Atmospheric Emitted Radiance Interferometer (AERI): Status and the Aerosol Explanation for Extra Window Region Emissions

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Introduction

High spectral resolution observations of downwelling emission from 3 to l9 microns have been made by the Atmospheric Emitted Radiance Interferometer (AERI) Prototype at the Southern Great Plains (SGP) Cloud and Radiative Testbed (CART) site for over two years. The spectral data set from AERI provides a basis for improving clear sky radiative transfer; determining the radiative impact of clouds, including the derivation of cloud radiative properties; defining the influences of aerosols in the window regions; and retrieving boundary layer state properties, including temperature, water vapor, and other trace gases. The data stream of radiometrically and spectrally calibrated radiances is routinely provided by Pacific Northwest Laboratory (PNL) to those science teams requesting it, and further information on the instrument and data characteristics is available in the ARM Science Team proceedings for 1993 and 1994 (Revercomb et al.; Smith et al.) and in several conference publications (Revercomb et al. 1993a,b, 1994; Smith et al. 1993).

The emphasis of this science team project is 1) monitoring the AERI performance at CART to define improvements for the design of the operational AERIs and AERI-X systems support; 2) improving our understanding of the radiative transfer of the clear sky, including aerosols; and 3) retrieving trace gas. In this paper we report on the first two areas which have been our major priority to date.

AERI Status

A somewhat diverse selection of topics related to the AERI instrument and its observations are contained in this section. We begin with the status of the prototype instrument and automated analyses from the SGP CART site, summarize tests that verified the high level of accuracy of the AERI calibration in the CART configuration, briefly describe a very successful recent field experiment conducted with the new operational version of AERI (AERI-01), and finish with the plan for bringing the new AERI to CART.

Prototype at CART

The AERI Prototype was first brought to CART in March 1993 and has operated in its current configuration since December 8, 1993. Sky spectra are observed every 10 minutes for at least 16 hours per day on week days, except during periods of precipitation. When precipitation is detected, a hatch automatically closes to protect the instrument. The operational schedule is currently constrained by the need for manual liquid nitrogen filling of the detector dewar. During Intensive Operating Periods (IOPs) when the CART site is continuously manned, sky data are collected 24 hours a day. Routine 24-hour operation will become the norm when the first operational AERI is delivered to CART with a Stirling cooler, as discussed at the end of this section.

AERI data have been used as the focus of an ARM Instantaneous Radiative Flux (IRF) Quality Measurement Experiment (QME). For every launch of the Balloon-Borne Sounding System, a spectrum is now calculated using the Line By Line Radiative Transfer Model (LBLRTM) constructed for ARM (Clough et al. 1994) and compared to AERI observations. While this quality measurement experiment is still being refined to provide all of the quality control and sky condition information needed for meaningful comparisons, it will soon be a valuable, automated resource for interpreting AERI data.

Calibration

Early comparisons of AERI minus LBLRTM difference spectra from the SGP indicated an unexpected positive bias in the longwave window region when compared to the mean differences for similar atmospheric conditions from the spectral radiance experiment (SPECTRE) in Coffeyville, Kansas in 1991 (Ellingson et al. 1994). Such a bias could be caused by an unidentified absorber in the atmosphere at the CART site, as discussed later. However, while not considered likely, the possibility of a calibration error needed to be investigated (the bias is only a few perecent of ambient radiance but several times larger than expected absolute calibration errors). Therefore, a careful investigation of the AERI calibration was conducted at CART in early April 1994, prior to the April Remote Cloud Sensing (RCS) IOP.

Two general mechanisms that could lead to an erroneously large window region radiance were considered: 1) a small obstruction of the field-of-view (FOV) for sky viewing, and 2) a blackbody temperature error. Changes of instrument transmission or detector sensitivity are not possible explanations, because the AERI is calibrated during every 10-minute sky viewing cycle using views of two reference blackbodies, one at 60°C and one ambient. Also, while the alignment and emissivity of the hot blackbody are especially important, any misalignment or surface degradation would cause errors of the opposite sign.

The FOV for sky viewing was checked by moving the whole instrument with respect to the viewing port and environmental baffle. The test was conducted when the sky was clear, which guarantees a large contrast in window region radiance from the sky and from the room temperature structure. The window region signal level was recorded as the instrument position was sequenced through small incremental steps in two orthogonal directions. A margin of at least three inches was found in every direction before a significant signal from the structure was observed.

A calibration was carried out on both the electronics and the temperature sensors and the associated conditioning and readout electronics. The electronics calibration showed essentially no change since December 1993 (equivalent to less than 0.01°C). A precision thermistor was used as a transfer standard to reference the hot blackbody thermistor readings to a guideline precision radiation thermometer (traceable to NIST) located in Wisconsin. The precision thermistor sensor calibration, performed on the hot blackbody at ambient temperatures to avoid temperature gradients, found agreement to within 0.03°C. Further, a temperature cycling test from 333 K to 300 K and back to 333 K showed good agreement between the two hot blackbody thermistors themselves. The maximum difference of 0.06°C occurred at the highest temperatures, where the largest cavity temperature gradients would be expected. The ambient blackbody sensors were not compared with the precision thermistor because they are never thermally stressed and the two individual sensors agreed to within 0.03 degrees. We conclude that the AERI calibration blackbody temperature sensors are accurate to about 0.05°C, while a temperature error of 0.5°C would be necessary to explain the observed bias as a calibration error (too high for ambient blackbody or too low for the hot blackbody). Later, we describe our new findings on the impact of aerosols, which we believe is very likely to explain the bias of early CART/SPECTRE comparisons.

As a final note on the AERI calibration, the current best estimates of calibration uncertainties due to uncertainties in the detector non-linearity, blackbody emissivity, and blackbody temperature are summarized in Figure 1. The spectra of these sources of absolute calibration error are compared with that for a change of downwelling radiance which occurs if the water vapor content is changed by 10% for the U.S. Standard Atmosphere.

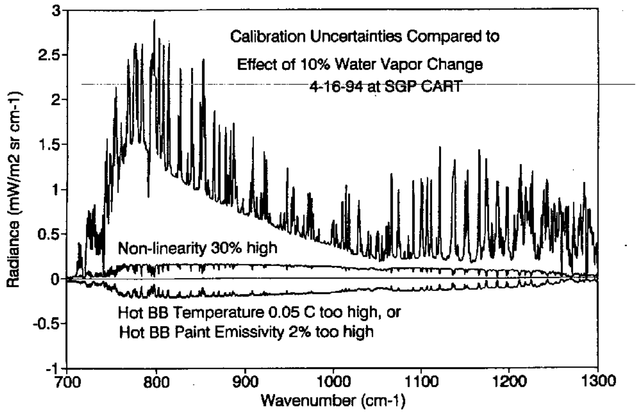

Figure 1. Size of AERI absolute calibration uncertainties from errors in the nonlinearity correction, the hot blackbody emissivity, and the hot blackbody temperature. Ambient blackbody temperature errors cause radiance errors of the opposite sign, and somewhat smaller in the window region. The effect of errors in the ambient blackbody emissivity is essentially negligible compared to that of the hot blackbody.

Field Experiment with the New AERI-01

The AERI-01 was a key component of a field experiment conducted in the Gulf of Mexico during January 1995 with the combined goals of improving sea surface skin temperature observations from shipboard as well as satellite and of evaluating the calibration of the new Geostationary Operational Environmental Satellite-8 imaging and sounding instruments. AERI once again demonstrated the hardiness of modern interferometric systems by its successful operation onboard a research vessel, the Research Vessel *Pelican*. The joint National Aeronautics and Space Administration (NASA) and National Oceanic and Atmospheric Administration experiment coordinated NASA ER2 high altitude aircraft flights of the University of Wisconsin (UW) High-resolution Interferometer Sounder (HIS) and the MODIS Airborne Simulator (MAS) with ship-board observations, including *in situ* sea surface temperature observations by the Brookhaven National Laboratory (BNL) “skimmer,” more conventional oceanic and meteorological observations, balloon launches with the UW CLASS system, and the AERI viewing the upwelling radiance at three angles as well as the downwelling radiance every 20 minutes.

The AERI produced what we believe are the first shipboard observations of sea surface emissivity at high spectral resolution and at multiple viewing angles. Also it simultaneously measured the sea surface temperature to an accuracy of better than 0.1°C, with very close agreement to the BNL observations sensitive to the top 15 cm of ocean. This experiment is described in detail in Smith et al. 1996. The experiment is a good demonstration of the absolute accuracy of the AERI and of techniques which can be applied to both land surface emissivity observations and to observations from the Unmanned Aerospace Vehicle AERI currently under design. In addition, on January 19, 1995, the ER2 collected data over the SGP CART site, which should provide the best example to date of simultaneous upwelling HIS and downwelling AERI spectral radiance observations for clear sky analyses over the CART site.

AERI-01 Schedule

The delivery of the first operational AERI will take place during the spring of 1995. This milestone has been delayed to make it possible to equip the instrument with a Stirling cooler that will eliminate the need for liquid nitrogen to cool the detectors. The AERI-01 will operate continuously, unconstrained by site manpower schedules. It has been shown that a Stirling cooler can be operated on the instrument without causing radiometric artifacts from vibration (potentially disturbing the interferometer or inducing detector microphonics) or from electromagnetic interference. The excellent radiometric performance realized with a Litton Stirling cooler is illustrated in Figure 2, showing an AERI longwave band sky spectra observed using the Stirling cooler compared with one using the normal liquid nitrogen cooler. A complete cooler subassembly has been designed and implemented on the AERI-01, including an integral cooling fan and capabilities to continuously monitor the cooler performance (power usage and detector temperature). We have experienced some cooler operational problems, but believe that they are very close to being resolved. The coolers being used are guaranteed for one year of operation and can be removed for refurbishment without removing or replacing the detector/dewar package.

Window Region Emissions: The Aerosol Explanation

One of the key spectroscopic issues to resolve with AERI data is the quantification of sources of opacity in the clear sky window region. Accurate surface energy budget modeling depends on understanding this issue. There are at least three important contributors to uncertainty in the window region opacity that are somewhat difficult to separate: 1) water vapor continuum, 2) aerosols, and 3) atmospheric water vapor profile. We have not included clouds or trace gases, assuming that clouds can be identified

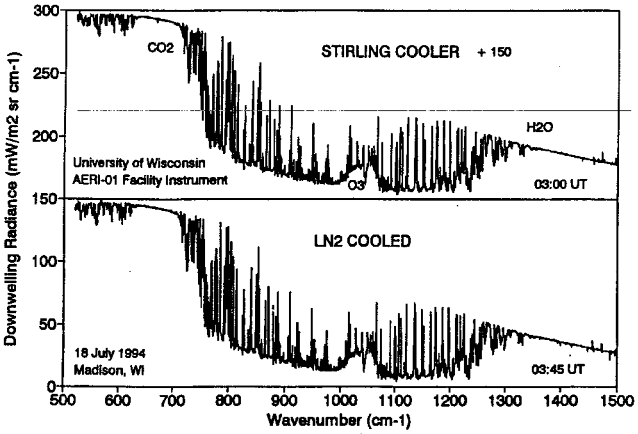

Figure 2. Comparison of a longwave AERI spectrum taken using a Stirling cooled detector to one using a liquid nitrogen cooled detector, while observing clear skies. The agreement is remarkable, considering that the spectra were observed 45 minutes apart.

and avoided by careful use of ancillary CART observations and that the signatures of trace gases can be identified and accounted for. Here we present evidence that the spectral signature of a typical rural aerosol (as defined by Shettle and Fenn [1979], and included in Phillips Laboratory radiative transfer codes LOWTRAN, MODTRAN, and FASCODE; and also in LBLRTM) is present in a large number of the AERI spectra from CART, and that aerosol absorption is the likely explanation for the bias reported at the last ARM Science Team Meeting between SPECTRE and CART AERI observations.

Figure 3 shows an example of a comparison between an AERI observed longwave window region spectrum and an LBLRTM calculation. The difference in the window region is typical of the smaller differences observed during the April 1994 Remote Cloud Sensing IOP studied closely for this analysis. The AERI minus LBLRTM difference or residual, shown in more detail in Figure 4, is somewhat larger than 1 mW/m^2 sr cm^{-1} in the low resolution background region between spectral lines, which is on the order of the discrepancy between SPECTRE and CART radiance differences in the window regions.

It is clear from the comparisons with the radiative impact of a rural aerosol with 20-km visibility calculated with LBLRTM that the residual spectrum can be accounted for in large part with such an aerosol model (Figure 4b). It is equally clear from the comparison with the calculated effect of a 10% increase in water vapor that the residual cannot be matched by adjusting the water vapor amount or by a percent change in the water continuum (Figure 4a). The effects of these water vapor changes are relatively too weak on the shortwave side of the 8-12 micron window region and too strong on the longwave side. The relatively large spikes in the residual spectrum from water vapor lines suggest that the AERI data can also be used to determine the correct absolute water vapor amount by evaluating a set of spectral lines for which the spectroscopy is well established. Such adjustments of the absolute water amount will also allow the uncertainty in the water vapor continuum deduced from AERI observations to be reduced.

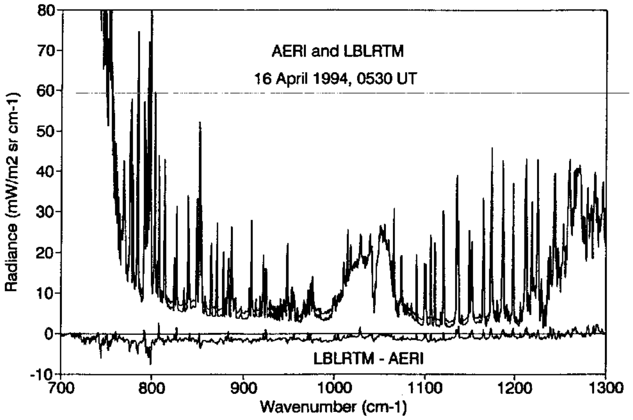

Figure 3. Comparison of an AERI observed longwave window region spectrum and calculated spectrum from LBLRTM.

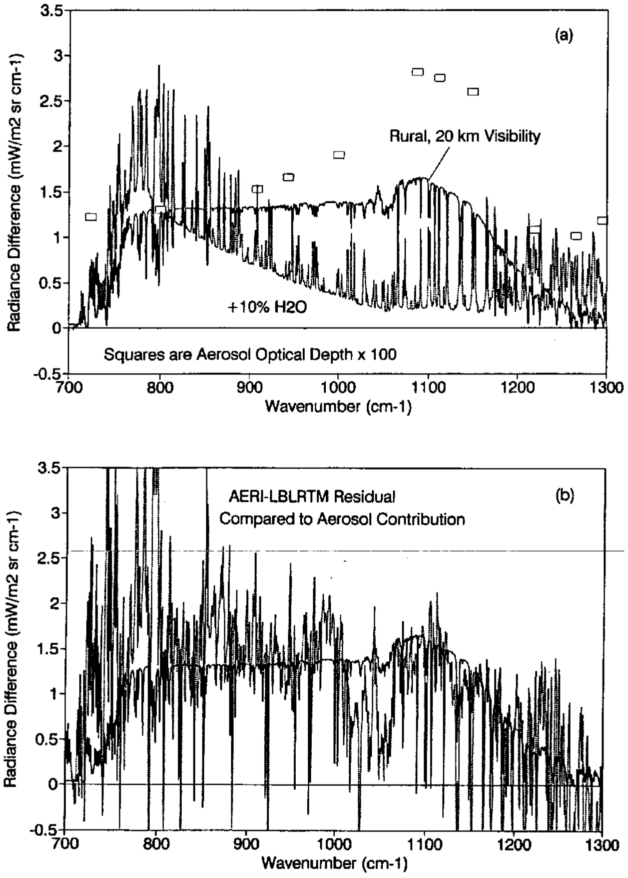

Figure 4. Rural aerosol spectral signature compared to that for (a) a 10% change in water vapor and (b) to one of the smaller AERI minus LBLRTM residuals observed during the RCS Intensive Operating Period in April 1994.

Aerosol retrievals from AERI data using the rural aerosol model in LBLRTM are summarized in Table 1. The minimum aerosol fit had a 0.53-micron visibility of 23 km and a radiance impact of 1.2 mW/m^2 sr cm^{-1}. The lack of a simple correlation with precipitable water or relative humidity suggests that more complex analyses are needed to provide a detailed understanding of the factors determining aerosol amount.

Table 1. Atmospheric properties and window region residuals for selected clear days during the April 1994 Remote Cloud Sensing IOP. The radiance residual listed is the 1000 cm^{-1} radiance of the aerosol fit to the AERI minus LBLRTM difference.

Day/Time April/UTC	**T/P °C/mb**	**Precip. Water cm**	**R.H. %**	**Visibility km**	**Residual** mW/m^2 sr cm^{-1}
16/05:30	14/933	0.9	47	20	1.3
17/02:30	23/985	1.2	44	23	1.2
17/08:30	17/984	1.3	49	18	1.7
23/11:30	15/975	2.5	76	18	1.4
24/05:30	20/972	2.9	69	l5	1.9
26/02:30	21/961	1.6	85	1.5	15.5
26/05:30	21/962	0.8	51	8	4.1
27/03:00	18/959	1.3	43	9	3.4

These data show that aerosols are present for extended periods at the SGP CART site, in amounts that can have significant impact on the downwelling radiance. This is a plausible mechanism to explain the relatively higher window region radiances observed by AERI at CART than during the SPECTRE period at Coffeyville in 1991.

Future AERI Plans

The first AERI operational version with no need for liquid nitrogen will be delivered to CART in the Spring of 1995, as mentioned earlier. The implementation of the boundary layer sounding AERIs at each of the SGP boundary sites and AERIs in the Tropical Western Pacific and the North Slope of Alaska is expected to follow as quickly as possible. The contract for these additional AERIs is being written and the systems will be built at a rate of at least two per year as soon as it takes effect.

Note: After this paper was submitted, an obstruction to the AERI-00 Prototype sky view was found by comparing spectra with those from the new AERI-01. The obstruction explains the AERI minus LBLRTM bias potentially explained as ubiquitous aerosols at the SGP CART Site in this paper. The paper is published in its original form to maintain the historical record. Corrected AERI prototype data are now available and some large aerosol signatures are still present. The detailed impact of the correction will be addressed in our 1996 Science Team paper.

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