Atmospheric Emitted Radiance Interferometer. Part I: Instrument Design

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ABSTRACT

A ground-based Fourier transform spectrometer has been developed to measure the atmospheric downwelling infrared radiance spectrum at the earth's surface with high absolute accuracy. The Atmospheric Emitted Radiance Interferometer (AERI) instrument was designed and fabricated by the University of Wisconsin Space Science and Engineering Center (UW-SSEC) for the Department of Energy (DOE) Atmospheric Radiation Measurement (ARM) Program. This paper emphasizes the key features of the UW-SSEC instrument design that contribute to meeting the AERI instrument requirements for the ARM Program. These features include a highly accurate radiometric calibration system, an instrument controller that provides continuous and autonomous operation, an extensive data acquisition system for monitoring calibration temperatures and instrument health, and a real-time data processing system. In particular, focus is placed on design issues crucial to meeting the ARM requirements for radiometric calibration, spectral calibration, noise performance, and operational reliability. The detailed performance characteristics of the AERI instruments built for the ARM Program are described in a companion paper.

1. Introduction

The central role of radiative processes in climate change led, in the 1980s, to an intercomparison of radiation codes used in climate models (Luther et al. 1988). The study group recommended "a program to simultaneously measure spectral radiance at high spectral resolution along with atmospheric data necessary to calculate radiances" (Ellingson and Fouquart 1991). In 1991, a plan to deploy state-of-the-art instruments was realized during the Spectral Radiance Experiment (SPECTRE; Ellingson and Wiscombe 1996). The experimental approach of SPECTRE became the core of a new initiative by the Department of Energy (DOE) known as the Atmospheric Radiation Measurement (ARM) Program (DOE 1990). The ARM Program extended the SPECTRE measurement concept by supporting the development of automated systems that would make long-duration measurements at dedicated observing sites. The ARM Program plan called for measurements of downwelling thermal emission at the surface with high spectral resolution and high absolute accuracy. The instrument selected for the measurement of thermal emission at "one wavenumber" spectral resolution was the Atmospheric Emitted Radiance Interferometer (AERI) developed by the University of Wisconsin Space Science and Engineering Center (UW-SSEC). The ARM Program has subsequently deployed AERI instruments at dedicated sites in the Southern Great Plains (SGP), the North Slope of Alaska (NSA), and the Tropical Western Pacific (TWP; Stokes and Schwartz 1994).

The AERI instrument is designed to meet the needs of the ARM Program for 0.5-wavenumber (unapodized) spectrally resolved emission data for application to studies of both clear-sky and cloud-radiative properties. The clear-sky AERI observations are contributing to a better understanding of infrared spectroscopic issues, in particular the water vapor continuum, important for validation of infrared radiative transfer models (Revercomb et al. 2003; Tobin et al. 1999; Turner et al. 2004). The remote sensing capabilities of the AERI instruments below cloud level are being used to provide real-time temperature and water vapor profiling in the lowest 2–3 km of the atmosphere (Feltz et al. 1998; Smith et al. 1999; Turner et al. 2000). The AERI instruments are also being used within the ARM Program to remotely sense cloud-radiative and microphysical properties (Collard et al. 1995; Mace et al. 1998; DeSlover et al. 1999; Turner et al. 2003).

In the following, the AERI instrument requirement specification for the ARM Program is presented along with the design features important for meeting those requirements. The predeployment performance data of the AERI instruments built for the ARM Program are

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TABLE 1. The development history of the AERI instrument evolved over a 10-yr period beginning in 1988 to encompass all of the ARM sites; the Southern Great Plains Central Facility (SGP-CF), the SGP boundary facilities (SGP-BFs), the Tropical Western Pacific (TWP) Nauru site, and the North Slope of Alaska (NSA) Barrow site.

Unit designation	Deployment site	Deployment date	Comment
A/C HIS	GAPEX Colorado	Oct 1988	UW-SSEC proof of concept
GB-HIS	WISP Colorado	Mar 1989	UW-SSEC development system
AERI-00	SPECTRE Kansas	Nov 1991	AERI prototype (LN2)
AERI-00	SGP-CF	Mar 1993	AERI prototype (LN2)
AERI-01	SGP-CF	Jul 1995	First operational AERI
AERI-00U	SHEBA Ship	Oct 1997	First operational ER-AERI
AERI-02	SGP-B6 Purcell	Nov 1998	BF-AERI
AERI-03	SGP-B4 Vici	Nov 1998	BF-AERI
AERI-04	SGP-B5 Morris	Dec 1998	BF-AERI
AERI-05	SGP-B1 Hillsboro	Dec 1998	BF-AERI
AERI-06	TWP/Nauru	Nov 1998	TWP-AERI
AERI-07	NSA/Barrow	Feb 1998	ER-AERI
AERI-08	TWP/Nauru	Mar 2001	TWP-AERI

presented in a companion paper (Knuteson et al. 2004, hereafter referred to as Part II). Future papers will document the traceability of the AERI calibration to absolute reference standards and provide an uncertainty analysis of the AERI field observations collected by the ARM Program.

2. AERI design

The AERI is a ground-based Fourier transform spectrometer (FTS) for the measurement of accurately calibrated downwelling infrared thermal emission from the atmosphere. This section presents the AERI development history, requirement specification, instrument description, temporal sampling strategy, environmental considerations, operational issues, and data products. Additional details of the AERI instrument implementation can be found in Minnett et al. (2001), which describes the Marine version of the AERI instrument built by UW-SSEC for the University of Miami.

a. Development history

The first major field campaign featuring high-spectral-resolution downwelling infrared emission observations at the surface was the Ground-Based Atmospheric Profiling Experiment (GAPEX) at Denver Stapleton Airport in October 1988 (Smith et al. 1990). During GAPEX, UW-SSEC successfully demonstrated the measurement proof of concept of ground-based high-spectral-resolution infrared profiling using the University of Wisconsin High-Resolution Interferometer Sounder (HIS) aircraft instrument operated in an uplooking mode from the surface (Revercomb et al. 1988). The first dedicated ground-based infrared emission instrument [known as the Ground-Based HIS (GB-HIS)] was built in 1989 by UW-SSEC using an MB-120 interferometer designed for industrial applications from ABB/BOMEM, Inc., of Quebec, Canada (Collard et al. 1995). This "development system" was modeled on the radiometric calibration approach of the aircraft HIS instrument and proved the feasibility of the instrument approach that would be used for the AERI instruments developed for the ARM Program. Table 1 summarizes the history of the AERI system development. Four generations of AERI instrumentation were developed at UW-SSEC in the 10 years between 1989 and 1998: the GB-HIS in 1989, the AERI prototype (AERI-00) in 1990, the AERI-01 between 1993 and 1995, and the AERIs for the TWP, NSA, and SGP boundary facilities in 1997–98. Between 1998 and 2003, the ARM Program had one AERI system operating at each of seven field locations (one at the SGP central facility, four at SGP boundary facilities, one at NSA-Barrow, and one at TWP-Nauru).

b. AERI requirement specification

Based on the performance of the AERI prototype system during SPECTRE in 1991, an instrument requirement specification was developed jointly with the DOE Pacific Northwest National Laboratory for the acquisition of AERI instruments for the ARM Program. UW-SSEC subsequently fabricated AERI instruments for the ARM Program to meet these requirements. Table 2 contains an annotated copy of the AERI requirement specification (dated 22 July 1992) including subsequent changes made to the original specification to accommodate the extended-range AERI (ER-AERI) instruments for the NSA site. In particular, the longwave spectral cutoff of the ER-AERI instruments was extended to cover much of the water vapor rotational band.

c. AERI instrument description

The AERI measures downwelling atmospheric emitted radiance from 3.3 (3020 cm^{-1}) to 19 μm (520 cm^{-1}), 25 μm (400 cm^{-1}) for the ER-AERI, with a narrow zenith field of view. Calibrated sky radiance spectra are produced about every 8 min containing the mean and standard deviation of zenith sky spectra during a sky dwell period of about 200 s. For the AERI-01 system, the sky dwell period is composed of 45 "forward" and 45 "backward" Michelson interferometer scans, while for the faster-scanning AERI-02 (and later systems), 90 complete scans are obtained in the same dwell time. The remaining time is spent viewing two internal calibration reference targets. The AERI real-time output, which is accessible through a network connection, consists of radiometrically and spectrally calibrated radiances corrected for all instrument effects. Figure 1 illustrates typical "clear sky" measurements of downwelling atmospheric infrared emission at the surface as observed at the ARM SGP, NSA, and TWP sites. The midlatitude AERI observations from the ARM SGP site (Oklahoma/Kansas) typically fall in the range between the Arctic and tropical measurements.

The AERI is composed of two major assemblies: the interferometer/optics bench assembly and the electronics support equipment rack. Figure 2 is a block diagram indicating the subsystem components that will be described in this paper. The interferometer/optics bench assembly protrudes through a thermally insulated side wall of a building, exposing the front-end optics and calibration blackbodies to ambient temperature, while allowing the interferometer and the electronics support equipment to operate at room temperature. The vertical plate that provides structural support for the front-end optics and blackbody assembly is an integral part of the optics bench. This plate, which is made of GE Noryl, also provides a thermal barrier between the inside and outside. The outside portion of the AERI is contained in a weatherproof enclosure with an open view port to the sky. An automated hatch mechanism closes the view port in rain or snow conditions. This enclosure attaches to the side of the building that houses the AERI and is passively designed to be at outside ambient temperature. Figure 3 shows the installation at the ARM SGP Central Facility near Lamont, Oklahoma. The AERI sensor (based on measurements of AERI-00U) weighs about 80 kg (175 lb), plus an additional 36 kg (80 lb) for the electronics rack. The measured power is 828 W peak (7.2 A at 115 VAC) and 529 W steady state (4.6 A at 115 VAC).

1) Interferometer/optics bench assembly

The interferometer/optics bench assembly is composed of the interferometer subsystem, the front-end optics and calibration blackbodies, and the mechanically cooled infrared detector. All of these items are structurally coupled to a common optical bench mounted to the field site facility structure via mechanical isolators attached to a slide plate. Figure 4 identifies the main optical assembly components of the AERI instrument.

(i) Interferometer subsystem

The interferometer used in the AERI system is the commercially available MR-100 series manufactured by ABB/BOMEM, Inc. The aft optics used is the "radiometric option" with a well-defined aperture stop and selectable field stop. The MR-100 is a stand-alone interferometer including the detector preamplifiers, analog filters, and analog-to-digital electronics. An autostart sequence upon power-up initializes the system using a "white light" source without the need for operator intervention. The interferometer uses an internal helium–neon laser in the detector sampling, leading to a highly stable spectral calibration. Table 3 summarizes the interferometer characteristics common to all the AERI instruments built for the ARM Program. The unused entrance port on the MB-100 four-port interferometer is covered with a massive copper block with a blackened, grooved surface containing a temperature monitor ("second-port temperature"). The thermal inertia of the copper block provides a stable reference for the unused entrance port during the 10-min calibration period. Since the emission from the "second port" is constant during sky and blackbody views, it is removed by the onboard calibration.

(ii) Calibration subsystem

The front-end optics and calibration subsystems were developed at UW-SSEC to meet the ARM requirement for absolute radiometric calibration. The AERI system uses a full-aperture two-point radiometric calibration with onboard reference blackbodies that use temperature measurements traceable to the National Institute of Standards and Technology (NIST) resistance standards. The calibration sources are precision blackbodies built at UW-SSEC using a geometry with high cavity emissivity. The ambient temperature reference blackbody (ABB) is unheated and operates near outdoor ambient temperature, and the hot temperature reference blackbody (HBB) is temperature controlled to a fixed temperature near 60°C. Three YSI Super Stable thermistors are imbedded in each blackbody cavity to measure temperature. A dedicated thermistor is used for temperature control. Figure 5 shows a picture of a UW-SSEC AERI blackbody with the thermal insulating jacket removed. Each thermistor is calibrated at UW-SSEC after the thermistor is installed in the blackbody using a NIST-traceable standard with absolute temperature knowledge to better than ± 0.03 K (3σ). The thermistor calibration uses the same high-precision readout electronics that are used in each AERI system. The resistance measurement is described later. This scheme eliminates errors associated with the self-heating of the thermistors during readout. The thermistor calibration is done at five different temperatures over the operating range. A least squares fit to the temperature/resistance calibration points is used to determine the three unique Steinhart and Hart thermistor coefficients relating thermistor resistance to temperature (Steinhart and Hart 1968). These coefficients are entered into the AERI real-time software configuration parameters for the instrument on which

TABLE 2. AERI instrument requirement specifications.

Item	Specification
General system elements	• Michelson interferometer with PC computer interface. • Full-aperture temperature-controlled calibration reference sources. • Automated system for providing sequential views of the sky (zenith) and two reference sources for calibration. • Environmental Monitoring System, for collection of blackbody temperatures and other housekeeping data. • Computer and Data Handling System. Its control functions involve sequencing all AERI operations, including scene switching, ingesting of interferometer and Environmental Monitoring System data, calibration, and data transfer. Data handling includes acquisition, processing, display, and networking.
Radiometric performance specifications	The required radiometric performance for the AERI is defined by specifying the spectral coverage and resolution, the spatial field of view, and the absolute calibration accuracy and reproducibility.
Spectral coverage and resolution (standard AERI)	Coverage: 550–3000 cm^{-1} (3.3–18.2 μm). Resolution: 0.5 cm^{-1}, unapodized. [max optical path difference (OPD) of 1 cm].
Spatial FOV	Angular FOV: <100 mrad full angle.
Radiomeric calibration	Absolute accuracy: <1% of ambient blackbody radiance. Reproducibility: <0.2% of ambient blackbody radiance.
AERI subsystem specifications	Blackbody cavity characterization • Temperature knowledge: ±0.1°C of absolute temperature. • Emissivity knowledge: better than ±0.1%. • Temperature gradient: 0.35°C (knowledge to within 0.1°C). • Temperature stability: better than 0.05°C over viewing period (≈120 s). Nonlinearity knowledge: better than 0.1%. Polarization: <0.1%.
Wavelength calibration	Channel wavenumber knowledge: better than 0.01 cm^{-1}.
Noise	<0.2 mW $(m^2\ sr\ cm^{-1})^{-1}$ for 670–1400 cm^{-1} (standard AERI).
(Rms for 2-min blackbody view)	<0.4 mW $(m^2\ sr\ cm^{-1})^{-1}$ for 420–1400 cm^{-1} (ER-AERI) (except 667 cm^{-1}, where CO_2 in the instrument reduces responsivity). <0.015 mW $(m^2\ sr\ cm^{-1})^{-1}$ for 2000–2600 cm^{-1} (except 2300–2400 cm^{-1}, where CO_2 in the instrument reduces responsivity).
Temporal sampling	Repeat cycle: ≈10 min with programmable limits for sky and blackbody viewing at absolute time intervals. (Note: Typically it is expected that the sky will be viewed for about 4 min and each of the two blackbodies for about 2 min.) Interferometer scan period: <2 s. (Note: The stated requirement would allow a 50 m s^{-1} cloud at 10 km to move only 10% of a 100-mrad FOV during a single scan.)
Operational requirements	The AERI automatic control system hardware shall contain these features: • Scheduled sequencing of the following operations: —Scene switching between sky and blackbody views. —Interferometer and housekeeping data acquisition and transfer. —Interferometer detector servicing. • Capability of remotely changing the operations listed above. • 24-h continuous operations with data output at 10-min intervals. • Scheduled maintenance: not less than 7 days. • Real-time display with flags for out-of-limit conditions. Examples of quantities to select from include the following: —Spectra from sky and blackbody views. —Housekeeping data (interferometer temperature, ambient temperature, blackbody temperatures, electronics temperature). —Blackbody spectral variance. —Scene mirror position. —Environmental Monitoring System measurement stability (determined from dedicated channels reading fixed precision resistors).
Operating environment	The operating AERI instrument front end including the scene mirror, blackbodies, and interferometer front window will be exposed to an outside ambient environment with temperature extremes from −30° to +40°C (−70° to +40°C for the ER-AERI systems). The AERI will be protected from rain or other nonoperating conditions by a waterproof housing with a hatch (this housing with hatch is not the responsibility of the AERI vendor). The remainder of the AERI system (the interferometer, electronics, and computers) will be housed in a controlled environment at 20° ± 5°C (the temperature-controlled housing is not the responsibility of the AERI vendor).
Networking	The AERI shall use TCPIP networking with ftp and bootp functions.

TABLE 2. (*Continued*)

Item	Specification
Data products	The AERI data products are divided into primary and secondary products. The primary products required for scientific use include evaluation of the data quality. The secondary products provide important auxiliary information for real-time monitoring of operations as well as historical data for subsequent quality control. Primary (every viewing cycle; ≈10 min): ● Calibrated spectra. ● Standard deviation for blackbody and sky views. ● Calibration coefficient and blackbody temperatures. Secondary (every cycle): ● Ambient air temperature. ● Ambient pressure. ● Ambient humidity. ● Instrument housekeeping data. ● Vertical sky images (Note: feature not implemented).

the blackbody is installed. The AERI blackbodies are all mechanically identical and can be interchanged without compromising alignment because of a unique alignment registration scheme. The overall temperature knowledge of the blackbody is required to be better than ±0.10 K (3σ). The UW-SSEC has experience with the fabrication and NIST-traceable calibration of over 40 of these blackbodies.

The blackbody emissivity is obtained from measurements of witness samples of the diffuse paint (Chemglaze Z306) used to coat the interior surfaces of the blackbodies and a model for the cavity effect. The overall blackbody cavity emissivity knowledge is required to be better than ±0.1%, with an emissivity greater than 0.990. Figure 6 shows the measured paint emissivity

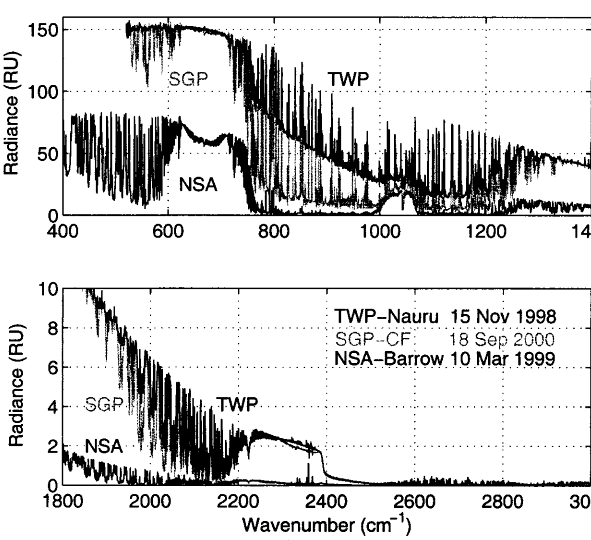

FIG. 1. AERI "clear sky" observations from the ARM TWP-Nauru (2002 UTC 15 Nov 1998), NSA-Barrow (1201 UTC 10 Mar 1999), and SGP Central Facility (0146 UTC Sep 2000) sites. The wavenumber range 400–3000 cm^{-1} corresponds to the thermal infrared wavelengths of 25–3.3 μm. AERI observations from the midlatitude ARM SGP site (Oklahoma/Kansas) typically span the range between the Arctic and tropical measurements. AERI radiance units, RU = mW (m^2 sr cm^{-1})$^{-1}$.

and computed cavity emissivity spectra used to represent the AERI blackbodies. The cavity emissivity is related to the measured paint emissivity, e_v^m, through the approximate relation

$$e_v^{\text{cav}} = \frac{e_v^m}{e_v^m + \dfrac{1 - e_v^m}{C_f}}. \tag{1}$$

A cavity factor C_f of 12.79 has been used in the radiometric calibration for all AERI systems to date based upon a theoretical estimate of the hemispheric cavity emissivity that makes use of the same cavity geometry (Sydnor 1970). A more recent Monte Carlo ray trace analysis of the cavity geometry indicates that the previous estimate of cavity factor is too low when the restricted field of view of the AERI system is considered at nearly normal incidence. Detailed results of this ongoing analysis will be reported at a later date. A preliminary estimate for the cavity normal emissivity gives a C_f of about 39.

(iii) *Spatial field of view*

In order to avoid the need for a telescope in front of the interferometer, the beam diameter defined by the entrance aperture to the interferometer was used along with the field angle to size the front-end optics and calibration references sources. A 45° gold-coated mirror attached to a computer-controlled stepper motor is used to switch between zenith sky and calibration reference sources. The polarization insensitivity of bare gold to the angular rotation of the scene mirror is used to avoid a polarization sensitivity of the interferometer, which would otherwise lead to a calibration error, since the reference sources are located at ±60° from the vertical sky view. Since the interferometer is immediately behind the scene mirror, the spatial field of view (FOV) of the AERI instruments is equal to the interferometer FOV. The FOV half-angle is determined by the selection of an internal field stop. The field stop used in the AERI prototype (15-mrad half-angle) and AERI-01 systems

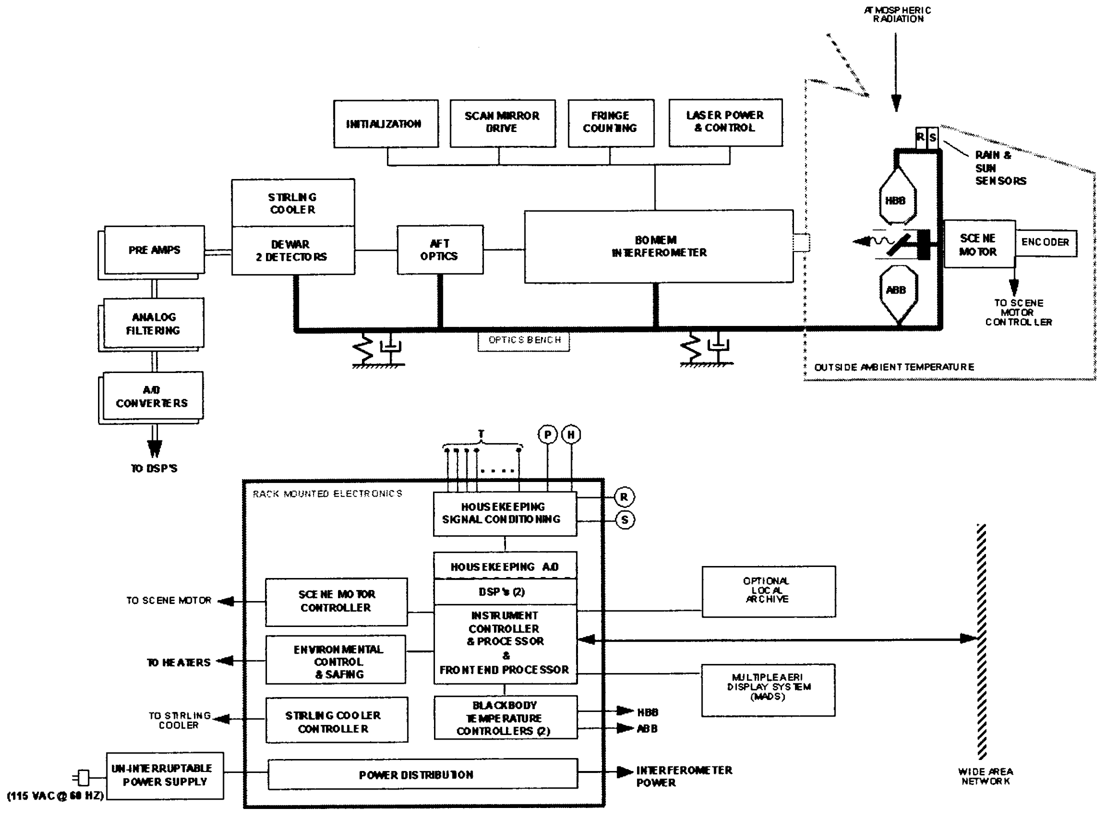

FIG. 2. Block diagram of the standard AERI instrument built for the ARM Program indicating the modular components of the interferometer and front-end assembly (upper) and electronics rack (lower).

(16-mrad half-angle) originally was chosen to minimize the effect of interferometer self-apodization (Revercomb et al. 1988). The field stop aperture chosen for the instruments AERI-02 through -08, and -00U, utilized a larger aperture (23-mrad half-angle) to achieve improved performance with an acceptable instrument line shape correction. Figure 7 shows the results of a special test that was developed to map the near-field radiometric field of view of each AERI instrument. The shortwave detector (InSb) is used to record the signal from a penlight illuminating holes machined in an alignment plate placed at the location of the sky and blackbody positions. Since the longwave and shortwave detectors are in a sandwich configuration, they share a common field of view. The field-of-view mapping procedure is used to safely align the beam with the hot, ambient, and sky view apertures.

(iv) Scattering immunity

The use of a sky view aperture addresses another potential contribution to radiometric calibration error,

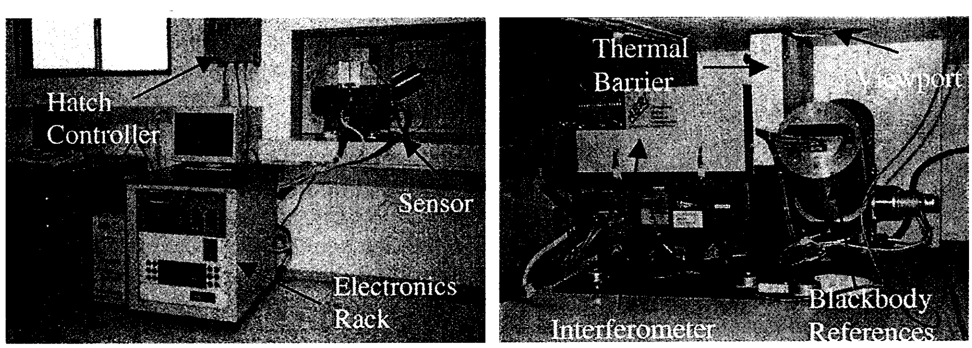

FIG. 3. Photographs of the AERI instrument setup in the Optics Trailer at the ARM SGP Central Facility: (left) the AERI electronics rack, the AERI sensor (aft portion), and the hatch controller; (right) the sky view port, the thermal barrier between fore and aft optics, and the calibration blackbodies.

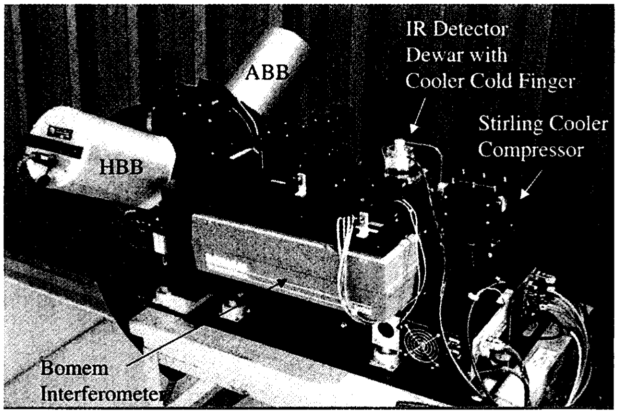

FIG. 4. AERI interferometer/optics bench assembly.

that is, the effect of scattering of the infrared beam by contamination of the scene view mirror. A heavy layer of dust particles on the scene view mirror effectively broadens the instrument beam. The effect is similar to a misalignment of the hot blackbody since the view from the instrument to the blackbody now extends outside of the blackbody cavity aperture. However, if the additional radiance contribution can be made equal from each of the hot, ambient, and sky scene views it will be removed to first order by the calibration process. The AERI systems have been designed to take advantage of this fact by providing a sky view aperture that is identical in diameter to the blackbody apertures and at equal distance to the scene view mirror. All of the aluminum surfaces viewable by the scene mirror via scattering are anodized and thermally coupled so that the interior surfaces are close to a common emissivity and temperature. This fore optics design combined with the AERI calibration approach leads to substantial immunity to scattering caused by dust on the scene mirror. Figure 8 is a photograph of the scene mirror on the shaft of a stepper motor. The black anodized "can" surrounding the scene mirror provides a uniform temperature source for any potential scattering effects.

(v) Detector subsystem

The detector subsystem used in the AERI instruments was implemented at UW-SSEC working with commercial vendors for the infrared detectors, the detector dewar, and the mechanical cooler. The AERI instrument uses detectors from Infrared Associates with mercury cadmium telluride (HgCdTe) for the longwave infrared band and indiumantimonide (InSb) for the shortwave infrared band. The infrared beam passes first through the InSb, with a longwave cutoff at about 1800 cm^{-1}, to reach the HgCdTe detector. The signals from each detector lead into separate preamplifiers. The operational advantage of this "sandwich" approach is that only one detector dewar is required to cool the two detectors. In the prototype AERI system, the detector dewar was cooled using liquid nitrogen. The ARM requirement for continuous operation at remote sites necessitated the integration of a mechanical cooler into the AERI design. The UW-SSEC integration of a mechanical cooler into the AERI design was the last major development in making the AERI system a truly autonomous and continuously operating system. The AERI uses the Litton 0.6-W linear "slip-on" configuration cryocooler shown in Fig. 9. This unit has a dual-opposed piston compressor that is connected to the re-

TABLE 3. Characteristics of the Michelson interferometer used in the AERI system.

Manufacturer	ABB-BOMEM, Quebec, Canada
Model	MR-100
Type	4-port Michelson; patented wishbone design; two corner cube retroreflectors
Spectral range	200–3020 cm^{-1} (collection range)
Sampling reference	HeNe laser
Effective sampling frequency (resampled rate)	15 799.0 cm^{-1}
Maximum optical path difference (X)	1.037 027 65 cm
Unapodized spectral resolution (1/2X)	0.482 147 22 cm^{-1}
Spectral sampling	0.482 147 22 cm^{-1}
Michelson scan rate (OPD cm s^{-1})	2 (1 for AERI-01 and AERI-00)
Fringe counting	Single fringe sampling, continuous
Samples per double-sided interferogram	32 768 (16 bit) samples per interferogram (DS)
Signal processing	DSP-based FFT and spectral coaddition
Apodization function	None (unapodized interferograms produced)
Entrance/exit window	Standard AERI: A.R. coated ZnSe; ER-AERI: CdTe (uncoated) entrance ER-AERI: KBr (uncoated) exit
Beamsplitter/compensator	KBr
Telescope	Aft
Field stop aperture setting	6.4 mm (4.5 mm for AERI-01)
Field-of-view half-angle (b)	23 mrad (16 mrad for AERI-01; 15 mrad for -00)
Aperture stop diameter	2.2 cm (7/8 in.)
Throughout (cm^2 sr)	6.3 E-3 (3.1 E-3 for AERI-01)
Dimensions	52 cm × 45 cm × 38 cm (w × l × h)
Mass	43 kg
Power	72.5 W

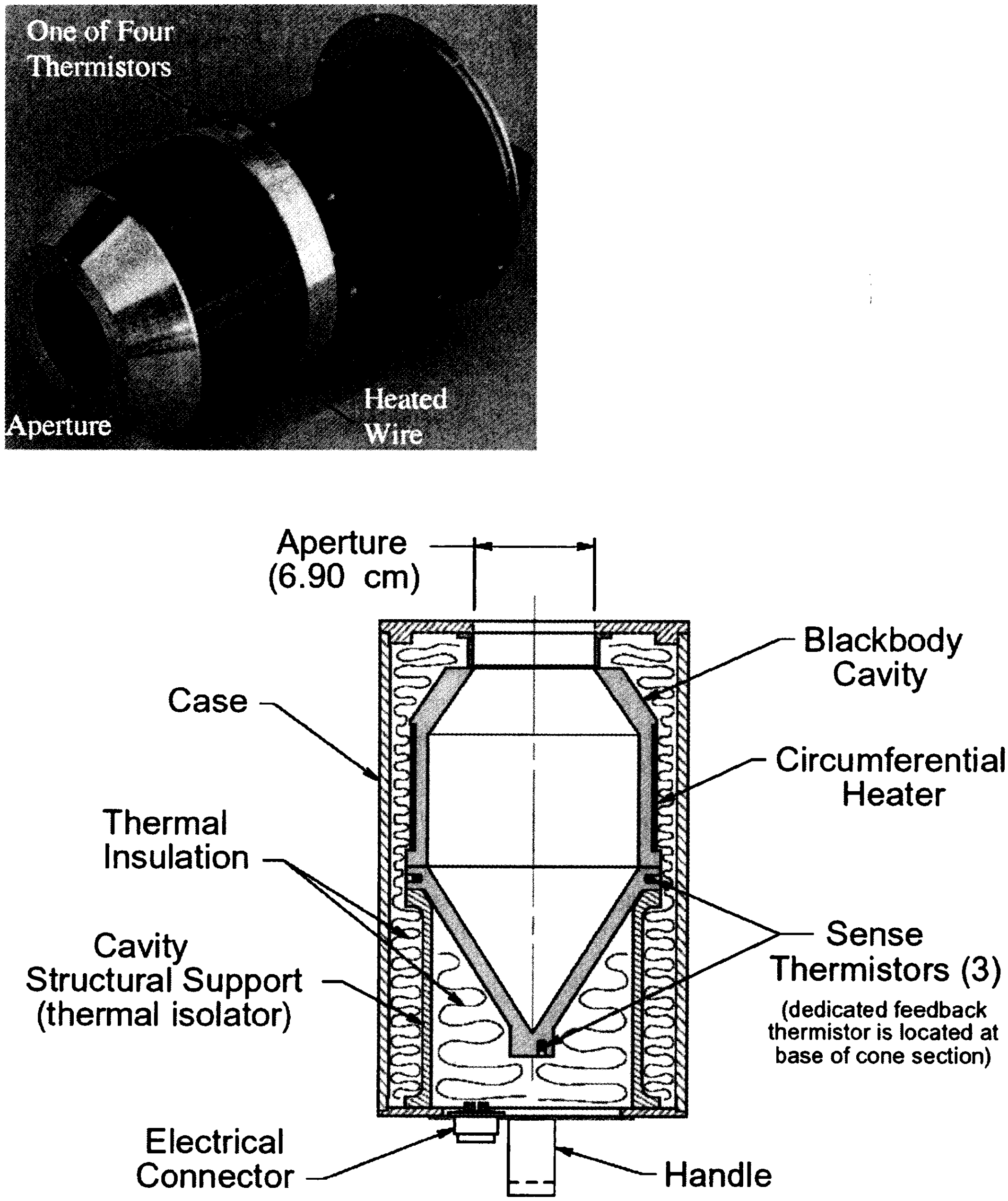

FIG. 5. Illustration of the AERI blackbody cavity used for internal calibration reference shown as a photograph and a cross-sectional diagram.

generator cold finger assembly by a flexible helium-gas transfer line. The cold finger slips into a well in the detector vacuum dewar, where it is thermally coupled across the vacuum wall at the bottom of the well using a compliant bellows in parallel with a mesh of gold wire. This configuration allows a cryocooler assembly to be replaced in the field without removing the optically aligned detector assembly from the interferometer. The compressor is vibration isolated from the interferometer cast aluminum case and is housed in a fan-cooled aluminum heat sink. The heat-rejection end of the cold finger located on top of the detector dewar is also configured with a fan-cooled aluminum heat sink. The cooler electronics uses a servo loop with feedback from a detector temperature sensor. A fixed resistor is used to determine the set point temperature. The nominal set point temperature for the AERI systems is 78 K. The ER-AERI systems developed for the ARM NSA site can also be set for operation at 68 K to enhance the longwave detector noise performance.

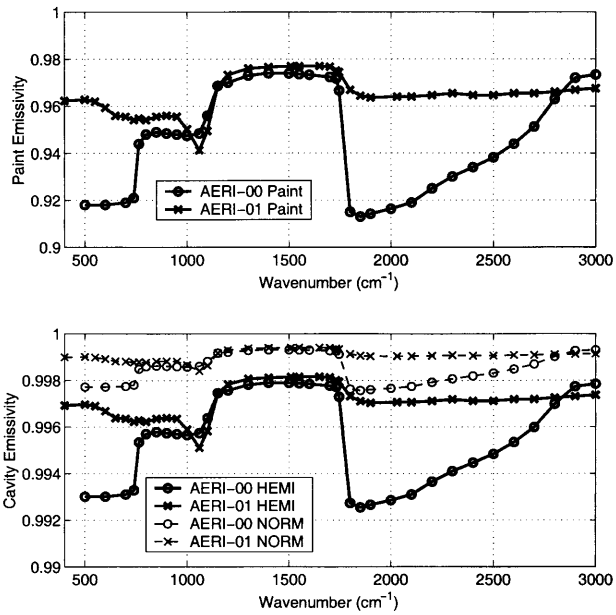

FIG. 6. Spectral curves derived from laboratory measurements of Chemglaze Z306 witness samples are used to represent (top) the paint emissivity for the AERI prototype (-00) and AERI-01 blackbodies and (bottom) the cavity emissivities corresponding to the geometry of the UW-SSEC blackbody for hemispheric (C_f = 12.79) and normal emissivity (C_f = 39).

2) ELECTRONICS SUPPORT EQUIPMENT

The AERI electronics support equipment includes the control/ingest computer, the scene mirror stepper motor controller, the blackbody temperature controller (BTC), the Stirling cooler controller, a housekeeping system with associated signal conditioning electronics (SCE), and the front-end processor (FEP) computer. Items are rack mounted for ease of maintenance. Figure 3 shows the electronics support equipment rack for the AERI-01 system at the SGP Central Facility in the foreground of the photograph. This section briefly describes some of the key functions of the electronics rack.

(i) Scene mirror controller

All AERI scene mirrors are controlled by Parker-Hannifin Corporation SX-6 motor drivers. The SX-6 is an intelligent microprocessor-controlled motor drive system that provides accurate, repeatable, and flexible mirror control. The motor drive communicates with the control/ingest computer via a serial port connection. By employing microstepping positioning at 36 000 steps per revolution, the control typically achieves ±5 arc min bidirectional unloaded accuracy. Encoder feedback is included in the system operation to ensure final positioning accuracy and to provide real-time information on system pointing accuracy. The SX-6 drive maintains a repeatability of ±5 arc s, typical, unloaded, and unidirectional. Nonvolatile homing routines ensure that the drive obtains accurate and repeatable home-location information upon power-up or reset. A configurable "stop-on-stall" coupled with overtemperature shutdown provides safe operation to protect operators and equipment.

(ii) Blackbody controller

The AERI BTC is a rack-mounted device designed and built at UW-SSEC. It is used to maintain the temperature of the hot blackbody reference within a narrow temperature range. A thermistor is used to sense the blackbody temperature. The voltage across the thermistor is compared to a reference voltage determined by set point switches, and the difference is applied to the input of an analog integrator. The output of the integrator controls the power applied to the blackbody heater. The negative feedback forces the steady-state voltage across the thermistor to be equal to the reference voltage and hence the blackbody temperature to be at the set point. The feedback amplifier includes a proportional component, in addition to the integral component, to stabilize the feedback loop. A linear power amplifier drives the blackbody heater. Under the expected ambient environmental temperature conditions, the stability of the AERI blackbody temperature controller is better than 2 mK over the period of an hour.

(iii) Housekeeping system

An extensive housekeeping system was developed for the AERI that provides a critical view into the instrument performance, especially from remote locations. A list of measured housekeeping values is given in Minnett et al. (2001). Housekeeping data are continuously recorded at high (5 s) time resolution and time averaged using real-time software to match the center of each scene dwell period. Figure 10 shows a schematic of the housekeeping system that is used to measure temperatures and voltages at various locations on the AERI system. The housekeeping system comprises two major components, a commercial off-the-shelf Keithley-Metrabyte DAS-HRES 16-bit analog-to-digital (A/D) multifunction ISA-bus card mounted in the control/ingest computer, and a Signal Conditioning Electronics (SCE) module mounted in the electronics rack.

The SCE was designed and built at UW-SSEC to provide the absolute accuracy and precision needed for measurement of the selected thermistors over a wide range of temperatures. The SCE comprises up to four Keithley-Metrabyte EXP-GP eight-channel signal conditioning boards, power supplies, and associated connective wiring. Analog signals and digital control lines connect the SCE EXP-GP boards with the DAS-HRES board mounted in the control/ingest computer. The control/ingest computer, controlling the DAS-HRES, scans through the channels of the SCE and records A/D data for each of the channels. Channel function is specified in configuration files, thereby providing easy reconfiguration for different applications including laboratory

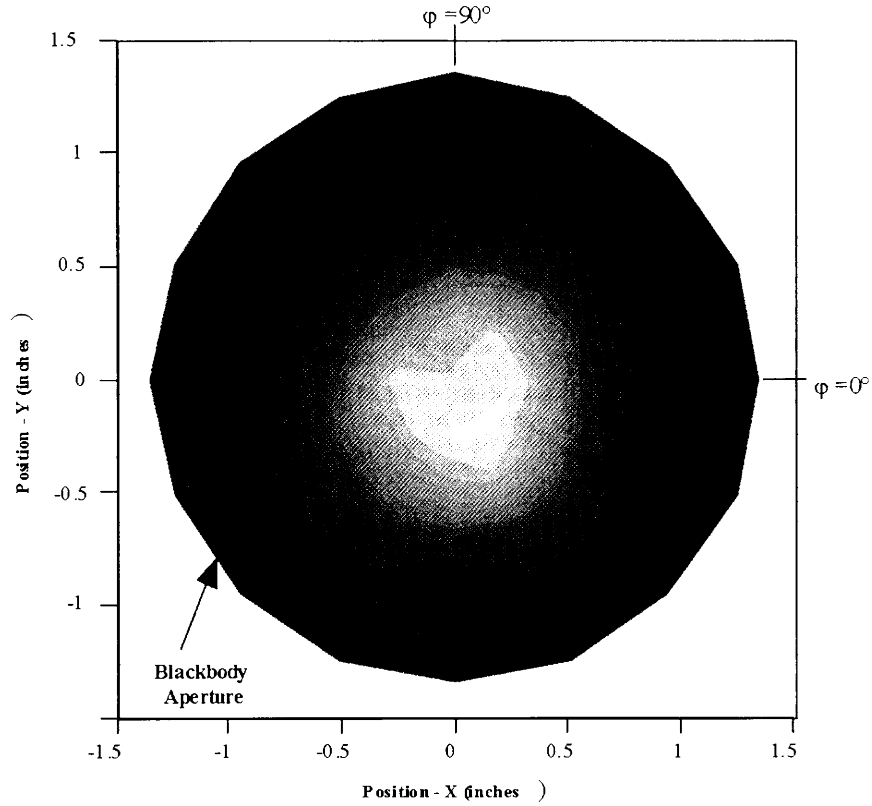

FIG. 7. Example of a radiometric field-of-view mapping at the aperture of the AERI blackbody. The FOV of each AERI instrument is measured in each of the reference blackbody and scene view positions. The FOV maps are used to verify optical alignment of the reference blackbody cavities.

calibrations. The control/ingest computer converts the A/D counts to physical units based on the configuration parameters. The SCE EXP-GP channels are individually configurable for a variety of sensor inputs including pressure, relative humidity, and temperatures derived from Yellow Springs Instruments (YSI) thermistors configured in a full bridge. The first eight channels of each AERI housekeeping system are manually calibrated using NIST-traceable fixed-resistor standards; calibration coefficients are generated using linear regression to provide A/D slopes and offsets for the individual channels. Six channels of the SCE are used to obtain calibrated

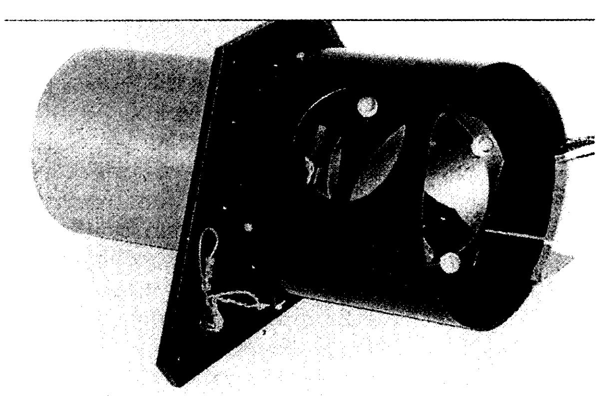

FIG. 8. Photograph of the gold-coated AERI scene mirror mounted in a holder on the shaft of a stepper motor. The black "can" surrounding the mirror helps provide immunity to scattering effects when the mirror is coated with dust particles, a common problem for remote field operations.

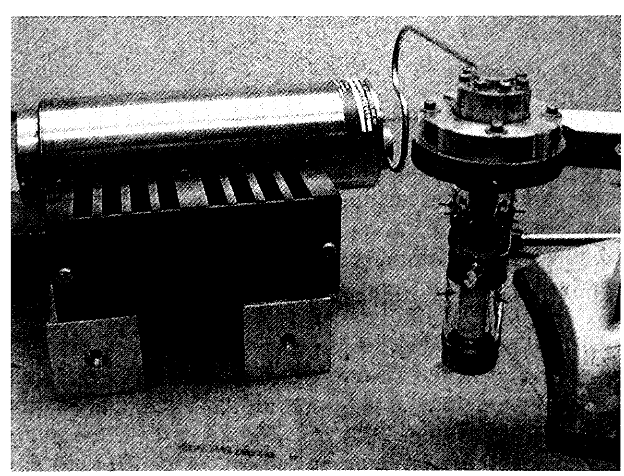

FIG. 9. The AERI HgCeTe/InSb detector assembly integrated with the Litton cryocooler.

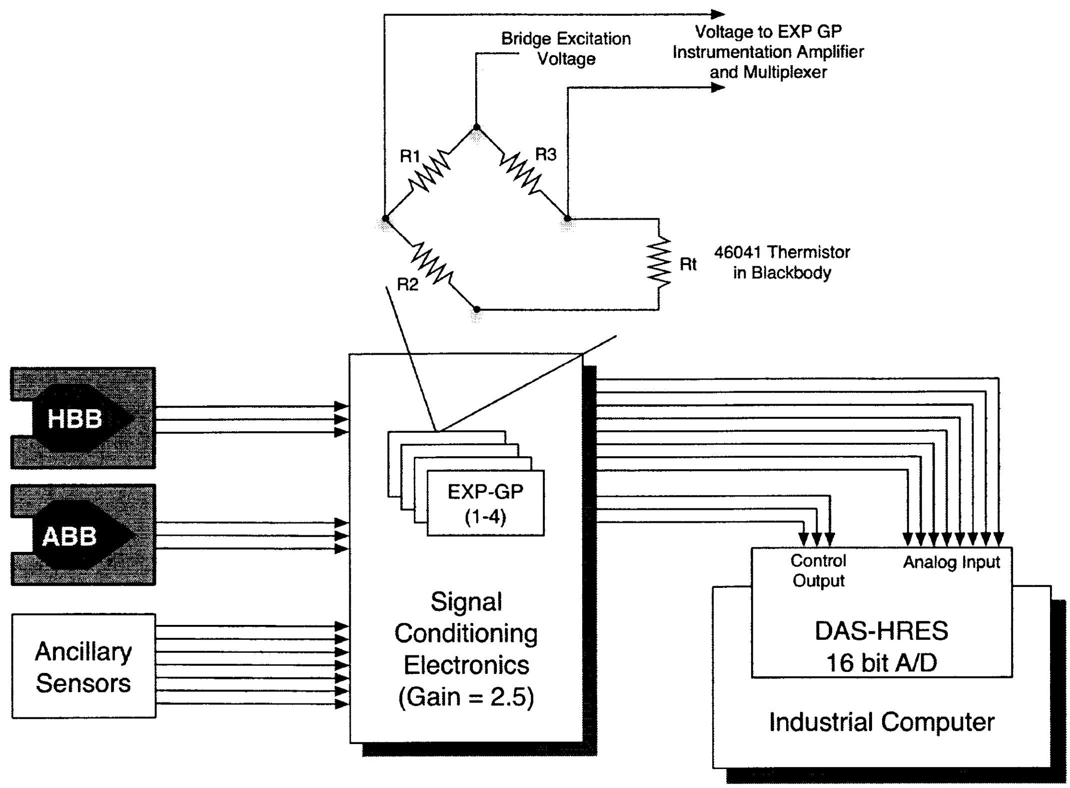

FIG. 10. AERI housekeeping system showing the interface between the rack-mounted computer used for data acquisition and the calibration reference sources.

readings of the thermistors from the ambient and hot blackbodies. Two channels are dedicated to temperature system quality monitors based on Vishay high-stability low-temperature coefficient thin-film fixed resistors. Standard conversion factors are used in the remaining housekeeping channels used to monitor nonessential temperatures and voltages.

The absolute accuracy of the UW-SSEC resistance measurement system as delivered is better than 10 mK (3σ error) over the range of resistances measured. Figure 11 is a plot of the residual (systematic) error of the AERI-NSA system after electronics calibration. The random noise on the readout temperature is less than 10 mK (3σ error) for a single measurement (mean of 200 readings collected within a fraction of a second). Since the reported blackbody temperature is an average of all the samples collected during the scene dwell period (about 20 measurements in the 100-s blackbody dwell period), the random error in the reported blackbody thermistor temperatures is only 2 mK (3σ error). The AERI electronics calibration has proven to be very stable with time. The variation of the 250-ohm fixed resistor in equivalent temperature was less than 30 mK over a 19-month period (February 1998–August 1999) of operation at the NSA site in Barrow, Alaska. The fixed resistor measurements are included in the AERI datastream so that they can be used for operational monitoring and in the quality control of archived data.

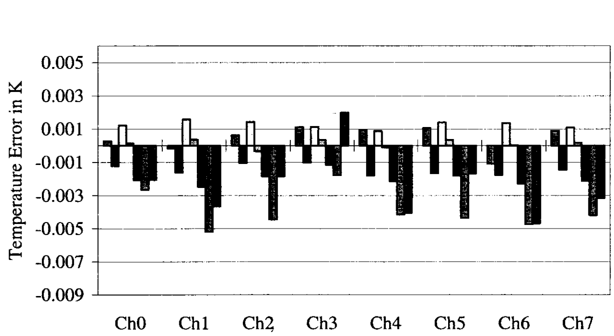

FIG. 11. AERI resistance measurement system calibration residuals for the AERI-NSA (-07) system. The equivalent temperatures for channels 1–7 are, respectively, 360, 337, 323, 288, 254, 233, and 222 K. A large sample set was collected to reduce the random component of the measurement to less than 1 mK. The residuals represent a systematic error arising from a linear fit in the count domain transformed into the temperature domain.

(iv) Control ingest and FEP computers

The control/ingest computer, which controls the sequence of data collection, acquires interferometer and housekeeping data, and transfers the raw data to the front-end processor, is a rack-mounted unit from Industrial Computer Systems, Inc., that uses an ISA bus. It contains one or more digital signal processing (DSP) boards used to communicate with the interferometer, an

A/D board used to sample housekeeping data from the SCE, and a network interface card for communication with the FEP computer. Data are collected on the ingest computer and passed to the FEP for real-time data processing. The ingest and FEP computers use a master–slave command structure whereby the FEP sends commands to the ingest computer. The command protocol is used to initialize a new data collection sequence at 0000 UTC each day. The output data files are produced on the basis of a UTC day, as per the ARM convection. The system is designed to continue data collection upon a commanded restart or a power cycle. The system control is largely immune to either power or network interruptions. The robustness of the control software is an integral part of the high reliability of the AERI instrument.

The AERI FEP converts raw data from the ingest computer into calibrated radiance products in real time. The software architecture of the real-time processing is described in Minnett et al. (2001); the data processing algorithms are described in Part II. The FEP also provides an operator display showing the current status of the instrument. The FEP acts as the interface to the external site data network with support for TCP/IP functions. In the AERI-00 and AERI-01 systems the FEP is a stand-alone computer. The functions of the FEP were integrated into the rack-mounted control/ingest computer in subsequent AERI systems (AERI-02 through -08 and -00U).

d. Temporal sampling

Time in the AERI system is set daily with a built-in GPS receiver or, in the case of AERI-01, via a network time server. Each sky spectrum is stamped with a time representing the center of the sky dwell period. The sky dwell period and the time interval between calibrated radiance spectra are controlled by several programmable configuration parameters. The Bomem MB100 outputs an interferogram every 1 s (2 s for AERI-01). A configuration parameter for the DSP code sets the number of interferograms to be used in computing the mean complex spectra for each scene view. This determines the scene dwell period. The number of views (blackbodies and sky scene views) contained in a sequence configuration file determines the time interval between calibrated radiance spectra. Some overhead is incurred by writing data to disk and moving the scene mirror. The standard mirror sequence used in the ARM Program produces a sky dwell period of about 200 s, with a nominal time between vertical sky scenes of about 8 min. A higher sampling rate and more continuous observations would be useful for remote sensing in the presence of clouds. Recent work has demonstrated that much higher sampling rates are possible with the existing AERI hardware simply by changing the sequence configuration file. Discussion of a "rapid sampling" AERI system is deferred to a future paper.

e. Operating environment

The standard AERI system is designed to operate in a surface air temperature range of $-30°$ to $+40°C$. In contrast, the lower temperature limit for an ER-AERI system is $-80°C$. In the ER-AERI design, heaters have been included on the scene mirror, the scene mirror motor, and the interferometer entrance window. The range of acceptable indoor electronics temperatures is $+10°$ to $+30°C$; however the self-calibrating nature of the AERI instrument makes it relatively immune to ambient temperature changes. Temperature sensors are used both outside and inside the thermal enclosure to alert the on-site operators when environmental conditions exceed the instrument specification.

f. Operational requirements

The ARM operational requirement is for an automated system providing real-time data acquisition, data processing, data quality control, and operator displays. The reader is referred to Minnett et al. (2001) for a description of the local operator display. The focus of this section is on the quality control metrics built into the real-time AERI software used to alert the instrument operators to problem conditions.

In order to satisfy the requirement for stand-alone operation in remote locations, a software-based quality control system with an interactive operator display was developed for the AERI instrument. An application was developed to run on the AERI FEP that generates a summary file from the calibrated data and associated intermediate data products. The summary file includes both instrument and science data quality measures. A real-time quality control application was also developed that passes the selected quality measures through a series of limits checks. Three ranges are defined for each quality metric; good (green), warning (yellow), and out-of-limits (red). An operator display was developed that visually indicates the instrument status and data quality using warning lights. An example of a quality metric is the instrument system responsivity at 10 μm. Limits for this quality metric are set at the time of instrument installation. The limits are chosen so that the responsivity warning light is green in the normal range of operation, but a yellow light is displayed if the responsivity decreases 5%–10%, and if it drops by 10% or more a red light is displayed. The site operators are instructed to clean the scene mirror when this warning light turns from green to yellow or red. Over 30 similar status indications are used to diagnose instrument problems remotely. Table 4 lists the variables that are used as real-time quality metrics for the AERI-01 system at the ARM SGP Central Facility. The real-time operator displays of all AERI instruments are viewable simultaneously through the Multi-AERI Display System (MADS), which uses the Internet to remotely view the status of

TABLE 4. Data quality metrics used in the monitoring of the AERI systems. The limits shown are from the AERI-01 system at the SGP Central Facility. The limits are customized to each instrument site location.

Variable	Red limits	Units
Outside air temp	253.15 313.15	K
Room air temp	288.15 303.15	K
Max sample std dev	0 0.02	K
ABB max temp diff	0 0.1	K
HBB max temp diff	0 0.7	K
LW responsivity	0.32 1.0	counts/[mW (m^2 sr cm^{-1})$^{-1}$]
SW responsivity	0.925 10.0	counts/[mW (m^2 sr cm^{-1})$^{-1}$]
Relative humidity	1.0 99.0	% RH
Atmospheric pressure	920.0 1040.0	mb
Hatch open	0 0	N/A
LW HBB NEN	0 1	mW (m^2 sr cm^{-1})$^{-1}$
SW HBB NEN	0 0.1	mW (m^2 sr cm^{-1})$^{-1}$
HBB temp	263.15 353.15	K
ABB temp	243.15 313.15	K
HBB controller temp	273.15 323.15	K
ABB controller temp	273.15 323.15	K
HBB temp stability	−0.5 0.5	K
Air temp near BBs	233.15 343.15	K
Computer temp	277.15 319.15	K
SCE temp	273.15 333.15	K
Rack ambient temp	277.15 319.15	K
Mirror motor temp	233.15 343.15	K
Motor driver temp	273.15 323.15	K
Encoder scene confirm	−5 5	0.01°
BB support structure temp	228.15 323.15	K
Internal second port temp	288.15 308.15	K
Detector temp	74.0 85.0	K
Cooler power supply temp	281.15 333.15	K
Cooler current	0.5 1.2	Amp
Cooler expander temp	281. 308.	K
Cooler computer temp	281.0 308.0	K
12 K ohm equivalent temp	293.446 293.496	K
2.5 K ohm equivalent temp	336.0803 336.1303	K

each AERI system. The MADS is now a Web-based tool for the monitoring of multiple AERI systems.

g. Data products

The standard AERI radiance data product is a continuous spectrum between 520 and 3020 cm^{-1} (the requirement is 550–3000 cm^{-1}). The ER-AERI radiance product at the North Slope of Alaska site is a continuous spectrum between 380 and 3020 cm^{-1} (the requirement is 400–3000 cm^{-1}). The AERI radiance data product is minimally sampled; that is, the spectral sample frequency is equal to the unapodized spectral resolution (see Table 3). Data files are produced daily for ingest into the ARM archive. The files contain the mean and standard deviation spectra (unapodized) over the sky dwell period for each atmospheric downwelling radiance observation collected during the UTC day. The radiance data include all the instrument-related corrections described in Part II, resulting in calibrated radiances with a standardized spectral scale and idealized instrument line shape function. The two detector bands (longwave HgCdTe and shortwave InSb) are stored separately. A summary file contains all the coincident housekeeping data and the quality metrics.

3. Field observations

The AERI instruments developed for the ARM Program have collected a large and growing set of infrared downwelling spectral measurements. Table 1 lists the initial deployment date of AERI systems at each ARM site location. These sites are collecting a nearly continuous record of observations 24 hours per day, 7 days a week. In addition, the UW-SSEC has operated a mobile AERI system during more than 30 dedicated field campaigns since the original GAPEX campaign in 1988. The AERI participation in these intensive field campaigns provides a valuable complement to the operational data collected at the ARM fixed sites.

4. Conclusions

The AERI instruments have successfully accomplished the goal of the DOE ARM Program for fully automated measurement of the downwelling infrared emission spectrum at the surface. The performance of the AERI instruments designed and built at UW-SSEC meet or exceed the ARM requirements for 1.0-cm^{-1} (apodized) resolution infrared spectral observations with high absolute accuracy. The requirement for 24-h unattended operation leads to the implementation of hardware (e.g. mechanical coolers) and robust software unique to the AERI system. The final instrument design addresses a number of issues important for remote operations: 1) an auto-restart capability to minimize the need for operator intervention, 2) a modular design for ease of maintenance, 3) operation in Arctic to tropical environments, 4) an optical design to minimize the effects of contamination (dust) on the scene mirror, and 5) real-time data processing that provides a standard data product corrected for all instrument specific effects. Detailed performance estimates are given in Part II, along with descriptions of the algorithms used in the real-time data processing.

A large number of high quality observations have been collected at tropical, midlatitude, and Arctic sites by the ARM Program. These AERI observations are providing a valuable contribution to the understanding of climate and radiation processes.

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