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LENGTH SCALE MEASUREMENT PROCEDURES AT THE NATIONAL BUREAU OF STANDARDS

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ABSTRACT

Precision graduated length scales have been measured by interferometry at NBS since 1965. An instrument called the Line Scale Interferometer was designed for this purpose. The history, development, improvement, operation and evaluation of the line scale interferometer are described here. Special emphasis is given to detailed operating procedures to provide guidance in the use of the instrument. Evaluating performance through a measurement assurance program is also emphasized.

Key words: Length; graduated scales; interferometry; measurement assurance; uncertainty.

1. INTRODUCTION

1.1 Purpose

This publication is primarily a documentation of current measurement procedures for calibrating graduated length scales, and, as such, it will serve as an operating manual for the NBS line scale interferometer. Its secondary purposes are to record the history of the instrument and to describe the measurement assurance program that provides continuous surveillance of the line scale measurement process.

There are five main sections: (1) "Introduction", which is general in nature, (2) "The NBS Line Scale Interferometer", which describes the instrument and traces its development from conception to the present and is partially adapted from a previous paper (reference 1), (3) "Measurement Procedure", which gives detailed instructions for operating the instrument, (4) "Measurement Results", which describes the analysis of measurement data and the writing of calibration reports, and (5) "Measurement Assurance", which explains the principles and details the practice of monitoring measurement process performance.

1.2 Line scales of length

Graduated length scales probably surpass any other measuring device in the variety of its forms. They are made in lengths from a few micrometers to over a meter (longer ones are made, but they are usually classified as measuring tapes or rods). Many materials are used including steel, Invar, brass, glass, silicon and quartz. Cross sectional shape can be rectangular, "H", "U" or a modified "X". Graduations are cut by diamond, photo-etched or deposited by metal evaporation. Width of graduations can be anywhere from sub-micrometer on up, and graduation spacing can be from one micrometer on up. Their lack of standardization can often make calibration a real challenge, and almost every scale presents a different measurement problem.

1.3 Line scale calibration and measurement assurance at NBS

In the industrial and technological worlds, length scales have always been important. One of the basic objectives of the National Bureau of Standards when it was established in 1901 was to maintain the national standard of length and provide a length scale calibration service. This service was the only means for disseminating the standard of length throughout the economy.

Measurement assurance, although it was not called that at the time, was practiced in a simplified form from the beginning. By 1928 it had reached an advanced form employing incomplete block designs and least squares data reduction (ref. 2, 3) for making intercomparisons of length standards. These statistical techniques were used until 1964. The measurement assurance program used since 1964 is described in section 5 of this paper.

2. THE NBS LINE SCALE INTERFEROMETER

2.1 Evolution of the instrument

From 1889 until 1960, the international prototype length standard and the national length standards were graduated platinum-iridium meter bars. Calibrations of all other scales were accomplished in comparators employing filar microscopes for measuring length differences between the standard and the scale being calibrated. Subintervals were determined by a lengthy process of intercomparison by subdivision (ref. 4).

In 1958, a committee of NBS scientists* chaired by I. C. Gardner, Chief of the Optics and Metrology Division, started planning for an interferometric line scale comparator in preparation for a proposed change in the definition of the meter. By international agreement in 1960, the meter was redefined as the length equal to 1,650,763.73 wavelengths in vacuum of the orange-red spectral line of the krypton 86 atom. A new era of length measurement by interferometry was opened by this change and the developement of high speed fringe counters in the preceding decade.

Prior to 1960, wavelengths from selected light sources were internationally sanctioned as secondary definitions of the meter

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* Committee members were H. D. Cook, L. A. Marzetta and M. L. Kuder of the Electronic Instrumentation Section, K. G. Kessler of the Spectroscopy Section, T. R. Young and J. B. Saunders of the Engineering Metrology Section, and B. L. Page of the Length Section.

to serve, among other uses, in measuring end standards of length. End standards have been measured by static interferometry since early in this century. Their optically plane and parallel measuring faces are ideally suited to this method because they can serve as mirrors in the measuring legs of interferometers. Line scales cannot be measured efficiently by the static method for a number of reasons including the multiplicity of intervals. They are best measured by dynamic (fringe counting) interferometry.

By 1961, an experimental fringe-counting interferometer (ref. 5) was operational using a mercury 198 light source as a length standard. Development of a final version proceeded, by good fortune, in parallel with the development of the laser (ref. 6). In 1964, the two activities converged and a successful measurement of a one-meter scale with helium-neon laser wavelengths was accomplished (ref. 7). Refinements in the NBS line scale interferometer were made and laser wavelength stability was improved until in 1966, a semi-automated line scale calibration system was in routine operation (ref. 8). Much of the credit for the success of this project belongs to Herbert D. Cook who worked virtually alone for several years designing and constructing the final instrument. The mechanical and optical structures are shown in figure 1.

Development work has continued on both the line scale interferometer and on lasers (ref. 9). The principle changes made in recent years are (1) rigid coupling and kinematic mounting of the microscope and the interferometer in 1970, (2) replacement of the Michelson interferometer with a commercial interferometer in 1979, (3) modernization of the microscope electronics in 1981, and (4) addition of a computer/controller in 1981 to completely automate instrument operation.

2.2 Original design and operation

In this section the instrument is described as it stood in 1966, but with the 1970 modification (kinematic mounting of the optical components). It is important to describe the instrument as it then stood to aid in understanding its present form because its design principles and much of its structure remain unchanged. For this reason the present tense is used here. Changes in the system are described in the next section.

Six principal elements comprise the instrument: (1) a waybed and carriage for mounting the measuring apparatus and translating the scale, (2) an interferometer with a laser light source to establish a length standard, (3) a photoelectric microscope with a servo system for scale graduation positioning, (4) a temperature controlled enclosure for environmental isolation, (5) devices for measuring temperature, barometric pressure and humidity and (6) data recording and processing equipment. The first three elements are shown in figures 1 and 2, and element (4) is shown in figure 9.

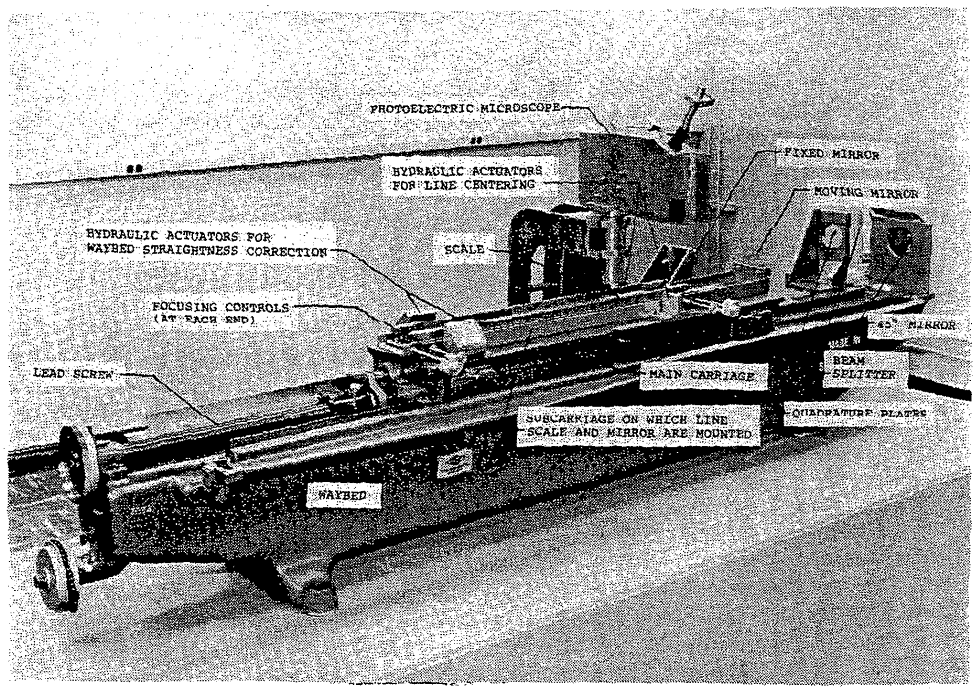

Figure 1. The line scale interferometer mechanical and optical components with the Michelson type interferometer

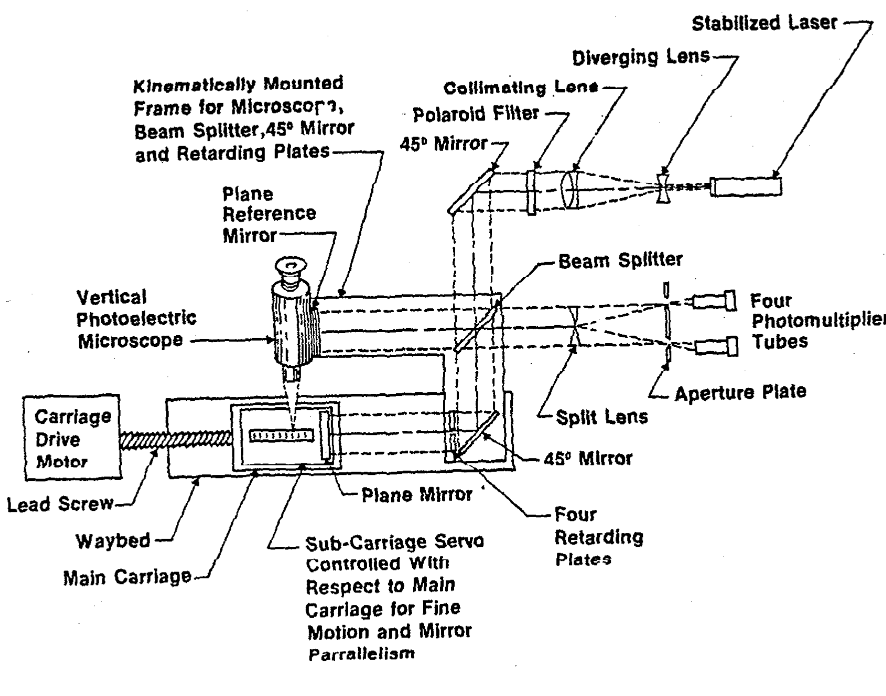

Figure 2. Schematic diagram of the line scale interferometer

The two-meter waybed and its carriage are the mechanical foundation of the instrument. A line scale is mounted on the carriage, and the carriage is moved on the ways by a motor driven lead screw. A modified Michelson interferometer is located at one end of the waybed with its moving mirror attached to the carriage, coaxially with the scale. The stationary reference mirror is mounted along the side of the waybed on the microscope support structure. The photoelectric microscope is mounted vertically above the carriage at the midpoint of the waybed, and is focused on the scale graduations. All stationary components of the interferometer together with the microscope are attached to a rigid mounting frame which, in turn, is kinematically supported on the waybed structure*. Interferometer components include the beam splitter and 45 degree mirror, the reference mirror and the retarding plates. It is vital that the microscope and stationary interferometer components remain dimensionally fixed during a scale measurement because any relative motion among these parts will be seen as part of the measured scale length, thus obviously resulting in errors.

The entire apparatus is housed in a vibration isolated enclosure held at 20 degrees C ±0.01 degree by a thermostatically controlled circulating water bath. All heat producing components such as the laser, microscope lamp, drive motor and electronic circuits are externally mounted. Laboratory temperature is maintained at 20 degrees C ±0.05 degree.

Fringes formed by the laser light in the interferometer are detected, counted and interpolated to 0.01 fringe, giving a continuous indication of carriage position. Four retarding plates divide the 50 mm diameter collimated laser beam into quadrants, each quadrant acting as a separate interferometer. When the carriage moves, a sinusoidal voltage is simultaneously obtained from each of four photomultipliers monitoring the fringe patterns in their respective quadrants. A 0, 90, 180,and 270 degree simultaneous phase relationship between the four interference patterns is obtained by initial adjustment of the retarding plates. Direction of fringe counting, fringe interpolation and servo control of mirror parallelism (mirror parallelism deviations between the fixed and moving mirrors result from waybed straightness errors) are derived from these four related signals.

Fringe interpolation and counting direction are displayed by applying the sine and cosine voltages from the photomultipliers to a cathode ray tube, the two voltages being applied to separate deflection axes. The resulting display spot follows a circular clockwise or counterclockwise path coinciding with the forward or

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* Kinematic mounting of the optical system was completed in 1970. Before that, the optical components were attached to the waybed and distortion caused by the shifting weight of the carriage was reduced by a steel beam connecting the upper body of the microscope to the upper frame of the beam splitter assembly.

reverse direction of the fringe patterns. One revolution of the spot equals one fringe and the fringe fraction is the polar angle of the spot. Digital interpolation is done by a built-in analog computer.

Mirror parallelism deviations caused by waybed straightness errors are detected, and two error voltages generated, by comparing the phase of the fringes in diagonally opposite interferometer quadrants, one error signal from each diagonal. These error signals actuate a dual hydraulic system which imparts corrective motions to the mirror as described below.

Referring to figure 1, the scale and moving mirror are on a subcarriage which, in turn, is mounted on top of the main carriage. This subcarriage is movable relative to the main carriage and it provides the mechanism for three functions: (1) maintaining mirror parallelism without changing the relative position of scale and mirror, (2) centering the scale graduations and (3) focusing the scale. Except for focusing, these functions are performed as parts of servo loops. The subcarriage is supported on flexure springs near the mirror end to permit longitudinal motion for line centering. Movement is imparted by hydraulic pressure generated from the line centering error signal working through a solenoid and piston arrangement. The springs also serve as a fulcrum for rotational motion imparted to the opposite end of the subcarriage by two hydraulic actuators. Error signals from diagonal quadrants A and C operate one hydraulic actuator and the error signals from B and D operate the other. The hydraulic actuators on the subcarriage are at right angles to one another and can, therefore, create the necessary motion to keep the moving mirror parallel to the fixed reference mirror while the carriage is travelling. Using plane mirrors in this way has the advantage of reducing potentially serious measurement errors caused by geometric errors in the waybed.

Detailed descriptions of the circuits and logic used to perform the fringe counting, fringe interpolation and mirror parallelism control can be found in reference 5.

Various helium-neon lasers have been used over the years starting with a manually stabilized version in 1964, then progressing to a commercial Lamb-dip stabilized model (ref. 10), and in 1977, to an NBS-developed iodine-stabilized laser, stable to a few parts in 10^{11} (ref. 9). High-contrast fringes are easily maintained over the one-meter path because of the extreme coherence of laser light.

Line scales are calibrated by making carriage displacement, as measured by the interferometer, correspond exactly to scale interval length. This correspondence is accomplished by the servo and nulling action of the photoelectric microscope when the carriage is stopped and a scale graduation is in view. As illustrated in figure 3, a vibrating mirror in the microscope sweeps a magnified image of the vertically illuminated graduation across a slit located in front of a photomuliplier. Electronic

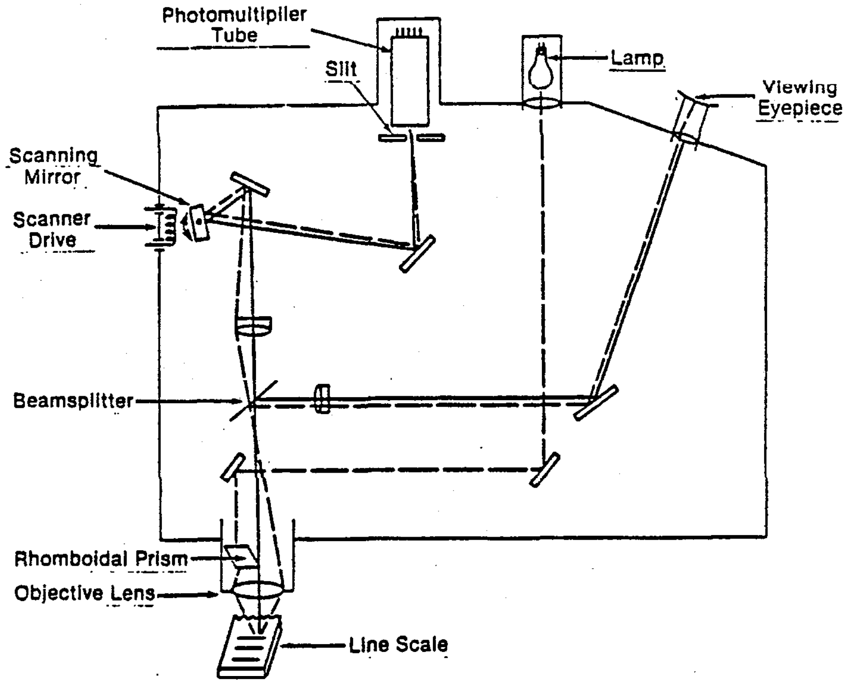

Figure 3. Schematic diagram of the photoelectric microscope

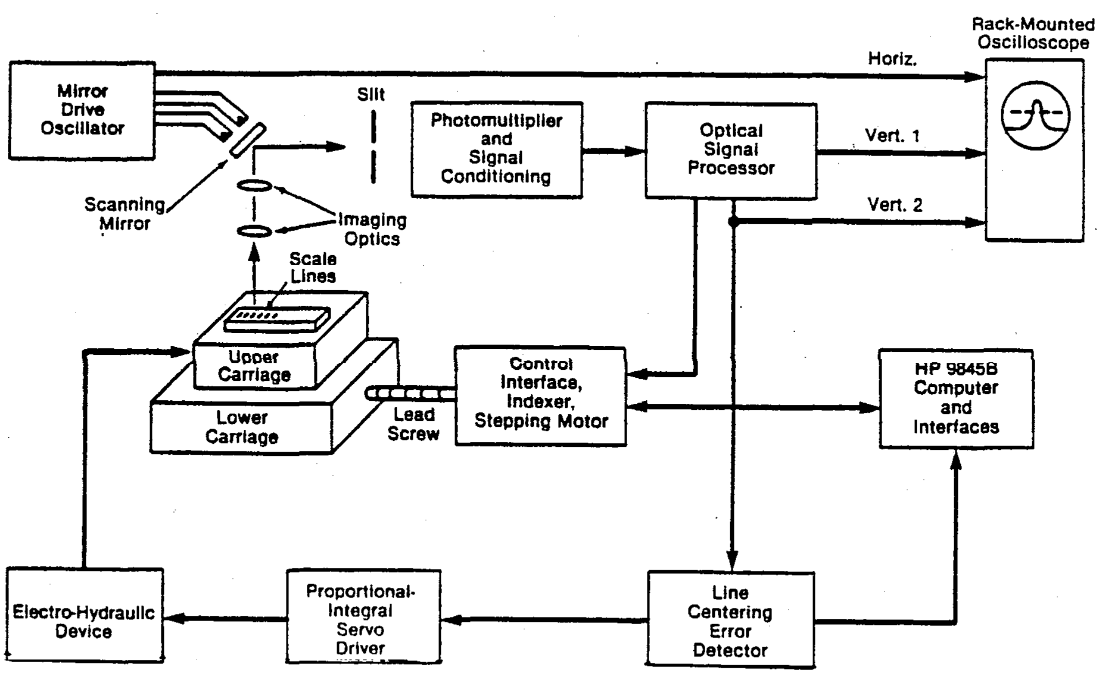

Figure 4. Schematic diagram of the microscope servo system

circuits process the resulting signal and generate an output voltage (error signal) proportional to the deviation between line center and microscope optical center. This error signal operates through a solenoid-piston assembly to apply a longitudinal adjustment to the subcarriage holding the scale and interferometer mirror. The graduation is centered when the error signal is nulled and the fringe count reading is then recorded. Proceeding up the scale in this manner produces a set of recorded fringe count readings corresponding to the interval lengths on the scale. These fringe counts are converted into length units by multiplying them by a factor which encorporates the vacuum wavelength, the refractive index of the ambient air and the thermal expansion of the scale to 20 degrees C. Several passes up and down the scale are made with the scale in both normal and reversed orientation to generate redundant data for averaging and statistical analysis. Length values are reported for a 20 degree C scale temperature, the internationally accepted temperature for dimensional measurements.

Data are recorded on punched paper tape, transferred to cards and processed in the NBS central computer.

2.3 Present form and operation

2.3.1 Microscope system electronics

Obsolescence and gradual deterioration of the original electronic systems made it desirable to bring them up to modern standards. The photoelectric microscope, and its associated servo system, was originally constructed with an electronic vacuum tube and early solid state technology. It has been totally redesigned with solid state integrated circuits and provisions for computer control. The present system is shown in figure 4.

A high speed stepping motor and a preset indexer interfaced with a microcomputer replaces the original dc-motor/cam-drive system for moving the carriage predetermined distances corresponding to nominal line spacings. The indexer can be operated either under manual or computer control. Except for the photomultiplier signal conditioning circuit, all of the microscope electronics are built into five circuit board modules housed in a single 483 mm chasis. These modules consist of the mirror drive oscillator, optical signal processor and line center error detector, indexer control interface and proportional-integral (PI) servo driver. The line signal derived from the photomultiplier is displayed on an oscilloscope operating in the XY plot mode. The horizontal input of the scope is driven by a sinusoidal signal from the mirror drive oscillator circuit. Hence, a signal is displayed on the screen showing the line position relative to the microscope center.

The purpose of the optical signal processor and the line center error detector is to transform the signal into a means for centering the line in the microscope field. The optical signal processor consists mainly of a pair of positive and negative peak detectors. The difference between the positive and negative peak voltage is used to scale the amplitude of the line signal and to generate the peak-present signal. The peak-present signal is used to disable the lead screw drive circuit and to activate the electro-hydraulic servo circuit for fine centering of the line. A threshold voltage derived from the scaled amplitude of the line signal is displayed on the oscilloscope as a horizontal line intersecting the line signal pattern (figure 4) and is used in the line centering error detector to produce a dc signal proportional to the distance of the line from the optical center. The sign of this signal reflects the direction of the line from the center. The threshold voltage can be adjusted with a potentiometer to select the optimum level (usually 50% of the amplitude) for triggering the centering-error detector. Using the two points where the threshold voltage intersects the line signal, the line centering error detector generates a bipolar dc voltage corresponding to the direction, and proportional to the distance, of the line from the optical center. This voltage is used as an error signal to run the PI servo driver which, in turn, moves the upper carriage through electro-hydraulic means to center the line with the optical center. This servo system loop will continuously and dynamically lock a line onto the optical center. The two point criteria for line centering was chosen because it closely resembles what an operator does when centering with a bifilar eyepiece. Centering can also be achieved using one point on either the right or left edge of the line for special measurement needs.

2.3.2 Interferometer

A Hewlett Packard* interferometer system has replaced the original Michelson type interferometer. It can be readily integrated into an automated, computer controlled system. The new interferometer, shown in figure 5, is mounted at the opposite end of the waybed from the Michelson. When the HP system is used alone, the parallelism control feature of the Michelson is lost and the straightness errors in the waybed are uncompensated. Under these conditions, great care must be taken to avoid Abbe offset by adjusting the scale axis to coincide with the interferometer axis so that measurement errors caused by carriage pitching are minimized. The interferometer has a helium-neon laser producing a continuous red beam. The cavity of the laser is stabilized by using an internal zero thermal expansion coefficient structure combined with a servo loop for automatic tuning. This laser interferometer system has a resolution of 0.025 wavelength. Measurement units can be displayed in either millimeters, inches or quarter wavelengths. Atmospheric

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*Certain trade names and company products are mentioned in the text in order to specify adequately the equipment and procedures used. In no case does such identification imply recommendation or endorsement by the National Bureau of Standards, nor does it imply that the products are necessarily the best available for the purpose.

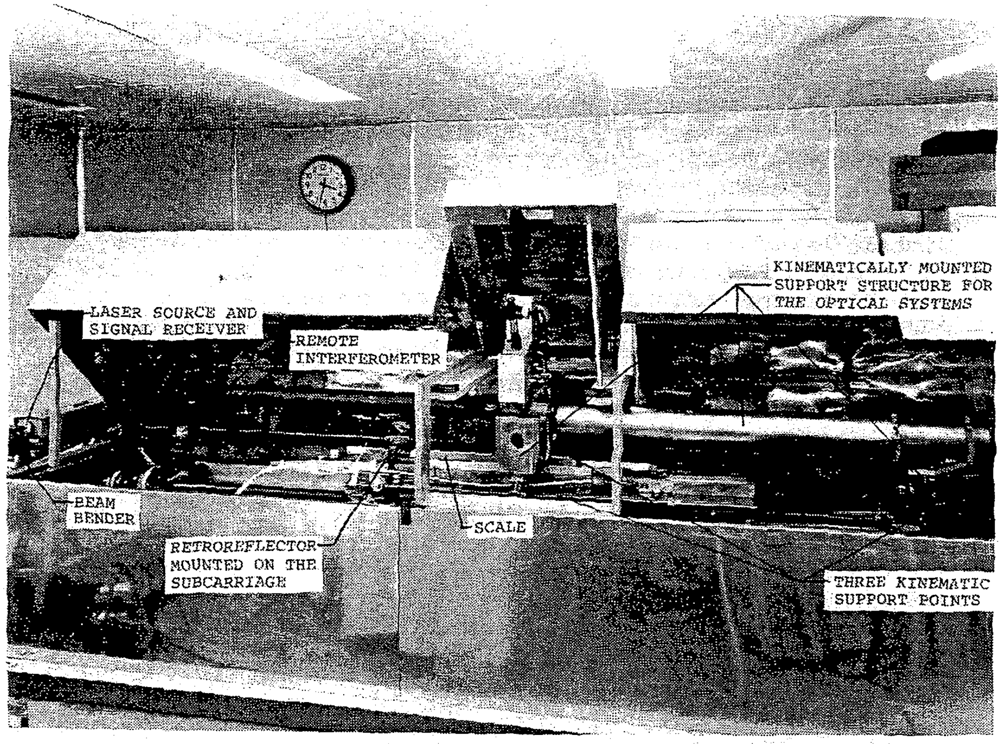


Figure 5. *The line scale interferometer with the commercial interferometer in place*

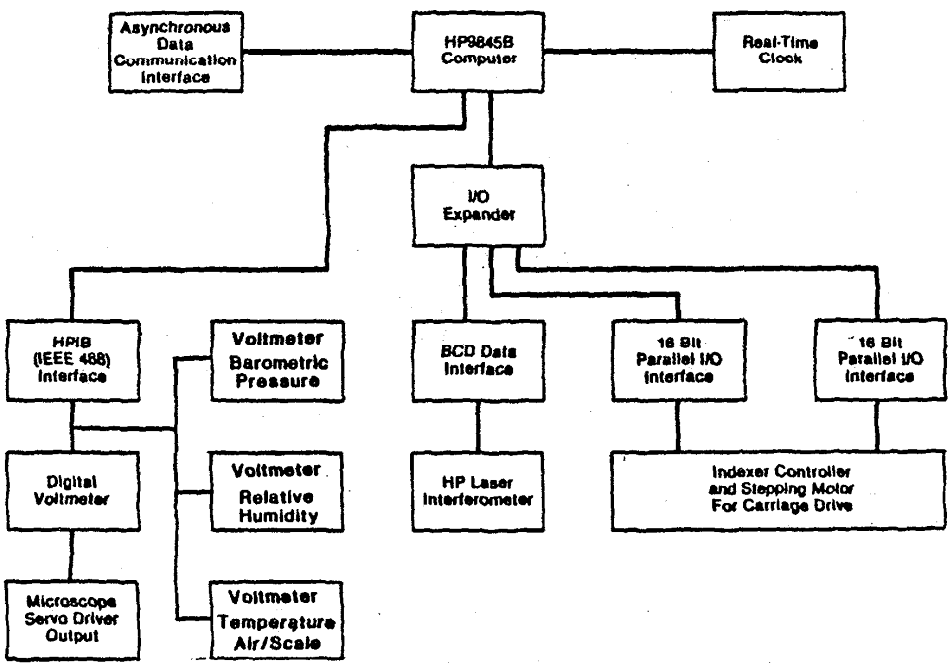


Figure 6. Block diagram of the interfaces in the automated measurement system

parameters and workpiece temperature can be compensated by dial-in switches when working in the millimeter or inch display modes. At NBS it is used exclusively in the quarter wavelength mode which is uncompensated. This ensures better compensation through the use of NBS calibrated temperature, pressure and humidity measuring instruments and computer generated computations.

2.3.3 Computer control and automation

The system has been completely automated using a Hewlett Packard 9845B microcomputer equipped with a crt display, two 256 k-byte cassette tape drives and various parallel and serial interfaces. The automated line scale measurement system is shown in figure 6.

Operation and control of the microscope servo, data acquisition from the interferometer outputs, and statistical analysis on the raw data can all be performed under computer program control. A clock module adds a real-time reference and time related control to the computer. It also enables the computer to keep track of the time of day to interpolate environmental effects. The indexer/controller is interfaced with the computer through two 16-bit parallel I/O interfaces. The interface connections allow the computer to command the indexer to perform jogging, indexing and running operations at both low and high speed.

A computer program (figure 7) operates the computer and calls for scale intervals, number of passes, coefficient of thermal expansion and other parameters to be entered as required. Once a scale is aligned, the microscope focused, and the temperature stabilized, operations in the automatic mode occur as follows: (1) the microscope servo centers the zero scale graduation, (2) the interferometer count is read when line centering criteria are met, (3) the stepping motor advances the scale to the next graduation, (4) the centering, reading and advancing sequences repeat at each selected interval until the terminal graduation is reached, (5) the selected number of passes up and down the scale are made, (6) air temperature, scale temperature, barometric pressure and humidity are measured and entered in the data file at the end of each pass, and, (7) when all data are recorded, the computer calculates, analyzes and tabulates the measurement results and prints the calibration report tables.

Increased efficiency has resulted from the improved and modernized automation. Scale calibration time from the reading of the first graduation to the final print-out has been reduced by factors ranging from five to ten.

2.4 Environmental measurement and control

Temperature, barometric pressure, humidity and carbon dioxide content influence the refractive index of air and, thus, the wavelength of light; temperature also affects the length of the scale being measured. Air temperature, scale temperature, barometric pressure and humidity are measured during every line

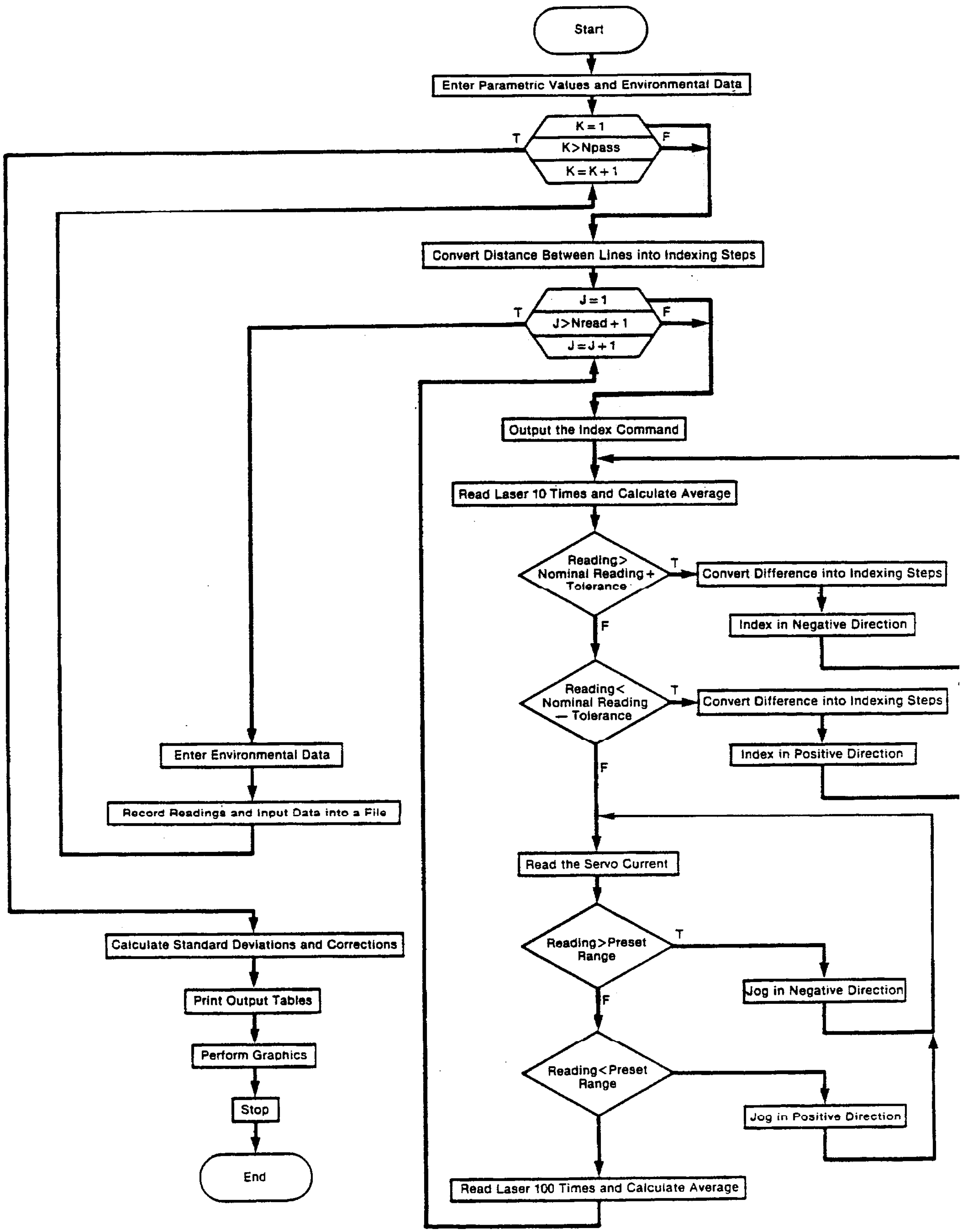


Figure 7. Flow chart for the automated measurement system

scale calibration. An average value is used for carbon dioxide content because it stays relatively constant and has a small effect on the refractive index.

2.4.1 Temperature measurement and control

Interferometer air path temperature and scale temperature are measured with copper-constantan thermocouples in combination with a standard platinum resistance thermometer (SPRT). A thermostatically controlled cell provides a stable 20.000 degree C temperature which is measured by the SPRT, and serves as a reference temperature for the thermocouples (figure 8). Thermocouples are used rather than thermistors because the long term stability of thermocouples is superior and because they can be easily referenced to the International Practical Temperature Scale through the SPRT.

Three concentric copper tubes comprise the reference cell. A thermoelectric cooler is attached to the outer tube and the fins of the cooler are exposed to air flow from a fan. Resistance heating wire is wrapped uniformly around the second tube and these windings are fed by a current controller. The inner tube is wound with platinum wire which constitutes one leg of a bridge circuit. A null detector in the bridge circuit feeds its error signal into the current controller. The platinum winding thus acts as a resistance thermometer with its null detector forming the feedback loop by controlling current through the heating coil. Constant cooling is therefore offset by modulated heating to produce the desired temperature. Cell temperature is monitored with the sprt. When cell temperature drifts away from 20 degrees C an adjustment is made by hand to a controller circuit potentiometer. Stability of the system is such that a daily adjustment will keep the cell temperature at a constant 20 degrees C to better than a millidegree.

Laboratory temperature is controlled at 20 degrees C ±0.05 degree by a special air conditioning system but, in addition, the interferometer enclosure is also controlled to give maximum temperature stability to the interferometer and the scale under calibration. The housing is constructed of 19 mm thick plywood and is lined with 1 mm thick copper. The 60 mm space between the plywood and the copper lining is completely filled by expanded polystyrene insulation and copper tubing soldered to the lining. A multibladed, 0.5 m diameter, slow-speed fan sits horizontally on the bottom of the enclosure. It is driven by an external motor and it gently stirs the air to reduce temperature gradients. Thermostatically controlled water circulated through the copper tubing produces the desired temperature within the enclosure.

The temperature of the circulating water is controlled by heating and cooling elements in the reservoir. A constant rate of cooling is achieved by circulating 14 degree C water from the laboratory chilled water supply system through a heat exchanger. Current through an electric heating element is modulated by a

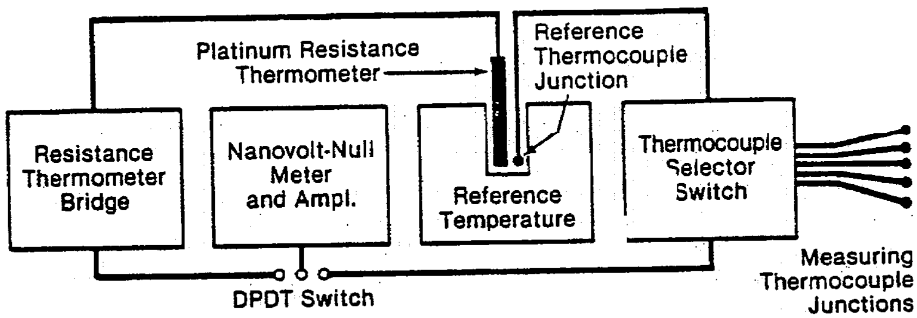


Figure 8. Schematic diagram of the temperature measuring system

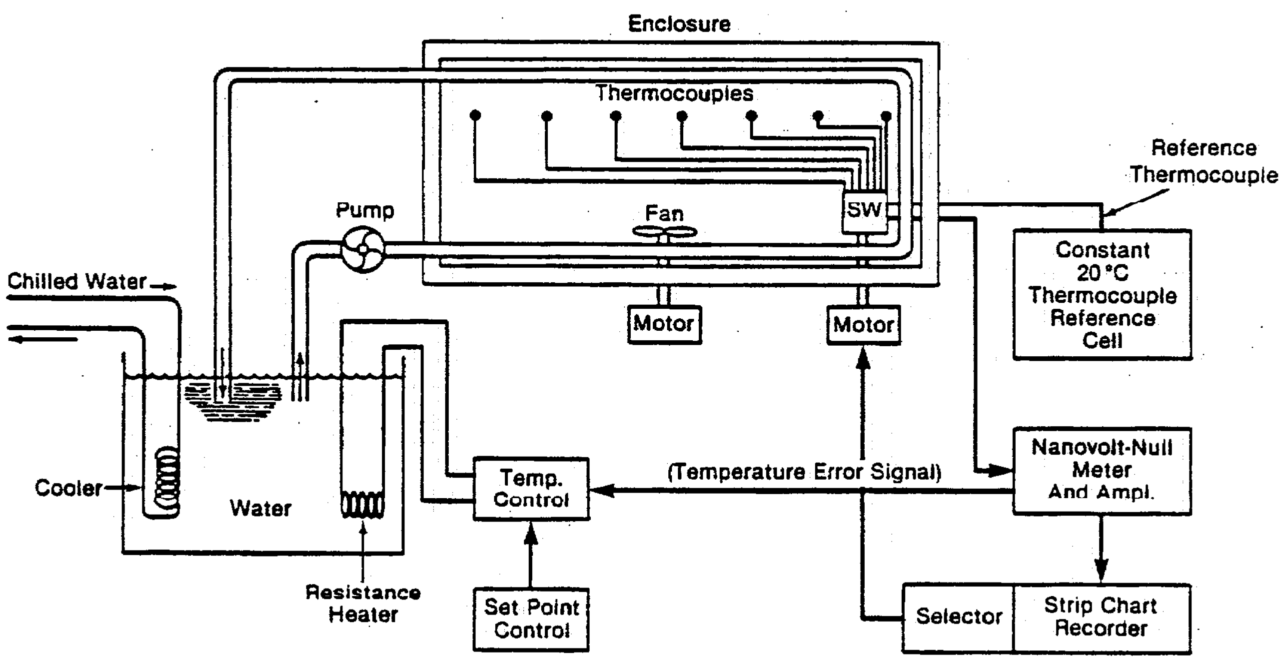


Figure 9. Schematic diagram of the temperature control system

timing circuit controlled by feedback from a thermocouple in the temperature measuring system (figure 9).

There are ten thermocouple junctions inside the enclosure. Two are in the interferometer air path, three are on the scale being measured and the rest are on various parts of the instrument where they are used to detect gradients and stability. A motor driven selector switch allows temperatures to be read sequentially and displayed on a strip chart recorder. There are two operating modes for the system: control and measurement. In the control mode, the selector switch is locked on one thermocouple in the interferometer air path. Since the reference point for the thermocouples is at 20.000 degrees C, any measurable thermal emf indicates a deviation from 20 degrees in the air path and is used as an error signal to adjust the water bath temperature and complete the loop back to air temperature. Null voltage is the 20 degree mark at the center of the recorder scale. Graduations in millidegrees extend for 50 divisions (0.05 degrees C) on each side of the center for use in the measurement mode. Periodically during a scale calibration the measurement mode is used by unlocking the selector switch and reading air path and scale temperatures for use in computing scale length.

The system is calibrated and related to the International Practical Temperature Scale of 1968 (ref. 11) using the procedures described in appendix A.

2.4.2 Atmospheric pressure measurement

Barometric readings are taken with an electro-mechanical pressure transducer. The transducer has a sealed chamber with a low stress diaphragm in one wall. As the diaphragm moves with changes in pressure its position is detected with a capacitance probe and an output voltage proportional to the atmospheric pressure is displayed. An NBS calibration establishes the exact relationship between pressure and voltage. See appendix B for calibration and verification procedures.

2.4.3 Water vapor measurement and control

Relative humidity is measured with a Dunmore type hygrometer. Electrical resistance of the sensing element in this instrument changes with air moisture content and, with periodic calibrations, uncertainties can be held to 1.5% relative humidity (ref. 12 and 13). See appendix C for calibration methods.

In order to reduce the possibility of rust forming on steel parts, laboratory relative humidity is held below 50%.

2.5 Length computations

Data from the line scale measuring system are in the form of fringe counts recorded at each observed scale graduation. These data must be converted into scale interval lengths at 20 degrees C. To accomplish this, the fringe count recorded at the zero graduation is subtracted from each succeeding fringe count. This results in interval lengths from zero expressed in half-wavelength units (quarter wavelength units for the HP interferometer). Conversion to length units is accomplished with the fringe multiplier.

2.5.1 Fringe multiplier

Three elements are combined in the fringe multiplier: (1) vacuum wavelength, λ_o , of the laser light, (2) refractive index of ambient air in the interferometer, n_{tpf} , and (3) scale expansion, α , from observed temperature to 20 degrees C.

Vacuum wavelengths for the iodine-stabilized laser are taken from CCDM recommended values (ref. 14). Vacuum wavelengths for other lasers are taken from NBS calibrations or other appropriate sources.

The refractive index of air is computed from Edlen's 1966 formula (ref. 15) (Note: the key to the symbols used below is on the next page):

$$n_{tpf} = 1 + AB - C \tag{1}$$

where

$$A = \{ p [8342.13 + 2406030 (130 - \sigma^2)^{-1} + 15997 (38.9 - \sigma^2)^{-1}] 10^{-8} \} / 720.775 \tag{2}$$

$$B = \frac{1 + p (0.817 - 0.0133t_a) 10^{-6}}{1 + 0.003661t_a} \tag{3}$$

$$C = f (5.7224 - 0.0457 \sigma^2) 10 \tag{4}$$

Wavelength in ambient air can then be determined from the fundamental relationship

$$\lambda_{tpf} = \frac{\lambda_o}{n_{tpf}} \tag{5}$$

Scale expansion to 20 degrees C is expressed by

$$\Delta L = \alpha L (20^\circ - t_s) \tag{6}$$

The wavelength in ambient air and the scale expansion are combined to form the fringe multiplier, M. For the Michelson interferometer which counts fringes (half wavelengths), it is

$$M_1 = 0.5 \lambda_{tpf} [1 + \alpha (20^\circ - t_s)] \tag{7}$$

and for the HP interferometer which counts quarter wavelengths, it is

$$M_2 = 0.25\,\lambda_{tpf}\,[1 + \alpha(20^\circ - t_s)] \qquad (8)$$

All units are metric (millimeters). When a scale is graduated in inches, the fringe multiplier is divided by 25.4 (1 inch = 25.4 mm, exactly).

KEY TO SYMBOLS

f	Water vapor pressure, mm Hg
L	Nominal scale interval, mm
p	Atmospheric pressure, mm Hg
t_a	Air temperature, degrees C
t_s	Scale temperature, degrees C
α	Linear thermal expansion coefficient for the scale, ppm/degree C
n_{tpf}	Refractive index of air at observed t,p,f
	Vacuum wavelength, μm
σ	$1/\lambda_o$, μm

2.5.2 Analysis of redundant measurements

Assigning uncertainties to measured length values requires statistical analysis to determine the random error component. Redundancy is built into the measurement process to provide sufficient data for this analysis. At least four and as many as fifty measurement passes are made for a scale calibration. Half of the passes are made with the scale mounted in the normal orientation (scale zero at the left) and half are made with the scale reversed (zero at the right). This reversal not only provides needed redundancy but also tends, when averaged, to cancel effects caused by possible machine distortions, photoelectric microscope bias and scale mounting distortions.

Data analysis for each measured interval includes determining mean length, standard deviation of the mean and measurement uncertainty. Uncertainty, U, is the sum of random error and estimated systematic error, se:

$$U = 3s_m + se \qquad (9)$$

where random error is taken as three times the standard deviation of the mean:

$$3s_m = 3\,\frac{\sqrt{\Sigma d^2/N-1}}{\sqrt{N}} \qquad (10)$$

and d is the deviation of a single measurement from the mean of N measurements. Variations resulting from differences between normal and reversed scale orientations are treated as random errors.

3. MEASUREMENT PROCEDURE

3.1 Planning and preparation

3.1.1 Evaluation of the scale

- Inspect for graduation quality: are they smooth, uniform, of good contrast, free from imperfections or blemishes? Graduations with sharp, smooth edges, free from imperfections, and having high contrast are the ideal. Although imperfect graduations may give good measurement precision, systematic errors can arise when the graduation viewing system is changed. There is a high probability that other viewing systems will find a different line center depending on the nature of the imperfections and the operating principle of the viewing system.

- Estimate the graduation width because it may be necessary to change the microscope objective lens if the graduations are very narrow or very wide. Table 1 is a guide to the selection of objective lenses.

Table 1. Objective lens guide

Graduation Width	Microscope Objective
2 µm or less	4 mm (40X) or 8 mm (20X)
2 to 5 µm	8 mm (20X) or 16 mm (10X)
5 to 25 µm	16 mm (10X) or 32 mm (5X)
25 µm or more	48 mm (3.3X)

Other factors must also be considered in lens selection. High magnification will make focusing difficult, especially if the scale is not flat to within the depth of focus of the lens. Low magnification will reduce reading sensitivity. Close graduation spacing may also be a factor because the microscope display screen must show only one line signal at a time and the signal must be spread out until this condition is met. When discussing calibrations with customers always emphasize that optimum graduation width is 5 to 10 um.

- Evaluate other scale characteristics with questions such as:
  1. Is the graduated face flat enough to avoid focusing problems?
  2. Are there longitudinal alignment marks on the scale?
  3. Are the graduations long enough to produce a good signal?
  4. Is the substrate material stable and is the thermal expansion coefficient known?
  5. Will the scale fit in the interferometer? (maximum width 150 mm, maximum length 1000 mm)
  6. Can the scale be supported at 2 points, or 3 points in the case of a grid plate?
  7. Is the scale rigid enough ? Scales that are thin or lack rigidity cannot be supported at 2 points and will require tedious shimming to make the top surface flat and in focus.

Once the scale is examined, the potential calibration accuracy can be estimated. If all scale characteristics are optimum then the highest accuracy can be attained if the customer needs it. Table 2 is a guide to accuracy ranges:

Table 2. Accuracy level guide

Scale Length (mm)	Accuracy level Low (µm)	Medium (µm)	High (µm)
1	.25	.10	.01
10	.50	.25	.05
100	.50	.25	.05
500	1.00	.50	.10
1000	1.50	.75	.20

3.1.2 Calibration plan

Once the accuracy potential of the scale is estimated either by examination or from the customer's description, the accuracy required and the intervals to be calibrated must be obtained from the customer. The instrument will run in the automatic mode only on groups of equal subdivisions. Calibrating more than 50 equal subintervals in one group should be avoided because of the magnitude of the work and because calibration of larger groups is generally not needed. For example, an entirely adequate calibration of a one meter scale graduated in millimeters is as follows:

Group 1. The 5 centimeter intervals (0,5,10,15,...100 cm):	20
Group 2. The millimeters in the first 5 centimeters:	50
Total:	70

This scheme provides a calibrated interval for any length from 1 to 1000 millimeters by measuring 70 intervals. Similar schemes can be devised for other scales.

The redundancy required to achieve the various accuracy levels is shown in table 3.

Table 3. Measurement redundancy guide

Accuracy Level	Total Number of Passes Required	Normal and Reversed Orient. Required?
Low	2	No
Medium	4	Yes
High	8 (minimum)	Yes

Actual measurement uncertainty is determined by the statistical analysis performed by the computer and displayed on the print-out.

3.1.3 Comparator preparation

- Clean and oil the ways, the lead screw and its bearings, the carriage rollers, the drive gears at the left end of the way bed, and the drive shaft where it passes through the housing. This maintenance should be done at least every 4 months. Heavy oil designated "Mobil Gear Oil C" is used on the gears. On all other parts use "Mobil Velocite CA". A large can of each of these oils is on hand.

- Add distilled water to maintain the reservoir level about one inch above the pump intake hole. Make sure that all return lines are flowing. Oil the pump motor every 3 months.

- Adjust the air circulating fan speed to give adequate air movement inside the housing. The fan drive motor should operate at about 100 rpm.

- Add fluid to the servo systems (line centering and parallelism) as needed. Add oil with the power off so there is no pressure on the fluid.

- Adjust the housing covers so they do not touch the microscope. Any pressure on the microscope will cause measurement errors.

- Center the two optical system support balls located under the microscope by tightening the collars, then loosen them so the balls are free to roll.

3.1.4 Scale preparation, mounting and alignment

- Cleaning. All scales, with a few exceptions, should be cleaned before calibration. Grease, dust, and finger prints on the graduations can seriously alter calibration results. If a steel scale has been greased for rust protection it must be degreased with mineral spirits then flushed with ethanol using clean surgical cotton to wipe it dry. Remove lint with a clean camel hair brush. Most scales will require only the ethanol, cotton and camel hair brush cleaning. Some grid plates come sealed in polypropelene cases and do not need cleaning. Always inspect a scale for cleanliness with a bench microscope or the comparator microscope.

- Scale mounting - general principles. (1) The method of supporting a scale influences its length except for very short scales. (2) The support method must be the same for calibrating and using a scale. (3) Many scales have markings indicating the points of support. (4) Whatever support method is used it should be easy to duplicate.

-Scale support methods.
(a) Bessel points
These points are symmetrically located 0.544L apart where L is the length of the scale body. Bessel points will minimize scale sag. One of the supports should be cylindrical or have an

inverted V cross section and should be fixed in position while the second support should be constructed so it allows freedom for expansion or contraction of the scale without imparting a twisting force. A ball in a longitudinal groove will provide this freedom, or it can be attained with crossed cylinders; the lower one fixed longitudinally under the scale and the other with an annular groove at its center so it can roll along the lower cylinder and support the scale. This latter support system is an integral part of the line scale interferometer carriage.

(b) Airy points

These points are located symmetrically 0.577L apart where L is the length of the scale body. Airy point support points are sometimes used for line scales although their best use is for long gage blocks because these points are designed to keep the end faces parallel. The support precautions stated in (a) above should be observed.

(c) Flat support

This type of support is unavoidable for long thin scales, but it requires tedious shimming and repeated flatness measurement. If there is any choice in the matter, flat support should be avoided.

(d) Other support points

Points other than Airy and Bessel are permissible but avoid point spacings that will cause excessive sag in the scale with consequent focusing problems.

- Support of grid plates

Plates measured in this apparatus are limited in size to 125 mm square. A three point support with the points forming an equilateral triangle is best. The points should be from 25 to 50 mm from the edge of the glass with two points parallel to one edge and the third in the middle of the opposite edge. Adhesive coding dots, about 1/4 inch in diameter, make good support pads. A 150 X 225 mm aluminum support plate is available for attachment to the carriage as a platform for grid plates.

- Scale alignment

Place the scale on the carriage mount with the zero graduation at the left (this is called "normal" orientation). The scale will be remounted later with the zero graduation at the right for measurement in the "reversed" orientation. Once the scale is mounted and focused in the microscope it should be aligned parallel to the ways. Most scales have alignment marks consisting of short longitudinal lines at each end of the rulings, some have continuous lines running through the rulings, and some have no marks (see figure 10).

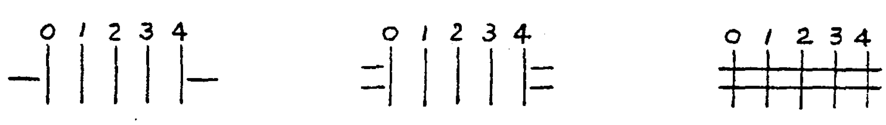


Figure 10. Typical alignment marks

Move the carriage back and forth and observe the alignment marks at each end. Make adjustments by hand at first, then with the knurled control knobs to bring the scale into good alignment. If no alignment marks are present use the tips of the graduations as a reference. Misalignment will cause length dependent errors proportional to the cosine of the misalignment angle.

3.1.5 Microscope magnification, illumination, focus and adjustment

- Magnification

The choice of magnification depends mainly on the graduation width, but it also depends on graduation spacing in finely divided scales, and on sag in long scales. Too high a magnification may make it difficult to maintain sharp focus throughout the length. On the other hand high magnification is needed to give enough separation of closely spaced graduations. Too low a magnification results in a loss of sensitivity. However, the 16mm(10X) or the 32mm(5X) objective lenses will provide optimum magnification for most scales. The table in section 3.1.1 is a guide for selecting objective lenses.

- Illumination

The illuminator lamp is powered by a d.c. source to ensure a smooth signal from the microscope detector (photomultiplier tube). Lamp voltage should not be raised above 12 volts to avoid burning out the filament. Position the lamp to give uniform illumination over the field of view. To achieve this, center a graduation in the field and observe the signal on the microscope monitor. Move the lamp around in its holder until a maximum line signal is seen and the background signal (straight part of the signal on each side of the graduation) is horizontal.

- Focus

Sharp focusing is very important in high precision measurements and should be done with great care. Coarse adjustments are made by releasing the two knurled screws locking the microscope tube and moving the microscope up or down. Always lock the kinematic support balls before making coarse adjustments (and remember to unlock them when finished). The microscope is heavy and a firm grip is needed to prevent it from slipping down through its full travel and causing damage. A lab jack is located under the microscope body to provide some control. Only an approximate focus is attempted by this procedure. Fine focusing is done by raising or lowering the subcarriage with the controls located at each end. Once the scale is in approximate alignment and focus the carriage should be moved back and forth to view alternately the terminal scale graduations. At each end check the focus by pressing down and lifting up on the carriage "U" channel which holds the scale. Note the effect on the monitor signal. The signal should be of maximum height when no pressure is applied and it should shrink in height when either upward or downward pressure is applied. Adjust focus carefully until this condition is met at both ends of the scale. Maintain alignment during this procedure. Check focus at the scale center. If the scale is not flat, the focus will not be sharp at the center. Serious degradation of focus can be remedied only by changing to a lower power objective or by changing the scale support method to reduce sag.

- Adjustments

Two additional mechanical adjustments must be made on the microscope itself (electronic adjustments are covered under 3.2, "Instrument Operation"). The first is to align the slit parallel to the graduations. This is done by swinging the photomultiplier housing, which contains the slit and is located at the top of the microscope, back and forth while watching the monitor signal. Alignment is achieved when the signal is at minimum width. The second adjustment is to mask the graduation to provide the correct line segment. Two black masking rectangles are visible in the microscope viewing eyepiece; one comes down from the top of the field and the other comes up from the bottom. They are independently controlled by adjustment screws on the left side of the microscope. The microscope does not operate on the full visible height of the field. The operational part of the field can be determined by moving one mask toward the center of the field until a barely perceptible change in signal height is seen then move the other mask until it also produces a change in signal height. These mask settings define the operational field. Further adjustments can then be made, if necessary, to limit the graduation segment to the desired length and location. Be sure to maintain alignment and focus during adjustment.

3.1.6 Interferometer preparation and alignment

- Preparation

If the compensating system for carriage pitch and yaw is not operating, the interferometer axis must be coincident with the scale graduation axis. Coincidence is achieved by changing the position of the retroreflector on the carriage until the center of the retroreflector, as indicated by the protruding pin, is coincident with the scale axis both vertically and laterally. Make this adjustment only after the scale is in focus throughout its length so that the scale elevation will not have to be changed except for fine focusing. Once the retroreflector is set on this axis the rest of the interferometer system is brought into alignment with it. Coincidence of 1 mm or better should be attained, and the longer the scale the more critical is the need for precise coincidence. Various methods can be used to project the scale axis to the retroreflector pin. One that works well is to lay a plastic ruler (to prevent scratching) on the scale face and extend its end to the retroreflector pin. When making adjustments on the microscope or the interferometer the kinematic support balls beneath the microscope should be locked with the knurled collars. Release the collars when adjustments are completed or serious measurement errors can occur. Readjustment of coincidence is needed only when a change is made in the location of the scale graduation axis relative to the retroreflector axis.

- Alignment

A complete alignment procedure is given in the appendix D . Most of the time it is only necessary to check the alignment and make fine adjustments. There is always a risk that alignment can be disturbed by visitors or others who touch the machine. The following procedure should be performed daily when high accuracy measurements are being made:

(a) Turn the laser head face plate so the two return beams show on the face plate target. Bring the small aperture into the beam with the lever on the face plate. Move the carriage all the way to the left.

(b) Check the coincidence of the measuring beam and the reference beam by alternately inserting and withdrawing a piece of paper in the measuring beam while watching the beam spots on the target.

(c) Move the carriage all the way to the right and repeat (b).

(d) If any misalignment is indicated by a lack of beam coincidence, follow the procedure in the appendix starting with step 8.

3.1.7 Temperature equalization and the measurement of environmental parameters

- Temperature equalization

The interferometer chamber is under automatic temperature control whenever the control circuits are turned on manually or by the timer. Thermocouple #5 is the sensor used to maintain control. See parts (c) and (d) in this section for the procedure to lock the system onto #5. Mounting, aligning, and focusing a scale changes the temperature of the chamber, the mechanical structure and the scale. Sufficient time must be allowed for these temperatures to stabilize and reach equality. The dynamics of thermal disturbances in this system are such that all parts must be in equilibrium before measurements are made.

The most practical schedule is to make all preparations for a calibration in the afternoon and set the timer to start the control system at about 3 a.m. The potentiometer on top of the reference temperature cell should be set to the value anticipated from experience to be the equilibrium point. Thermal conditions in the chamber will be sufficiently stable to start measurements the next morning.

An accelerated schedule can be used when short lengths are being measured or when repetitious measurements are being made and the chamber is opened for only a short time to make the preparations. For example, in calibrating grid plates where changes from one scale to another on the same plate are being made, and in calibrating short scales such as stage micrometers which require short preparation times. A judgment of the readiness of the system must be based on the temperatures at various critical points inside the chamber such as the three scale mount points, the air path, and the optical system support tube (thermocouples 1, 2, 3, 4, 5 and 8).

- Temperature measurement

Two systems are involved in measuring temperature: the temperature reference system which maintains a constant 20.000 degrees C temperature in a cell and the measuring system which employs ten thermocouples placed at various points throughout the chamber as shown in the table 4. The reference thermocouple for the measuring system is in the 20 degree cell so that the measuring thermocouples can be read directly without correcting for reference temperature. See 2.4.1 for a detailed description.

Table 4. Thermocouple locations

Thermocouple Number (switch position)	Location
1	Scale mount, right end
2	Scale mount, center
3	Scale mount, left end
4	Air in interferometer path, right end
5	Air in interferometer path, left end
6	Waybed, right end
7	Waybed, left end
8	Remote interferometer support beam
9	Chamber lining at water exit
10	Chamber lining at water entrance
11	Zero volts for nulling voltmeter

The reference temperature is maintained at 20.000 degrees C automatically for the short term (one day). A daily check and adjustment is necessary to compensate for slow drift. The reference temperature check and adjustment are performed at the beginning of each day as follows:

(1) Turn on the galvanometer illuminator and adjust the glass scale so the galvanometer cursor reads zero. (It may occasionally be necessary to adjust the mirror angle using the knob at the top of the galvanometer to get the cursor approximately centered on the glass scale.)

(2) Depress and lock the R_0 switch on the Mueller bridge and adjust the R_0 knob to give 2.0 ma through the SPRT. After approximately four minutes the SPRT current heating effect will stabilize and the galvanometer can be read.

(3) Adjust the potentiometer on the temperature controller until the galvanometer reading is zero. This must be done in steps with three or four minutes between to allow the thermometer to stabilize after each change. Turning the pot clockwise (increasing numbers) will move the galvanometer cursor to the right, and turning it counterclockwise will have the opposite

effect.

(4) When a zero galvanometer reading is achieved, release the R_0 switch to verify that the zero has not shifted. If no shift has occurred, depress and lock R_0 again and leave it locked. The system is calibrated for use with thermometer current flowing.

(5) DO NOT CHANGE ANY BRIDGE SETTINGS OR CONTROLS. The bridge is set at the 20.000 degrees C resistance of the SPRT so that when the galvanometer null reading is reached, the temperature in the reference cell is correct. The only controls on the bridge that should be operated are the R_0 switch and the R_0 current adjusting knob. A calibration report inside the bridge cover gives the value for the bridge resistance setting.

Temperature readings with the thermocouples can be made when the reference temperature stabilizes at 20 degrees C. Readings are made as follows:

(a) Normally, the system will be under control from the automatic operation of the timer switch, but if it isn't, activate the system with the timer switch.

(b) Set the Model 148 nanovoltmeter on the 3μv range. (For controlling chamber temperature, either the 10uv or the 3μv range can be used.)

(c) Swing the strip chart recorder out of its housing and grasp the chain at the upper left side. Pull this chain along to change the thermocouple numbers in the illuminated window until #5 appears. The system is locked on this thermocouple for chamber temperature control. Turn the rotary switch located to the left of the illuminated numbers from 11 to 10. When it is on 11 the chamber temperature is controlled continuously, but when it is on any other number control only occurs when that number is illuminated in the window. Unlock the control system from #5 by snapping upward the toggle switch on the left side of the recorder housing. Proceed to #11 by pulling the chain. Number 11 provides a null voltage and when this is reached the nanovoltmeter "zero suppress" controls must be adjusted to make the recorder pointer read exactly 20.000. The thermocouples can now be read in sequence as the chain is pulled along. Readings are taken directly from the chart recorder scale. Twenty degrees Celsius is at the center and the scale extends .05 degree in each direction. Scanning once through all the thermocouples will show the temperature condition in the chamber. Generally, after sufficient equalization time, the temperatures should not deviate from 20 degrees C by more than 0.01 degree except for #9 and #10 which are indicators of circulating bath temperature.

(d) When a scale is being measured, adjust the "zero suppress" at #11, record readings of #1, #2, #3, #4 and #5, and then lock it on #5 by snapping the toggle switch down. Temperature control is maintained using the thermocouple displayed in the window at the time the toggle switch is snapped down. Return the rotary switch to 11 to put the system in the continuous temperature control mode.

- Atmospheric pressure measurement
The electronic pressure transducer used to measure barometric pressure displays a voltage proportional to the atmospheric pressure (see 2.4.2). An NBS calibration establishes the exact relationship between pressure and voltage and this relationship is programmed the computer. It is important to locate the pressure transducer at the same elevation as the interferometer because pressure varies with elevation. A 30 cm change in elevation will result in a .03 mm change in pressure.

- Humidity measurement
A Dunmore type electronic hygrometer is used to measure relative humidity and the manufacturer's calibration graph is used to convert the meter reading to percent relative humidity (see 2.4.3). Exposure of the sensing element to organic solvents or their vapors can ruin the element.

3.2 Instrument operation

The following discussion assumes that a scale is mounted, aligned, and focused on the carriage in the NORMAL orientation (zero graduation at the left) and that the chamber temperature is under control and equalized.

3.2.1 Turning on the apparatus

There are two racks of electronic equipment. One has the interferometer, microscope, and carriage drive controls and displays. The other has the pressure and humidity transducer electronics plus the carriage pitch and yaw correction electronics. Each rack has a multiple outlet box that serves as a main switch. The microscope illuminator power supply is located on the elevated walkway behind the machine. Turn it on with the voltage selector switch on the 0 to 8 volt position then switch to the 0 to 16 volt position. Do not set the rheostat above the 12 volts indicated by the red marker on the dial. These procedures protect the lamp filament. Check the switches on the individual units to ensure that they are all turned on. The laser should be emitting light as indicated by the beam alignment meter. One hour warm-up is sufficient for measurement of a long scale, one-half hour for short scales. Laser stability is the principle concern in warm up. If measurements are being made every day it is best to leave the system on all the time except perhaps for weekends. At night, turn off the line servo, turn down the oscilloscope intensity and reduce the microscope illumination.

3.2.2 Controls, adjustments and displays

The following list of controls, displays and their functions is keyed to figure 11. Some of the obvious controls and displays are left out for the sake of brevity.

a. Interferometer display panel
"Prints - Plots/Min." switch should be set to MAX. "Print" switch should be set to TIMED. "Smooth" button should be ON. "Direction sense" switch should be set according to instructions displayed on the computer screen during entry of preliminary data (R for scale in normal orientation and F for scale in reversed orientation). Units switch should be on $\lambda/4$. In this mode the automatic wavelength compensation is inoperative and the computer performs the compensation.

b. Resolution extender, line centering meter and servo current meter panel
The switch on the resolution extender should remain in the "extended" position to increase the interferometer resolution by a factor of 10. Least count is then 0.025 wavelength. The decimal point on the interferometer display is actually one place to the left of its indication when the extended mode is used with millimeter or inch units. The mode has no decimal point.

The line centering meter is one of two displays of the line-centering error signal, the other one being on the oscilloscope. The graduation is centered in the microscope field when there is a null reading on this meter.

The line-centering servo current, indicated on the last meter on this panel, is controlled at 0.4 ±.02 ampere by a computer programmed jogging procedure. When the retroreflector is mounted on the scale support the program should be changed to control at 0.4 ±.10 ampere.

c. Line display oscilloscope panel
Press the CH1 and CH2 switches and set the CH1 and CH2 dials to .1 volt /div. on the dual trace amplifier. On the time base amplifier press the CHOP, AC COUPL, and EXT switches and set the VOLTS/DIV. dial to 50 mv. Adjustment for the trace displays is made by pressing the two GND switches and adjusting the two POSITION controls so that two horizontal trace lines coincide at two squares down from the top for a dark graduation on a bright background and two squares up from the bottom for a bright graduation on a dark background. Left to right centering is done with the position control. Release the two GND switches and, with a graduation in view, control the width and height of the line signal as described below. See figure 4 for a view of the line signal trace.

d and f. Line signal processor and line servo panel (d), and the high voltage power supply panel (f). (These two panels are described together because they interact.) A number of important adjustments are made from these panels: (1) Line signal width is set by dual operation of the SCAN WIDTH control on panel d and the red CAL control on the time base amplifier on panel c. As one control is raised the other is reduced to change the signal width while keeping the total trace

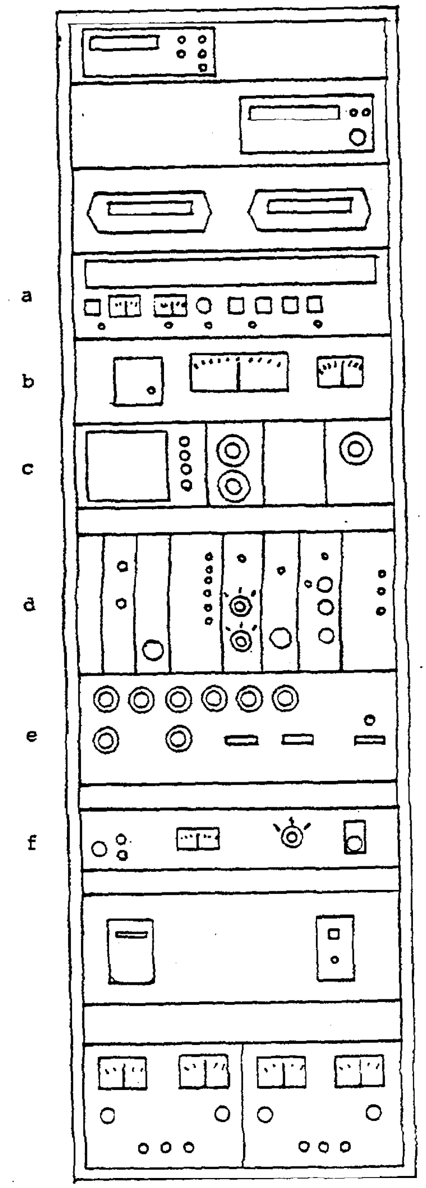


Figure 11. Controls and displays

out to the edges of the screen. Ideal width is about two grid divisions at the half height of the signal. When a scale with very small graduation intervals is being calibrated, the signal width must be widened so that only one graduation at a time is showing on the screen. The system will tend to servo on the space between graduations if more than one is present. This is the most difficult calibration to do, but it can usually be accomplished with the combination of a high magnification objective lens and careful adjustment of signal width.

(2) Line signal height is adjusted by the high voltage control on panel f, and by the gain control on the separate microscope chassis located on the back shelf of the interferometer housing. Both controls should be adjusted to obtain the cleanest line signal. Signal height should be about 3/4 of the screen height.

(3) The BRIGHT/DARK selector switch refers to the reflectivity of the graduations. It should be on BRIGHT when the graduations are bright on a dark background, and it should be on DARK when the graduations are dark on a bright background.

(4) The LINE PRESENT indicator should be lit only when a line signal is present on the screen. Turn the control knob clockwise 1/4 turn and then slowly turn it counterclockwise until the light just comes on with a steady glow.

(5) The THRESHOLD LEVEL should be set at 1/2 the line signal height in most cases. Set the selector switch on THRESHOLD and adjust the THRESHOLD LEVEL control until the half-height point is reached. This control works only when the line-present indicator light is on.

(6) The SERVO REVERSAL serves to correct the occasional tendency of the servo to repel the line rather than center it. The repelling condition only occurs when the servo switch is first turned on.

(7) The PROPORTIONAL-INTEGRAL controls influence the damping rate of the line centering process. Operate these two controls in tandem, that is, they should both be set at about the same angle. Start with the controls set at the center then apply one jog to the lead screw drive motor. The error signal on the screen should damp out within 9 to 11 seconds. Turning the controls clockwise will increase the damping counterclockwise will decrease it. Too much damping will cause imprecision from hysteresis and too little damping will cause imprecision because interferometer readings will be taken by the computer before the line is centered.

(8) The LASER DISPLAY switch permits a choice of laser display modes. In the AUTO mode changes in count are displayed only when the computer is taking data and this is often advantageous. In the MANUAL mode the display registers changes continuously. The manual mode should be used to set the counter near zero at the first scale graduation.

e. Indexer panel

The indexer controls the stepping motor driving the lead screw. It is under computer control when the switch is set to EXT, and under manual control in the UP and D positions. The SELECT switch is only operative under manual control and has JOG and RUN options. The UP position will cause the carriage to move to the left when the FUNCTION EXECUTE switch is moved downward and the D position will cause the carriage to move to the right. The SPEED control affects only high speed operation. If the speed is set too high the motor will falter and lose count. Faltering can be detected from the sound of the motor.

3.2.3 Computer/controller operation

Load the "SCALE 1" program into the computer from back-up tape #2 by using the GET "SCALE 1" command. Remove the back-up tape and substitute a data tape. The RUN key will start the program. Questions automatically appearing on the screen will lead the operator through the process of entering preliminary information and starting the run. Some of the questions require explanation:

- Data file name - this is a six place (max.) alpha-numeric identifier for the data.

- Indexing speed - high speed indexing is generally used for intervals of 1 mm or more, low speed for intervals less than 1 mm.

- Lamp - wavelength source: use 1 to indicate the HP laser.

- Scale - scale length units: 0 for millimeters, and 1 for inches.

- Low - starting graduation for the measurement, generally 0.

- High - ending graduation for the measurement in inches or millimeters.

- Step - nominal distance between calibration points.

- Coeff - thermal expansion coefficient for the scale expressed in ppm/degree C. (e.g. 11.5E-6 for a steel scale).

- System - systematic error to be used for the calibration expressed in ppm, e.g. 0.2E-6. See section 5.5 for a discussion of systematic error.

- N pass - number of measurement passes to be made on the scale, e.g. 2 means one pass up the scale and one pass down the scale, returning to the starting point. It must always be an even number of passes so that closure is achieved.

- Temp1 - initial temperature of air in degrees C (read to thousandths of a degree).

- Stemp1 - initial scale temperature in degrees C (read to thousandths of a degree)

Note: Pressure and humidity are read automatically by the computer/controller at this point.

- N Read - the number of intervals to be measured. This equals the length of the scale divided by the interval length.

- Graduation tolerance - a length limit applied to the measured position of the graduation to ensure that the correct graduation is in view. The computer/controller must decide if the right graduation is in view when it makes each stop. It does this by computing the length to that point from the fringe count and comparing it to the nominal length plus or minus the tolerance. The tolerance must be small enough to prevent setting on the wrong graduation but not so small that the natural errors in the scale will preclude an acceptance. For example, if the spacing is 0.1 mm between lines and scale errors of 0.005 mm probably exist, the tolerance should be 0.010 mm. If the tolerance is set too small the system will not read but will continue to jog back and forth looking in vain for the line.

- Date - expressed as month/day/year.

- Start - time of day pass is started using the 24 hour clock, e.g., 1300 for 1:00 pm.

- Direction - measurement direction: use 1 for going up the scale and -1 for going down the scale.

- N group - always use 1. This input has no meaning at present.

3.2.4 Reading initial environmental conditions

Read and enter the values for air and scale temperature when asked to do so by the computer. Following the procedures in 3.1.7, read thermocouples 1, 2, and 3 for scale temperature, and 4 and 5 for air temperature. Enter the mean values. Pressure and humidity are read automatically by the computer/controller.

3.2.5 Starting a run with the scale in the normal position (0 graduation at left)

Before answering the last question on the screen and pushing the CONT key to start the first pass, the laser display should be adjusted to read a small positive number. This is done by setting the LASER DISPLAY switch to MANUAL on the line signal processor and then pushing the RESET button on the laser display until the display reads a small positive number (under 100).

3.2.6 Reading intermediate and final environmental conditions

Repeat the reading procedure each time the environmental data is requested by the computer. Keep a recording barograph in operation so the trend of pressure can be observed. Weather fronts or thunderstorms can cause such rapid pressure changes that interferometric length measurements will lose precision and the degree of loss is length dependent. Do not attempt to make high precision measurements on lengths over one decimeter if the pressure change approaches 1 mm/hour.

3.2.7 Reversing the scale

When the run is complete, and the data are judged to be satisfactory, open the housing lid and reverse the scale so that the zero graduation is at the right end. Align and focus the scale then set the zero graduation under the microscope. While the housing is open either turn the temperature control off at the clock-timer or turn the thermocouple switch to No. 10 so the system will not try to correct for the disturbance. Return the system to full function when the housing is reclosed.

3.2.8 Setting controls for reversed scale orientation

Set the DIRECTION SENSE switch to F and, with the line servo on, reset the interferometer display to a small positive number.

3.2.9 Temperature stabilization

The time necessary to stabilize and control the temperature to 20 degrees C depends on how much the temperature was perturbed during scale reversal. The temperature can be monitored periodically by observing all the thermocouples. On long scales having high thermal expansion coefficients it may be necessary to allow overnight for stabilization. On other scales it may be possible to start measurements in an hour or two. Scale temperature and the temperature of the beam holding the remote interferometer are the most critical.

3.2.10 Starting the reversed scale run

The run may be started as soon as the temperature is acceptably uniform and controlled, and the switches are properly set.

3.2.11 Combining the data from normal and reversed runs

Data combination is an option in the "SCALE" program. Follow the instructions on the screen if both data sets are on the same tape. If they are on separate tapes combination is accomplished by using the pause key to stop the computer as soon as it finishes processing the normal run. Substitute the data tape with the reversed run and use the "CONT" key to resume the data processing.

If there are several pairs of normal and reversed runs they can be combined by using the "COMBIN" program which must be loaded into the computer from another program tape.

3.2.12 Operational check list

The check list in appendix E is an important aid in making reliable measurements. Review the list frequently to ensure that nothing is being overlooked in the operation and maintenance of the line scale interferometer.

4. MEASUREMENT RESULTS

4.1 Evaluation

Appraisal of calibrations must be made in conjunction with the measurement assurance program in Section 5. The combined data print-out contains information on which to base an evaluation. Figure 12 shows an example of each of the tables in a print-out. Each table has a letter designation (a through e) to correspond with the discussion of important features given below.

a. Individual pass table
There is one table for each pass made in the measurement procedure. They are not normally printed out unless, in trouble shooting, one needs to search for possible mistakes in entering data such as temperatures, pressures, etc. The means of air temperature, pressure, humidity and scale temperature are shown. The fringe multiplier is computed from the vacuum wavelength and the ambient air conditions, using the Edlen formula (see Appendix G). In the column of fringe counts the count at the zero line has been subtracted so the printed values are the lengths of the intervals in fringes. The lengths in millimeters are the result of multiplying the length in fringes by the fringe multiplier.

b. Summary tables for normal and reversed scale orientations
This table lists the correction to each measured interval at 20 degrees C for each pass. A correction is the measured value for the length minus the nominal value.

c. Comparison of mean normal and mean reversed corrections data
The difference column is particularly significant for long scales. If the differences are large in the middle of the scale and small at the ends it may mean that the microscope needs to be adjusted so its optical axis is perpendicular to the scale surface. This adjustment is described in appendix F. It also means that the scale probably sags in the middle, resulting in poor focus where the differences are large. It must be a matter of judgment whether or not to make the tedious optical axis adjustment since it may last only as long as the microscope position and objective lens remain unchanged. The reduction in measurement precision resulting from the poor focus reflects the reality of poor scale quality and can, with considerable justification, be allowed to stand. If the difference is particularly large at a specific interval then the graduation itself should be examined for asymmetry or for dirt near its edges. The scale must be recleaned and remeasured if any such condition is found.

d. Mean of normal and reversed data
Look at the uncertainty column in this table to see if it meets the measurement requirements. If it does not, it may be necessary to make more measurements (both normal and reversed) to reduce the random error component of uncertainty. If the uncertainty is unusually large for a particular interval the

500 MM GLASS SCALE

PASS 1   DATE 9/12/84   START 945

GROUP	AIR TEMP	AIR PRESS	VAPOR PRESS	EFFECTIVE WAVELENGTH	SCALE TEMP	FRINGE MULTIPLIER
1	20.0030	753.235	7.017	.6328211674	19.9940	3.16410596047E-04

INTERVAL	FRINGES	LENGTH	CORRECTION
0.000 TO 100.000	316044.19	99.99973	-.00027
0.000 TO 200.000	632088.06	199.99936	-.00064
0.000 TO 300.000	948132.21	299.99908	-.00092
0.000 TO 400.000	1264176.16	399.99873	-.00127
0.000 TO 500.000	1580220.43	499.99849	-.00151

a.

500 MM GLASS SCALE

INTERVAL (MILLIMETERS)	CORRECTION (MM)	CORRECTION (MM)	CORRECTION (MM)	CORRECTION (MM)
0.000 TO 100.000	-.00027	-.00023	-.00026	-.00024
0.000 TO 200.000	-.00064	-.00057	-.00063	-.00061
0.000 TO 300.000	-.00092	-.00083	-.00090	-.00089
0.000 TO 400.000	-.00127	-.00116	-.00125	-.00120
0.000 TO 500.000	-.00151	-.00138	-.00147	-.00141

b.

S0024N/S0024R

Comparison Of Mean Normal And Mean Reverse Correction Data

INTERVAL (MILLIMETERS)	MEAN NORM. CORR. (MM)	MEAN REV. CORR. (MM)	DIFFERENCE (NORM.-REV.) (MM)
0.000 TO 100.000	-.00025	-.00027	.00002
0.000 TO 200.000	-.00061	-.00063	.00002
0.000 TO 300.000	-.00088	-.00090	.00002
0.000 TO 400.000	-.00122	-.00122	.00000
0.000 TO 500.000	-.00145	-.00143	-.00002

c.

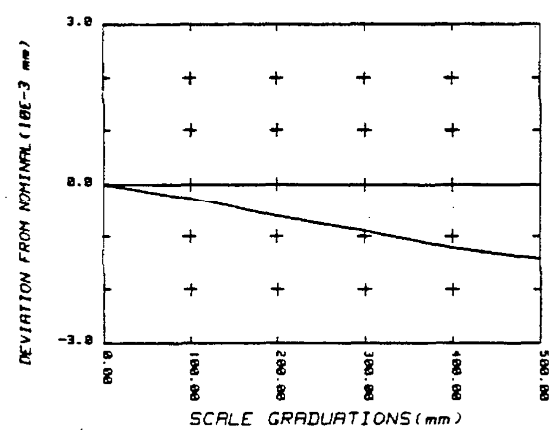
S0024N/S0024R

Mean Of Normal And Reverse Data

500 MM GLASS SCALE

INTERVAL (MILLIMETERS)	LENGTH (MM)	CORRECTION (MM)	RANDOM (MM)	SYSTEMATIC (MM)	UNCERT. (MM)
0.000 TO 100.000	99.99974	-.00026	.00002	.00001	.00003
0.000 TO 200.000	199.99938	-.00062	.00003	.00003	.00006
0.000 TO 300.000	299.99911	-.00089	.00003	.00004	.00008
0.000 TO 400.000	399.99878	-.00122	.00004	.00006	.00010
0.000 TO 500.000	499.99856	-.00144	.00005	.00007	.00012

d.



e.

Figure 12. One example of each table in a typical computer print-out

FORM NBS-443
(REV. 10-83)

U.S. DEPARMENT OF COMMERCE
NATIONAL BUREAU OF STANDARDS
GAITHERSBURG, MARYLAND 20899

REPORT OF CALIBRATION

S0055A

a. For: One Meter Steel Length Scale
SIP No. 15480

Submitted by:

b.

c. This length scale was calibrated by interferometry using a stabilized helium-neon laser as the length standard. The design and operation of the interferometer is described in Precision Engineering, Vol. 4, No. 4, October 1982, "Interferometric Measurement of Length Scales at the National Bureau of Standards."

d. Measurements were made of the last ten millimeters, the last ten centimeters, the ten decimeters, and the subdivided millimeters at each end of the scale. Results of the calibration are given on the following pages of this report. Each length value is the mean of 8 measurements and the uncertainty in each value is

$$U = \sigma_m + S.E. = \text{Random} + \text{Systematic}$$

Where σ_m is the standard deviation of the mean value and S.E. is the estimated systematic error.

e. Measurements were made using the segment of each graduation between the two longitudinal lines that run the full length of the scale.

During measurement, the scale was supported at the two points indicated on the face of the bar.

f. Normally, the millimeters and centimeters at the zero end of the scale are measured. On this bar the millimeters and centimeters at the one meter end of the scale were measured because there is some corrosion in the area of the first 50 millimeters that makes a few of the graduations unusable. This corrosion was present when the bar was received here. No attempt should be made to remove the corrosion because of the danger of altering or destroying graduations.

g. All lengths are reported at a temperature of 20° Celsius (68° Fahrenheit). A coefficient of linear thermal expansion of 11.7×10^{-6}/° Celsius was used in normalizing the lengths to 20° Celsius.

Measurements were made by William B. Penzes

For the Director,

David L. Betten

for Robert J. Hocken, Chief
Automated Production Technology Division
Center for Manufacturing Engineering

Test No. 738/S0055A
Date: July 10,1985

Figure 13. Typical scale calibration report (only one example of a table and a graph is shown)

h.

Files accumulated during this analysis:

S0055A / S0055B
S0055D / S0055C

Meter Bar SIP No. 15480 Lengths at 20 Deg. C

Mean Of Normal And Reverse Data

INTERVAL (MILLIMETERS)	LENGTH (MM)	CORRECTION (MM)	RANDOM (MM)	SYSTEMATIC (MM)	UNCERT. (MM)
0.000 TO 100.000	100.00018	.00018	.00001	.00001	.00002
0.000 TO 200.000	200.00025	.00025	.00002	.00002	.00004
0.000 TO 300.000	300.00028	.00028	.00005	.00003	.00008
0.000 TO 400.000	400.00065	.00065	.00006	.00004	.00010
0.000 TO 500.000	500.00062	.00062	.00006	.00005	.00011
0.000 TO 600.000	600.00071	.00071	.00007	.00006	.00013
0.000 TO 700.000	700.00056	.00056	.00006	.00007	.00013
0.000 TO 800.000	800.00073	.00073	.00006	.00008	.00014
0.000 TO 900.000	900.00038	.00038	.00006	.00009	.00015
0.000 TO 1000.000	1000.00000	.00000	.00007	.00010	.00017

i.

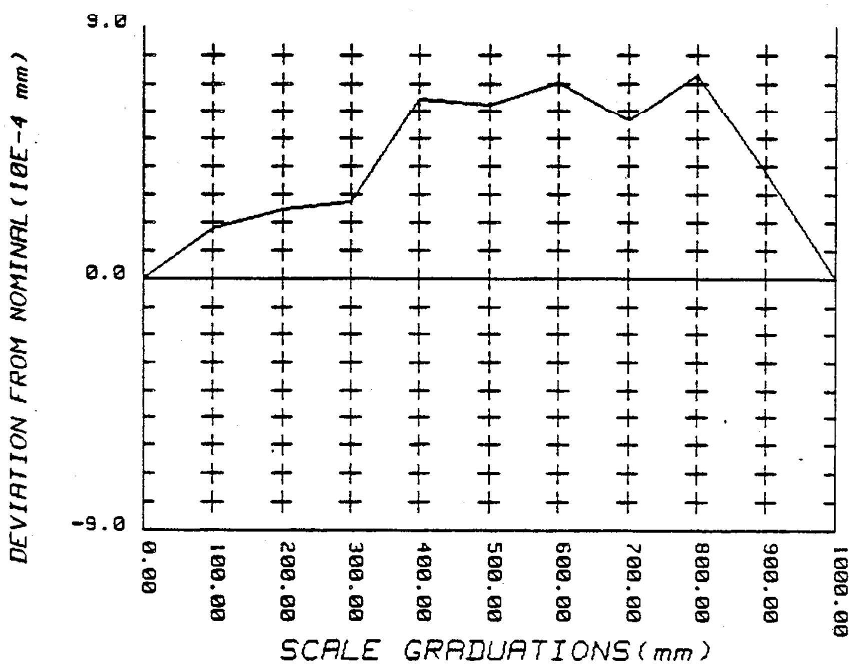


Figure 13. continued) Typical scale calibrtation report

graduation in question should be examined for asymmetry, dirt, or other flaws that could explain the lack of measurement precision. If it is dirt, or other removable flaw, the scale must be cleaned and remeasured. If the flaw is permanent, let the uncertainty stand but describe the flaw and its effect in the calibration report. This table is used in the calibration report together with the graph and text.

e. Graph of corrections
Plots of corrections are seldom smooth lines, however, they should be scanned for points that stand out from the general pattern. Use the graph in conjunction with table d for detecting possible dirty or flawed graduations.

4.2 The Scale Calibration report

Each calibration report must contain certain basic information such as scale identification, measurement method, support method, graduation segments used, number of measurements, reporting temperature, thermal expansion coefficient, table of measured values, explanation of uncertainty and any special information of importance to the owner.

A typical calibration report is shown in Figure 13. The elements of the report are identified by letter and each one is discussed below.

a. Scale identification
Each scale should have a numeric or alpha-numeric identification imprinted on it to link the report to the scale. If no identification is present an NBS number should be assigned and engraved freehand with a diamond tipped pencil or with a pantograph engraving machine.

b. Name and address of the scale owner

c. Standard introductory paragraph describing the scale and the method of calibration.

d. Scale measurement results
This is a standard statement describing the derivation of uncertainty. Modify it by inserting the actual number of measurements made.

e. Scale support method and line segment used
A description of the method of supporting the scale during calibration is included here so the scale user can duplicate it. The graduation segments used during calibration are described for the same reason.

f. Special information can be added to describe such features as defects in the scale, special precautions for using the scale, or recommendations for periodic recalibration in the case of suspected instability.

g. Temperature and scale thermal expansion coefficient
This is a standard statement indicating that all length values are reported at 20 degrees Celsius. The thermal expansion coefficient of the scale is also given.

h. Tables of measurement results
The computer print-out of the normal-reversed summary table is used here.

i. Graph of corrections
The graph of deviations from nominal lengths is used here.

5. MEASUREMENT ASSURANCE

5.1 Definition and principles

Measurement assurance (ref. 16) can be defined as a systematic program employing controls, redundant measurements and statistical analysis to determine the uncertainty of a measurement process on a continuing basis. The concept of treating regularly performed measurements as a process is the essence of the program. Any organized measurement procedure that generates statistically significant amounts of data can be treated as a process and can be monitored with controls and analyzed to reveal its characteristics.

A collection of values from repetitive measurements of a stable control standard can be characterized by the limiting mean value, process precision, systematic error and process uncertainty. The values can be plotted against time to produce a control chart showing the limiting mean and process precision. The basic assumption in most statistical techniques is that the data are a random sample from a stable probability distribution and, in most cases, a normal frequency distribution is formed. This assumption can be tested by histographic analysis and, if it meets the test and remains stable, as proven by the control charts, the process is said to be in a state of statistical control.

These are powerful tools for process evaluation because they can be used to detect errors and malfunctions of all types. Equally important, the effects of planned process changes are visible on the control chart and are quantified by the statistics. If control standard measurement data taken after each process change are analyzed as a subgroup, the effect on process precision and the limiting mean will be revealed.

Control standards have been employed in the line scale calibration process for over 50 years. The ideal control to have carried forward into the interferometric process would have been the platinum-iridium meter bar No. 27 that served as the national length standard from 1890 to 1960. Unfortunately, the graduation quality is poor by modern criteria and these bars cannot be measured with adequate precision for present needs.

Since 1966, the principle control for the interferometric process has been a modern Invar meter bar, SIP No. 5727 (usually referred to as M5727), which has an H-shaped cross section with millimeter graduations on its neutral axis. It is supported at its Airy points during use. Other controls of different lengths, materials and graduation characteristics have recently been introduced.

M5727 is always measured shortly before or after the calibration of a high precision scale more than 0.25 meter long and it is occasionally measured at other, less critical, times. Over 70% of scales calibrated are less than 0.25 meter long. Potential length-dependent systematic errors are greatly reduced for these short scales and there is less need for process evaluation with the control bar.

There are other methods for evaluating process performance at short lengths. Principal among these is the statistical analysis produced from each scale calibration. A typical analysis shows random errors that are proportional to length. Another tabulation lists differences between mean normal and mean reversed length values. A third evaluation comes from the graph of length deviations. If any of these process indicators depart from expected values, a control bar measurement should be performed. See Section 4, Measurement Results, for evaluation details.

5.2 NBS control standards

Measurement assurance for line scales consists of periodically measuring three control standards. These controls were selected for special characteristics important to the program. The most important characteristic is dimensional stability because a control that changes length would be useless for determining consistency of performance in the interferometer. Other characteristics are covered in the descriptions that follow.

5.2.1 Invar Meter bar M5727

This is the primary control for line scales. It is an Invar, H cross section bar manufactured c. 1960 by SIP. It is graduated every millimeter for the one meter length and has two subdivided millimeters (with 0.1 mm intervals), one at each end of the bar outside the one meter area. Measurements of M5727 started in 1964. This bar sags enough in the center to degrade focus somewhat in the area from 300 to 700 mm and this leads to slightly lower precision in that area. The long measurement history, the stability and the high quality graduations (for metal bars) make this an invaluable control standard.
Specifications:

Material: Invar (43% nickel steel)
Coefficient of thermal expansion: 1.23 ppm/degree C
Graduation location: on the neutral axis of the bar
Graduation width: 10 µm
Cross section: H
Alignment and graduation segment marks: two
longitudinal parallel lines, 0.2 mm apart,

running the full length of the scale.
Support method: support at the two points indicated on the front face of the bar.
Microscope objective: 32 mm (5x)

5.2.2 Twenty inch steel bar No. 6495

This is also an H cross section bar made by SIP c. 1940 for the twenty foot waybed now located in Room A 15. It is graduated at 0.05 inch intervals for 20 inches. Measurements of this bar started in 1982. It is flat (no focusing problems from sag), has high quality graduations, and has a high coefficient of expansion. The high expansion coefficient is an advantage for detecting temperature measurement problems.
Specifications:

Material: steel
Coefficient of thermal expansion: 11.5 ppm/degree C
Cross section: H
Graduation location: neutral axis
Width of graduations: 5 μm
Alignment marks: two short lines bracket the tips of the 0 and 20 inch graduations. Use the tips of these for alignment and for identifying the terminal graduations.
Line segment for measurement: use a 0.2 mm segment just below the bracketing lines described above.
Support method: support at the points marked on the outer face of the bar.
Microscope objective: 32 mm (5x)

5.2.3 Twelve centimeter quartz scale No. 5541

This quartz scale with chromium graduations is the only representative of modern transparent-substrate scales in the measurement assurance program. The scale was made c. 1960 but its manufacturer is unknown. It is graduated at each millimeter for its full length of 120 millimeters. Measurements of this scale started in 1982.
Specifications:

Material: fused quartz
Coefficient of thermal expansion: 0.4 ppm/degree C
Graduation location: upper surface
Graduation width: 12 μm
Alignment and line segment marks: two parallel lines 0.2 mm apart running the length of the scale.
Support method: Airy points
Microscope objective: 32 mm (5x)

5.3 Monitoring the process with the control standards

5.3.1 Measurement of Invar meter bar M5727

At least three measurements per year must be made of the decimeters on M5727 to provide the data base needed for measurement assurance. In addition it should be measured whenever any of the following conditions arise: (1) If a precision scale longer than 0.25 meter is calibrated, M5727 should be measured before or after (or both in special cases). (2) If any significant change is made in the measurement process such as modifying the comparator structure, changing any units of the laser system, or recalibrating the temperature measurement system. (3) If causes of suspicious data cannot be otherwise run down.

After any of these kinds of changes, a series of measurements of the decimeters on M5727 should be made, analyzed, and entered on the control charts to determine if there is a change in the measurement parameters. Only one process change should be made at a time so the cause of any performance change can be identified by measurement of the appropriate control standards.

Measurement assurance data should be maintained on the subdivided millimeter, the first 10 millimeters, the first 10 centimeters and the decimeters.

5.3.2 Measurement of 20 inch steel bar No. 6495

No. 6495 can be used in place of M5727 whenever its characteristics will be useful. For example, this scale has a thermal expansion coefficient ten times larger than M5727 so it is ideal for detecting temperature measurement errors. This scale must be measured at least twice a year to maintain an adequate measurement assurance data base. Measure two groups of graduations: (1) all the 0.05 inch intervals in the first inch and (2) each inch from 0 to 20.

5.3.3 Measurement of 12 centimeter quartz scale No. 5541

This quartz scale should be measured at least twice a year to build its data base. Measure the millimeters in the first centimeter and each centimeter from 0 to 12.

5.4 Measurement assurance data and its evaluation

5.4.1 Evaluation scope

This discussion will be concentrated on the principal control standard M5727 because it has a long history and a comprehensive data base. Measurements have been made since 1964 on the decimeter intervals. In 1984, repeat measurements were started on a group of centimeter, millimeter, and tenth millimeter intervals but there are insufficient data accumulted on these shorter intervals to be significant at this time. Results of measurements on the 20 inch and 12 centimeter control standards, which have relatively short histories, will also be discussed as well as two special intervals, 3 and 29 micrometers long. The latter two intervals give clues to the lowest uncertainties achievable.

By monitoring all these intervals, it is possible to detect (1) the effect of process changes at any length, (2) out-of-control conditions of the process at any length, (3) the effect of graduation type or quality on measurement precision, (4) temperature effects, and (5) the secular stability of the control standards. No other method of measurement error analysis can provide comparable breadth of information.

5.4.2 M5727 data evaluation

Figures 14 through 23 are control charts for some of the intervals on M5727. The principal interval, 0 to 1 meter, is shown in figure 14. Vertical dividing lines between groups of values indicate the dates of major measurement process changes. Group mean values, indicated by solid lines, and group random error limits (process precision), indicated by dashed lines, are process parameters.

Each time the measurement process is changed, the subsequent measurement values are treated as a sub-group. New process parameters are computed starting with the fourth value (a minimum for statistical significance) and are then updated periodically as data accumulates.

Process precision is taken to be $\pm 3s$ where s is the standard deviation of a single value. The significance of the random error limits is that they predict future process performance based on past performance. There is a 99.7% probability that the next value will fall within these limits. If a new data point falls outside these limits the measurement process is statistically out of control and the cause of this condition must be sought and corrected. Once the cause is corrected, it is statistically acceptable practice to delete the outlying point from the record.

There are four mean values on each of the M5727 control charts. In table 5 the symbols for these means and the process changes they represent are shown.

Table 6 is a summary of mean values for most of the intervals being monitored on M5727. Table 7 is a pro-rata adjustment of table 6 to a condition of equality of the 0 to 1 meter lengths, that is, zero correction. This removes all the length dependent differences to reveal the relative lengths of the intervals as measured by the four different processes.

Figure 14, the 0 to 1 meter control chart, shows that each of the two interferometric process changes make the interval appear longer. If all the mean lines and error limit lines are removed from the chart one might conclude from visual inspection that the meter bar is growing. However, the other charts must be examined and other possibilities considered before concluding that the bar is unstable.

Figures 15 and 16 (0 to 500 mm and 500 to 1000 mm intervals) also show the growth pattern, as expected, since their sum is equal to

Table 5. Process changes for M5727

Symbol	Process Change
M1	Mean of data from classical meter bar intercomparisons (individual points not shown)
M2	Mean of data from first interferometric measurements.
M3	Mean of data taken after the microscope, beam splitter, and reference mirror were rigidly coupled and kinematically mounted.
M4	Mean of data taken after substitution of an HP interferometer system for the original Michelson type, plane mirror, interferometer. No carriage pitch and yaw correction after this change.

the one meter interval. But when one examines figures 17, 18, 19 and 20, the evidence for instability is less convincing. Comparing the first two groups of interferometric measurements (M2 and M3) in figure 14 gives credence to the instability hypothesis but fails to do so in figures 17, 18, 19 and 20. This is because the mechanical distortions of the interferometer and microscope were not uniform over the length of the scale and the measured values were, therefore, not consistent as can be seen in table 6. Kinematic mounting of the optical elements freed the system from practically all of the mechanical distortions present in the original structure.

At the time of the first group of interferometric measurements (M2) the microscope, beam splitter and reference mirror were bolted to the waybed. Although rigidity was given to the structure with an "I" beam, coupling the microscope body to the top of the beam splitter assembly, this mounting system caused changes to occur in the distance between these optical components when the carriage, weighing over 90 kg, moved on the waybed. Any change in the relative positions of these components during a measurement resulted in an error. For this reason the M2 values are the least reliable of the interferometric measurements. However, when they were made in the 1960s, the agreement with the results of the classical meter bar intercomparisons was considered very good. The usual uncertainty for intercomparison measurements at that time was 0.5 µm. In table 6, agreement between M1 and M2 is 0.20 µm or better in all cases. The same can be said for the agreement of M1 with M3 and M4. In table 7, with relative lengths, the agreement is 0.12 or better. It is quite remarkable that such continuity was achieved in view of the major changes in techniques. Special importance was given to designing the photoelectric microscope to agree with human observers in graduation position interpretation.

Table 6. M5727, summary of mean values

Mean Corrections
(in µm)

Interval (mm)	M1	M2	(3s)	M3	(3s)	M4	(3s)
0 to 1000	1.33	1.13	(.23)	1.34	(.20)	1.42	(.11)
100 to 900	.88	.78	(.29)	.83	(.16)	.90	(.10)
100 to 800	.58	.54	(.34)	.54	(.14)	.63	(.11)
200 to 900	1.08	1.05	(.42)	1.05	(.11)	1.11	(.11)
200 t0 800	.76	.81	(.51)	.76	(.07)	.84	(.12)
0 to 500	-.01	.02	(.11)	.11	(.21)	.12	(.10)
100 to 600	.14	.15	(.23)	.11	(.14)	.19	(.09)
200 to 700	.31	.42	(.47)	.34	(.10)	.44	(.13)
300 to 800	.78	.86	(.43)	.77	(.12)	.86	(.10)
400 to 900	.80	.81	(.24)	.75	(.18)	.80	(.09)
500 t0 1000	1.34	1.16	(.14)	1.20	(.31)	1.29	(.10)
0 t0 200	-.16	-.18	(.35)	-.05	(.19)	-.06	(.05)
200 to 400	.28	.24	(.18)	.30	(.07)	.31	(.05)
400 to 600	.06	.18	(.24)	.03	(.10)	.09	(.05)
600 t0 800	.44	.40	(.13)	.43	(.06)	.44	(.05)
800 to 1000	.71	.54	(.23)	.64	(.12)	.62	(.06)
0 to 100	.04	.10	(.22)	.16	(.07)	.15	(.04)
100 to 200	-.20	-.27	(.19)	-.22	(.14)	-.22	(.05)
200 to 300	.00	-.04	(.08)	-.01	(.06)	-.01	(.04)
300 to 400	.28	.28	(.10)	.31	(.05)	.32	(.04)
400 t0 500	-.13	-.04	(.17)	-.13	(.06)	-.12	(.06)
500 to 600	.19	.22	(.08)	.16	(.12)	.22	(.06)
600 to 700	-.03	.00	(.07)	.01	(.07)	.04	(.09)
700 to 800	.47	.39	(.11)	.41	(.07)	.40	(.06)
800 to 900	.30	.23	(.20)	.30	(.08)	.27	(.06)
900 to 1000	.41	.31	(.08)	.35	(.10)	.37	(.05)

Table 7. M5727, summary of mean adjusted values

Mean Calibration Corrections
(in µm)

Interval (mm)	M1	M2	M3	M4
0 to 1000	.00	.00	.00	.00
100 to 900	-.19	-.13	-.25	-.24
100 to 800	-.35	-.25	-.40	-.36
200 to 900	.15	.26	.11	.12
200 to 800	-.01	.13	-.04	-.01
0 to 500	-.67	-.54	-.55	-.59
100 to 600	-.53	-.42	-.56	-.52
200 to 700	-.35	-.14	-.33	-.27
300 to 800	.12	.30	.10	.15
400 to 900	.13	.24	.08	.09
500 to 1000	.67	.54	.55	.59
0 to 200	-.43	-.41	-.32	-.34
200 to 400	.02	.02	.03	.02
400 t0 600	-.21	-.05	-.23	-.19
600 t0 800	.18	.18	.16	.15
800 t0 1000	.44	.26	.36	.36
0 to 100	-.09	-.02	.04	.01
100 to 200	-.31	-.39	-.36	-.35
200 t0 300	-.16	-.15	-.14	-.17
300 to 400	.15	.17	.17	.19
400 to 500	-.27	-.15	-.26	-.27
500 to 600	.06	.10	.03	.08
600 t0 700	-.16	-.10	-.13	-.10
700 to 800	.34	.28	.29	.25
800 to 900	.16	.11	.15	.13
900 to 1000	.28	.15	.21	.23

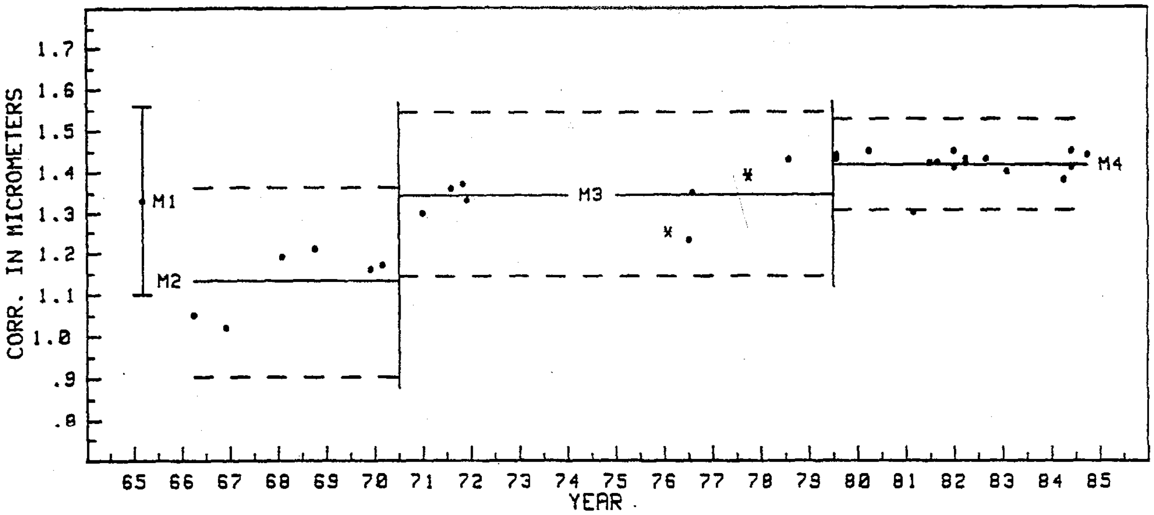


Figure 14. M5727 control bar (0 to 1000 mm)

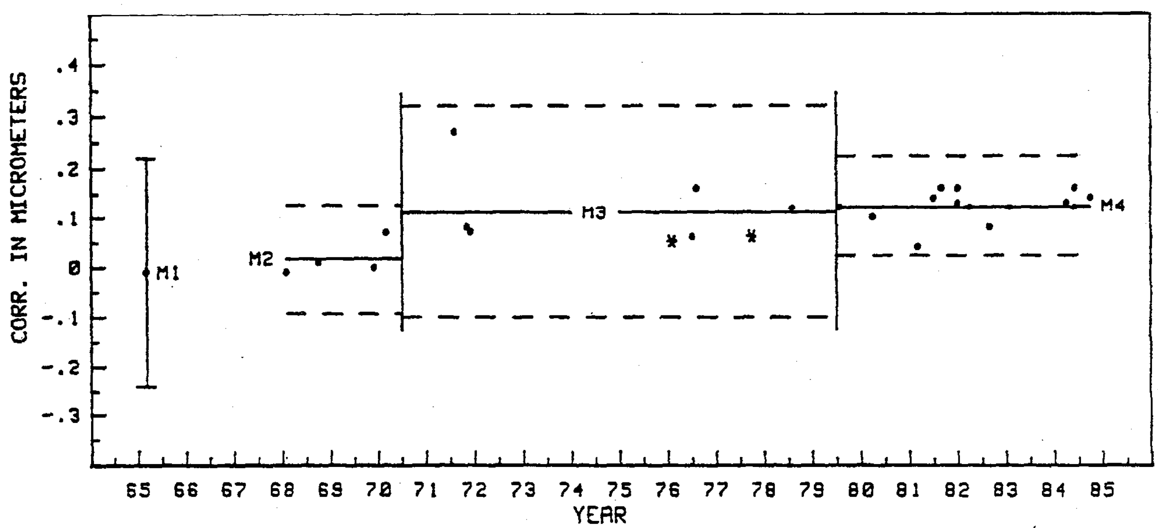


Figure 15. M5727 control bar (0 to 500 mm)

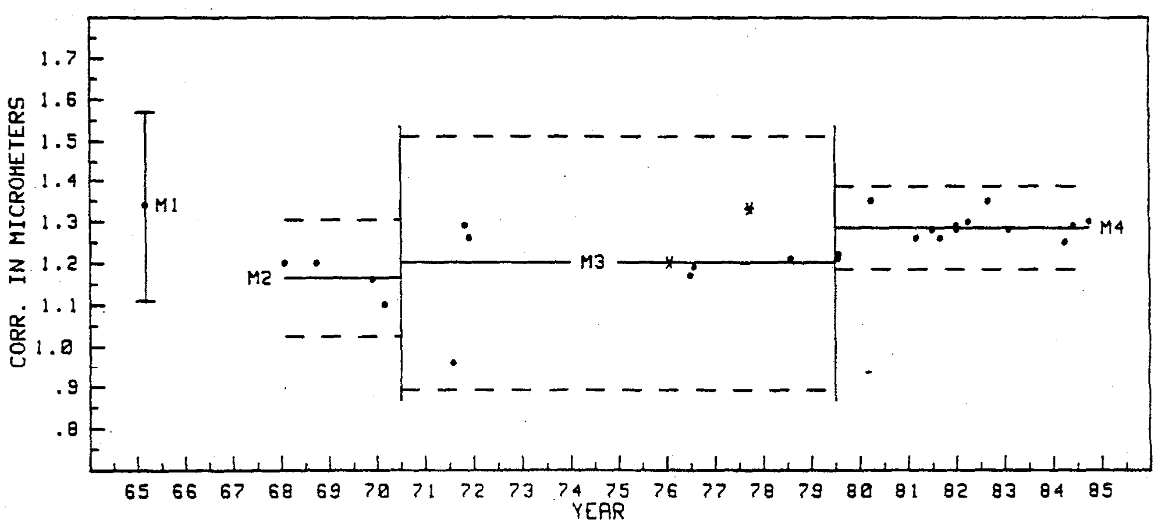


Figure 16. M5727 control bar (500 to 1000 mm)

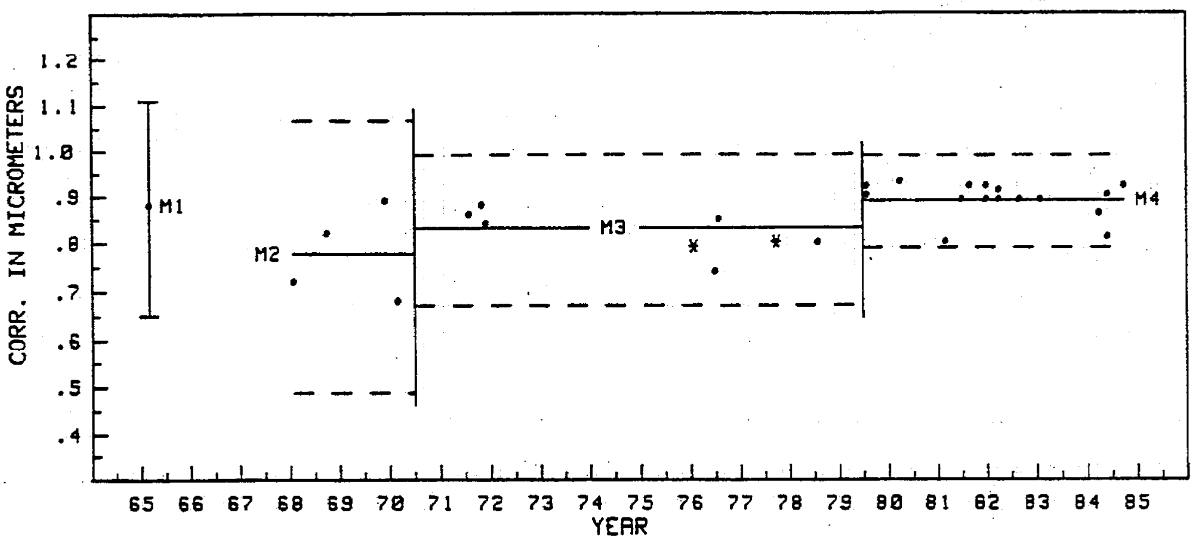


Figure 17. M5727 control bar (100 to 900 mm)

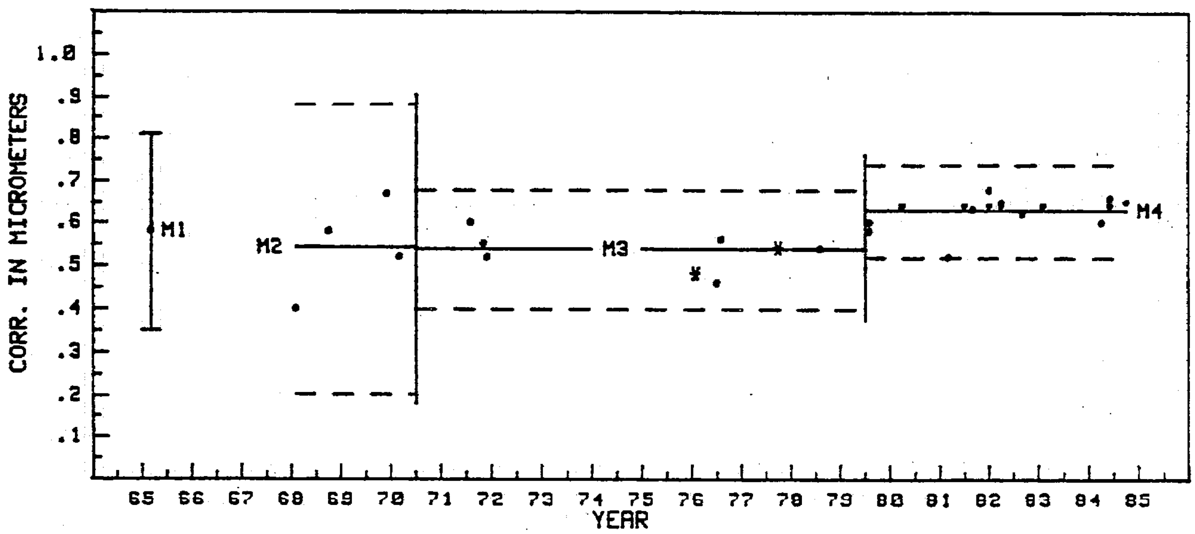


Figure 18. M5727 control bar (100 to 800 mm)

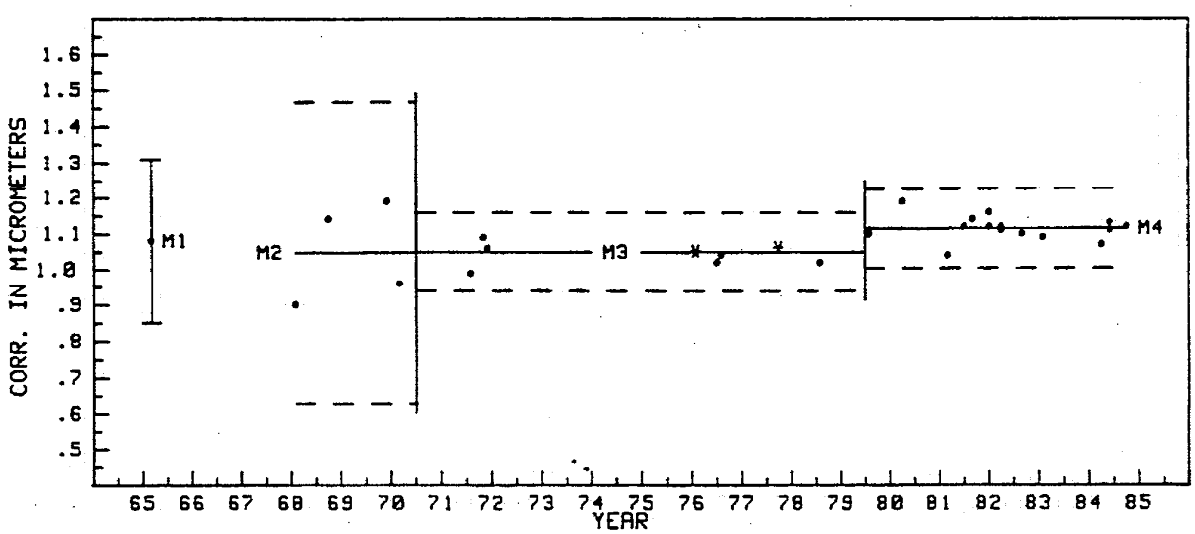


Figure 19. M5727 control bar (200 to 900 mm)

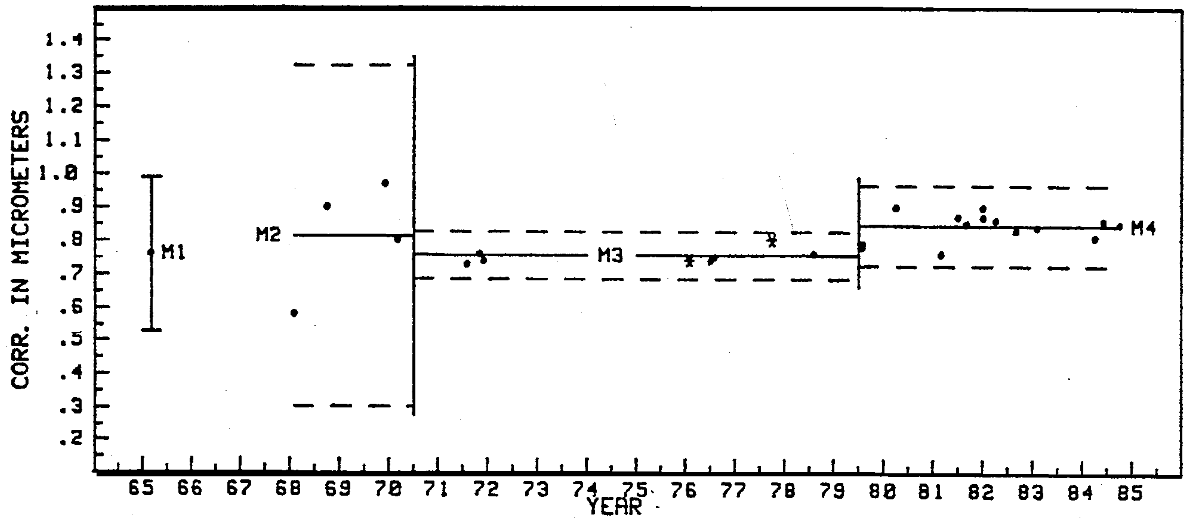


Figure 20. M5727 control bar (200 to 800 mm)

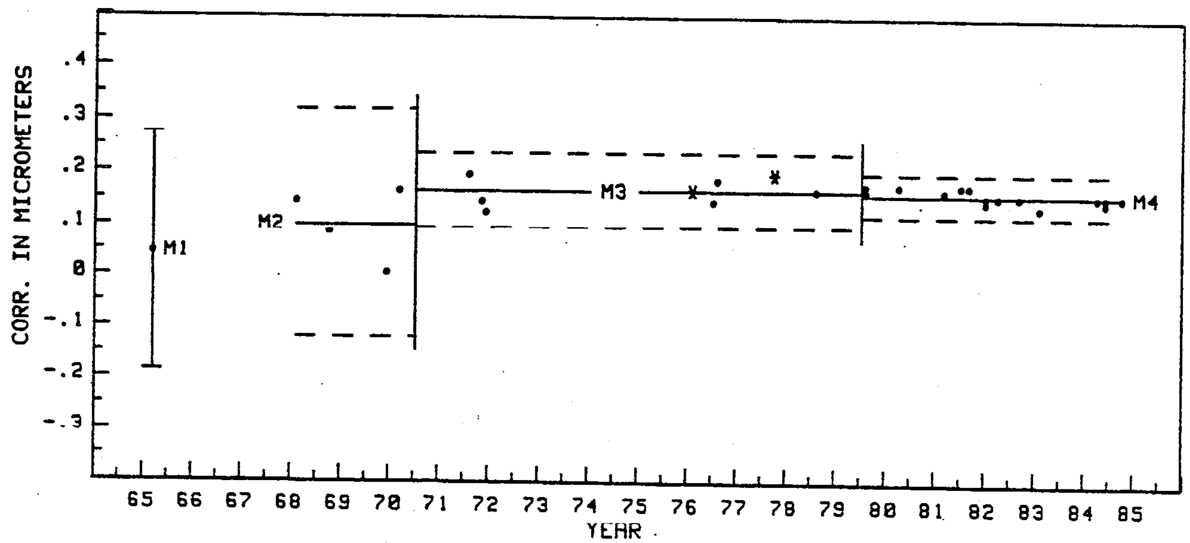


Figure 21. M5727 control bar (0 to 100 mm)

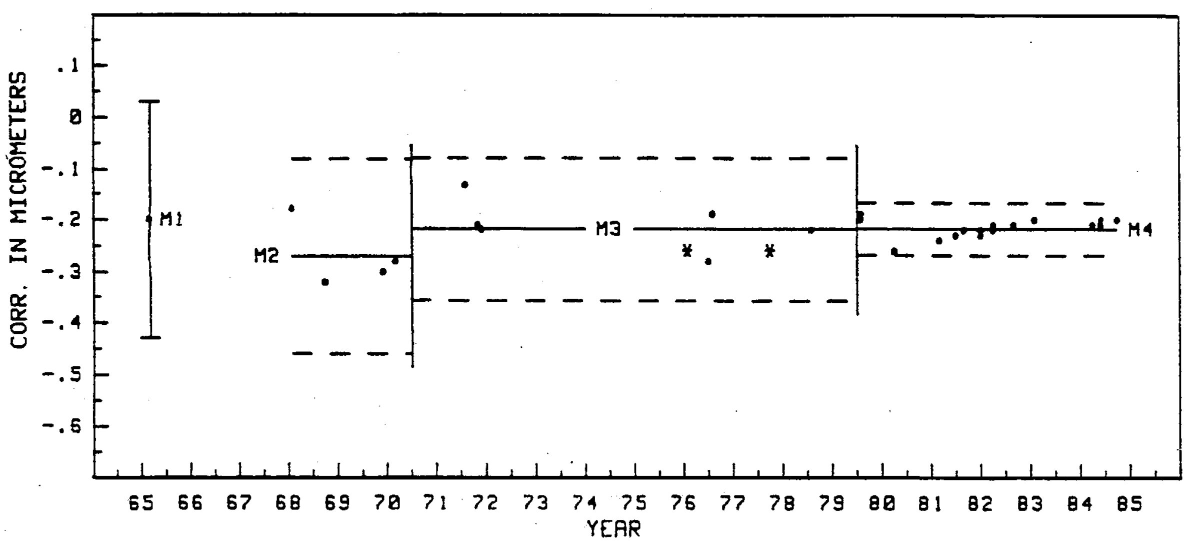


Figure 22. M5727 control bar (100 t0 200 mm)

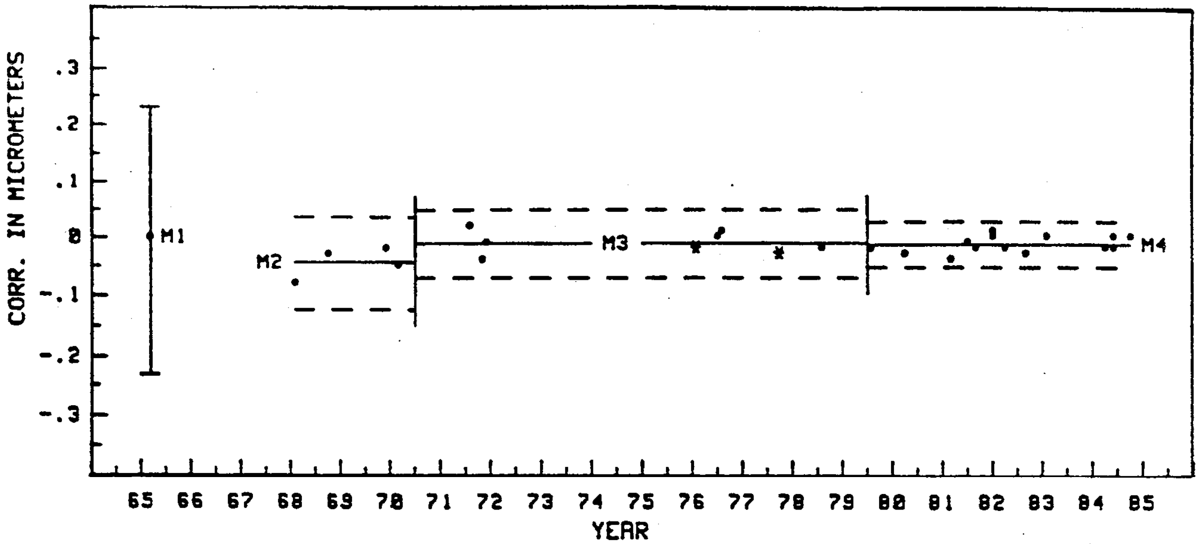


Figure 23. M5727 control chart, 200 to 300 mm

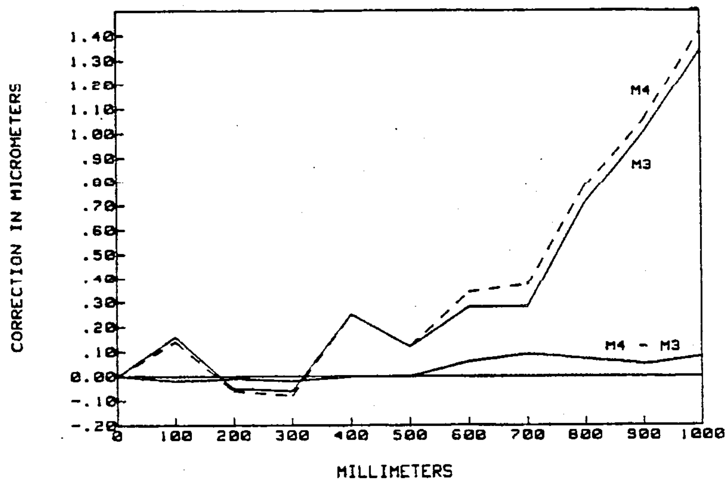


Figure 24. M5727, corrections to the dm intervals

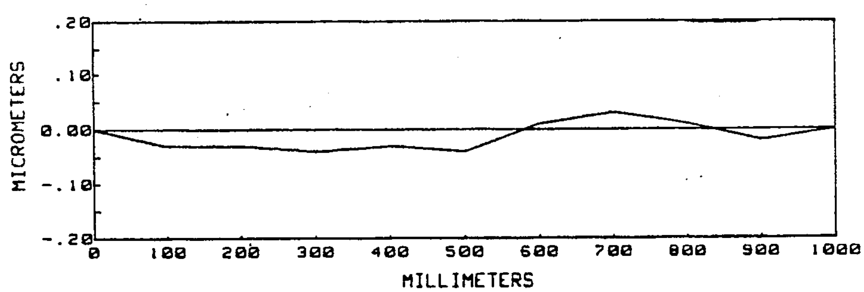


Figure 25. M5727, adjusted corrections to the dm intervals

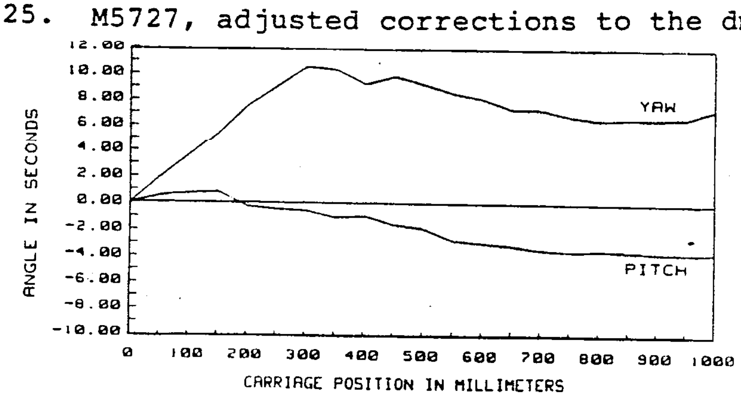


Figure 26. Interferometer carraige pitch and yaw

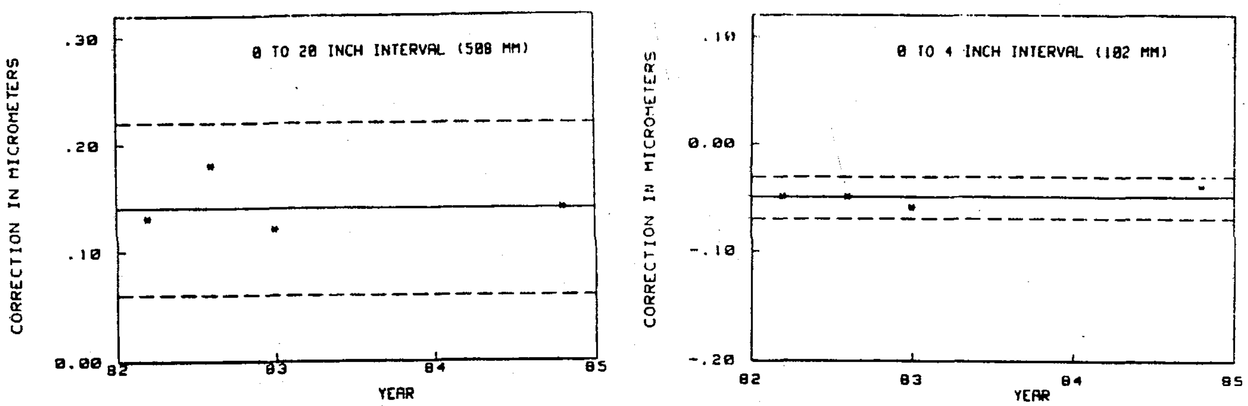


Figure 27. No. 6495, 20 inch scale, control charts

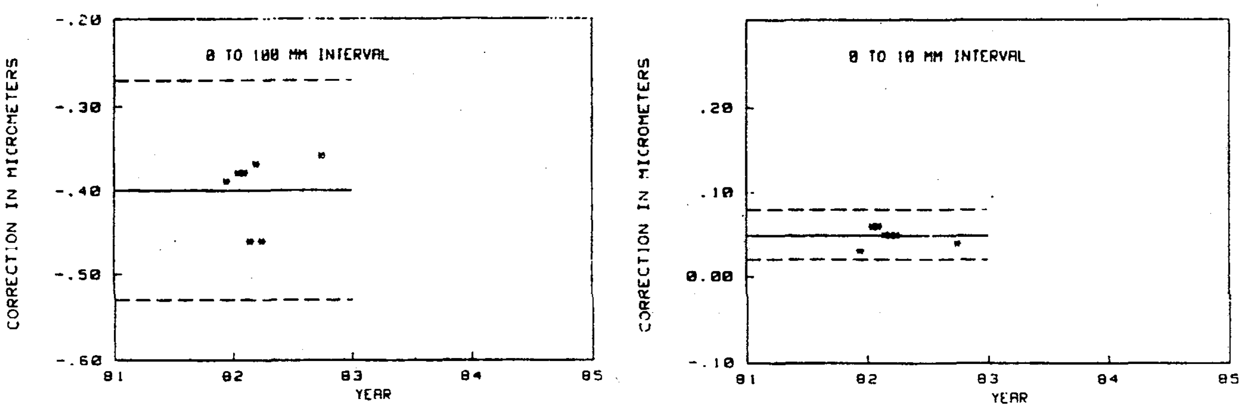


Figure 28. No. 5541, 12 cm scale, control charts

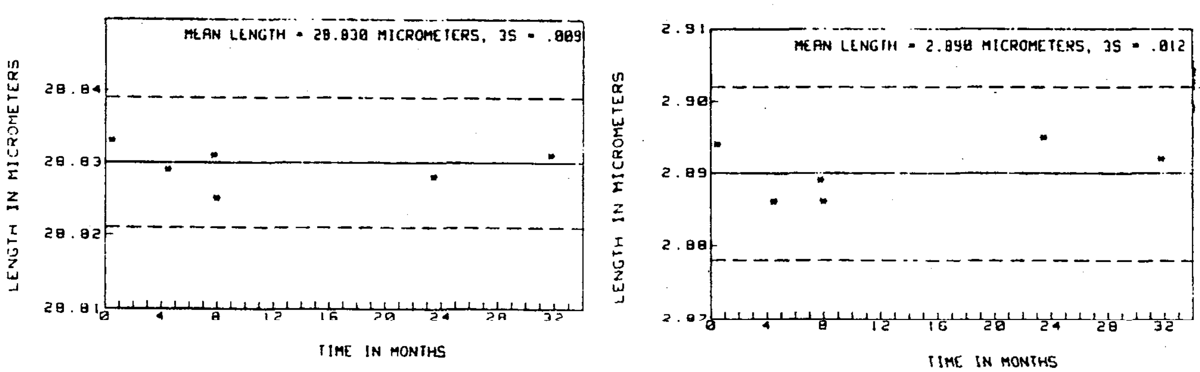


Figure 29. 3 um and 29 um intervals, control charts

On the subject of stability of M5727, there is also the distinct possibility that the increase in length values between M3 and M4 on all these charts is caused by an error in the assumed wavelength of the HP laser. The manufacturer's value is being used because the wavelength has not been measured at NBS. On the other hand, during the period represented by M3 there are two benchmark measurements made with an iodine stabilized laser (ref. 9) whose wavelength is known to a few parts in 10^9. Data points from these measurements are represented by asterisks on the charts.

Another possible contributing factor to the M4 - M3 difference is the loss of automatic correction for carriage pitch and yaw with the demise of the Michelson interferometer. Lack of carriage correction is compensated by careful alignment of the scale graduation axis with the interferometer axis to minimize Abbe' offset and its consequent length measurement error. This error is proportional to the sine of the pitch angle, and it is a random error if the scale axis is high and low by an equal amount an equal number of times. The bias, if any, is likely to be small. Figure 26 is a graph of carriage pitch and yaw.

In December 1981, an experiment was performed to determine the effect of off-axis measurements. On three consecutive days, with no change in interferometer alignment, M5727 was measured at three elevations relative to the interferometer axis: 3 mm below, 3 mm above, and on-axis. Results are shown in table 8 together with the M4 values which are the mean values for that period.

For a 5 second carriage pitch and a 3 mm off-axis mounting, the error in the 0 to 1 m length should be 0.07 µm. In table 8 the measured error averages 0.13 µm which suggests that the actual

Table 8. Effect of off-axis mounting of M5727

Interval (mm)	Corrections in Micrometers						
	3 mm High	3 mm Low	On-axis	Mean of High & Low	M4	High - On-axis	Low - On-axis
0 to 100	.15	.14	.14	.14	.15	.01	.00
200	-.05	-.10	-.08	-.08	-.07	.03	-.02
300	-.04	-.13	-.07	-.08	-.08	.03	-.06
400	.29	.19	.25	.24	.24	.04	-.06
500	.23	.07	.16	.15	.12	.07	-.09
600	.43	.27	.37	.35	.34	.06	-.10
700	.48	.31	.42	.40	.38	.06	-.11
800	.90	.70	.82	.80	.78	.08	-.12
900	1.16	.93	1.08	1.04	1.05	.08	-.15
1000	1.56	1.29	1.45	1.42	1.42	.11	-.16

pitch value may be about 8 seconds. It is unlikely that the bar has been off axis by more than 1 mm in practice, and this would result in an error, probably random, of 0.04 µm at most.

Still another contributing factor could be interferometer alignment. Misalignment always results in shorter values for the measured length, an error proportional to the length and the cosine of the misalignment angle. Alignment of the Michelson was more difficult than alignment of the HP system. It required careful tracking of the laser beam as the plane mirror was moved through the full range of carriage travel and, after the beam was expanded and collimated at a 2 inch diameter, another centering procedure was performed. Alignment of both the Michelson and the HP require very careful visual judgments. The fact that the 3s limits are larger for M3 than for M4 in all but three cases in table 6 probably indicates that the Michelson alignment procedure is more error prone and can result, on average, in shorter length values.

Figure 24 shows the complete calibration plots for M3 and M4 and the difference, M4 - M3. The length proportional component of the difference has been removed in table 7 and figure 25. This latter plot of adjusted differences shows a systematic difference with an 0.04 µm maximum. Its cause has not been proven, but it could be the result of the change from control to no control on carriage travel geometry.

A final comment about meter bar M5727: the graduated surface is not flat when the bar is mounted for measurement. Like most scales of this length and design it sags somewhat in the center area resulting in some degradation of graduation image sharpness. Careful focusing of the 0 and 1 meter graduations is always done in the preparation procedure and an objective lens is selected which is a compromise between high magnification and depth of focus. The 0 through 200 mm and the 800 through 1000 mm graduations are in good focus but the 300 through 700 mm graduations are, to varying degrees, slightly out of focus. The lowering of measurement precision caused by this condition occurs in individual runs where the normal and reversed passes are made but does not occur in the long term as demonstrated by the precision indicators in figures 21, 22 and 23 and in table 6.

5.4.3 No. 6495 data evaluation

Only limited data are available for twenty inch control standard No. 6495, but figure 27 shows that measurement precision on it may prove to be better than that for comparable lengths (500 mm and 100 mm) on M5727. This is a good sign that the temperature measurement system is working well because the thermal expansion coefficient for No. 6495 is nearly ten times that of M5727.

5.4.4 No. 5541 data evaluation

Data available from measurements on twelve centimeter quartz control standard NBS No. 5541 are also limited. The control chart in figure 28 shows a measurement precision somewhat worse than comparable intervals on M5727. This finding is unexpected because the graduations on the quartz scale are judged to be of excellent quality and superior to those on M5727. Further measurements should provide interesting information on this type of graduation.

5.4.5 Data from very short intervals

Measuring very short intervals minimizes all length dependent errors. Sufficient data are not yet available from the short intervals on the control standards, but figure 29 shows results on two very short intervals, 29 μm and 3 μm long, from a special scale measured over a 32 month period from 1976 to 1979. These data afford an assessment of the measurement process at a level where length dependent errors are at the vanishing point. The 3s limit of 0.01 μm represents the best precision attainable at that time. Ten millimeter and 4 inch intervals are shown in figures 27 and 28 for comparison and they show 0.03 μm and 0.02 μm limits respectively.

5.4.6 Summary and conclusions

This review of measurement assurance data reveals three areas where potential improvements in the measurement process can be made. First, the wavelength of the HP laser must be measured to remove its uncertainty. Second, the procedure for interferometer alignment should be improved, if possible. Third, the uncertainty about the effect of carriage travel geometry on the measurements must be eliminated. This review also reveals the power of measurement assurance to pinpoint problems.

A summary of long term precision for various lengths and control standards is given in table 9.

Table 9. Summary of long term precision

Nominal Length (mm)	Control Standard	Long Term Precision, 3s (μm)
1000	M5727	0.11
700	M5727	0.11
500	M5727	0.10
200	M5727	0.05
100	M5727	0.06
508 (20 in.)	SIP No. 6495	0.08*
101.6 (4 in.)	SIP No. 6495	0.03*
100	NBS No. 5541	0.12*
10	NBS No. 5541	0.03*
0.029	Special	0.01*
0.003	Special	0.01*

* Based on limited data.

5.5 Error sources and error analysis

Measurement uncertainty has two components: that resulting from random error and that resulting from systematic error. These two components are added to give the stated uncertainty. Random error is taken as three times the standard deviation of the mean value as shown in section 2.5.2.

Random errors are easily observed and quantified from redundant measurement data. Systematic errors come from a number of sources and result in incorrect length values. They are not readily observed, but must be searched out and corrected by painstaking experiment and analysis.

The following is a list of potential systematic error sources:

-Wavelength
- a. Vacuum wavelength of the laser
- b. Refractive index of air determination
  - (1) Refractive index equation
  - (2) Air temperature measurement
  - (3) Atmospheric pressure measurement
  - (4) Humidity measurement

-Interferometer
- a. Alignment of interferometer axis with carriage path axis
- b. Structural characteristics
  - (1) Constancy of distance between reference mirror and microscope
  - (2) Constancy of distance between beam splitter and microscope
  - (3) Constancy of distance between measuring retroreflector and scale

-Scale
- a. Scale temperature measurement
- b. Thermal expansion coefficient
- c. Graduation quality

Most of the above parameters are also sources of random error.

With the exception of structural characteristics of the interferometer and scale graduation quality, these parameters cause length-dependent errors. Their relative effects are illustrated in table 10 where it is shown, for example, that an error of 0.01 degree C in the temperature measurement of a one meter steel scale will result in a 0.1 μm error in the measurement of its length.

The structural characteristics of an interferometer can be significant contributors to error but in this case their contributions have been greatly reduced by rigid construction, kinematic mounting of critical components, and precise temperature control.

No controlled experiments have been completed to evaluate the influence of graduation quality on systematic and random errors. It is reasonable to assume, however, that ideal graduations should be between 2 and 10 um wide, have smooth sharply defined edges, be symmetrical, be uniform and free from imperfections, and have high contrast with a flawless background. Equally important is the flatness of the graduated face because a poorly focused graduation is even more deleterious to precision than a poor quality graduation. See 3.1.1, Evaluation of the scale, for further discussion of this subject.

There are two ways of estimating the systematic component of uncertainty. First, a complete error analysis can be made where each error source is evaluated and assigned an uncertainty and the overall uncertainty is taken as a combination of the individual uncertainties. Second, where completely independent and equally valid measurements of the same scale are available, the difference between these measurements is an estimate of systematic error. It is best to use both methods and that is done here.

Estimated systematic error contribution of each source is listed in the last column of table 10. The combined value is 0.15 µm/m.

Two interchanges were made to evaluate the systematic error by the second method. The first interchange was with the National

Table 10
Relationships Between Length-Dependent Errors and Errors in Measurement Parameters
and
Estimated Process Systematic Error (S.E.)

Parameter	Error in a One-Meter Length: 1 part in 10^7 or 0.1 um/m	Error in a One-Meter Length: 1 part in 10^8 or 0.01 um/m	Process S.E. parts in 10^8
Wavelength			
Vacuum wavelength	1 part in 10^7	1 part in 10^8	2
Refract. index eq.	1 part in 10^7	1 part in 10^8	5
Air temp.	0.1 deg. C	0.01 deg. C	0
Pressure	0.3 mm	0.03 mm	4
Rel. Hum.	12% rh	1.2% rh	1
Interferometer			
Alignment	0.45 mm/m	0.14 mm/m	1
Scale			
Steel temp.	0.009 deg. C	0.001 deg. C	2
Glass temp.	0.012 deg. C	0.001 deg. C	
Invar temp.	0.067 deg. C	0.007 deg. C	
Quartz temp.	0.25 deg. C	0.025 deg. C	

Research Council of Canada in 1973-74, and it resulted in a difference of 0.10 µm/m on a one meter invar scale. This exercise took place when Lamb dip stabilized lasers were in use with their uncertainties of several parts in 10^8.

The second interchange, sponsored by the International Bureau of Weights and Measures (BIPM), and involving fourteen of the national laboratories of the industrialized countries ran from 1977 to 1984. The NBS value on the one meter SIP steel scale agreed with the mean of twelve values (two values were not used because they were identified as outliers by statistical test) to the nearest 0.01 µm/m. An iodine stabilized, helium-neon laser with a wavelength stability of a few parts in 10^{11} and an uncertainty of only 2 or 3 parts in 10^9 was used in the NBS measurements.

This evidence shows that systematic error in NBS measurements is no greater than 0.15 µm/m and is probably 0.10 µm/m or better when the iodine stabilized laser is used and all subsystems are calibrated and adjusted. This must be verified by close surveillance of the two principle control standards, M5727 and No. 6495. The value on the one meter length of M5727 obtained during the period when measurements of the BIPM bar were made provides an especially strong benchmark.

5.6 Minimizing errors

In the short term, every scale measurement should be done with care by following established procedures. The following precautions and procedures are recommended:

-Review the operational check list (Appendix A) before starting a measurement.

-Update the measurement assurance data frequently by measuring one or more of the control standards. <u>This is indespensable for detecting measurement errors and instrument malfunctions.</u>

-In the long term, improvements in the measurement process should be made. Scientific methods should be scrupulously followed in designing the experiments used to examine the effectiveness of changes made in the instrumentation or procedures. Make only one change at a time and then test its effect by measuring the appropriate control.

6. APPENDICES - DETAILED PROCEDURES

Appendix A - Temperature measurement system calibration (see 2.4.1)

Four components of the system require calibration or verification: the Mueller bridge, the standard platinum resistance thermometer (sprt), the thermocouples and the nanovoltmeter. Calibration procedures and frequency are given below.

- Mueller bridge

Recommended procedures are in NBS Monograph 126, appendix H (ref. 11). All the necessary auxiliary equipment and supplies are available in the line scale laboratory.

Auxiliary Equipment and Supplies
10 ohm standard resistor, NBS No. 77613
adjustable decade resistance box
precision slide wire resistor
supply of clean mercury
heavy gauge solid copper wire

Because it changes with time, the 10 ohm standard resistor should be calibrated every two or three years by the NBS Electricity Division. The most probable value for the resistor at any given time is best arrived at by fitting a curve to the data. Five data points have been taken on this resistor since 1968.

Proceed with preparation and calibration in the following sequence:

1. Clean and grease the bridge decade switches.
2. Clean and renew the mercury on the R & N switch and the 10 ohm decade switch.
3. Replace the batteries if necessary.
4. Clean the peg in the "Zero-Meas-Ratio" switch and fit it tightly (contact resistance here will introduce errors).
5. Adjust the ratio arms to equality.
6. Determine the bridge zero.
7. Measure the 10 ohm standard at least 2 times.
8. Connect the decade resistance box and the slidewire resistor to the bridge.
9. Calibrate the 10 ohm decade of the bridge at 10, 20 and 30 ohms only (no need to go farther).
10. Calibrate the 1 ohm decade at 1 through 10(X)
11. " " .1 " " " .1 " 1(X)
12. " " .01 " " " .01 " .1(X)
13. " " .001 " " " .001 " .01(X)
14. " " .0001" " " .0001 " .001(X)
15. Remeasure the 10 ohm standard resistor at least 2 times
16. Compute the bridge corrections and write the calibration report.

- Standard platinum resistance thermometer

Initial calibration of any SPRT must be done by the NBS Temperature Group where several thermometer constants are determined and a table is prepared for the calibration report. R_0, the resistance at 0 degrees C, is the only constant that will change as long as the International Practical Temperature Scale of 1968 is in effect. R_0 must be periodically remeasured in the laboratory with a triple point of water cell, following procedures given in NBS Monograph 126, section 7. Mechanical shock to the SPRT is the usual cause of change in R_0, therefore, an SPRT that remains undisturbed such as in the line scale system is more likely to be stable than a system that is moved about.

- Thermocouples

Copper-constantan thermocouples have an average value of 40 microvolts per degree C, the value found in handbooks. This equals 0.025 degree per microvolt. Experience at NBS has shown variations from 0.0248 to 0.0252 degree per microvolt in calibrations. When the line scale interferometer is in use the temperatures of the scale and in the air path do not deviate from the 20.000 degree reference by as much as 0.025 degree. Under this condition it is not necessary to do a full calibration of the individual thermocouples. Instead, a verification of thermocouple equality is made by placing all the measuring junctions in a common heat sink such as the cavity in a copper block. After equilibrium is reached, the readings of the individual thermocouples should not deviate from each other by more than a millidegree for a temperature differential of 0.1 degree. Since thermocouples are very stable, one test for equality will suffice. If, at any time, a full calibration is deemed necessary, the procedure is described in NBS Monograph 152,section 4.1 (ref. 17).

Thermocouples must be electrically insulated from each other. Each thermocouple in this system is insulated by a layer of transparent tape, and if this insulation slips off, or wears through, a short circuit can occur. If any two or more become shorted the whole system will give erratic readings that make it obvious that something is wrong.

- Nanovoltmeter

Accuracy of temperature measurements depends upon the accuracy of the thermocouple voltage readings. Periodic comparison of the nanovoltmeter with a standard source is necessary to ensure validity. Use a precision voltage divider together with a reasonably accurate voltage input to obtain accurate nanovolt-level voltages for the comparison. Be sure to follow the manufacturers instructions for eliminating the effects of thermal emfs and offset currents.

Appendix B - Barometer calibration (see 2.4.2)

The barometer described in section 2.4.3 is a Rosemount Model 1201F. It was originally calibrated by the NBS Pressure Group. Over a period of three years it has been regularly compared with a standard aneroid barometer maintained by the Pressure Group to ensure that its original calibration is still valid. This periodic verification should continue at monthly intervals.

The comparison must be made with a transfer standard since it is not convenient to move the Rosemount to the standard barometer. A Wallace & Tiernan Model FA 139 aneroid barometer in the line scale laboratory is the transfer standard and it is calibrated by comparison with the standard barometer. It is then carried back to the laboratory and immediately compared with the Rosemount. Be sure, when comparing two barometers, that they are at the same elevation (that is, on the same table). Keep a record of the comparisons and have the Rosemount recalibrated by the Pressure Group if there is any evidence of a change.

Appendix C - Hygrometer calibration (see 2.4.3)

Calibration instructions for the hygrometer are in the manual but periodic checks against a chilled mirror standard hygrometer or other accurate reference should be made approximately every three months as a quick method of verification.

Appendix D - Interferometer alignment (see 3.1.6)

The following procedure is for aligning the interferometer when no carriage pitch and yaw correcting devices are operating. If such devices are operating, omit step 3. It is also assumed that the interferometer is badly out of alignment. If alignment verification or trimming adjustments is all that is needed start with step 8, but read step 5 to learn how adjustments are made.

1. Mount scale at selected elevation and bring it into focus.
2. Remove the remote interferometer.
3. Set the center of the retro coincident with the scale graduation axis. Make this adjustment both vertically and laterally (see 3.1.6).
4. Place the two hole magnetic target on the face of the retro and center it. Also turn the face plate on the laser so its target is at bottom center. Use the large face plate aperture in the laser beam.
5. Adjust laser elevation and azimuth until the beam tracks the target holes as the carriage is moved back and forth over its full range. Make elevation adjustments by turning all three knurled nuts equally on the large threaded vertical studs, but start with the laser head approximately horizontal as indicated by a spirit level. Make azimuth adjustments by moving the beam bender along the laser head axis. Loosen the set screw holding the beam bender and make adjustments with the screw provided. Tighten the beam bender set screw after each adjustment and re-aim the beam with the knurled knobs in the base of the beam bender. Make the elevation and azimuth adjustments when the carriage is farthest from the laser and check the adjustment when the carriage is closest to the laser. The coarse alignment is now complete.
6. Remove the target from the retro and switch to the small

aperture on the laser face plate. Track the reflected beam on the face plate target as the carriage is moved back and forth, and make elevation and azimuth adjustments as before when the retro is farthest from the laser. Check the spot position when the carriage is close. If it is off, adjust the beam bender to center the spot on the target cross mark, then move the carriage to the far end and make further adjustments. Make this alignment precisely.

7. Mount the remote interferometer and attach the two hole magnetic target to its face. Using the large aperture on the laser face plate, adjust the remote interferometer vertically and laterally until the beam enters and exits through the holes. This completes coarse adjustment of the remote interferometer.

8. Make the final fine adjustment using the small aperture. Start with the carriage close and adjust the remote interferometer by rotating it around the horizontal and vertical axes until coincidence is achieved at the target cross mark. Move the carriage to the far end and adjust laser elevation and beam bender axial position until coincidence is achieved. Continue back and forth until alignment is achieved. When making these fine adjustments, sensitivity can be enhanced by holding a piece of paper between the remote and the retro and alternately blocking and letting through the beam reflected from the retro as the target is being watched. If step 6 was done carefully and the angle of the remote interferometer was adjusted carefully in step 8, then only small adjustments in the laser elevation and azimuth should be necessary.

Appendix E - Operational check list

The following is a list of important adjustments, calibrations, maintenance items, and precautions that must be observed to ensure the integrity of line scale measurements. Each item has a section number at the end for reference to more details.

1. Kinematic support balls centered and unlocked (3.1.5)
2. Interferometer aligned (3.1.6 and Appendix B)
3. Scale cleaned, mounted, aligned, focused and set on the zero line (3.1.4 and 3.1.5)
4. Uniform illumination in microscope field (3.1.5)
5. Microscope masks adjusted to the proper line segment and microscope slit aligned with graduation (3.1.5)
6. Housing covers not touching microscope (3.1.3)
7. Oscilloscope controls set correctly (3.2.2)
8. Microscope photomultiplier voltage, gain and time constant set for optimum line signal (3.2.2)
9. Line signal on scope adjusted for width and height (3.2.2)
10. Bright/dark switch set for type of line (3.2.2)
11. "Line present" control adjusted (3.2.2)
12. Threshold level adjusted to 50% of line signal height (3.2.2)
13. Error signal adjusted for damping rate (3.2.2)
14. Laser and electronics sufficiently warmed up (3.2.1)
15. Reference temperature at 20.000 degrees C (3.1.7)
16. Temperature uniform and stable, fan running (3.1.7)
17. Atmospheric pressure sufficiently stable (3.2.6)

18. Water level in reservoir sufficient (3.1.3)
19. Hydraulic lines bled of air and filled with fluid (3.1.3)
20. Water pump motor oiled every 3 months (3.1.3)
21. Waybed and lead screw cleaned and oiled every 3 months (3.1.3)
22. Environmental measurement systems calibrated at appropriate intervals (Appendices A, B, and C)

Appendix F - Microscope angle adjustment (see 4.1 c)

The purpose of microscope angle adjustment is to make the optical axis normal to the scale axis. When this condition is met there will be minimum differences between the normal and reversed measurement values on a scale that is out of focus in the center because of sag. The reason for these measurement differences is that the apparent position of a graduation differs from its true position as shown in figure 30. Graduation displacement, x, microscope angle, θ, and the distance, d, of the graduation below the focal plane are related by

$$x = d \tan \theta.$$

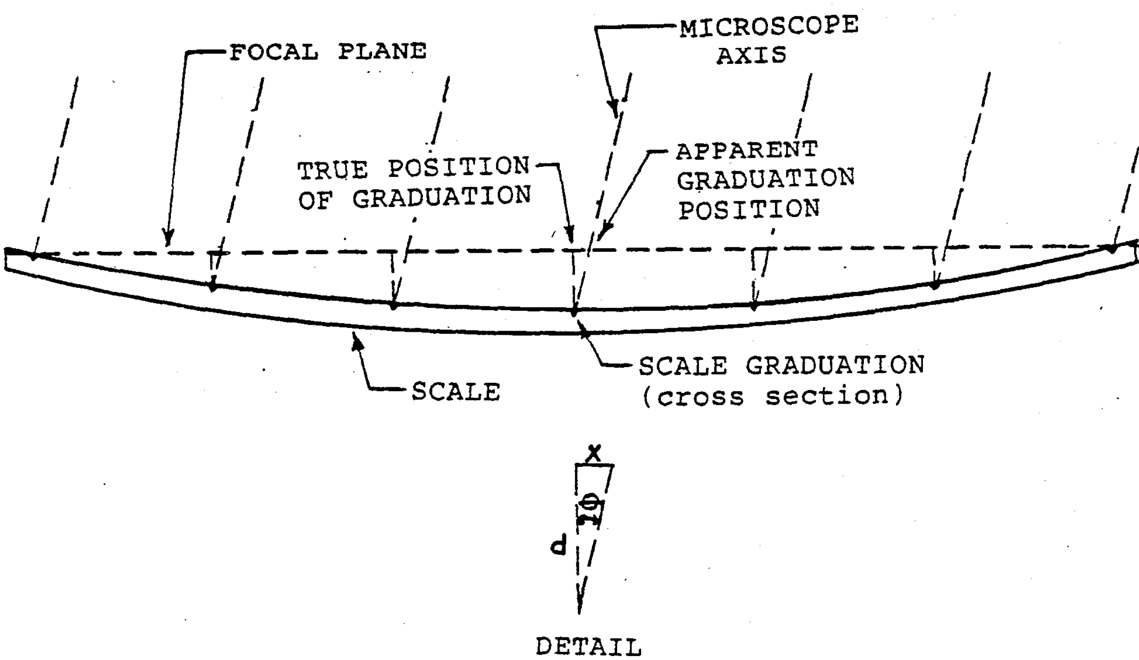


Figure 30. Effect of scale sag and microscope canting on apparent position of graduations

Table 11 shows graduation displacements for various values of microscope angle and scale sag.

Table 11. Graduation Displacement (in micrometers)

Sag (μm)	Microscope Angle (degrees) 0.1	0.5	1	2
1	.00	.01	.02	.04
5	.01	.04	.09	.18
10	.02	.09	.18	.35
50	.09	.44	.87	1.75

Angle adjustment of this microscope is a difficult procedure and the adjustment is frequently lost when the objective lens is changed or refocusing is done by moving the microscope in its collar. Furthermore, after the initial careful adjustment, the procedure has questionable value for two reasons: (1) Averaging normal and reverse values results in an accurate measurement even though the microscope is not precisely normal to the scale because the displacement of the out of focus graduations is symmetrical. (2) The effect of a small angular deviation is to increase the random error and thus the uncertainty in the out of focus area. This increased uncertainty reflects reality since a scale that sags is not of ideal quality and cannot be used to the degree of accuracy implied by measurements made with a perfectly oriented microscope.

Two methods are described below for orienting the microscope normal to the carriage travel: (1) autocollimation and (2) trial and error. The first is of marginal value because the special autocollimating lens does not produce good results and the second is tedious because it entails repeated measurements of a meter bar in normal and reversed positions. Only the angle of the microscope with the line of the carriage travel is critical. In the other direction, crosswise of the carriage, the angle is important only to the extent that it might effect scale illumination.

- Autocollimation procedure

(1) Mount the mirror on the carriage while the 32 mm objective lens is in place. Bring the mirror edges at both ends into sharp focus so the mirror lies in the plane of the carriage travel as a scale would when being measured.
(2) Replace the objective lens with the 8-inch collimating lens and raise the microscope so the end of the lens housing is about one inch above the mirror surface.
(3) Remove the masking assembly from the side of the microscope housing and insert in its place the red filter assembly (point A in the diagram).
(4) Center the red filter disc in the field of view while the normal illuminating lamp is in place.
(5) Remove the microscope illuminator lamp assembly and the

photomultiplier tube assembly to expose the microscope slit. Illuminate the slit with a high intensity lamp pointed down the microscope tube. This projects an image of the slit onto the red filter.
(6) The slit should be imaged at B (approximately on the center of the red filter) as a bright line. Adjust the illumination and the filter position as needed. The part of the image that goes through the slit in the filter is reflected from the mirror and returns to appear at C (somewhere along the slit).
(7) Rotate the collimating lens 180 degrees and observe that the reflected part of the slit image moves. This is because the lens is off axis. Make a mental note of the mean of the two slit image locations.
(8) Change the angle of the microscope until B coincides with the mean location of C. Change the angle by raising or lowering the right end of the meter long, 4-inch diameter, support tube at the support ball. When B and C coincide, the microscope optical axis is normal to the mirror.

-Trial and error procedure
(1) Measure M5727 in both normal and reversed positions and examine the N-R difference. If N-R is negative by 0.15 µm or more between the 300 and 700 mm lines then lower the right end as in step 8 above. If N-R is positive then the right end should be raised. Remeasure M5727 and again examine the N-R difference. Adjust the microscope tilt as necessary to bring the difference down to 0.15 µm or less.

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