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AN AUTOMATIC INSTRUMENT FOR FAST AND ACCURATE MEASUREMENT OF LINE STANDARDS.

by

J. Koning
P.H.J. Schellekens

Eindhoven, University of Technology, the Netherlands

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SUMMARY

An instrument is described for fast and accurate automatic measurement of line standards. Standards of length up to 1.40 m can be measured at a rate of less than 3 seconds per reading. Accuracy of measurement is claimed to be within 0.2 µm, all in.

ZUSAMMENFASSUNG

Es wird ein zur genauen und schnellen automatischen Messung von Strichmassen geeigneter Komparator beschrieben. Die Länge des Messbereiches ist 1,40 m. Die Messzeit pro Strich liegt unter 3 Sekunden. Die Ungenauïgkeit der Messung ist insgesamt geringer als 0,2 µm.

RÉSUMÉ

Un comparateur automatique pour mesurer rapidement et précisément des étalons à trait est indiqué. Des étalons de longeur plus de 1,40 m peuvent être mesurés d'une rapidité moins de 3 secondes la lecture. La précision de mesure est fixée sur 0,2 µm tout compris.

INTRODUCTION

When working on a ruling machine for manufacturing of line standards need was felt for fast and accurate measurement of the products, conventional methods being much too slow and not sufficiently accurate. A suitable instrument has been designed. It consists of a mechanical structure to support and position the standard, a fotoelectric microscope, a servo system for fine positioning of the standard, a laser interferometer for the measurement of displacements and electronic counting systems with associated equipment. (Fig. 1).

MECHANICAL CONSTRUCTION

The basis of the instrument is an I-beam (length 3 m. width 0.15 m, height 0.40 m, the total mass of the instrument being appr. 500 kg). Ground steel bars are mounted on this beam and adjusted for straightness down to about 0.01 mm. The carriage is mounted on 5 roller bearings acting as wheels.
Both length and range of the carriage are 1.4 m. The carriage is coupled to a leadsrew by means of a nut, which has been designed according to kinematical principles thus operating virtually without play. Coarse control of the carriage is done by means of a small motor which rotates the leadscrew over a gear reduction. Fine control is obtained by an a.c. servomotor which - by intermediate of a gear reduction, a micrometer screw and a lever system - imparts a small translation to the leadscrew and thus to the carriage.

FOTOELECTRIC MICROSCOPE

The lines of the standard are observed by a fotoelectric microscope; the line to be measured being imaged on a vibrating slit. The light transmitted by the slit is collected on a fotoelectric field effect transistor. When the electrical signal is applied to an oscilloscope, a one-dimensional "image" of the line is obtained if the horizontal deflection of the scope has the same frequency and phase as the vibrating slit.
The pattern can be varied by means of the slit amplitude. Using large amplitudes a pattern is obtained which is convenient for visual adjustment.

If, however, the amplitude is decreased to roughly half the linewidth, a straight pattern is obtained when the line is slightly out of center from the axis of the microscope. As the time base is a sine wave, this means that the signal consists mainly of a sine wave of the same frequency and phase as those of the vibrating slit. On the other flank of the line the situation is the same, exept that the phase is reversed. If the line is centered on the axis of the microscope the output signal does not contain the slit frequency but only even harmonics.

SERVO SYSTEM

An electrical signal of this particular nature is suitable for controlling the a.c. servomotor. The properties of the servo loop are such that a line is automatically positioned on the axis of the microscope, once it is brought into the field of the microscope by means of the coarse control. The system comes to rest well within 1 second, and the line position is reproducible to within 100 nm.

INTERFEROMETER

The interferometer is based on a Kösters prism. Therefore it is possible to have both legs parallel and very close together (≈50 mm.), resulting in a compact design and reasonable equality of temperature in both legs. Corner cubes are used as reflectors, one being mounted on the carriage, the other on the microscope structure. Therefore the interferometer is largely insensitive to displacement of components other than the displacement of the carriage relative to the microscope. Both corner cubes are used off-axis, so the light beams return to the Kösters prism at a higher level than the beams leaving the prism. Therefore no detrimental feedback to the laser is possible and two interference patterns can be collected on both sides of the prism. As these patterns have a phase difference of 90°, they are suitable -after clipping- as input signals for a bi-directional counter.
Optically a corner-cube interferometer behaves as an interferometer with parallel mirrors (exept for an inconsequential inversion of the wave fronts) hence we obtain fringes of equal inclination. As the laser

beam is very narrow, all light is concentrated in the central spot of the circular fringe pattern and consequently the output is high. With a simple fotodiode 1 volt can be obtained without amplification. However fotosensitive FET's are used for fast response.
A wavelength stabilised laser (Spectra physics no. 119) is used; the wavelength in air is calculated using Edlén's formula).

ELECTRONICS

The output of the interferometer is recorded by a bi-directional counter and can be transferred to a memory and from there to a fast tape puncher. A second counter is used to control the coarse displacement. This counter is set to zero when the coarse control motor is switched on thus indicating the displacement relative to the last measured position. The output of the counter is routed over selector switches and a gate to a relay by which the coarse control motor can be switched off if the desired position is reached whilst at the same time the servo system is activated. By these means it is equally possible to measure standards with other intervals than 1 mm, and also non-metric standards. The velocity of the coarse control system is about 1 mm/s, which is sufficient for our purpose.

TEMPERATURE

In the laboratory the temperature is controlled to 0.2 K. The environment of the instrument is provided with an auxiliary control to 0.05 K. The instrument is thermally insulated by 40 mm foam plastic and aluminum foil. Nevertheless, the temperature normally rises about 0.05K during a run of measurements. Evidently, a linear rise of temperature can be eliminated by measuring a standard in both directions and averaging the results.
Temperature is measured by platinum resistance thermometers of IPTS standard quality, using a Diesselhorst compensator.

POSSIBLE ASYMETRY OF MICROSCOPE

If the optical axis of the microscope does not coincide with the mechanical axis, and therefore it is not perpendicular to the surface of the standard, systematic errors arise if the distance of the surface as seen from the objective lens of the microscope is not constant during the motion of the carriage. This case occurs when the standard is not straight. This error can be eliminated by turning the microscope over 180° around its mechanical axis and averaging the readings taken in both positions.

NORMAL PROCEDURE OF MEASUREMENT

As a consequence of the observations mentioned a complete measurement has to consists of two double runs, each double run being a set of measurements immediately followed by a run in the opposite direction. In between both double runs the microscope is reversed over 180°.

The time cycle used is normally between 2 and 3 seconds per measurement so a double run made on a standard of one meter length divided in mm intervals, takes about 1½ hour, including time for reading thermometers, barometer, etc. and for heading the punched tape.
Processing of the tapes is done by the computing center of this University. Measurements are tabulated, averaged etc. as required. Graphs can be plotted at any convenient scale.

RANDOM ERRORS

If the differences between both sets of measurements of a double run are plotted, a curve is obtained whose general shape can be predicted. The differences caused by microscope asymetry and detected by reversing the microscope, give rise to a smooth curve. Therefore it is possible to eliminate these errors from the separate runs. From the spread of the separate runs the random error can be evaluated. By such an analysis has been concluded to a random an error of 80 nm (standard deviation).

SYSTEMATIC ERRORS

As stated before, errors due to temperature drift and asymetry of microscope are eliminated. To gain insight in the magnitude of remaining systematic errors (slanting axis of microscope mounting, around which the microscope is rotated, influence of finite exit pupil of the interferometer, adjustment of the standard on the instrument, etc.) the standard was reversed end-for-end and readjusted. Differences between measurements before and after reversion were slight and of a random nature. The differences found in the measurements of a scale, 530 mm long, and of reasonable but by no means perfect line quality, are reproduced in Fig. 2. Random error in these differences taken as 2 x standard deviation amounts to 80 nm. as was to be expected.

ACCURACY OF MEASUREMENTS

Random error and most systematic errors are evaluated by the experiment described in the preceding paragraph. However, three groups of effects remain which give errors proportional to the length measured, and which give identical effects on repeating a set of measurements. An estimate is given here.

Calibration of thermometers.

Our thermometers are calibrated against two standardthermometers. These standardthermometers were calibrated against IPTS-fixpoints by the care of the Kamerlingh Onnes Laboratory, Leiden. The procedure followed in calibration, and the reproducibility obtained, warrant a claim of 5 mK, resulting in an error of 0.5 x 10^{-7} in length.

Error in wavelength assumed for the laser.

This wavelength is at present not compared directly with the primary standard of length. Measurements by PTB, NPL and NBS, reported by Mielenz (2), indicate that the wavelength assumed is correct to 1 x 10^{-7}.

Coefficient of refraction of air.

Measurements by BIPM (3) tend to be higher than values calculated by Edlén's formula. An error of 1 x 10^{-7} has to be reckoned with.

It seems reasonable to conclude that the all-in error of the calibration stays within 200 nm.

LITERATURE

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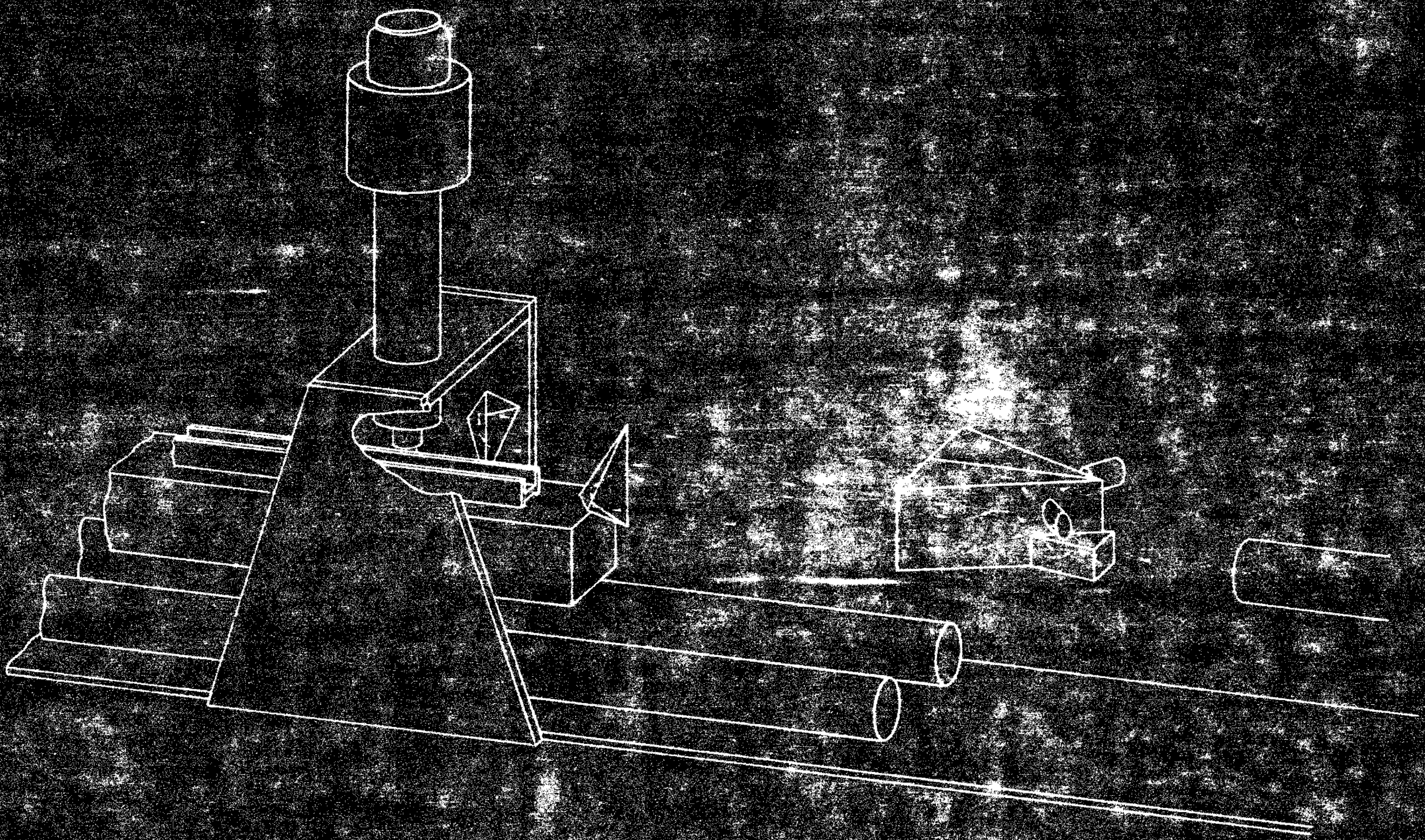
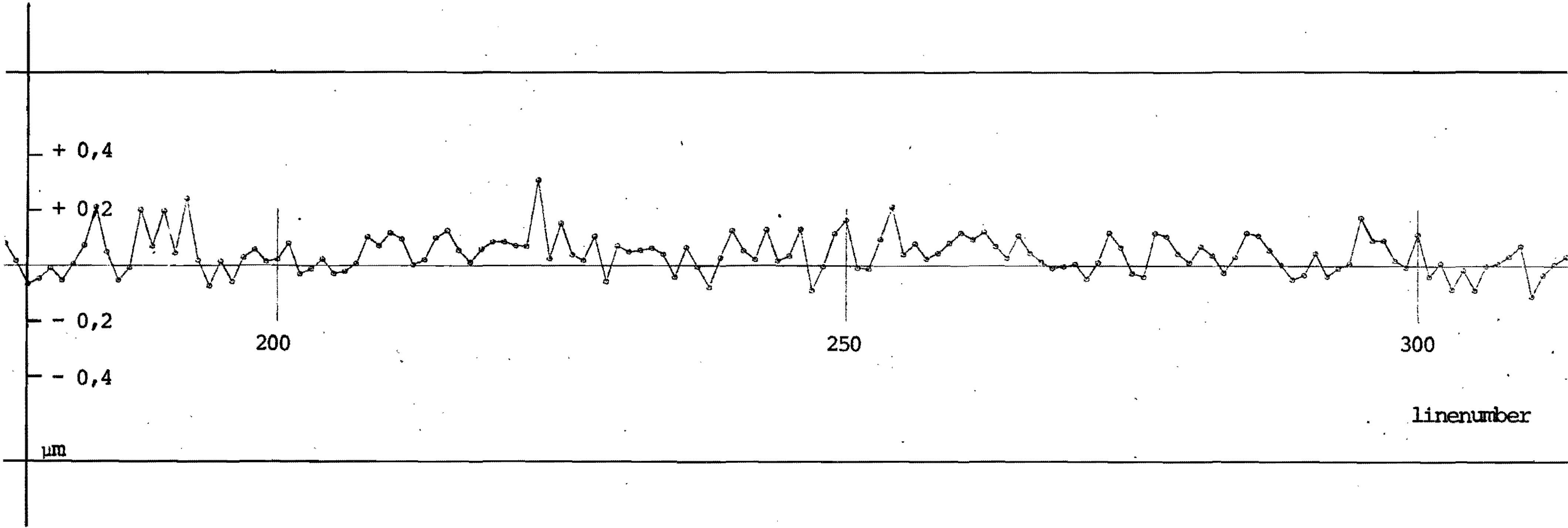


Fig. 1



+200 +250 +300

Fig. 2

appendix to WT 0237.

additional information for Dr P. H. Sydenham; 5-Jy-1971

Temperature measurement. At present a dual-probe Quartz-thermometer (Hewlett Packard model 2801A) is used in addition to the Pt-resistance thermometer mentioned in the paper. These probes are calibrated against standard resistance thermometers; these standard thermometers are calibrated against IPTS fixpoints by Kamerlingh Onnes laboratory; Leiden. Temperature is calculated according to IPTS 1968, calibrations are believed to be accurate within 5 mK (±0,005 ~~±0,001~~ deg centigr.)

One probe is mounted in a small aluminium block and clamped to the standard-to-be-measured. The other probe is fixed to a "transistor-heat-sink" of about 100×200 mm² - so as to achieve good equality of temperature with the air. The "heatsink" is very close to the optical path of the interferometer.

In the past a large temperature rise (some tenths of degrees centigr) occurred after the instrument was switched on; therefore measurements were only made after some hours of equalisation, and an unknown temperature gradient was not impossible. Recently a heat source was discovered in some zener diodes associated with the foto [illegible] circuits, consequently the electronic circuit was removed almost completely from the thermal-isolating enclosure. Temperature rise is now within 0,02 °C/h, which is inconsequential, and can be corrected by the following procedure.

Determination of wave length. Wavelength in air (or rather the step value λ/8) is determined by a simplified version of Edlén's formula. From this wavelength a fictitious wavelength is calculated: $\lambda_{fict.} = \lambda_{t,p,e}\left[1 - \alpha(t-20)\right]$, α being the coefficient of linear expansion of the standard. By using this fictitious wavelength, the length of the standard at 20°C is obtained directly.

Both temperatures, air and water vapour pressure, are punched at regular time intervals. The time interval ~~calc~~ can be chosen freely as required by the rate of change of these parameters. Separate interfaces are used for punching interferometer counts and for temperatures and pressures, each being controlled by a separate, free-running, clock. The interfaces are interlocked to prevent "double-punching"

The computer programme is arranged in such a way that a new value of $\lambda/8$ is computed each time a new value of temperature or pressure is read. This value of $\lambda/8$ is used for evaluating all following interferometer counts until a new value of $\lambda/8$ is calculated. By these means a slow rise of temperature is of no consequence, as long as no significant temperature difference in the instrument occurs.

Pressures are read at regular intervals on a precision aneroid and on a psychrometer resp. and are inserted in the interface by means of thumb-wheel switches. The circuit is arranged for easy change to automatic insertion of pressure data if a suitable instrument becomes available [a digital barometer is in an experimental state]

Jim