Measurement of Small Aperture Areas

J. A. Fedchak, A. C. Carter, and R. Datla

National Institute of Standards and Technology, Gaithersburg, MD, USA

1. Introduction

Precise and accurate knowledge of small aperture areas is critical to blackbody radiance temperature calibrations performed by the Low Background Infrared (LBIR) calibration facility at the National Institute of Standards and Technology (NIST). The uncertainty in the geometric size and shape of an aperture is directly related to the uncertainty of the calibration. We are presently developing a technique of measuring aperture areas with diameters as small as to 0.05 mm. We require a standard uncertainty to better than 0.1 %.

An instrument for determining the absolute geometric aperture area has been established at NIST (Fowler and Litorja 2003). The technique is based on diffraction corrected optical edge detection and utilizes a high-quality microscope, an interferometer referenced X-Y stage, and a CCD camera. Presently this instrument is limited to circular apertures of diameter greater than 0.35 mm. The measurement accuracy is better than 0.01 % for apertures greater than 3.5 mm, and is better than 0.1 % for aperture diameters larger than 0.35 mm. This instrument is highly commissioned and a single measurement can take many hours.

The LBIR facility has developed an *in situ* technique to radiometrically deduce the size of small apertures. The diffraction corrected signals due to radiation passing through small apertures is compared to those of larger apertures that have known aperture areas (Smith *et al.* 2003). This measurement is performed during a blackbody calibration and does not necessarily represent the geometric aperture area. It does, however, provide the user of the calibrated blackbody with an effective area for computing radiance.

Presently, we are developing a technique to determine the geometric area of small apertures. This is also a relative comparison technique. An integrating sphere is used as a Lambertian source. The aperture of interest is directly mounted to the integrating sphere. A detector, mounted some distance from the sphere, is used to monitor the optical flux passing through the aperture. Since the aperture is directly illuminated by a Lambertian source, diffraction corrections should be minimal. By comparing the detector signals between a large aperture with a known area to that of a smaller aperture with an unknown area, we can obtain precise and accurate measurements of the area or radius of a small aperture. In this paper we discuss the current progress and development of this aperture area measurement technique. A primary goal of this study is to understand the relationship between the effective aperture area, as seen by a detector, and the geometric aperture area. We are particularly interested in apertures with diameters between 0.350 mm and 0.050 mm, as these areas cannot be determined using the NIST absolute instrument.

2. Apparatus and Experimental Technique

In our approach we mount the aperture directly to an integrating sphere. The sphere is illuminated by a high-power LED that has a spectral output in the visible. A photodiode is also mounted to the sphere to monitor the optical intensity within the sphere. Throughout this paper, this photodiode will be referred to as the monitor detector. The aperture is the only open port on the sphere. A portion of the flux passing through the aperture is measured by a silicon photodiode aligned with the aperture and the center of the sphere. This detector, which will henceforth be referred to as the signal detector, is mounted on a 60 cm translation stage. The encoder on the translation stage has a displacement measurement accuracy of 0.1 μm. Data is collected as a function of the separation between the aperture and detector. Presently the signal detector is a 1 mm^2 photodiode. Other detector sizes or types may be used in the future.

Thus far, only green LEDs with a nominal wavelength of 530 nm have been used to illuminate the sphere. Approximately 1 W of optical power is produced by the LED. Careful baffling inside the integrating sphere insures that the light will reflect at least 3 times before exiting the aperture. Most of the optical radiation in the field of view of the signal detector will have undergone many reflections within the sphere. The electric power to the LED is electronically chopped. A lock-in amplifier technique is used to filter the signal from both the signal and monitor detectors. Reflections of the LED light from surfaces outside of the sphere may also be detected. A stationary baffle placed about 8 cm in front of the detector eliminates most of these reflections. In addition, a 3 mm aperture 50 mm in front of the signal detector limits the detector field of view to approximately 5°.

A set of circular apertures with diameters ranging from 0.05 mm to 5 mm is used to test the system as it is developed. These are photo-chemically etched metal apertures; the edge is defined by 8 μm – 13 μm thick nickel plating. The radii of the apertures with diameters larger than 0.35 mm were determined using the absolute instrument described above. These apertures are typical of those used by the users of the LBIR facility. The apertures are attached to the sphere using blackened aperture mounts. These have a 35° knife edge which faces the signal detector.

3. Data and Analysis

The optical intensity on the signal detector is related to the aperture area by $I = \pi \cdot L \cdot F \cdot A$, where L is the radiance in the sphere illuminating the aperture, A is the aperture area, and F is the geometric configuration factor between the detector and aperture. A normalized signal is determined by dividing the signal produced by the signal detector by that of the monitor detector. The ratio I/L is proportional to the normalized signal. The configuration factor, F, is a function of the detector area, the aperture area, and the separation, d, between the signal detector and aperture. In addition, a correction should be applied which accounts for any diffraction due to the aperture or baffling. Since we will be concerned with the ratio of normalized signals between two different apertures, many of these terms, such as the detector area that appears in F, cancel or are negligible. Assuming diffraction corrections to be negligible, I/L should be proportional to $1/d^2$ for large separations.

Data is taken as a function of the separation between the detector and aperture. The absolute distance between the aperture and the detector is difficult to measure. Therefore the normalized signal is fit to a/d^2, where $d=s+b$, s is the position read from the encoder on the translation stage, and b is a fit parameter which represents the distance between the zero position of the encoder and the aperture. The amplitude of the fit, a, is proportional to aperture area. The ratio of the aperture areas between any two apertures is determined from the fit parameter a (*e.g.*, a_1/a_2). There are several advantages to this analysis technique. Random errors are minimized by taking many data points. Some systematic errors are also eliminated. For example, the distance between the zero position and aperture may depend on the aperture mount, making comparison between two different apertures difficult. However, since any offset is determined by the fit, knowledge of the absolute separation is unnecessary. In addition, deviations from a $1/d^2$ fit serves as a guide to further improvements in the apparatus. For example, stray reflections striking the signal detector may cause the signal to vary as something other than $1/d^2$, indicating that changes in baffling, or some other component of the experiment, may be necessary.

Preliminary data has been taken for the aperture set discussed in the preceding section. Aperture area ratios are determined between any two apertures by taking the ratio of the fit parameters, a, as discussed above. To facilitate a comparison to the aperture radii determined using the NIST instrument, we compare the square root of the aperture area ratio to the radii ratio calculated from the measurements of the absolute instrument. Radii ratios between apertures of similar diameter are likely to have smaller systematic uncertainty than those between large and small apertures. For example, the radii ratio between a 5 mm to 3.5 mm diameter aperture or a 0.6 mm to 0.35 mm diameter aperture may have smaller systematic uncertainties than the ratio of the 5 mm to 0.35 mm diameter aperture. We expect this because configuration factor or diffraction corrections should nearly cancel for apertures of similar diameter. In the current experimental configuration, we find aperture radii ratios typically compare to within 0.5% of those calculated from the NIST absolute instrument for apertures of similar diameter. The diameter of the largest aperture in the test set is 5 mm and the smallest aperture with a known area has approximately a 0.35 mm diameter. The measured radii ratio between these two apertures compares to within 1% of that determined with the absolute instrument.

While this is still below the ultimate goal of developing an aperture area measurement instrument capable measuring small apertures to within 0.1%, it is clear that there are many ways to improve accuracy. Structure seen in the residuals from the fitting procedure, as well as considerations derived from ray-tracing, indicates that some improvement can be achieved by adjusting the size and position of the first baffle as well as reducing the field of view of the detector. Accuracy may also be improved by using a more sophisticated configuration factor in the fit. Improvements in the optical alignment, as well as reducing stray and retro-reflections should also improve performance.

4. Conclusion

We are presently developing an instrument to measure the areas of small apertures. While the goal of 0.1% agreement has not been achieved to present date, it is believed that it will be reached in the near future based on the current results and the opportunity to resolve the perceived set of experimental deficiencies. Currently we can only test our method down the 0.35 mm diameter aperture limit of the NIST absolute instrument. Our ultimate goal is to measure apertures as small as 0.05 mm with an uncertainty of 0.1%. Systematic uncertainties will have to be well understood to measure the area of apertures with diameters as small as 0.05 mm.

In the future, we would also like to use an infrared source to illuminate an infrared integrating sphere for similar testing. Most of the radiometric calibrations performed by the LBIR facility cover a wavelength range of 2 µm to 25 µm. Configuration factors and diffraction corrections used in the calibrations are computed using the geometric area of the apertures. The geometric areas, or radii, are measured using techniques that employ optical wavelengths. The technique described in this paper will not only allow us to measure the geometric aperture area, but will also allow us to understand the difference between geometric areas and effective aperture areas at optical and infrared wavelengths.

References

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