MSX Reference Objects

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This article considers two infrared sources—emissive reference spheres and reference stars—used for on-orbit calibration of the Midcourse Space Experiment's Spatial Infrared Imaging Telescope III. The metal reference spheres have an electrodeposited emissive coating. They are ejected from the spacecraft, and their signatures span the sensor's dynamic range as they move away. The properties of the spheres are well characterized so that their deployed signatures can be accurately predicted. Error analysis required to relate the uncertainty in the spheres' properties to the uncertainty in their signatures is outlined. Observations of the telescope's calibration stars, whose signatures are determined to high accuracy, are used to complement information obtained from the reference spheres.

INTRODUCTION

As space-based optical sensors become more accurate and their performance requirements more exacting, correct calibration becomes increasingly essential to their proper operation. The Midcourse Space Experiment (MSX) provides a functional demonstration of emerging sensor technologies and generates an archival database for application in future remote-sensing programs and architectures. Correct MSX calibration is crucial to reinforce the confidence of prospective users that MSX data will meet their needs.

The importance of calibration and the volume of MSX data were key reasons for the formation of a dedicated Data Certification and Technology Transfer (DCATT) Team to oversee, review, and underwrite the correctness of the MSX database. The final calibration of the MSX sensors will be based on three calibration methods, each independently traceable to National Institute of Science and Technology (NIST) standards: ground chamber calibration, stellar calibration standards, and deployed reference spheres. One essential DCATT task is to monitor the ground calibration of MSX sensors. Another activity is to develop calibration sources, both celestial and deployable, with emphasis on sources for the Spatial Infrared Imaging Telescope III (SPIRIT III) instrument, which ensure that MSX sensors can be accurately calibrated on-orbit. This article will focus primarily on the deployed reference spheres.

We begin by summarizing our overall approach to calibration and presenting an overview of MSX infrared calibration sources. We next focus on the reference spheres, their thermal dynamics, their radiative signature, and the uncertainty analysis that will be used to assess their data quality. Finally, we briefly discuss MSX reference stars.

MSX ON-ORBIT CALIBRATION

The role of calibration in the MSX experiment is best understood in terms of an end-to-end measurement (including data analysis) using a calibrated sensor. Such a measurement process is indicated schematically in Fig. 1. A target emits photons, which propagate into the sensor. The photons and sensor interact and generate a reading in volts or counts. A characterization of the sensor is used to transform the raw recorded reading to scientific units (e.g., W/cm^2 for a point source) for the flux incident on the sensor. In its simplest form, such a characterization is an empirical relationship between the recorded reading and corresponding scientific units; in practice, the SPIRIT III Performance Assessment Team's "convert" code, which incorporates the aggregate of laboratory measurements and modeling performed to understand the sensor, embodies the characterization. Finally, a model relating the source properties to the signal reaching the sensor is used to determine the source characteristics of interest.

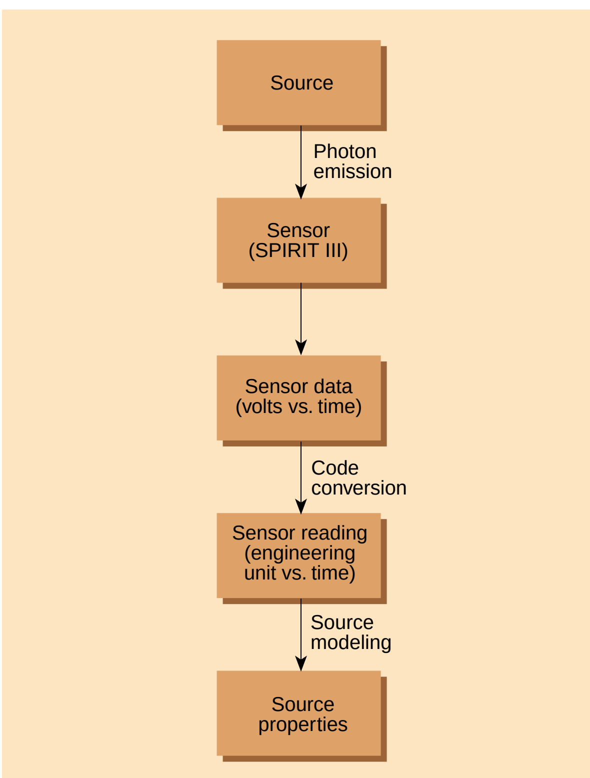

Figure 1. A typical SPIRIT III measurement process.

Clearly, properties of unknown sources cannot be determined if the sensor itself is not characterized. The purpose of calibration is to use the predicted signatures from a series of sources whose properties are known to characterize the sensor, that is, to establish the relationship between the recorded reading and corresponding scientific units throughout the sensor's dynamic range. The process is shown schematically in Fig. 2, which indicates that sensor characterization can be modified, most simply by changing the calibration coefficients, to provide the correct relationship between the physical signal and the sensor reading. The correctly characterized sensor can then be applied to unknown sources.

In practice, the signature of the calibration source is never known exactly, and the available known sources seldom span the full operating regime of the sensor. A deficiency in calibration-source characterization will contribute to the discrepancy between sensor reading in counts and measured signal. A key calibration objective is to make the uncertainty from the calibration source sufficiently small that only the sensor calibration parameters must be adjusted after a calibration measurement is made. This objective has been a driver in the development of DCATT calibration sources.

Figure 3 shows a top-level schematic of the SPIRIT III calibration process, which is formulated to be transferable to the radiometric standards of the NIST. In addition to internal calibration sources, the on-orbit SPIRIT III, which has been previously calibrated on the ground, observes fabricated calibration objects (reference spheres) that are ejected from the spacecraft. Calibration stars are also observed. This article stresses the reference sphere experiment; a brief discussion of the calibration stars is also given.

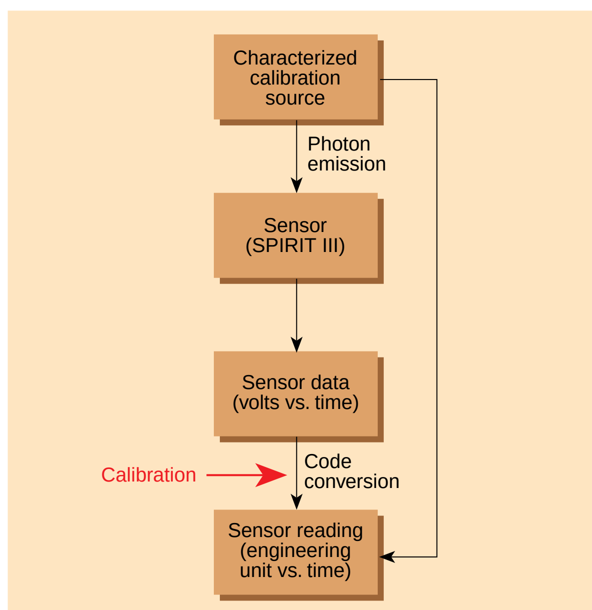

Figure 2. A SPIRIT III calibration measurement process.

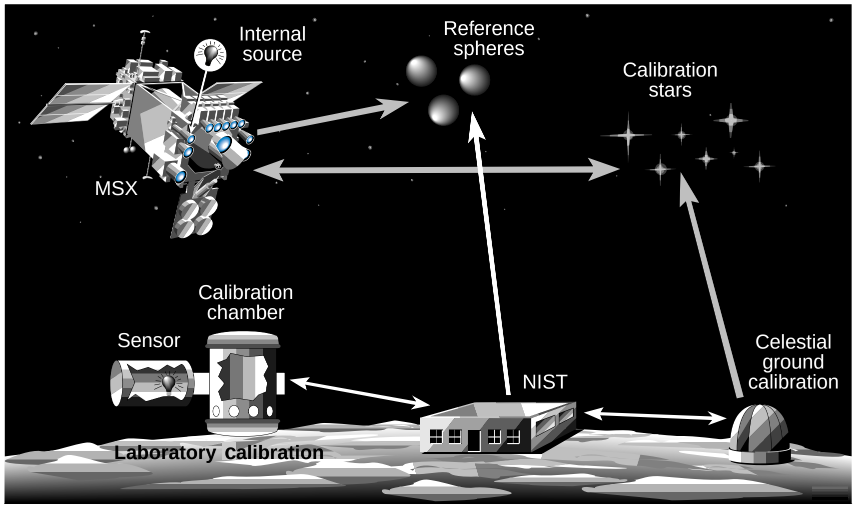

Figure 3. NIST-traceable MSX calibration process.

REFERENCE SPHERES

A reference sphere[1–3] is a fabricated source of infrared thermal radiation. MSX carries five emissive calibration spheres that will be deployed and observed periodically throughout the mission. During a calibration experiment, the sphere is ejected from the MSX spacecraft at about 14 m/s. As it moves away, its signature spans the dynamic range of the SPIRIT III sensor. The ejector velocity, including uncertainty in both direction and speed, is characterized on the ground. During the experiment planning process, velocity is used to calculate the sphere's expected trajectory. Shortly after deployment, the sphere's signature is expected to saturate the SPIRIT III sensor. Accordingly, the sphere is first acquired and tracked just after deployment by a separate onboard instrument, the UVISI (Ultraviolet and Visible Imagers and Spectrographic Imagers) Widefield Visible Imager, and conveyed to SPIRIT III after about 3 min. At that time, the sphere's signature enters the increased dynamic range of the SPIRIT III sensor.

The orbital periods of the sphere and the MSX spacecraft will be out of phase by about 20 days; after receding from the spacecraft, the sphere will eventually return to the vicinity of the MSX. The sphere will be ejected in a direction of the MSX orbital plane and above the tangent altitude to maximize the viewable time and minimize the risk of collision in later encounters. To track the sphere as a resident space object, it will be acquired by MIT Lincoln Laboratory's Haystack radar and its orbit will be determined; a precise orbital determination will also support future observations of the sphere if the program chooses to view it again as it periodically reenters SPIRIT III's dynamic range.

This metal sphere, mainly composed of 6061-T6 aluminum to provide thermal inertia, is designed to mimic an ideal blackbody as closely as possible. To produce the desired near-blackbody behavior, a thin emissive coating (<50 μm) is vapor-deposited on its surface. To conserve payload mass, the MSX emissive reference sphere is only 2 cm in diameter. (During the MSX mission, larger calibration spheres will be launched from the ground into suborbital trajectories.) Sphere properties are as follows:

Density (ρ), 2.70 ± 0.05 g/cm^3
Specific heat (c_p), 0.215 ± 0.005 cal/g · K
Emissivity (ϵ), 0.95 ± 0.02
Deployment temperature (T_i), 250 ± 1 K
Radius (r_s), 1.0 cm

Figure 4 schematically depicts the sphere structure and indicates how an on-orbit sphere interacts with its surroundings. It receives radiation from the Earth's thermal emission, from the Sun (when the sphere is not in shadow), and from the sunlight scattered off the Earth; it absorbs most of this radiation and scatters the rest. The absorbed radiation is reemitted as thermal radiation. Thus, radiation reaching the sensor is thermal radiation from the sphere plus environmental radiation scattered off the sphere.

A deployed reference sphere embedded in its thermal environment is a complex object. Work performed by the DCATT Team falls into three categories: sphere signature modeling and uncertainty analysis of the calibration experiment, specification of the sphere's material properties and deployment conditions, and characterization of the Earth's thermal environment. We will discuss the first of these activities in the following section. C. F. Wilson, V. Miselis, E. Kintner, and their coworkers performed the second activity at MIT Lincoln Laboratory (which was responsible for fabrication of the spheres). For the third activity, DCATT work at Lincoln Laboratory has shown how codes such as LOWTRAN can be used to characterize the Earth's thermal environment. (C. L. Hamilton has used

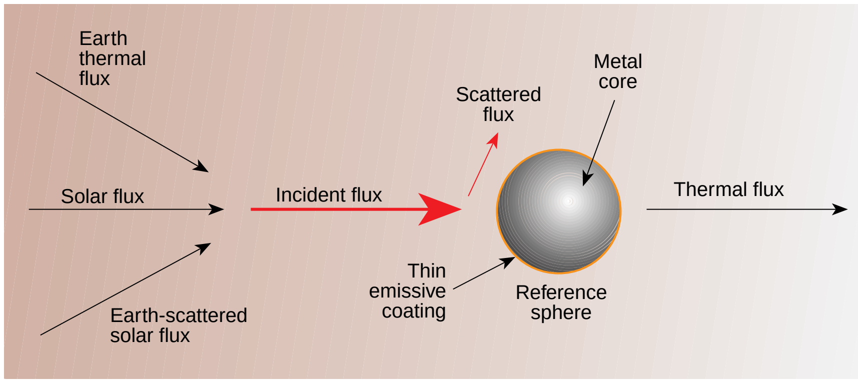

Figure 4. Deployed emissive reference sphere in the thermal environment.

near–real-time weather satellite data available on the Internet to derive input parameters for such codes.)

THERMAL MODELING AND UNCERTAINTY ANALYSIS

The rate of change of the heat content of the sphere is the difference between the absorbed and radiated power. Thus, the equation for the sphere's thermal dynamics is

$$V\rho c_p \frac{dT}{dt} = -A\epsilon(\sigma T^4 - j_{incident}) ,$$

where

ϵ = gray- body emissivity of the sphere,
V = volume of the sphere,
A = surface area of the sphere,
σ = Stefan–Boltzmann coefficient, i.e., 5.670×10^{-12} W/(cm$^2 \cdot$ K^4),
$j_{incident}$ = thermal flux incident on the sphere, i.e., $j_{Earth} + j_{Sun} + j_{Earth\text{-}scattered-solar}$.

Figure 5 (red curve) shows a modeled temperature history for an unshadowed orbit (sphere is facing the Sun). The Earth is modeled as an isothermal gray body with a temperature of 280 K, and the scattering of sunlight off the Earth is modeled as diffuse. Because the sphere's thermal environment is constant, its temperature relaxes to a constant value as it moves around the Earth. For an orbit in which the sphere moves into and out of the Earth's shadow, the temperature would change considerably, as shown by the black curve in Fig. 5.

In an ideal square waveband spanning wavelengths λ_1 and λ_2, the amount of radiation reaching the sensor from the sphere is

$$I = \frac{2\pi\epsilon C_1 R^2}{r^2}\int_{\lambda_1}^{\lambda_2} \frac{d\lambda}{\lambda^5[\exp(C_2/\lambda T)-1]} + (1-\epsilon)\frac{R^2}{r^2}\int_{\lambda_1}^{\lambda_2} d\lambda \frac{dj_{incident}}{d\lambda} ,$$

where

I = irradiance into the sensor aperture,
$C_1 = 5.9544 \times 10^3 W \cdot \mu^4/\text{cm}^2$,
$C_2 = 1.439 \times 10^4 \mu \cdot$ K,
R = radius of the sphere,
r = range to the sphere,
λ_1 = low end of the band, and
λ_2 = high end of the band.

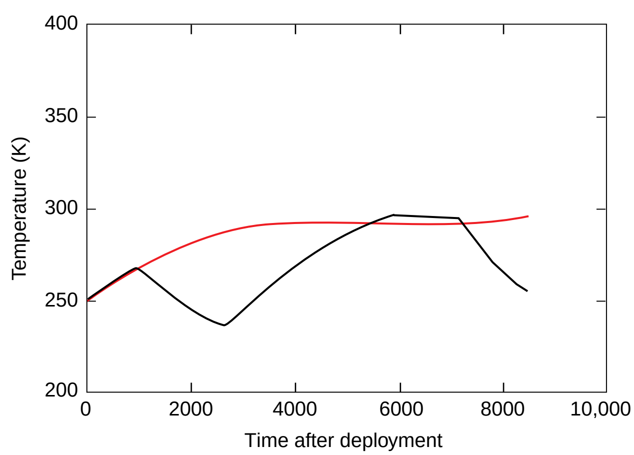

Figure 5. Reference sphere temperature history: unshadowed orbit, red; shadowed orbit, black.

The sphere signature has two components: the Planck radiation emitted from the sphere, and the environmental radiation scattered from the sphere. The preceding equation only approximates the radiation from the sphere entering a SPIRIT III waveband, since the actual wavebands are spectrally dependent transmission functions rather than idealized square bands.

An error analysis relates the uncertainty in the sphere signature to uncertainties in the sphere properties and in the characterization of the environmental radiation. Sphere properties like emissivity (and its uncertainty) are determined by ground laboratory measurements. The Earth's thermal environment and its uncertainty are characterized by use of satellite data. Then the time dependence of the sphere temperature is analyzed to relate the signal uncertainty to the temperature uncertainty, which depends on the uncertainties in the sphere properties and thermal environment. Calibration-source performance requirements constrain the uncertainties of the in-band intensities. An error analysis demonstrates the relationship between the uncertainties of the sphere and environmental properties and the sphere's performance as a calibration source.

The emissivity of a gray-body sphere provides an example. Such a sphere has a nominal value ϵ that has no spectral dependence, and an uncertainty $\delta\epsilon = \epsilon - \langle\epsilon\rangle$ (in an ensemble of reference spheres, the expectation value $\langle\delta\epsilon^2\rangle$ is the standard deviation of the sphere's emissivity). The baseline value of the temperature history is T_0. The mean-square uncertainty in sphere temperature due to emissivity uncertainty is $\langle\delta T^2\rangle$.

That an uncertainty in emissivity produces an uncertainty in sphere *temperature* has a noteworthy consequence. An uncertainty in temperature induces an uncertainty in all the SPIRIT III bands, and the uncertainties in the bands are therefore correlated. A consequence of this correlation is that the mean-square uncertainty in the ratio of two bands is significantly smaller than the sum of the mean-square uncertainties of the individual bands.

In addition to the emissive spheres, a reflective reference sphere consisting of a thin hollow shell with a metal surface will be deployed from MSX. Analysis of the earthshine reflected off the sphere into the SPIRIT III sensor will help characterize the Earth's thermal environment.

REFERENCE STARS

To provide an on-orbit calibration independent of the reference spheres, stars will also be used as MSX calibration sources.[4,5] Cohen et al.[5] have determined the spectra of several stars by analyzing the database of spectral observations with state-of-the-art models. Their published work now provides the scientific standard for infrared stellar spectra and is the baseline adopted by the DCATT. In addition, the DCATT is performing ground measurements to determine calibration-star spectra and to experimentally characterize the uncertainty in spectral irradiance.

A challenging difficulty with such ground measurements is that the signal from the star is attenuated by the atmosphere, and atmospheric models are inadequate to correct the signal for the attenuation (given an ideal observing environment, such a correction can be performed in the 16–24-μm waveband). However, under favorable viewing conditions, the atmospheric attenuation of one star (e.g., Sirius, i.e., αCMa) can be correlated with the attenuation of another star (e.g., Arcturus, i.e., αBoo). Thus, after care is taken to ensure consistent observing conditions (such efforts include observation of each star with at least two telescopes and with at least two sensors that have been subjected to rigorous ground characterization), the spectra of the entire ensemble of about 10 infrared calibration stars can be determined in terms of one or two primary reference stars.

To establish trends in long-term sensor performance, the ensemble of DCATT calibration stars is restricted to the limited set for which high-quality data from the 1970s are available; to ensure that the calibration stars are nonvariable or of known variability, they will be monitored throughout the MSX mission. The signals of the primary star will then be found by first-principles models, which are tuned to account for the entire database of celestial infrared observations. As indicated in Fig. 6, such models are also used to determine stellar spectra for wavelengths at which observations are not feasible. The sources of uncertainty for the reference

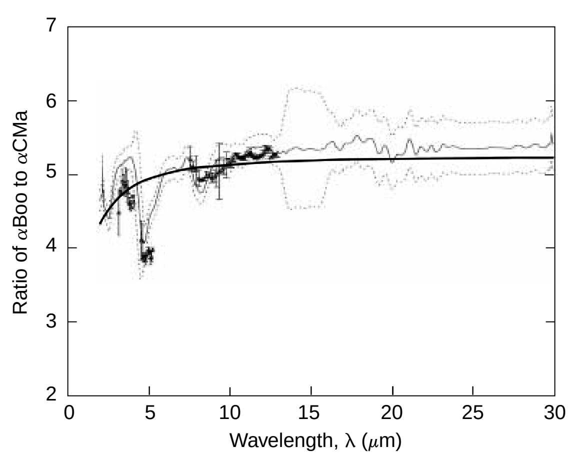

Figure 6. Sample stellar spectral ratio of two stars, αBoo and αCMa. Three families of curves are shown: thick, smooth solid curve, Ref. 6; triangles and vertical lines representing error bars, Ref. 4; and a thin, irregular solid curve and associated dotted error envelopes, Ref. 5.

stars are the uncertainty of the ground sensors, the uncertainty with which atmospheric attenuation is compensated, and the uncertainty of the model used for the primary reference star.

SUMMARY

Proper calibration is essential to ensure the correctness of the MSX SPIRIT III database. To secure accurate calibration, in addition to SPIRIT III's internal sources, the DCATT uses two kinds of external reference sources: (1) emissive reference spheres, which are man-made, near-blackbody sources ejected from the spacecraft; and (2) reference stars, which are stable, well-characterized, permanent, independent calibration sources. To quantify calibration uncertainty, the uncertainties associated with these sources are being tracked and accounted for. The quantitative success of the reference sources supports the development of sources to meet calibration standards in future programs.

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