A NIST Thermal Infrared Transfer Standard Radiometer for the EOS Program

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A program to establish radiometric traceability between the National Aeronautics and Space Administration's (NASA's) Earth Observing System (EOS) instrument calibration facilities and the National Institute of Standards and Technology (NIST) radiance scale is underway [1,2]. Currently, flight instruments intended to measure Earth's radiance are calibrated before launch against working standards such as lamp-illuminated integrating spheres (for visible, near-infrared, and short-wavelength infrared channels) and 200 K to 400 K blackbody sources (for "thermal-infrared" channels in the spectral range of roughly 2 µm to 20 µm). Such a working standard provides an extended-area, approximately Lambertian source that overfills the entrance pupil of the radiometer, so that radiance responsivity is determined. To ensure the high accuracy required for instruments used in the EOS program, the output of the working standards will be compared to the radiance scale maintained at NIST. A practical way to verify the scales in the EOS program is to use a portable transfer radiometer that is first calibrated at NIST, then shipped to the location where the working standards reside. Such an approach has been used successfully in NASA's Sea-Viewing Wide Field-of-view Sensor (SeaWiFS) calibration community [3]. Here the transfer radiometer provided by NIST, the SeaWiFS Transfer Radiometer (SXR), had six narrow-band channels in the visible and near-infrared part of the spectrum, and was used to view integrating spheres and plaques. Plans are in place for NIST to provide similar radiometers for the EOS program: the Visible Transfer Radiometer (VXR), the Shortwave Infrared Transfer Radiometer (SWIXR), and the Thermal infrared Transfer Radiometer (TXR) [2].

This article focuses on the TXR. The purpose of the TXR is to compare the radiance scales of the cryogenic blackbody working standard sources used for EOS calibrations. Currently, a breadboard version of the TXR is being built and characterized. In this article, the design and calibration plans for the TXR are described, and the planned measurement program for the TXR is outlined.

EOS Thermal-infrared calibration facilities and sources

A typical facility used to calibrate such EOS instruments as the Moderate-Resolution Imaging Spectrometer (MODIS), the Clouds and the Earth's Radiant Energy System (CERES), or the Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) consists of a large vacuum chamber fitted on the inside with a light-tight, nitrogen-cooled shroud. The shroud is cooled to near 77 K, providing an infrared background that is low compared to a 200 K to 400 K blackbody source. During its calibration, the flight instrument views an extended-area blackbody source in this low-background, vacuum environment. The blackbody sources used as working standards are typically of a cavity design having a black coating on the inside. The shape of the cavity varies. Mathematical models of the effective cavity emissivity typically yield emissivity values close to 1. Typical aperture diameters range from 4 to 10 cm. Heating is often done electrically. The cavities are usually fitted with a number of temperature sensors such as platinum resistance thermometers (PRTs) for measuring the temperature of the cavity walls. Because of the unavailability of a convenient thermal infrared transfer radiometer for making a direct radiance scale tie to NIST, separate radiance scales are currently established at the EOS instrument calibration facilities. These scales are generally based on use of the Planck radiation formula with the modeled emissivity and the NIST-traceable temperature of the PRTs. Several issues have been raised regarding the accuracy of these contact-thermometry-derived scales. They include, for example, changes in the PRT calibration upon being fixed to the cavity walls, reliance on modelling for emissivity, cavity loading, and spatial uniformity of radiance across the output aperture. When the TXR is available, it can be used to verify these contact-thermometry-derived radiance scales radiometrically by comparing against the detector-based radiance scale maintained by NIST.

Optical layout of the breadboard version

The TXR has two channels based on filtered semiconductor photodetectors that share a common telescope. Channel 1 has a center wavelength nominally at 5 µm and Channel 2 has a center wavelength nominally at 10 µm. The bandwidths of the channels are each nominally 1 µm, defined primarily by bandpass filters. All internal optics are cooled to near 77 K to reduce background. Thus, the radiometer is packaged in a portable liquid nitrogen cooled cryostat, which can be mounted in the cryogenic vacuum chambers at EOS instrument calibration facilities. It has its own vacuum, nitrogen fill, nitrogen vent, and pressure-relief lines, so that it can be evacuated and cooled independently of the calibration chamber.

A layout of the optical design is shown in Fig. 1. The telescope consists of the planar fold mirror and the two off-axis parabolic mirrors. It is focused at infinity so that the TXR views the working standard sources in the same way as the flight instruments. Two apertures, one near the entrance of the cryostat (aperture stop, 20 mm diameter) and one at the foci of the mirrors (field stop, 6 mm diameter), define a 2° full-angle field of view. A tuning-fork chopper immediately behind the second aperture deflects rays into the beam dump when closed, or allows them to pass onto the second parabolic mirror when open. This provides background subtraction and enables ac measurements (frequency nominally 42 Hz) for narrow electrical bandwidth detection using a lock-in amplifier on each channel. After the second parabolic mirror, a dichroic beamsplitter at 45° splits the beam into two by reflecting short-wavelength rays (wavelengths less than about 7 to 8 µm) and transmitting long-wavelength rays. From there the beams pass through individual bandpass filters that define the 1 µm bandpass for each channel and non-imaging concentrators to the detectors. An InSb detector is used for the 5 µm channel and a HgCdTe (MCT) detector is used for the 10 µm channel. The beamsplitter, filters, concentrators, detectors, and cooled pre-amplifiers are mounted on a common, temperature-controlled stage designed for an operating temperature near 78 K. Additional details of the optical design are discussed in Ref. 4.

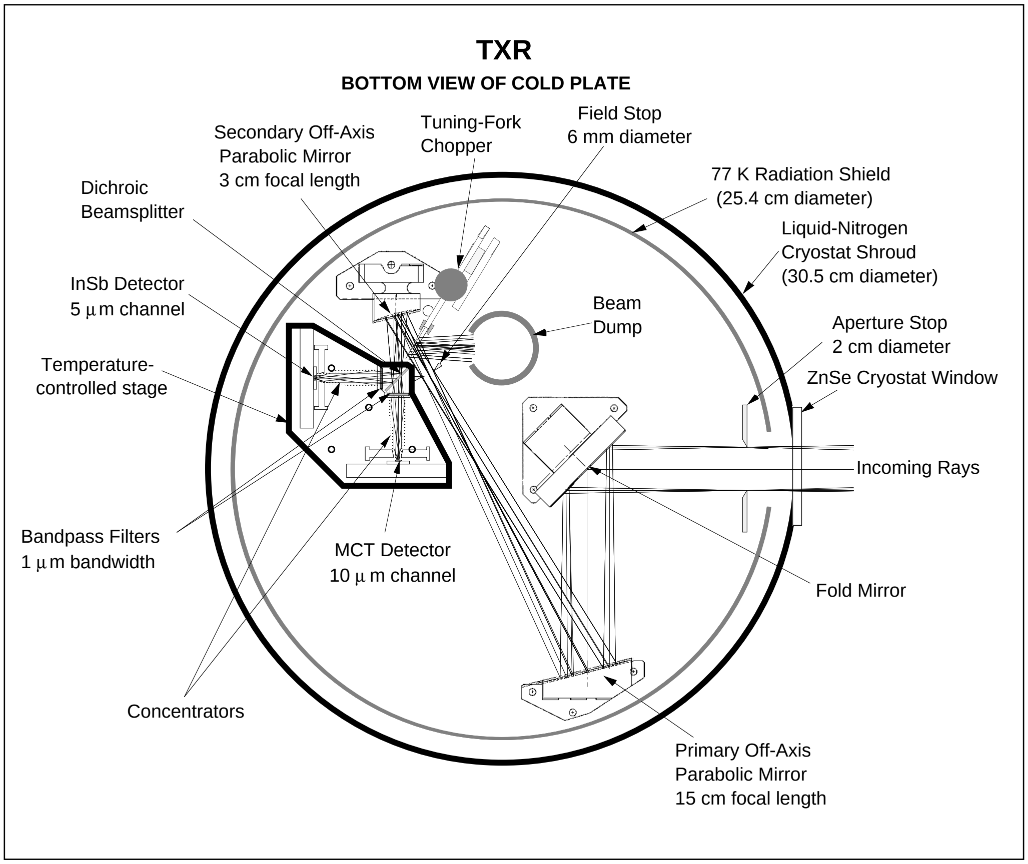

Figure 1. Plan view of the TXR optics mounted on the cold plate of the cryostat. This is a view from the bottom of the cryostat.

Field of view

The purpose of the telescope is to provide a narrow field of view so that the source overfills the entrance pupil of the radiometer, as required for radiance measurements. A ray trace was performed on the system to aid in laying out the optics. Marginal and central rays are shown in Fig. 1. The geometrically-determined full field of view, measured at the aperture stop, is 2°. Thus the diameter of the viewed source area with source placed a distance 30 cm in front of the aperture stop is 3.2 cm. For radiance measurements, this diameter must be less than the diameter of the exit aperture of the source to be tested. Of the candidate working standard blackbody sources that exist at this time at the EOS instrument calibration facilities, the source having the smallest aperture appears to be the Narrow Field Black Body used for the CERES instrument. This source has an elliptical aperture having minor and major diameters of 3.8 × 4.7 cm, respectively. Thus the TXR field of view is small enough for radiance measurements on at least one spatial point on this smallest-area source. On larger sources, there is enough resolution for spatial mapping of the radiance across the exit aperture.

Signal and noise

For each channel i (i = 1, 2), the signal in volts at the output of the preamplifier is estimated by integrating the product of the absolute spectral responsivity and the spectral radiance,

$$S_i(T) = \int R_i(\lambda) L_\lambda(\lambda, T) d\lambda \qquad (1)$$

where the absolute spectral responsivity is estimated by

$$R_i(\lambda) = A_i \Omega_i \tau_i(\lambda) G_i R_{Di}(\lambda) \qquad (2)$$

and $L_\lambda(\lambda, T)$ is the spectral radiance of a source of radiance temperature T. Here A_i is the area of the entrance pupil (which in this case is the aperture stop), Ω_i is the projected solid angle of the field of view at the entrance pupil, G_i is the pre-amplifier gain, $\tau_i(\lambda)$ is the transmittance within the field of view, and $R_{Di}(\lambda)$ is the responsivity of the bare detector. An estimate of the signal and noise levels expected for blackbody temperatures over the range 200 to 400 K can be found in Ref. 4. The minimum signal/noise ratio (200 K blackbody) for in-band, in-field measurements is expected to be of order 3000 to 4000. Thus, the TXR noise-equivalent radiance is low enough that it is not expected to limit the accuracy of the scale transfer.

Calibration

The complete calibration of a filter radiometer such as the TXR consists of measuring the absolute spectral radiance responsivity $R_i(\lambda)$ for each channel i. In principle, this could be done in one step by using an extended area (nominally 5 to 10 cm diameter) Lambertian tunable monochromatic infrared source of known radiance. However, such a source does not exist at NIST presently, even at visible wavelengths. Of the sources that do exist, the extended area Lambertian sources are not monochromatic, and the monochromatic sources are not extended-area Lambertian ones. Thus the measurement of $R_i(\lambda)$ will be split into two parts: the relative spectral responsivity $\rho_i(\lambda)$ and the absolute radiance responsivity K_i, where

$$R_i(\lambda) = K_i \rho_i(\lambda) \qquad (3)$$

A monochromatic source will be used to measure $\rho_i(\lambda)$, followed by a separate measurement of K_i using an extended-area Lambertian source. By substituting for $R_i(\lambda)$ from Eq. (3), the radiometric performance equation, Eq. (1), becomes

$$S_i(T) = K_i \int \rho_i(\lambda) L_\lambda(\lambda, T) d\lambda \qquad (4)$$

The monochromatic source that will be used to measure $\rho_i(\lambda)$ is part of the newly-developed Infrared Detector Comparator Facility [5]. With this facility, NIST has the capability of measuring the relative spectral response of detectors over the wavelength range of 2 to 20 µm.

The extended-area Lambertian source for measuring K_i is a cryogenic cavity blackbody source (known as the Large-Area BlackBody, or LABB) currently under development at NIST. Its design is based upon that of a similar blackbody source developed previously [6]. The cavity consists of a thin aluminum shell having a cylindro-conical shape and a 10 cm exit aperture. The inside of the shell has an infrared black coating. Rhodium-iron temperature sensors (known as Resistance Temperature Devices, or RTDs) are embedded into the shell, and heaters are mounted against the outside of the shell. The sensors and heaters are used in conjunction with temperature control electronics to vary and control the cavity temperature over the nominal range 200 to 400 K. A liquid nitrogen cooled jacket surrounds the entire shell excluding the exit aperture.

Prior to using it for calibration of the TXR, the LABB will be characterized and calibrated against the NIST radiance scale at the Low Background Infrared Radiation (LBIR) Facility at NIST [7]. This facility features a 0.6 m diameter × 1.5 m long vacuum chamber with a helium-cooled, light-tight inner shroud to provide a 20 K background environment for blackbody calibrations. An extension to the LBIR Facility, described in Ref. 6, will be used to provide the necessary vacuum housing for the LABB. In the LBIR Facility, a liquid helium cooled radiometer operating on the principle of electrical substitution serves as an absolute cryogenic radiometer (ACR) [8]. This provides measurements of radiant power in terms of electrical power, enabling the calibration to be traceable to electrical units. Using the ACR in combination with precision apertures in the LBIR chamber, broadband absolute radiant power measurements will be made on the LABB at selected RTD setpoints covering the 200 to 400 K range. The spectrally-integrated radiance temperature T at each RTD setpoint of the LABB will be derived from these measurements.

The absolute calibration (measurement of K_i) of the TXR will be carried out in the Medium Background Infrared (MBIR) Facility currently under development at NIST. This facility features a 1.2 m diameter × 1.8 m long vacuum chamber with a liquid-nitrogen-cooled, light-tight inner shroud surrounding a rollout-optical bench. This provides a nominally 77 K background in a vacuum of nominally 10^{-4} Pa (10^{-6} Torr), similar to that used in the calibration of EOS flight instruments. The TXR will be mounted along with the LABB on the optical bench in the MBIR. Alignment will be made so as to ensure that the radiation emitted from the exit aperture of the LABB overfills both the aperture stop and field stop of the TXR, enabling the measurement of radiance. The absolute calibration of the TXR will then consist of measuring $S_i(T)$ for each channel i with the TXR viewing the LABB in radiance mode. During these measurements, the radiance temperature T will be known from the readings of LABB RTDs calibrated on the LBIR. Thus $L_\lambda(\lambda, T)$ will be known from the Planck formula and Eq. (4) can be solved for K_i in terms of known quantities,

$$K_i = \frac{S_i(T)}{\int \rho_i(\lambda) L_\lambda(\lambda, T) d\lambda} \qquad (5)$$

Figure 2 summarizes the plan for transferring the NIST scale of radiance to EOS calibration labs. The starting point is the ACR of the LBIR Facility. This will be used to calibrate the LABB in the LBIR Facility. The LABB will then be taken to the MBIR Facility at NIST, where it will reside. The TXR will be calibrated for absolute radiance response against the LABB in the MBIR Facility. The relative spectral response calibration of the TXR will be done in a separate step using the Infrared Detector Comparator Facility at NIST. Having measured $\rho_i(\lambda)$ and K_i, the calibrated TXR will be sent in turn to the various EOS flight instrument calibration laboratories where it can be used to verify the radiance calibration of large-area blackbody sources.

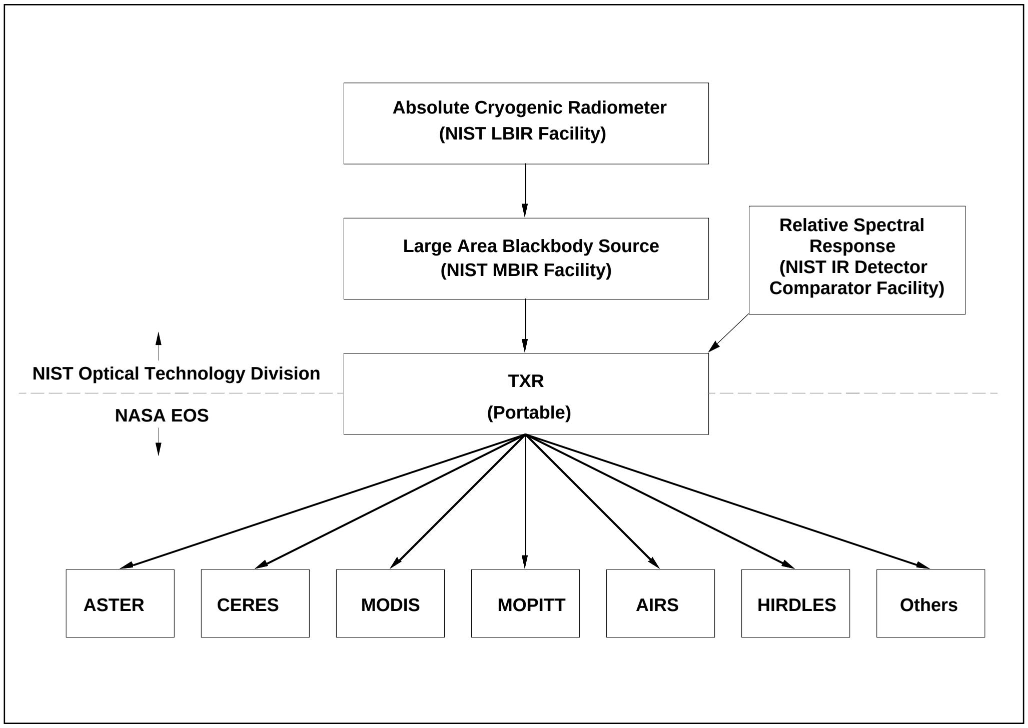

Figure 2. Summary of the plan for transferring the NIST thermal-infrared detector-based radiance scale to EOS flight instrument calibration facilities.

Use of the TXR at EOS instrument calibration facilities

To use the TXR, it needs to be mounted so as to view source X, representing any large-area blackbody source to be calibrated, in radiance mode. The quantity to be determined is $L_{\lambda,x}(\lambda, T_x)$, the spectral radiance of source X with its temperature setpoint at T_x. The TXR will measure signals $S_{i,x}(T_x)$ at each source setpoint. Thus, the measurement equation becomes

$$S_{i,x}(T_x) = K_i \int \rho_i(\lambda) L_{\lambda,x}(\lambda, T_x) d\lambda \qquad (6)$$

It is then a matter of mathematics to determine the unknown $L_{\lambda,x}(\lambda, T_x)$ in terms of the known quantities $S_{i,x}(T_x)$, $\rho_i(\lambda)$, and K_i. Further details of how this might be done can be found in Ref. 4.

Conclusion

A thermal infrared transfer radiometer is being designed, built, characterized, and calibrated by NIST to provide radiometric traceability in the NASA EOS program. This radiometer will measure the spectral radiance of large-aperture blackbody sources having radiance temperatures from 200 to 400 K to provide a NIST-traceable radiance calibration of the blackbody sources. This will enable, for the first time ever, radiometric traceability of thermal infrared EOS flight instruments to the radiance scale maintained by NIST.

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