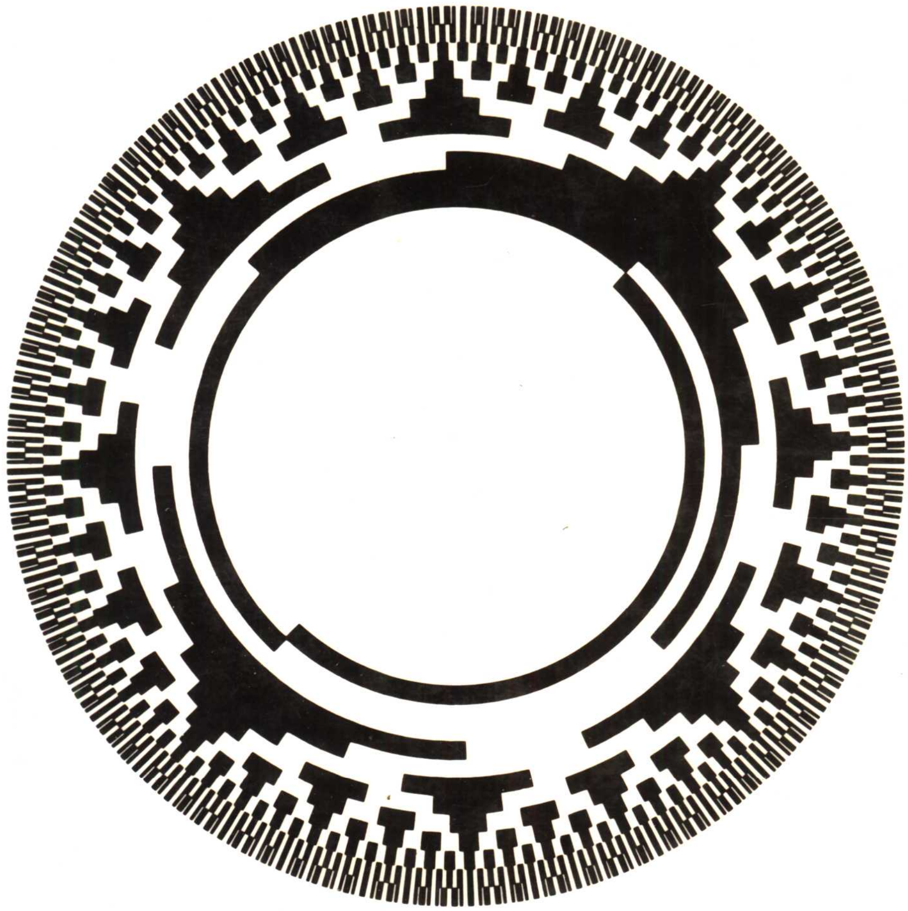
PHOTOMASKS, SCALES AND GRATINGS



D.F.Horne

British Library Cataloguing in Publication Data
Horne, Douglas F.
Photomasks, scales and gratings
1. Microelectronics
I. Title
621.381'71 TK7874
ISBN 0-85274-482-X

Published by Adam Hilger Ltd,
Techno House, Redcliffe Way, Bristol BS1 6NX.
The Adam Hilger book-publishing imprint is owned by The Institute of Physics.

Typeset by Quadraset Ltd, Radstock, and printed in Great Britain by J. W. Arrowsmith Ltd, Bristol.

Author's preface

Mask-making is an essential operation in the manufacture of microelectronic and opto-electronic devices. High accuracy instrument movements controlled by laser interferometers, high quality lenses, high resolution photographic emulsions and photoresists, and computer-aided design, when combined together, enable us to project very fine line patterns.

Thin film masks control light, deep ultraviolet, or x rays to form precise shapes on photoresist coated semiconductor wafers which have been protected by silicon dioxide. Following exposure and development of the photoresist the silicon dioxide coating is etched ready for fabrication of microcircuits by diffusion processes.

Complex operation patterns on masks can no longer be made efficiently by photoreduction from artwork. Computer-aided design has become an essential feature of the mask-making process and, because of damage caused by very small dirt or dust particles in air or liquids, there is an increasing need for high quality environmental conditions at every stage of manufacture.

Scales and eyepiece graticules are essential components in all optical instruments. Moiré fringe gratings are used as radial or linear scales in the control of precision machinery whilst diffraction gratings provide the means for spectrochemical analysis. Their manufacture is described within this book but further information is published in *Optical Instruments and their Applications* (Adam Hilger, 1980).

Any opinions which I have expressed are, of course, my responsibility and do not indicate the policy of the Cranfield Institute of Technology, Rank Precision Industries Ltd, or any other company from whom I have received information.

I wish to thank all those who have supplied me with technical details and photographs and wish to acknowledge in particular the helpful suggestions of Dr E G Loewen of Bausch and Lomb Analytical Systems Division, Rochester, USA.

Permission has been given by the following companies for publication of material concerning their products. Names are listed in order of page printing and this is an acknowledgement of the assistance which made this book possible.

Rank Precision Industries Ltd, Leicester LE2 0SP (Messrs S C Bottomley and G W Lee)
SIP, Société Genevoise d'Instruments de Physique, Geneva
Hewlett-Packard Company, Santa Clara, California 95050, USA (Mr D A Harland)
Moore Special Tool Co. Inc, Bridgeport, Conn. 06607, USA (Mr Wayne R Moore)
Bakelite Xylonite Limited, Croydon, Surrey CR9 3AL (Mr R J Moody)
Croda Premier Oils Ltd (Medyna oil), Stoneferry, Hull HU8 0BJ (Mr L Malin)
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Cementation (Muffelite) Limited, Walton-on-Thames, Surrey (Mr R M Lustig)

I wish to thank my wife for typing the manuscript and also the staff of Adam Hilger Ltd for the care they have taken whilst editing this book.

December 1982 D F Horne

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1 Dividing and Ruling of Scales

1.1 Introduction

Scales have lines engraved into a polished surface by a diamond cutter, etched through a ruled resist, or copied by means of a photoresist and chrome-coated glass master. The term scale is used when the lines are designed to be bridged by some form of vernier or micrometer device to make accurate, intermediate settings. The scale may be circular, as on a theodolite or circular table, or linear for the measurement or control of machine tables.

When calibrating scales we are concerned with accuracy or agreement of a measurement with the true value of the measured quantity. The difference between the measured value and the true value is the error of the measurement. The word 'precision' is used when considering the closeness together of repeated measurements of the same quantity.

A comparator is an instrument with which a scale may be calibrated in terms of another scale of known accuracy, such as a master scale, or with which the subdivisions of scale may be calibrated with regard to its total length.

In order to maintain standards of accuracy it is essential that standards be traceable to a single source. This has led each major country to have national laboratories which have close connections with the International Bureau of Weights and Measures, Sèvres, France. In the UK the National Physical Laboratory (NPL), which was founded in 1900, had to establish and maintain precise standards of measurement and the British Calibration Service provides industry with authenticated calibration of scientific instruments and certification of measurements.

The International Bureau of Weights and Measures (BIPM) was established after the signing by seventeen sovereign states of the *Convention du Mètre* in 1875. At the conference in 1875 it was agreed that the metre would be determined as a line standard for the following reasons:

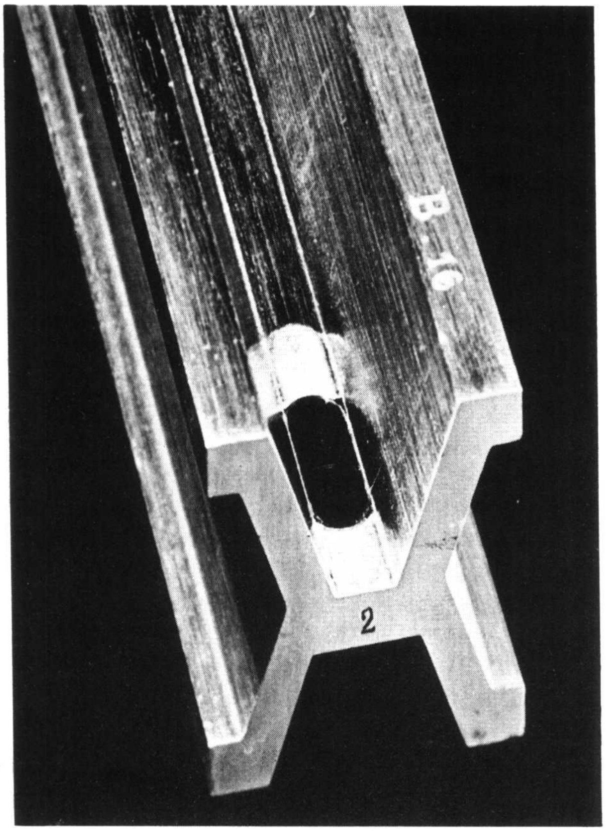
(*a*) End standards must be touched to be used, and important faces are subject to wear and damage, whereas line standards are observed and not touched.

(*b*) Over a length of one metre it was impossible to obtain two faces sufficiently flat and parallel to be used as an end standard.

(*c*) Advances in optics had made good microscopes available.

(*d*) Better temperature control was possible using a line standard because the lines could be observed without contact.

A new standard metre was ruled in 1889. This was a line standard made of 90% platinum and 10% iridium with lines one metre apart engraved on the exposed neutral plane of a rod of X (Tresca) section. The lines were intersected by two parallel lines to limit the length of line to be viewed. At 0 °C the defining lines were to be separated by a distance equal to the unit metre length of the Mètre des Archives. This definition of the metre standard remained in force, with some modification of detail, until the prototype



1.1.1
The international prototype metre. The lines are narrow grooves with sharp upper angles, free from burrs, for good definition.

was superseded by the wavelength of light definition adopted in 1960 (Fig. 1.1.1).

In September 1889, when the international prototype metre was adopted, Michelson and Morley published an article in *The American Journal of Science* entitled 'On the Feasibility of Establishing a Light Wave as the Ultimate Standard of Length', in which they described the Michelson interferometer. In 1892–3 Michelson and Benoit realised these ideas when they made the first direct measurement of the metre in terms of the cadmium red line. In 1905–6 Benoit, Fabry and Pérôt repeated the determination using a Fabry–Pérôt interferometer.

Much work followed in various standards laboratories throughout the world, including the National Physical Laboratory in Britain, but the optical metre was adopted only after the introduction and development of improved sources of monochromatic light employing, instead of natural elements, pure isotopes of even atomic charge and mass, notably mercury 198 and krypton 86. Finally, in 1960, the metre was defined as 1 650 763·73 wavelengths *in vacuo* of the radiation corresponding to the transition between the levels $2p_{10}-5d_5$ of the krypton 86 atom.

Reference scales held in each national laboratory have been calibrated in terms of the krypton wavelength and these reference scales are used for the calibration of the working standards required by industry.

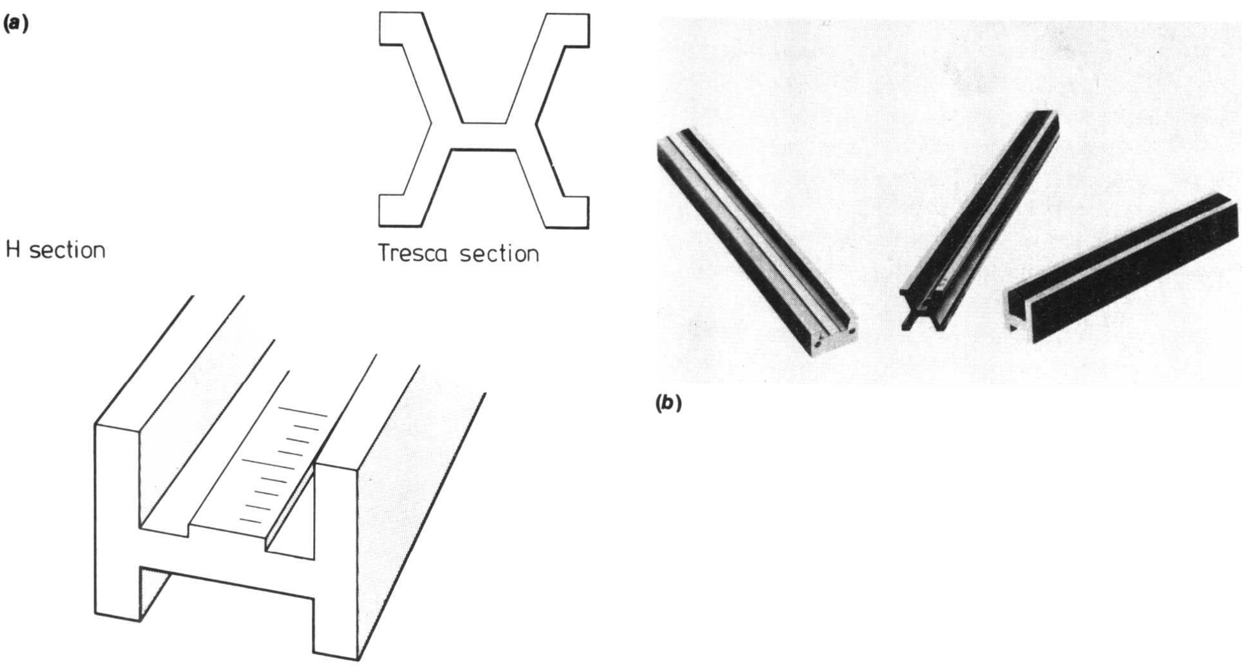
A side effect of higher accuracy in measurement was the international standardisation of the inch in 1959. The prototype metre had long been accepted as the international standard of length, but the definition of the yard compared with the metre differed between the UK and the USA. In 1951 Canada had redefined her inch to be exactly 25·4 mm. Finally, in 1959, the Canadian compromise was adopted by the UK and the USA.

The coherence of lasers, which have been developed since 1960, gives several important practical advantages over krypton, cadmium and mercury light sources and it has been possible to stabilise their wavelengths with extreme precision. The reproducibility of a saturated-absorption stabilised laser source is about a hundred times better than the practical accuracy of a krypton 86 lamp.

It is possible that the Advisory Committee for the Definition of the Metre may recommend a new standard, based on the laser, at the General Conference of Weights and Measures in 1983.

There are now no national line standards but precision scales are widely used as sub-standards, in engineering and research, for calibration and measurement. Such scales are usually made from 58% nickel–iron, which has the double advantage of being stain-resisting and also having a coefficient of linear expansion equal to that of steel (§1.8).

Chromium-plated mild steel is also used for scales as this is a cheaper material and is much easier to machine and polish. The general section used for sub-standard scales is an H section,



1.1.2
The official international standard is the wavelength of krypton 86, but the standard scale remains the most precise basis for industrial measurement. SIP manufacture scales in channel, Tresca and H section alloy.

ruled on its web, and the proportions are such that the upper surface of the web lies in the neutral plane of the section (Fig. 1.1.2).

The thermal expansion per degree centigrade per metre length is approximately 8 μm for crown glass, 8 μm for cast iron and 11 μm for steel. Precise temperature control is essential if accuracy is to be achieved.

Once graduated, a scale cannot be altered. Many factors could cause a line to depart from its prescribed position during ruling including:

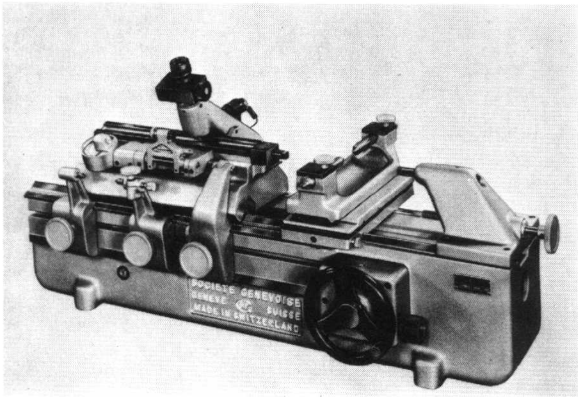
(*a*) Error in the standard or in reading the standard.
(*b*) Deflection of the diamond in cutting the line.
(*c*) Line width not uniform.
(*d*) Lines not parallel.
(*e*) Variation of temperature from exactly 20 °C.
(*f*) Difference of temperature between the reference standard and the standard to be ruled.
(*g*) Ruled surface not flat.
(*h*) Lines not symmetrical.

End standards and, in particular, slip gauges are important for intermediate steps in the calibration of measuring instruments. It is convenient to measure slip gauges with a gauge interferometer and accuracy to better than a microinch (0·025 μm) can be achieved after allowing for variations in temperature, barometric pressure and humidity (Fig. 1.1.3).

Angular relationships are essential in the construction of squares, the use of auto-collimators or levels, the checking of machine-way straightness, the indexing of lead screws, and the measurement of tapers, gears, splines and cams. Some of the more important measuring instruments for angle measurement are protractors, sine bars, auto-collimators, theodolites, clinometers and circular tables. All of these require calibration against a standard provided by a natural force or quantity or by a geometrical principle.

Gravity provides a datum for level bubbles, the wavelength of light for gauge interferometers, and the sine principle or dividing of a circle for angles.

The sine principle uses the ratio of the length of



(*a*)

(*b*)

1.1.3
(*a*) The Société Genevoise d'Instruments de Physique MUL-300 universal measuring machine for lengths up to 305 mm (12 inch). Its uses include inspection of plugs and gauges. (*b*) The type of scale used on SIP MUL-300 universal measuring machines. It is divided every millimetre and viewed by means of micrometer microscopes or projector screens.

two sides of a right-angle triangle in deriving a given angle and depends on an established system of length measurement with its traceability to a natural standard through calibrated gaugeblocks. The accuracy of a divided circle depends on the precision of a photoelectric microscope and the techniques employed. A circle can be divided into any number of parts whose accuracy is proved once the circle is 'closed'. No outside authority, such as a national laboratory, is needed for the verification of angles obtained by either method.

1.2 Linear dividing

Line standards are used in laboratories, standards rooms and engineering shops for precise measurement and the accurate location of sensing devices. Scales are graduated every 1·0 mm (0·05 inch) and have a calibration accuracy of ±0·0025 mm (±0·0001 inch) at 20 °C. While long scales are of Tresca or H section, short scales usually have a rectangular section with graduations engraved on the centre strip. Precision linear scales are used in conjunction with a scale-reading micrometer microscope.

Metal scales are produced by ruling with a sharp tool directly into a polished surface or by etching through ruled resist or through photoresist.

Stainless steel is the most commonly used alloy because it will take a good polish, is stable, and does not tarnish. Glass is also used for many small scales because it is easily polished and will transmit or reflect light. Although most glasses have a coefficient of expansion less than that of steel there are some which have the same coefficient and are particularly useful as a material for scales used with measuring machines.

Graduations on glass are usually produced by etching through a ruled wax or photoresist, which has been activated by light during printing, and filling the grooves with a pigment. A common alternative to the etching process is to evaporate chromium, into lines and figures, through the resist.

In some circumstances, particularly for projection printing, fine-grain photographic emulsions are used to produce a master which can then be used for printing with a photoresist. The accuracy of the graduation lines depends on the precision and repeatability of the dividing machine, close control over environmental conditions, and absence of vibrations which may cause line inaccuracies.

Linear ruling machines usually have an accurate lead screw for successive indexing of the scale intervals. Progressive errors and pitch are corrected by cams which have been adjusted following calibration and recalibration of the machine. Periodic errors can be due to drunkenness of the screw or to errors in the thrust bearing and must be adjusted for maximum accuracy. It is very important that a linear dividing machine gives consistent repetition for it then becomes possible to correct errors by comparison against a reference scale.

Another type of control depends on a master scale. This is mounted in line with the scale to be ruled and on the same carriage, so that any variations due to small errors of flatness in the ways apply to both scales. The ruling mechanism produces a line on the scales when a photoelectric microscope signals that the master graduations are exactly in the correct position. Photoelectric microscopes are very accurate in the null position, and variations in the calibrated master scale can be eliminated from the copy scales by feeding in known corrections. Problems with this type of machine are the need to have a variety of master scales and the time required for changing over from one type to another to suit ruling requirements.

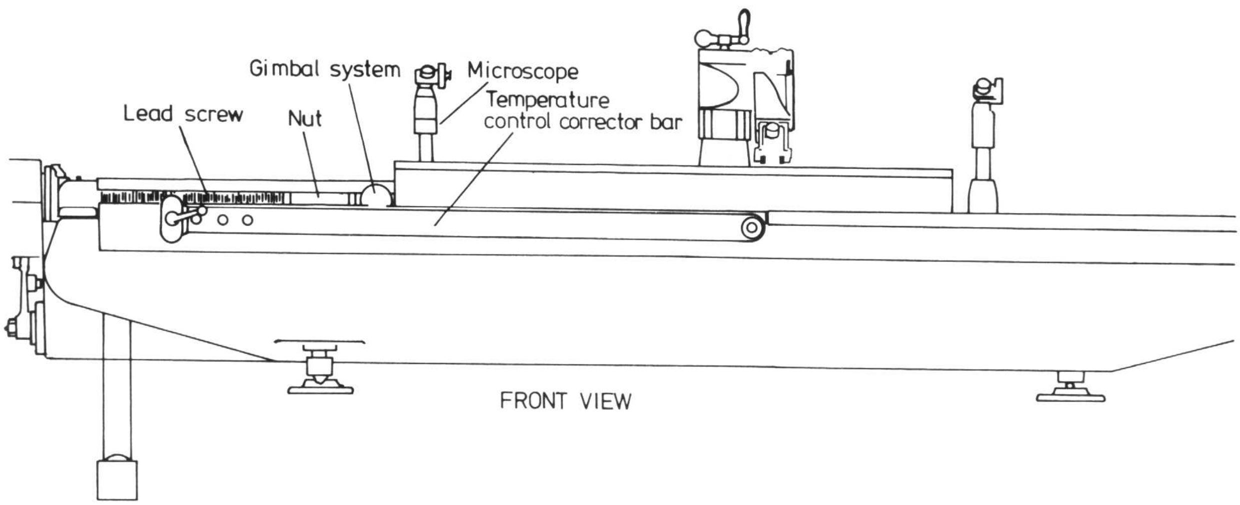
A linear dividing machine, designed by Hilger and Watts Ltd, will consistently rule scales to an accuracy of $\pm 0{\cdot}0025$ mm ($\pm 0{\cdot}0001$ inch) at 20 °C (68 °F), either automatically or by hand setting providing there are good environmental conditions and regular maintenance.

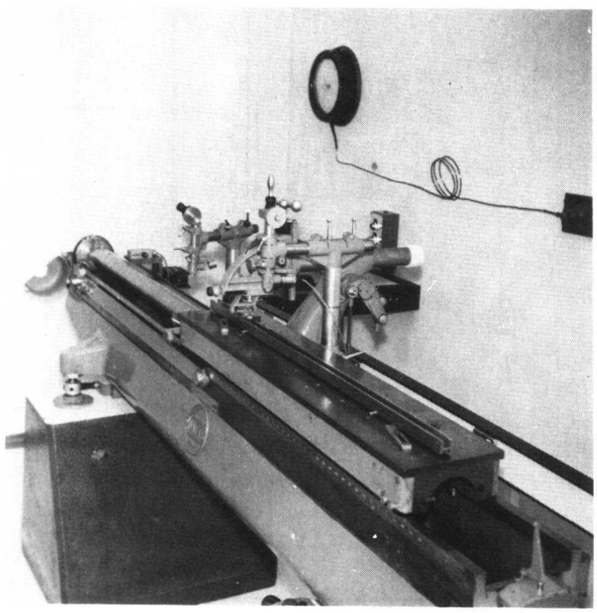
Accuracy depends upon a precision lead screw whose small deviations from nominal are compensated by a profiled corrector bar which imparts a minute variable degree of rotation to the nut controlling the advance of the work table. An automatic corrector is incorporated so that scales can be ruled to their correct lengths at temperatures other than normal. The very high standard of workmanship of the horizontal and vertical guiding ways on the machine bed ensures consistent operation and accurate repetition. The sturdily constructed bed of stabilised Meehanite has a three-point support and carries movable microscopes for the calibration and examination of the work (see §6.7).

Operation is either automatic for regularly spaced scales, the total number of lines being preset on a counter, or manual for logarithmic and widely spaced scales (Fig. 1.2.1).

For automatic operation the scale interval is set by means of a pawl, which picks up a calculated number of teeth on a selected ratchet wheel arranged to rotate with the screw. Hand setting is by means of a divided drum and vernier adjacent to the ratchet wheel.

The ruling mechanism is a tracelet, adjustable for ruling horizontal or bevelled scales, and so arranged that the steel or diamond cutter rules a line during the table rest period and is lifted clear during the table advance. The sequence and lengths of line are preselected by means of variable-length stops mounted on a disc, the rotation of which is synchronised with the cutting operation by means of a ratchet. Line thicknesses are controlled by the size of the cutting tool and applied load. To facilitate the ruling of graticules





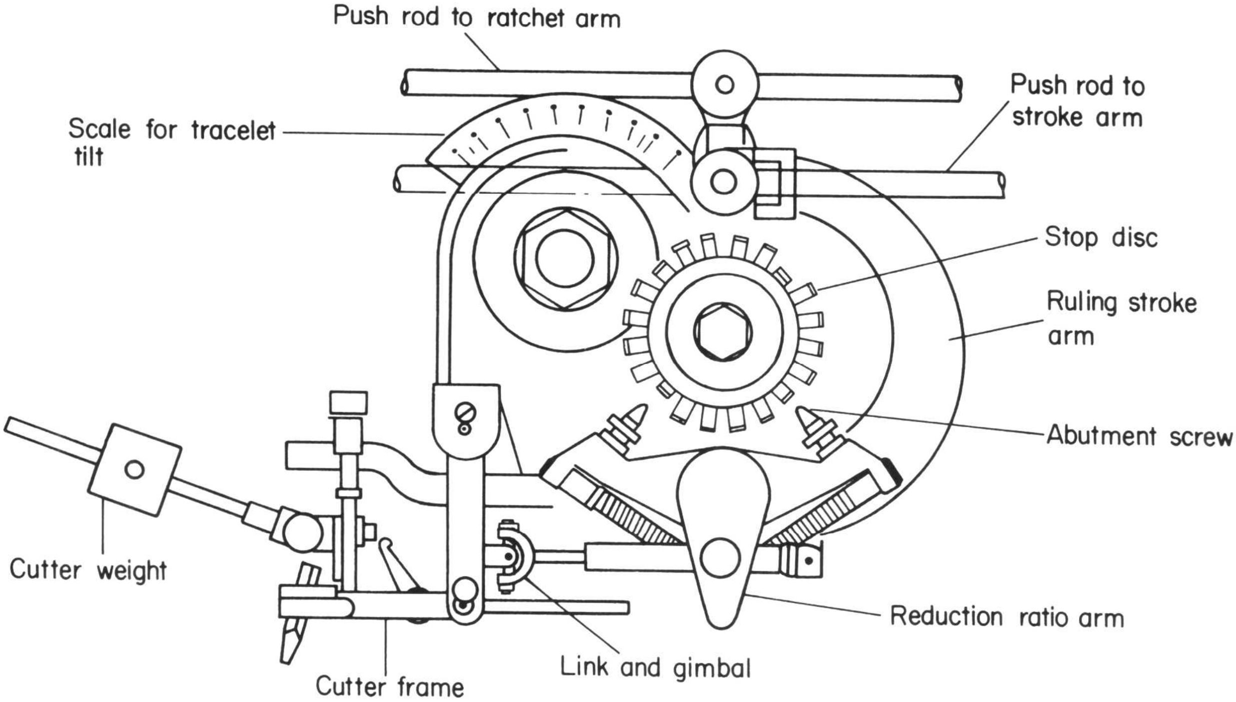
1.2.1
A 40 inch linear dividing machine in the Rank Precision Industries Special Facilities factory. The temperature must be constant to within 0·1 °C during the period of ruling at the work level. The machine is controlled from outside the room to avoid temperature disturbance by the operator.

with cross lines, a circular table to clamp to the work table is supplied as an accessory.

The lead screw is moved intermittently by means of an arc and ratchet motion, the stroke of the arc being adjustable to vary the space between rulings. The machine is fitted with a lead screw with 2 mm (0·1 inch) pitch. The ratchet wheel fitted to the end of the lead screw is interchangeable with others which have different numbers of teeth to give different basic scale intervals.

The lead screw nut is fitted with an arm which is kept in contact, by spring pressure, with a corrector bar attached to the rear of the main bed. This corrector bar is shaped to compensate for the slight errors which may exist in the pitch of the lead screw.

The tracelet mechanism is timed to rule scale lines during the standstill period of the intermittent table movement. Two tracelets are provided, one for fine scales such as line standards and for ruling on glass and a second, heavier, for



1.2.2
Metal-ruling tracelet.

ruling coarse lines on metal scales. A tracelet attachment is also available for ruling longitudinal fiducial lines (Fig. 1.2.2).

Diamond tools are necessary for ruling:

(*a*) highly finished metal line standards with fine lines,

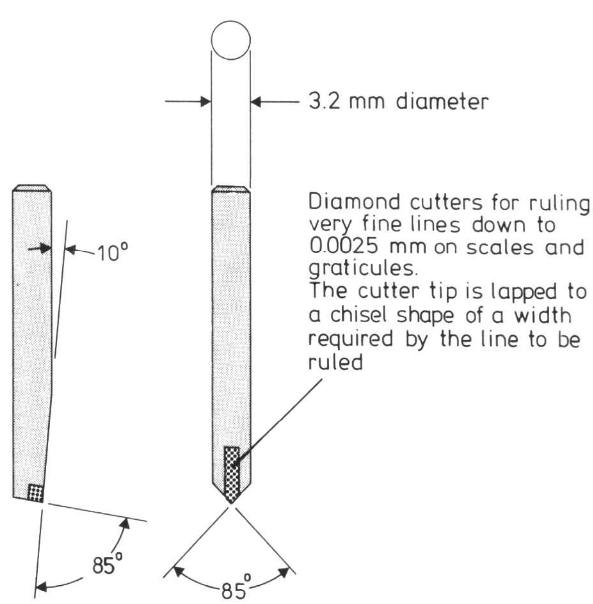
(*b*) dark-background scales on glass blanks which have been thinly coated with metal or other material by high-vacuum evaporation,

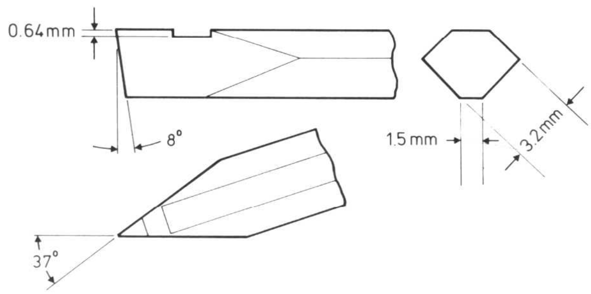
(*c*) directly on the surface of glass.

Diamond tools are normally purchased complete from a manufacturer. There are various preferred shapes (Fig. 1.2.3).

For (*a*), a diamond with 120° included angle coming to a sharp edge is normally considered the best. The variation of loading on the tool gives the line width, and the line itself is actually a groove without burrs in the surface of the metal. For (*b*), the diamond tool should take the form of a very sharp chisel whose width is equal to the width of the line to be ruled. For (*c*), the tool must be very sharp.

1.2.3
The chisel-shaped diamond tool must completely remove resist but not scratch the glass surface.





1.2.4
Steel cutter for ruling in silver.

Steel tools are normally used:

(*a*) for cutting through resist coating on glass blanks in preparation for etching grooves in the glass with hydrofluoric acid,

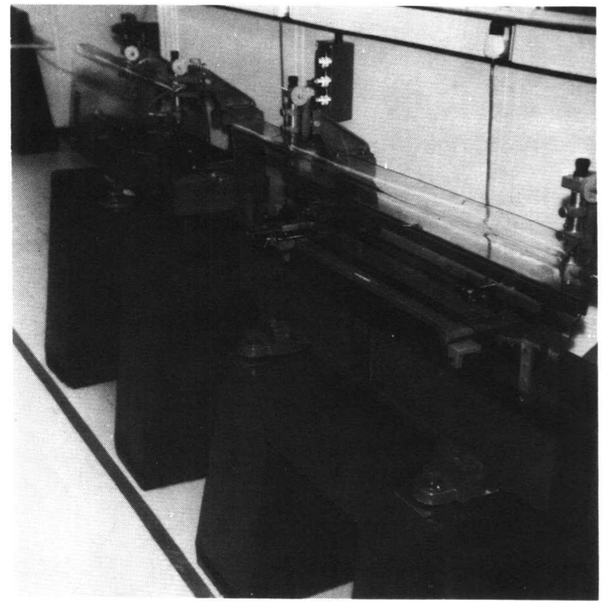
(*b*) for cutting coarse metal scales on, for example, ground surfaces (Fig. 1.2.4).

Linear scales which have been divided must be checked for accuracy and, for this purpose, they are compared with a reference scale which has itself been calibrated against a National Standard.

Longitudinal comparators and transverse comparators are both used for checking the length of scales after ruling (Fig. 1.2.5). A longitudinal comparator has the known and unknown scales placed end to end on a table which can be accurately traversed under two photoelectric microscopes. The microscopes can be fixed in an infinite number of longitudinal positions to suit the particular scale which has to be calibrated.

One microscope is set over a line on the known calibrated scale and the other over a similar line on the unknown scale. Measurements are taken on both microscopes, the table is moved to the next line, measurements are taken, and so on. On comparing the measurements on the line positions of the known scale with the figures in the calibration test certificate one can easily calculate the dimensions of the lines on the unknown scale. A calibration certificate can therefore be prepared for the 'unknown' scale.

If a linear ruling machine has been calibrated against a line standard, and the ruling machine is known to repeat movements with precision, then it can be used to calibrate an 'unknown' scale (Fig. 1.2.6).



1.2.5
A longitudinal comparator for lengths up to 305 mm (12 inch) on the left and a transverse comparator for lengths up to 1·08 m (40 inch) on the right. Photoelectric microscopes read the master, which is then replaced by the 'unknown'. The instrument is used for overall lengths, not for intermediate dimensions.

A transverse comparator is an instrument in which the known calibrated scale is placed side by side with the unknown scale. The two microscopes which are required for the measurements are placed over the appropriate lines of the known master scale. The carriage supporting the two scales is then moved sideways so that the engraved lines on the unknown scale are brought under the microscopes. As the microscopes are rigidly mounted, and simultaneous recordings are taken at each end, the accuracy of measurement does not depend on the accuracy of movement of the carriage. The process is a comparison of each scale in turn with a fixed distance, represented by the separation of the microscopes. Sensitive thermometers are always fixed to the carriage to ensure constant temperature conditions during calibration.

The development of the laser interferometer has introduced a new method for the measurement of long lengths where it may replace end bars and line standards.

1.2.6
A linear ruling machine, calibrated against a master, can be used to calibrate new scales. A photoelectric microscope measures the position of ruled lines. The photograph shows a scale held in a fixture while being calibrated.

Techniques in which light reflected from a moving object interferes with light coming directly from the same source have been used for many years to measure distances very accurately. The two beams of light produce light and dark fringes that indicate their relative phases. As the object moves, the fringes moving past a fixed line enable us to calculate the distance moved in terms of half-wavelengths of the light used in the instrument.

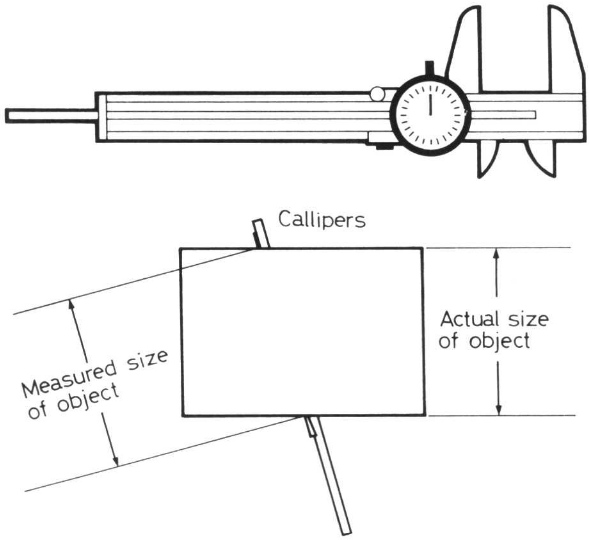
The intensity and purity of light from a helium–neon gas laser makes possible the use of electronic counting methods. Fringes can be reliably counted at more than a million per second.

Because of the high inherent accuracy and reliability of a modern laser interferometer it cannot be calibrated against a standard of higher accuracy. Calibration must therefore be against another laser interferometer, or two other interferometers if there is any disagreement on performance. The calibration method requires the use of a long straight bed with a moving carriage. The two laser interferometers to be compared are mounted at each end of the bed, facing inwards, and their corner cube reflectors are fixed back-to-back on the moving carriage. When the carriage is moved along the bed the fringe count should be exactly the same on each instrument, but in the opposite direction. If there is an unexplained difference in fringe count then another laser interferometer is necessary to detect which is the faulty instrument.

One of the most reliable helium–neon (632·8 nm) laser interferometers is made by Hewlett-Packard. With the permission of the Hewlett-Packard Company the following extract is taken from an article by J Dukes and G Gordon in the *Hewlett-Packard Journal.*

> The laser interferometer system is a portable distance-measuring standard which measures distances from zero to more than 200 ft (60 m). It has 1 μin (0·025 μm) resolution and is accurate within five parts in 10^7. It has electronic averaging to keep readings steady, even in the presence of minute vibrations, and it has good immunity to air turbulence, the most common cause of poor interferometer performance.
>
> At one extreme, the interferometer's 200 ft (60 m) range makes it attractive for steel tape calibrations, precision aerospace applications, and seismographic experiments. At the other extreme, its 1 μin (0·025 μm) resolution is useful for calibration of gauge blocks and microscope stages. In between these extremes lies the vast area of precision tool calibration, from micrometers to automatic milling machines, and feedback control. To aid in these calibrations, the interferometer has a simple optional accessory that automatically calculates machine errors and shows them in perspective by plotting them on an x–y recorder.

A laser interferometer, as any other measurement tool, must be used correctly to realise its full accuracy. Consider vernier callipers which measure the distance between the jaws on a line perpendicular to the jaws. If the object to be

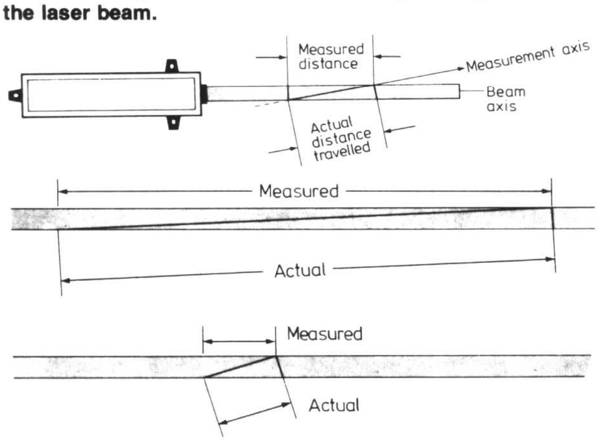


1.2.7
Vernier callipers and the inaccuracies caused by incorrect placing of the object.

measured is not placed correctly in the callipers, the measurement will not be accurate (Fig. 1.2.7).

The basic rule for operating the laser is analogous and a matter of simple geometry. For a measurement to be accurate, the laser must be aligned so that the beam is parallel to the axis of measurement. If the laser reflector moves along a diagonal path across the beam the measured distance is shorter than the actual travel. This error is commonly referred to as cosine error (Fig. 1.2.8).

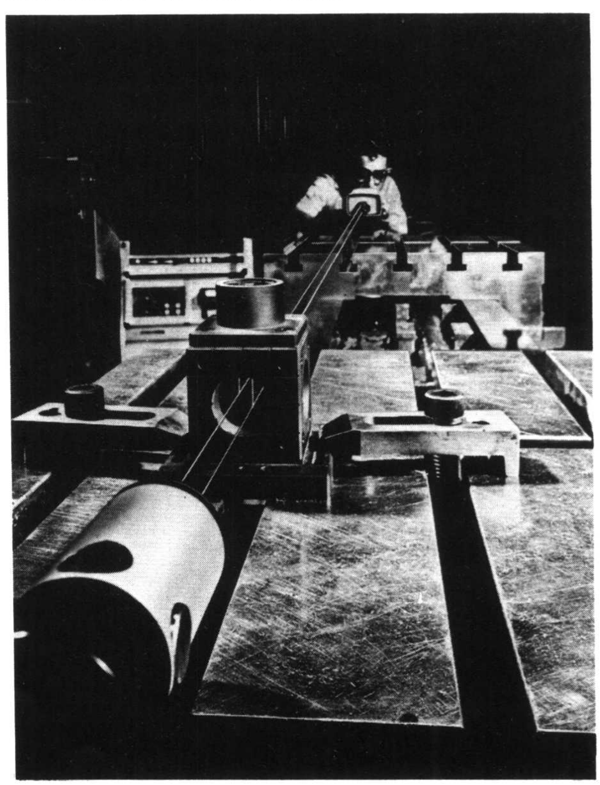
1.2.8
Small and large cosine errors caused by misalignment of the laser beam.



The width of the laser beam is approximately 5 mm (0·2 inch) and is ideal for projecting over short as well as long distances. Because of the beam width and the fact that the laser operates on a heterodyne principle, a great amount of return signal loss can be tolerated. This means that it is possible for the laser reflector to move laterally across the beam by an appreciable distance and still have the laser operate. Over long distances this error may be small but over small distances it can be considerable.

Cosine error is removed when proper alignment limits the possible cross-travel of the reflector to an acceptably low value for the measurement distance travelled by the reflector and for the desired accuracy of measurement. Assume that a measurement is desired that requires a reading to within 2·54 μm (0·0001 inch) over a 254 mm (10 inch) travel. This corresponds to an accuracy of one part in a hundred thousand or 1×10^{-5}.

1.2.9
Linear interferometer consisting of laser head, remote interferometer and retroreflector.



The amount of cosine error introduced by misalignment can be measured for a given set-up. It is determined by observing the sideways and up-and-down motion of the returning beam spot, on the front of the interferometer, while the reflector is moved along the machine axis (Fig. 1.2.9). The alignment procedures aim to minimise this returning spot motion, at least to a point where any remaining cosine error can be neglected.

For distances of around 1·27 m (50 inch) or more, cosine error can be ignored for all except the most exacting measurements. This results simply because, for the laser to work, most of the returning beam must enter the return port. Thus, the displacement must be less than about 2·54 mm (0·1 inch) from one end of travel to the other. However, the wavelength of light in air depends directly on the velocity of light in air, which in turn depends upon air temperature, pressure, and relative humidity. Air that is less dense, for example low-pressure high-temperature air, results in a higher velocity of light and a longer laser wavelength. The thumbwheel switches on the display unit allow the user to take this variation in wavelength into account.

The distance shown on the laser display at any time is equal to the product of the laser wavelength, in millimetres or inches, times the number of wavelengths of motion counted since reset was last pressed. In practice, this product operation is done in two steps. The number of wavelengths counted is multiplied by the ratio of the wavelength in air to the wavelength in a vacuum, and this result is then multiplied by the vacuum wavelength of the laser light (Fig. 1.2.10).

1.2.10
Hewlett-Packard laser, calculator laser display and plotter.