

Straylight-Induced Radiometric Effects in Far-Infrared Space Instruments and Mitigation Using Broadband Black Coatings

Dina Katsir¹, Tamas Rev¹

¹Acktar Ltd., Kiryat Gat, Israel

ABSTRACT

Infrared instruments used for deep-space thermal imaging must measure weak scene radiance in the presence of radiation generated and redistributed inside the instrument itself. In the mid- and far-infrared (MIR/FIR), internal reflections, out-of-field radiation, and thermal emission from instrument structures can contribute directly to detector signal and therefore to the radiometric error budget. This paper examines broadband black coatings as radiometric boundary conditions for such instruments, using the Europa Thermal Emission Imaging System (E-THEMIS) as a representative case study. E-THEMIS measures Europa in three spectral bands spanning 7–80 μm and is designed for Kelvin-level temperature precision on a cold planetary surface. Published instrument data show that calibration must explicitly account for emission from the telescope housing and other detector-visible structures, while internal baffling is used for straylight rejection. The E-THEMIS instrument paper also identifies Acktar Fractal BlackTM on the telescope cavity, filter-assembly components, and sunshade interior. The present work connects coating-level properties—spectral reflectance, emissivity as a function of temperature, coating thickness, and environmental stability—to instrument-level functions including multi-bounce straylight suppression, internal radiance control, and cryogenic performance. The resulting design framework emphasizes that black coatings in FIR instruments should be selected from the spectral, thermal, geometric, and environmental error budget rather than from visible appearance alone.

Keywords: far infrared; straylight; radiometry; broadband black coatings; emissivity; reflectance; cryogenic instrumentation; E-THEMIS; Europa Clipper

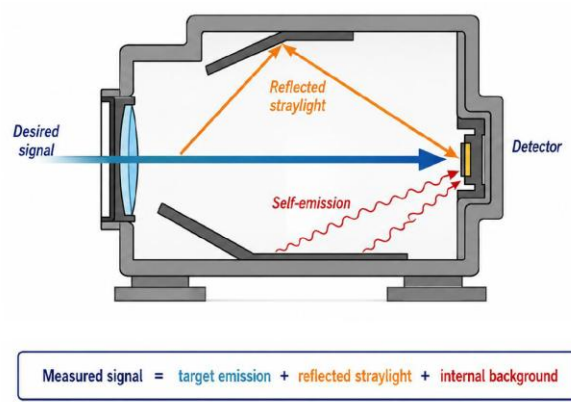
1. INTRODUCTION

The performance of a thermal-infrared space instrument depends on more than detector sensitivity. Radiation reaching the focal plane can include the desired scene signal, stray radiation propagated through non-nominal optical paths, and thermal emission from instrument structures visible to the detector. In a simplified form, the detected power can be separated into target, stray, and instrument self-emission contributions. The first is the desired scene term; the latter two are instrument-dependent backgrounds that must be suppressed, stabilized, characterized, or calibrated.

This distinction becomes particularly important for instruments observing cold planetary targets. As scene temperature decreases, the thermal spectrum shifts toward longer wavelengths. Internal surfaces that appear optically black in the visible or near infrared can therefore require separate characterization in the MIR/FIR. At the same time, instrument structures may operate far above the target temperature, so detector-visible baffles, cavities, housings, shields, and calibration assemblies become part of the radiometric model rather than passive mechanical boundaries.

The Europa Thermal Emission Imaging System (E-THEMIS) on NASA's Europa Clipper mission provides a representative case. E-THEMIS acquires thermal-infrared images in three bands spanning 7–14 μm , 14–28 μm , and 28–80 μm . Its published instrument description reports Kelvin-level radiometric performance and explicitly models radiance from internal telescope structures during calibration [1]. The same publication identifies Acktar Fractal BlackTM on selected internal surfaces [1]. This combination makes E-THEMIS a useful case study for connecting surface optical and thermal properties to instrument-level radiometric behavior.

The objective of this paper is therefore not to assign a standalone temperature improvement to one coating. Instead, the paper develops a coating-selection framework for FIR instruments in which spectral reflectance, emissivity, thickness, geometry, temperature, and environmental stability are treated together. The E-THEMIS case is used to establish the system-level context; Acktar and published cryogenic coating data are then used to illustrate the material-level trade space.



$$P_{\text{det}} = P_{\text{target}} + P_{\text{stray}} + P_{\text{self}}$$

Figure 1. Simplified radiometric contributions in a thermal-infrared instrument: desired target radiance, reflected internal straylight, and thermal self-emission from detector-visible structures.

2. RADIOMETRIC EFFECTS OF INTERNAL SURFACES

2.1 Reflected straylight and multiple internal interactions

Straylight is radiation that reaches the detector through paths outside the intended imaging sequence. Depending on instrument geometry, these paths may involve off-axis illumination, reflection from baffles or housings, scattering at edges, or repeated interaction with several internal surfaces. If the power remaining after each interaction is governed approximately by the surface reflectance in the relevant band, then a multi-bounce path is progressively attenuated as low-reflectance surfaces are introduced. The exact result depends on geometry and BRDF, but the design principle is robust: reducing reflectance reduces the radiance available for subsequent parasitic propagation.

Geometry and surface treatment are complementary rather than interchangeable. Baffles block direct paths and control angular acceptance; field stops restrict the accepted field; low-reflectance surfaces reduce the strength of paths that remain. E-THEMIS follows this combined approach: its telescope includes a carbon-fiber baffle and internal baffling machined into the housing for additional straylight rejection [1].

2.2 Thermal self-emission as a radiometric background

In the thermal infrared, detector-visible structures also emit radiation according to their temperature, emissivity, solid-angle view factor, and spectral band. This contribution is physically distinct from reflected straylight. Increasing emissivity can increase emitted radiance at a fixed temperature, so a black surface should not be treated automatically as a low-background surface. Instead, the surface becomes a radiative boundary condition whose temperature and emissivity must be known well enough for the instrument architecture and calibration method.

The E-THEMIS calibration model makes this point explicit. External target and deep-space views include radiance from telescope structures, while the internal calibration flag is located behind the telescope. The published formulation therefore includes terms for the telescope housing (“wall”), radiation shield, optics, view factors, emissivity, and measured temperatures [1]. This is a direct system-level example of internal surfaces participating in the radiometric signal.

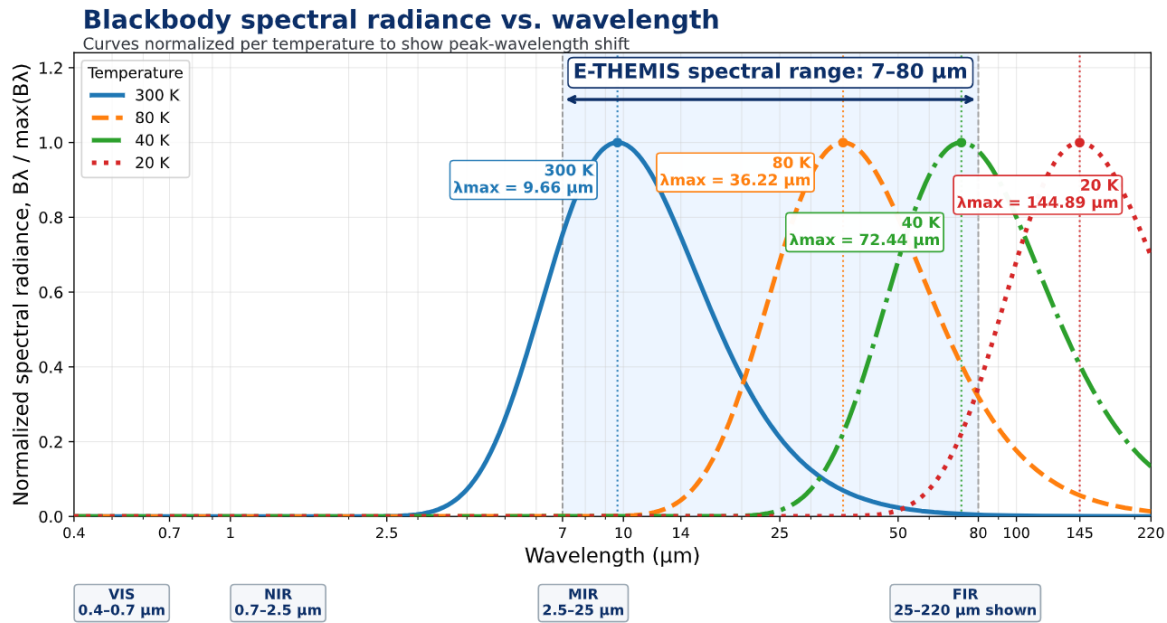


Figure 2. Normalized Planck spectral-radiance curves illustrating the shift toward longer wavelengths with decreasing temperature. The shaded region marks the 7–80 μm E-THEMIS spectral range reported in Ref. [1].

3. E-THEMIS AS A FAR-INFRARED CASE STUDY

3.1 Spectral and radiometric requirements

E-THEMIS was developed to map Europa’s surface temperature and thermophysical properties with an uncooled microbolometer focal plane. The instrument uses three spectral bands: 7–14 μm (Band 1), 14–28 μm (Band 2), and 28–80 μm (Band 3). The published design associates these bands with progressively colder scenes; Band 3 was selected to support measurements of approximately 80–110 K targets [1]. The long-wavelength coverage therefore follows directly from the low radiance and shifted Planck spectrum of Europa’s cold surface.

The science requirements demand small temperature differences to be measured reliably. Christensen et al. report a 1 K precision requirement over surface temperatures from 90 K to above 130 K and a 3% accuracy requirement. Measured performance summarized in the instrument paper includes approximately 1.1 K NEDT in Band 2 for a 90 K scene under representative TDI and spatial-aggregation conditions and about 2 K absolute accuracy at 90 K [1]. These values illustrate why uncontrolled internal-radiance terms can be relevant even when they are small relative to room-temperature optical signals.

3.2 Internal thermal environment and calibration

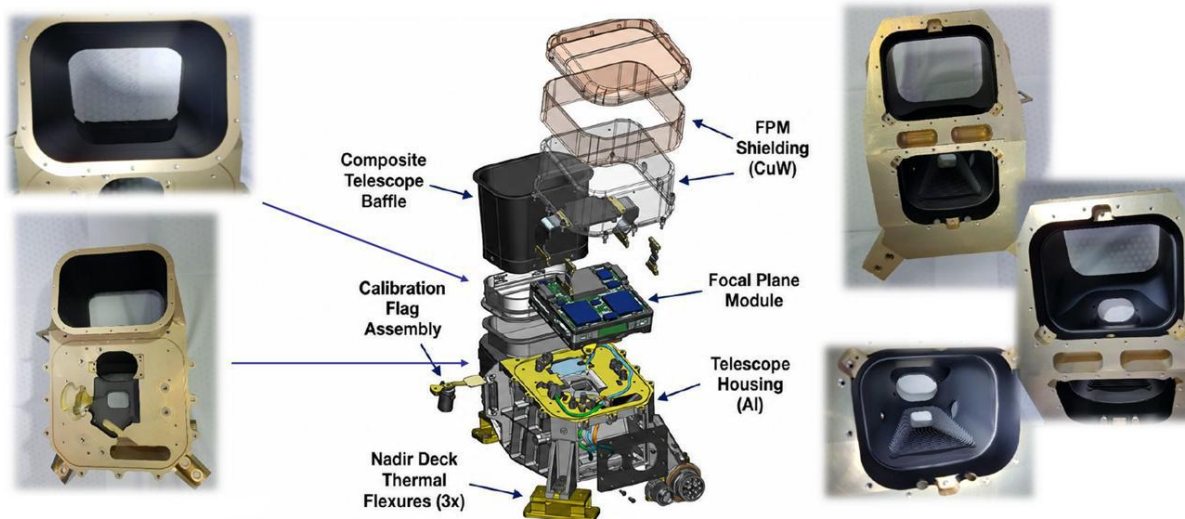
E-THEMIS combines a cold observed scene with a substantially warmer instrument structure. The spacecraft deck was modeled from about $-60\text{ }^{\circ}\text{C}$ to $0\text{ }^{\circ}\text{C}$ at Jupiter, while focal-plane electronics dissipate significant internal power and can operate much warmer. The sensor design therefore uses thermal isolation, MLI, radiator surfaces, survival heaters, and the thermal mass of the aluminum telescope housing. The instrument stability requirement is approximately $\pm 0.1\text{ }^{\circ}\text{C}$ per minute during the calibration interval [1].

Radiometric calibration uses periodic observations of the internal calibration flag and deep space. Because the calibration flag does not include the telescope in the same optical path as external observations, the instrument model corrects for telescope throughput and thermal emission from the optics and housing. The housing contribution is linked to measured internal temperatures and emissivity information [1]. For surface selection, this means that “black” must be defined by a predictable spectral and thermal response, not by visible appearance alone.

3.3 Acktar Fractal Black™ within the published E-THEMIS design

The E-THEMIS instrument paper states that the telescope cavity, filter-assembly components, and sunshade interior use Acktar Fractal Black coating to provide high-emissivity, diffuse radiating surfaces for calibration purposes [1]. The coating therefore appears in the same instrument regions where straylight control, radiative exchange, and calibration stability interact. The publication establishes the coating locations and their intended radiative function, while the instrument-level calibration model establishes why those surfaces must be characterized.

The published E-THEMIS results do not isolate a standalone Kelvin-level improvement attributable only to Fractal Black. The appropriate interpretation is that the coating is one integrated element of an optical-thermal architecture that includes geometry, baffling, temperature sensing, calibration views, and radiometric modeling. This distinction is maintained throughout the present work.



Based on E-THEMIS Sensor Assembly expanded view in Christensen et al. (2024); labels preserved from the paper figure.

Figure 3. E-THEMIS Sensor Assembly showing major optical, mechanical, and focal-plane components. The central exploded view is adapted from Christensen et al. [1]. Acktar Fractal Black is reported on the telescope cavity, filter-assembly components, and sunshade interior [1].

4. SPECTRALLY EXTENDED BLACK COATINGS

4.1 FIR spectral reflectance

For FIR instrumentation, reflectance must be considered across the detector band rather than inferred from visible appearance. Acktar development measurements extend from approximately 700 to 200 cm^{-1} , corresponding to about $14.3\text{--}50\text{ }\mu\text{m}$. The measurement shown in Figure 4 was obtained with a T240/TIR wide-range beamsplitter on an Ultra Black sample identified as Acktar lot 4420-12. The curve demonstrates wavelength-dependent reflectance across the MIR/FIR range and therefore provides information that cannot be replaced by a single room-temperature emissivity number.

The relevance to instrument design is direct. Spectral reflectance influences the attenuation of parasitic internal paths, while the distribution between specular and diffuse components determines where residual radiance is redistributed. The required measurement band should therefore follow detector sensitivity and the expected thermal spectrum. A coating that is highly absorptive in the visible may not have identical performance at $30\text{--}50\text{ }\mu\text{m}$, so broadband characterization is required when the instrument response extends into the FIR.

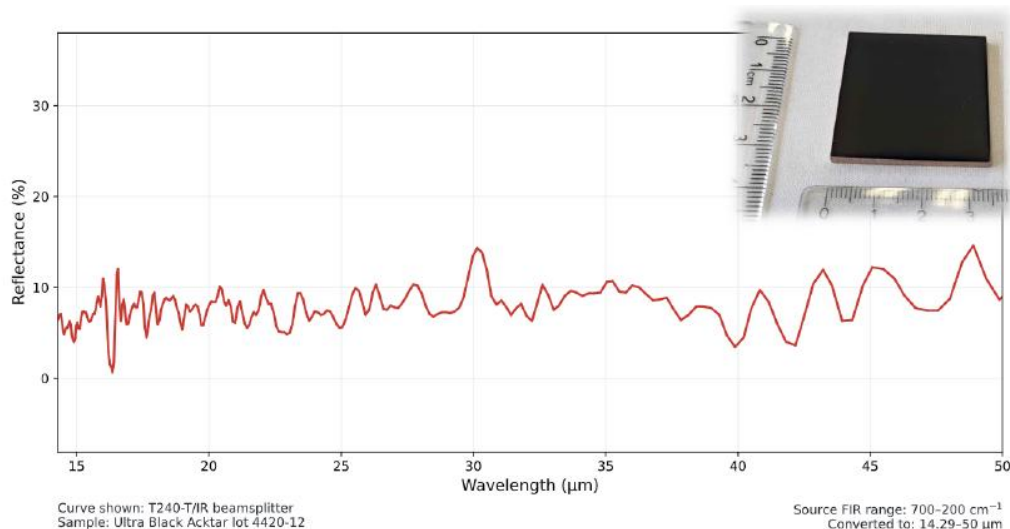


Figure 4. Measured MIR/FIR reflectance of an Acktar Ultra Black sample (lot 4420-12) using a T240/TIR wide-range beamsplitter. The original measurement range of $700\text{--}200\text{ cm}^{-1}$ corresponds to approximately $14.3\text{--}50\text{ }\mu\text{m}$.

4.2 Emissivity, temperature, and long-wavelength behavior

Emissivity defines the thermal-radiative coupling of an internal surface. At a fixed temperature, higher emissivity increases emitted radiance, but it can also establish a more blackbody-like and therefore more predictable boundary condition. Whether this is beneficial depends on where the surface is located, whether it is visible to the detector, how well its temperature is known, and whether radiative exchange or straylight attenuation is the dominant function. Independent measurements of Fractal Black have reported high emissivity over extended MIR/FIR wavelength ranges, including measurements extending to 100 μm [3].

For cryogenic hardware, $\epsilon(T)$ is as important as room-temperature spectral emissivity. Cryogenic emissivity measurements of Fractal Black have previously been reported by Rev et al. [2] using a calorimetric method developed at ISI Brno [4]. The dataset considered here uses 40-mm Al 6061 disks with nominal coating thicknesses of 20, 30, and 45 μm . Figure 5 shows the coated samples and calorimetric measurement configuration used for cryogenic emissivity characterization. The resulting normalized emissivity curves are shown in Figure 6. The response decreases at low temperature, with the strongest decrease for the 20 μm sample, while the 30 and 45 μm samples remain closer to their room-temperature normalized values over much of the measured range.

The result should not be interpreted as identifying one universally optimal thickness. Thickness interacts with material optical properties, substrate coupling, mechanical tolerances, coating mass, masking requirements, and edge definition. The engineering implication is narrower but important: room-temperature or visible-band performance should not automatically be extrapolated to cryogenic FIR operation, and coating thickness can be a radiometrically relevant design variable.

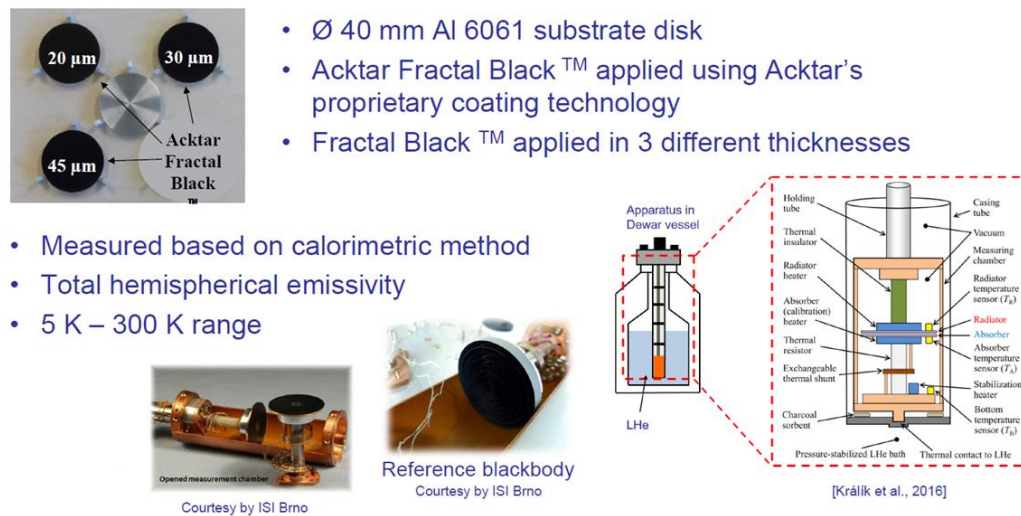


Figure 5. Cryogenic emissivity measurement configuration for Acktar Fractal Black coatings applied to 40 mm Al 6061 substrates with nominal coating thicknesses of 20, 30, and 45 μm . Total hemispherical emissivity was measured over approximately 5–300 K using a calorimetric method. Measurement setup courtesy of ISI Brno; measurement methodology described in Ref. [4].

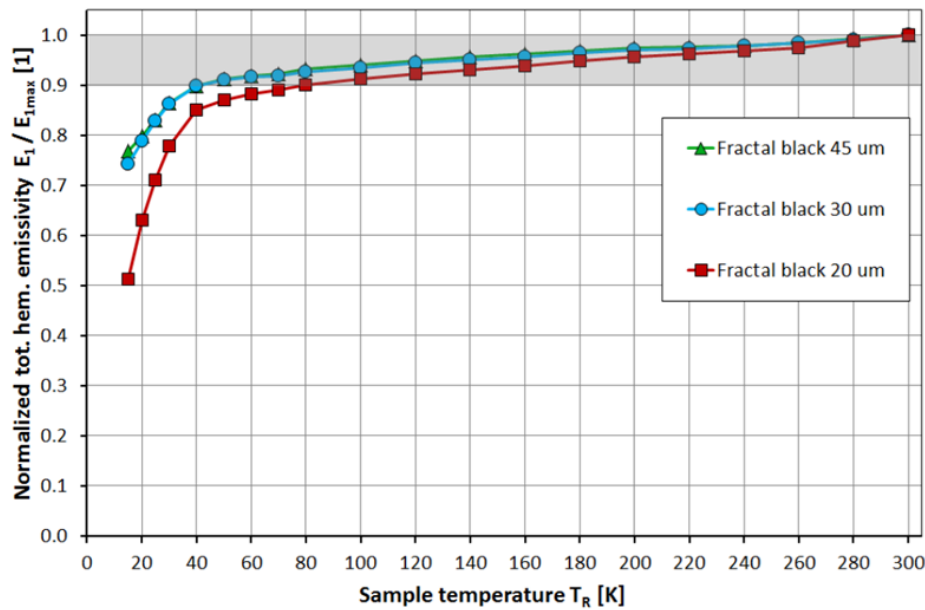


Figure 6. Normalized total hemispherical emissivity as a function of sample temperature for Acktar Fractal Black coatings with nominal thicknesses of 20, 30, and 45 μm . Measurement data courtesy of ISI Brno; measurement methodology described in Ref. [4].

5. ENVIRONMENTAL AND QUALIFICATION CONSIDERATIONS

A coating selected for a spaceborne FIR instrument must preserve its radiometric and mechanical function through the relevant mission environment. Vacuum and outgassing affect contamination risk; thermal cycling and cryogenic operation can alter adhesion or surface morphology; radiation can modify materials and detector-visible backgrounds; and cleanliness requirements can be unusually restrictive for planetary missions. These factors belong in the same trade space as reflectance and emissivity because a surface that changes after qualification no longer represents the boundary condition used in the radiometric model.

The E-THEMIS program illustrates the system-level rigor of this requirement. The published development included environmental and thermal-vacuum testing, radiometric calibration, radiation qualification of critical materials and components, and stringent contamination-control review. The instrument paper states that E-THEMIS materials were subject to qualification and verification for planetary-protection and contamination requirements and that radiation testing supported the selection of optical and thermal coatings [1]. These statements establish the environmental context but do not by themselves provide coating-specific Fractal Black degradation values.

Acktar heritage includes Fractal Black experience in thermal-vacuum cycling, long-term cryogenic reference-blackbody use, and radiation/thermal-cycling programs. A Fractal Black-coated reference blackbody has also been used for repeated cryogenic measurements at ISI Brno. Figure 7 shows the reference surface together with a representative emissivity curve. Additional Acktar heritage includes thermal-vacuum and radiation/thermal-cycling qualification activities on spaceborne optical and infrared hardware. Because detailed numerical results from several of these activities originate from external organizations such as UCL, ISI Brno, and mission contractors, they are used here as supporting engineering heritage rather than as newly generated E-THEMIS performance data.

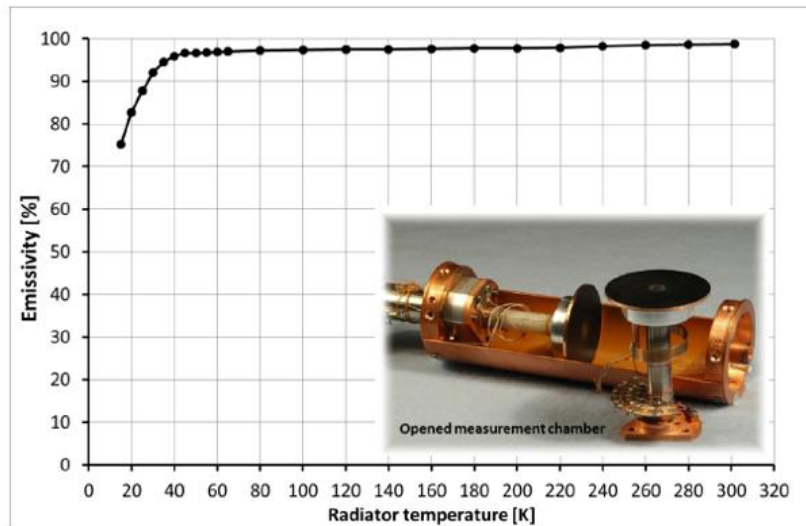


Figure 7. Fractal Black-coated reference blackbody used in repeated cryogenic emissivity measurements at ISI Brno. The measured emissivity remains high over a broad temperature range. Courtesy of ISI Brno.

6. ENGINEERING IMPLICATIONS FOR FIR COATING SELECTION

Coating selection for FIR hardware should begin with the dominant radiometric function of each surface. Optical requirements define the relevant detector band, spectral reflectance, and scattering behavior. Thermal requirements determine the importance of emissivity and surface temperature. Geometry establishes whether a surface is directly detector-visible, part of a multi-bounce cavity, or part of a calibration assembly. Mechanical requirements constrain substrate compatibility and allowable coating thickness, while the mission environment determines the required stability under vacuum, contamination control, thermal cycling, and radiation.

The dominant metric is therefore surface-specific. Spectral reflectance or BRDF may control a straylight baffle, emissivity as a function of temperature may dominate a calibration cavity, while coating thickness and long-term stability may become limiting constraints for cryogenic hardware. Coating selection should therefore be driven by the local radiometric error budget rather than by visible appearance.

7. CONCLUSIONS

Far-infrared radiometric instruments operate in a regime where internal surfaces can participate directly in the detected signal. Reflected straylight and thermal self-emission are separate physical contributions and must be treated separately. A low-reflectance surface can suppress parasitic optical paths, while the same surface can emit thermal radiation according to its emissivity and temperature.

E-THEMIS provides a representative flight case. The instrument observes Europa over 7–80 μm , requires Kelvin-level radiometric performance, includes dedicated baffling, and explicitly models telescope-housing radiation in calibration. Christensen et al. also identify Acktar Fractal Black on the telescope cavity, filter-assembly components, and sunshade interior [1]. These published facts support the use of E-THEMIS as a system-level example without attributing a standalone Kelvin improvement to the coating.

The broader coating-design lesson is that visible blackness is insufficient for FIR hardware. Selection should be based on spectral reflectance over the detector band, emissivity as a function of temperature, coating thickness and substrate, detector-visible geometry, and environmental stability. The Acktar FIR reflectance data and cryogenic Fractal Black measurements illustrate why these variables must be considered together.

Broadband black coatings are therefore best treated as radiometric boundary conditions rather than cosmetic finishes. When their spectral, thermal, mechanical, and environmental properties are matched to the local instrument error budget, they can support both straylight suppression and predictable radiometric calibration in cryogenic and far-infrared space instruments.

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