A COMPARISON OF THE LASER POWER AND TOTAL IRRADIANCE SCALES MAINTAINED AT THE NATIONAL BUREAU OF STANDARDS

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Systematic errors among the various measurement scales and standards are a never-ending source of concern to the National Bureau of Standards. This is particularly true when measurements are supported by different groups at the NBS. Each group will assign limits of systematic error to the measurement for which they are responsible, but users who are reasonably well-informed will want to know how much difference is actually found between measurements based on the work of the different NBS groups. If both groups have assigned conservative limits to systematic error, this difference may be appreciably less than the sum of the limits of systematic error, unless one or both groups has overlooked significant sources of error. In either case, users trying to reconcile differences need to know whether an appreciable part of their discrepancy may lie in their standards.

The calibration of instruments for laser power and energy measurements has been based on two different sets of standards, depending on the history of the calibrating laboratory and the equipment available. Some work has been based on lamps calibrated by comparison with black body radiation by the Optical Radiation Section of the National Bureau of Standards, and other work on calibrated calorimeters or detectors traceable to the electrical standards used in the Laser Measurement Techniques Section. It has been reported[1,2] that a 9% discrepancy was found between measurements based upon the different standards available from these two NBS sections. More extensive measurements placed the discrepancy at 4%.[3] The wide circulation of reference 2 may lead many people to believe that the rather common discrepancies in laser power and energy measurements are to a significant extent due to discrepancies in the NBS standards. The purpose of this paper is to report a recent intercomparison that demonstrates the level of agreement between the scales presently maintained by the two NBS sections.

The two scales involved in the intercomparison were the upper end of the NBS total irradiance scale maintained by the Optical Radiation Section, and the lower end of the laser energy (and average power) scale maintained by the Laser Measurement Techniques Section. The upper end of the total irradiance scale is disseminated on 1000 watt DXW, quartz, halogen, coiled-coil filament lamps with ceramic reflectors yielding approximately 140 mw/cm^2 at 40 cm. from the lamp. Originally this scale was realized by comparison of the total irradiance from the lamp with that from a black body[4], but it has been recently re-realized with an electrically radiometer (a radiometer with a heater built into its receiver), and the scale is being shifted about 2.5% at its upper end as a result[5]. The laser energy scale is realized and maintained by a group of calorimeters designated the C-series, which can be used to measure average laser powers as low as .[6]

The intercomparison was carried out with the same radiometer that was used to re-realize the NBS total irradiance scale. It is an improved version of a type that has been described previously.[7] The features of this radiometer that are noteworthy to this intercomparison are its linearity due to electrical calibration and its accomodation of different irradiation geometries with negligible systematic error. During the laser energy scale intercomparison, the radiometer had a one cm diameter aperture surrounding a one half cm diameter opening in a cavity receiver. During its usual operation, the radiometer is equipped with a 0.02516 ± 0.00002 cm area circular aperture in front of the cavity receiver.

The experimental arrangement for the laser energy scale intercomparison has been described in detail[8]. The essence of the technique is that the laser beam passes through an aperture in an opaque screen, and is incident on a wedged glass beam splitter. The directly transmitted beam is collected by the radiometer, the first surface reflection from the beam splitter is collected by a C-series calorimeter; and the second internal reflection from the beam splitter is collected by a detector that activates a timer. The rest of the low order reflections are collected on black baffles. A shutter is provided so that the aperture can be closed, and the measurement procedure is to open the shutter for a preset period of time, the actual shutter open period being determined by the detector-activated timer. During the shutter closed period (i.e. calorimeter rating period[9]), an electrical current is passed through the receiver heater of the radiometer and the voltage across the heater and current through it are measured for calibration of the radiometer.

The average power incident on the radiometer during the measurement period is calculated relative to the laser energy scale by the following procedure: the energy measured by the calorimeter is divided by the time interval during which the shutter was open, and the result is multiplied by the transmittance/reflectance ratio of the beam splitter, which in turn is measured by replacing the radiometer by another C-series calorimeter.

Two measurements of nominal five minute duration were run in the above described configuration; and two measurements of nominal one minute duration were run with the position of the calorimeter and radiometer interchanged, using the reciprocal of the transmittance/reflectance ratio of the beam splitter to calculate the average power incident on the radiometer as measured by the calorimeter. The principle difficulty in these measurements was that the calorimeter and laser measure different quantities. The output of the calorimeter is proportional to the energy incident on it, whereas the output of the radiometer is a complex integral transform of the instantaneous power incident on it. (It is only for a constant power input to the radiometer that a steady state output that is proportional to the incident power is obtained.)

To reduce the data obtained from the radiometer, it was assumed that the radiometer was a linear, single time constant (lumped parameter) system, in which case the instantaneous power $P_r(t)$ incident on it during the shutter open period is given by

$$P_r(t) = F_o\,[v(t) - v_o + \tau\,\dot{v}(t)]\,VI/(v_e - v_o) \qquad (1)$$

where F_o = 1.00274 is a correction factor for the various errors associated with realizing a radiant power scale with the radiometer[9], $v(t)$ is the instantaneous radiometer output voltage during the shutter open period, v_o is a zero offset voltage, τ is the time constant of the radiometer (thirty seconds in this case)[10], the dot indicates differentiation with respect to time, V is the voltage across the receiver heater and I is the current through it during the shutter closed period, and v_e is the steady state output of the radiometer during this period.

In the laser energy scale intercomparison, the quantity obtained from the calorimeter was the average power during the shutter open period, thus we integrate Eq. 1 from t_1 to t_2, and divide the result by t_2-t_1, to obtain the average power, $\bar{P}_r$, incident on the radiometer as measured by the radiometer. The result is

$$\bar{P}_r = F_o\,VI\,F_1, \qquad (2)$$

where

$$F_1 = \left\{ \int_{t_1}^{t_2} v(t)dt - (t_2 - t_1)v_o + \tau \, [v(t_2) - v(t_1)] \right\} \Big/ (t_2 - t_1) \; (v_e - v_o), \qquad (3)$$

can be considered as a correction factor. The accuracy of F_1 is dependent upon the linearity and single time constant assumptions necessary for Eq. 1. For the highest accuracy the receiver heater circuit should be opened and closed in exact synchronization with the opening and closing of the shutter. Also before the actual measurement, V should be adjusted so that the radiometer output voltage does not change as the shutter is opened and closed. In this case the radiometer would be operating under steady state conditions and F_1 would be equal to 1.0. However, in the actual measurement, these ideal conditions could not be achieved for two reasons. First, the receiver-heater circuit was opened and closed manually, and only approximate synchronization with the opening and closing of the shutter could be obtained. Secondly, the laser output fluctuated as much as five percent over a few minutes, so an exact match between the radiant power and electrical power was not possible.

The lower curve in Fig. 1 is the radiometer output voltage during one of the measurements. The actual data was recorded digitally with a four second sampling period, and the curve was drawn by connecting the points. The shutter was opened at zero minutes and closed at one minute. The spike in the curve at zero minutes was caused by closing the receiver heater slightly before the shutter was opened. A similar spike in the opposite direction appearing just before the shutter is closed, is superimposed upon a sudden increase in laser output.

The upper curve in the figure is the instantaneous power during the interior fifty-two seconds of the shutter open period, as calculated from the radiometer

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The estimated limits of systematic error are 0.3% for the radiometer, 1.0% for the calorimeter, and 0.3% for the beam-power ratio ~~ratio of powers~~ for the beam splitter used in the comparison.

output (lower curve) using Fig. 1 and numerical differentiation. This procedure was not applied at the end points of the interval in order to avoid introducing the spurious effects of the previously mentioned spikes into the data. Similarly, the points t_1 and t_2 were chosen about four seconds away from the ends of the shutter open interval (towards its center) when calculating the average power using Eqs. 2 and 3. Of course the average powers computed over two similar but non-identical intervals cannot be expected to agree exactly due to laser fluctuations. None the less, the differences to be expected under the conditions of the measurements described in this paper are small. The square in Figure 1 represents the area that corresponds to a 0.14% error in average power for the data of the figure.

In accordance with the above, the data in Table I compares the average power, during the entire shutter open period, as measured by the calorimeter with the average power, during a period falling within the shutter open period but of eight seconds less duration, as measured by the radiometer. We can readily identify at least four possible sources of the scatter of the values of $\overline{P}_c/\overline{P}_R$ in the right hand column of the table. They are the intrinsic noise associated with the radiometer, the intrinsic noise associated with the calorimeter, the failure of the assumptions used in deriving Eq. 3 for F_1, and the differences in the average power from a fluctuating source when calculated over slightly different nested intervals. We make no attempt to assess the relative magnitude of these effects here. The significant point is that the average value of $\overline{P}_c/\overline{P}_R$ is a measure of the agreement between the total irradiance and laser energy scales presently maintained at NBS, and the 0.09% discrepancy is well within the estimated limits of error associated with the two scales.

Furthermore, taking account of the recent total irradiance scale shift, we see a difference that agrees satisfactorily with the 4% reported in reference 3.

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REFERENCES

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3. D. A. McSparron, NBS Tech. Note 449, June 1968, page 2.

4. W. E. Schneider, Appl. Opt. 9, 1410 (1970).

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6. E. D. West, W. E. Case, A. L. Rasmussen, and L. B. Schmidt, NBS J. Res. 76A, 13 (1972).

7. J. Geist, NBS Tech. Note 594-1, June 1972, page 27.

8. Reference 6, page 19.

9. Reference 7, page 4. Notice that F_0 has a different value in the present paper than in Reference 5. This is caused by the different aperture geometries necessary for the different types of measurements. Notice also that the estimated limit of error associated with the value of F_0 used in the present paper is ±0.00279. This limit is considerable lower than that reported in reference 5 for the same reason.

10. Reference 5 page

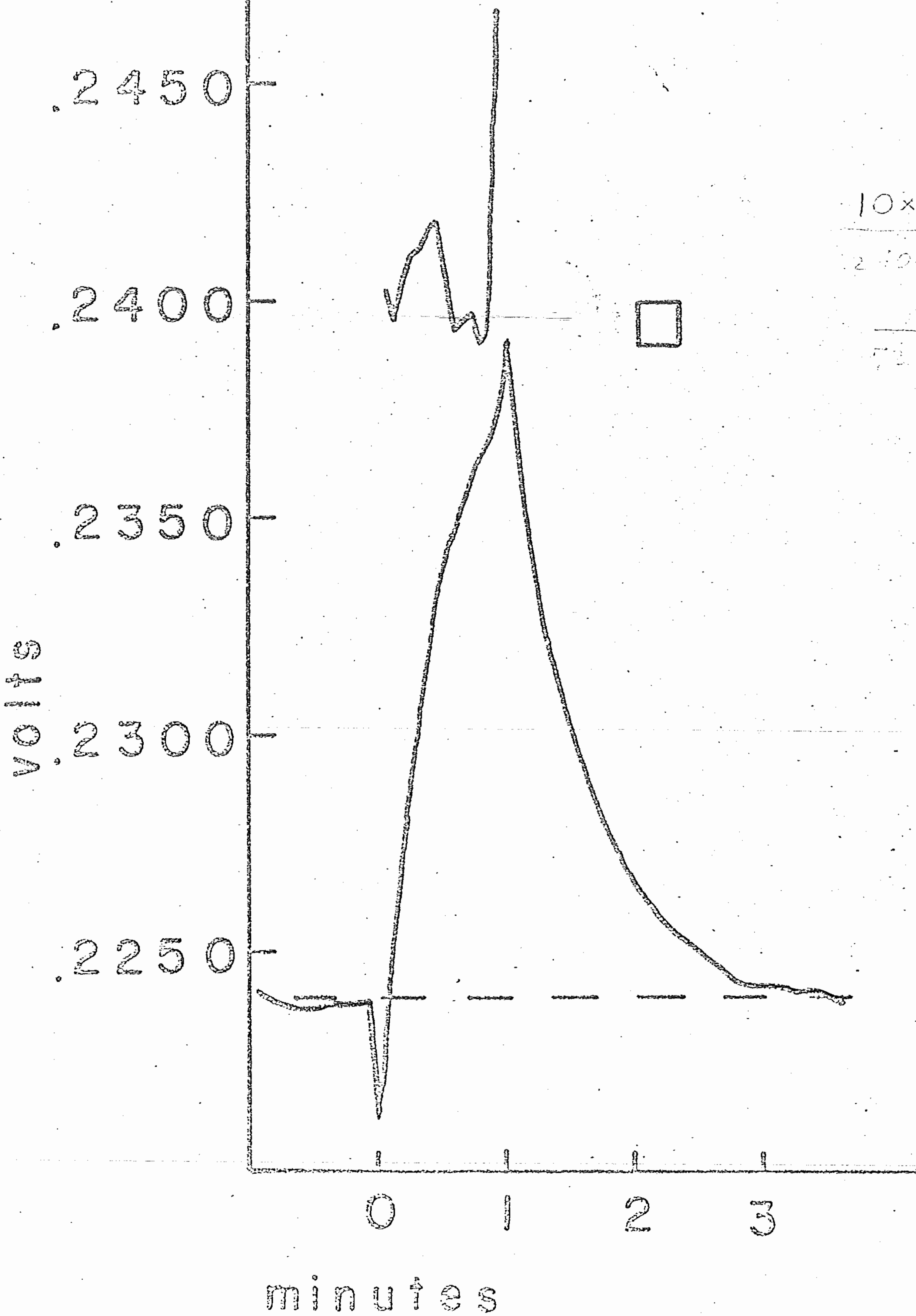
TABLE 1. Comparisons of $\overline{P}_R$ the average power incident on the radiometer as measured by the radiometer* and $\overline{P}_c$ the average power incident on the radiometer as measured by the calorimeter**.

Measurement Number	Duration † (sec.)	C_1	$\overline{P}_R$	$\overline{P}_c$	$\overline{P}_c/\overline{P}_R$
1019713	300	0.9615	8.474	8.484	1.0012
1019714	300	0.9777	8.317	8.335	1.0022
1020713	60	1.0798	5.352	5.356	1.0007
1020714	60	1.0054	5.190	5.188	0.9996

*ECR 2

**C2-2

† of shutter open period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