An ac/dc technique for the Absolute Integrating-Sphere Method

Y. Ohno, R. Köhler and M. Stock

Abstract. For over sixty years, the Bureau International des Poids et Mesures (BIPM) has maintained the results of international comparisons of luminous intensity and luminous flux as "world-mean" values, in the form of groups of lamps. It was recently decided that this is no longer a satisfactory and reliable means of maintaining the photometric units of the International System of Units (SI). To maintain the luminous-flux unit, an attempt was made at the BIPM to use the Absolute Integrating-Sphere Method developed at the National Institute of Standards and Technology (NIST). A new technique (ac/dc) employing a chopper for the external source, which allows simultaneous measurement of the internal and external sources, has been developed to overcome an unexpected problem with the characteristics of the BIPM sphere, in that the heat from the lamp affected the sphere coating. The ac/dc technique allows absolute calibration of the integrating sphere while the internal lamp is operating and being measured. Having implemented this technique and replaced the sphere coating, experiments on the derivation of the unit are in progress at the BIPM and the NIST, the preliminary results of which are reported.

1. Introduction

A new method has recently been developed by Ohno to realize the SI unit of luminous flux, the lumen, using an absolutely calibrated integrating sphere rather than goniophotometry [1, 2]. This method, referred to as the Absolute Integrating-Sphere Method and studied by others [3], was officially employed to realize the luminous-flux unit at the NIST [4], and has now been extended to detector-based luminous-flux calibrations [5, 6]. A series of recent experiments at the NIST has shown that this method is highly reproducible [6].

For over sixty years, the BIPM has maintained the results of international comparisons of luminous intensity and luminous flux as "world-mean" values, in the form of groups of lamps. It was recently decided that this is no longer a satisfactory and reliable means of maintaining the photometric SI units. An attempt was made to use the Absolute Integrating-Sphere Method to reproduce and maintain the luminous-flux unit using the BIPM 1.5 m integrating sphere.

In the early stage of the experiments, a large discrepancy was observed between the derived unit and the BIPM-maintained unit of the lumen. A new technique employing a chopper for the external source has been developed in order to investigate the causes of the discrepancy. This, referred to as the ac/dc technique, is based on a similar principle to that used for detector linearity measurements [7], applied to an integrating sphere. It allows simultaneous measurement of the internal source (dc signal) and the external source (ac signal), and thus detection and correction of any changes of sphere responsivity caused by the internal lamp when it is turned on and off. An experiment using this technique revealed that the heat from the internal lamp had a significant effect on the coating of the BIPM sphere. This finding made it possible to resolve the greater part of the discrepancy.

The ac/dc technique, used with the Absolute Integrating-Sphere Method, allows the absolute calibration of an integrating sphere under the exact operating conditions of the internal lamp in the sphere. Experiments at the BIPM using this technique showed acceptable agreement between the units derived at the BIPM and the NIST. This paper describes the principles of the ac/dc technique and the preliminary results of the measurements performed at the two institutes.

2. First experiments at the BIPM

The principles of the Absolute Integrating-Sphere Method are described in the literature [4-6]. The installations in the BIPM photometry laboratory consist of a photometric bench attached directly to the 1.5 m diameter integrating sphere, as shown in Figure 1. The chopper was not installed during the first stage, and all the measurements were made on the dc signal. Because of this layout, the use of the BIPM sphere is slightly different from that at the NIST. The flux

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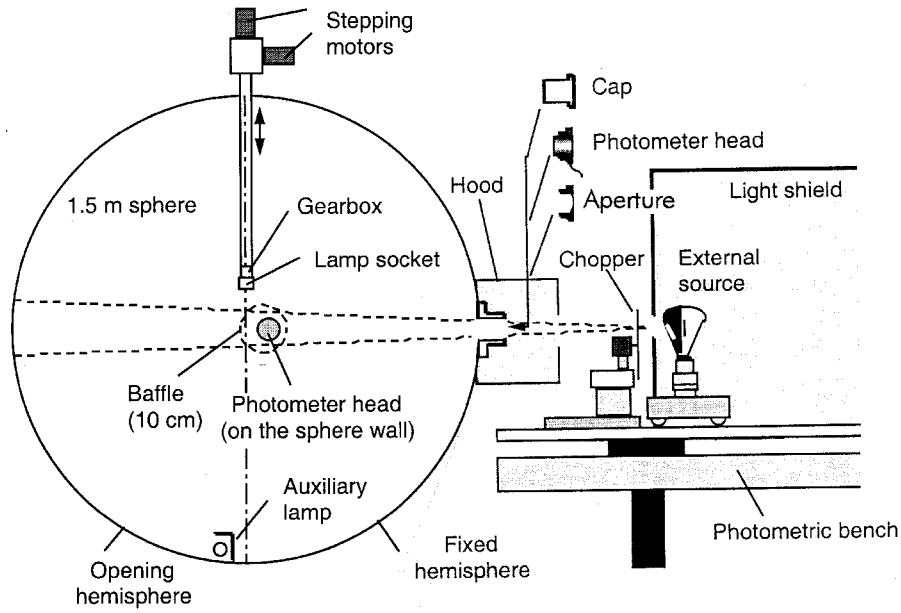

Figure 1. Experimental arrangement of the BIPM integrating sphere with the external source installed on a photometric bench. (The lamp holder can be moved to position the test lamp at the centre of the sphere, or off-centre upwards.)

from the external source is introduced into the sphere from the centre opening, passing through the centre of the sphere, and hits the sphere wall perpendicularly. No correction for the incidence angle is therefore necessary. However, the internal lamp must either be removed when the external beam is introduced (in this case, self-absorption correction for the lamp is made) or mounted off-centre in the sphere to avoid intercepting the external beam (in which case the effect of the off-centre position of the lamp is corrected for). The opening of the sphere is designed so that the calibrated aperture or the photometer head can be mounted in the same reference plane.

The other measurements made for the characterization of the sphere were similar to the original NIST method, including a two-dimensional scan of the sphere to determine the spatial response distribution function, a scan of the illuminance uniformity of the external source in the aperture plane, and determination of the relative spectral responsivity of the sphere/photometer system.

When the first results became available, they showed almost 2.5% discrepancy from the BIPM-maintained lumen (1985 world mean). It was suspected that the cause might be the effect of heat on the sphere coating owing to a large difference in the flux level between the internal lamp ($\approx$2500 lm) and the external beam ($\approx$0.4 lm). To investigate such effects, a new method employing a chopper with the external source (ac/dc technique) was introduced.

3. The ac/dc technique

Figure 2 depicts an integrating-sphere system for the ac/dc technique (shown with the NIST sphere geometry). The BIPM sphere geometry for this technique uses the off-centre configuration described in Section 2. The external source is chopped and introduced into the sphere continuously throughout a measurement session. When the internal lamp is turned on, the ac signal from the external source is superimposed on the dc signal from the internal lamp. The ac component may be three or four orders of magnitude smaller than the dc component, but it can be measured with a lock-in amplifier. By monitoring the ac signal while the internal lamp is turned on and off, any changes of the sphere responsivity – arising from thermal effects of the internal lamp on the sphere coating or on the photometer head, change of self-absorption by the internal lamp, etc. – can be detected and corrected. By relating the ac signal to the dc signal of the external source (ac/dc ratio calibration, performed with and without the chopper), the ac signal always provides the absolute calibration of the integrating sphere with automatic correction for these effects. The non-linearity of the photometer head can also be detected although it cannot be automatically corrected.

The detected ac signal is completely independent from the dc component. The dc component is proportional to $\Phi_{\mathrm{int}} + (\Phi_{\mathrm{ext}} R)$, where Φ_{int} is the total flux of the internal source, Φ_{ext} is the external beam flux, and R is the duty cycle of the chopped external beam. In our case, R is close to 0.5. Since Φ_{ext} is normally three or four orders of magnitude smaller than Φ_{int}, the contribution of $\Phi_{\mathrm{ext}} R$ can either be neglected or corrected for if required.

The absolute luminous flux of the internal lamp is thus determined from the dc and ac signals from the sphere photometer measured simultaneously and

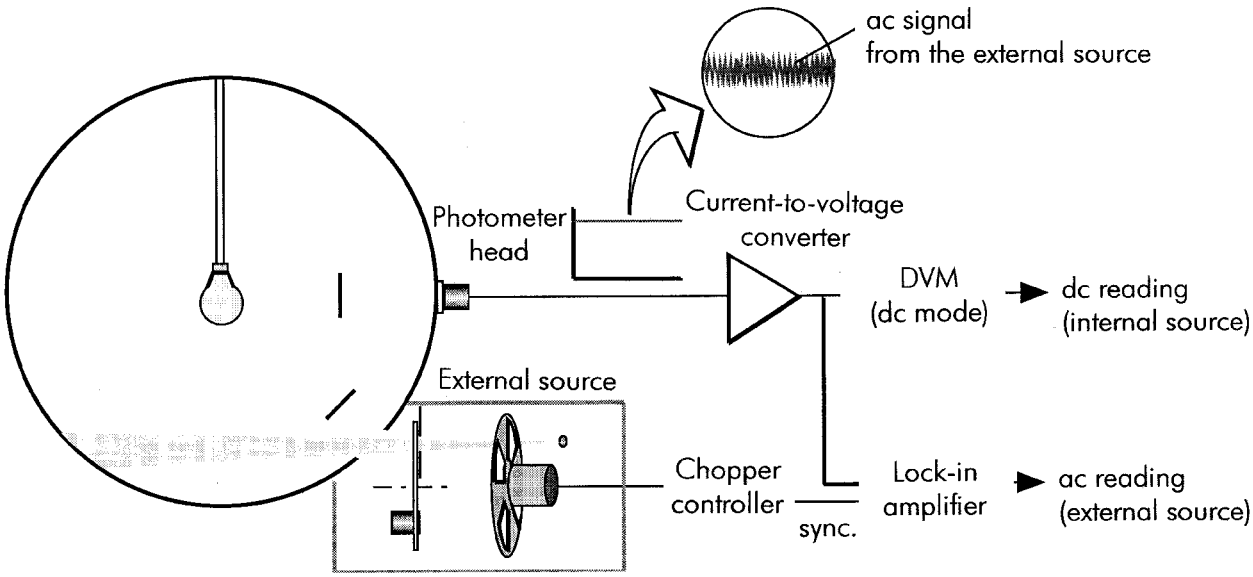

Figure 2. Construction of the integrating-sphere system employing the Absolute Integrating-Sphere Method with the ac/dc technique (NIST sphere geometry). DVM: digital voltmeter.

the dc illuminance of the external source (measured while the internal lamp is stabilizing), thus there is no need for sequential measurement of the external source. During the measurement at the BIPM, the ac/dc ratio was calibrated at each measurement run because the movement of the chopper was not automated.

4. Measurement of effect of heat on integrating sphere

Figure 3 shows the results of ac/dc measurements with the original BIPM sphere. The ac signal is the chopped external-source signal obtained from the lock-in amplifier, and represents the relative sphere responsivity. The dc signal is from the internal lamp and the curves show when the lamp was turned on and off. As suspected, the sphere responsivity changed dramatically (by $\approx 2\%$) after turning on the first lamp. Since the BIPM sphere employed a temperature-controlled photometer head, this change was attributed to the effect of heat of the internal lamp on the sphere coating. Even though the change of reflectance may be small, its effect is amplified by a factor of $1/(1-\rho)$ where ρ is the reflectance of the coating. Previously, in normal substitution measurements, this did not matter since the sphere was used to compare two sources of similar electrical and luminous power under similar temporal behaviour. With the Absolute Integrating-Sphere Method, a relatively high level of flux from the internal test lamp ($\approx$2500 lm for a 250 W lamp) is compared with a very low level of flux (less than 1 lm) from the external beam. Thus, the reflectance of the sphere coating was strongly affected by the large difference of the heat load. This coating was a mixture of zinc oxide and titanium oxide based on the old BIPM recipe. The BIPM sphere has consequently been re-coated with a different material based on barium sulfate. Newer measurements of the sphere temperature dependence have shown that the effect has only negligible influence when using a 250 W lamp in the 1.5 m integrating sphere.

Similar experiments were performed at the NIST to evaluate the effect of heat on the sphere coating. The NIST 2.5 m integrating sphere [5] has a barium-sulfate-based coating with $\approx$98 % reflectance in the visible region. Figure 4 shows the results of ac/dc measurements performed at the NIST using a 1000 W FEL-type tungsten-halogen lamp operating at 3100 K. A change of no greater than 0.05% was observed, which is almost negligible. As the change is so small, it is difficult to determine how much of it is attributable to the coating or how much to the photometer head (temperature-controlled type). The data verify that this type of sphere coating has almost no thermal effects in normal lamp measurements.

The ac/dc technique not only allows the testing and correction of the temperature effects of the integrating sphere, but also the detection of photometer non-linearity, in which case a sharp change of the ac signal is observed when the internal lamp is rapidly turned on and off. In this case, as the change of the ac signal represents the change of the gradient (derivative) of the linearity curve, it does not automatically correct the errors, but it is a useful tool for detecting non-linearity.

Another important benefit of the ac/dc technique is that the self-absorption of the internal lamp can be corrected for the condition when the internal lamp is operating. Some discharge lamps are known to change their self-absorption characteristics when they are operating, a factor that was previously impossible to measure.

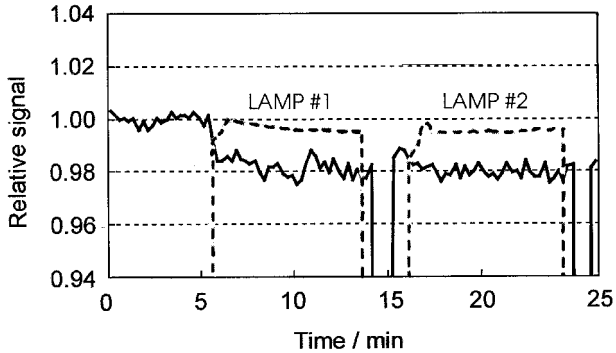

Figure 3. Results of ac/dc measurements for the original BIPM 1.5 m integrating sphere with a 250 W incandescent lamp: ac signal (solid curve); dc signal (dashed curve).

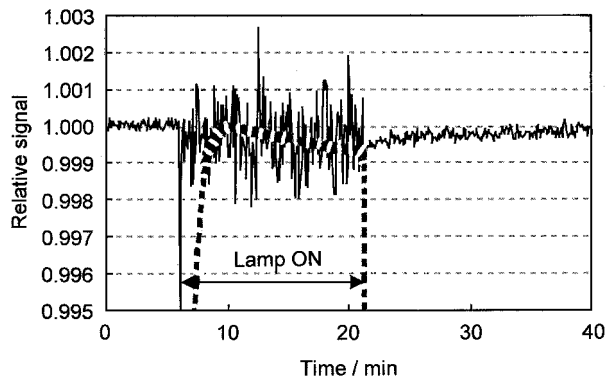

Figure 4. Results of ac/dc measurements for the NIST 2.5 m integrating sphere with a 1000 W tungsten-halogen lamp: ac signal (solid curve); dc signal (dashed curve).

5. Preliminary results of deriving the unit

Even with the original sphere coating, which had a strong thermal effect and was not very uniform over the two hemispheres, the results of the lumen realization after employing the ac/dc technique became very consistent with the results of the BIPM key comparison of luminous flux. The values of several BIPM secondary standard lamps measured using the Absolute Integrating-Sphere Method were 0.5% to 0.7% lower than the assigned 1985 world-mean values (with estimated expanded uncertainty $(k = 2)$ of $\approx$0.7%). This corresponds well with the NIST value ($\approx$0.5% lower than the BIPM 1985 world mean) at the 1998 Consultative Committee for Photometry and Radiometry (CCPR) comparison of the luminous-flux unit. Direct comparisons between the two institutes are planned after further experiments at the BIPM.

6. Conclusions

The ac/dc technique for the Absolute Integrating-Sphere Method has been developed through collaboration between the BIPM and the NIST. This technique has made possible absolute calibration of an integrating sphere under the exact operating conditions of the internal lamp in the sphere. It has proved useful in evaluating and correcting for the effect of heat on integrating spheres, as well as for other effects and errors associated with the operation of the internal lamp. The technique also has potential in the measurement of discharge lamps with an integrating sphere, allowing for correction of the self-absorption of the test lamp when the lamp is operating in the sphere.

The preliminary results of deriving the lumen at the BIPM employing the ac/dc technique showed promising agreement with the unit derived at the NIST. Further work is in progress at the BIPM using the newly coated integrating sphere to confirm the stable reproducibility of the unit without relying on standard lamps.

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