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Measurement of small apertures

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Abstract
The Low Background Infrared calibration facility at the National Institute of Standards and Technology (NIST) is developing an instrument to measure the relative areas of apertures with diameters ranging from 5 mm to 0.05 mm. NIST already has the capability of determining the absolute area of apertures with diameters larger than 0.35 mm. Our goal is to measure the area or radius of a 0.05 mm diameter aperture to a standard uncertainty of better than 0.1%. We report on the current status of this effort and plans for improvement. We are near the goal for apertures larger than 0.350 mm.

1. Introduction

Precise and accurate knowledge of aperture areas is critical to absolute radiometry. The Low Background Infrared calibration (LBIR) facility in the Optical Technology Division of the National Institute of Standards and Technology (NIST) requires knowledge of aperture areas as small as 0.050 mm in diameter to perform radiance temperature calibrations of blackbody sources. Broadband calibrations cover the entire infrared spectrum; the facility also performs infrared spectral calibrations over the wavelength range of 2 µm to 30 µm. In a typical calibration, the infrared source is considered to be a perfect blackbody emitter behind a cold circular aperture with a known geometric area or radius. Diffraction corrections are applied to the data to achieve accurate radiance temperature calibrations. The uncertainty associated with the radiance temperature is directly related to the area or radius of the aperture. In this paper, we present the current status of our ongoing work to develop an aperture area measurement instrument capable of determining the geometric area of apertures with diameters ranging from 0.05 mm to 5 mm. Our goal is to measure the area of small apertures to a standard uncertainty of better than 0.1%.

Previously, the LBIR facility had developed an *in situ* technique to radiometrically deduce the size of small apertures [1]. The diffraction-corrected signals due to radiation passing through small apertures are compared with those of larger apertures that have known aperture areas. 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.

Two methods for determining aperture area have been established at NIST [2, 3]. The first method is an absolute measurement technique and is based on diffraction-corrected optical edge detection. The instrument consists of 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 as small as 0.35 mm. This instrument is highly commissioned and a single area measurement can take from 2 h to 3 h. The second instrument is a relative instrument and is based on a flux-transfer method. A Lambertian source is produced by focusing a 250 W quartz-halogen lamp into a specially constructed integrating sphere. An aperture wheel, containing the aperture of interest and an aperture of known area, is illuminated by the radiation from the integrating sphere and is located 2 m from the sphere. The light passing through the aperture is collected and focused by a spherical mirror onto a detector. Diffraction issues limit the aperture diameters such that the relative instrument can compare with apertures of similar diameter.

Apertures with diameters as small as 0.050 mm have been accurately measured by Hartmann [4] using a comparison method. Using a 1 kW FEL lamp as a light source, the aperture of interest is mounted on a translation stage and placed 3 mm to 5 mm in front of a trap detector. The reference aperture has a diameter of 5 mm and is mounted directly on the trap detector, which is located 4 m from the light source. The throughput of the aperture of interest is then compared with that of the reference aperture. In this setup, the throughput of the 0.050 mm aperture will produce a diffraction pattern as described by an Airy function. Corrections for the Airy rings not collected by the trap detector must be applied. Uncertainties of the order of 10^{-3} are reported using this method.

Our approach is different than those outlined above but shares some similar elements. Ours is also a comparison method. A Lambertian source is produced by illuminating an integrating sphere with a high-power LED. The aperture of interest is directly mounted to the integrating sphere. A detector, mounted some distance from the sphere, is used to collect a portion of the light passing through the aperture mounted on the sphere. By comparing the detector signal of a larger aperture with a known area to a smaller aperture with an unknown area, we can obtain a precise and accurate measurement of the area or radius of a small aperture. Details of the present experimental arrangement will be discussed in the following section.

This relative aperture area measurement instrument is presently being tested using a set of small apertures with diameters ranging from 0.05 mm to 5 mm. The radii of the apertures with diameters greater than 0.350 mm have been measured using the absolute instrument at NIST. Comparison of our relative results to the absolute results has been an important tool to aid the development of the instrument. In addition, two other sets of apertures with diameters ranging from 2 mm to 0.05 mm have been measured. Results from all these measurements will be discussed in section 4. In this paper, we are mostly interested in comparing apertures of known area. Presently, our main focus is evaluating the quality and accuracy of our instrument. However, we will make some remarks concerning the evaluation of smaller apertures in section 4.

In section 3, the data analysis technique will be discussed. Some concluding remarks pertaining to future developments of the apparatus will be made in section 5.

2. Description of the apparatus

A schematic of the apparatus is shown in figure 1. An integrating sphere is illuminated with a high-power LED. The diameter of the sphere is about 152 mm. A photodiode is mounted to the sphere and is used to monitor the optical power within the sphere. Hereafter this detector will be referred to as the monitor. The aperture of interest is directly mounted to the sphere. A photovoltaic detector is placed along an axis orthogonal to the detector and collects a portion of the light exiting the aperture. This detector will be referred to as the signal detector. A circular baffle placed a few centimetres from the sphere and concentric to the axis between the signal detector and aperture helps to reduce stray light and reflected light from reaching the signal detector. The signal detector is mounted on a 60 cm translation stage equipped with an encoder with 0.1 µm resolution. Data are collected as a function of the separation of the signal detector from the aperture.

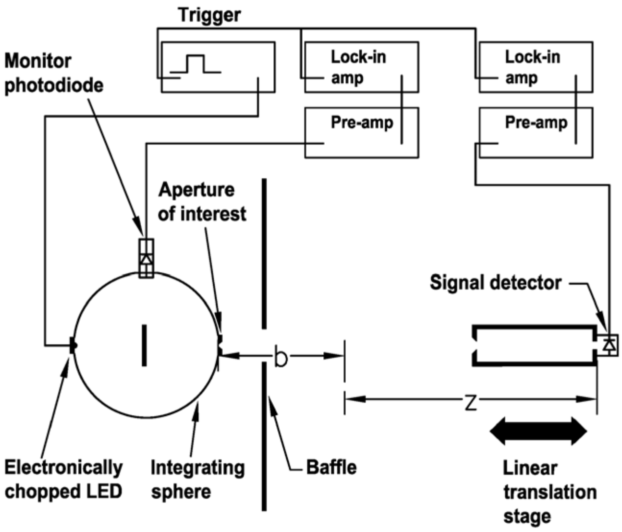

Figure 1. Schematic of relative aperture area instrument.

To date, only green LEDs with a nominal wavelength of $\lambda = 530$ nm have been used to illuminate the sphere. Approximately 1 W of optical power is produced by the LED. The output of the LED is approximately Lambertian. The electric power to the LED is electronically chopped so that a lock-in amplifier technique is used to monitor the light level in the sphere as well as to measure the portion of flux striking the signal detector. Careful baffling within the sphere insures that the light from the LED must bounce at least three times within the sphere before exiting the aperture. Since the aperture is mounted directly to a Lambertian source that has a spectral output in the visible, little or no diffraction corrections are necessary. This is because an ideal Lambertian source, by definition, will uniformly illuminate all possible angles of the aperture. Diffraction corrections are only necessary to the extent that the sphere is non-uniform. The situation is aided by the fact that the wavelength of green light is about 100 times smaller than the 0.05 mm diameter of the smallest aperture under consideration. This is in contrast to the typical situation of a blackbody calibration performed by LBIR. In that case, the blackbody sits a small distance behind the aperture and does not illuminate all possible angles; additionally, the wavelength of the infrared light is only 25 to 1.7 times smaller than the 0.05 mm aperture.

Two different photodiodes were used to collect the signal data in this study. One was a circular photodiode 1 mm in diameter; the other was a square detector 2.4 mm on a side. In both cases, a light baffle was fixed to the detector to restrict the angular field-of-view (FOV) to about 35 mrad. In addition, a black opaque baffle, mentioned earlier, was placed approximately 10 cm in front of the sphere. A hole in the screen, approximately 30 mm in diameter, allows the light exiting the aperture of interest to pass through the screen and to be subsequently detected by the signal detector. The signal detector size and the positioning of the baffles are presently in the process of optimization.

A set of circular apertures with nominal diameters ranging from 0.05 mm to 5 mm is used to test the system as developed. These are photo-chemically etched metal apertures; the edge is defined by a 8 µm to 13 µm thick nickel plating. The outer diameters of the apertures are 9.5 mm. There are 17 different aperture sizes in the set. The radii of the apertures with diameters larger than 0.35 mm were determined using the absolute instrument described above. In addition to the set of 17 apertures, the relative aperture areas from two other sets of apertures were measured. These two smaller sets of apertures were later commissioned for use in other instruments. In both these sets, the apertures had nominal diameters ranging from 0.05 mm to 2 mm and were of similar construction to the larger set of apertures. In addition, the radii of the apertures with nominal diameters larger than 0.35 mm were also determined using the absolute aperture area instrument. All the apertures tested are typical of those used by the users of the LBIR facility.

The apertures are attached to the sphere using blackened aperture mounts. The design of the aperture mounts is also under consideration for improvement. Half of the apertures in the set are permanently attached to a mount with a 35° knife edge which faces the signal detector. Aperture mounts were also constructed which allow the removal of the aperture. These mounts are constructed such that the aperture of interest is sandwiched between a thin black plate with a 30° knife edge facing the signal detector and a backing plate which faces the sphere. The hole in the aperture mount is about 6 mm in diameter. The part of the mount facing the interior of the integrating sphere is painted with high diffuse reflectivity white paint.

Only relative aperture areas are measured. Therefore, to determine an aperture area, measurements must be made on two different apertures. Ideally, the larger of the two apertures would have a known area, measured, for example, using the absolute instrument mentioned above. Our test set of apertures contains several apertures with a known area. All these apertures have diameters larger than 0.350 mm. Since we are presently concerned with evaluating the quality of our instrument, in this paper we will only be comparing apertures of known areas. A discussion of the results for apertures of smaller areas will be presented in sections 4 and 5.

The detector signal decreases with the distance from the aperture and is typically recorded every 2 cm over a total distance of 50 cm. The signal level will also be different for different apertures. It is important to ensure that the electronics in the detection and amplification systems operate linearly over the range of data taken. This is particularly true for the lock-in amplifier sensitivity scale. In general, it is desirable to change the lock-in amplifier scale or pre-amplifier gain to compensate for a change in the signal level. For most apertures, two or more data sets are collected: one with optimal electronic settings for that aperture and another with settings similar to those used for other apertures, thus ensuring a linear comparison between two apertures.

3. Data analysis

To make a relative aperture area measurement, data must be collected on two or more apertures. Only one aperture is attached to the sphere at a given time. For any given aperture, the optical intensity, I, on the signal detector is related to the aperture area, A, by

$$I = \pi \cdot L \cdot F \cdot A, \qquad (1)$$

where L is the radiance in the sphere illuminating the aperture and F is the geometric configuration factor between the detector and aperture. Since the signal produced by the monitor detector is proportional to L, we can define a normalized signal by dividing the signal produced by the signal detector by that of the monitor detector. Thus fluctuations in the source radiance are removed from the signal. 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 total 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 are 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 fitted to a/d^2, where $d = z + b$, z 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 between the areas of 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 readings. Some systematic errors are also eliminated. For example, the distance between the zero position and aperture may depend on the aperture mount, making a 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 serve 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.

4. Results and discussion

In table 1, we present recent measurements of relative aperture radii from apertures with known areas. Results from three sets of apertures are presented in the table. The first set, labelled as (1), are apertures from the test set, whereas those labelled as (2) and (3) are from sets which are no longer available for evaluation. We calculate the relative aperture radii as follows: given any two apertures with areas A_i and A_j, we compute the relative radii ratio as $\sqrt{a_i/a_j}$, where a_i and a_j are the fit parameters discussed in the preceding section. Since the aperture radii are directly measured by the absolute instrument, the relative radii ratio is easily computed as r_i/r_j.

Table 1 shows ratios between apertures with similar diameters. As discussed in section 3, data are typically taken such that apertures with similar diameters have similar experimental conditions, such as the sensitivity scale of the lock-in amplifier. This technique also minimizes uncertainties that do not scale linearly with aperture size, such as configuration factor changes (which are expected to be negligible in the present case) or aperture dependent light scattering issues.

From table 1, it is seen that the difference between the radii ratios measured with the relative aperture area instrument and those computed from the absolute instrument is generally of the order of 0.1% and is less that 0.3% in all the cases. (In this paper we are comparing aperture radii as opposed to aperture areas. This facilitates a direct comparison with the results of the absolute area instrument, as well as the nominal diameters of the apertures. If we had compared the ratio of aperture areas, the percentage difference in table 1 would increase by a factor of 2.) These differences are of the same order as the quality of the fit to $1/d^2$. As the aperture diameters approach 0.05 mm, the quality of the fit becomes limited by the signal noise in the data. This is shown in figure 2. Figure 2 is a graph of residuals in the fit for 2 mm, 1 mm, 0.1 mm and 0.05 mm diameter apertures. It is clear that in order to improve the technique for smaller apertures, a larger signal is required.

Table 1. Comparison of the relative aperture radii ratios measured in the relative aperture area instrument with that determined from the results of the absolute aperture area instrument. Set 1 is the set of test apertures. Sets 2 and 3 are aperture sets that were measured on both the relative instruments and the absolute instrument but are no longer available for measurements.

	Relative radii ratio		
Nominal diameters/ mm	Relative instrument	Absolute instrument	Percentage difference
Set 1			
5/3.5	1.428 481	1.428 347	0.01
3.5/2.5	1.399 661	1.399 145	0.04
2.5/2	1.251 150	1.249 884	0.10
2/1.5	1.332 247	1.333 71	−0.11
1.5/1	1.497 686	1.500 005	−0.15
1/0.35	2.853 338	2.846 322	0.25
Set 2			
2/1	2.006 187	2.005 627	0.03
1/0.5	1.997 877	2.000 000	−0.11
Set 3			
2/1	1.992 172	1.994 052	−0.09
1/0.5	1.992 603	1.993 418	−0.04

For the larger apertures considered in this study, features appear in the fit residuals that are not randomly distributed around zero. For example, the fit residuals for the 2 mm diameter aperture shown in figure 2 have a maximum deviation of +0.06% from zero at the furthest distance from the sphere investigated and tend to increase with distance from the sphere. The most likely cause of this correlation is the light originating within the sphere that is reflected off of one of the baffles, or another laboratory surface, and reaches the detector. These features are not apparent in the fit residuals for the smaller apertures because the random fluctuations are much larger.

It is also interesting to compare the aperture radii ratio of a large aperture with several smaller apertures. When the apparatus is fully developed, it may be desirable to have more than one large aperture with a well-known area to be used as standard reference. We can eliminate errors due to non-linearity between lock-in amplifier scales by multiplying the results of table 1 to obtain the radii ratio of a large aperture to a much smaller one. For example, we can determine the radii ratio between a 5 mm and a 2 mm aperture by multiplying the results of 5 mm/3.5 mm by that of the 3.5 mm/2 mm. These results are summarized in table 2 for aperture set 1. The results presented in table 2 are generally identical to those obtained by directly dividing the fit parameters determined using different lock-in scales. This indicates that the non-linearity between lock-in amplifier scales is smaller than other uncertainties. We plan to quantify the scale to scale non-linearity at a later date.

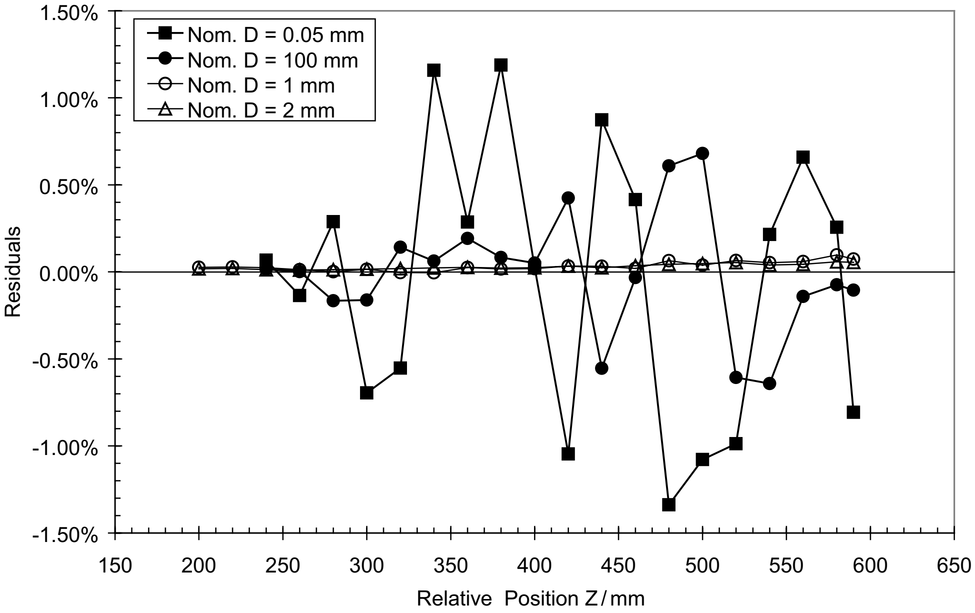

Figure 2. Examples of the residuals from a fit to the equation $a/(z+b)^2$. The y axis represents the difference between the data (I/L) and the fit.

Table 2. Radii ratios of a 5 mm diameter aperture to smaller apertures for set 1.

	Relative radii ratio		
Nominal diameters/ mm	Relative instrument	Absolute instrument	Percentage difference
5/3.5	1.428 481	1.428 347	0.01
5/2.5	1.999 389	1.998 465	0.05
5/2	2.501 535	2.497 859	0.15
5/1.5	3.332 664	3.331 407	0.04
5/1	4.991 284	4.997 127	−0.12
5/0.35	14.241 82	14.223 43	0.13

5. Summary and future improvements

The LBIR facility at NIST is developing a relative aperture area instrument to measure the geometric area of small apertures relative to larger apertures with a known area. Our goal is to measure the area of the smaller aperture to 0.1%. The results presented here indicate that we are near that goal but have not yet attained it, particularly for the smaller apertures that are of the most interest.

Several improvements need to be made. For the smaller apertures considered, the signal noise is a limiting factor in the measurement. Providing more light power to the sphere, increasing the pre-amplifier gain or increasing the detector size are relatively simple solutions to this problem and are presently under consideration.

Improvements in the baffling, aperture mount and detector mount should also improve the quality of the data. We hope to minimize or eliminate features which appear in the fit residuals by reducing the reflected and scattered light entering the signal detector. While this is not presently a severe limitation, eliminating these signals will, at least, aid in evaluating the uncertainty of the instrument.

A thorough and systematic study of the uncertainties of the system has not yet been performed. This will be a critical step to develop the instrument into a valuable tool for measuring the areas of small apertures. Presently, we use apertures of known area to evaluate the accuracy of the relative aperture area instrument. Other techniques will be employed to evaluate the accuracy of the technique for smaller apertures. One indication of the uncertainty is the fit to $1/d^2$. Other uncertainties such as systematic biases and random sources such as electrical noise will also contribute.

Thus far, there do not appear to be any significant impediments to reach our goal of determining the relative aperture areas for apertures as small as 0.05 mm to a standard uncertainty of 0.1%. Improvements in light baffling and signal strength should be relatively straightforward. A thorough evaluation of the uncertainties still needs to be performed. We hope to meet these goals in the near future.

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