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Optical Radiation Measurements:

Photometric Instrumentation and Research (1970 to 1971)

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Preface

This is the second issue of a series of Technical Notes entitled OPTICAL RADIATION MEASUREMENTS. The series will consist primarily of reports of progress in or details of research conducted in radiometry and photometry in the Optical Radiation Section of the Heat Division and will appear about every six weeks.

The level of presentation in OPTICAL RADIATION MEASUREMENTS will be directed at a general technical audience. The equivalent of an undergraduate degree in engineering or physics plus familiarity with the basic concepts of radiometry and photometry [e.g., G. Bauer, Measurement of Optical Radiations (Focal Press, London, New York, 1965)] should be sufficient for understanding the vast majority of material in this series. Occasionally a more specialized background will be required such as for some of the electronic techniques required in this issue. Even in such instances, a careful reading of the assumptions, approximations and final conclusions should permit the non-specialist to understand the gist of the argument if not the details.

At times, certain commercial materials and equipment will be identified in this series in order to adequately specify the experimental procedure. In no case does such identification imply recommendation or endorsement by the National Bureau of Standards, nor does it imply that the material or equipment identified is necessarily the best available for the purpose.

Any suggestions readers may have to improve the utility of this series are welcome.

Henry J. Kostkowski, Chief,
Optical Radiation Section
National Bureau of Standards

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(1970 to 1971)

Edward F. Zalewski, A. Russell Schaefer,
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This document was written primarily to serve two purposes. First, some of the basic instrumentation which has recently been developed for use in photometry at NBS is described. The design and application of photodetector amplifiers, lamp power circuitry, and mechanical instrumentation are discussed. Second, three photometric experiments are described: the stability testing of some flux lamps and intensity lamps and the determination of the dependence of relative intensity on orientation. These experiments and their conclusions have proven useful in pointing out areas which need further investigation and in planning the directions of future work.

Key words: Instrumentation; lamp orientation; lamp power circuitry; lamp stability; photodetector amplifier; photometry.

1. Introduction

A little over a year ago there was at NBS a merger of several related groups, including radiometry and photometry, into one managerial unit. This was done in order to bring the programs of these heretofore independent groups into concert. Before the merger there already was a move under way in the photometry group to expand the research program and modernize the instrumentation. This work continued, of course, and evolved into the research programs presently under way.

Because the instrumentation developed during this period is now used in several of the present programs, we have decided to describe it in a single document for ease of reference in future publications. In addition to a description of our instrumentation, we have described three of the experiments that were either completed or well under way at the time of the merger. The results of these experiments have proved useful to us in the planning of further research in photometry.

In keeping with the intention of this series on research in optical radiation measurement, we have tried to be as detailed as possible in the descriptions of our equipment and procedures. There is a danger that beyond a certain point additional details become trivia. It is difficult to determine where this point actually lies because it is a function of the background of the individual reader. We apologize in advance for those sections that the reader may find boring and welcome any comments or questions that may arise in those sections he or she finds obscure.

In the description of our instrumentation we discuss the current to voltage converters that were designed and built at NBS for the amplification of the photodetector output. The operation of a stable DC lamp power circuit is presented. And finally, we describe the various pieces of hardware we have constructed to support and align the lamps and to perform various photometric measurements.

Under the heading of photometric research we have included two different sets of measurements on lamp stability and one set on lamp characterization. The two experiments on lamp stability are a study of the drift of a specific type of lamp that may be used as a standard of geometrically total luminous flux and a study of the reproducibility of the output of a type of lamp that is currently used as a luminous intensity standard. The lamp characterization experiment deals with the orientational dependence of the output of three types of lamps that have been used as either luminous intensity or spectral irradiance standards.

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2. Instrumentation

2.1 Photodetector Amplifier

Introduction:

One critical aspect of procedures for the measurement of light is the method used for measuring the rather small electrical currents produced by photosensitive detectors. Two of the most common types of these detectors, the selenium barrier-layer cell which has been used for many years in photometry at NBS, and the silicon photodiode now being employed in experiments here, are essentially current sources. It has been found that they must be operated into a very low impedance circuit in order to maintain a linear relationship between the illuminance incident on these detectors and the resultant current output. The device used to accomplish this task, besides having a very low input impedance, must be quite stable, must be linear over the range of currents encountered, and must have a low noise characteristic. In addition it must be sensitive enough to handle the currents involved, which typically range from a tenth to a hundred microamps.

In the past, two methods were used at NBS to fulfill the above requirements. These were essentially current balancing techniques which created an effective zero impedance across the photodetectors. One method, described by Barbrow [1][1], involves balancing the current from a photocell against that from a stable source supply. The other method shown in figure 1 balances the output current of two photocells to achieve a low impedance. Each photocell viewed a different source and a null was achieved by varying the distance between the comparison source and the receiver. These techniques are fairly simple and fulfill the requirements of low input impedance and high sensitivity. However, these circuits are somewhat cumbersome to use, the stability and linearity are open to question, and they are difficult to adapt to an automated data acquisition system.

A simple experiment to compare a commercially available DC current to voltage converter-amplifier with these earlier methods indicated that the signal-to-noise ratio and the stability of the current to voltage converter were at least as good as the current balance and the photocell balance circuits. Because of this one would expect a notable improvement in measurement capability by utilizing state-of-the-art operational amplifiers. It was therefore decided to design and construct a very stable, sensitive, low noise DC current to voltage converter using an operational amplifier with good stability and noise specifications.

Operational amplifier principles:

A few basic principles of operational amplifiers which make them suitable for the present application will now be discussed. For a detailed treatment and derivation of some of the following expressions, see e.g. Graeme et al. [2]. Operational amplifiers are simply high gain amplifiers, often having two differential input terminals and a single output. There are certain useful properties which a so-called perfect or ideal operational amplifier would possess. These are an infinite input impedance, Z_i; a zero output impedance, Z_0; instantaneous response time, implying infinite bandwidth; infinite internal or open loop gain, A; and output voltage V_0 such that

$$V_0 = A(V_2 - V_1) \tag{1}$$

where V_2 and V_1 are the two input voltages. The ways in which the device can be used depend largely on the type of feedback network employed. Figure 2 shows the basic configuration in which the operational amplifier (op amp) is used as a current amplifier, or more specifically, a current to voltage converter. In this diagram a typical real photocell of near infinite impedance is represented by an ideal negative current source i_s with infinite impedance coupled with a finite impedance R_s in parallel. The equivalent voltage source is shown in the insert for ease of analysis. In this case the positive polarity input is tied to common so that the voltage drop across the op amp inputs can be

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[1]Figures in brackets indicate the literature references at the end of this paper.

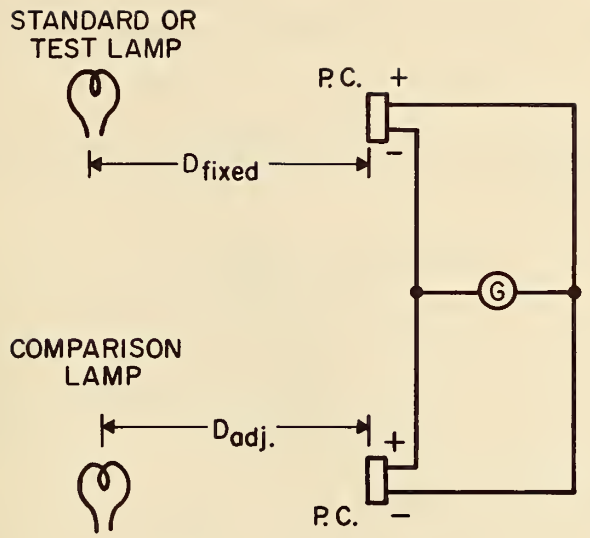

Figure 1. Balanced photocell circuit. This figure depicts a system in which the output of a comparison photocell (P.C.) is successively balanced against that of a photocell measuring the illuminance from a standard lamp and that from a test lamp. Values of D_{adj}, the adjustable distance between the comparison lamp and photocell, for the two balanced conditions yield the intensity of the test lamp:

$$I_T = \frac{I_s D_s^2}{D_T^2}$$

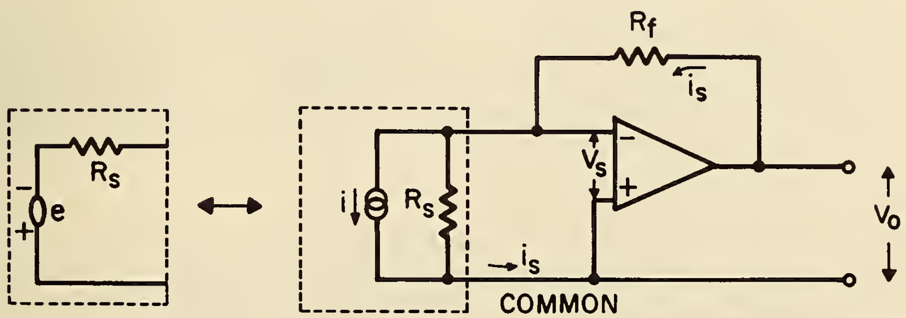

Figure 2. Basic current to voltage converter circuit. The dotted insert shows the equivalent voltage source.

represented by V_s. This is called an "inverting circuit", since the polarity of the amplified signal will be changed in polarity. The properties mentioned above now imply that

$$V_0 = -AV_s \text{ as } A \to \infty \tag{2}$$

and, since all the current i_s must flow through the feedback network because of infinite input impedance of the op amp,

$$i_s = \frac{e - V_s}{R_s} = \frac{V_s - V_0}{R_f} \tag{3}$$

From eqs. (2) and (3)

$$i_s = V_s \frac{1 + A}{R_f} \tag{4}$$

and thus the input impedance of this circuit is

$$Z_s = \frac{V_s}{i_s} = \frac{R_f}{1 + A} \tag{5}$$

Hence in the case of infinite or near infinite gain ($A \to \infty$) the impedance is quite low, practically zero. Equation (5) also implies V_s is approximately zero for finite signals i_s. Because of this well-known condition in which the signal input is practically at common potential (i.e. $V_s \approx 0$, virtual ground) and because the circuit input impedance is very low, this is an excellent device for measuring current sources. Note also that $i_s = e/R_s = -V_o/R_f$ for $A \to \infty$ implies the current i_s is independent of the feedback resistor R_f. Changing R_f alters V_0, but has no effect on i_s. The closed loop gain of the circuit which can be expressed as the ratio of the output voltage to the equivalent source voltage gives a measure of the amplification of unwanted op amp noise voltage and offset voltage. From eqs. (3) and (4),

$$V_0/e = \frac{-A}{\left(R_s/R_f\right)(1+A) + 1} \quad . \tag{6}$$

If $R_s \approx R_f$, then this ratio is approximately one, for large A, hence this circuit is often called a unity gain amplifier. Therefore, the voltage noise in this circuit is not very important unless R_f becomes greater than the photocell impedance. High frequency current noise can be a problem at these high impedances. To overcome this a small capacitor can be placed in parallel with R_f as a filter.

Current to voltage converter -- first version:

With this background let us proceed to the design of the first version of a current to voltage converter. This work was initiated by Dr. Bruce Steiner. The final design and construction was done by Mr. Louis Marzetta of the Electronic Instrumentation Section at NBS. The schematic diagram is shown in figure 3. The heart of this device is an Analog Devices Model 310 J varactor bridge operational amplifier. The most important characteristics which this op amp possesses for the present application are its stability (input offset voltage drift of ±30 μV/°C; ±100 μV/% power supply drift) and its low input noise characteristic (10 μV p-p voltage noise for 0.01 to 1 Hz and 10 μV rms voltage noise for 1 to 100 Hz; 10^{-15} A p-p current noise for 0.01 to 1 Hz and 2×10^{-15} A rms current noise for 1 to 100 Hz). Using the highest feedback resistor of 10 megohm and no filtering capacitance, which is the worst possible case, this means any current noise to be converted along with the signal is still a factor of 10^8 smaller than the signals encountered at this level (about 0.1 microamp). Hence current noise does not pose a problem. Furthermore, because of the unity gain configuration, voltage noise will only contribute about 10 μV noise on any given range: this is about 10^4 less than output voltages generally encountered.

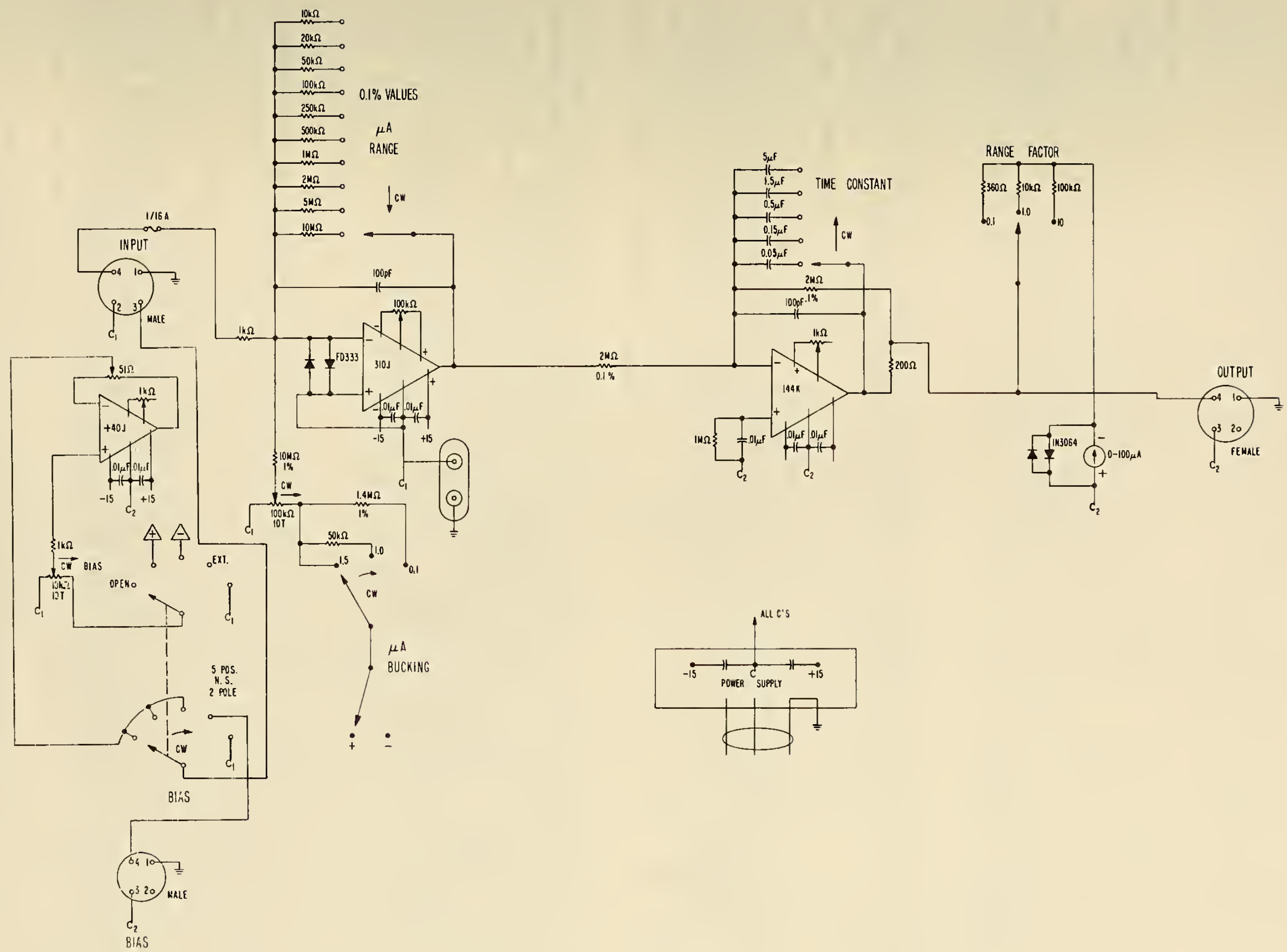

Figure 3. Current to voltage converter: first version. C_1 and C_2 are circuit commons connected at the power module common.

It is important to have very stable feedback resistors in the circuit. For this reason 0.1% tolerance, low temperature coefficient (50 ppm/°C) metal film resistors were chosen. These provide 0 - 10 volt output ranges for input currents from 0.1 to 100 microamps. Low leakage capacitors were used in all critical circuit locations because of the high sensitivity of the op amp and to maintain good accuracy in the transfer through it. A small capacitance is placed in parallel to limit the bandwidth enough to prevent misbehavior due to high frequency current noise.

The second stage Analog Devices Model 44 K op amp which also has a low noise voltage characteristic is used as a noninverting voltage follower which provides a well isolated low impedance voltage output. Its main purpose, however, is to provide the ability to select a given RC time constant filter independent of the feedback range selected. Five selectable capacitors in parallel with a two megohm resistor yield instrument time constants of 0.1, 0.3, 1, 3, and 10 sec. for averaging of noisy signals. An output voltage meter switchable to three ranges (0.1, 1.0, and 10 volts full scale) gives an indication of output, although in most cases data are recorded by reading the voltage output with a digital voltmeter.

Provision was made for bucking out a signal current of either positive or negative polarity. This is supplied by a divider circuit which introduces ±0 to 0.1, 0 to 1.0, or 0 to 1.5 microamps of current from the power supply into the signal input of the op amp.

An allowance was also made for voltage biasing a photodetector if desired. The voltage bias, which appears across the signal input leads, can be selected from the power supply internally, providing plus or minus 0 to 15 volts. Alternatively the bias can be switched to a rear panel input which allows the use of an external bias source. The Analog Devices Model 40J is used as a noninverting follower to allow good isolation and high input impedance for the voltage bias source, yet a very low impedance is maintained at the signal input leads for the photodetector current source. With the switching used one can connect the return signal lead to either a positive or negative internal bias, an externally applied bias, common potential, or an open circuit.

There are several more design features of this instrument that are not evident in the schematic diagram in figure 3. First, the power supply used was a modular unit constructed to power operational amplifier circuits with good stability and low noise. Second, to minimize any AC pickup from this supply, the entire unit and its AC power input cord are located in a separate compartment shielded from the rest of the instrument. Third, the common of the circuit has been left floating, with a terminal on the rear panel to allow a user the option of grounding the common. Finally, all inputs and outputs are on 4-pin plugs which follow this convention: Pin 1 - chassis ground, Pin 2 - common, Pin 3 - low or return signal lead, Pin 4 - high or input signal lead.

Current to voltage converter checkout:

After completion this unit was subjected to extensive usage and checkout procedures which will now be briefly described.

In order to get an approximate value of the voltage noise for this device, its input was open circuited to simulate the high impedance from a current source. The output was monitored with a five digit, dual-slope integrating digital voltmeter (IDVM) sampling with a 1/10 second gate, which had an average normal mode rejection ratio of about 10 db or less for the frequencies encountered (except for harmonics of 0.1 second where it is considerably greater). The voltage noise registered under these conditions for the maximum instrument bandwidth of 0 - 10 Hz was about 10 μV, independent of feedback range.

To determine an approximate level of stability, the input was again open circuited, and the output read with the IDVM. A constant signal input was generated simply by introducing a current through the bucking circuit. This served as a test of both the stability of the operational amplifier and that of its internal power supply. Output was read automatically every 20 minutes with a data acquisition system. The output was found to vary only a couple of parts per hundred thousand over a period of eighteen hours.

Linearity was checked using the following procedure. A picoammeter source was used to generate a current, and a Leeds and Northrup Model K-3 potentiometer was employed for measuring current and voltage. This was done in conjunction with a voltage divider (Leeds and Northrup volt box, Model 7592) used in the voltage measurements and a 10,000 ohm metal film resistor of excellent stability characteristics used for the current determinations. The procedure was to measure a set current from the picoammeter source with the potentiometer, then switch this current into the operational amplifier and record the voltage output with the potentiometer for each feedback resistor. The process was then repeated for another current. Three different ranges of input current were tested. They were: 0.1 to 1.0 μa in steps of 0.1 μa, 1.0 to 10.0 μa in steps of 1.0 μa, and 10.0 to 100.0 μa in steps of 10.0 μa.

Analysis of the linearity data was done by fitting a straight line to voltage out versus current in for each feedback resistor and for each of the three sets of current values, resulting in thirty curves. The results indicate the device is linear to within a few tenths of a percent for all currents encountered, and if one chooses the feedback resistor so that a signal of about one volt or more is put out (as is usually done in actual practice), then linearity is within a few hundredths of a percent. These linearity results are undoubtedly limited by the experiment, and not the op amp itself, since experiments elsewhere [3] have shown that operational amplifiers used in this way are linear even over a greater range and to a greater degree than indicated by the results of this experiment. This work was done primarily to ascertain that there were no malfunctions which might manifest themselves as a grossly nonlinear output response.

In summary, this current to voltage converter appeared to be quite satsifactory over the range of precision and accuracy required for intended laboratory use. However, it was found during actual use that in order to attain the low noise levels expected from the manufacturer's specification, it is necessary that the op amp common be grounded rather than floating. When this connection was made the noise decreased by a factor of ten.

Current to voltage converter -- second version:

As might be expected it became apparent that several improvements could be made on a second design of a current to voltage converter. First, it was thought desirable to be able to reverse the input with a switch to accommodate those photodetectors which had been wired with a reverse polarity. Second, it might be useful at times to have a greater bandwidth than 0 - 10 Hz. This could be provided by a switch that in one of its positions places no capacitance across the second stage op amp, thus allowing a much faster time response (of the order of several microseconds). Third, a more sophisticated filter, such as a three pole filter giving a higher filtering ratio with a smaller inherent time constant would be desirable. Fourth, it was found there were times when even more gain would be desirable: an additional feedback resistor of 30 megohm would give a maximum useful sensitivity of 0.1 volts output for 0.003 μa input. Also, a switch and resistor installed in the noninverting second stage feedback network would permit one to switch in a factor of ten voltage gain. This would result in a maximum sensitivity of 0.1 volts out for 0.3 nanoamps in. The final change desired would be to install an input socket to include the option of introducing a bucking current from an external source. This would allow use of a bucking current greater than that supplied by the internal bucking circuit.

A second current to voltage converter was constructed which incorporated the above mentioned modifications. The circuit diagram is shown in figure 4. Instead of the varactor bridge, however, an Analog Devices Model 42K FET operational amplifier was used because of its even lower input noise specification and smaller size. Testing proceeded in about the same manner as for the first device. The results are summarized below.

Noise and stability appear to be of about the same level as with the first model, with one exception. There was initially a slight degradation in voltage noise (to about 20 microvolts) when the time constant was set at zero. It was range independent. The test was done with the same IDVM as in the previous checkout. Linearity of this instrument within experimental limits was again found to be the same as that of the previous one. The extra feedback resistor was useful, but the optional gain of ten on the second stage, since it also amplifies the noise voltage by a factor of ten, has not been useful as yet. As with the previous instrument, it has been necessary to run the common at ground potential to reduce noise effects. There initially was a problem with the 42 K op amp. It became

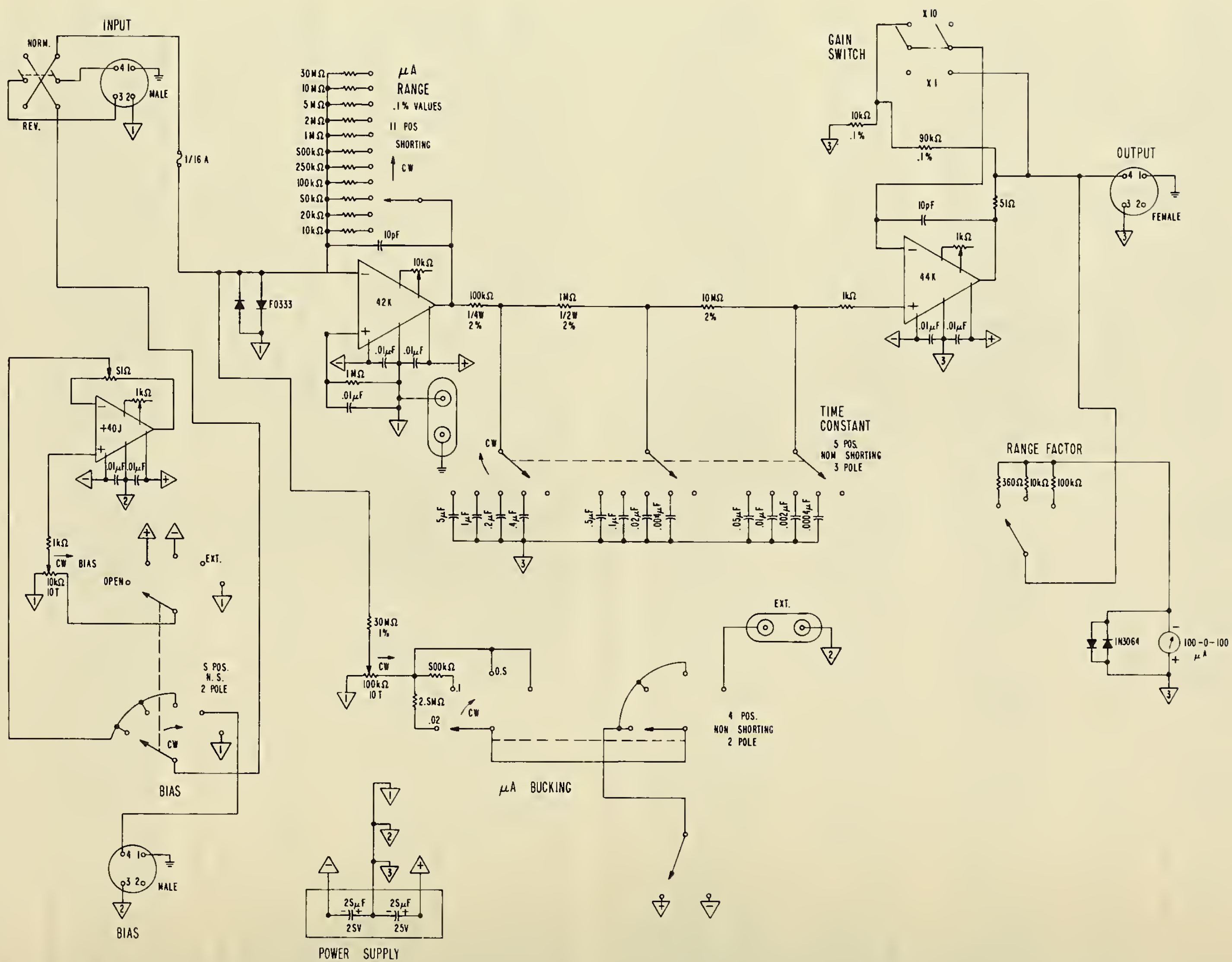

Figure 4. Current to voltage converter: second version. ▽1, ▽2, and ▽3 are circuit commons connected at the power module common.

unstable and put out maximum voltage with no signal on the input. This was thought to be due to the extremely high intrinsic impedance and sensitivity of the FET op amps. Initially the protective diodes for the 42 K op amp were mistakenly connected directly from the negative to the positive input leads. The problem was corrected by connecting the diodes directly to common instead of first to the positive input and by installing a different 42 K op amp. The new op amp seemed somewhat less susceptible to this anomaly and also exhibited a lower voltage noise level of less than 10 μV.

In conclusion, both of these instruments have performed very well in their intended usage. It is anticipated that similar instruments will be constructed for future use in photometric and radiometric applications at NBS.

2.2 Lamp Power Circuitry

Introduction:

In order to obtain a steady light output from a tungsten filament lamp for use in deriving standards for radiometry and photometry, a very stable source of electrical power must be provided for the lamp. It is known empirically that, for a typical gas filled tungsten lamp, the light flux is approximately proportional to the 3.4 power of the voltage and the 6.2 power of current [4]. Thus, if it is desired to hold the flux output to within 0.01% of a constant value, then the voltage must be held to within about 0.0029% and the current to within 0.0016%. These are fairly stringent requirements which must be met by the power supply and circuitry over the time of the measurement involved. In some cases this may be several hours. The following material discusses a type of supply and circuit which has been found applicable to the above mentioned requirements.

Lamp current and voltage measurements:

Figure 5 shows a schematic of the circuits which are typically used. If it is desirable to make measurements of the load voltage and current with a potentiometer, in order to assure maximum accuracy, then a voltage divider network or "volt box" and current measuring shunt must be employed. This divider has an impedance which is low enough (typically 750 ohms/volt) that a significant amount of current will be diverted through it from the load. Hence some judgement must be exercised in choosing the location of the current measuring shunt relative to the measurement of the voltage. If the parameter of greatest interest is the voltage across the load, then the position of the current measuring shunt should be as shown in part A of figure 5. Only the voltage divider appears across the load. This is in keeping with good measurement practice since the potentiometer can be at a low potential in this configuration, thus reducing the chance of measurement error due to stray leakage. The current actually measured through the shunt can then be corrected by calculating the amount of current diverted from the load by the voltage divider.

If, on the other hand, the load current is the parameter of greatest interest, then the current measuring shunt should be as shown in part B of figure 5. This will allow a true measure of the current passing through the load, and the voltage measured across the load and current shunt can be corrected by using the known resistance of the current measuring shunt. The inconvenience caused by having to correct for the presence of the voltage divider can be eliminated by using instead a high input impedance digital voltmeter. The impedance of a high accuracy digital voltmeter is typically 10^7 ohms or more; therefore, it will draw negligible current from the circuit.

Another decision to be considered is whether to regulate the voltage across the circuit or the current through it. There are certain advantages and disadvantages to each approach. The well regulated power supplies currently available monitor the voltage across a load impedance using remote error sensing leads. These sensing leads complete a feedback circuit that controls the current or voltage by supplying a small bucking or boosting output. Taking these facts into account, the easiest way to power the lamp circuit is to simply connect it to the supply power output with the remote sensing leads connected directly to this supply output (circuit input) as indicated in part A of figure 5. The error sensing leads were not connected directly across the load, as might at first seem appropriate, because they are active current carrying leads, and connecting them in such

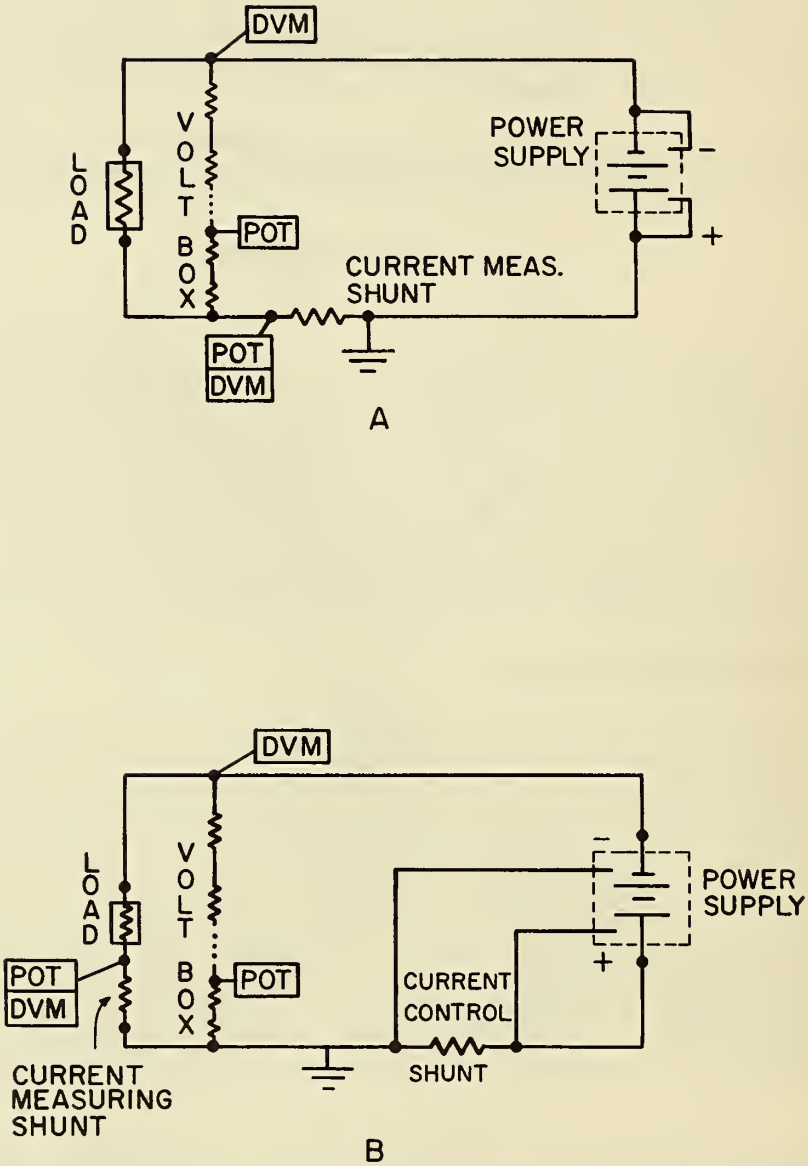

Figure 5. Lamp power circuits: A, voltage controlled; B, current controlled. The locations of the remote sensing leads from the power supply are indicated. The appropriate positions of the "high" lead of the digital voltmeter and potentiometer for the measurement of load parameters are indicated.

a way could conceivably cause errors in determining the actual voltage and current parameters of the load itself.

Because of several factors, for instance, shifting contact potentials at the load terminals due to lamp replacement or load resistance changes (e.g. that of a lamp filament) that are a function of time, it has often been found desirable to regulate the current through the load rather than the voltage across it. This is accomplished by sensing and controlling the voltage drop across a current control shunt which is shown in part B of figure 5. In this case the remote error sense leads are used to maintain a constant voltage across the control shunt. This results in a constant current being supplied to the circuit. More details of this method will be discussed later.

Basically, then, the lamp power circuit consists of a stable power source; a current controlling shunt used with the supply to regulate the current flowing in the circuit; another shunt used to measure the current flowing through the load; a relatively high impedance voltage divider across the load to allow potentiometric measurement of the load voltage; a potentiometer for precise continuous measurement of load voltage or current; and a digital voltmeter for digital measurement and output of these parameters. The location of the electrically "high" measuring leads of the potentiometer and digital voltmeter with respect to ground for measurement of various parameters is indicated in figure 5.

In addition to the above considerations, several more comments on this circuit are in order. First, the location of the system ground is significant. For stable high accuracy and precision measurements, it is desirable to have the potentiometer and peripheral devices properly guarded. Also one side of the potentiometer, voltage divider, and current shunts should be at ground potential to minimize stray leakage currents, as mentioned previously. This is accomplished by the configuration shown in figure 5.

Second, although the power supply used could be operated with both terminals above the ground potential, in the circuit in figure 5 one side is very near ground potential, since the current control shunt is normally only a fraction of an ohm. For the supplies presently used it is preferable to have the positive output rather than the negative one at ground potential, hence the polarity shown was adopted.

Third, the current shunts must be overrated so that they will not heat up and change resistance values at the current levels used. Low temperature coefficient shunts (<30 ppm/°C) with a power rating at least ten times that actually required are desirable.

Fourth, a four terminal system with separate leads for voltage measurement should be used throughout the circuit.

Finally, the potentiometer, voltage divider, and digital voltmeter should be guarded and of reasonably high quality, capable of precisely measuring at least five significant digits.

<u>Stable DC power supplies</u>:

Using the apparatus described above with loads of a size typically encountered in our experimentation, the Kepco Series JQE power supplies were found for our purposes to give adequate regulation in both the current and voltage modes, and the Hewlett-Packard Harrison series performed similarly in the voltage mode. In order to maintain some versatility in the maximum voltage and current output capability, two supplies are used together in parallel for higher currents and in series for higher voltages. The output of this type of supply can be remotely programmed with a variable resistance. In order to run two of the supplies together in the manner referred to above it is preferable to program only one and have it control the other supply. This is often called the "master/slave" combination. Some difficulty was initially encountered in determining how best to run these supplies in the "master/slave" configuration in series and in the current regulating mode, but after some experimentation the arrangement shown in figure 6 was settled upon. The details of how these supplies operate can be found in the manufacturer's handbooks and operating manuals.

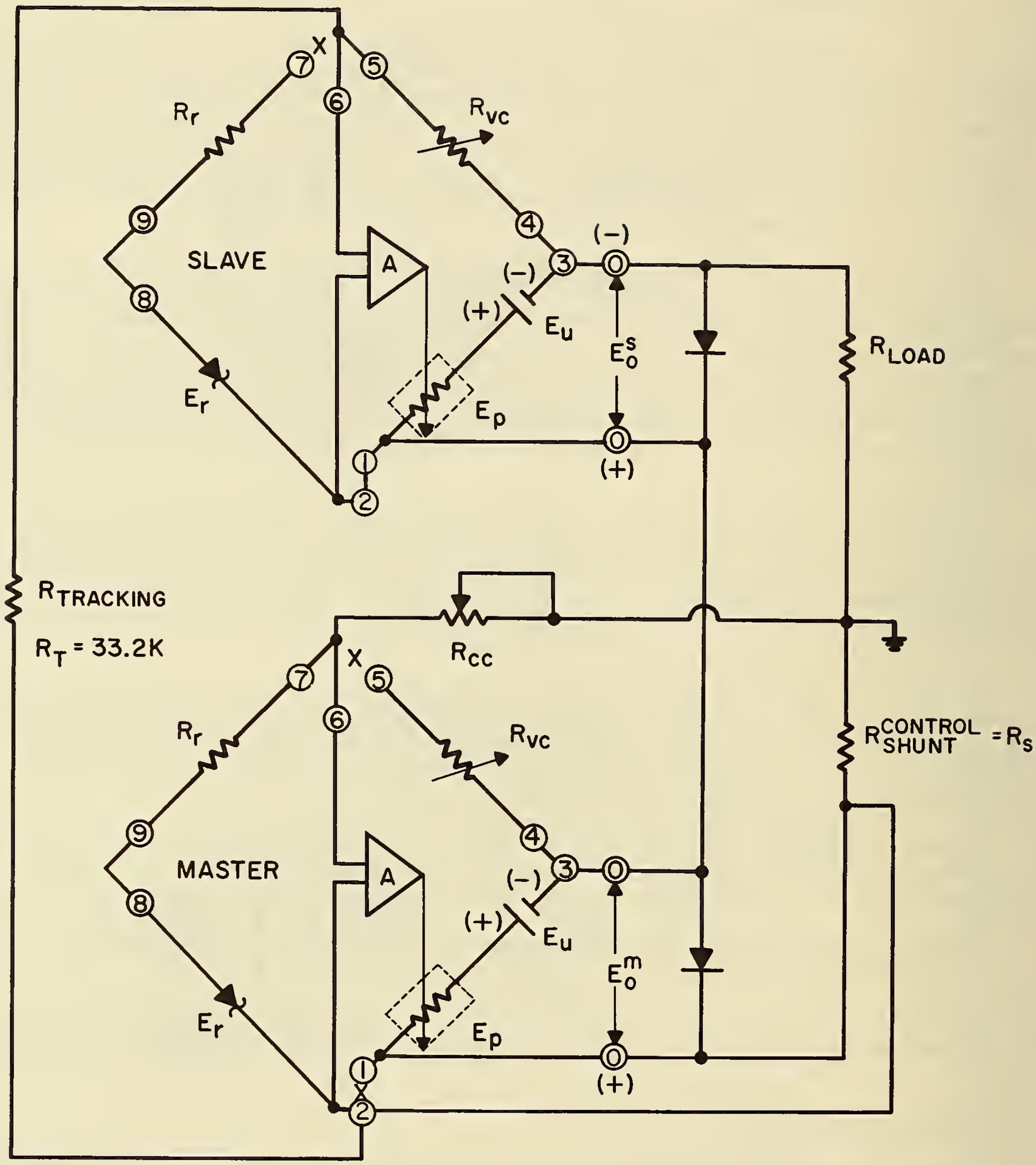

Figure 6. Lamp power supply circuit, master/slave, constant current, series configuration using Kepco JQE series power supplies. The bridge circuits are internal to the power supplies and the numbered circles represent the external connections on the instrument. (See the manufacturer's instruction manual for more information.)

For the Kepco power supplies used in our experiments, R_s, the current control shunt, was chosen such that at maximum current about an 0.5 volt drop occurs across it. The current control, R_{cc}, a 0-500 ohm potentiometer in our case, should be a high quality, low temperature coefficient device. The voltage output of the slave supply is equal to that of the master supply multiplied by the ratio of the slave supply voltage control resistor, R_{vc}, to the tracking resistance, R_t. Since R_{vc} is 60 KΩ, R_t was chosen about 30 KΩ, so that with the R_{vc} of the slave supply set at about the halfway position, both supplies contribute equal amounts of power. The power ratio can be altered at will by adjusting R_{vc}. It is apparent that R_t should also be a high quality resistor. Two diodes are placed across the individual supply outputs to protect them against possible transient reverse potentials. This provides a harmless bypass for any reverse current. Each diode, of course, must have a reverse breakdown voltage greater than the maximum voltage output of the power supply. The diodes should be able to carry the maximum short circuit current that the power supplies are capable of producing. It is advisable to use not only heavy power leads, but also heavy shielded sense and control leads to minimize stray noise pickup.

The supplies and circuit described have been used to regulate current through resistive loads typical of tungsten lamps at maximum supply voltage capability and approximately half maximum current capability. Under these conditions, the degree of regulation is about one part in 10^5 over a period of about fifteen hours. Performance appears to be degraded somewhat at higher current output levels. The system is capable of regulating in the voltage mode at all levels of output to the order of one part in 10^5 for periods of twelve hours. The circuit has proven to be stable, versatile, and convenient for automation, particularly when using the digital voltmeter. The potentiometer is useful to maintain a check on the digital voltmeter calibration and to provide simultaneous and continuous analog monitoring of any desired parameter in addition to the digital measurements of the voltmeter.

2.3 Mechanical Instrumentation

Optical bench enclosure and baffles:

Two Ealing Double Rail optical benches are presently in use in photometric research: one is 3m and the other is 5m long. Each optical bench is mounted on hardwood surfaced laboratory benches that have been bolted to the floor. The bench tops are covered with black suedine cloth (manufactured by Vertipile, Inc., type FF8-7184) and the cloth is held in place around the outside edge of the table by iron strips one inch wide.

Bolted to the table top at each corner is a channel-frame column (such as Unistrut or Globestrut) 40 inches high. These four columns support a channel-frame rectangle which spans the length and width of the table. This structure serves as a support for the baffles and for the materials which form a light-tight enclosure. The baffles are hung from wheel assemblies which roll inside the length of the channel. Black suedine covered aluminum sheets cover the top of the enclosure and several sets of black drapes about 30 inches wide cover the sides. The drapes are made of a double thickness of the black suedine material, back to back, with a sheet of black polyethylene between them. Strip magnets are sewn into the material around the edges of each drape to hold it closed against the iron strip along the table edge and against thin, suedine covered iron sheets about 8 inches wide hung in the spaces between the drapes.

By housing the optical bench with magnetically secured drapes, each section of the bench is made independently and rapidly accessible. In addition to being opaque, the drapery material is of very low reflectance in order to minimize scattered light. The baffles are made of aluminum sheet cut to fit within the channel-frame enclosure and covered on both sides with the suedine cloth. The cloth extends about one inch on the sides of each baffle to meet with the drapes which billow slightly. Several different size baffles are used and since the baffles clip onto the movable wheel assemblies they can be easily inserted, changed or moved to new positions.

Optical bench alignment:

The optical benches have been mounted on their respective table tops in a kinematic manner. The procedures used may be generally useful and will therefore be summarized for one (5m) of the benches.

The 5m bench has eleven supporting posts each having two leveling screws as shown in figure 7A. Each supporting post rests on an 8" × 1¼" × ¼" aluminum supporting plate. One of the leveling screws in each of the four supporting posts located at the ends and adjacent to the center of the bench has a conical tip. These tips rest in three Vee grooves and a round hole in their respective supporting plates as shown in figure 7B. The remaining leveling screws have round tips or bottoms and rest on flat portions of the supporting plates.

The optical bench was aligned relative to the optic axis defined by the beam from a one milliwatt He-Ne laser in the following manner. The laser was mounted on a channel-frame platform separate from the structure which encloses the optical bench. It was then aligned so that the beam would pass through the center of a baffle hung anywhere within the channel-frame enclosure; the track in which the wheel assemblies rolled having previously been made horizontal with the aid of a spirit level. The optic axis is approximately 15 inches above the optical bench rails.

The optical bench was then made level along both the long and short horizontal directions using a spirit level. Leveling was started at the center support posts and progressed out to the ends. This procedure had to be repeated several times to make the optical bench approximately level along its entire length. All the screws holding the optical bench together were then loosened and gradually retightened. The bench was allowed to rest in this new position overnight and releveled the next day.

The optical bench was then brought into position relative to the laser beam with the aid of two pointed rods mounted in carriers with fixed position stems. The height of the rods was adjusted so that the points were at the center of the laser beam. The optical bench was then positioned so that these two rods could be moved anywhere along the bench and still intersect the beam. The optical bench was then fixed in place by bolting the three supporting plates having grooves and the one having a hole to the table top. This alignment procedure resulted in no discernable twist along one half of the bench and 0.2° to 0.3° twisting between the support posts along the mating half[2]. The distance between the laser beam and the bench rails was constant to within 1 mm.

Lamp orientation mounts:

Three different lamp mounts, based on two different design principles, have been used for the rotational positioning of the lamps relative to the optic axis. In one design, rotation is accomplished by pivots that are colinear with the three axes of rotation; whereas in the other design two curved surfaces sliding against each other provide rotation.

In the first design category, the mount employed was originally used to position radiance standards. A sketch of this mount is shown in figure 8. It is very similar to a pair of gimbals with one-half of the circle cut away. Two pillars attached to the base support the outer pivots. This pair of pivots forms a horizontal axis to allow a pitch rotation; that is, a rotation about an axis perpendicular to the optic axis. The semicircular ring attached to these pivots is held almost horizontal by a section of a 7½-inch radius worm gear which extends down to engage a worm screw.

The semicircular ring has an inside diameter of 7 3/4 inches. It contains a third pivot which allows a rotation around the optic axis (roll rotation). The axis of this pivot is perpendicular to that of the first two. A platform 7 inches in diameter is attached 8.75 inches below this pivot by means of a vertical metal strip. The platform is fixed to the axis of a gear and worm assembly identical to the one used for pitch rotation.

The third rotation around the vertical axis (yaw rotation) is accomplished by a small turntable, Unislide Model A2504TS, mounted on the platform. The lamp socket is then mounted on this turntable and the height adjusted so that the three axes of rotation intersect at approximately the center of the lamp filament.

The relative pitch and roll angles could be read to a resolution of one minute of arc

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[2]The 5m bench was shipped in two sections.

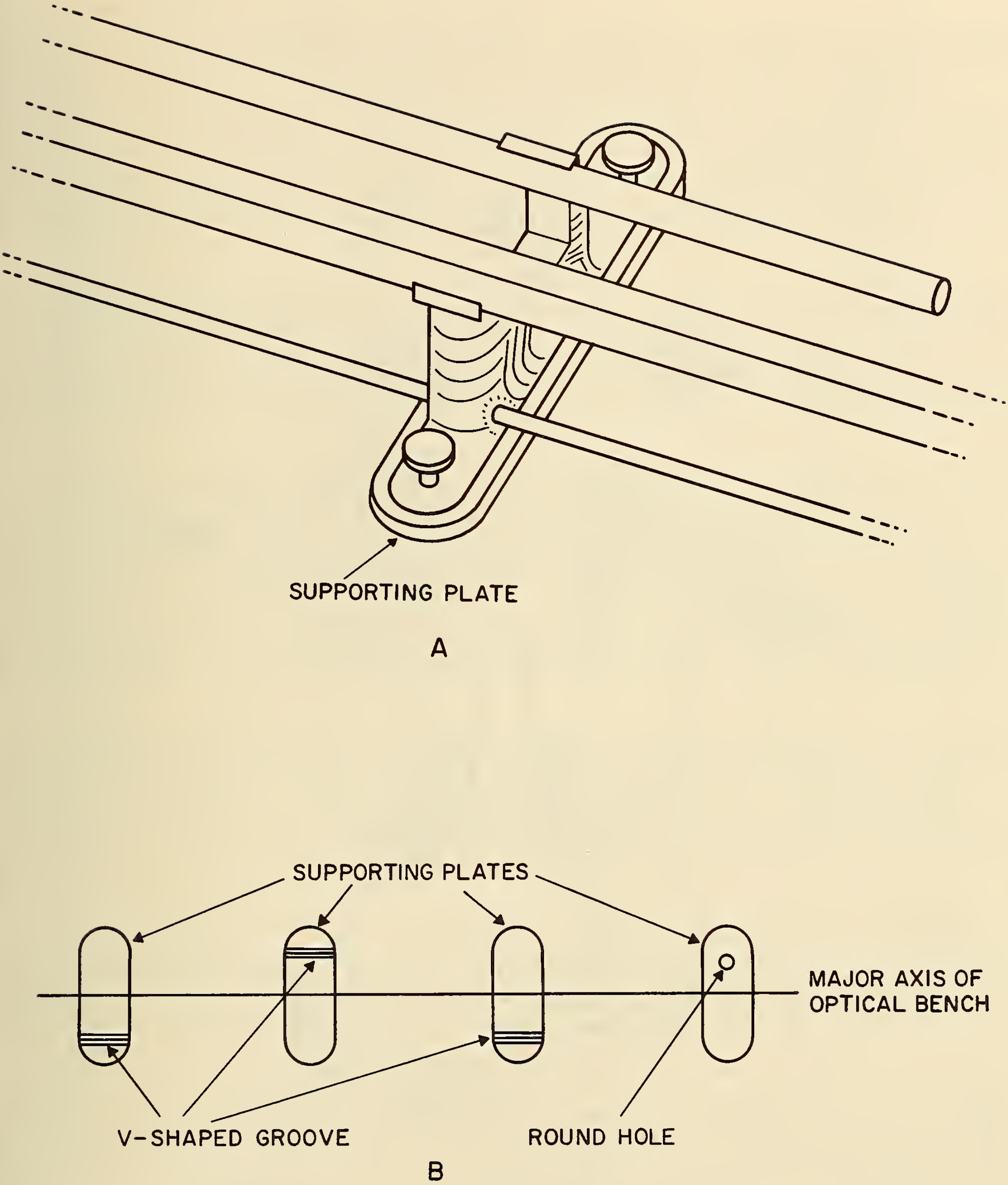

Figure 7. Optical bench: A, optical bench support post with leveling screws on flat plate; B, schematic diagram of optical bench. Only the three plates with vee grooves and the one with a hole, all of which mate with the conical support screws, are shown. The flat plates with round tipped screws are not shown but are situated between these four supporting plates.

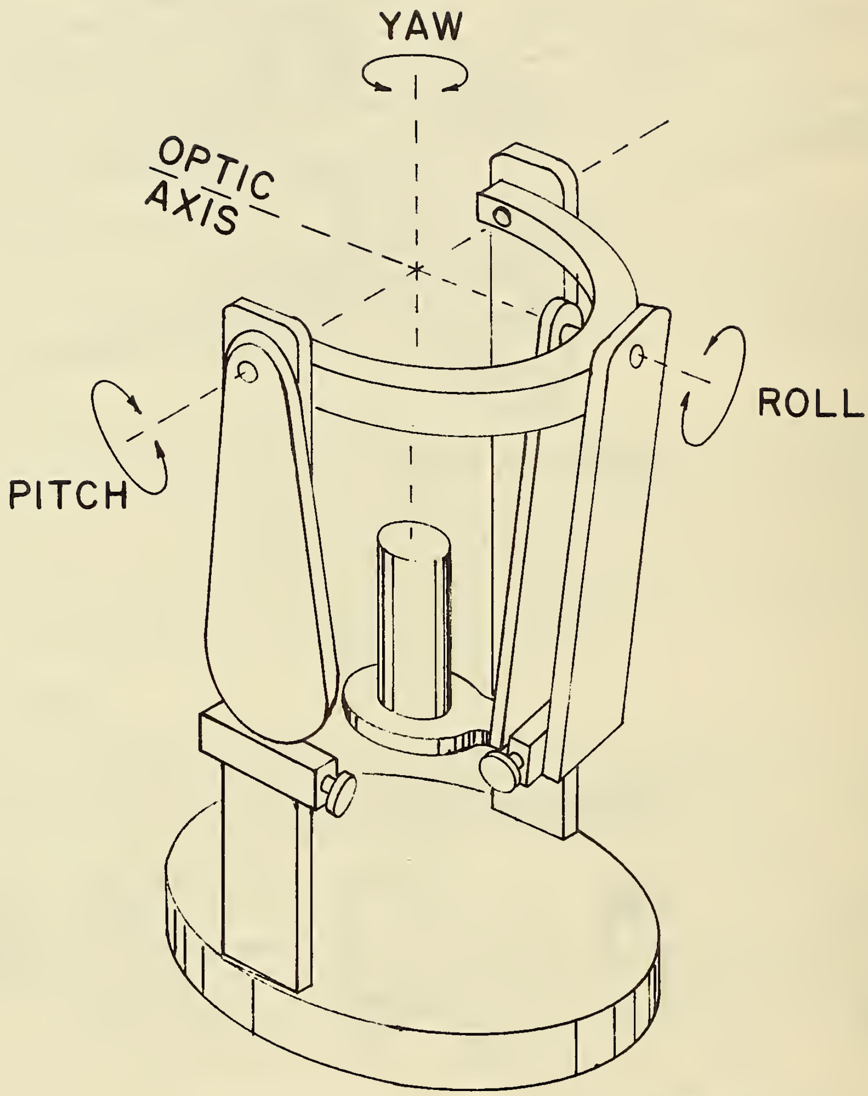

Figure 8. Radiance Lamp Mount.

from scales attached to the worm drives, and the yaw angle could be read to a resolution of six minutes of arc from a scale on the turntable. This mount performed well in reproducing the lamp orientation in pitch and roll; however, some care had to be taken in repositioning the yaw angle because of the lower resolution of this adjustment and the lightweight character of the turntable. This objection is, however, outweighed by the scattered light problem posed by the presence of the lamp mount structure around the sides and in back of the lamp. This is especially critical in an intensity or irradiance measurement since the entire lamp, and hence part of the lamp mount, is viewed by the detector. This mount has, however, proved quite useful in studying the variations in lamp intensity as a function of orientation and in other experiments where only relative measurements are needed. For convenience, this mount will be referred to as the "radiance lamp mount".

In order to eliminate the problem of scattered light from the lamp mount, two mounts based on the sliding surfaces principle were designed and constructed. One of the mounts consisted of a convex spherical section sliding in a mating concave spherical section, the other was a cylindrical section sliding within a mating section. The axis (or axes) of rotation is (are) then through the center of the cylinder (sphere). Since only a small section of the cylinder or sphere is used, there are no mechanical supports around the lamp to scatter light into the detector.

A cross sectional view of the sliding sphere mount is shown in figure 9. The radius of the spherical surface was 8 inches and the diameter of the section (platform) was 8 inches. Four thumbscrews (only one pair is illustrated) are mounted symmetrically on the outside block; that is, along two perpendicular lines. These screws pushed against the inside spherical surface along two directions parallel to the spherical tangents. This produced a rotation either around the optic axis (roll) or around an axis perpendicular to the optic axis (pitch). The screw lengths and positions chosen allowed about a 10° rotation in pitch and roll. The yaw rotation was accomplished by means of a small turntable as described in the previous mount. As in the previous mount the socket height was adjusted so that the center of the lamp filament was at the intersection of the three axes of rotation.

In order to read the pitch and yaw variations on this mount, a small mirror was affixed to the lamp socket and the beam from a one milliwatt He-Ne laser was reflected from it to a scale on the laboratory wall. The laser beam was approximately four inches below and parallel to the optic axis. With this device the relative rotations could easily be determined to a resolution of better than 0.1°. No measurements of roll variation were made with this mount and, therefore, no provisions were made for the measurement of roll angle. An optical lever similar to the one used to measure pitch and yaw could have been constructed for this purpose.

The main advantage in using a sliding sphere mount is the elimination of scattered light from the lamp mount itself. On the other hand, the main disadvantage is the difficulty encountered in making an adjustment. This is due to the many degrees of motion possible with a sphere. For example, in the adjustment of pitch,the yaw angle might change slightly because the motion was not firmly constrained to be only around the pitch axis.

This difficulty in maintaining alignment prompted the design of a third mount based on a cylinder sliding in a cylinder. The rotation is, of course, constrained to be around a unique axis and all orientation adjustments can be made below the lamp socket. The sliding cylinder mount has been adopted for use in the luminous intensity calibrations performed at NBS. However, since it was not used in any of the experiments described in this paper and since it is an obvious modification of the sliding sphere mount, further discussion of its construction will be omitted.

Lamp alignment:

The lamp mounts were aligned relative to the laser beam on the optic axis. That is, the roll axis was adjusted to be colinear with the optic axis and the pitch and yaw axes were adjusted to be at right angles to the laser beam: this set the zero position of all three rotations. In order to locate the axes perpendicular to the optic axis a pentaprism [5] was employed. The pitch and roll axes on the radiance lamp mount were located by means of small holes through the center of the pivots. In the cases where the pivot was not on the axis, a solid object was set on the lamp mount to intercept the beam. The

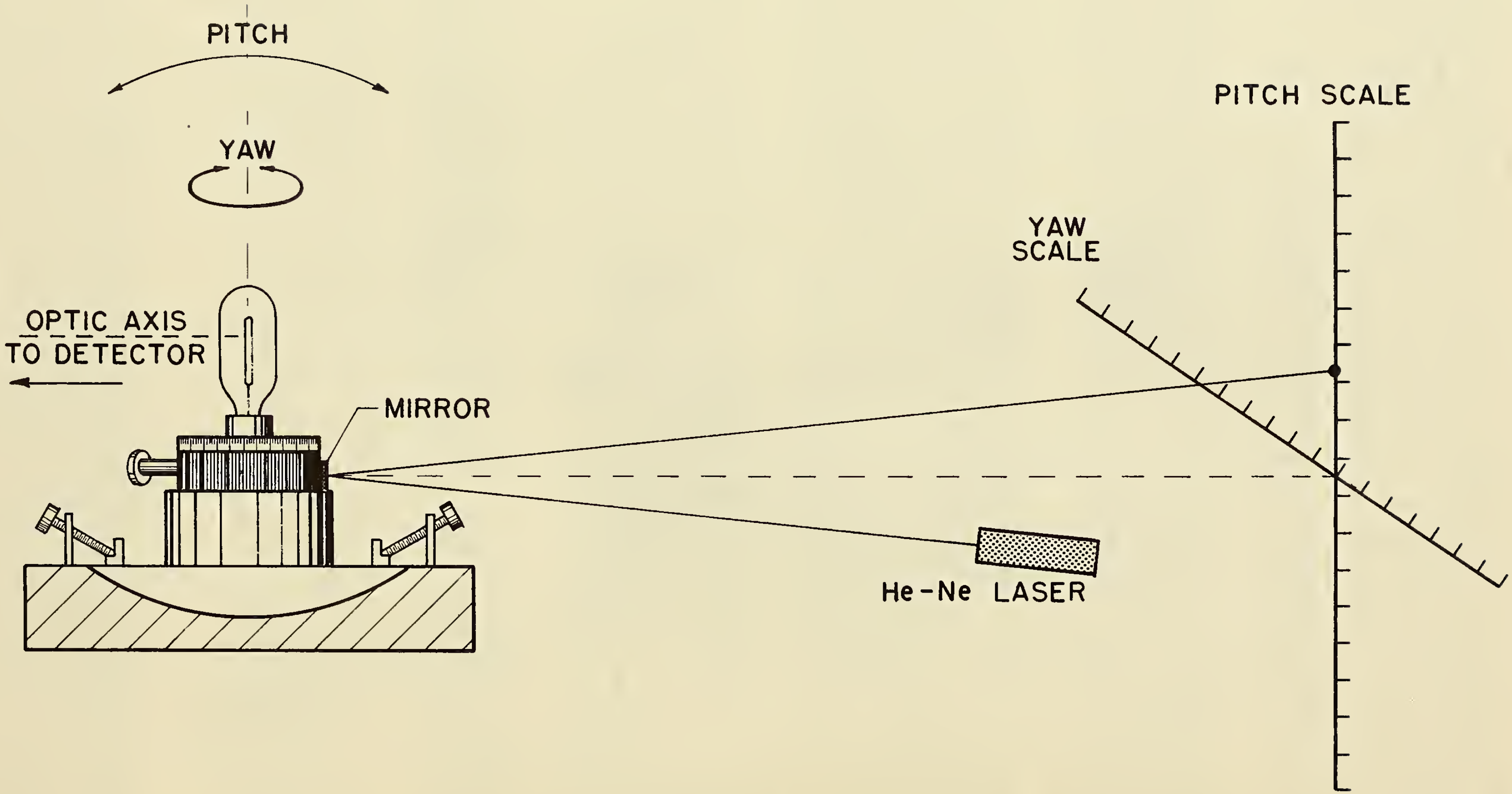

Figure 9. Sliding sphere mount.

object was then rotated about one of the rotation axes and the mount position adjusted until the laser spot appeared stationary.

As a slight digression it should be noted that in these several lamp mount designs the three axes of rotation are not all independently adjustable. For example, in the radiance lamp mount and in the sliding sphere mount, a variation of the pitch angle away from the zero position rotates both the roll and yaw axes away from their original orientation. Furthermore, in the radiance lamp mount rotation of the roll angle does not alter the direction of the pitch axis, whereas, in the sliding sphere mount it does. Therefore, at some higher level of accuracy it may not only be important to specify the lamp orientation relative to the optic axis but also the device on which the lamp was oriented in the process of calibration. Since the experiments described in this paper are only relative measurements and not absolute calibrations, the transferability of lamp orientation does not pose a problem at present.

After the lamp mount has been aligned relative to the optic axis, the detectors and the lamps themselves must be aligned to the same axis. In these experiments no attention was paid to the precise orientation of the detectors and only their position on or near the optic axis was noted. On the other hand, the effects of orientation on the lamp output was studied and in this case two methods were used to locate or reference the lamp orientation.

The first method has been employed in photometry for many years: it is a visual sighting technique which employs a plumb line, fiducial lines etched on the bulb and the filament supports within the bulb. The shadows of the filament supports and the plumb line projected on the laboratory wall were made coincident to set the zero of pitch alignment. (Note that this does not necessarily correspond to the zero of alignment for the lamp mount.) Next the lamp was rotated to bring the fiducial lines into alignment with the optic axis. This was done either by sighting through the bulb to the detector or by using the laser beam. This method is not compatible with frosted bulb lamps or with the radiance lamp mount.

The other method involves prealignment of the lamp socket before insertion of the lamp. In this case the lamp base must be of mechanically sound construction so that it can be reproducibly reinserted into the socket. The lamp base that satisfactorily fits this purpose is a medium bipost base. The pins are 1/4 inch in diameter, at least 3/4 inches long and are spaced 7/8 inches apart. As will be seen, a kinematically sound and compact socket can be constructed to reproducibly reposition lamps with these bases.

In this technique the socket is prealigned by using a pair of parallel 1/4 inch diameter rods which fit in place of the lamp. Fixed parallel to the rods is a mirror to reflect the laser beam onto the laboratory wall. This yields a measurement of the pitch and yaw orientation of the socket. Alternatively the socket can be positioned to coincide with the zero setting of the lamp mount. In addition, the use of a jig to align the socket allows a precise distance measurement to be made to the plane formed by the two rods rather than to an inaccessible point within the lamp bulb.

Lamp sockets:

The medium bipost socket used in all the experiments described in this paper consists of two silver plated 3/8 × 1 1/8 × 1 1/4 inch blocks mounted on a piece of transite. The lamp pins fit into holes in the blocks and are held by horizontally placed screws. Electrical connections are made directly to the block by means of separate screws. One of the metal blocks is mounted on the transite by means of a pivot to allow for bulb expansion. These sockets are manufactured by the Elastic Stop Nut Corporation, Model 1985-AL.

Because the lamp base pins are held against the walls of a cylinder, this socket reproducibly maintains the pitch and roll alignment of the lamp. However, the yaw alignment is not maintained since one of the blocks can rotate. The following socket was designed to eliminate this deficiency. Although it was not used in any of the experiments described in this paper, its design was prompted by the results of some of them. Therefore, a description of it is included here.

Two views of this socket are shown in figure 10. The lamp pins are held by spring

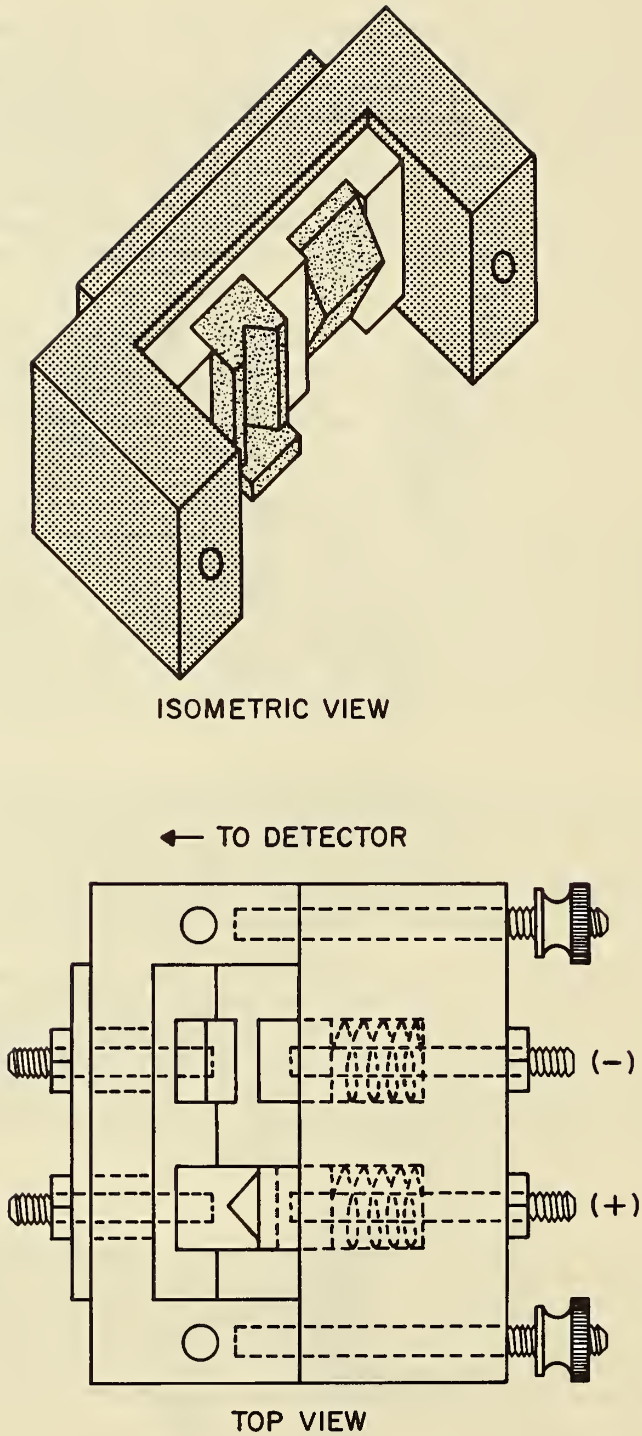

Figure 10. Kinematically designed lamp socket.

tension against two stainless steel blocks. One of the blocks has a Vee groove terminating in a flat plate. By holding one of the lamp pins against this groove and flat, the pitch, roll and lamp height can be maintained when the lamps are replaced in the socket: providing, of course, that the same pin is placed in the groove each time. The other stainless steel block is cut from hexagonal bar stock to form a roof shaped piece. When the socket is closed the pin is held against the "peak of the roof", thereby fixing the yaw rotation and still allowing the lamp base to expand.

The lamp pins are held by two gold-plated copper "pistons", and the pistons are held under tension by coiled springs inside the nylon block. The two outside screws shown protruding from the nylon block serve to close the socket. The remaining four screws hold the stainless steel blocks and the copper pistons in place and serve as electrical connections.

The convention that has been adopted in the use of this socket is depicted in the figure. That is, the Vee block is the positive electrode and the lamps are viewed by the detector from the side of the socket containing the Vee block. In this direction, that is, looking at the lamp from the detector position, the Vee block is on the right.

3. Experimentation

3.1 Flux Lamp Stability Tests

Introduction:

In the Fifth International Intercomparison of Photometric Units, lamps of a special type [6,7] were used to represent the various national laboratory units of luminous flux at a color temperature of 2788 K (IPTS-48). They were full wreath filament clear bulb, gas filled lamps. This intercomparison showed these lamps to be relatively stable. The present work was undertaken to evaluate further these lamps as possible standards of luminous flux.

The 200 watt lamps of this type are designed to operate at 95 volts and have a rated life of 1,000 hours at this voltage. For the International Intercomparison the lamps were seasoned for 120 hours at the voltage necessary for 2788 K operation (approximately 95 volts), and had their bases plated with a nickel cadmium alloy. For the present test 24 uncalibrated lamps were procured from GEC, England. These 24 lamps were received with unplated brass bases and had been seasoned for 20 hours at 95 volts. Subsequently several lamp bases were plated with either pure nickel, nickel cadmium, or silver. The measurements then consisted of reading the total luminous flux of the various lamps, set consecutively at current and at voltage, every 5 burning hours after an initial seasoning of 40 or 60 hours (including the 20 hours seasoning performed by the manufacturer).

Experimental techniques and equipment:

The lamps were seasoned on regulated AC: six lamps at 102 volts (approximately CIE source A) and 8 lamps at 95 volts. The luminous flux measurements were made after 10 minutes warm-up with the lamps operated on DC in a 2 meter integrating sphere by a substitution method. A blue glass filter (Corning 5900) was used to reduce the effects of non-uniformities in the sphere wall spectral reflectance. The photometer detector was a Weston selenium barrier-layer photocell equipped by the manufacturer with a filter [8] which modifies the spectral response to approximately match the CIE luminous efficiency function [9]. In order to reduce the errors due to self absorption of the lamps, a standard (NBS 8380) of the same type and manufacturer was used. This standard had been previously calibrated including absorption correction as part of the international comparison. The standard was run at the beginning and end of each set of measurements to check for drifts in the photometer.

During seasoning the test lamp voltages were set on a moving iron AC voltmeter (3/4% accuracy class). The 2 meter diameter integrating sphere was coated with Burch sphere paint. The detector was a hermetically sealed, viscor corrected Weston barrier layer cell (Model 856, YYLSV). The detector photocurrent was measured with a commercial operational amplifier. The lamp voltage and the current, and the operational amplifier output were read on a digital voltmeter (.003% accuracy).

Results:

The results of the experiment are shown in figures 11 and 12. For each of the test lamps the data is normalized to the first measured value of total luminous flux. In each case for the first reading only, the lamps were set at voltage and readings taken of the flux and current. Subsequently the lamps were set at both voltage and current, as indicated in the figures and flux measured for each setting. Lamps NBS 9135 and 9136 were not measured at current until 135 hours of burning. Lamps NBS 9138, 9139, 9140 and 9143 suffered a filament failure at 85, 75, 90 and 70 hours, respectively.

Conclusions:

The figures vividly demonstrate the superiority of setting lamps of this type by current rather than voltage. All of the lamps set at voltage showed a steady decrease in flux output. This decrease was typically at the rate of 1% per 40 hours of burning. In contrast the lamps set at current increased slightly or held constant within the precision of the measurements. Previous experience has shown this equipment to have an overall precision level of about 1/4%. As the figures indicate, this was about the precision level of the present experiment. Figure 12 indicates that the lamps should be seasoned for at least 50 hours before initial calibration.

In the limited time period covered by this test no particular effect due to base plating material was noted. In the long run, it would be expected that plating with materials such as nickel-cadmium would offer more corrosion resistance than plain brass.

The occasional out-of-pattern point present in most of the lamp curves is probably due to variation in the experimental technique, and no particular significance should be attached to these points. The distinct shift in the flux values at 170 hours for lamp NBS 9135 run at current is in a different category. The cause of this shift is not known at this time and is particularly hard to explain since the shift is not mirrored in the flux values measured at voltage. It is unlikely that the shift is due to changes in the sphere or electrical measuring setup since other lamps measured on the same run in the same apparatus do not show a corresponding pattern. Shifts of this kind emphasize the desirability of running more than a single standard at any given time.

The lamp failures noted above present a problem. Three out of the six lamps run at 102 volts failed. Although the lamps were designed to operate at 95 volts, the manufacturer states he knows of no reason why they could not be run at higher voltage with, of course, a corresponding reduction in life. He further states that this test is the only one he knows that has shown this effect. In each case the failure was one of filament breakage. It would appear that some critical parameter has been exceeded and hence high failure rates can be expected at this voltage. We have decided to use these lamps only at color temperatures of 2788 K or lower.

It should be noted, particularly since the manufacturer states our experience is unique, that these tests were conducted on a limited sample from a single production run and may not be indicative of the performance of similar lamps from other production lots.

3.2 Orientational Dependence of Relative Luminous Intensity

Introduction:

In the calibration of the intensity or irradiance from a lamp, it is obviously important that both the direction in which the lamp is viewed and the lamp orientation be specified. This is necessary simply because a lamp is a nonuniform source [10,11]. The magnitude of the nonuniformity and consequently the extent of the possible error in the calibration of the lamps used as standards at NBS has not been documented in sufficient detail. The study that will be reported here was, therefore, carried out in order to get a more detailed picture of this effect and to identify the cause.

The terms used in this paper to describe the three orientational degrees of freedom

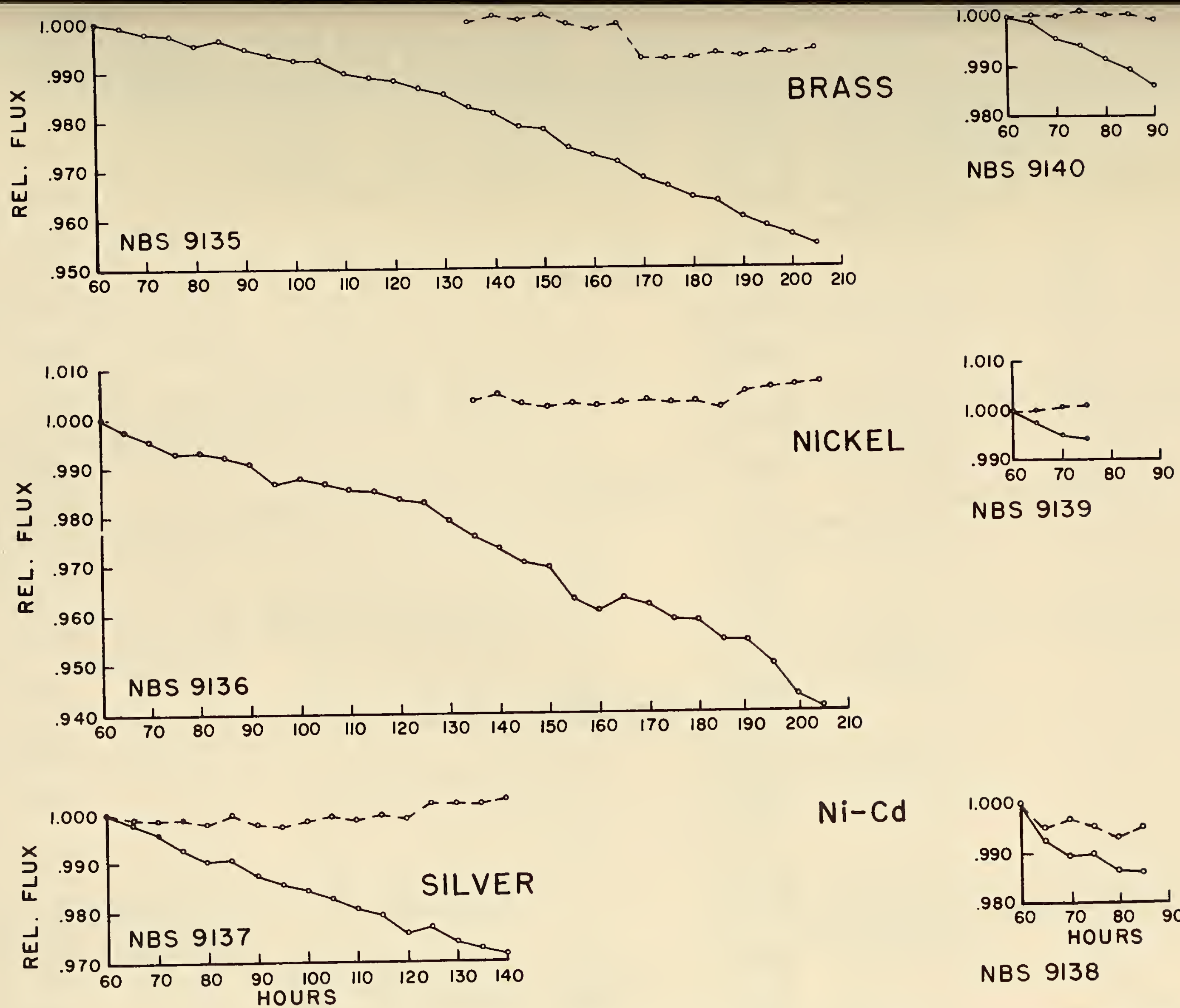

Figure 11. Total luminous flux output stability of 200 watt flux lamps run at 102 volts. In all cases, the lower curves indicate the flux readings made after setting the voltage. Where it occurs, the upper curves represent flux values read after setting the current. Elements indicate the lamp base plating material used.

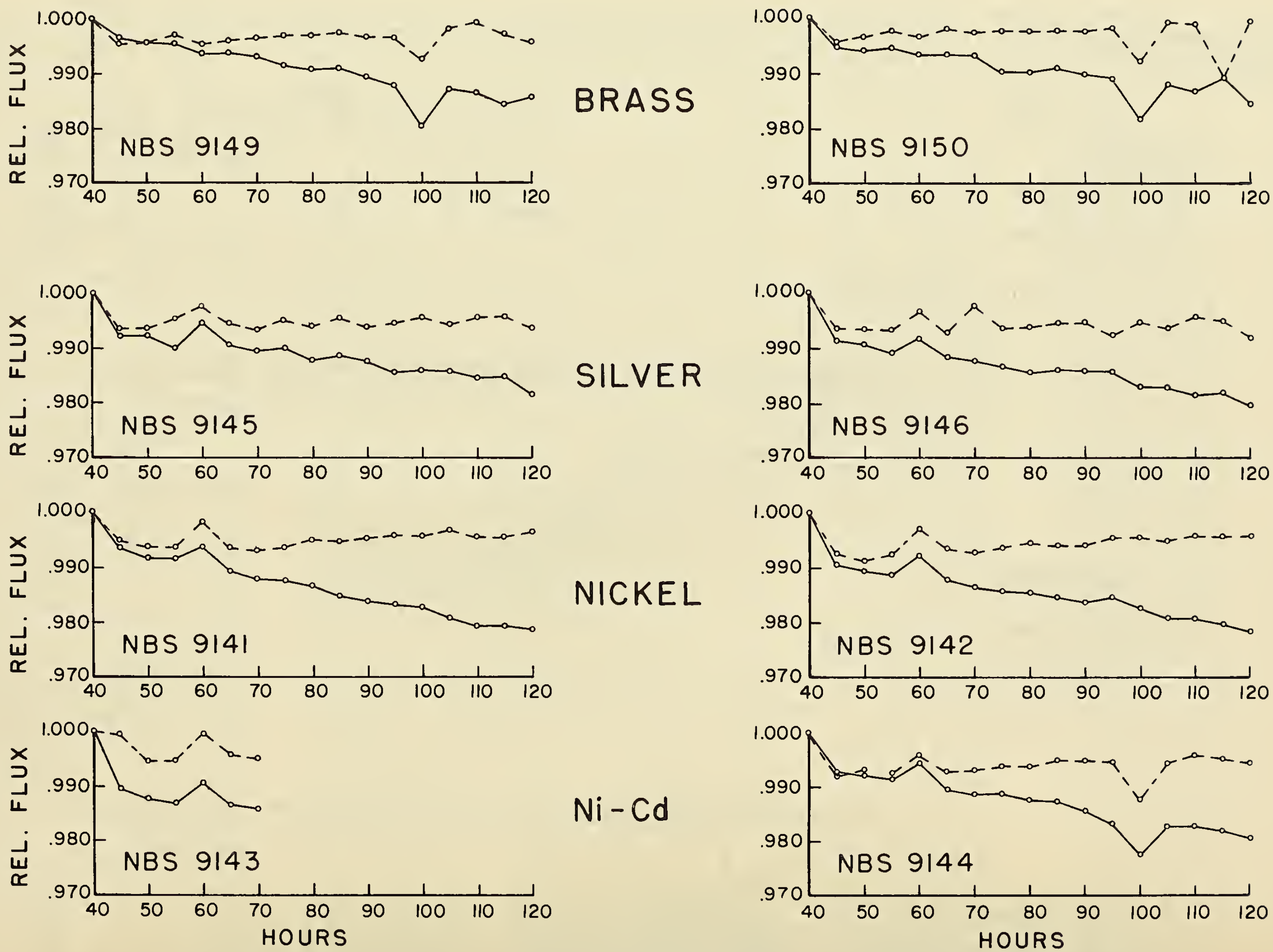

Figure 12. Total luminous flux output stability of 200 watt flux lamps run at 95 volts. In all cases, the lower curves indicate the flux readings made after setting the voltage. Where it occurs, the upper curves represent flux values read after setting the current. Elements indicate the lamp base plating material used.

are the nautical terms: pitch, roll and yaw. They were introduced in the discussion of the lamp mounts. Results for three different types of lamps will be given here. They are (1) 500 watt clear T-20 bulb (2½ inch diameter, tubular), medium bipost lamps with C-13 filaments (single coil with 7 or 9 supports in a monoplaner "W" configuration). (2) 100, 300, 500 and 1000 watt frosted bulb, medium bipost, C-13 filament lamps. The 100, 300 and 500 watt lamps of this type had T-20 bulbs and the 1000 watt lamp had a T-24 (3 inch) type bulb. (3) Tungsten-halogen lamps with a CC-8 type filament (coiled-coil supported only at the ends) and a 3/4 inch diameter, tubular, clear quartz envelope. Lamps of type 1 and 2 have been in use at NBS as standards of luminous intensity and type 3 as standards of spectral irradiance.

Equipment:

All the lamps were seasoned for 2% of rated life at rated volts. The photometric and electronic equipment used were described earlier. However, the detector amplifier for most of the measurements was a commercial DC current to voltage converter feeding into a five digit integrating digital voltmeter. For the pitch and yaw measurements of the clear T-20 bulb, C-13 filament lamps the sliding sphere mount was used. For all other measurements, the radiance lamp mount was used. In both these setups, the angles could be measured with a resolution of at least 0.1°.

Photopically corrected [8] selenium barrier layer cells and uncorrected silicon photodiodes were used as detectors. The results from both types of detectors were identical and, therefore, their specific instance of use will not be identified. The source to receiver distance was typically 2.5 to 3 m and the detector diameters ranged from 0.5 to 4 cm.

Results and discussion:

Figure 13 shows the variation of the relative intensity with the pitch and yaw angles for the clear bulb C-13 filament lamps. Four different detectors were used simultaneously. To obtain these plots a correction was made for the detector position relative to the optic axis. The most striking feature of this figure is the large variation of the intensity with the pitch angle: on the steepest part of the slope the intensity changes by as much as 2% per degree. Over a greater range the curve somewhat resembles a sine wave (see figure 17). This pitch dependence appeared to be common to all the lamps of this type that were measured. The positions of the maxima varied from lamp to lamp falling approximately in the range ±2° from the aligned zero position (relative to the plane of the filament supports). The relative intensity versus yaw angle plot in figure 13 is also typical of the lamps studied. However, there did not appear to be a correlation of the peak intensity with the aligned zero position and the curves did not appear to have a pattern over the range studied. The steepest slope was about 0.5% per degree. On studying the effects of different roll positions on the luminous intensity for these kinds of lamps, the effect could not be detected at the 0.2% level of the noise.

Figure 14 shows the pitch versus relative intensity plots for the 100, 300, 500 and 1000 watt inside frosted bulb, C-13 filament medium bipost lamps. The effect follows approximately a cosine curve, as shown by the solid lines. The total variation of output is almost 0.5% over the range covered and appears to be independent of the lamp size. At the 0.2% level of the noise there were no discernable effects due to a change in the yaw or roll angles over a range of ±5°.

The pitch and yaw variation of a typical CC-8 filament lamp is shown in figure 15. The lamps were operated with the filament in a vertical position, that is, the axis of the coil was vertical. The results for these lamps very nearly resemble those for the clear bulb C-13 filament lamps, except that in the region near the peak of the intensity versus pitch curve for the CC-8 filament lamps there is a slightly greater flat region. The yaw variation also appears to be smoother in the case of the CC-8 filament lamps. These are subtle differences, however, and a larger number of lamps would have to be examined before any general conclusions can be drawn.

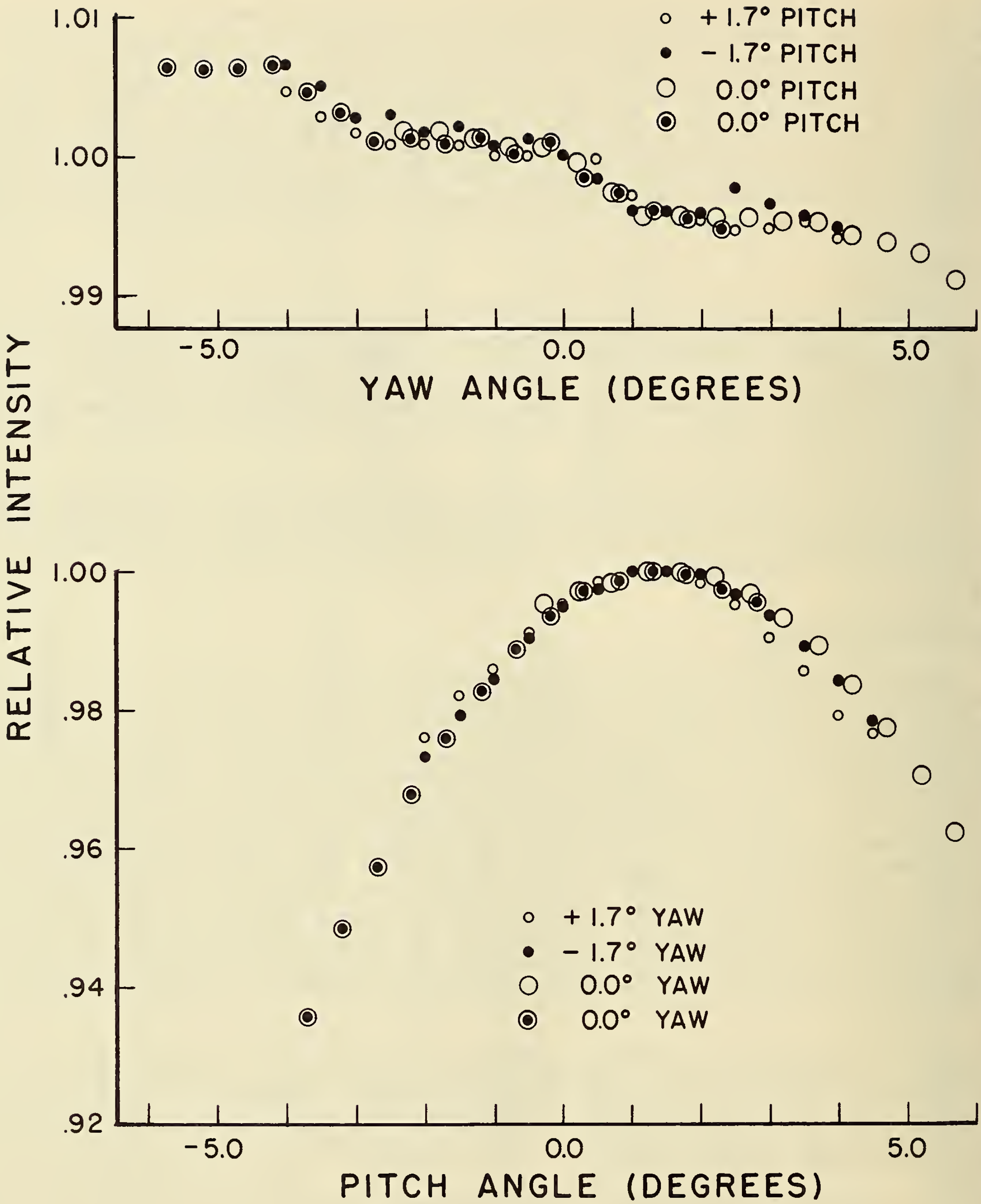

Figure 13. Orientational dependence of relative luminous intensity for clear bulb C-13 filament lamps. The different point symbols indicate measurements made by four separate detectors of intensity versus pitch dependency at several yaw angles and intensity versus yaw dependency at several pitch angles.

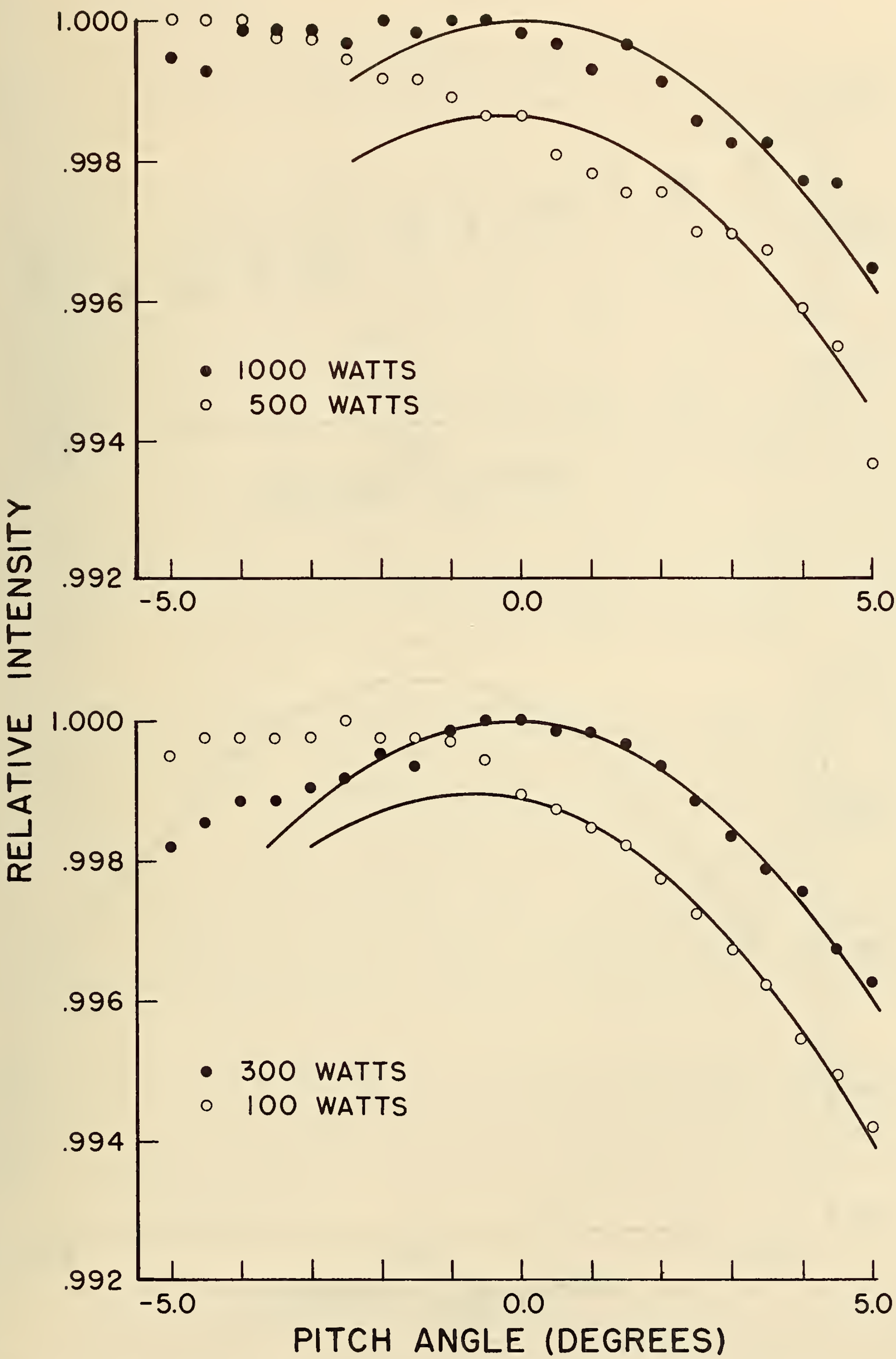

Figure 14. Relative luminance intensity versus pitch dependence of inside frosted C-13 filament lamps. The solid line indicates theoretical intensity versus pitch dependence for a perfectly diffuse cosine law emitter.

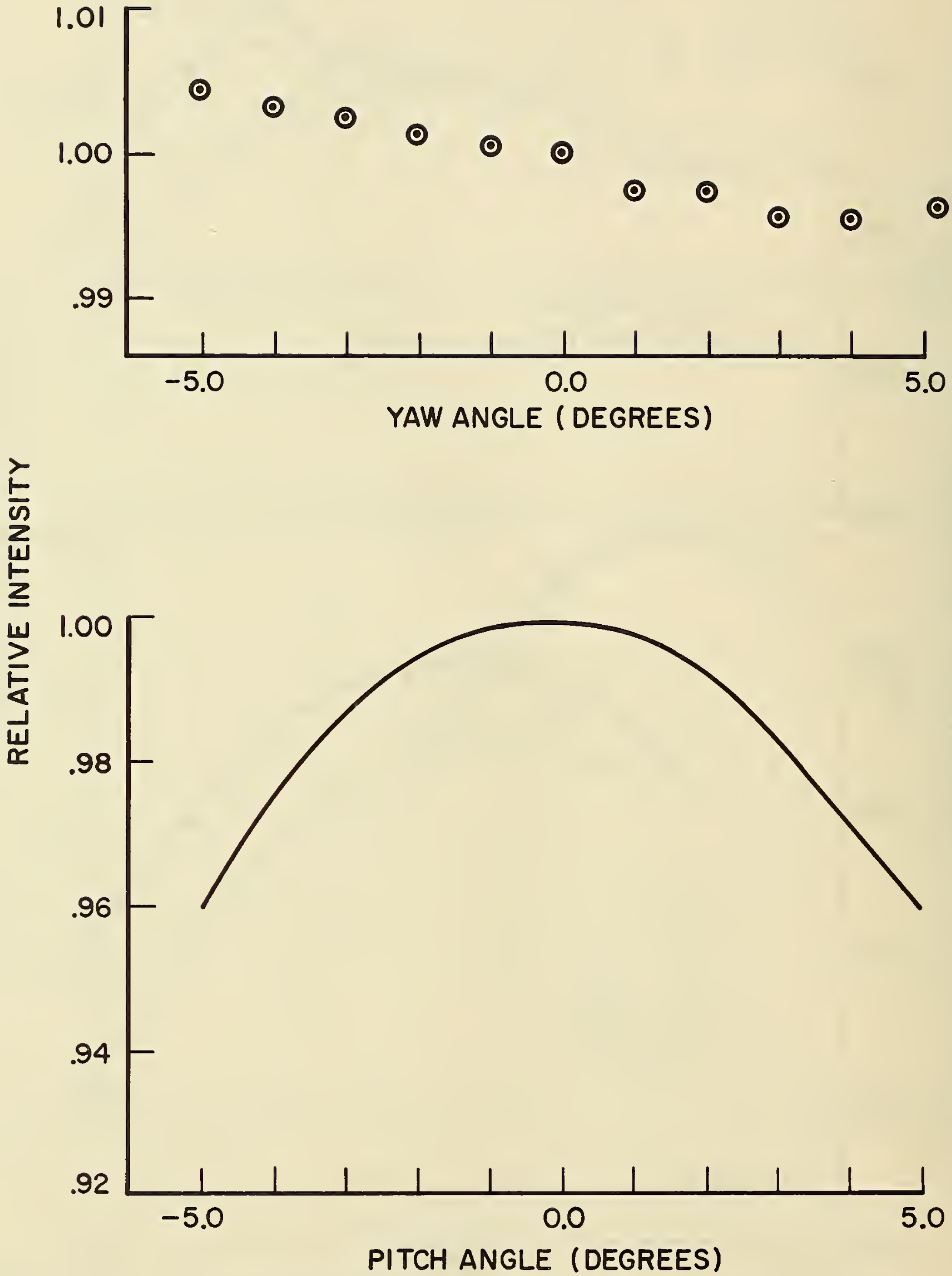

Figure 15. Orientational dependence of relative luminous intensity for CC-8 filament clear bulb quartz halogen lamps.

The origin of this effect:

Having established the order of magnitude of the orientation effect on the luminous intensity of these lamps, two experiments were performed to disclose the sources of the effect. The coiled structure of the lamp filament and possible lens effects due to striations in the envelope seemed to be the most probable causes of a nonuniform distribution.

In the first experiment a group of three lamps was obtained which had specially designed filaments. These filaments were essentially C-13 filaments except that they were not monoplanar. The two horizontal rods which hold the filament support pins were set at about 45° instead of being parallel to each other. This filament design was motivated by the suspicion that the pitch effect in regular C-13 filament lamps is due to the shadowing of the rear part of the filament by the front part. This kind of shadowing is inevitable in a coiled filament. If all the segments (lengths between support pins) of the filament are in the same vertical plane, as they are in regular C-13 filaments, then the extent of shadowing at any particular pitch angle is almost the same for each segment of the filament. The contributions of the individual segments of the filament to the pitch dependence therefore add up or, as one could say, "interfere" constructively to give a large pitch dependence for the whole lamp. In the non planar C-13 filament design used in the special lamps, one would expect the pitch dependences of the different segments of the filament to peak at different pitch angles. These dependences would thus combine in such a way as to yield a more flat pitch dependence curve for the lamp as a whole. Pitch dependence curves were run for the three lamps of this type. Figure 16 shows a typical pitch dependence curve. Here the pitch dependence on the steepest part of the curve is less than 1% per degree change in the angle: approximately half of the slope in the curve of the monoplanar C-13 filament. This leads to the conclusion that most of the effect is due to the shadowing effect of the filament coils, and the fact that in a regular C-13 filament the different segments of the filament are in the same plane.

In the second experiment an attempt was made to obtain an estimate of the contribution to the pitch effect due to the striations in the glass envelope. Two clear bulb lamps with C-13 filaments and noticeably striated bulbs were used. The pitch variation of the intensity was first measured. Then the glass envelope was cut vertically almost to the base. One half of the envelope was cut away and the remainder was left attached to the base of the lamp and the filaments were removed. These lamps were placed in front of and as close as possible to a frosted bulb lamp that had been totally masked except for a small rectangular area. This area was of approximately the same dimensions and at the same height as the filament in the original clear lamps. The frosted bulb lamp was kept in a fixed vertical orientation and only the sliced glass envelope was moved. A frosted bulb lamp was used to simulate the filament because of the possible interactions between the striations of two clear glass envelopes. Figure 17 shows the pitch dependence of the lamps before they were sacrificed and of their glass envelopes afterward. The variation due to the envelope is about 1% over a 10° interval.

As a final note, figure 18 depicts one of the more extreme examples of intensity variation as a function of pitch rotation. The slope is about 10% per degree at the steepest points. Such variations were observed on a few of the clear bulb, C-13 filament lamps studied. It has been suggested that this behavior is due to the planarity and straightness of the several coils in the filament. If this is true then it is ironic because of the natural inclination to choose the most symmetric and apparently defect-free lamps for possible standards.

Conclusions:

There are two conclusions that may be drawn from these experiments. The first is in regard to the amount of orientation control necessary in order to reproduce the luminous intensity output of clear bulb C-13 and CC-8 filament lamps. If no attempt is made to set the lamp at a position of zero gradient in pitch and yaw and if the pathological cases such as the one shown in figure 18 are eliminated, then the greatest pitch gradient one might encounter would be of the order of 2% per degree. Similarly, the greatest yaw gradient expected would be about 0.5% per degree. Therefore, in order to reproduce the intensity or irradiance to about ±0.1% based on orientational considerations alone, the

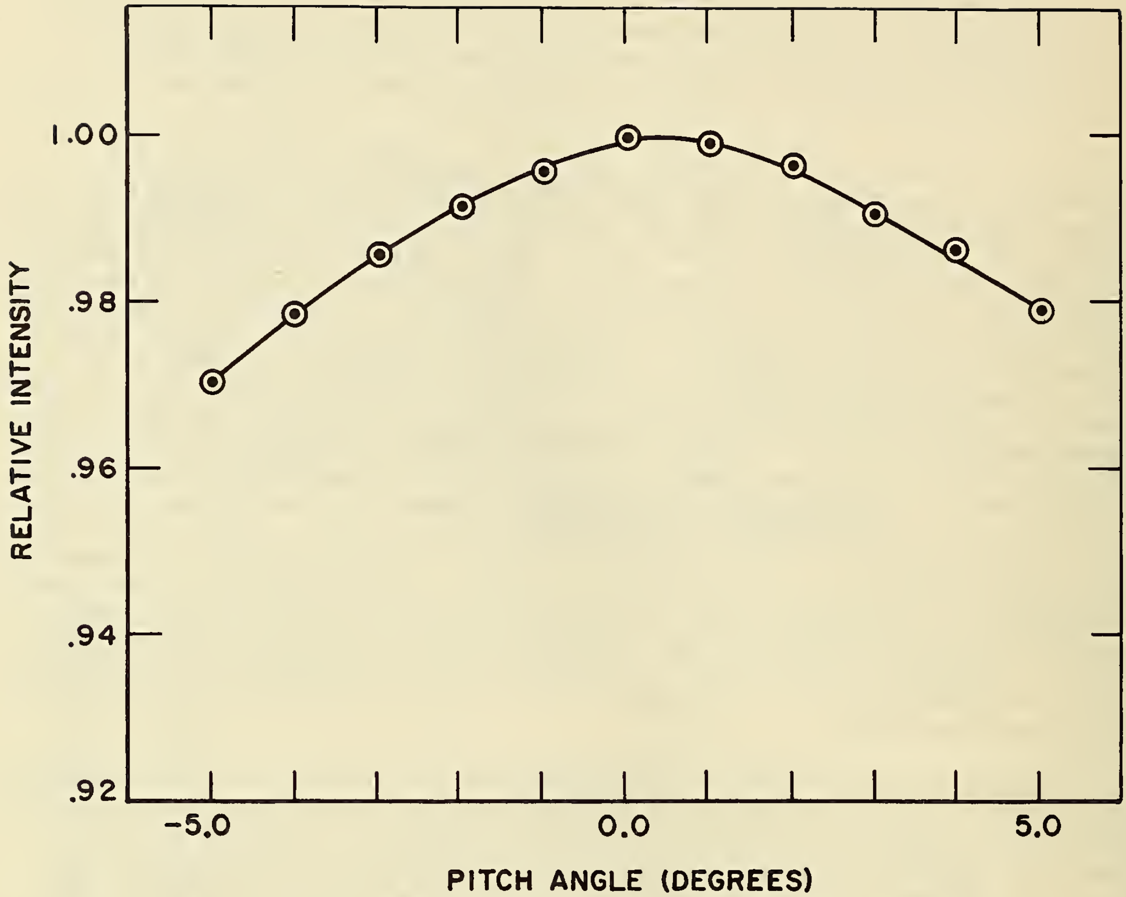

Figure 16. Relative luminous intensity versus pitch dependence for special nonplanar filament clear bulb lamp.

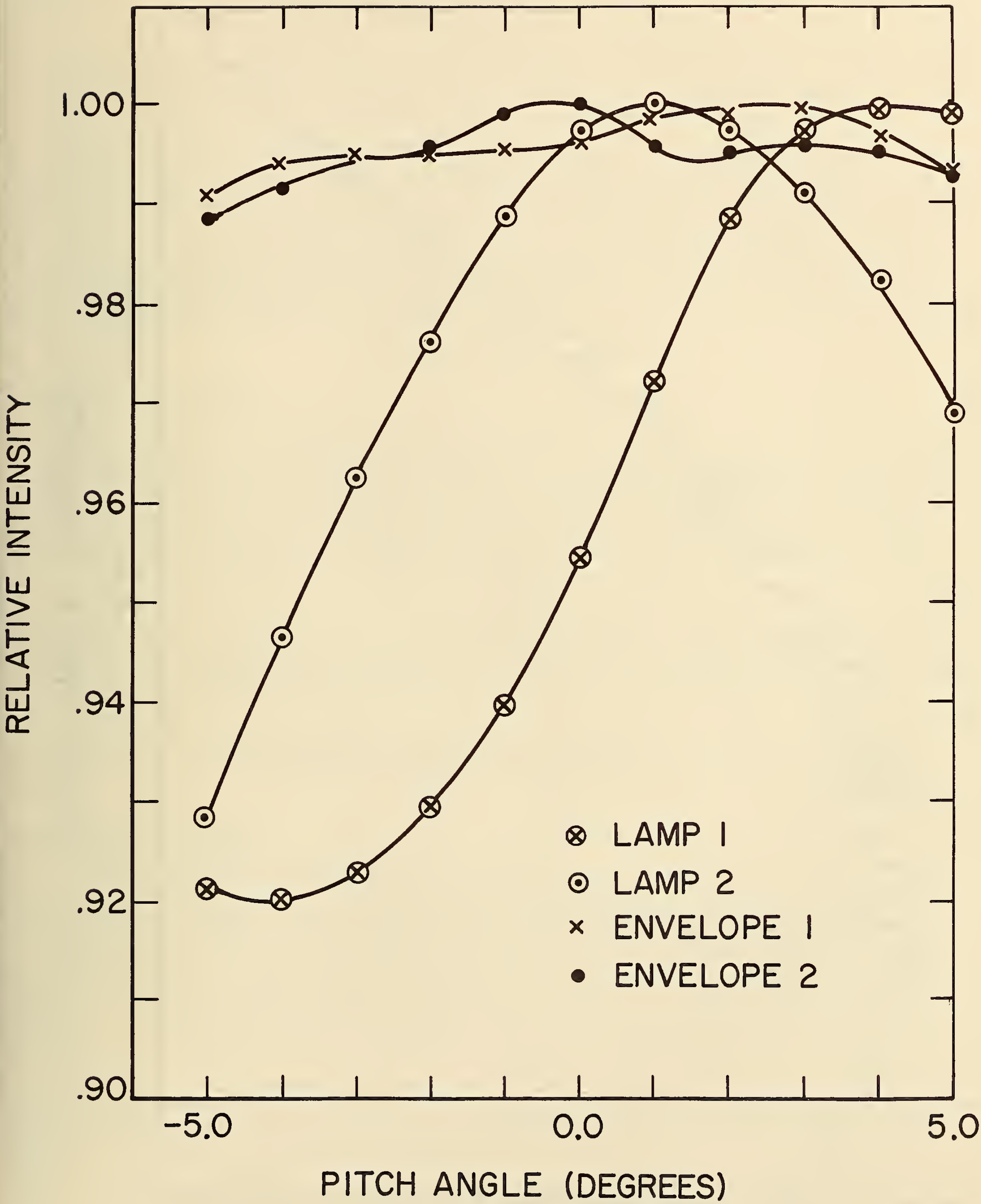

Figure 17. Contribution of glass envelope striations to relative luminous intensity versus pitch dependence.

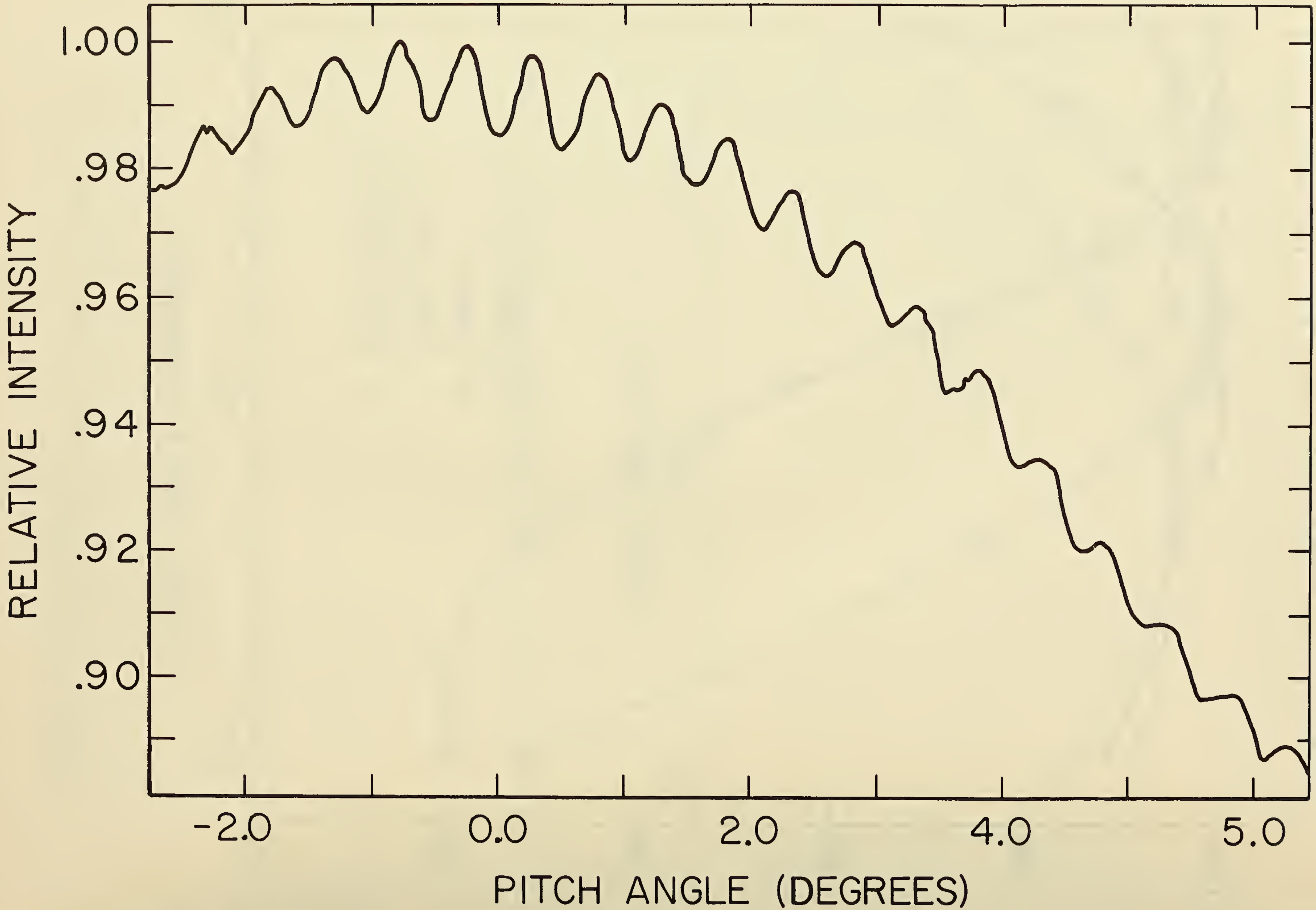

Figure 18. Extreme example of relative luminous intensity variation as a function of pitch rotation. The pitch angle subtended by the detector was about 1/4°.

pitch realignment must be less than ±0.05° and the yaw realignment must be less than ±0.2°. For the frosted bulb lamp the pitch realignment must be within ±0.5°.

The second conclusion is that in clear bulb lamps the major contribution to intensity variation is due to the coiled structure of the filament. The contribution from bulb striations is smaller by about a factor of ten.

Taken together, these two conclusions lead to a choice of a frosted bulb lamp as a standard lamp because of the looser restrictions on orientation. Two objections can be raised against such a choice. First, the realignment requirements quoted above were for the case of the largest pitch and yaw gradients. The lamps can be oriented to a position of almost zero gradient in both rotations in order to relax these requirements. Second, the use of a large source, such as the frosted bulbs, introduces a greater error in the assumed inverse-square law behavior of intensity standards. The last objection to the use of frosted bulbs can, of course, be eliminated if the source to receiver distances are large compared to the size of the source and the detector.

3.3 Intensity Lamp Stability

Scope of the experiment:

This experiment, as originally conceived, had several purposes. The main thrust of the measurements was to evaluate the reproducibility of six lamps of a type that have been used as standards of luminous intensity at NBS. The lamps were obtained from two manufacturers. Of the four lamps from manufacturer A, two were selected at the factory for quality of appearance (e.g. filament centered and vertical, envelope uniform, etc.), and two were obtained through normal commercial channels. The two lamps from manufacturer B were selected at the factory for quality of appearance.

The lamps were checked for relighting reproducibility in two ways. In one series of measurements they were relit after a cool-down period but were otherwise undisturbed. In another series the lamps were removed after cool-down and then replaced in the socket before relighting. In addition to the relighting reproducibility measurements, the lamps were run continuously for sixteen hours to check drift.

Besides monitoring lamp voltage, current, and the output from four different detectors during each run, the temperature was checked at four positions along the optical bench. Finally, this experiment served as a "shakedown cruise" for much of the equipment described earlier.

Equipment and procedures:

The lamps studied were 500 W, clear bulb, medium bipost, C-13 filament, gas filled lamps. They were seasoned for 2% of rated life at rated voltage (10 hours at 120 V AC). During each measurement run the voltage was set at 85.000 V as read on a five digit integrating digital voltmeter. The voltage was maintained by two Hewlett-Packard model 6274A DC power supplies set up in a master-slave, constant voltage, series configuration. The lamps were mounted in the commercial socket described earlier. Although this socket was affixed to the radiance lamp mount, the lamps themselves were not reoriented for each run because of the additional time it would have taken. The reproducibility of orientation depended, therefore, primarily on the socket.

The digital voltmeter mentioned above had remote programming capability and BCD readout. The voltmeter was controlled by a data acquisition system and its output was recorded on punched paper tape by this data system. The data system also had the capability of switching the inputs to the digital voltmeter.

Temperature was monitored with four thermocouples positioned within the optical bench enclosure. One thermocouple was set about one-half inch away from the back of the lamp bulb and another was set about twenty inches in front of the lamp and about ten inches below the optic axis. The thermocouple nearest the lamp was used to indicate the realization of a thermal steady state condition. The thermocouple below the optic axis indicated the approximate ambient temperature in that section of the enclosure containing the lamp.

The other two thermocouples were positioned to read the approximate temperature change of the detector mount and the approximate ambient temperature near the detector. These thermocouples were switched directly into the digital voltmeter via low-noise (< 5μV) reed switches in the data acquisition system.

The four detectors were all about the same distance from the lamp and were held symmetrically around the optic axis in a single mount. Two of the detectors were photopically corrected selenium barrier layer cells and the other two were uncorrected silicon photodiodes. The detectors were obtained from four different manufacturers. The detector outputs were switched into the current to voltage converter (first version design) via one set of switches in the data system and the output of the converter was switched into the voltmeter via a different switching circuit board in the same system.

About halfway through this experiment one of the selenium barrier layer cells failed and was replaced with a similar cell. Unfortunately during the process of changing this detector, the entire mount was moved and could not be returned precisely to its original position. This meant that the two series of measurements on each lamp could not be compared to the same initial detector readout.

Voltage was sensed at the lamp socket and current was measured with a resistor in series with the lamp. Both of these signals were fed into the voltmeter via the data system.

In the repeatability measurements, the lamps were run for thirty minutes before relighting or replacing. All ten measurements described (that is, lamp current and voltage, four temperatures, and four detector outputs) were taken sequentially by the data acquisition system once each minute during a run. During the sixteen hour run, the same data readout sequence was initiated every twenty minutes. The readout sequences were initiated by a clock in the data system itself. The time during each sequence was also recorded on the punched paper tape readout.

Results and discussion:

No significant temperature changes occurred during the short runs except for the thermocouple nearest the lamp. There was a temperature increase of this thermocouple which could be correlated with the lamp warm-up measured in terms of either the increase of the detector output or the filament resistance as a function of time. Temperature changes recorded during the long runs could not be correlated with the other changes in the system.

The detector outputs were noisier (±0.1%) than had been expected. It was later found that this noise was definitely in the current to voltage converter and could be reduced by connecting the operational amplifier common to ground. This was pointed out earlier in the discussion of the construction of these current to voltage converters. Because of this problem it was difficult to compare the relative noise or relative signal differences to less than ±0.1% in the output of each detector. Excepting the output of a failing selenium detector, the relative outputs of the four detectors were identical within the limiting noise band. That is, any output trend shown by a given detector followed that of the other three detectors. It was therefore assumed that the observed changes above the noise were most likely due to the lamps.

Voltage during each run was stable to ±0.002%. Between each run the voltage setting was reproduced to within ±0.005%.

The lamp output variations are summarized in the table. This table was compiled using the output of only one of the four detectors, since their outputs were all identical within the limit of ±0.1%. The "warm-up" is the time required for the detector output variations as a function of time to decrease to within the noise limit. The columns labeled "repeat" are the differences between the averages for the first and second 30 minute runs and the first and third 30 minute runs for each lamp. The averages were taken over the 15 minute time interval extending from the 10 minute to the 25 minute point of each run. Finally, the column entitled "average drift over 10 min." is the difference between the output averaged over the 5 minute intervals between 10 to 15 minutes and 20 to 25 minutes of each run.

TABLE I.

Lamp Repeatability Experiments

		Relit in Place			Repositioned			
Lamp Number	Manufacturer	Warm-up (min.)	Repeat (%)	Average Drift over 10 min. (%)	Warm-up (min.)	Repeat (%)	Average Drift over 10 min. (%)	Sixteen hour drift (% hr^{-1})
1-70	A selected	8	-	+0.04	8	-	+0.02	-0.008
		9	+0.05	0.0	7	-0.20	+0.03	
		7	-0.08	-0.02	7	-0.18	+0.11	
3-70	A selected	*	-	-0.04	12	-	-0.09	+0.020
		*	+0.14	+0.24	9	-0.61	-0.05	
		*	+0.08	-0.06	13	-0.60	+0.01	
9160	A unselected	22	-	+0.19	10	-	+0.10	+0.029
		11	+0.14	+0.02	8	+0.23	+0.13	
		9	+0.21	+0.02	8	-0.39	+0.13	
9162	A unselected	10	-	-0.12	8	-	+0.06	+0.024
		10	+0.16	-0.03	8	-0.16	-0.06	
		7	+0.06	-0.02	8	-0.19	-0.01	
9100	B selected	11	-	+0.06	11	-	+0.10	**
		10	-0.07	-0.04	8	-1.05	+0.03	
		13	-0.01	+0.01	7	-0.47	0.0	
9102	B selected	8	-	+0.03	7	-	-0.03	+0.004
		9	-0.08	-0.12	9	+0.11	-0.01	
		9	-0.08	-0.03	9	+0.05	-0.02	

* Lamp never stabilized below amplifier noise

** -7.4% discontinuity observed during this run

Conclusions:

Several conclusions can be drawn from the table. First, there is definitely a difference in the repeatability of "in-place" and "repositioned" relightings. This was attributed to the lamp socket design because of, first, the inherent inability of this type of socket to reproduce the lamp orientation and, second, the findings of the lamp orientation experiments of the last section. The kinematic lamp socket design described earlier in this paper was shown to be a definite necessity by this experiment.

Second, it appears as if the inherent repeatability of the lamps given by the "in-place" results is of the order of 0.1%. It must be remembered that this is at the level of the amplifier noise and cannot be entirely attributed to the lamps themselves. The inherent lamp repeatability remains a quantity to be evaluated by further experimentation.

Third, the average warm-up time for this type of lamp (and voltage) is about ten minutes and in almost all cases is less than fifteen minutes by a safe margin.

Fourth, there are a disturbing number of large drifts of the output (0.1% or greater) even after the lamp has warmed up (e.g., the second run of lamp 3-70, the first run of lamp 9160, etc.) indicated in the "Repeat, In Place" column. Again this is close to the noise limit but appears to be a real effect and merits further study.

Fifth, the tendency of the lamps to drift to higher output at constant voltage is inconsistent with a simple model of tungsten evaporation leading to higher filament resistance. This may be taken to mean that the lamps have not been fully seasoned; however, other effects such as thermal etching [12] could account for this tendency. The data from this experiment are insufficient to determine for these lamps the adequacy of the "2% of rated life at rated voltage" seasoning schedule typically used in photometry. However, they do point out the need for additional measurements to answer this question.

Finally, there does not appear to be a significant difference between the lamps of the two different manufacturers or between the "selected" and the "unselected" lamps. Although this is a very limited sample, it does mean that perhaps one type of lamp (for example a specific filament or bulb geometry) may be found to be more stable than another type. It also means that lamps selected for quality of appearance do not necessarily perform well.

4. Conclusion

The electronic and mechanical instrumentation has performed well thus far and will probably not be a limiting factor in our experiments in the near future. The problems that require immediate attention were indicated in the last experiment. They can be classified under two headings: detector characterization and lamp characterization. The limitations introduced into the calibrations by the lamp and detector reproducibility and drift need to be determined. Among other things a study of the detector linearity and spectral response must be undertaken.

The stability and reproducibility of lamps and detectors is presently being studied. Work on the other problems confronting luminous intensity and geometrically total luminous flux calibrations is planned. The fact that there is light has been established in the early literature [13]. The question of how much light there is, however, still remains with us.

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16. ABSTRACT (A 200-word or less factual summary of most significant information. If document includes a significant bibliography or literature survey, mention it here.)

This document was written primarily to serve two purposes. First, some of the basic instrumentation which has recently been developed for use in photometry at NBS is described. The design and application of photodetector amplifiers, lamp power circuitry, and mechanical instrumentation are discussed. Second, three photometric experiments are described: the stability testing of some flux lamps and intensity lamps and the determination of the dependence of relative intensity on orientation. These experiments and their conclusions have proven useful in pointing out areas which need further investigation and in planning the directions of future work.

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