High Spectral Resolution Fourier Transform Infrared Instruments for the Atmospheric Radiation Measurement Program

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Accurate and spectrally detailed observations of the thermal emission from radiatively important atmospheric gases, aerosols, and clouds have been identified as crucial for realizing the overall objectives of the Atmospheric Radiation Measurement (ARM) Program to improve the treatment of radiation and clouds in climate models. The observed spectra will be used for many diverse functions, including identifying and eliminating absolute errors in calculated spectra for known atmospheric states; evaluating and improving cloud radiation calculations; characterizing the distribution and evolution of effective cloud radiative properties; and studying the state parameter changes associated with cloud formation, evolution, and dissipation.

The deployment of several high spectral resolution instruments at each of the geographically distributed ARM Cloud and Radiation Testing (CART) sites will characterize climatologically diverse conditions, including the temporal and spatial properties of atmospheric weather systems. As part of the Instrument Development Program (IDP), the University of Wisconsin (UW) and the University of Denver (UD) are developing three types of Fourier transform infrared (FTIR) instruments: the Atmospheric Emitted Radiance Interferometer (AERI), the AERI-X and the Solar Radiance Transmission Interferometer. The spectral characteristics of these instruments are defined in Table 1.

The AERI prototype, built by the UW, will be deployed at the Southern Great Plains CART site in March and is the primary subject of this paper. Operational versions of the AERI will be installed both at the central site and at four extended boundary locations to sample horizontal inhomogeneities for radiometric studies and for remote sensing. The ultra-high-resolution Solar Radiance Transmission Interferometer (SORTI) (built by the UD) is operating successfully at UD and will be tested at a CART this summer. The radiometric performance of the 0.1 cm^{-1} AERI-X interferometer subsystem being developed by the UD will be demonstrated this year. The complete AERI-X system will make use of the AERI calibration, operational control, and analysis subsystems. More details on the SORTI and the AERI-X will be provided at a later date.

AERI Measurement Characteristics

The spectral measurement characteristics of the AERI are illustrated in Figure 1 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 a CART this year, spectra of this type will soon be collected

Table 1. System Configurations Summary.

	AERI	AERI-X	SORTI
Function	Zenith Viewing Atmospheric Emission	Extra High-Resolution Zenith Viewing Atmospheric Emission	Ultra-High-Resolution by Solar Tracking for Atmospheric Transmission
Spectral Coverage	3-19 µm	7-14 µm	3-13 µm
Spectral Resolution	1 cm^{-1}	0.1 cm^{-1}	0.003 cm^{-1}
Calibration Sources	2-3 high emissivity blackbodies	2 high emissivity blackbodies	Uses airmass variation to derive transmission

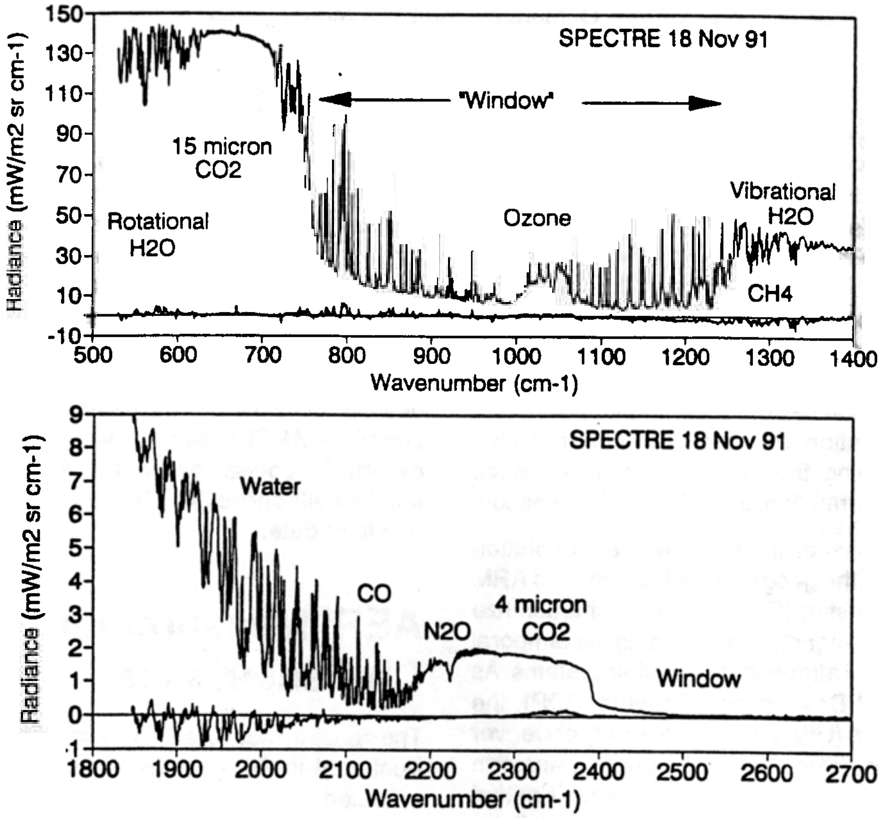

Figure 1. Sample spectra from the AERI longwave and shortwave bands. The difference of the measurements from spectra calculated with the Air Force Phillips Lab line-by-line program (FASCOD3) is also shown.

every 10 minutes, 24 hours a day. 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. The spectra shown are apodized to a resolution of 1 cm^{-1}, high enough to generally separate features caused by broad continua or cloud reflectance from those of absorption lines. 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 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).

AERI System Design

The AERI instrument is an advanced version of the "Baby HIS" (high spectral resolution interferometer sounder), 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 cornercube Michelson mirrors mounted on a common rocking arm supported by flex pivots. It has proven to be very rugged and dependable. The interferometer data are digitized in the MB100 module, transferred to an IBM personal computer in the electronics module. Here it is Fourier transformed by a DSP card and stored, 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 is 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 developed during the IDP. In the future, we plan to incorporate a mechanical Stirling cooler to eliminate the need for routine use of LN_2.

The AERI radiometric calibration subsystem uses a new approach developed under the ARM program IDP. 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 providing 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 2-minute views of the reference blackbodies and 4-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 National Institute for Standards and Technology (NIST) standards using a Guideline 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 radiometric and wavelength calibration implement techniques developed under the HIS program at UW (Revercomb et al. 1987/89; 1988b; 1989a) have been verified under the IDP by intercomparison tests with the HIS aircraft instrument. The technique used to correct for HgCdTe detector nonlinearity is new and was developed during the IDP. In addition, a technique for accurately defining the spectral resolution function from self-apodization was also developed.

Because of the operational aspects of the CART deployment, a major effort has been devoted to developments required for automated operations. Significant software development has been performed to accomplish reliable operation:

- analysis computer resource allocation
- ARM network interface
- intra-AERI network for data transfer to AERI-FEP
- power failure recovery software
- daily reset for data set management
- AERI status interrogation
- QC displays of spectra and housekeeping
- remote modification of operating configuration
- LN_2 auto-fill system for detector dewar

Relatively minor modifications will make most of this software directly applicable to support the task of making the AERI-X operational, as proposed here.

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 in conjunction with the National Aeronautics and Space Administration's First ISCPP Regional Experiment cirrus cloud study (11 November - 7 December 1991); the joint agency STORM Fronts Experiment Systems Test (STORM-FEST) program at the boundary layer site near Seneca, Kansas, (1 February - 15 March 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 ARM Program applications.

An example of cloudy brightness temperature spectra from SPECTRE is shown in Figure 2. As found with HIS aircraft observations, clouds often do not behave as pure "blackbodies" for which the brightness temperature would be constant in the regions between absorption lines in the atmospheric window between 8 and 13 microns (770-1250 cm^{-1}). The low cloud spectrum in the figure is close to that of a pure blackbody cloud, but the middle cloud shows major derivations from that simple behavior. The deviations from blackbody behavior are being used to derive cloud microphysical properties (Smith et al. 1993).

Examples of differences between observed and calculated spectra are shown for selected water vapor features in Figure 3. These are both regions where verification for the long paths and variable temperatures of the actual atmosphere is important.

The two STORM-FEST spectra on the top section of Figure 3 are in excellent agreement with calculations for the weak lines from 1100 to 1225 cm^{-1}, a region which

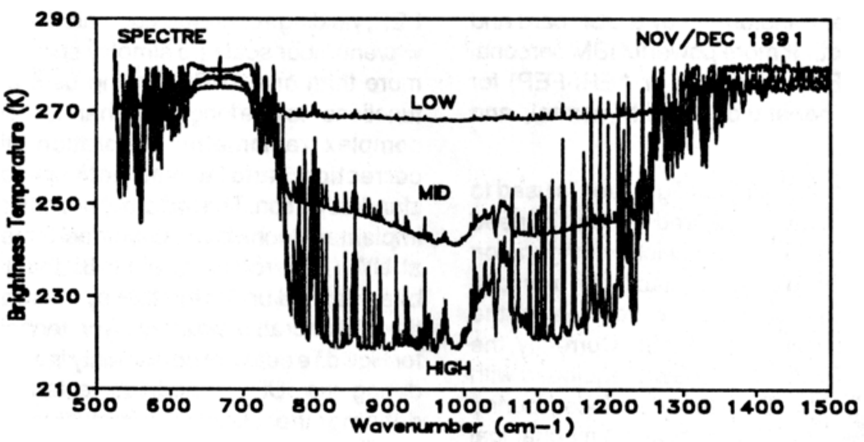

Figure 2. AERI measurements of the downwelling spectra of clouds showing deviations from pure blackbody emission.

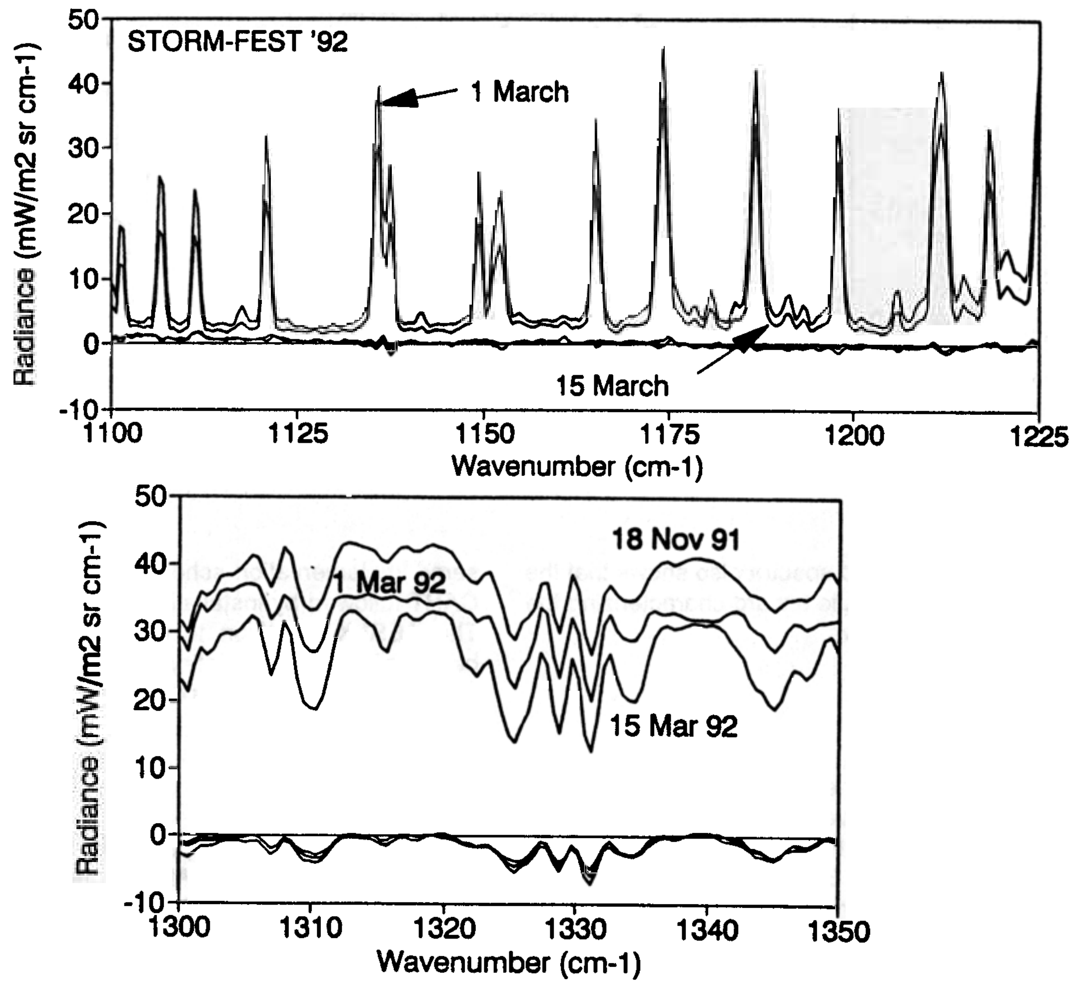

Figure 3. Examples from STORM-FEST of water vapor spectroscopy for which recent improvements have been made (upper) and for which improvements are still needed (lower). The curves plotted about the zero line are differences between AERI observations and FASCODE calculations.

consistently showed large differences before the recent update of the HITRAN line parameter database (Revercomb et al. 1989b; 1990; 1991). The bottom section of Figure 3 illustrates substantial, 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, is also believed to be due to deficiencies in the water continuum (Knuteson et al. 1993; Theriault et al. 1991).

The influence of atmospheric temperature structure on the downwelling radiance spectrum is illustrated in Figure 4, which shows a close-up of the 15 micron CO_2 band. The positive curvature of the general radiance trend between 625 and 710 cm^{-1} is indicative of a temperature inversion in the atmospheric boundary layer, as was present on 1 March 1992 during this observation. The negative curvature of the same region for the 15 March spectrum shows that the temperature decreased with altitude in the boundary layer. The excellent correspondence of the detailed features of

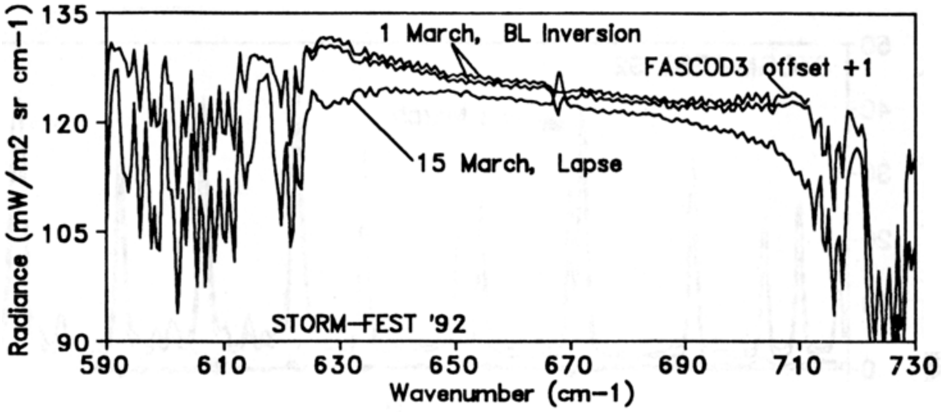

Figure 4. Spectra illustrating the strong sensitivity of high resolution downwelling radiances to the temperature lapse rate.

the calculated and observed spectra also shows that the individual CO_2 lines contribute toward characterizing the vertical temperature structure.

Summary

Major accomplishments of the AERI IDP effort have been to 1) develop and extensively test a new radiometric calibration subsystem with improved accuracy and robustness; 2) interact with Bomem, Inc., leading to the development of a two-channel interferometer with the required software characteristics; 3) develop new operational control software and network interfaces; 4) develop new analysis techniques to handle the complete calibration, including a detector nonlinearity correction, wavelength scale standardization, and a finite field-of-view correction; 5) integrate the required hardware, operational control software, and analysis software into a complete system which interfaces to the CART data system and operates remotely without the attendance of expert operators; and 6) perform extensive field testing of the AERI system prototype.

The AERI prototype is operating at the Southern Great Plains CART site, and the first operational AERI has had extensive field testing in preparation for deployment at CART. We expect the SORTI and the AERI-X to follow the same implementation scheme, with prototype testing at CART followed by installation of an operational version. The AERI-X transition to operations should be rapid, because it will make use of systems for real-time processing and automatic operations developed for the AERI.

References

Best, F. A., H. E. Revercomb, R. O. Knuteson. 1992. Calibration Issues for the Atmospheric Emitted Radiance Interferometer (AERI). Utah State University, Logan, Utah, September 14-16, 1992.

Knuteson, R. O., H. E. Revercomb, W. L. Smith. 1993. Forward Model Comparisons with the High-resolution Interferometer Sounder (HIS). *Proceedings of the Optical Remote Sensing of the Atmosphere Sixth Topical Meeting*, Salt Lake City, Utah, March 8-12, 1993. Optical Society of America, Washington, D.C.

Revercomb, H. E., H. Buijs, H. B. Howell, R. O. Knuteson, D. D. LaPorte, W. L. Smith, L. A. Sromovsky, and H. W. Woolf. 1987/1989. Radiometric Calibration of IR Interferometers: Experience from the High-resolution Interferometer Sounder (HIS) Aircraft Instrument. *RSRM '87: Advances in Remote Sensing Retrieval Methods*, eds., A. Deepak, H. Fleming, J. Theon. A. Deepak Publishing, Hampton, Virginia.

Revercomb, H. E., D. D. LaPorte, W. L. Smith, H. Buijs, D. G. Murcray, F. J. Murcray, and L. A. Sromovsky. 1988a. High-Altitude Aircraft Measurements of Upwelling IR Radiance: Prelude to FTIR from Geosynchronous Satellite. *Mikrochimica Acta [Wien]* **11**:439-444.

Revercomb, H. E., H. Buijs, H. B. Howell, D. D. LaPorte, W. L. Smith, and L. A. Sromovsky. 1988b. Radiometric Calibration of IR Fourier Transform Spectrometers: Solution to a Problem with the High Resolution Interferometer Sounder. *Appl. Opt.* **27**:3210-3218.

Revercomb, H. E., W. L. Smith, L. A. Sromovsky, R. O. Knuteson, H. Buijs, D. D. LaPorte, and H. B. Howell. 1989a. Radiometrically Accurate FTS for Atmospheric Emission Observations. *Proceedings 7th International Conference on Fourier Transform Spectroscopy*, ed., D. G. Cameron. *SPIE* Vol **1145**.

Revercomb, H. E., W. L. Smith, R. O. Knuteson, H. M. Woolf, and H. B. Howell. 1989b. Comparisons of FASCODE Spectra with HIS Observations. *Proceedings of the 12th Annual Review Conference on Atmospheric Transmission Models*, 5-7 June, eds., E. P. Shettle and F. X. Kneizys, Optical/Infrared Technology Division, Geophysical Laboratory, Hanscom Air Force Base, Massachusetts.

Revercomb, H. E., R. O. Knuteson, W. L. Smith, H. M. Woolf, and H. B. Howell. 1990. Spectroscopic Inferences from HIS Measurements of Atmospheric Thermal Emission. *Optical Remote Sensing of the Atmosphere, 1990 Technical Digest Series*, Vol 4. Optical Society of America, Washington, D.C.

Revercomb, H. E., R. O. Knuteson, W. L. Smith. 1991. High-resolution Spectral Measurements of Upwelling and Downwelling Atmospheric Infrared Emission with Michelson Interferometers. *Proceedings of the 14th Annual Review Conference on Atmospheric Transmission Models*, eds., L. W. Abreu and F. X. Kneizys, Phillips Laboratory, Hanscom Air Force Base, Massachusetts. Report #PL-TR-92-2059 SR, No. 267. Hanscom Air Force Base, June 11-12, 1991.

Revercomb, H. E., F. A. Best, R. G. Dedecker, T. P. Dirkx, R. A. Herbsleb, R. O. Knuteson, J. F. Short, and W. L. Smith. 1993. Atmospheric Emitted Radiance Interferometer (AERI) for ARM. *Fourth Symposium on Global Change Studies*. 73rd Annual Meeting of the American Meteorological Society, Anaheim, California, Jan 17-22, 1993. American Meteorological Society, Boston, Massachusetts.

Smith, W. L., H. M. Woolf, H. B. Howell, H.-L. Huang, and H. E. Revercomb. 1987/1989. The Simultaneous Retrieval of Atmospheric Temperature and Water Vapor Profiles - Application to Measurements with the High-resolution Interferometer Sounder (HIS). *RSRM '87: Advances in Remote Sensing Retrieval Methods*, eds., A. Deepak, H. Fleming, J. Theon. A. Deepak Publishing, Hampton, Virginia.

Smith, W. L., X. L. Ma, S. A. Ackerman, H. E. Revercomb, and R. O. Knuteson. 1993. Remote Sensing Cloud Properties from High Spectral Resolution Infrared Observations. *J. Appl. Meteorol.*, in press.

Theriult, J.-M., H. E. Revercomb, R. O. Knuteson, and H.-L. Huang. 1991. Intercomparison of FIT and HIS spectral measurements with FASCODE calculations in the 7-11 μm region. *Optical Remote Sensing of the Atmosphere*, Williamsburg, Virginia, November, 1991. Optical Society of America, Washington, D.C.