strument and is limited only by the resolution of the original material.

d. The process, as described, can be used in production and should be learned quickly by the First Order Stereo-Instrument Operator.

e. Further investigation as to utilization of these basic formulas (as shown in Figure 7) should be considered by those interested in the use of panoramic convergent photography for mapping.

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*Coordinate Measurement: The Elusive Micron**

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ABSTRACT: *There exists a noticeable gap between the 1 micron least reading on coordinate measuring equipment and the attaining of true 1 micron accuracy. This is caused by inherent limitations of screws and scales which form the basic measuring reference. Often overlooked is the problem of transferring dimensions from the measuring reference to the working plane. For example, nearly all existing designs depend to a greater or lesser extent on both the straightness and orthogonality of two sets of ways, and their interaction. An error of only 0.9 seconds of arc in 9 inches corresponds to an error of 1 micron. Calibration of coordinate measuring tables is very difficult to perform reliably to less than a micron, since a precision ruled grid is the only good method available. Until now such grids have been difficult to obtain. A new facility is nearing completion that will fill this gap by ruling grids with errors small enough to be ignored in most practical situations of photogrammetry.*

INTRODUCTION

WHILE typical accuracy obtainable in current aerial photography is rarely better than 5 μ, there would be a distinct advantage in evaluating photographs with coordinate measuring equipment which is accurate to 1 μ. The reason for this is simply that instrumental errors would not have to be considered in data reduction. Even with modern computers it is desirable to avoid storing error information in a memory unit whose size and cost one should hold at a minimum. Coordinate measuring equipment for many years has been designed for 1 μ readout over 240 mm. square areas, but working accuracy has rarely been of the same order. Even calibrations to an accuracy of 1 μ have been very difficult to perform for lack of good reference standards. It is worth examining the difficulties involved both in instrument design and calibration in order to

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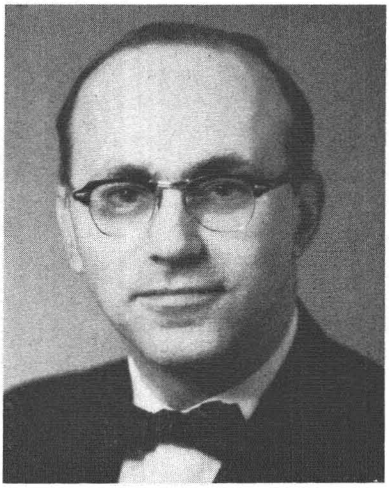
appreciate what methods could lead to improved accuracies in the future.

MEASURING ELEMENTS

Screws and scales have been the traditional measuring elements, although in recent years grids have also been proposed (Raentsch, 1959; Smialowski, 1963). Screws of 1 μ accuracy are fairly common with 25 mm. range of travel but are very difficult to produce in longer lengths, especially when travel up to 250 mm. is required. If screws are hardened and lapped and are of a diameter large enough to minimize sag, residual errors are usually small or gradual enough so that simple correction cams can keep errors from accumulating to more than 1 μ. However, it is important to guard against periodic errors which no man-made screw has ever escaped, and which are also generated by bearings whose axis or alignment does not coincide with that of the thread. Poor quality or design of thrust bearings can have the same effect, although designs exist which lead to end play of less than 0.01 μ.

Periodic errors are particularly insidious because they frequently escape notice when calibration is performed against the usual reference standard whose divisions are an even multiple of the screw pitch. A simple solution is to calibrate metric screws against inch scales or vice versa. Design of devices to transfer motion of the nut to a moving stage has progressed to where this should be no problem. Basic to screws (except for ball screws that are more difficult to produce to the required accuracies) is that rapid motion generates error-producing heat, and also that mechanical wear requires periodic recalibration. A very important advantage of screws lies in the ease with which their rotation can be made to give a corresponding electrical output by using any one of a large number of rotary resolvers or digitizers.

Scales can be both optical or electrical, although the latter have not yet been produced to 1 μ accuracy. The advantages of scales lie in freedom from wear, and from thermal problems due to rapid traversing. Automatic photoelectric readout has been achieved by the Moire fringe method, but not quite to 1 μ accuracy. Visual settings to cleanly ruled lines can easily be made to 0.5 μ, with 0.1 μ regarded as a limit for most observers. Photoelectric line setting can achieve 0.03 μ precision, which is more than adequate when other limitations are considered. Scales



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240 mm. long can be produced with errors less than 1 μ between any two lines, and even better scales will be available in the future.

Slide motions can also be measured interferometrically. This involves expensive interferometers but with ultimate capability of detecting relative motions as small as 0.003 μ, measured in terms of the wavelength of a suitable spectral light source (Loewen, 1963). For ruling master diffraction gratings this approach has proven invaluable, but requires, among other things, elaborate control over environment (temperature and vibration in particular), as well as fully automatic operation. The presence of a human operator makes the ultimate unobtainable. It is also necessary to pay full attention to the basic system geometry.

GEOMETRIC CONSIDERATIONS

Unless certain details of geometry are considered, not even perfect screws or scales give accurate measurements. Of primary importance in coordinate measuring, as distinct from one-dimensional length measurement, is the straightness and orthogonality of the two sets of coordinate slides. The coordinate reference system is simply not definable to a degree better than the straightness of each axis plus the angle between them. While this seems perfectly obvious, it is a point seldom given the importance it deserves, as can be seen from reading most manufacturers' specifications for instruments. A simple calculation shows that a departure of as little as 0.9 seconds of arc in either straightness or right angle corresponds to 1 μ in 9 inches of travel.

Not many slides can be depended upon for 1 second control in all coordinate positions, especially with the usual compound design that suffers from variable loading conditions in extreme settings. Bed type designs are sometimes used to get around this, when other considerations allow it, because here both X and Y slides are separately mounted on a common base and do not interact mechanically with each other as they move.

The tilts or rotations just discussed are those around a vertical axis, perpendicular to the plane of measurement. Unfortunately these tilts have still another—and quite different effect on measuring errors—where they combine with rotations around the other two axes. This effect derives from the fact that most measuring systems, in order to achieve compactness, locate the measuring element at some distance below and often to one side of the axis or plane in which measurements are made. First-order errors are the inevitable result, as Abbe pointed out in 1890. Such errors, shown in Figure 1, are simply equal to the sine of the tilt angle α multiplied by the distance between measuring axis and measuring element, measured in whatever plane errors are under consideration. Elaborate measuring systems have been built where this distance is 12 inches or even more, which means that every second of arc tilt produces a reading error of 1.5 μ.

The so-called Abbe Comparator principle states that for maximum accuracy "The measuring element must lie in a straight line projection of the axis of measurement," and when adhered to, completely eliminates first-order tilt errors by reducing the tilt angle multiplying factor (d) to zero. It is important that whenever the principle is violated, as it often is for very good reasons, the results be carefully considered. This has not always been the case.

It is interesting to note that there exists a fairly old, but little known optical technique by which it is possible to read scales mounted conveniently below the measuring plane in such a way that any tilt errors are optically compensated. The advantage lies in making it possible to obtain accurate measurements independently of tilts around a horizontal axis, without the bulky designs inherent in straight application of Abbe's principle, but when applied merely to scales offers no relief from the need to make ways straight and square. To achieve the latter requires the use of grid plates, as discussed below.

Environmental Effects

Temperature is by far the single most important effect ascribable to environment. Absolute temperature is less important than temperature fluctuations and the gradients they produce. Even when measuring elements, such as scales, have the same coefficients of expansion as the objects evaluated, their normally internal, protected location results in time lags with respect to external changes of temperature quite different from the more exposed photographs on a platen. A similar situation results from body heat radiated from a human observer sitting on one side of an instrument. Such effects can often be reduced appreciably if the air is kept in thorough circulation all around the instru-

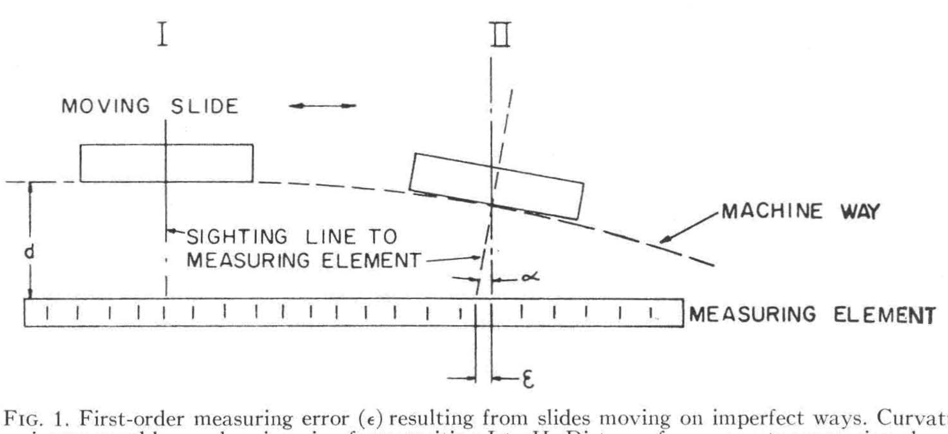

FIG. 1. First-order measuring error (ϵ) resulting from slides moving on imperfect ways. Curvature of way is measured by angle α in going from position I to II. Distance from ways to measuring element (screw or scale) is d. For the small angles actually involved $\epsilon = d\alpha$.

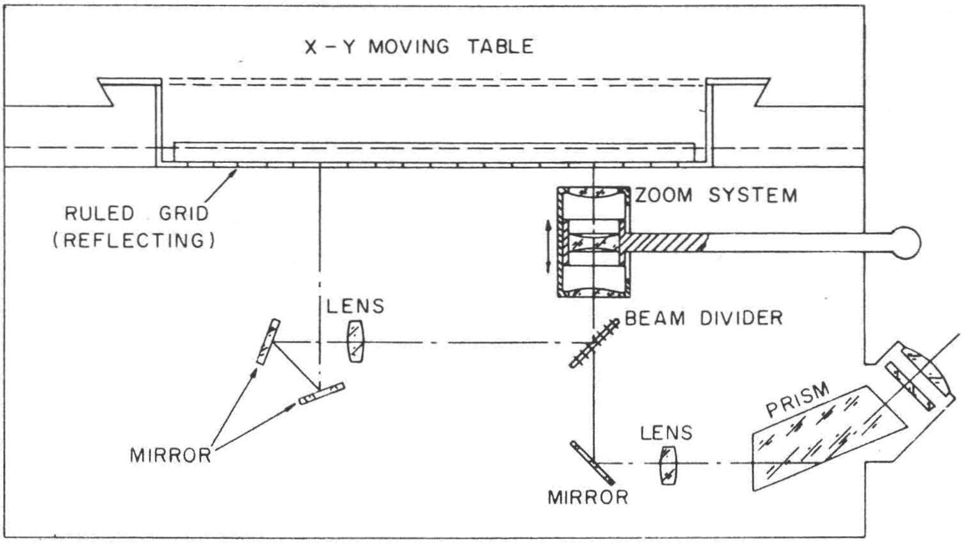

FIG. 2. Schematic of an optical coordinate table based on precision ruled grid. Effect of way errors avoided through optical compensation. Variable magnification telescope in parallel ray path (grid plate used as mirror) adjusts location of plane above table in which complete compensation is obtained. After Raentsch.

ment, with auxiliary fans for example, although most operators are not likely to appreciate this.

Dirt is the traditional enemy of precision, especially where smooth moving slides are needed and where optics are involved, but the point hardly needs emphasizing here.

The Use of Grid Plates

Once the sources of important errors have been identified, methods for their reduction are usually fairly obvious, although they often are difficult and expensive to carry out in practice. As a result the use of grid plates or ruled grids, as described for example by Raentsch and Smialowski, represents an important step forward. The idea is to produce on a glass plate a 2 dimensional array of lines, or other suitable index marks, and make an optical comparison between their positions and those of an object being printed. Assuming that a satisfactory design has been chosen for interpolating between index positions, there now exists, for the first time, the opportunity to obtain highly precise coordinate measurements without requiring more than average quality in the slide motions. Obviously the burden for producing high accuracy has been simply shifted to the supplier of grids, who hopefully can be depended upon to supply grids to the required accuracy.

Optical compensation for tilting effects can be applied to grids as well as scales, a typical schematic, taken from Raentsch, is shown in Figure 2. Of interest to machine tool builders, but hardly to photogrammetrists, is that by varying the focal-length of the optical system the tilt effect compensation can be adjusted to apply both in the plane of the table as well as any reasonable distance above it. However, at any given setting, compensation is complete in one plane only.

Testing of Coordinate Measuring Systems

A common and simple method of testing coordinate measuring systems consists of using calibrated scales to check each coordinate motion separately. Unfortunately, this is entirely inadequate because it provides no information on slide straightness, orthogonality, or the possible interactions between slides in their extreme positions. A complicated and tedious series of measurements is required for a full exploration of errors.

The only technique that reveals all the necessary information in a single step is to use a precision ruled grid. Since sharply ruled lines 5 to 8 μ wide can be pointed to quite readily with a precision of the order of 0.25 μ, the calibration process becomes quite a simple one as soon as ruled grids of perhaps 0.5 μ accuracy are available. Ruling grids to such accuracy is not a simple undertaking, requiring specially built equipment, and as a result they have not been generally available. It is anticipated that this gap will soon be closed. At present one is usually forced to use grids ruled to lower degrees of accuracy, but furnished with calibrations for each point of intersection. Such calibrations are difficult to obtain to sub-micron accuracy, and taking the errors into account adds appreciably to the labor involved in using the grids.

Conclusion

It is possible, by taking advantage of known error reducing effects, to design 9 inch square coordinate measuring machines to attain the 1 μ accuracy that has so long been no more than the least reading. The effort and cost involved may be appreciable, but small compared with what will be involved in attempting a significant break through the "1 μ barrier." All restrictions become intensified and remote control becomes essential. However, when photographic data of sufficient quality become available, the corresponding instruments will be developed.

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Photo Interpretation in the Highway Materials Program of the U. S. Forest Service

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Introduction

The information interpreted from aerial photography has distinct application in many engineering phases of Forest Service work. This paper, however, is concerned primarily with the role of photo interpretation in the highway materials program in the states of Utah and Nevada and parts of Idaho, Wyoming, Colorado, and California which make up the Intermountain Region.

Several years ago a photogrammetric reconnaissance program was initiated to accelerate the Region's road location program. This program utilizes photogrammetric principles to provide area and route reconnaissance information for forest engineering personnel. An area reconnaissance is a photogrammetric study of several routes that may serve the transportation needs of a general area. A route reconnaissance is more refined in that the routes located by photogrammetric methods adhere to grade and alignment controls specified by field engineers. A complete route reconnaissance consists of route delineated photos, and information sheets that list grades, sideslopes, exposure, vegetative cover, and drainage data referenced to center line stations.

The Photo-Materials Investigation Phase

Recently, it was decided to supplement the reconnaissance program with a photo-materials investigation phase that would anticipate problems such as heavy rock cut sections, unstable soil conditions, ground water fronts, landslide susceptible situations,