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On-orbit absolute blackbody emissivity determination using the heated halo method

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Abstract

We present a novel method to measure the absolute spectral emissivity of a blackbody cavity *in situ* using the heated halo, a broadband thermal source. Laboratory demonstrations have yielded spectral emissivity measurements of a 0.999 emissivity blackbody that are in agreement with results based on Monte Carlo ray trace modelling. The combined uncertainty of the measurement is less than 4×10^{-4} ($k = 3$) in the 580 cm^{-1} to 2800 cm^{-1} spectral range. This is equivalent to a detection limit of 11 mK in the error in radiance temperature for a calibration blackbody (at 330 K, 1500 cm^{-1}) due to blackbody cavity emissivity drift. These results provide the experimental foundation for this technology to be implemented on satellite instruments and thus eliminate a key, time-dependent, systematic error from future measurements on-orbit.

(Some figures may appear in colour only in the online journal)

1. Introduction

Measurements of spectral infrared radiance from space are an effective benchmark of global climate change, if they are made with demonstrable on-orbit accuracy. A time series of spectrally resolved thermal infrared radiance emitted from Earth to space contains signatures of the longwave forcing of the climate, the climate's response, and the longwave feedbacks inherent in that response, and therefore establishes a high-accuracy record of climate change and, in addition, provides powerful constraints on climate models. The timely detection of decadal climate signals above natural variability requires measurements with a high level of accuracy (Leroy *et al* 2008). Recent studies (Anderson *et al* 2004, National Research Council 2007, Ohring 2008) call for measurements of thermal infrared radiance with combined uncertainties better than 0.1 K ($k = 3$) in radiance temperature for the detection of spectral climate signatures. This level of uncertainty, proven on orbit, has not yet been accomplished by space-based high-resolution infrared sounders.

The determination of satellite sensor uncertainty during prelaunch calibration cannot be assumed to be valid over the operational lifetime of the instrument. The harsh conditions of spacecraft launch and the low Earth orbit environment can lead to secular drifts in instrument physical properties that are manifest as a time-dependent bias in the absolute calibration. Degradation affecting blackbodies, which provide the fundamental radiometric calibration for spaceborne infrared sounders, is a particular concern. Demonstration of adequate instrument uncertainty levels during the mission requires that diagnostics be performed on-orbit, confirming that the uncertainty budgets obtained during prelaunch calibration are still tenable (Dykema and Anderson 2006).

Spaceborne measurements of infrared radiance can be most accurately calibrated with blackbodies. The spectral radiance $B_{\tilde{\nu}}(T)$ emitted by a blackbody cavity of uniform temperature T with an infinitesimal aperture is described by the Planck function

$$B_{\tilde{\nu}}(T) = \frac{2hc^2\tilde{\nu}^3}{\exp(hc\tilde{\nu}/k_B T) - 1}, \quad (1)$$

where h is Planck's constant, c is the speed of light in a vacuum, k_B is the Boltzmann constant and $\tilde{\nu}$ is the spectral index in

cm^{-1}. The spectral radiance $I_{\tilde{\nu}}$ emitted by a cavity with a finite aperture with Lambertian reflectance is

$$I_{\tilde{\nu}} = \varepsilon_{\tilde{\nu}} B_{\tilde{\nu}}(T) + (1 - \varepsilon_{\tilde{\nu}}) B_{\tilde{\nu}}(T^{\mathrm{eff}}), \tag{2}$$

where $\varepsilon_{\tilde{\nu}}$ is the cavity emissivity, and T^{eff} is the effective temperature of the radiation from the background environment assuming that it is spatially isotropic and isothermal. The values of the physical constants that appear in the Planck function are known with much lower uncertainties than is required for remote sensing applications. Thus the dominant source of uncertainty in a well-designed blackbody arises from the measurement of the cavity temperature and the effect of the non-unity emissivity of a practical blackbody with a macroscopic aperture. Demonstration of a high-accuracy infrared radiance scale requires that both blackbody temperature and emissivity be diagnosed on-orbit. The measurement of cavity temperature on-orbit, traceable to fundamental physical standards using phase-change materials, has been discussed in earlier papers (Krutikov *et al* 2006, Best *et al* 2008, Gero *et al* 2008). Furthermore, blackbody emissivity measurements using single mode quantum cascade lasers have been demonstrated and are being developed for spaceborne applications (Gero *et al* 2009). Here we present a novel method to measure the emissivity of a blackbody using a broadband thermal source called the heated halo.

For satellite instruments, blackbody cavity emissivity is generally modelled numerically, and/or determined experimentally during prelaunch calibration. No infrared spectrometer currently in orbit incorporates an on-board diagnostic measurement to quantify changes in cavity emissivity over the mission lifetime. Thus it is generally assumed, without any direct means of confirmation, that the cavity emissivity will remain constant for the duration of the mission such that (1) and (2) will continue to apply unmodified.

The effect of exposure to the low Earth orbit environment on various materials was investigated on the Long Duration Exposure Facility (LDEF). LDEF included several polyurethane paint coatings, including Aeroglaze Z306, which is the coating employed in the laboratory experiments for this paper. After 5.7 years of space exposure the paint surfaces underwent significant physical changes, including oxidation from atomic oxygen, paint erosion, the removal of resins, the appearance of silicate residues, cracking and quantitative changes in optical properties (Golden 1994). The susceptibility of paint to degradation in space has thus been demonstrated. There exist, however, no diagnostics of paint optical properties of blackbodies on board the satellite instruments that rely on these properties for radiometric calibration.

We propose a new method to monitor blackbody emissivity using a broadband thermal source called the heated halo. The heated halo is a thermally controlled cylindrical body, painted black, akin to a blackbody that has openings on both sides. The heated halo is placed in front of the blackbody under test and aligned with its optical axis (figure 1). The blackbody radiation is then observed with a given detector, with the heated halo at two different temperatures. Knowledge of the geometry of the experiment and the temperature of the apparatus allows the blackbody emissivity to be obtained, based on the amount of radiation reflected from the heated halo by the blackbody under test. The geometry and usage of the heated halo are such that it can be readily integrated into the optical systems of satellite instruments to measure blackbody emissivity on-orbit.

In this paper we present a laboratory demonstration of the diagnostic of cavity emissivity with the heated halo using an existing blackbody and two different infrared spectrometers. In section 2 we outline the theoretical basis underlying the measurement. Section 3 describes the experimental apparatus, including the spectrometers, the blackbody and the heated halo, as well as the experimental procedure. Section 4 presents the discussion of the results obtained with the heated halo. We summarize our conclusions in section 5.

2. Theory

We first discuss the theoretical framework underlying the heated halo measurement. The geometric, thermal and radiometric properties are considered.

The observed spectral radiance $\tilde{I}_{\tilde{\nu}}$ from a practical blackbody is given by

$$\tilde{I}_{\tilde{\nu}} = \varepsilon_{\tilde{\nu}} B_{\tilde{\nu}}(T_{\mathrm{bb}}) + (1 - \varepsilon_{\tilde{\nu}}) I_{\tilde{\nu},\mathrm{bg}}, \tag{3}$$

where $\varepsilon_{\tilde{\nu}}$ is the blackbody spectral emissivity, $B_{\tilde{\nu}}(T_{\mathrm{bb}})$ is the Planck function (1) evaluated at the blackbody temperature, T_{bb}, and $I_{\tilde{\nu},\mathrm{bg}}$ is the spectral radiance from the background environment. Nominally, the background radiance is given by

$$I_{\tilde{\nu},\mathrm{bg}} = B_{\tilde{\nu}}(T_{\mathrm{rm}}^{\mathrm{eff}}), \tag{4}$$

where $T_{\mathrm{rm}}^{\mathrm{eff}}$ is the effective temperature of the radiation from the background environment assuming that it is spatially isotropic and isothermal. For the case that the heated halo is placed in the optical chain between the spectrometer and the blackbody, the background radiance becomes

$$I_{\tilde{\nu},\mathrm{bg}} = F B_{\tilde{\nu}}(T_{\mathrm{ha}}) + (1 - F) B_{\tilde{\nu}}(T_{\mathrm{rm}}^{\mathrm{eff}}), \tag{5}$$

where F is the geometrical view factor of the heated halo by the blackbody, and T_{ha} is the heated halo temperature. The view factor characterizes the fraction of the solid angle viewed by the blackbody that contains radiation emitted by the heated halo. F can be determined geometrically based on the physical dimensions of the blackbody and the heated halo.

In order to remove biases in the observing system, the heated halo measurement is compared with a reference measurement in which all components of the system are at ambient temperature. In this case the blackbody and the heated halo are nearly isothermal, and the output radiance from the blackbody-heated halo system ($I_{\tilde{\nu},\mathrm{ambient}}^{\mathrm{model}}$) can be modelled by (3) and (5) with high accuracy. This result is then compared with the radiance observed by the spectrometer ($\tilde{I}_{\tilde{\nu},\mathrm{ambient}}^{\mathrm{observed}}$) to compute a bias term

$$\mathrm{d}I_{\tilde{\nu}} = I_{\tilde{\nu},\mathrm{ambient}}^{\mathrm{model}} - \tilde{I}_{\tilde{\nu},\mathrm{ambient}}^{\mathrm{observed}}. \tag{6}$$

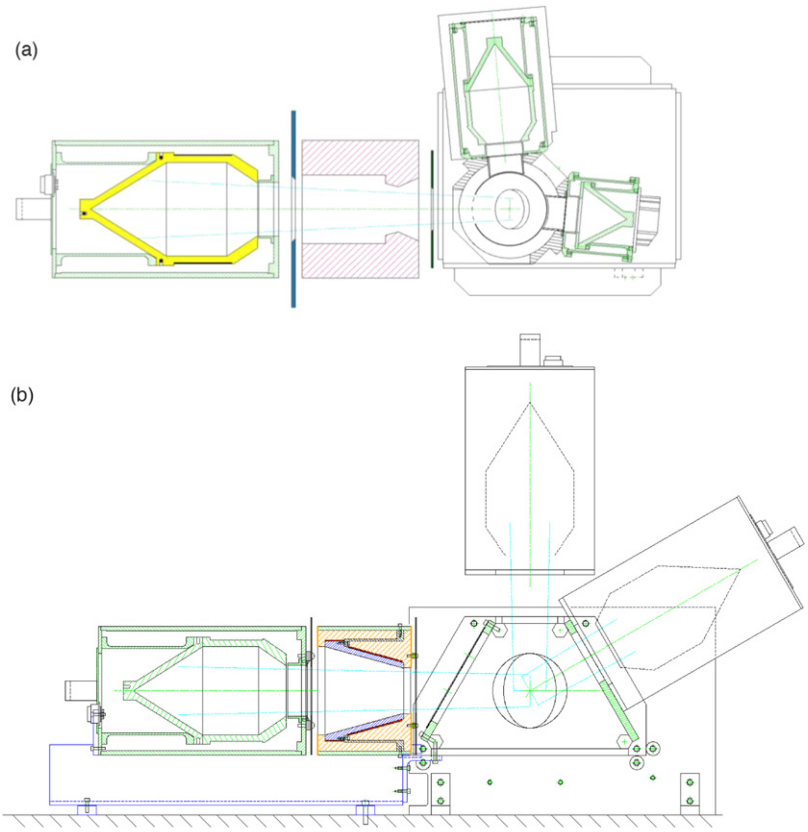

Figure 1. Cross sectional schematic of the heated halo experiment, as implemented with (*a*) the S-HIS and (*b*) the ARI. The AERI blackbody, at ambient temperature, is on the left. The temperature of the heated halo, to the right of the AERI blackbody, is raised about 75 K above ambient temperature. While the heated halo is outside the direct view of the sensor to the right, its broadband radiation is reflected from the blackbody cavity and observed by the sensor. A radiation shield is placed between the heated halo and the blackbody to prevent excessive heating of the blackbody.

This bias term is then used to correct the radiance observed for the elevated temperature heated halo measurement,

$$I_{\tilde{\nu}}^{\text{corrected}} = \tilde{I}_{\tilde{\nu}}^{\text{observed}} + \mathrm{d}I_{\tilde{\nu}}. \tag{7}$$

For the elevated temperature heated halo measurement, we combine (3) and (7) to obtain

$$\varepsilon_{\tilde{\nu}} = \frac{(\tilde{I}_{\tilde{\nu}} + \mathrm{d}I_{\tilde{\nu}}) - I_{\tilde{\nu},\mathrm{bg}}}{B(T_{\mathrm{bb}}) - I_{\tilde{\nu},\mathrm{bg}}}, \tag{8}$$

where $I_{\tilde{\nu},\mathrm{bg}}$ is given by (5). All of the terms on the right-hand side of (8) can be measured or modelled accurately, thus it is used to solve for the spectral emissivity of a given blackbody.

3. Experiment description

We describe the experimental apparatus used in the emissivity measurement. Then we outline the experimental procedure implemented on the basis of the framework from section 2, as well as the numerical analysis used to obtain the emissivity result.

3.1. Experimental apparatus

3.1.1. Spectrometers. Two different spectrometers were used to make emissivity measurements with the heated halo. The Scanning High-resolution Interferometer Sounder (S-HIS) is an infrared Fourier transform spectrometer designed for autonomous operation on-board research aircraft (Revercomb *et al* 2005). The core of the instrument is a dynamically aligned plane mirror interferometer (ABB, Québec, Canada), with a KBr beamsplitter, and a maximum optical path difference of ± 1 cm, leading to an unapodized spectral resolution of 0.5 cm^{-1}. In order to obtain good noise performance across a broad spectrum of the infrared, three detectors (two photoconductive HgCdTe and one InSb) are used to cover the spectral range from 580 cm^{-1} to 2800 cm^{-1} (3.6 μm to 17.2 μm). The S-HIS has been deployed extensively from 1998 to the present aboard the NASA DC8, Proteus, ER-2, WB-57 and Global Hawk research aircraft in field campaigns worldwide for the sounding of temperature, water vapour and clouds. The instrument was reconfigured to operate in a laboratory environment and to interface with the heated halo (figure 1(*a*)). A purge box was constructed around the instrument and a nitrogen purge was used in order to reduce contamination of the spectra by ambient air, particularly by water vapour.

The Absolute Radiance Interferometer (ARI) is an infrared Fourier transform spectrometer developed under the NASA Instrument Incubator Program (IIP) as a prototype of the Climate Absolute Radiance and Refractivity Observatory (CLARREO) (Taylor *et al* 2011). The ARI is designed to make high-accuracy measurements of thermal infrared radiance that meet the stringent requirements of the CLARREO mission: 0.1 K combined uncertainty in radiance temperature ($k = 3$). The instrument uses a novel validation subsystem that employs *in situ* phase change cells that directly tie blackbody temperature to the fixed points of the ITS-90 temperature scale, as well as both the heated halo and a quantum cascade laser to monitor changes in blackbody emissivity. The instrument is based on an interferometer with a wishbone cube corner design (ABB, Québec, Canada), with a CsI beamsplitter, a maximum optical path difference of ±1 cm, and an unapodized spectral resolution of 0.5 cm^{-1}. The configuration of the ARI in this experiment uses a pyroelectric detector to measure the thermal infrared spectrum between 200 cm^{-1} and 2000 cm^{-1} (5 µm to 50 µm). While the noise performance of this detector is not as good as those in the S-HIS, it can make measurements in the far-infrared component of the spectrum. The instrument operates inside a purge box purged with nitrogen.

3.1.2. Blackbody. The Atmospheric Emitted Radiance Interferometer (AERI) is a ground-based instrument that was developed at the University of Wisconsin for the US Department of Energy Atmospheric Radiation Measurement program (Best *et al* 2003, Knuteson *et al* 2004a, 2004b). Over a dozen AERI units have been deployed and operated successfully from 1988 to the present, making measurements of absolutely calibrated downwelling spectral radiance worldwide. The AERI uses two high-emissivity blackbodies for radiometric calibration. The blackbody employs a light-trapping cavity geometry painted with diffuse Aeroglaze Z306 (Lord Corp., Erie, PA) (figure 1), with an aperture of 6.9 cm. Three thermistors (YSI, Yellow Springs, OH) are embedded in the blackbody to measure its absolute temperature to within a combined uncertainty of 0.05 K ($k = 3$). A thermal insulating jacket around the cavity isolates the blackbody from the ambient thermal environment and helps us to maintain isothermality. The AERI blackbodies are mechanically identical and interchangeable. Due to its excellent performance and the researchers' extensive experience with this blackbody, it was selected for emissivity testing with the heated halo.

3.1.3. Heated halo. The heated halo is a broadband thermal radiation source. It is designed to interface with a blackbody and cover a large fraction of the solid angle of its field of view, while being physically outside of the field of view of the detector observing the blackbody. Two heated halo designs are used in this experiment: one for the S-HIS and one for the ARI. The S-HIS heated halo is a hollow aluminium cylinder that is painted black (Krylon, Cleveland, OH), with an interior diameter of 8.9 cm and a front aperture diameter of 5.8 cm (figure 1(*a*)). The cylinder is heated with Kapton thermofoil heaters (Minco, Minneapolis, MN) and isolated from the ambient thermal environment with an insulating jacket. Four thermistors measure the temperature along the length of the cylinder. The ARI heated halo is of similar construction but the shape is conical, with a front aperture diameter of 6.1 cm and a rear aperture diameter of 12.1 cm (figure 1(*b*)). In both cases, a circular radiation shield with an aperture diameter of 7.6 cm is placed between the AERI blackbody and the heated halo in order to reduce radiative heating of the blackbody by the heated halo.

The key observable parameters of the heated halo are its temperature (T_{ha}), measured by thermistors, and its geometric view factor (F). The view factor is the solid angle fraction of the blackbody's field of view that is covered by the heated halo. Based on the geometries of the AERI blackbody and the heated halo, the view factor was calculated to be 0.61 for the S-HIS and 0.45 for the ARI version of the heated halo.

3.2. Experimental procedure

In order to make an absolute measurement of blackbody emissivity using the bias correction described in (6), the spectrometer observes the blackbody at two different temperatures of the heated halo. First, a radiance measurement is made with the blackbody and heated halo at ambient room temperature (about 293 K). Then heater power is applied to the heated halo and its temperature is raised by about 75 K. Once it has stabilized around 368 K, a second radiance measurement is made with the blackbody at ambient temperature and the heated halo at the elevated temperature. With the S-HIS, the AERI blackbody as well as the internal calibration blackbodies were observed for a period of 1 h. During this time, temperature measurements of the blackbody, heated halo, and housekeeping points along the apparatus were made every 6.5 s. Figure 2 shows the temperatures of various points on the apparatus during the course of the emissivity measurement. The observations were averaged in order to reduce detector noise.

Due to the worse noise performance of the pyroelectric detector, a much longer averaging time was necessary to get adequate results with the ARI. With this instrument, the AERI blackbody as well as the internal calibration blackbodies were observed for a period of 75 h. Because of the higher type A uncertainty in this measurement from the detector, the reference measurement with the heated halo at ambient temperature was not performed with the ARI, as the resulting correction would not be significant in relation to the magnitude of the uncertainty.

3.3. Analysis

Due to the large thermal gradients present in the apparatus, radiative and convective heating occurs during the measurement period in the thermally passive components (e.g. blackbody), as shown in figure 2(*a*). In order to account for this effect, the instantaneous emissivity of the blackbody (8) is computed during every scan cycle of the spectrometers, which takes 6.5 s for the S-HIS and 100 s for the ARI. During this time, the spectrometers observe the AERI blackbody, as well as its two internal calibration targets, in order to determine the calibrated scene radiance (Revercomb *et al* 1988). The temperature measurements of the apparatus are averaged over this same period. Since the rate of change of temperature of the apparatus is

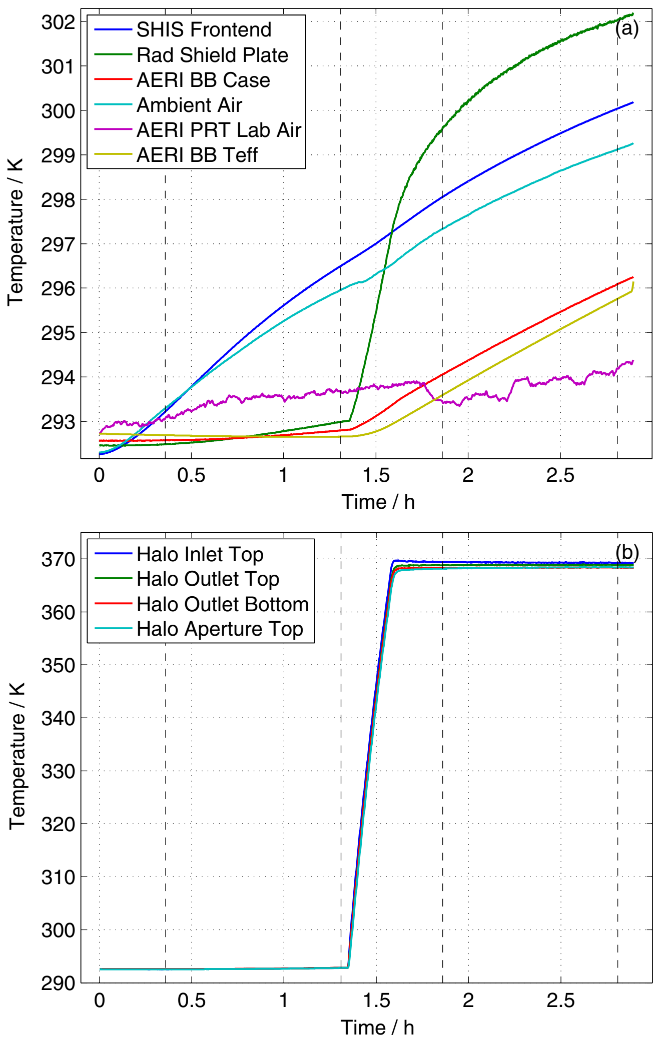

Figure 2. Experiment temperatures throughout the course of an emissivity measurement with the S-HIS. (*a*) Temperatures of the S-HIS front end, radiation shield, AERI blackbody case, ambient air and blackbody. (*b*) Temperatures of the heated halo. The black vertical lines indicate the time intervals in which data were used for the emissivity measurement: the ambient temperature heated halo observation occurs at 0.3 h to 1.3 h; the elevated temperature heated halo observation occurs at 1.8 h to 2.8 h.

slow compared with 100 s and negligible compared with 6.5 s, the resulting time series of instantaneous emissivity measurements can be averaged to obtain the mean emissivity result,

$$\varepsilon_{\tilde{\nu}} = \langle \varepsilon_{\tilde{\nu}}(t) \rangle_t = \left\langle \frac{(\tilde{I}_{\tilde{\nu}}(t) + \mathrm{d}I_{\tilde{\nu}}) - I_{\tilde{\nu},\mathrm{bg}}(t)}{B(T_{\mathrm{bb}}(t)) - I_{\tilde{\nu},\mathrm{bg}}(t)} \right\rangle_t . \quad (9)$$

A Savitzky–Golay filter of order 3 and a frame size of 71 is applied to the spectral emissivity in the results presented in this paper, in order to smooth out high frequency spectral features.

4. Results and discussion

The emissivity spectrum of the AERI blackbody, as measured by the S-HIS instrument using the heated halo method, is shown in figure 3(*a*). Some of the high frequency oscillations can be attributed to detector noise, particularly at the extremities of the spectrum, as well as any residual water vapour lines that were not removed by the nitrogen purge. The overall shape of the emissivity curve, notably the step in emissivity around 1200 cm^{-1}, is consistent with the properties of the Aeroglaze Z306 paint (Persky 1999).

The emissivity spectrum of the same AERI blackbody, measured with the ARI and the cylindrical heated halo, is shown in figure 3(*b*). The overall shape of this curve is in good agreement with the S-HIS result, including the step feature at 1200 cm^{-1}. The high frequency oscillations throughout the spectrum are a result of pyroelectric detector noise. These are again larger in the wings of the spectrum. The lower emissivity feature around 600 cm^{-1} is likely due to residual carbon dioxide in the system. The spectrum shows that the emissivity of the AERI blackbody is very good out to about 400 cm^{-1} ($\varepsilon_{\tilde{\nu}} > 0.997$), but drops significantly between 400 cm^{-1} and 200 cm^{-1}. This is in agreement with other experimenters' experience with paints in the far infrared segment of the spectrum (Werner *et al* 2009).

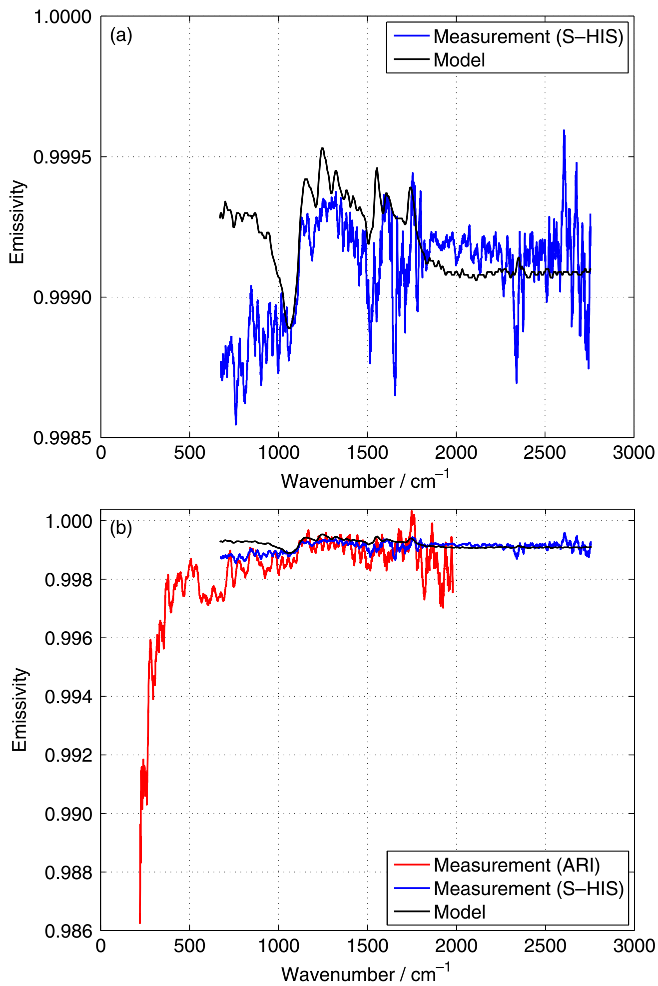

Figure 3. (*a*) Emissivity of the AERI blackbody measured with the S-HIS, compared with the model calculation. (*b*) Same as (*a*), but also showing the emissivity of the AERI blackbody measured with the ARI. The combined uncertainty of the model is 6×10^{-4} ($k = 3$). The uncertainty in the measurements is shown in figure 4.

Table 1. Type B experimental uncertainties ($k = 3$).

Component uncertainty	Value	Unit
Stray radiation (f_{stray})	0.01	% of radiance
Heated halo view factor (dF)	10	%
Heated halo temperature (dT_H)	5	K
Calibration accuracy (dT_{cal})	0.01	K
Room temperature (dT_R)	5	K
Blackbody temperature (dT)	0.1	K

There are six main sources of systematic measurement uncertainty (type B) in the evaluation of emissivity: stray radiation, the view factor (F), calibration accuracy, and the measured temperatures of the heated halo (T_{ha}), effective room temperature (T_{rm}^{eff}) and the blackbody temperature (T_{bb}). The component uncertainties are listed in table 1. The stray radiation factor is based on experimental results. Initial optical configurations were susceptible to some stray radiation, that is a direct view of the heated halo in the detector field of view due to scattering or unwanted reflections. This issue was addressed by careful baffling of the heated halo, and the term used in the uncertainty analysis is an estimate of any residual stray radiation that may still be present in the optical system. The view factor (F) was calculated geometrically, and has an uncertainty due to the geometric alignment of the optical system. The calibration accuracy represents the absolute accuracy of the radiance measurement by the S-HIS. The bias correction (6) and (7) removes first-order systematic errors in the S-HIS observed radiance, thus this uncertainty term represents any residual from this correction. Uncertainties in the measured temperatures arise primarily due to thermal inhomogeneities along the surfaces being measured. Using multiple thermistors to measure the temperature gradients found on these surfaces, the uncertainties in the effective temperature can be ascertained.

The uncertainty in emissivity arising from each of these six components is calculated analytically by applying variational analysis to (8). The spectral results of the component uncertainties as well as the combined uncertainties are shown in figure 4(*a*) for the S-HIS and figure 4(*b*) for the ARI. The combined uncertainty of the emissivity measurement is less than 4×10^{-4} for the S-HIS across the entire measured spectrum between 580 cm^{-1} and 2800 cm^{-1}. The combined uncertainty of emissivity for the ARI measurement is less than 6×10^{-4} between 400 cm^{-1} and 2000 cm^{-1}, and rises to 20×10^{-4} between 200 cm^{-1} and 400 cm^{-1}. The dominant contribution to the combined uncertainty is from stray radiation.

In order to validate the observation, the measurement of emissivity with the heated halo is compared with a model of the AERI blackbody emissivity (Best *et al* 2009). The input to the model is the measured surface emissivity and diffusivity of Aeroglaze Z306 paint from witness samples of the AERI blackbody paint preparation. These observations at given spectral points, as well as the AERI cavity geometry, are input into a Monte Carlo ray-trace model to obtain effective cavity emissivity (Sapritsky and Prokhorov 1992, 1995, Prokhorov 1998). The ray-trace model output is then fitted and parametrized in order to obtain spectral blackbody emissivity over the entire range of interest.

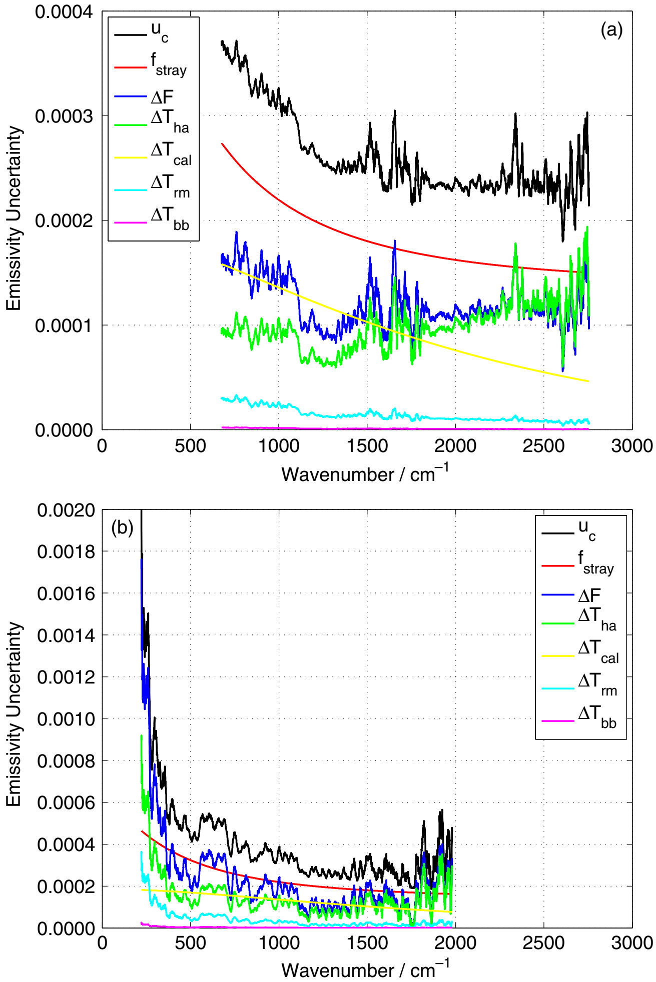

Figure 4. Type B experimental uncertainties ($k = 3$) for emissivity measurement with the heated halo for (*a*) S-HIS and (*b*) ARI. The six main contributing sources are uncertainties in stray radiation (f_{stray}), heated halo view factor (ΔF), heated halo temperature (ΔT_{ha}), calibration accuracy (ΔT_{cal}), room temperature (ΔT_{rm}) and blackbody temperature (ΔT_{bb}). The magnitudes of the component uncertainties are shown in table 1. The combined uncertainty ($k = 3$) is shown with the top black curve.

Figure 3 also shows the comparison between the model result and the heated halo measurements. The uncertainty in the model calculation is 6×10^{-4} ($k = 3$). The model and measurement results are in general agreement within their uncertainties. The agreement between 1000 cm^{-1} and 2800 cm^{-1} is particularly good. The Aeroglaze Z306 spectral feature at 1200 cm^{-1} is very well reproduced. The agreement is less good between 600 cm^{-1} and 1000 cm^{-1}. The most likely explanation is that the model does not realistically reproduce the cavity emissivity in the long wave end of the spectrum due to the limitations of surface parametrization in terms of diffusivity in the model. Both independent measurements using the heated halo show good agreement in this region, thus the model is more suspect.

Given the uncertainty in the measurement of emissivity, we can calculate the corresponding error in blackbody radiance temperature that is detectable with this method. Using (1) and (2), we can calculate the resultant change in blackbody radiance temperature arising from a given change in emissivity.

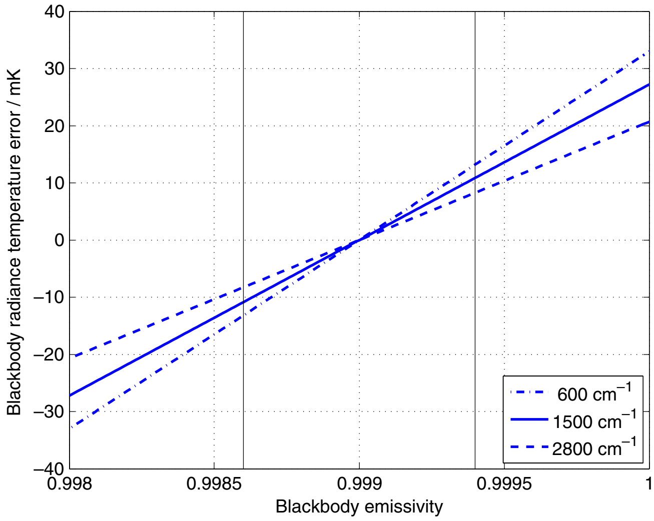

Figure 5. Error in the calculation of blackbody radiance temperature arising from an uncorrected change in blackbody cavity emissivity. The horizontal axis indicates the value of uncorrected drifted cavity effective emissivity from the initial value of 0.999. The vertical axis shows the corresponding error in the calculation of blackbody radiance temperature based on the uncorrected value of cavity effective emissivity. The calculation is for a blackbody at 330 K. Results are shown at 600 cm^{-1}, 1500 cm^{-1} and 2800 cm^{-1} for the same error in emissivity. The solid vertical lines represent the type B combined uncertainty ($k = 3$) achieved with the heated halo method and the S-HIS.

This relationship is shown in figure 5. This result shows that a cavity emissivity drift of 4×10^{-4}, which is the uncertainty from the heated halo measurement with the S-HIS, corresponds to a blackbody radiance error of 13.2 mK, 10.9 mK and 8.3 mK at 600 cm^{-1}, 1500 cm^{-1} and 2800 cm^{-1} respectively. Thus the heated halo method allows the detection of changes in blackbody emissivity at levels that are well below 0.1 K.

5. Conclusions

A novel method has been implemented to measure the spectral emissivity of a blackbody with a heated halo. Using the S-HIS and ARI spectrometers, the emissivity of the AERI blackbody was measured in the 200 cm^{-1} to 2800 cm^{-1} spectral range. The measurement is repeatable and robust, and employs a bias correction that removes first-order radiometric errors and allows an absolute measurement of emissivity to be made. The low level of systematic experimental uncertainty (4×10^{-4} for the high performance S-HIS detectors) facilitates the detection of radiometric errors due to emissivity drift in a given blackbody on the order of 10 mK in radiance temperature. These results are encouraging that the heated halo can be deployed on a space-based instrument in order to monitor the on-board calibration blackbody emissivity, *on-orbit*, throughout the lifetime of the mission. The heated halo, a broadband thermal measurement, provides an alternative, complimentary method of on-orbit emissivity determination to the quantum cascade laser-based reflectometer also under development (Gero *et al* 2009).

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