INTERNATIONAL MEASUREMENT CONFEDERATION

Reprinted From :
IMEKO TC Series No.28

Proceedings of the Symposium on

MEASUREMENT AND INSPECTION IN INDUSTRY BY COMPUTER AIDED LASER METROLOGY

EVOLUTION OF AUTOMATIC LINE SCALE MEASUREMENT AT THE NATIONAL INSTITUTE OF STANDARDS AND TECHNOLOGY

W.B. Penzes and J.S. Beers

Balatonfured, Hungary
September 24-27, 1990

EVOLUTION OF AUTOMATIC LINE SCALE MEASUREMENT AT THE NATIONAL INSTITUTE OF STANDARDS AND TECHNOLOGY

W.B. Penzes and J.S. Beers

National Institute of Standards and Technology
Gaithersburg, MD 20899

INTRODUCTION

For many years the international length standard was the platinum iridium meter bar. Until 1960 all graduated scales were calibrated by optical comparators referenced to that meter bar [10]. In 1960, by international agreement, a new length standard was adopted. The meter was redefined as a specific number of wavelengths in vacuum of a specified spectral line of the krypton 86 atom. In 1983, the Conference Generale des Poids et Mesures (CGPM) adopted the new definition of the meter, which states that the meter is the length of the path travelled by light in vacuum during a time interval of 1/299792458 of a second [12]. Designated laser wavelengths are sanctioned as working length standards.

In 1961, at the National Institute of Standards and Technology (NIST, formerly National Bureau of Standards, NBS) an experimental fringe counting interferometer became operational using a mercury 198 light source as a length standard [1]. In 1964 a Helium-Neon Laser light source was available to measure line scales, and by 1966 a semi-automated interferometric line scale calibrator was in service [2]. Since that time numerous modifications and improvements have been made to the measuring system, and the measuring procedures [13].

THE MAJOR COMPONENTS OF THE MEASURING SYSTEM

1) A two meter waybed with a lead screw driven carriage.
2) A photoelectric microscope with a line centering servo system.
3) An interferometer with a stabilized Helium-Neon laser light source to establish a length standard.
4) A vibration isolated, temperature controlled, environmental chamber for the measuring instrument.
5) Temperature,relative humidity and atmospheric pressure measuring devices.

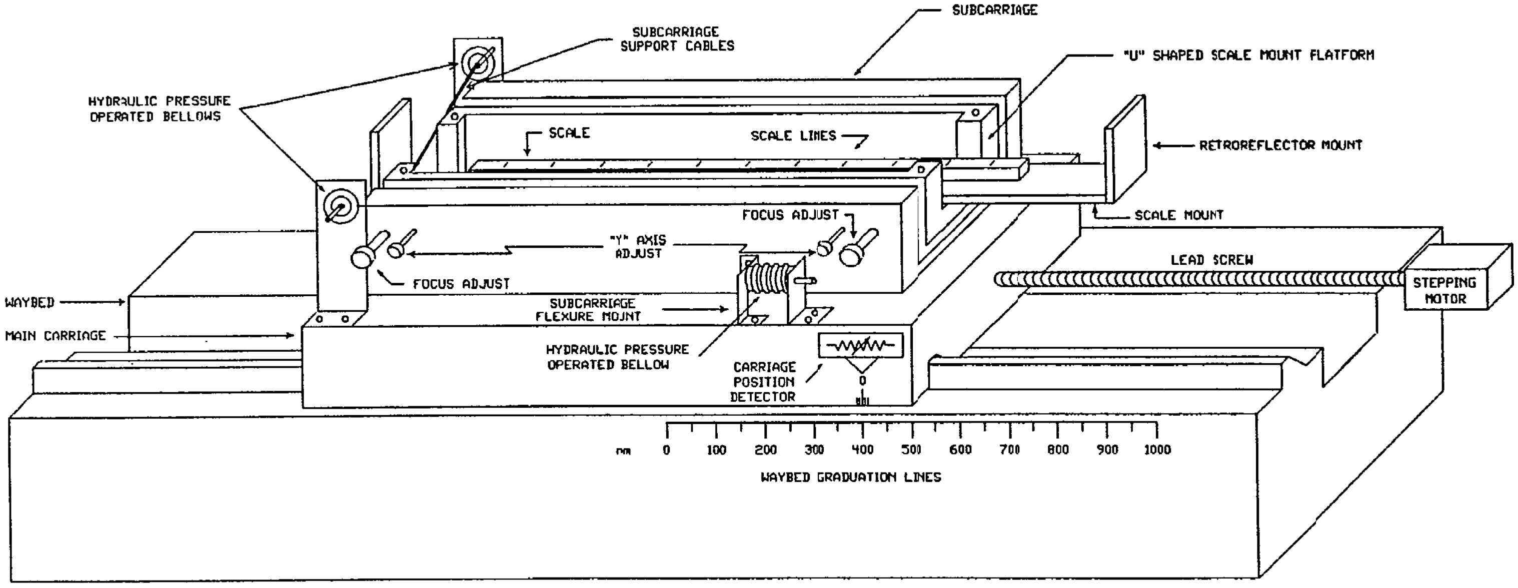


FIGURE 1. LINE SCALE WAYBED AND ITS COMPONENTS

6) A data acquisition, processing, and instrument control computer.

THE WAYBED

In Fig. 1 the two-meter waybed and its major components are shown. The components are as follows:

The main carriage with the lead screw.
Flexure and cable mounted subcarriage.
Scale mount platform with a "y" and "z" axes adjuster.
The scale mount with the interferometer retroreflector.

The main carriage is attached to the lead screw by a nylon nut and moves on hand scraped guideways with high-precision roller bearing contacts. The lead screw is operated with a flexure-coupled computer-controlled stepping motor for coarse scale positioning.

The subcarriage is mounted to the main carriage at the right end on two flexures and suspended on cables at the left end. The right end flexures are attached to a hydraulic pressure operated bellows which, with a servo controller, operates in the line centering process. The cables at the left end are also attached to a pair of hydraulic pressure operated bellows. This serves to compensate the main carriage yaw and pitch errors so that the subcarriage with the scale and the interferometer retroreflector follows a straight line motion.

The scale mount platform has two parts. The first part is a "U" shaped channel attached to the subcarriage with two sets of adjusting screws. One set provides vertical adjustment for scale focusing, and the other set is for lateral adjustment in scale alignment.

The second part of the scale mount platform is a (110 cm x 5 cm) Invar plate which is attached to the "U" channel platform at one fixed point. Retroreflectors are mounted at each end of the Invar plate for the use of two interferometers simultaneously. The measuring artifact (meter bar or other scale) is placed on the Invar scale mount and supported at the Bessel or Airy points. A wedge is used at one point and a roller at the other supporting point.

THE PHOTOELECTRIC MICROSCOPE

The photoelectric microscope is schematically shown in Fig. 2.

The principal components are:

1) A scale illuminating tungsten lamp
2) The torsional pendulum scanner
3) Several mirrors and lenses
4) The slit
5) The photomultiplier
6) The viewing eye piece

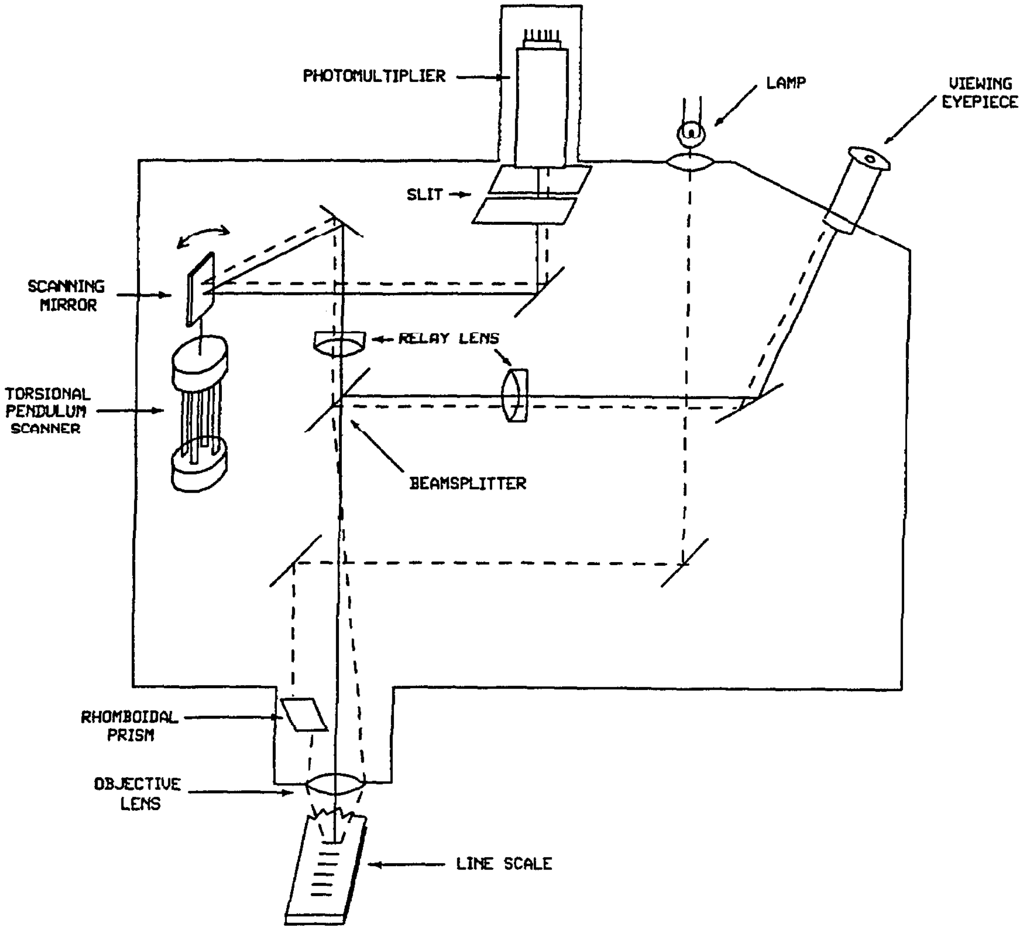


FIGURE 2. SCANNING PHOTOELECTRIC MICROSCOPE

Fig. 3 displays the schematic of the line scale line-centering servo system.

The microscope with its servo electronics performs a sinusoidal scanning of the scale lines. This mode of scanning was selected over the linear scanning to avoid all the harmonics of the scanning frequency.

The torsional (angular) scanner has a very high vibrational Q (Q = 1000) with a resonant frequency of 70 Hz. The large Q of the scanner produces very high sensitivity and excellent stability of the scanning frequency. The high sensitivity of the scanner allows very narrow scanning with high reliability. The scanning width is limited only by the perfection of the optical components and the wavelength of the illuminating light source. The scanner has a range of one micrometer to two-hundred micrometer.

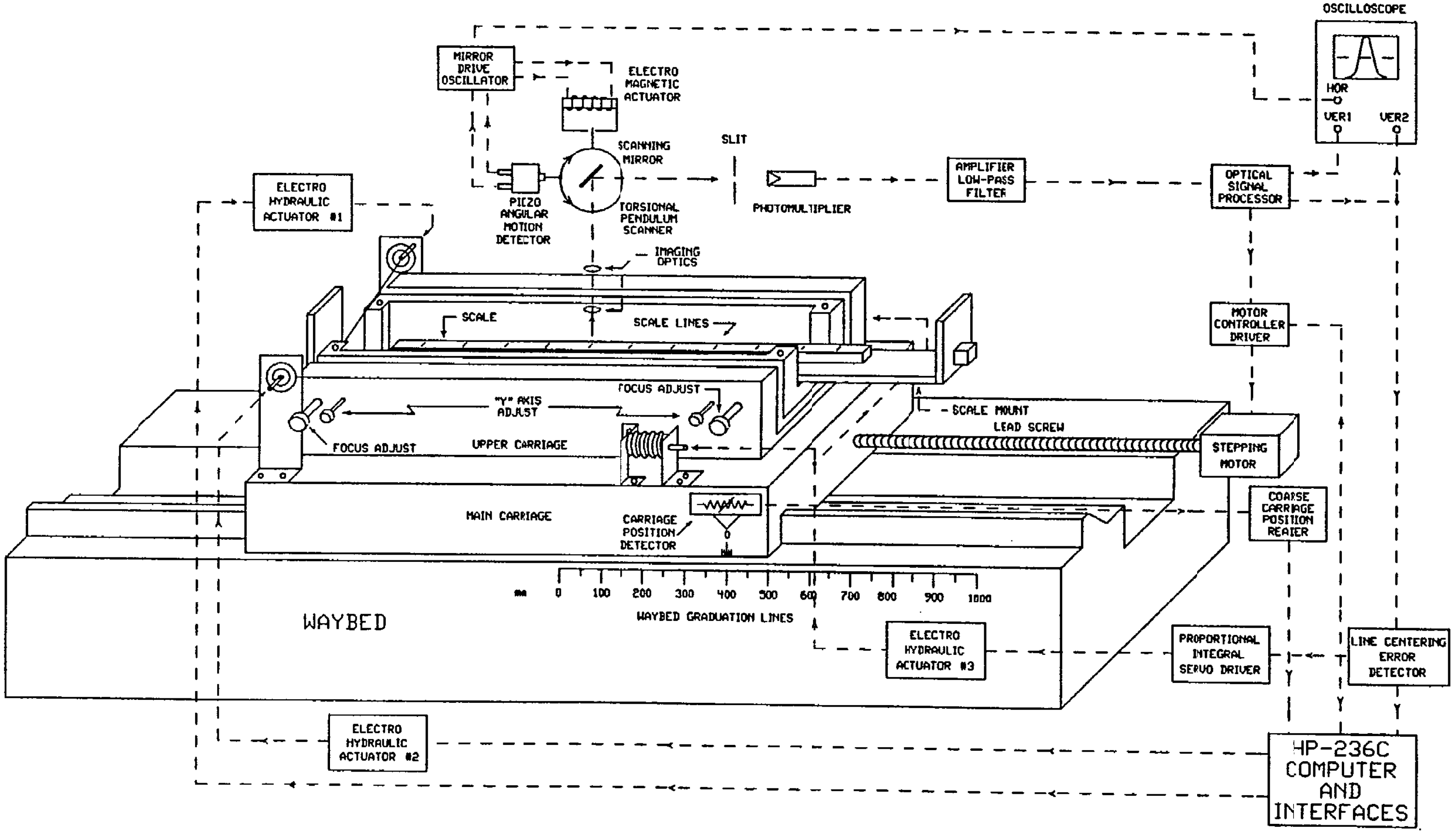


FIGURE 3. LINE SCALE MICROSCOPE SERVO SYSTEM

The microscope is actually an edge detector. It detects each edge of a graduation line. The midpoint between the two edges is the line center. The signal processor detects the maximum and minimum intensity levels of the line image and the background image. The threshold level for electronic triggering is midway between these levels. The triggering occurs when the aperture receives half of the light from the line and the other half from the background outside of the line. This occurs when the microscope is aimed directly at the edge of the line.

The microscope with the electronic detection circuits is capable of detecting and processing line edges independently or can detect line centers. The microscope can also process black lines with a reflective background or reflective lines with a black background.

LASER INTERFEROMETER

From 1961 until 1979 a Michelson plane-mirror interferometer system was used for the line scale measuring instrument. In that period several different light sources were used as length standards. Among those, a mercury-198 lamp, and a Lamb dip stabilized, Helium-Neon laser. In 1979 the Michelson interferometer was replaced by the commercially available Hewlett-Packard (HP)-5526A* laser interferometer system which is shown in Fig. 4. Compared with the Michelson system, the alignment of the optical components are much simpler. The system consists of the following components;

HP-5500C Zeman stabilized laser head
HP-5505A laser display unit
HP-10565A remote interferometer
Movable retroreflector.

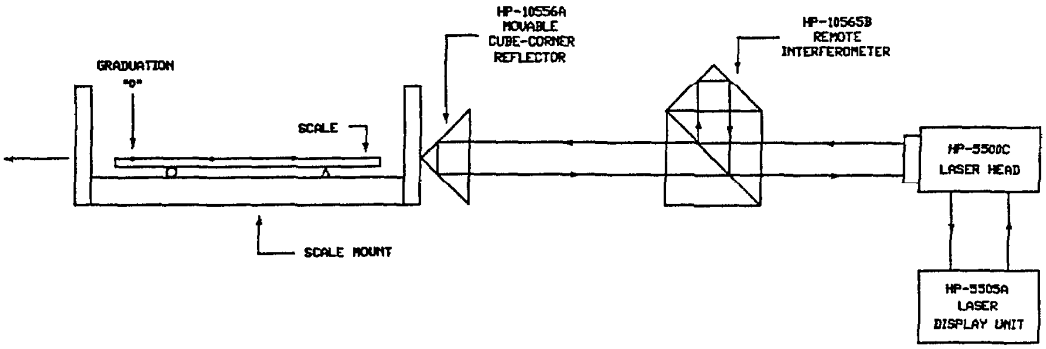


FIGURE 4. THE LINE SCALE LASER INTERFEROMETER

This laser measuring system was in use for a brief period in tandem with the Michelson flat mirror system. An iodine stabilized laser was used periodically in the Michelson to compare against the other system. The HP laser wavelength short term stability is one part in 10^8 and the long term stability is one part in 10^7. The iodine stabilized He-Ne laser long term stability is one part in 10^{10} [3].

VIBRATION ISOLATION

The instrument is housed in a basement laboratory of the metrology building at NIST. The instrument rests on a heavy concrete slab which is isolated from the floor by four inflated truck tire inner tubes.

TEMPERATURE MEASURING AND CONTROL

The laboratory temperature is held at a constant 20°C ±0.05°C. Inside the interferometer enclosure the temperature is kept at 20°C to within ±.01°C and is measured to ±.001°C. Fig. 5 shows the temperature reference measuring and control schematic.

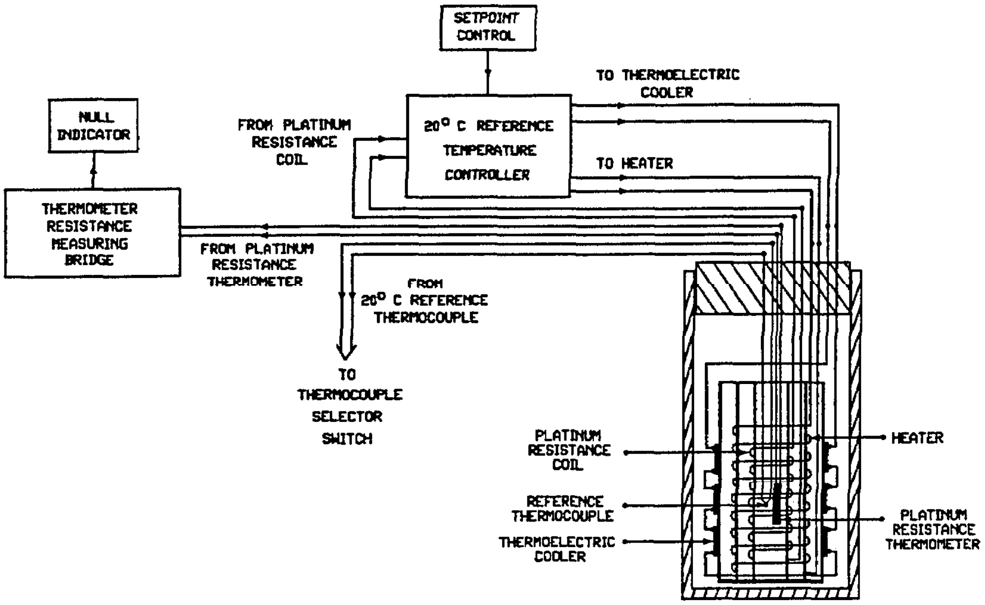


FIGURE 5. REFERENCE TEMPERATURE MEASURING AND CONTROL SYSTEM

The standard platinum resistance thermometer (SPRT) is placed in a temperature controlled well and it's temperature is measured with a Mueller resistance measuring bridge. The well temperature is controlled by an ac bridge-type proportional controller which can keep the temperature at 20°C ±0.0005°C. To assure the accuracy of the reference temperature the measuring bridge is periodically calibrated. The SPRT is also periodically calibrated by the triple-point-of-water method [5]. Fig. 6 shows the schematic diagram of the temperature measuring and control arrangement.

A distilled water reservoir is constantly cooled by a heat exchanger with a constant flow of water, chilled to 14°C. A submerged electric heater proportionally heats the water and keeps it at the 20°C set point. A submerged pump circulates the water in the copper lined enclosures walls. The combination of a thermistor in the water line and the air temperature measuring thermocouple inside the enclosure supply the error signals to the controller which in turn controls the temperature inside the chamber.

To avoid temperature gradients inside the enclosure a 50 cm diameter low speed fan stirs the air. To ensure that the fan does not generate any heat it is driven externally by an ac motor.

The temperature inside the chamber is monitored with thermocouples at 10 different points. For calculation purposes only five thermocouple outputs are used. Two thermocouples measure the air temperature near the path of the laser beam and three thermocouples measure the scale temperature. In both cases, the average temperatures are used for computation. All the thermocouples are also periodically calibrated against SPRTs.

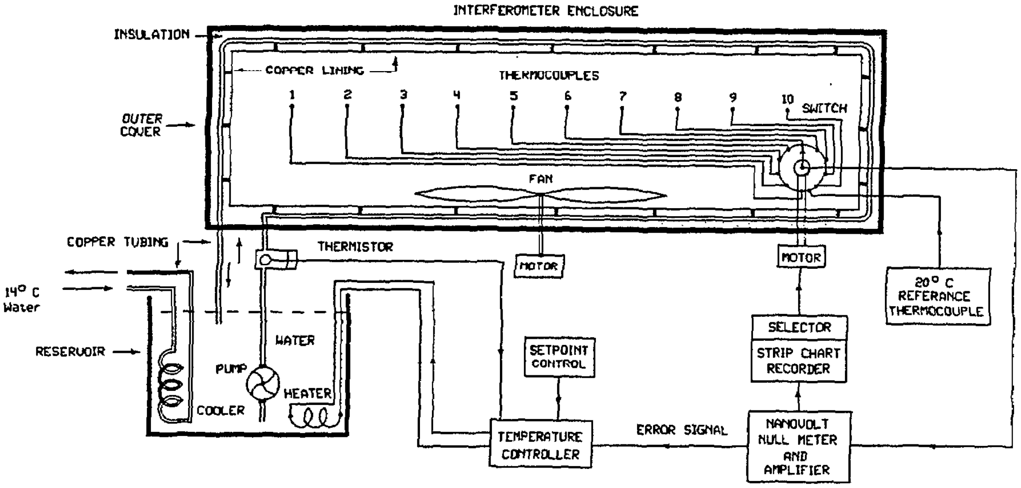


FIGURE 6. LINE SCALE TEMPERATURE CONTROL SYSTEM

RELATIVE HUMIDITY AND ATMOSPHERIC PRESSURE MEASURING DEVICES

The relative humidity is measured with a hygrometer having an array of sensors capable of detecting from a few percent to almost one hundred percent relative humidity. The sensor is located near the interferometer. The hygrometer has a 0-5 volts dc output for the range of 0 to 100 percent relative humidity. This instrument is accurate for a full range of operating temperature (-20 to + 60°C) to ±1.5% relative humidity. A digital voltmeter measures the output voltage which is sent to the computer through the HP-IB interface. The hygrometer is periodically calibrated at the NIST humidity calibration facility [6,7].

Atmospheric pressure is measured in the laboratory at the same elevation as the interferometer laser-beam paths. The instrument produces 0 to 10 volt dc output as a function of pressure. This voltage is measured with a digital voltmeter and is sent to the HP computer via the HP-IB interface. The pressure transducer has a long term stability of 0.33 mm Hg for the full range of operating temperature of -50°C to +78°C. The transducer was found to be fifteen times more stable in the controlled environment which made it suitable for accurate automatic pressure measurement. The transducer is periodically calibrated by the NIST pressure group.

SYSTEM COMPUTER

The line scale measuring instrument uses an HP desktop computer. It has several functions. It takes instructions from the operator, reads the data from several instruments, controls the line scale measuring process, calculates the lengths, analyzes the data and prints out the report. Fig. 7 shows the schematic of the computer and its interfaces. There are two 16 bit I/O interfaces. One is used to control the stepping motor. The second one controls the line centering process for the instrument. The BCD interface is connected to the HP laser measuring system display unit which counts in quarter wavelengths and tenths of quarter wavelengths.

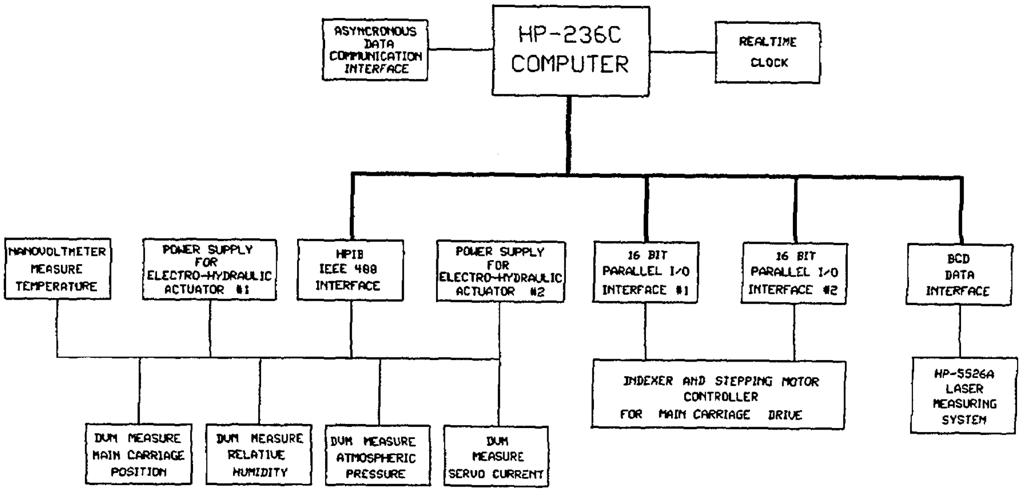


FIGURE 7. COMPUTER INTERFACES FOR THE LINE SCALE MEASURING SYSTEM

The HP-IB interface has several instruments connected to it. One Digital Volt Meter (DVM) measures the line centering servo current. Another DVM measures the relative humidity and a third measures the atmospheric pressure. There is also a nanovolt meter which measures the air and scale temperatures in the enclosure with high accuracy. There are also two programmable dc power supplies which supply dc voltages to the yaw-and-pitch-correcting electro-hydraulic actuators.

THE YAW AND PITCH CORRECTION OF THE SUBCARRIAGE

At the time when the Michelson plain mirror interferometer was used with the line scale measuring instrument an angular error in the carriage motion could have caused the loss of the fringes and the counting process would have been interrupted. In order to avoid this condition, a yaw and pitch correction mechanism was introduced. In Fig. 3 the schematic diagram of the motion error correcting system is shown.

When the Michelson interferometer was replaced with the HP-5526A system the yaw and pitch correction system became inoperative. Since that time, in order to avoid measurement errors, the scale to be calibrated had to be mounted very carefully on the scale mount so that the scale graduation lines axis was exactly coincident with that of the interferometer axis. It was found that if the scale axis deviated one millimeter above or below the interferometer axis, a five arc-second pitch caused 0.07 micrometer error to be introduced in one meter length.

Recently a new yaw and pitch correction system was installed. Unlike the earlier system this is not a closed servo control loop. The yaw and pitch errors of the subcarriage are mapped with an autocollimator. The two electro-hydraulic actuators are driven with the programmable power supplies to develop the necessary pressure to move the subcarriage with the scale back to the same axis as the interferometer axis. The carriage position is measured with a newly installed device which has an output of 0 to 10 volts for a carriage position of 0 to 1000 mm. Each mapped point is represented by two corrective voltage values, one value for each electro-hydraulic device. These values are stored in the computer memory. Each time the carriage moves to a new position the computer reads the carriage position and calls out the right voltage values from the memory. The evaluation of this new system is continuing. Preliminary data indicates that the corrected subcarriage pitch is within one arc-second, and the yaw is within two arc-seconds of the straight-line motion.

THE LINE SCALE MEASURING INSTRUMENT OPERATION

After the scale is mounted, the graduation lines are aligned and focused, the peripheral instruments and scale temperatures are stabilized and the instruments warmed up, the line scale interferometer is ready to start the measurements. The measurement process is governed by the computer program which is written in the HP Basic language.

Several parameters have to be entered by the computer operator. The parameters include the data file name, scale type (mm or inch), the low and high scale graduations, and the intervals of the measured scale. The thermal expansion coefficient of the scale, the estimated systematic error and the number of measurement passes also have to be entered. The CO_2 content is not monitored, but an average value is entered, because it is relatively constant in the room. For the environmental data entry there are two choices. They are either entered by the operator or the computer reads them automatically. These data are the air and scale temperatures, the relative humidity and the atmospheric pressure.

When all preliminary data are entered, the computer starts the measuring process. First, it checks if the line is present and centered, then it reads the interferometer, calculates the number of steps for the stepping motor and starts the carriage motion. The carriage is moved by the stepping motor to the vicinity of the next predetermined interval. As soon as the graduation line appears in the microscope field of view the stepper stops. The line-centering electro-hydraulic servo takes over and the line-centering process begins. When the error signal between the electronically defined line center and the optical line center is zero, the line is centered. The computer then reads the interferometer and *instructs the stepper to move the carriage to the next predetermined* graduation line. The computer keeps track of the number of stops and when the carriage arrives at the last graduation line the first "pass" is finished. Then the computer instructs the stepper to change direction for the second pass, and the calibration process begins in the reverse direction. At each stop during a pass, the environmental data is collected by the computer. This data is used to compute deadpath corrections and the length of each interval. The two passes are then averaged.

After the two passes are finished with the "normal" scale orientation (when zero graduation is at the left end) the scale is then reversed so the zero graduation is at the right end and the same calibration is repeated with the reversed orientation. The final value for each calibrated line will be the mean value of the four measurements.

CALCULATING THE LENGTHS

In the scale calibration process each graduation line being measured is represented by a number of quarter wavelengths. These counts have to be converted to lengths at 20°C. In order to do that, a count multiplier *(M) must be computed from*

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

where λ_{tpf} is the laser light wavelength at ambient air

α is the expansion coefficient of the scale
t_s is the scale temperature.

The laser light wavelength is derived from the fundamental expression

$$\lambda_{tpf} = \frac{\lambda_\circ}{n_{tpf}} \qquad (2)$$

where $\lambda_\circ$ is the laser light wavelength in vacuum and n_{tpf} is the refractive index of air.

The refractive index of air is calculated using Edlen's 1966 formula [8]. Then it is used to calculate the laser wavelength in ambient air, and the interval lengths are calculated.

INTRODUCING DEADPATH CORRECTION

The latest addition to the NISTs line scale measuring instrument is the installation of a revised computer program, which allows the operator to make measurements during adverse atmospheric conditions, especially when the barometric pressure fluctuates rapidly which in turn changes the refractive index of air. This is achieved by introducing the deadpath correction in the measurement process and in the length calculation automatically. In order to do this the data acquisition computer and its interfaces were updated to handle the longer computer program and the larger volume of data.

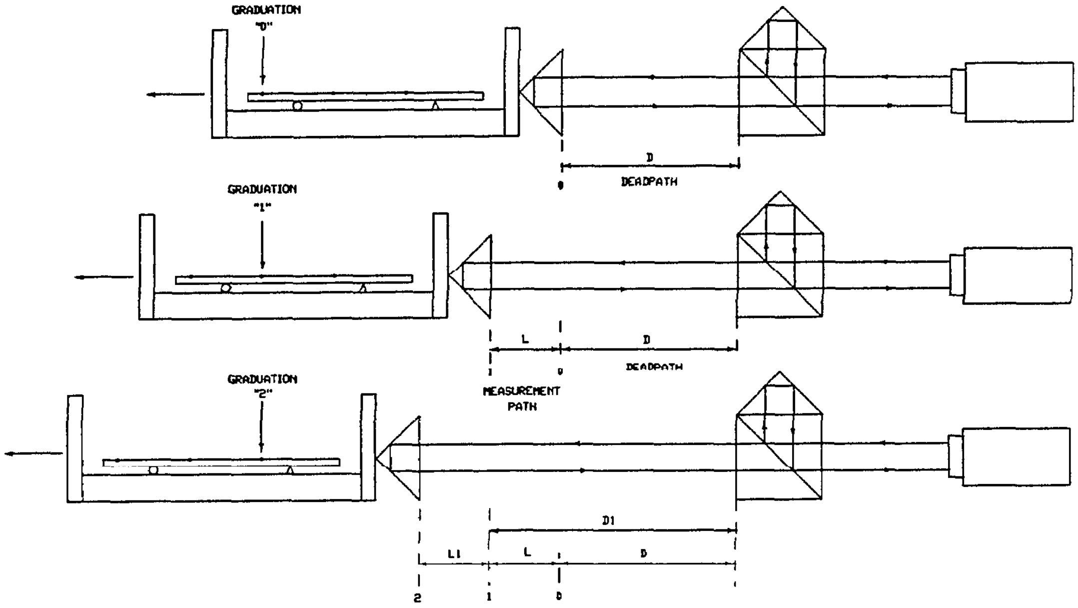


FIGURE 8. DEADPATH CORRECTION SCHEMATIC DIAGRAM

The active optical path in the line scale interferometer is the space between the retroreflector and the remote interferometer (see Fig. 8). This space has a standing wave pattern in it, which is stretched or compressed like a coiled spring by changes in the refractive index of the air in the path. When a line scale is being measured, the path has two parts: (1) the deadpath which is the part between the remote interferometer and the retroreflector at its starting position, and (2) the "livepath" which is the part being counted as the retroreflector moves to its next position. If the refractive index of air in the path changes during this move then a deadpath correction must be applied to compensate for the fact that the standing wave pattern has shifted. The correction is a function of the deadpath length and the change in refractive index.

EVALUATION OF RANDOM ERROR

For each measured value of length, measurement uncertainties are assigned. The uncertainty is determined by statistical analysis of several measurements done on each individual scale. For each measured length we have to determine the mean value of the length, the random error, and the estimated systematic error. So the uncertainty can be determined by the following expression

$$U \doteq 3s_m + S.E. \,, \qquad (3)$$

where U is the sum of the random error and the estimated systematic error. The random error is taken as three times the standard deviation of the mean value;

$$3s_m = \frac{3}{\sqrt{N}} \sqrt{\frac{\Sigma d^2}{N-1}} \,, \qquad (4)$$

where d is the deviation of a single measurement from the mean of N measurements.

ESTIMATING THE SYSTEMATIC ERROR

There are several possible error sources in the measurement process. The following table lists the most likely ones.

A 0.01 µm error in 1 meter length would result if the entered parameters were in error by

		The estimated S.E. in 10^8
1 part in 10^8	the vacuum wavelength of the laser	2 parts
1 part in 10^8	the refractive index equation	5 parts
0.03 mm Hg	the atmospheric pressure	4 parts
1.2%	the relative humidity	1 part
0.001 °C	the steel scale temperature	2 parts
0.14 mm/m	the interferometer misalignment	1 part .
		Total of 1.5 parts in 10^7

this value is the worst-case estimate, which indicates that all the errors accumulate in the same direction.

In practice the S.E. is probably below one part in 10^7 for one meter length. Fig. 9 and fig. 10 display a typical calibration report with the correction table.

U.S. Department of Commerce
National Institute of Standards and Technology
Gaithersburg, Maryland 20899

REPORT OF CALIBRATION

M3644

For: 50 MM Glass Scale

Submitted by:

The stage micrometer was calibrated by interferometry using a stabilized helium-neon laser as the length standard. The design and operation of the interferometer is described in NBSIR 87-3625, "Length Scale Measurement Procedures at the National Bureau of Standards."

Results of the calibration are given on the following pages of this report. Each length value is the mean of 4 measurements and the uncertainty in each value is

$$U = 3\sigma_m + S.E. = \text{Random} + \text{Systematic}$$

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

The graduations are not numbered so the zero graduation was taken to be the one farthest to the left when the stage micrometer is held so the label can be read in the normal manner with the unaided eye.

Measurements were made from line center to line center using the full tip to tip length of the short graduations and an equivalent segment of the long graduations.

All lengths are reported at a temperature of 20° Celsius (68° Fahrenheit).

A coefficient of linear thermal expansion of $11.5 \times 10^{-6}/°$ Celsius was used in normalizing the lengths to 20° Celsius.

For the Director,
National Institute of Standards and Technology

Ralph C. Veale, Group Leader
Dimensional Metrology
Precision Engineering Division
Center for Manufacturing Engineering

Order No. MHV-1001
Test No. 731/246109-90
Date: June 6, 1990

Figure 9

```
M3574n/M3574r

Mean Of Normal And Reverse Data


  INTERVAL              LENGTH     CORRECTION  RANDOM     SYSTEMATIC  UNCERT.
(MILLIMETERS)            (MM)        (MM)       (MM)        (MM)       (MM)

0.000 TO     5.000     5.00001      .00001     .00002      .00000      .00002
0.000 TO    10.000    10.00040      .00040     .00000      .00000      .00000
0.000 TO    15.000    15.00042      .00042     .00002      .00000      .00002
0.000 TO    20.000    20.00041      .00041     .00003      .00000      .00003
0.000 TO    25.000    25.00078      .00078     .00002      .00000      .00002
0.000 TO    30.000    30.00077      .00077     .00001      .00000      .00002
0.000 TO    35.000    35.00093      .00093     .00002      .00000      .00003
0.000 TO    40.000    40.00080      .00080     .00001      .00000      .00002
0.000 TO    45.000    45.00071      .00071     .00002      .00000      .00002
0.000 TO    50.000    50.00036      .00036     .00003      .00001      .00004
```

M3574n/M3574r

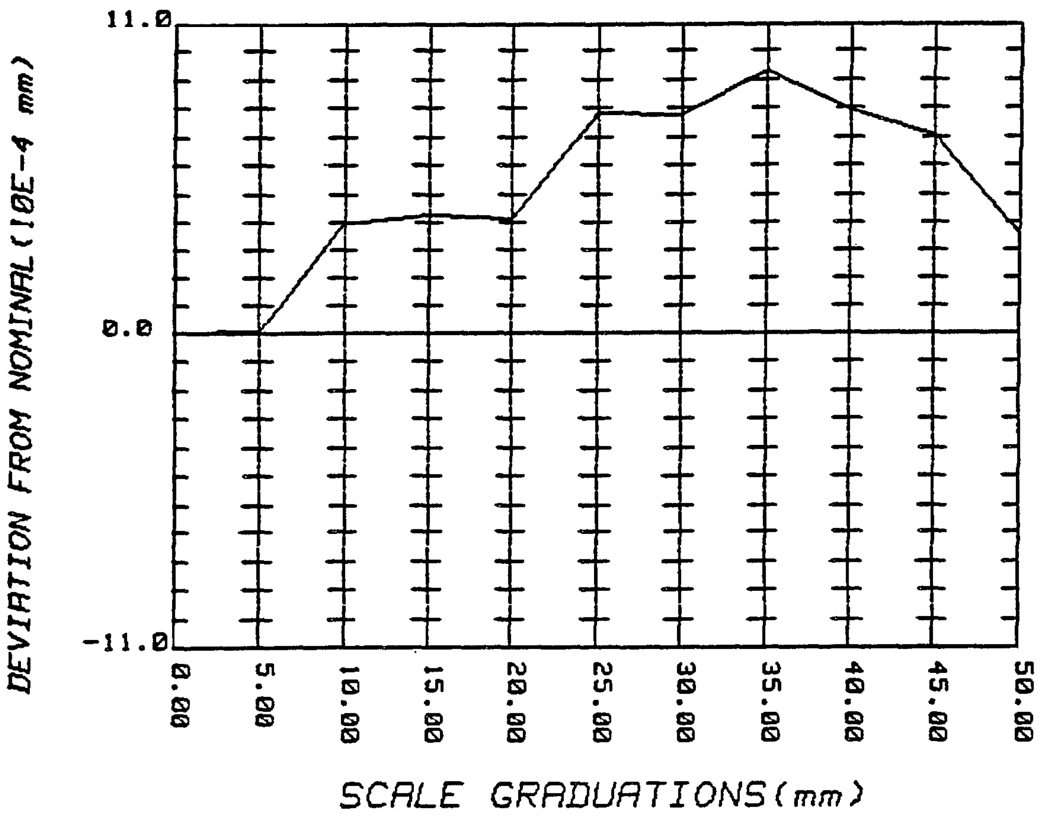
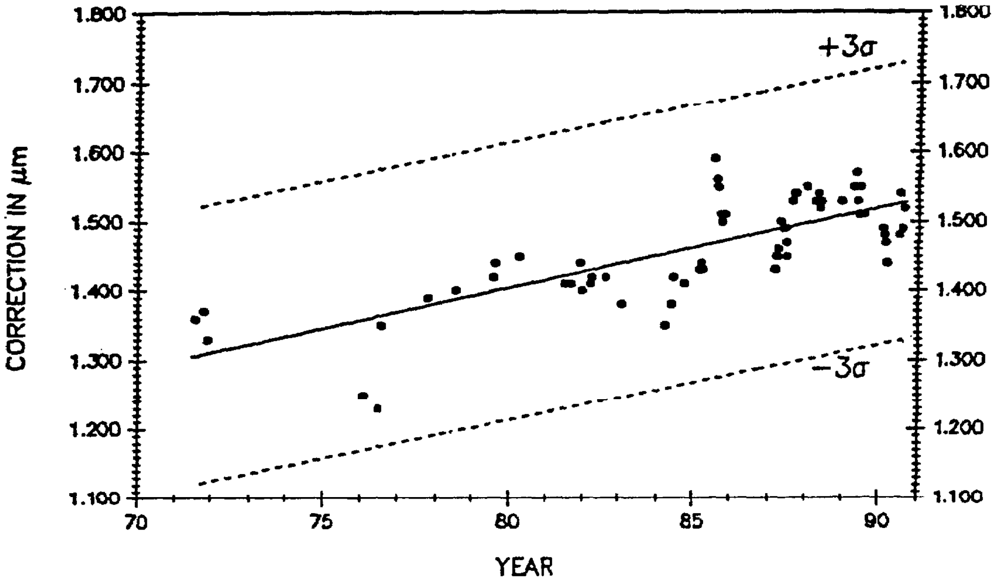


Figure 10

MONITORING THE MEASUREMENT SYSTEM

In a complex measuring system it is essential to know that all the components are working properly. Substantial errors can enter the process if, for example, the interferometer is misaligned, the barometer is out of calibration, or the distance between the remote interferometer and the microscope changes during a measurement. The method for detecting such errors is to use control standards in a measurement assurance program [9]. Three control standards are used to monitor this process. The principal control is an SIP meter bar, M5727, which has an H shaped cross section with its neutral plane graduated in millimeters.



CONTROL BAR M5727, 0 TO 1 METER

Figure 11

This bar is measured periodically and the values for the measured intervals are plotted on a time scale. Figures 11 and 12 show the data for the one meter and 0.1 meter intervals respectively. A linear regression line is fitted to the data and limits (dashed lines) based on 3 times the standard deviation of a single value (99.7% confidence level) are also shown. Once these limits are established they are very useful in judging future measurements. If a new measurement falls outside the limiting lines it is a strong indication of malfunction and a search for the problem is made.

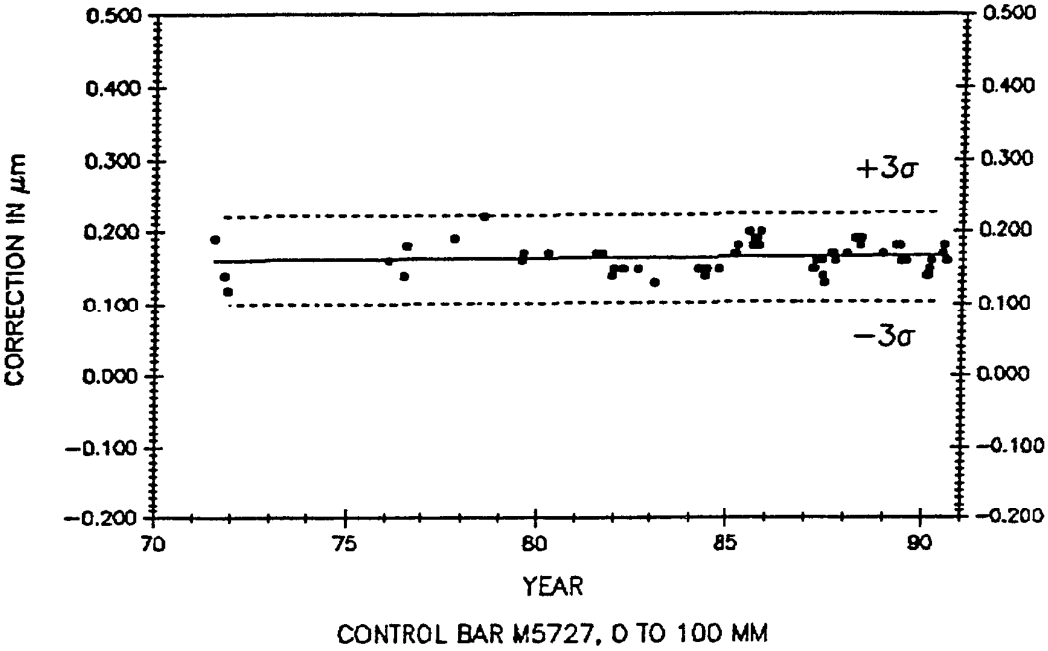


Figure 12

The slope of the regression line shows that the bar has slowly lengthened over the years at the rate of 0.012 micrometer per year. Secular change is normal in most metals.

REFERENCES

[1] H.D. Cook and L.A. Marzetta, "An Automatic Fringe Counting Interferometer for Use in the Calibration of Line Scales," Journal of Research of the National Bureau of Standards, 65C, (1961).

[2] K.E. Gilliland, H.D. Cook, and K.D. Mielenz, "Use of a Laser for Length Measurement by Fringe Counting," Metrologia, 2, (1966) p.95.

[3] H.P. Layer, "A Portable Iodine Stabilized Helium-Neon Laser," IEEE Transactions on Instrumentation and Measurement, 4, (1980).

[4] R.J. Hocken and H.P. Layer, "Lasers for Dimensional Measurement," CIRP Annals, 28, (1979) p. 305.

[5] J.L. Riddle, G.T. Furukawa, and H.H. Plumb, "Platinum Resistance Thermometry," NBS Monograph 126, (1973).

[6] G.O. Handegord, et al., "Humidity and Moisture," Vol. 1, Reinhold Publ. Corp., NY, (1963) p. 265.

[7] C.P. Hedlin, "Humidity and Moisture," Vol. 1, Reinhold Publ. Corp., NY, (1963) p. 273.

[8] E. Edlen, Metrologia, 2, (1966) p. 71.

[9] J.M. Cameron, "Measurement Assurance," Journal of Quality Technology, 8, (1976)

[10] B.L. Page, "Calibration of Meter Line Standards of Length at the National Bureau of Standards," Journal of Research of the National Bureau of Standards, 54, (1955).

[11] J.S. Beers, "Length Scale Measurement Procedures at the National Bureau of Standards," NBSIR 87-3625 (1987).

[12] "Documents Concerning the New Definition of the Meter," Metrologia, 19, (1984), p. 163.

[13] J.S. Beers and Kang B. Lee "Interferometric measurement of length scales at the National Bureau of Standards". Precision Engineering, Oct. 1982, Vol. 4, No. 4.

* Certain commercial equipment, instruments, or materials are identified in this paper in order to adequately specify the experimental procedure. Such identification does not imply recommendation or endorsement by the National Institute of Standards and Technology, nor does it imply that the material or equipment identified are necessarily the best available for the purpose.