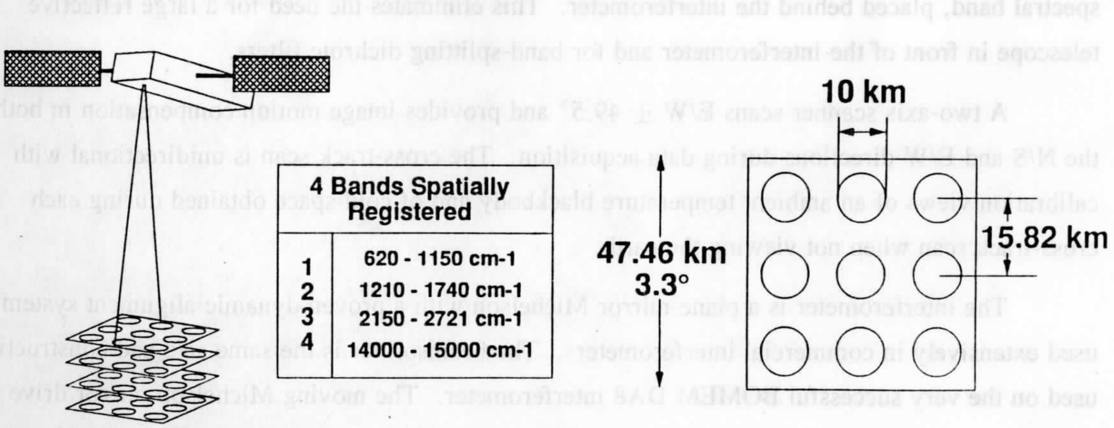


Figure 3. ITS (top) and AIRS (bottom) spectra for the US standard atmosphere using FASCOD3 line-by-line calculation with HITRAN92 line files. Water contributions are shown by the shaded regions.



4 Bands Spatially Registered	
1	620 - 1150 cm-1
2	1210 - 1740 cm-1
3	2150 - 2721 cm-1
4	14000 - 15000 cm-1

Figure 4. ITS spatial resolution and coverage pattern.

The anticipated radiometric performance of the ITS is illustrated in Figure 5. The required performance, determined from temperature and water vapor retrieval simulations, is achieved with some margin in all three spectral bands.

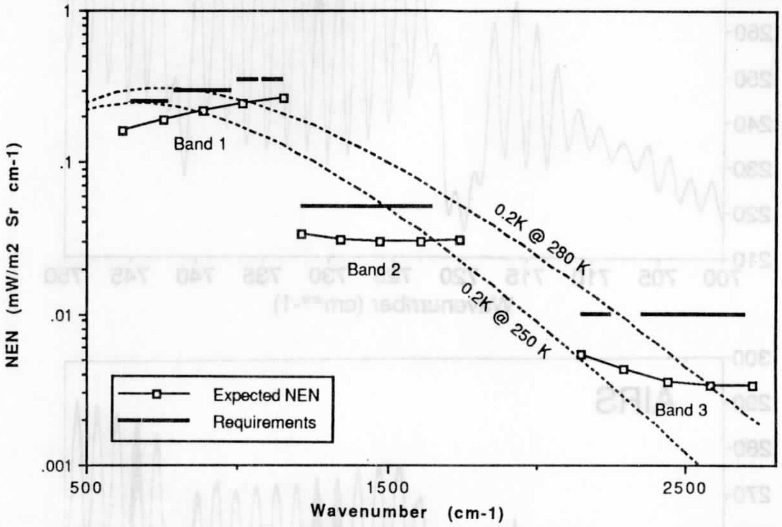


Figure 5. ITS noise performance compared to requirements and to 0.2 K at 250 and 280 K.

2.1 ITS Design Overview

The instrument is a Fourier Transform Spectrometer, a mature technology that has been well proven in both the commercial market and in atmospheric sounding research, where high radiometric accuracy and ruggedness are very important. Both the instrument approach and the requirements are based on a vast amount of experimental experience with airborne and ground-based interferometer measurements.

The basic layout of the instrument optical bench is shown in Figure 6. Note the optical simplicity and compactness. The telescopes are simple refractive elements, one for each IR spectral band, placed behind the interferometer. This eliminates the need for a large reflective telescope in front of the interferometer and for band-splitting dichroic filters.

A two-axis scanner scans E/W ± 49.5° and provides image motion compensation in both the N/S and E/W directions during data acquisition. The cross-track scan is unidirectional with calibration views of an ambient temperature blackbody and of cold space obtained during each cross-track scan when not viewing the earth.

The interferometer is a plane-mirror Michelson with a proven dynamic alignment system used extensively in commercial interferometers. The beamsplitter is the same size and construction used on the very successful BOMEM DA8 interferometer. The moving Michelson mirror drive is a dual porch swing design, which allows the different resolution requirements of the three spectral bands to be accommodated, without pushing the capabilities of available analog-to-digital converters.

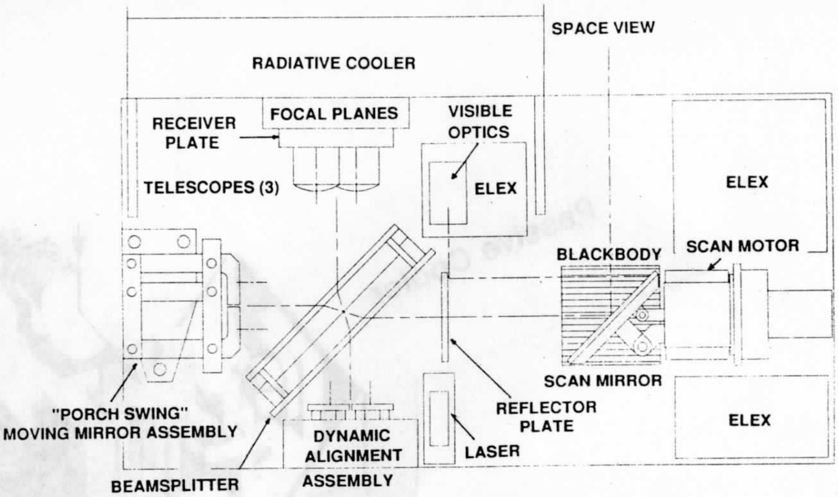


Figure 6. ITS basic electro-optical design.

The three coaligned telescopes behind the interferometer allow a simple, compact interface to the detectors and to the radiative cooler. A 3 x 3 array of infrared detectors is located immediately behind an array of field stops at the focal plane of each telescope. These arrays use PV HgCdTe and PC HgCdTe detectors and associated electronics of the same type used on current operational sounders. A new flat-panel radiative cooler design provides the desired 85 K detector temperature. The data system uses a highly redundant approach which can reliably reduce the data rate to 1.15 Mbps.

The ITS concept offers high performance with low development risk in a compact, lightweight design. The overall instrument form and envelope is shown in Figure 7. The small size and power requirements are quite exciting, because they are very similar to those for the current HIRS filter wheel sounder. Therefore, the advanced capabilities of the ITS can be made available without major changes to the level of spacecraft resources already needed for HIRS.

2.3 ITS Summary

The ITS, by providing high spectral resolution measurements (resolving power of 1000) with a mature and well proven technology, represents the next logical step for improving global, operational remote sensing from polar-orbiting infrared observations. The instrument has been optimized for operational meteorological sounding by reducing the design to the essentials needed to achieve sounding objectives with a minimum of spacecraft resources. The ITS has overall size and power requirements that are very similar to those of the HIRS, but tropospheric temperature water vapor sounding capabilities approaching the ultimate possible from passive IR sounding. The use of proven Fourier Transform Spectroscopy will make it possible to realize this vital improvement as soon as possible.

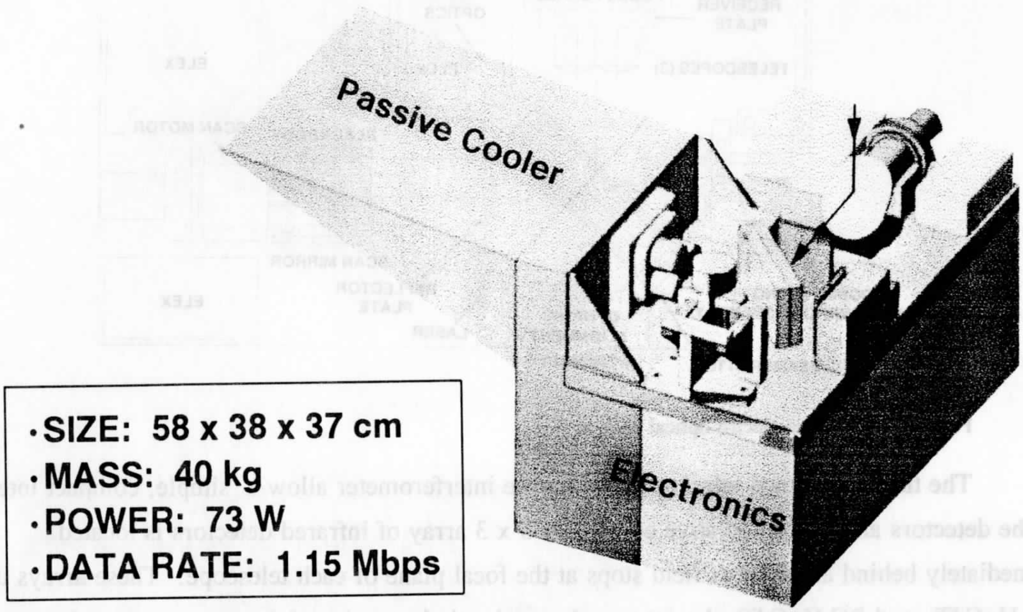


Figure 7. Overall ITS design characteristics.

3. AERI: ATMOSPHERIC EMITTED RADIANCE INTERFEROMETER

The AERI is a ground-based system that measures accurately calibrated spectra of downwelling radiance for atmospheric radiation studies and for remote sensing. It provides a new capability for continuous boundary layer sounding to complement both satellite and other ground-based observations and demonstrates the soundness of the fundamental design principles of the ITS.

3.1 AERI Measurement Characteristics

The spectral measurement characteristics of the AERI are illustrated in Figure 8 by the sample clear sky spectra collected during the DOE Spectral Radiance Experiment (SPECTRE) conducted in Coffeyville, Kansas in the Fall of 1991. When the first operational version of AERI is installed at the Southern Great Plains ARM site this year, spectra of this type will soon be collected every 10 minutes, 24 hours a day.

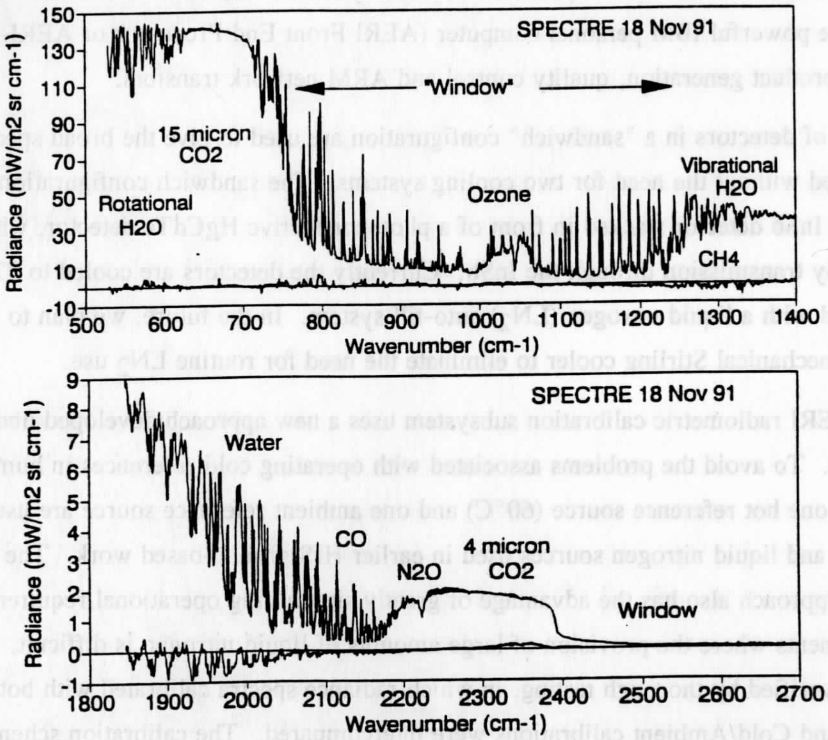


Figure 8. Sample spectra from the AERI longwave and shortwave bands. The difference of the measurements from spectra calculated with the Air Force Philips Lab line-by-line program (FASCOD3) is also shown.

The spectral coverage is essentially continuous from 3 to 19 microns, although regions with little spectral interest such as the opaque portions of the 6.3 micron water band are not shown. In addition to sky radiances, the AERI instrument generates spectra of the standard deviation during the 4 minute sky view, which allow the stability of the sky view to be assessed. To satisfy the requirements for verifying radiative transfer models and for remote sensing, the AERI incorporates state-of-the-art radiometric performance. The absolute calibration accuracy is better than 1% of the ambient radiance, and the calibration reproducibility and noise levels are less than a few tenths of a percent (Revercomb, et al., 1993).

3.2 AERI System Design

The AERI instrument is an advanced version of the "Baby HIS", a prototype designed and fabricated at UW in 1989 as part of the HIS Program (Smith, et al., 1987/89; Revercomb, et al., 1988a). AERI employs a commercially available interferometer (Michelson Series MB100 from Bomem, Inc. of Quebec, Canada), with corner-cube Michelson mirrors mounted on a common rocking arm supported by flex pivots. It has proven to be very rugged and dependable. The interferometer data is digitized in the MB100 module, transferred to an IBM personal computer in the electronics module where it is Fourier transformed by a DSP card and stored, and then linked to another more powerful IBM personal computer (AERI Front End Processor or AERI-FEP) for data analysis, product generation, quality control and ARM network transfers.

A pair of detectors in a "sandwich" configuration are used to give the broad spectral coverage desired without the need for two cooling systems. The sandwich configuration consists of a shortwave InSb detector stacked in front of a photoconductive HgCdTe detector, which views the longwave by transmission through the InSb. Currently the detectors are cooled to 77 K using a dewar equipped with a liquid nitrogen (LN_2) auto-fill system. In the future, we plan to incorporate a mechanical Stirling cooler to eliminate the need for routine LN_2 use.

The AERI radiometric calibration subsystem uses a new approach developed under the ARM program. To avoid the problems associated with operating cold references in humid environments, one hot reference source (60°C) and one ambient reference source are used instead of the ambient and liquid nitrogen sources used in earlier HIS ground-based work. The Hot/Ambient approach also has the advantage of greatly simplifying operational requirements in many environments where the provision of large amounts of liquid nitrogen is difficult. The new approach was verified by thorough testing, in which radiance spectra calibrated with both Hot/Ambient and Cold/Ambient calibrations were intercompared. The calibration scheme involves periodic cycling through two-minute views of the reference blackbodies and four-minute zenith sky views to yield a calibrated sky spectrum approximately every 10 minutes.

The blackbody reference sources are high emissivity cavities (about 0.995) carefully designed, fabricated, and tested at the UW to provide the extremely well characterized sources required for the Hot/Ambient calibration (Best, et al., 1992). The hot and ambient sources are of identical design, although the temperature of the hot source is controlled to 60°C while the ambient source is allowed to float. Cavity temperature monitors have been carefully calibrated and referenced to NIST standards using a Guildline digital Platinum Resistance Thermometer. Thermal models show that the temperature gradients in the hot reference cavity are less than 0.3 °C.

Extensive real time analysis is performed in the AERI-FEP, yielding accurately calibrated radiances on a standard wavenumber scale (to simplify spectral calculations when more than one AERI is being used). The basic analysis functions include longwave channel nonlinearity correction, complex radiometric calibration, finite field of view correction, and wavelength calibration and scale standardization. The technique used to correct for HgCdTe detector non-linearity is new (Revercomb, et al., 1992b).

Because of the operational aspects of the deployment for ARM an automated system has been developed which would be well suited to operational ground-based weather applications.

3.3 AERI Field Experience

The AERI prototype has been extensively tested in the field. It operated very successfully in three campaigns, including the Spectral Radiance Experiment (SPECTRE) at Coffeyville Kansas conducted by DOE in conjunction with the NASA FIRE cirrus cloud study (11 Nov. - 7 Dec. 1991), the joint agency STORM-FEST program at the boundary layer site near Seneca Kansas (1 Feb. - 15 Mar. 1992), and aboard the research ship Point Sur off Monterey California for Navy sponsored atmospheric refractivity observations (8-11 May 1992). We present a small sampling of results to illustrate the high quality of the AERI data for precise radiometric applications.

Examples of differences between observed and calculated spectra are shown for selected water vapor features in Figure 9. These are both regions where verification of radiative transfer models for the long paths and variable temperatures of the actual atmosphere is important. The two STORM-FEST spectra on the top section of Figure 9 are in excellent agreement with calculations for the weak lines from 1100 to 1225 cm^{-1}, a region which consistently showed large differences before the recent update of the HITRAN line parameter data base (Revercomb, et al., 1989b; 1990; 1991). The bottom section of Figure 9 illustrates consistent differences in a region where the water vapor continuum from foreign broadening needs substantial improvement (Revercomb, et al., 1989b). The region around 2000 cm^{-1} which shows large differences between AERI and FASCOD3 (Figure 8) is also believed to be due to deficiencies in the water continuum (Knuteson, et al., 1993; Theriault, et al., 1991).

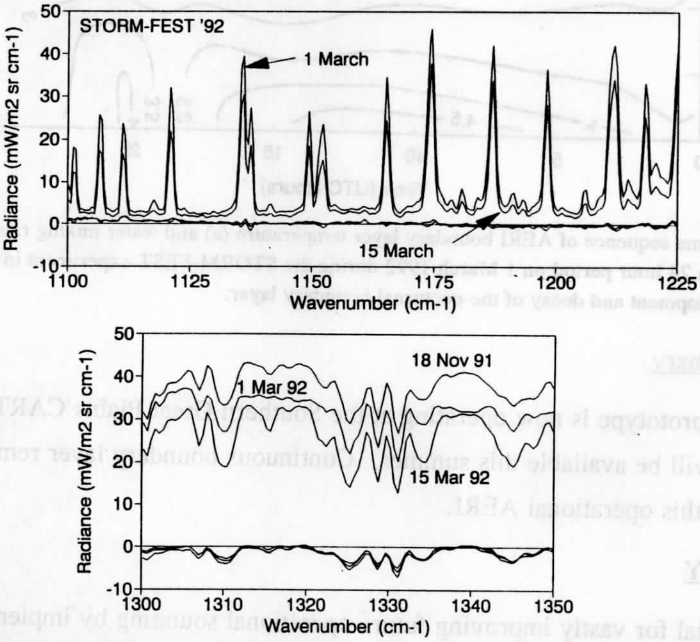


Figure 9. Examples from STORM-FEST of water vapor spectroscopy for which recent improvements have been made (upper) and for which improvements are still needed (lower). The curves plotted about the zero line are differences between AERI observations and FASCODE calculations.

Accurate techniques to retrieve profiles from AERI spectra have been developed (Smith, et al., 1993a,b) and will soon be applied routinely to AERI data for ARM. An example of the excellent time continuity possible from AERI retrievals is shown in Figure 10.

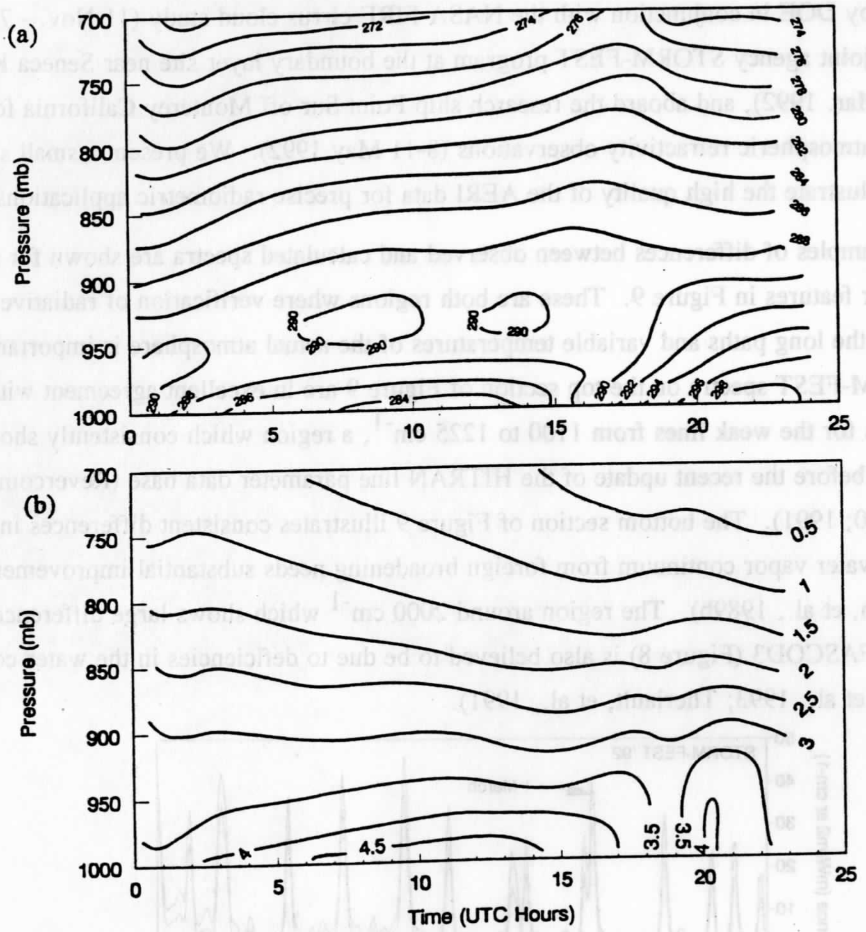


Figure 10. Time sequence of AERI boundary layer temperature (a) and water mixing ratio (b) retrievals for a 24 hour period on 1 March 1992 during the STORM-FEST experiment in Seneca KS. Note the development and decay of the nocturnal boundary layer.

3.4 AERI Summary

The AERI prototype is now operating at the Southern Great Plains CART site, and the first operational AERI will be available this summer. Continuous boundary layer remote sensing will be performed with this operational AERI.

4. SUMMARY

The potential for vastly improving future operational sounding by implementing these advanced instruments as part of a complement of satellite and surface sounding systems is quite exciting. With ITS in orbit and the establishment of a ground-based IR sounding system, the full potential for higher vertical resolution from remote sounding can be closely approached.

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