a full-time pursuit for a limited number of specialists, and a supplemental pursuit for innumerable other workers in the various fields of geology. Just as the microscope extended the range of the biologist's observation, so also has the aerial camera and the stereoscope enlarged the range and scope of the geologist's observation, giving a new perspective on the earth's surface, and a new degree of refinement in studying its varied phenomena.

BASIC FACTORS IN PHOTOGRAMMETRIC INSTRUMENT PERFORMANCE*

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INTRODUCTION

IT IS my privilege to speak on the practical aspects of the broad subject of "Basic Factors in Photogrammetric Instrument Performance." The Bausch & Lomb Optical Company and I extend sincere thanks for this opportunity to present our point of view on this debatable subject. Essentially, we believe that a thorough understanding and application of this subject to manufacturing photogrammetric instruments is our major responsibility to the profession; and it is, in fact, the responsibility of every reliable manufacturer who supplies photogrammetrists with their essential instruments and operating supplies. Unless these instruments and supplies meet practical basic specifications, the cost, quality, and rate of production of the maps produced are unfavorably affected. Of course, many factors affect performance, but we are primarily concerned with those factors which, through continued improvement of instrumental performance, can improve the economics or logistics of map production.

PURPOSE OF PANEL DISCUSSION

In the panel discussion which follows this paper,† it is not our intention to discuss the merits of specific instrumental approaches to photogrammetry. That is the purpose of the various exhibits at this meeting. Instead, we propose to discuss, in a logical sequence, questions concerning basic performance factors related to all types of photogrammetric instruments, accessories, and operating supplies. Particular emphasis is placed on those factors which directly affect practical performance in map production.

It is our further purpose to discuss these factors insofar as possible in the practical language of the engineer who operates the equipment and produces the map. These factors can then be understood more readily by the practical photogrammetric engineers and administrators who constitute the larger portion of this organization. These are the men who can apply the basic understanding of these principles in using optical instruments and photogrammetric supplies, to produce maps to specified standards for many other engineering purposes. We plan to discuss the more basic factors in order to evaluate their approximate economic or logistic performance.

Discussion of this subject is predicated on the fact that every practical photogrammetric system of instruments in use today requires about the same basic type of instruments, accessories, and supplies. These all have similar

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† The panel discussion will be included in a later number of this journal, probably the June issue.—*Editor.*

effects on map production performance and are manufactured to fixed specifications. These classifications are:

1. Aerial cameras for obtaining photography on film or glass plates.
2. Ground surveying instruments using optical, electronic, and barometric principles for obtaining and checking vertical and horizontal positions of ground control points.
3. Contact or projection printers for obtaining diapositives.
4. Multiple projection or comparator type instruments for extending ground control by bridging methods. (Mathematical and slotted-template systems require measuring comparators.)
5. Double projection or comparator type instruments (optical or mechanical or both) for compiling the map.
6. Scale changing equipment, such as coordinatographs, pantographs, or copy cameras for enlarging or reducing the scale of the drawn map.

The primary purpose of this paper is to propose a logical grouping of the major performance factors in map production, in order to better understand and evaluate their individual and collective effects on mapping instrument performance, and therefore mapping costs or logistics. These factors for all operating systems fall into three main groups, for which definitions are proposed. Each of these groups can be defined, and quantitative limits on engineering or economic performance can be established by the individual and collective experience of map producing organizations, both national and international. Users of all types of equipment, from every major continent, have in the last three years visited Bausch & Lomb and have discussed their mapping problems. The experience shared with us has been appreciated as being most useful in evaluating the instrumental performance of all systems.

DEFINITIONS OF MAJOR GROUPINGS OF PERFORMANCE FACTORS

The first and most important group of performance factors which requires defining is designated as Map Production Performance. This group is defined as including those performance factors which are directly related to organizational and administrative control of map production in photogrammetric organizations which produce and distribute the maps. The over-all effect of this group of factors can be measured only by the cost of producing a map to a particular set of specifications, with a certain system of instruments, by a particular organization. A certified public accountant can of course determine this cost by use of standard accounting methods. Each organization naturally prefers not to publish this information for many reasons; but, as an example, if the cost of a five foot contour map with a reasonable amount of planimetry for highway maps is $1 per acre, this would result in a map cost of about $500 and more per pair of photographs used, depending of course on map specifications. This gives us very approximate figures but indicates the order of magnitude of the cost factor being discussed.

The second major group of performance factors is the group defined as that which directly controls map accuracy. The proposed designation of this group of factors is "Map Accuracy Performance." Map accuracy, of course, affects map production performance, but it is treated separately and can be measured independently. The over-all measure of map accuracy performance is simply the flying height at which the photographs were taken and were used to produce a particular type of map, field checked to a specified contour interval accuracy, as well as planimetric accuracy. The ratio of flying height to specified contour interval, known as the "*C*" Factor, is also an approximate measure of accuracy; "approximate" because collective experience has shown that this accuracy factor decreases with increase in flight height. The checking of map accuracy performance is performed by a field survey of the finished map, but standard survey methods, using both traverses and profiles for checking. It is of course understood that "normal-angle" systems require considerably higher accuracy than wide-angle systems to be economically equal, but that they do have a place in production of specific types of maps.

The third important group of performance factors has been designated map reproducibility performance, for lack of a better operational term. Map reproducibility is defined in this paper as the ability of the average skilled engineer to reproduce repeatedly, within certain measured limits, a series of map manuscripts from the same undisturbed stereoscopic model. This actually can be called the precision of the system. Measuring map reproducibility performance involves making and projecting a stereoscopic terrain model from a particular set of photographs with a particular system of instruments. The map reproducibility may then be checked by redrawing the map manuscript from this stereoscopic model several times, by several skilled engineers. Map reproducibility actually is expressed as a series of measurements of the variations of positions of contour lines, as related to slope of the terrain, of point elevations, of profiles, and of horizontal location of planimetry. These variation measurements as a group form the measure of map reproducibility performance. It is noted that the term "personnel error" is often used to approximate what is defined here as variation in map reproducibility.

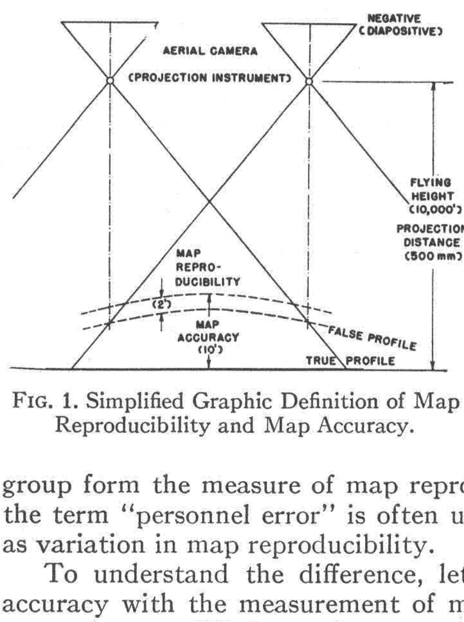

FIG. 1. Simplified Graphic Definition of Map Reproducibility and Map Accuracy.

To understand the difference, let us contrast the measurement of map accuracy with the measurement of map reproducibility for drawing the contours of a map. We know that map reproducibility of a system of instruments may be considered excellent, as is the situation with the more mechanically complex instruments; but the map which is reproduced precisely may be proven to have limited map accuracy performance, by field survey checks. This does happen with all photogrammetric systems, as you are all aware. For example, Figure 1 represents a wide-angle system with the cameras (or projectors). The map reproducibility of a profile position on a map or model is illustrated as a 2 foot maximum variation, using photographs flown at a height of 10,000 feet. However, the map accuracy may be limited by as much as a 10 foot variation of the profiles from their true vertical position, in this case a flat area. Thus, for profiles of a particular system, we can have a 2 foot map reproducibility performance, but only a 10 foot map accuracy performance. Bettering the map reproducibility performance of a system from 2 feet to $1\frac{1}{2}$ feet through improving the instruments is of somewhat questionable economic value, when the total map accuracy performance of the system may be limited to a 10 foot profile accuracy. This is especially true if, at the same time, other map production cost factors are increased or map accuracy is adversely affected.

It is understood, of course, that the performance measurements of map production, map accuracy, and map reproducibility are somewhat debatable subjects. However, several of the factors which affect these three performance groups can be measured and specified as to limits. This is the reason we are discussing them specifically in the panel.

MAP PRODUCTION PERFORMANCE

The factors which improve map production performance are primarily administrative ones, and are listed here to foster an appreciation of their importance:

1. Efficient organization administration.
2. Sound financial resources and reputation.
3. Efficient methods of distribution of maps to users.
4. Effective personnel policies to maintain operating efficiency.
5. Mapping instruments purchased from manufacturers with established reputations for furnishing continued service, and instruments each inspected to specifications based on map production experience.
6. Engineering knowledge of specifications of a map, and the final engineering use for which the map is made. (This is particularly applicable to such fields as forestry, geology, highway, and pipeline construction, as well as military applications.)
7. Engineering knowledge of map production planning in order to secure maximum economic or logistic performance of the photogrammetric instruments used.
8. Engineering knowledge of mapping instrument equipment and operating supplies, their capabilities and their limitations.
   This includes:
   a. Ease of supervision of engineers who operate equipment; simplicity of understanding equipment; and ease of training surveying engineers to operate the equipment.
   b. Cost, and size of equipment.
   c. Amount of instrument maintenance.
   d. Cost at specified quality of supplies and service, including film, glass plates, processing materials, etc.
   e. Operational convenience and fatigue in using the instruments.
   f. Cost of methods of securing and extending ground control in all types of areas.
9. Flexibility of equipment to meet demand for wide variety of map specifications as to final scale and accuracy, from the small scales of inaccessible territory to the large scale of accessible urban terrain.

Most of these factors cannot be measured individually, and the improvement of each is guided by operating experience.

MAP ACCURACY PERFORMANCE

In the same way, we may list the important factors which affect map accuracy, some of which can be established, specified, and measured.

1. Number of ground control points per pair of photographs. (Cost of securing ground control is a major expense factor in most map production operations today. Estimates of 30–40% are usual. The most efficient number of points is determined by the method of control extension used and is determined by experience.)
2. Accuracy of ground and geodetic control points using precise surveying instruments, such as theodolites, shoran, altimeters, etc., as determined by surveying methods.
3. Adjustment of the stereoscopic model to ground control points. This is a skill factor difficult to measure except for its effect on accuracy.
4. Maintenance of mechanical alignment, minimum backlash, and minimum wear of mechanical parts which can introduce distortions in the map. This is difficult to measure and control directly.
5. Maintenance of minimum uncompensated distortions from the several instrumental and operational sources which introduce *Y*-parallax in individual models, and cause erratic warps, both in individual models and in extension of ground control in a series of models. These distortions are measured by optical bench methods and photographic plate methods.
   a. radial distortion

b. tangential distortion
c. scale (shrinkage) distortion
d. tilt distortion
e. differential scale distortion
f. random distortions

6. Conformity of design of instruments to basic photogrammetric principles; instruments which draw form lines do not meet these principles.
7. Base-height ratio, which is the ratio of distance between camera stations to flying height, or distance between projectors to projection distance in the stereoscopic model. It is limited by the angular coverage of a system and the overlap of photographs, including convergent systems.
8. Type of terrain. The more rugged the terrain, the greater the effect of the residual distortions.

MAP REPRODUCIBILITY PERFORMANCE

The group of major factors affecting map reproducibility performance can also be listed as follows:

1. Base-height ratio (see definition in factor (7) under map accuracy.)
2. Projection distance of stereoscopic image (the ratio of this distance to flying height determines the plotting scale.)
3. Coordination of hands and eyes controlling mechanically or directly the movement of the floating mark and pencil point.
4. Size of floating mark and pencil point.
5. Total operating resolution of system, particularly required in identifying detail, including:
   a. weather conditions of haze, light, season, etc.
   b. contrast of ground objects
   c. lenses and filters
   d. film and processing
   e. camera focusing
   f. depth of focus of projected image in the final model
   g. vibration or motion of camera
   h. shutter efficiency and speed
6. Residual *Y*-Parallax. This is lack of registration in the fore and aft direction of the two images forming the projected stereoscopic model, and is caused by the accumulated effect of uncompensated distortions, listed under factors affecting map accuracy performance, factor 5.
7. Illumination of the projected image.
8. Constancy of projected stereoscopic image model during operation, particularly a factor when using mechanical projection systems, due to the effect of temperature on them. (Film diapositives are impractical to use for precise work because of lack of model constancy due to temperature and humidity effects.)
9. Characteristics of the terrain—slope, vegetation, planimetry, and contrast.
10. Accuracy of reproduction instruments and materials on the final manuscript of the drawn map.

RELATIVE IMPORTANCE OF PERFORMANCE FACTORS

With the major performance factors which affect map production, map accuracy, and map reproducibility now listed, the controversial problem becomes the determination of the relative importance of factors to be improved, in the interest of producing lower cost maps to specification. If progress is to be made, it is important to make sound decisions on instrument performance, for, after all, we are a relatively small industry, judged by annual map production expenditures.

Research and engineering funds generally are expected to be curtailed as we enter the normal post-war period. Therefore, in the panel meeting, we expect questions to be raised, and opinions expressed, which will help those associated with photogrammetric research and development organizations, as well as map production organizations, to understand and draw conclusions as to the relative importance of the various performance factors. With this, we can then direct our development work toward improving the performance of photogrammetric instruments in such a manner as to produce quality maps at lower costs or in shorter periods of time. It appears that only in this way will the demand definitely grow for maps for present uses, as well as new photogrammetric uses other than aerial surveying.

In attempting to improve any particular factor, it seems logical that we must first determine, by sound interpretation of experience and facts, the relative economic importance of each of the three performance groups—map production, map accuracy, and map reproducibility. For example, we feel that improvement of operating resolution by improvements in lenses, in camera mounts, in shutters, in filters, in film products, and in operating procedures is important in bettering the over-all factor of map reproducibility. We are working on this problem constantly, and always will be, because resolution of any system will never be good enough until you can tell if the young lady in the aerial photograph, taken from 40,000 feet, is a blonde or a brunette.

But how important economically is this factor of resolution? We often have been told by photogrammetric authorities that one important reason for the erratic behavior in the "*bz*" curve, using photogrammetric systems of instruments to extend control, is insufficient resolution of the stereoscopic images. However, the results of recent studies and tests on the basic behavior of the "*bz*" curve, using various photogrammetric instruments under operating conditions, have shown a need primarily for less residual distortion from a practical and economic viewpoint. That is, there is a need for less distortions in all systems of instruments from all sources, film, lenses, instruments, earth curvature, and atmosphere. These are examples of what the instrument tests indicated to us was important in the way of effects on map reproducibility, as well as map accuracy, and the causes of the effects. These effects are known to be observable in all systems of photogrammetric instruments.

OPERATIONAL EFFECTS OF KNOWN DISTORTION

In Figure 3 on the left is shown one operating effect on the horizontal scale on an extension of three models, the solid lines being the desired undistorted model, and the dotted lines the distorted model produced by the photogrammetric equipment used. This effect was illustrated in an article (1) published by J. A. Eden of the British War Office in London in the PHOTOGRAMMETRIC ENGINEERING, December 1948.

In Figure 3 on the right, a second operational effect, also noted at times in map production, is shown as reported by J. T. Pennington of Ft. Belvoir in the March 1947 issue of PHOTOGRAMMETRIC ENGINEERING (2). In agreement with J. T. Pennington, our experience and observations show that these effects are eliminated to the degree that *tangential distortion* is eliminated in the system. Mr. Eden reports his opinion that this effect was due to "personnel error" or calibration errors.

Tangential distortion is represented as measured in an image plane. In Figure 2 here is shown in dotted lines a true photograph of a square grid. In solid lines is illustrated the actual shape of the representative photograph of the true grid line picture, when tangential distortion is present in the lens.

In Figure 2 is shown uncompensated tilt distortion as measured in an image plane and caused, not by tilting the camera, but by film handling, lens decentration, and tilt of film support planes with respect to lenses. Figure 4 on the right illustrates the operational effect that this tilt distortion would cause in a stereo model of a tall monument. Objectionable amounts of tilt in a 400′ monument

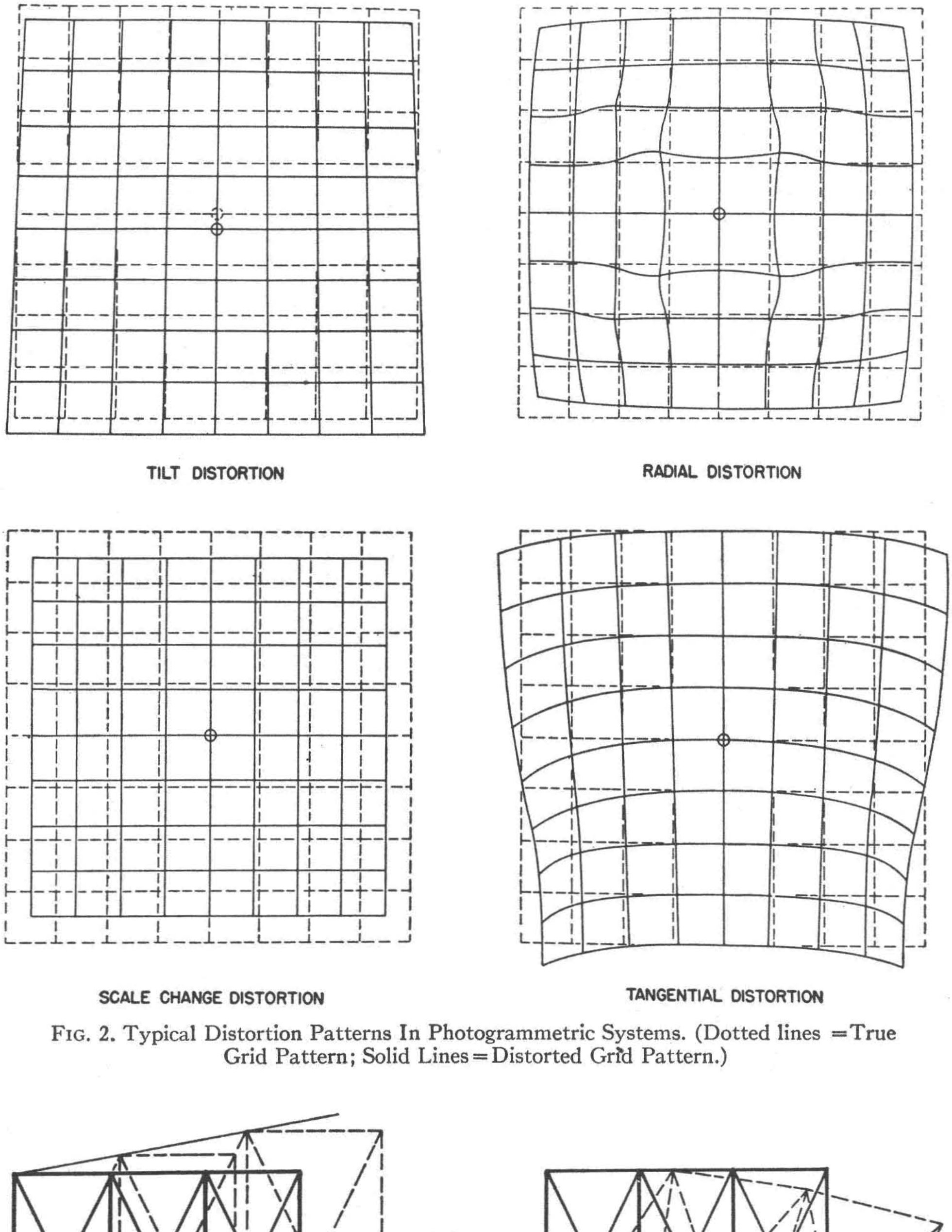

FIG. 2. Typical Distortion Patterns In Photogrammetric Systems. (Dotted lines = True Grid Pattern; Solid Lines = Distorted Grid Pattern.)

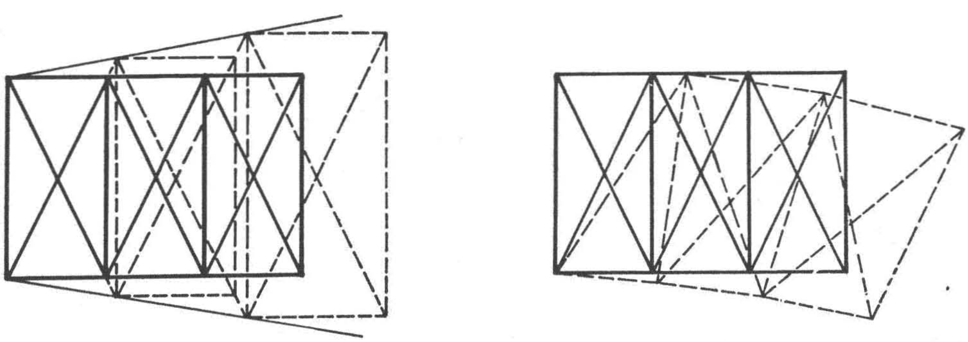

FIG. 3. Operational Effect of Tangential Distortion. (Solid lines = True Grid Pattern; Dotted Lines = Distorted Grid Pattern.)

would be observable if photographed from 1200 feet and its stereoscopic model established. Operational techniques can eliminate this factor.

Figure 2 also illustrates the scale distortion pattern from several operational causes. On the left of Figure 4 is the well known operational effect of this scale distortion on the vertical scale of the monument. Adjustment of the diapositive projection printer will compensate this effect, if the magnitude is established in operation.

In Figure 2 is shown the effect of radial distortion in a photograph of a grid picture. The solid lines represent the way a picture is distorted from the true (dotted line) grid.

The operational effect of radial distortion, based on a recent operating test, using 16,000 foot photography in Multiplex equipment, is shown in Figure 5, upper diagram, by the characteristic "*bz*" curve due to this distortion on the base line of a series of extended models. The "*bz*" curve shown varies in two successive test "bridges" for the same engineer as well as for two different engineers operating the same equipment. This variation was supposedly strongly affected by resolution, causing the "personnel variation" or lack of map reproducibility. For this test, we furnished to Mr. R. K. Bean of the U. S. Geological Survey an experimental set of compensating diapositives for use under production conditions, to compensate the residual radial distortion in the Multiplex system. The results are shown in the lower diagram of Figure 5. The "*bz*" curve was reduced to about that due to the curvature of the earth. It is evident that the map reproducibility of the "*bz*" curve was considerably improved as well as the map accuracy. This compares favorably with a recent published report on map reproducibility of another more complex bridging instrument (3).

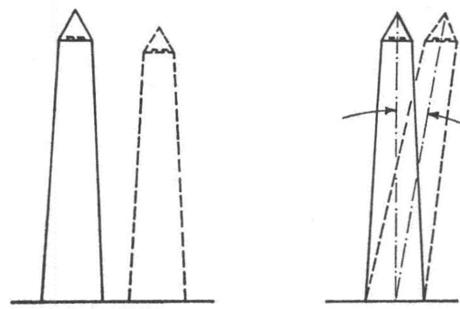

FIG. 4. Operational Effects of Scale Distortion and Tilt Distortion. (Solid lines = True Grid Pattern; Dotted Lines = Distorted Grid Pattern.)

The lack of reproducibility of the "*bz*" curve has been attributed to the lower operating resolution of the Multiplex system, by authorities both here and in Europe. This is further substantiated by the trend of development in many quarters, where resolution is made the primary factor in instrumentation, but the equipment in productive use appears to tell us a different story about this effect. These and other tests strongly emphasize that the various distortions can be reduced to give improved results in all systems. Particularly important are these results in reducing costs by "bridging" ground control, instead of securing extension of horizontal and vertical ground control by field methods. This point of view regarding improving distortion should not be misunderstood. Improving resolution will always be important, particularly in forest mapping, in order to facilitate observing the ground between the trees; but supplying improved resolution at the expense of accuracy, and eliminating the economies of accurate bridging techniques, is at least to be questioned strongly.

Consequently, if those who produce maps are observing any of these effects of residual distortion in their photogrammetric equipment system in map production, by understanding their behavior, they can usually trace them to the true source and have them compensated or corrected. This ability to establish the existence of radial and tangential distortion is possible only when using the type of equipment capable of bridging. In single model projection equipment, incapable of bridging, these effects are intermingled, and in a single model are practically impossible to segregate. Thus inaccuracy in a single model can then be attributed only to the more popular general excuses for lack of accuracy, such as blaming the camera calibration, the random distortion in film, resolution, and "personnel" errors.

In operating tests of performance for all photogrammetric instruments, particularly new systems, much emphasis has been placed on taking pictures of flat

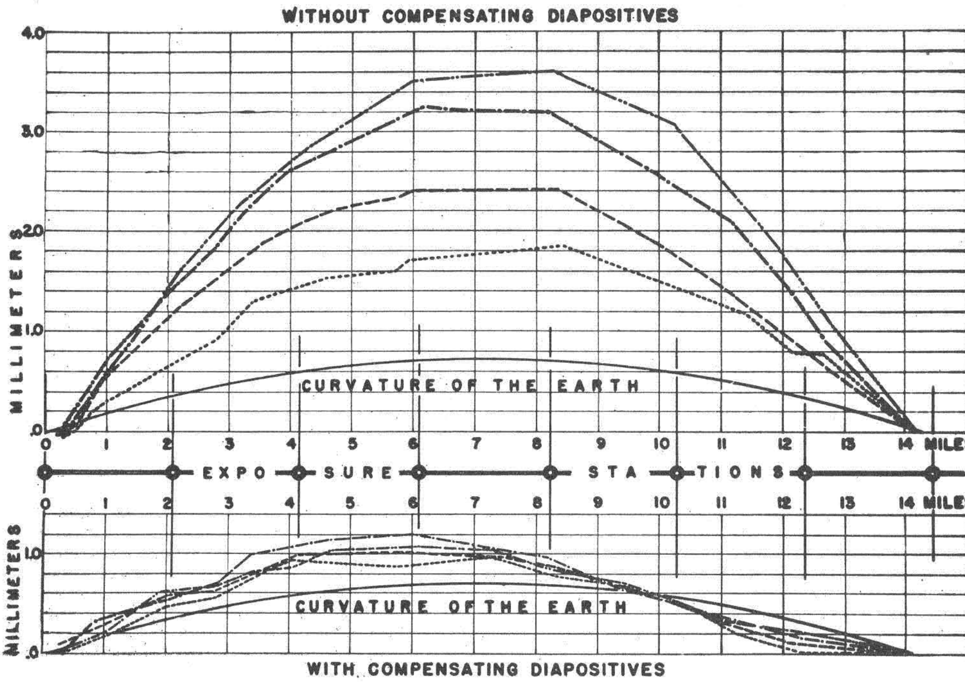

FIG. 5. Effect of Radial Distortion on the "bz" Curve Using Different Operating Conditions.

or rolling terrain and producing a final stereoscopic model which is accurate. But excessive amounts of tangential distortion, tilt, and scale distortions can be present, and yet have no effect on the flatness of stereoscopic models of flat terrain. Residual radial distortion has a small but definite effect and can be computed (4). Only the effects of differential scale distortion from film and random distortions, caused by such occurrences as vacuum failure, are readily observable. Such a model-flatness test is believed therefore questionable for use in checking the map accuracy performance of a system of instruments, as has been borne out recently by some rather expensive experiences of various organizations. When instruments having distortions which do not show up in such flat tests are later used in terrain which is rugged relative to flying height, these distortions unfortunately have a more positive effect on map accuracy. They can be observed and controlled readily in production only by using equipment capable of testing under extension of control over ground test areas of several models of rugged terrain, and numerous known control points of various elevations. Such tests are frequently necessary in productive use in any systems where lenses are disturbed, film mishandled, or mechanical wear and misalignment can occur to introduce the operating effects of these distortions.

CONCLUSION

This paper concludes a series of papers in PHOTOGRAMMETRIC ENGINEERING pointing the way toward a sound economic and logistic basis for comparing photogrammetric instruments.

The first paper (5) published in September 1948, invited attention to the functional factors which show the differences and similarities between various systems of instruments.

The second paper (6), published in December 1948, called attention to the fact that by slight changes in performance figures, such as the "*C*" factor, overlap, base-height ratio, angle of lens coverage, etc., one system of instruments can easily be made to appear superior to another for comparison purposes.

The third paper (7), published in January 1949, called attention to the distortions in all systems of photogrammetric instruments, their individual causes, and their combined effects.

The fourth paper (8) was published in September 1949 and describes the recommended manufacturing specifications, and discusses methods of compensating the distortions which affect map accuracy and map reproducibility in order to produce improved photogrammetric performance.

The fifth and final paper of the series, based on these other four papers, brings to your attention a method of judging the economic and logistic impact of the differences in performance between photogrammetric systems, by suggesting methods of establishing engineering performance standards of map production, map reproducibility, and map accuracy.

To my colleagues at Bausch & Lomb, and to those in photogrammetric organizations with whom we cooperate, goes considerable credit for the many contributions which made possible this series of papers.

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