Precision Measurement and Calibration

Optics, Metrology, and Radiation

Handbook 77 — Volume III

United States Department of Commerce
National Bureau of Standards

UNITED STATES DEPARTMENT OF COMMERCE • Frederick H. Mueller, *Secretary*
NATIONAL BUREAU OF STANDARDS • A. V. Astin, *Director*

Precision Measurement and Calibration

Selected Papers on

Optics, Metrology, and Radiation

A compilation by Sherman F. Booth of previously published technical papers by the staff of the National Bureau of Standards.

Issued in three volumes*

I. Electricity and Electronics.
II. Heat and Mechanics.
III. Optics, Metrology, and Radiation.

National Bureau of Standards Handbook 77—Volume III

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Abstract

This Handbook is a three-volume compilation of approximately 150 selected papers previously published by the staff of the National Bureau of Standards on precision measurement, calibration, and related subjects. It was prepared to meet the urgent need of newly established standards laboratories for a "textbook" and reference source in these fields. Volume I contains papers in electricity and electronics; Volume II, heat and mechanics; and Volume III, optics, metrology, and radiation. Each volume contains a complete index of the entire Handbook by author, subject, and title.

Foreword

The National Bureau of Standards is charged with the responsibility of establishing and maintaining the national standards of physical measurement, and of providing means for their effective utilization. This responsibility carries with it the mission of providing the central basis for a complete, consistent system of physical measurement, adequate for national growth in research and technology.

The recent tremendous increase in industrial activity, particularly in the missile and satellite fields, has led to an unprecedented demand for precision measurement, which, in turn, is bringing about the establishment of hundreds of new standards laboratories. Many of these new laboratories must cover the entire field of measurement, and must do so with a staff not previously trained in work on standards of precision measurement.

To aid these laboratories in transmitting the accuracies of the national standards to the shops of industry, the Bureau has prepared this three-volume Handbook. It is a compilation of publications by the Bureau staff that have been found of value to those who are establishing and operating new standards laboratories. Omitted are some extended works, as well as a few shorter papers that are otherwise readily available.

It is hoped that this compilation will serve both as a "textbook" and a reference source for the many scientists and engineers who must be trained in the shortest possible time to fill responsible positions in this critical area.

A. V. Astin, *Director*.

Preface

Because of the urgent need for this Handbook, it has been reproduced by a photoduplication process. As a result, the individual publications that make up the compilation will be found to vary in such details as style, size of type, and method of pagination.

Each paper reproduced for the compilation is essentially complete as originally published and retains its original page numbering. All pages have also been numbered in regular sequence throughout the three volumes. Thus, the volume page number and the original page number are combined, for example 100/10.

Because of the short time available, a complete review of each paper included was not possible. However, some efforts were made to bring the older papers up to date, and only those papers have been included that are of current value. Nevertheless, users should be cautioned that the state of the art may have advanced beyond that represented in some of the older papers.

These three volumes, extensive as they are, include only a fraction of the published work of the National Bureau of Standards relating to standards. However, many of the reprinted papers contain extensive bibliographies that will enable the user who is confronted with a special problem to locate additional information.

The papers that appear or are cited in this three-volume Handbook were originally published over a period of several years as circulars, research papers, chapters of books, and as articles in scientific and technical periodicals. Thus individual copies of many papers are no longer readily available. More recent Bureau publications, and in some cases the older papers for which prices are given, may still be obtainable by purchase from the Superintendent of Documents, U.S. Government Printing Office, Washington 25, D.C. Other papers may often be obtained directly from the authors or from the publishers of the Journals in which the papers appeared. The papers referred to in the various lists, if not generally available as stated above, are usually available for reference in technical, university, Government depository, and public libraries.

Selected Papers on

Optics and Metrology

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Optics and Metrology

Radiation

SOME FUNDAMENTALS OF MODERN DIMENSIONAL METROLOGY

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ABSTRACT

Progress in technology now requires that for some purposes the ultimate in precision and accuracy be very closely approached in the measurement of primary dimensional standards that are defined by material surfaces. A research and development program at NBS is aimed toward careful evaluation or measurement of many factors that are sources of error and the devising of means and methods for eliminating, or at least reducing, sources of error wherever possible. Some principles are reviewed, and progress toward complying with them is reported.

Units of measurement are discussed in relation to increase in accuracy, particularly the proposed redefinition of the meter in terms of light wavelengths and the recent redefinition of the inch in terms of the meter. Other subjects treated are: progress toward increased stability of materials of standards, the relation of both macro- and micro-geometry to accuracy, control and accurate measurement of temperature, methods of attaining high amplification, improvements in interferometry, and possible future developments. It is shown that knowledge gained in these respects has practical application not only in measurements to highest degrees of accuracy but also in facilitating commercial measurements.

Presented at the twenty-eighth annual meeting of the American Society of Tool and Manufacturing Engineers in Detroit, Michigan, April 21-28, 1960.

INTRODUCTION

This paper discusses some of the latest developments in attaining extremely high precision and accuracy in the measurement of lengths and the dimensions of master gages. The demands for high reliability in functioning of modern mechanisms of many types require control of two main factors: (1) the uniformity and stability in the composition and structure of materials, and (2) uniformity of dimensions of components. The control of dimensions of mechanical parts has reached such a state that we at the top of the pyramid of dimensional standards must seek the ultimate in precision and accuracy as a practical engineering matter relative to dimensional standards that are defined by surfaces.

There always has been concern for highest accuracy in length measurements, primarily as a matter of scientific accomplishment, but also as related to line standards of length such as tapes and scales used in civil engineering, and for establishing highly accurate values for the wavelengths of light of certain spectrum lines. The Bureau of Standards' custody of the national standards in many fields of technology makes it necessary for NBS to provide calibration services in order to make such standards available to the public. Naturally most of this work is conducted at the highest practical levels of accuracy, as otherwise the transfer of the units represented in the standards from the national standard to the working levels in industry would be seriously impaired. Moreover, it is incumbent on the Bureau to strive to keep a step ahead of the industrial public's actual requirements for accuracy so that such requirements may be adequately fulfilled. This means that there must be continuing programs of research and development relative to measuring methods and equipment as well as in the maintenance of standards.

The Engineering Metrology Section is the branch of the Bureau that specializes in measurements of dimensions that are defined by surfaces, such as master gages and end standards other than gage blocks, which are calibrated by the Length Section. In its program, more especially in recent years, the emphasis has been on careful evaluation of those factors which are sources of error in measurement and on devising ways and means to eliminate or at least reduce sources of error wherever possible. An important phase of this program has been popularly known as the research program on measurement to the ten-millionth inch.[3]

We had known in a general way that certain factors were affecting the accuracy of our measurements. And we had applied corrections for them to the extent that our knowledge of them permitted, in the full realization that we were not attaining the ultimate in precision and accuracy in routine calibrations, but realizing at the same time that there was no particular need for such ultimate refinement. In recent years such a need has developed, and it has arisen from the activities of practical engineers. Accordingly, this paper presents, not merely information of an interesting and academic nature, but a general review of recently attained knowledge that has been gleaned by laborious effort largely within the Bureau and also by some other investigators. The field is too broad to cover fully within the scope of this paper, but the material presented is applicable by metrologists not only in achieving the ultimate in accuracy but frequently in solving the everyday problems of measurement in the numerous metrology laboratories that are springing up throughout the country.

The paper deals with some phases of units of measurement, dimensional standards, both macro- and micro-geometry, in relation to design of standards and to measurement, methods of amplification, and control and measurement of environmental factors. It reviews some of the principles relating to achieving the ultimate in accuracy and some of the more recent developments in equipment and methods for implementing those principles.

REDEFINITIONS OF LENGTH UNITS

In this discussion it is appropriate to start with fundamental units of length, particularly since one is shortly to be redefined and the other has recently been redefined. The unit on which all of our length measurement is based is the meter. It is to be redefined in terms of wavelengths of light. Certain spectrum lines have in the past been considered for use as length standards, notably the red line of cadmium, the green line of the mercury isotope 198, and certain lines of krypton isotopes. For example, nine different determinations of the wavelength of the red cadmium line were made in the interval from 1892 to 1940. The average difference of these determinations[17] from their mean is 0.14 parts per million, and they exhibit no trend with time, thus indicating the consistency of the procedures employed for relating the wavelength of the cadmium red line to the meter as defined by the International Prototype Meter.

Once a value is assigned to a wavelength, it can be used as a standard of length, when applied with suitably accurate equipment, to a higher degree of accuracy than any material standard, especially for lengths shorter than one meter. This situation led to the adoption in 1927 of the wavelength of the red cadmium line as a provisional international standard of length by the International Conference on Weights and Measures. This action had the further effect of leading toward a redefinition of our fundamental unit of length in terms of a light wavelength instead of in terms of a material standard, namely the distance between the centers of two ruled lines on a platinum-iridium bar that is in the custody of the International Bureau of Weights and Measures at Sevres, France.

It is expected that the International Conference on Weights and Measures at its meeting in 1960 will define the meter as 1,650,763.73 times the wavelength in vacuo of the orange-red radiation, corresponding to the transition between the energy levels $2p_{10}$ and $5d_5$ of the krypton 86 atom. This redefinition will not change the length of the meter in the least, but it is done with the intention of defining it more accurately than it can be defined by two ruled lines on a metal-alloy bar. Another important reason for this is that such a material standard cannot be expected to remain unchanged for all time or forever survive all possible accidents and catastrophes. Various national standards laboratories, including NBS, are developing equipment and techniques for calibrating material standards in terms of this

[17]*Superior numbers refer to References at end of paper.*

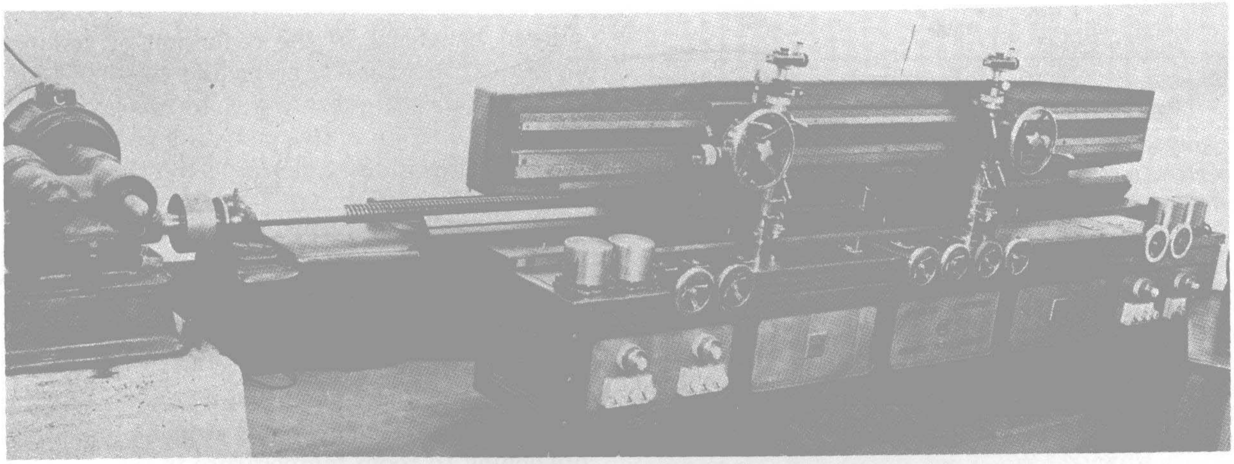


Fig. 1—Longitudinal comparator for line standards.

wavelength standard. There is inherent in the new procedure the possibility of upgrading the accuracy of lengths shorter than a meter to approximately 1 part in 10 million.

At present comparisons of line standards are made at NBS by means of a longitudinal comparator shown in Fig. 1. In a series of intercomparisons in 1952-53 of 9 meter bars among themselves and with Prototype Meter 27, the primary standard of length of the United States, the values obtained are believed to be not in error by more than 0.2μ (8 microinches) and in most cases not in error by more than 0.1μ (4 microinches); that is, within 1 to 2 parts in 10,000,000.[9]

In selecting the orange-red line of Kr_{86} as being one of the most suitable lines for the primary length standard, a great many factors related to atomic properties were taken into account. Most of these are enumerated in Engelhard's paper.[2] Looking toward future improvements in wavelength standards, the NBS has already developed even better wavelength standards using atomic beam techniques.

The other important redefinition is an event that has already happened, namely the redefinition of the yard and correspondingly the inch

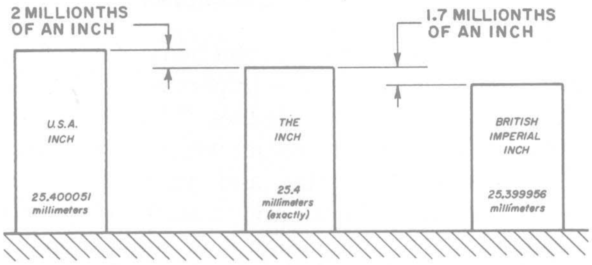


Fig. 2—Length changes resulting from the redefinition of the inch.

effective on July 1, 1959. In science and technology worldwide agreement has been achieved by this redefinition of these units, and the discrepancy between our values and those of the United Kingdom of nearly 4 parts in a million has been obliterated. The present inch is 2 microinches shorter than the one previously used in the U. S. and about 1¾ microinches longer than the earlier British inch. The change has practical effect only when measurements to six significant digits are involved; that is, for tool engineers, normally only when measurements are to microinches. Tabulated values of the change in value from the old to the new inch for standard lengths of gage blocks are shown in Table I with a diagram illustrating the different inch units in Fig. 2.

Anyone having a report showing the lengths of gage blocks expressed in U. S. inches may convert to lengths in international inches by *adding* amounts shown in Table I to the deviation from nominal length given in the original report.

Conversely, anyone desiring to convert the lengths of gage blocks expressed in international inches to lengths in U. S. inches may do so by subtracting the amount shown from the values in the report.

The manufacturers most affected by the change are those of gage blocks and other highly accurate length standards, measuring machines, jig borers, and jig grinders.[14] The transition has proceeded very smoothly and the change has been hailed as very desirable because now we have only one inch or yard unit. Domestically these are now known simply as "the inch" and "the yard."

Table I

Nominal Length of Gage Block	Change in Microinches
0.010 to 0.250 inch inclusive	none
0.300 to 0.750 inch inclusive	1
0.800 to 1.000 inch inclusive	2
2.000 inch	4
3.000 inch	6
4.000 inch	8
5.000 inch	10
6.000 inch	12
7.000 inch	14
8.000 inch	16
10.000 inch	20
12.000 inch	24
16.000 inch	32
20.000 inch	40

MATERIALS FOR CONTACT LENGTH STANDARDS

In the case of the meter bar, the choice of an alloy of 90 percent platinum and 10 percent iridium has proved to have been an excellent one for primary length standards from the standpoint of stability. However such an alloy is not economically available for widespread use in length standards. Practically all contact standards are made of steel or one of the hard carbides. The Bureau is engaged in an extensive investigation with the object of achieving the production of gage blocks of dimensional stability, surface quality, and other physical properties necessary to permit reliability of measurements to from 0.1 to 0.2 microinch per inch. The program has thus far been successful in developing three groups of gage blocks, each with a different material or treatment, that have met the requirements and have shown a dimensional stability of 0.2 microinch/in./yr. A voluminous progress report of this investigation is available.[7] In this report optimum hardening and stabilization treatments developed for 52100 steel are described as follows:

"With hardened steels, the difficulty of completely balancing the dimensional changes occurring from structural transformation against residual stresses can be minimized by keeping these factors at low levels. As a starting point, it was decided to eliminate almost all of the retained austenite, which would not only reduce the possibility of growth but would possibly give a higher hardness and allow a higher tempering temperature or longer time at temperature to obtain a final hardness of 65 Rc. The higher tempering temperature was considered beneficial in the reduction of residual stresses. The standard procedure used for hardening by direct quench was to austenitize at 1550°F for 15 minutes and quench to room temperature in a quenching oil having an accelerated cooling rate."

"The residual stresses resulting from thermal gradients on cooling from the hardening temperature are often reduced by martempering. The martempering treatment adopted consisted of austenitizing in a chloride bath at 1550°F for 15 minutes, quenching in a sodium nitrate-nitride bath at 300°F for 30 seconds, and then quenching to room temperature in oil"

"Both of the above hardening treatments were followed by a stabilization treatment designed to remove retained austentite, temper the martensite, and reduce residual stresses. This treatment for blocks hardened to 65 Rc consisted of an immediate refrigeration at −140°F for an overnight period, and a final temper at 250°F for nine hours. The interval between steps was kept as short as possible."

The most stable of the nitrided 410 stainless steel gage blocks are blocks in the annealed condition and nitrided by the conventional two-stage process, and whose nongaging surfaces were not ground or otherwise machined after nitriding. It was not possible to observe the behavior of these blocks during the first year after heat-treatment. However, thereafter the overall change in length computed on the basis of one year is a consistent +0.2 microinch/in./yr.

Another set of annealed 410 stainless steel gage blocks was nitrided by the conventional single-stage process. Also, the white layer on the nongaging surfaces was ground off so as to leave a hard, bright, nitrided case. The stability of these blocks ranged from +0.1 to +0.3 microinch/in./yr. with an average of +0.2.

ACCURACY OF STANDARDS RELATED TO GEOMETRY

A contact standard is a solid body of which its geometry is one of its most important attributes. Webster's Dictionary defines "geometry" as "that branch of mathematics which investigates the relations, properties, and measurement of solids, surfaces, lines, and angles." For the purposes of this discussion it is convenient to develop principles relating to macro-geometry and others relating to micro-geometry.

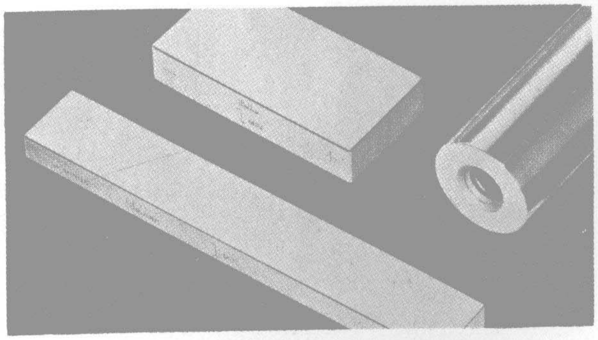


Fig. 3—Earlier and improved (top) angle gage block designs, and improved combination length bar (right).

Macro-Geometry

The macro-geometry or design of standards usually has an important bearing on the accuracy to which they may be made and used. The principles to be applied in optimum design of a standard for a given purpose will probably be evident to an experienced designer who gives the matter some thoughtful consideration, but they are not always obvious. I am not prepared to set forth a complete set of applicable principles, if indeed it is possible to compile such a set. A very important principle is that the design of a standard should generally be such that elastic distortion under the measuring loads normally applied is kept to a minimum. This can be illustrated by two recent examples of improvements in design that have produced greater accuracy by minimizing distortion.

The first example is that of two angle gage blocks, the first or older design at the left in Fig. 3, having long, relatively narrow wringing surfaces that are supported by an insufficient amount of metal. In an angle block the deviation from planeness of the wringing surface has an important effect on the accuracy of the block as an angle standard. If over a 2-in. length the midpoint is one microinch higher or lower than the ends of the gaging surface and the surface is curved, the variation in angle from end to end is 0.8 second. At the right of the figure is shown the more modern design of shorter and wider wringing surfaces and more adequate supporting metal. Needless to say, by the use of such blocks a higher degree of accuracy is attainable.

The second example is the design of a thread in the end of a combination length bar. To build up a standard of a desired length, bars of suitable lengths are selected from an assortment and screwed together with a torque in the range from 10 to 20 lb.-in., using connecting studs. It was found that the design of this threaded connection[8] has an appreciable effect on the reduction in length resulting from the torque applied. In Fig. 4 the older design of connection is shown at the left and the improved design at the right. The latter has short lengths of engagement and chamfers in the end of the threaded hole. The design is so proportioned that the decrease in length caused by the axial compressive force balances the increase in length caused by the radial bursting force and the moment associated with the axial compressive force. It was found by L. W. Nickols of the National Physical Laboratory that, using connecting studs of uniform diameter, the average reduction in length per threaded connection of the earlier type was about 6 microinches at 10 lb.-in. and 13 microinches at 20 lb.-in. torque. With the improved design the change in length per joint amounted to about 1 microinch and was independent of the assembly torque. This improved design permits substituting threaded connections for simply wrung connections in assemblies requiring highest accuracy, with much greater convenience in handling.

The force of gravity affects distortion. A familiar example is the need to support a bar standard, when measured horizontally, at the Airy points, in order that the ends of the standard may remain parallel to each other and the flexure of the bar held to a minimum. The distance between the Airy points is 0.577 times the length of the bar.

Another such example is that if a gage block is measured vertically and supported at its lower end it is shorter than when supported horizontally. The amount of shortening is proportional to the square of the length so that for long blocks this factor becomes significant. The applicable formula is

$$\delta = \frac{wL^2}{2\,AE}$$

where

δ = amount of shortening
w = weight per unit of length of the block
L = total length of block
A = cross-sectional area
E = Young's modulus of elasticity

For a steel block
$\delta = 4.55\,L^2 \times 10^{-9}$ in.

and
δ = 1 microinch when $L = 14.85$ in.

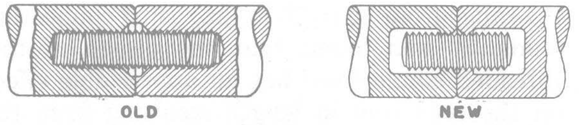


Fig. 4—Earlier and improved designs of threaded connections of combination length bars.

A distortion factor that is often overlooked is the penetration of a measuring contact point into the surface of a standard and a test piece. If these are of different materials it is necessary to evaluate the difference between the penetrations and apply it as a correction to the measurement. The chart presented in Fig. 5 is a quick means for determining such amounts. The chart also shows some equivalent compressive loads. It is necessary to be certain that the compressive strengths of the materials involved are not exceeded.

Another principle relating to macro-geometry of standards is the principle of averaging by design to attain a single, highly accurate measurement in the place of taking several measurements of a given dimension and then averaging the results. The following are some examples:

1. About the year 1840 Sir Joseph Whitworth produced plane surface plates by grinding a group of three plates, pairing them off successively during the process.

2. Approximately 40 years ago the principle of averaging was applied and is still used in the Hoke process of mechanical lapping of precision gage blocks to produce a group of blocks of uniform length. The averaging is accomplished by systematic interchange of short and long blocks in their positions between the laps. Major Hoke also applied this principle in the lapping of gears to produce uniformity of tooth spacing and thickness.

3. A gage indexing fixture, Fig. 6a and 6b, similar to a rotary table, in which the indexing

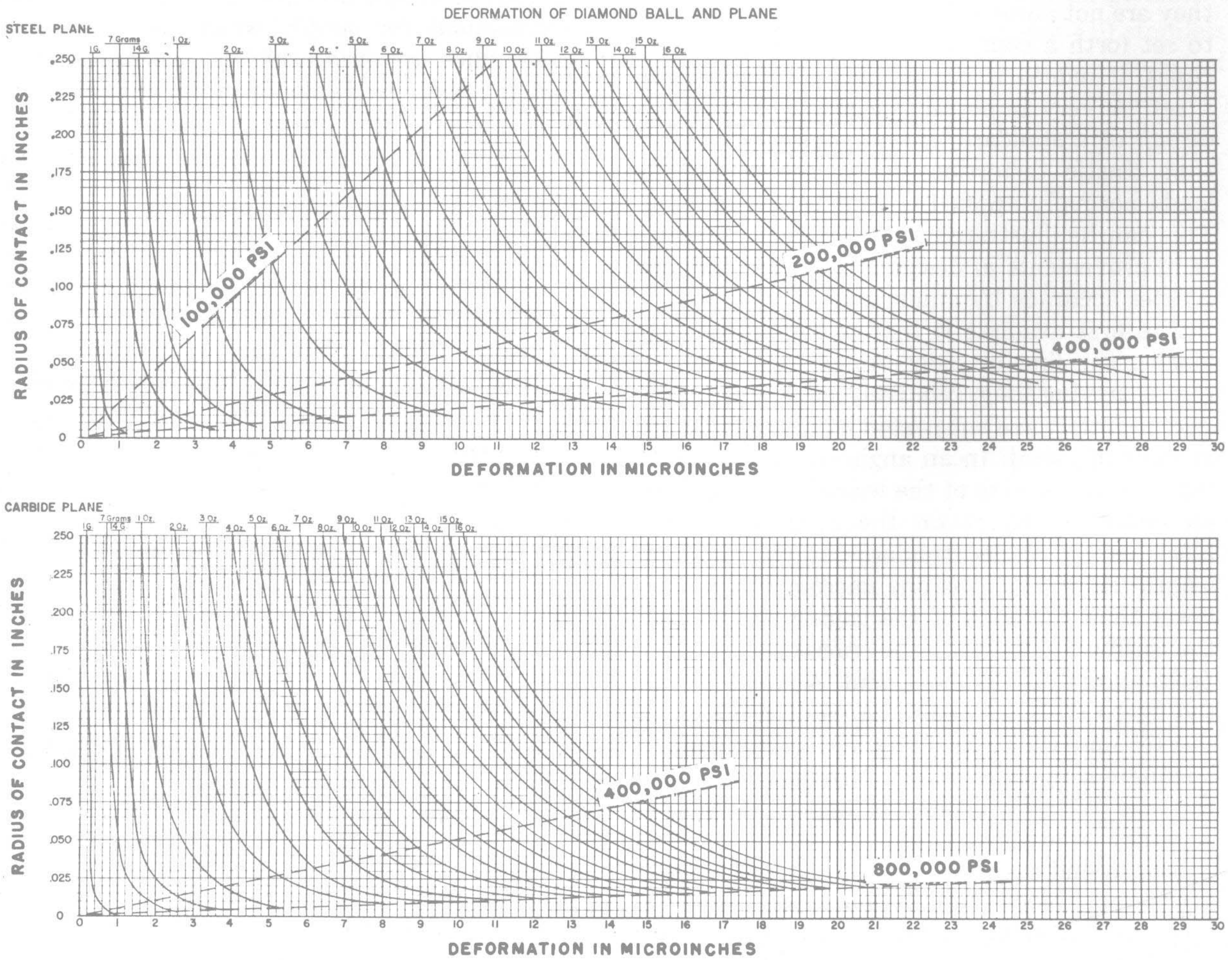


Fig. 5—Chart showing relationships between materials, radius of contact, and elastic deformation; also compressive loads for mechanical comparators.

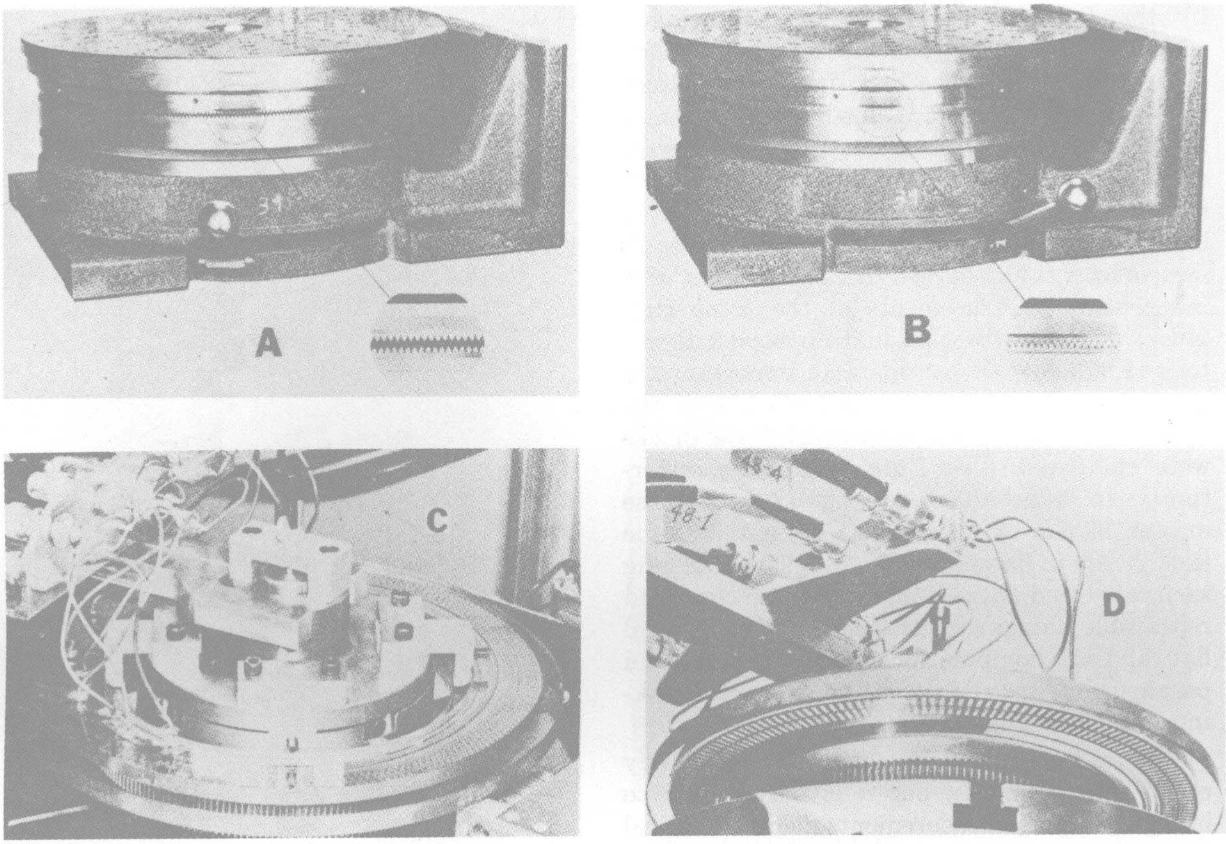


Fig. 6—Averaging principle applied to angle measurement. Mechanical fixture shown open for free rotation (A) and locked in position (B). (Courtesy of AA Gage Co.) Transducer discs showing driver (C) and coupler (D). (Courtesy of Telecomputing Services, Inc.)

of the table with respect to the base is controlled mechanically by the meshing of 360 serrations around the periphery. Thus all of the 360 serrations enter into the positioning of the table at each degree interval. All deviations of the positions of the respective serrations from the nominally correct positions are averaged, resulting effectively in very nearly zero deviation for each position.

4. A transducer[10] for indicating the angular position of a shaft to an accuracy approximating 1 part per million that is essentially a highly accurate electrostatic phase shifter. A pair of dimensionally stable glass discs, Fig. 6c and 6d, each carrying a pattern, photoetched from a copper film deposited on the glass, are rotatable with respect to each other. These patterns (one, a driver, consists of 200 sinusoidal elements, and the other, a coupler, of segments of circles concentric with the center of rotation) face each other and are closely spaced. The coupler pattern picks up the signal contributions of all 200 driver elements simultaneously, thus averaging out the effects of random pattern deviations in the driver and coupler elements.

Similarly, an Inductosyn system of circular form has been adapted[1] to control rotary positioning tables to an accuracy of 2 seconds.

5. The Societe Genevoise of Geneva, Switzerland, as long as ten years ago applied the averaging principle to photoelectric scanning of lines on a ruled bar to produce another ruled bar of higher accuracy.*

Micro-Geometry

Under the heading of micro-geometry we would consider small deviations from nominally correct form, including surface roughness and deviations from planeness, parallelism, roundness, etc. For length or dimensional measurements to 0.1 microinch accuracy such deviations must not exceed a fraction of a microinch, and even then the length measurement must be confined to a specific and readily located position on each surface. An example of the importance of flatness and parallelism deviations in measurements of highest accuracy is afforded

**No published description has been found.*

by the Bureau's experience in measuring a 16-in. and an 18-in. gage block to better than 1 part in 5 million, the first time in its history that the Bureau has certified blocks to such high accuracy.[6] In these measurements results obtained by two completely independent methods agreed to the nearest microinch or better for both gage blocks. The Bureau's measurements also agreed to 2 microinches with independent measurements of the same gage blocks made by the National Physical Laboratory (England). Of considerable importance in this accomplishment was the accuracy of the Bureau's master blocks with which these blocks were compared. The Bureau had the opportunity to select from among 17 sets those master blocks of a given make that had the least errors in flatness and parallelism of gaging surfaces. Good flatness made possible close and repeatable wringing of the blocks to an optical flat, and the combination of good flatness and parallelism reduced observational errors in making the length comparisons.

Surface roughness is a factor in the accuracy of all measurements, but it is particularly so in high accuracy measurements made by optical interference methods.[13] Such measurements determine an optical length whereas what is normally required is the mechanical length. This problem is dealt with later in a discussion of interferometry.

For the measurement of fine finishes such as are required on good dimensional standards the most generally applicable means is the microinterferometer, also called the interference microscope. The earliest of these was developed by Linnik,[5] a Russian, and was manufactured 15 or more years ago by Carl Zeiss of Jena (Fig. 7). A newer design is made by Zeiss of Oberkochen, Fig. 8. Others are the Hilger and Watts, London, Fig. 9a; the "Multimi" of C. E. Johansson, Eskilstuna, Fig. 9b; the "Rugometre" of La Precision Mecanique, Paris; one by Hahn and Kolb, Stuttgart; one by Askania, Berlin; and one by Cook, Troughton and Simms, York, England. Detailed descriptions of these are available in the references.[12]

The Johansson instrument and some others apply the principle of multiple-beam interference in which very narrow, sharp, dark bands are produced. Under certain conditions this permits a more accurate evaluation of scratch depth than two-beam interference. In general the roughness depth measuring range for two-beam interference starts at about 1 microinch and for multiple-beam from 0.04 to 0.2 microinch. Multiple-beam interference is particularly useful in evaluating small irregularities other than scratches, as for example the thickness of laminae of crystals as exhibited by steps on the surface.

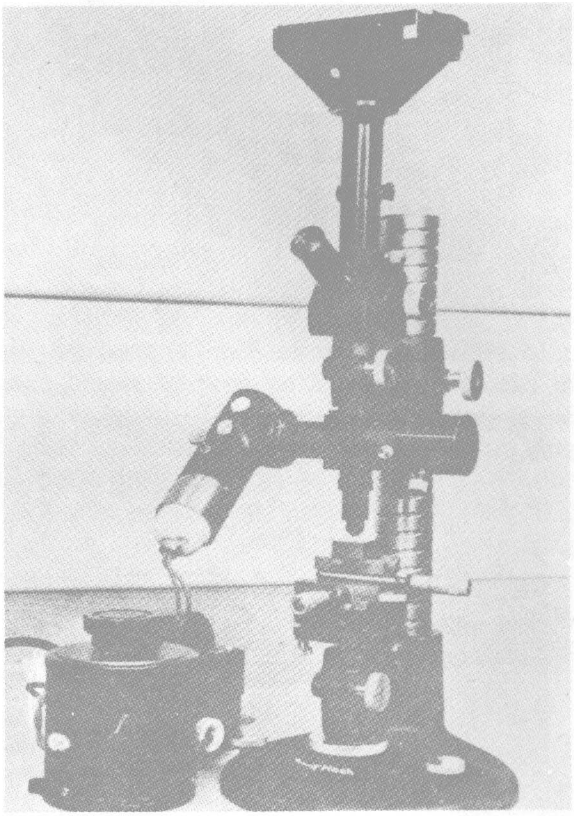


Fig. 7—Linnik microinterferometer.

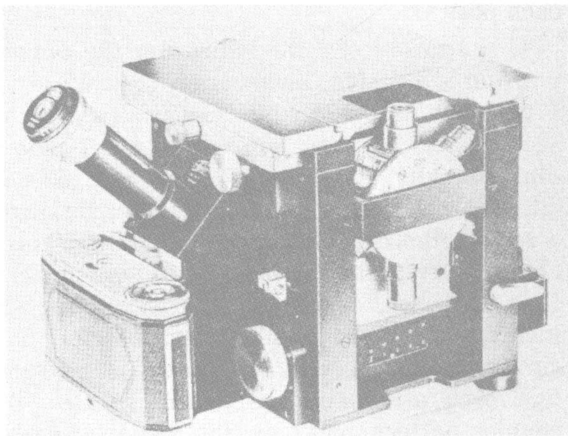
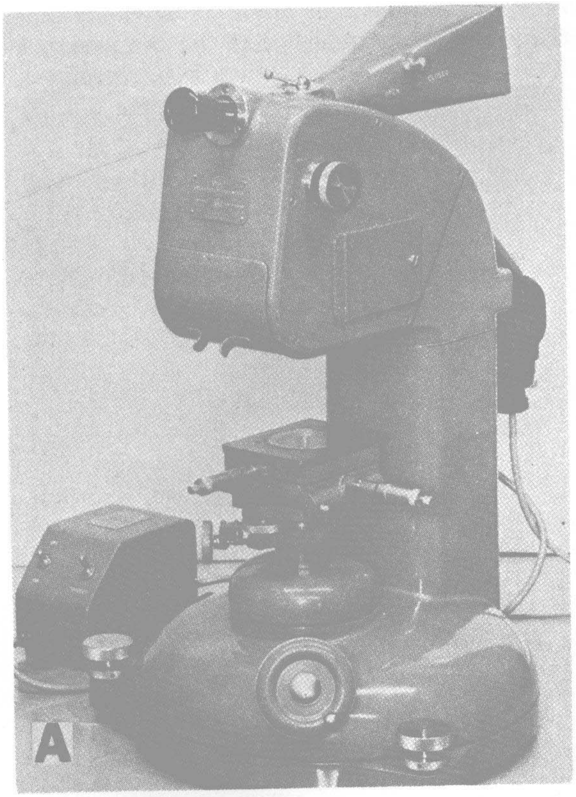


Fig. 8—Zeiss microinterferometer. (Courtesy of Carl Zeiss, Inc.)



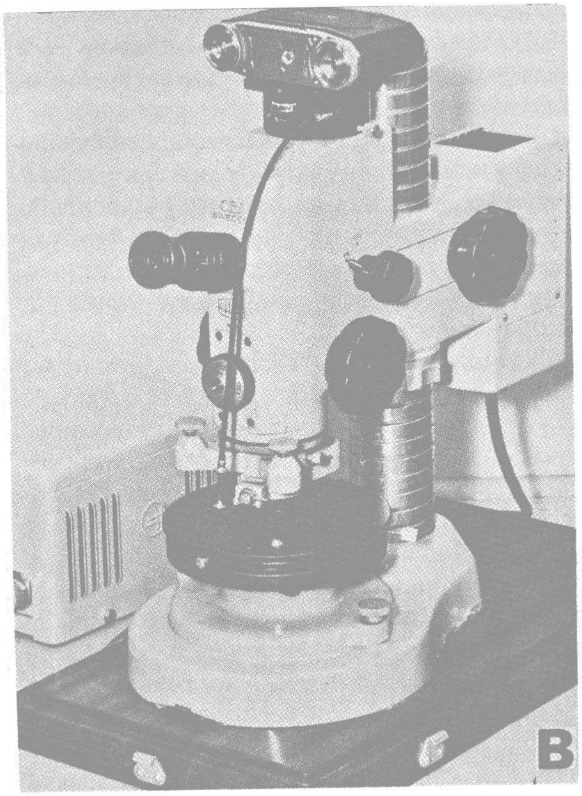


Fig. 9—A. Hilger and Watts microinterferometer.
B. Johansson microinterferometer.

TEMPERATURE CONTROL AND MEASUREMENT

In high-accuracy determinations of lengths or sizes, the accurate measurement of temperature is fully as important as the measurement of dimension. By international accord the nominal dimensions of gages and product shall be correct at a temperature of 68°F (20°C). Thus the most accurate calibration of dimensional standards requires that their actual sizes be determined at 68°F. For extreme accuracy in calibration this involves:

1. Good temperature control at or near 68°F of the ambient air and shielding against heat sources and voids.
2. Accurate measurement of actual temperature of both the dimensional standard and the test piece.
3. Knowledge of the coefficient of thermal expansion of both items in the room temperature range. This may require measurement of this coefficient.

Accurate temperature measurement presents a most serious aspect because there are at least four temperature-dependent variables directly involved in a measurement—two of temperature measurement and two of thermal expansion measurement. Let us assume that, using an electrical resistance thermometer, we are able to read the thermometer with an uncertainty of 0.001°C and that this reading represents the temperature of a thermocouple on the surface of the steel gage block used as a standard. This uncertainty is about the least that we can attain in temperature measurement. If the coefficient of expansion of the block is 0.0000115 in. per deg. C, then in 1 inch of length the uncertainty in the length of the block is $(11.5 \times 10^{-6}) \times (1 \times 10^{-3}) = 11.5 \times 10^{-9}$ or 0.0115 microinch. If there is a like uncertainty in the temperature of the test piece, the total uncertainty for both is 0.023 microinch. Thus, if we are trying to measure to an accuracy of 0.1 microinch, practically one-fourth of this may be lost in temperature measurement alone. Superimposed on this are any uncertainties in the values of the coefficients of thermal expansion of the standard and test piece. Unless these attributes are measured for both the specific standard and test piece involved, the discrepancy in coefficients of the two pieces may be 1 μin./in. Thus, if the temperature