# ,ens Characteristics as Related to Iodel Flatness

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Stereomodel deformations which are directly attributable to optical characteristics of any part of a lens system are notably of a systematic nature. Although these errors may be within the usual specifications for contours (90 percent within ½ contour interval), their systematic trend can conceivably have a significant influence in the calculation of earthwork quantities from highway design maps.

An analytical study has been conducted to ascertain the effect of individual optical elements of the lens system, including camera lenses, projection lenses, and diapositive glass. Because of its extensive use in highway design mapping, the study hinges on Kelsh-type plotting instruments. In conjunction with these instruments, such camera lenses as the Metrogon, Aviogon, Pleogon, and Planigon are discussed. Procedures for testing plotting equipment and isolating causes of deformation are outlined. Data are derived for compensation of combined distortion, within minimum tolerances, for the restitution of stereomodels relatively free from deformations causing systematic errors.

USE of photogrammetric data and maps for highway location and design is generally :cepted by most highway departments. Whether or not photogrammetric surveys are fficiently reliable for payment of earthwork quantities is a topic of current interest, ; there are great potential savings in manpower which can be realized by obtaining rthwork quantities from photogrammetric data. Research work by the California vision of Highways has shown that the most important factor in the accuracy of rthwork quantities is the vertical accuracy of the survey measurements (5). Instigation of photogrammetric map accuracies (4) had demonstrated that photogrametric measurements can be of an accuracy which justifies statistical analysis, escially if systematic errors and blunders are eliminated.

The causes of errors in the photogrammetric system are extremely difficult to olate. Perfect restitution of the stereomodel, point for point, is undoubtedly an ideal tuation which is not attained in everyday practice. Every stereomodel is deformed some extent, and it is the degree of deformation which determines whether or not it ll be detected. In this country, where film-base photography is the accepted medium stead of glass-plate photography, there is a tendency to dispose of all deformation a function of instability of the film-base. Although the film-base perhaps remains e most important single cause of model deformation, other causes should not be erlooked or quickly branded as playing a relatively minor roll in the over-all probn. By analyzing the cause of individual errors, the necessary data can be compiled a basis for distortion compensation. After compensation is accomplished, the sidual errors would tend to be of a random nature rather than systematic. The relts, then, would lend themselves to valid statistical analysis, which in turn would ıke the science of photogrammetry more useful for detailed engineering studies.

There are two broad sources of error which can be accounted for to some extent the photogrammetrist; namely, instrument calibration and the characteristics of the lens components in the total system. The scope of this study encompasses only th latter considerations, especially those associated with Kelsh-type plotters because the instruments are undoubtedly far more important in the production of highway design mapping than any other type. There is adequate literature dealing with instrument calibration (1, 9), and no particular need exists at this time to elaborate on the subjec There is also considerable literature covering cameras and camera lenses, as well as plotting equipment, but there is a lack of coverage, available to the practicing photogrammetrist, which includes all the lenses in a photogrammetric system, relating them to the final product; that is, the stereomodel.

The significant feature of the Kelsh-type plotter is the formation of the stereomode by direct projection of the 9- by 9-in. diapositive. This solution of the photogrammet problem was first made by Harry T. Kelsh in the years immediately following World War II. The best known instrument of this group is the Kelsh plotter as manufactured by the Kelsh Instrument Company. A variation of it is the Nistri-Photomapper, manufactured by the O. M. I. Corporation of Rome, Italy. Other commercial makes have appeared on the market, but regardless of manufacturer they all share the identical feature of direct projection of the original negative size. This solution permitted simplification of instrument design, thereby making it possible to produce a relatively inexpensive instrument capable of forming a large-size model. In common with all direct projection instruments, the model scale is a function of the magnification facto of the projection lens.

The perfect restitution of the model depends entirely on whether or not the cone of rays emerging from the projection lens is angularly identical with the cone of rays received by the camera lens. Any deviation whatsoever of the projected rays from their original entrance paths will contribute to model deformation. Causes for deviations may be divided into three broad independent groups, as follows:

1. Mechanical—imperfections in instrument fabrication and/or unsatisfactory calibration;
2. Photographic—any shift of the image position on the aerial film or on the diapositive after exposure; and
3. Optical—lack of data pertaining to lenses, or failure to compensate for radial distortion.

Because this paper is concerned with only optical causes, mechanical and photographic causes will not be dwelled on in further discussion.

## ANALYSIS OF MODEL ERRORS

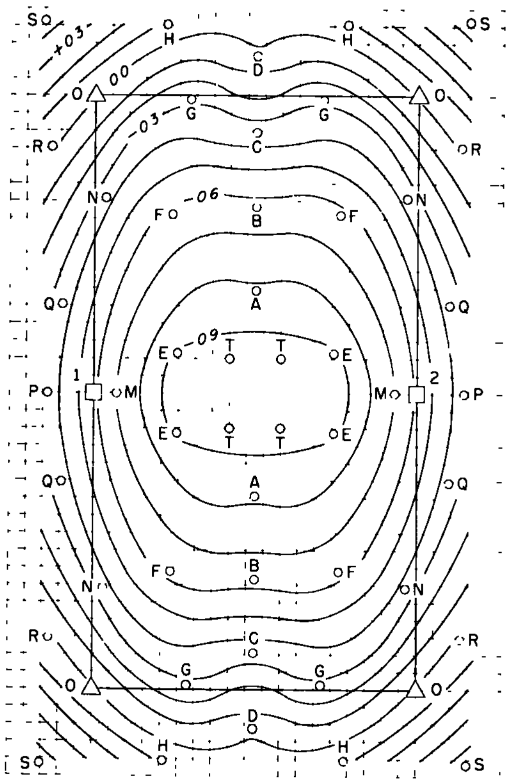
A mathematical analysis of a stereomodel provides a method of predicting model deformation in terms of vertical error. The usual assumptions are that the photographs are truly vertical, and that any two exposures comprising a stereo pair are identical in scale. In addition, a base-height ratio and a width-height ratio must be assigned to determine the size of the neat model. The data for analysis are the distortion values of any lens component in the system. These are customarily given in the calibration report.

Of the various methods of computation, the one devised by J. G. Lewis (6) has bee used in this report. Lewis' method analyzes vertical errors of 16 points that are wel distributed in 52 locations in the total model area, with 32 of them being in the neat model area. The distribution of the points in relation to a 25-mm grid model is show in Figure 1 and similar figures referred to in the text. The neat model in Figure 1 is the rectangular area with the corners marked by triangles. The base-height ratio is 0.62 and the width-height ratio is 1.12, which corresponds to a neat model size of 3.72 by 6.72 in. at photo scale. This is a realistic size for large-scale design mapping. Another method of computation is given by Friedman (3) which also is satisfactory providing base-height and width-height ratios are modified to fit conditions usually associated with larger scales.

The distortions in a system accumulate algebraically. One may begin an analysis with the algebraic sum of all the known distortions to determine the resulting vertica

rror in the model, or the known dis-
ortions can be separated according to
ens component, analyzed individually,
nd the separate results at each point
dded to arrive at the final vertical
rror. Either way will yield the same
nswers. However, if calibration data
re available for the camera lens only,
ne components will have to be separated
or analysis, and the final results in the
nodel determined by adding the separate
rrors. This makes it necessary to re-
ort to methods of analysis other than
nathematical to determine errors by the
rojection lens of the plotting instrument.
. calibration report is very seldom avail-
ble for a projection lens.

Probably the most effective method for
esting performance of a projection lens
s the "grid model" method. Precise
rids on glass are used as diapositives
n the formation of a grid model with a
ase-height ratio equivalent to the value
sed in mathematical analysis. Vertical
rrors are determined by reading the
nodel at the optimum projection distance.
 perfectly restituted model would read
s a truly plane surface, whereas any
eformation would show as a vertical
eparture from this criterion. Grid
nodel deformations are a result of all
rrors associated with the plotter, and
erve as a final test of the over-all per-
rmance of the instrument. The instru-
ent, therefore, must be carefully cali-
rated and tested to minimize the influ-
nce of mechanical sources of error. As-
ıming that all other sources of errors
ave been accounted for, the resulting
ertical errors in the grid model are at-
ibutable to the distortion in the pro-
ction lens.



Assumptions: Camera and projection lenses distortion-free

Instrument: 5X projection plotter
Model Scale: 1 in. = 50 ft
Contour Interval: 0.1 ft
B/H = 0.62 W/H = 1.12
25 mm grid at model scale

Figure 1. Model deformation caused by 0.06-in. thick glass.

## CAMERA CALIBRATION

Most mapping projects require the use of nominal 6-in. photography, with several
signs of lenses available in cameras of different manufacture. The calibration re-
rt which accompanies a cartographic camera assures the user that the camera was
signed and manufactured to certain standards, and further provides detailed data
rtaining to focal length, distortion pattern, and resolving power of the lens as mount-
 in the camera. Cameras which have not been certified by a qualified testing agency
uld not be used for cartographic photography.

Although calibration reports contain basic data important to the user, there is a
sconcerting lack of uniformity among reporting agencies in the manner of presenta-
on, which may occasion doubt as to the consistency of results. To illustrate, the
llowing four agencies present data in varying ways and to different tolerances:

U. S. Bureau of Standards: Lists both equivalent and calibrated focal lengths to a
ated tolerance of ± 0.10 mm. Six distortion values are given to a stated tolerance
 ± 0.02 mm, based on both E. F. L. and C. F. L.

Fairchild Camera and Instrument Corporation: Lists both equivalent and calibrated focal lengths to a stated tolerance of ± 0.10 mm. Eleven distortion values are given to a stated tolerance of ± 0.01 mm, based on both E.F.L. and C.F.L.

Zeiss-Aerotopograph: Lists calibrated focal length to a stated tolerance of ± 0.02 mm. Fourteen distortion values are given to a stated tolerance of ± 0.002 mm, presumably based on C.F.L.

Wild-Heerbrugg Instruments, Inc.: Lists calibrated focal length with no stated tolerance. Eight distortion values are given with no stated tolerance, presumably based on C.F.L.

The apparent confusion in data presentation is noted here because it is a situation with which the practicing photogrammetrist must cope. It does not necessarily mean the data are not usable: it does mean, however, that data are not transferable from the terms of one agency into the terms of another agency, so that two cameras reported individually by two agencies cannot be compared on a uniform basis. This is particularly annoying because the photogrammetrist is forced to regard any camera report as absolute, unless of course evidence exists to the contrary.

Procedures for camera calibration are explicitly explained by Sewell (7), and Washer and Case (14). The latter reference applies to U.S. Bureau of Standards methods. Washer has further enumerated and described the various sources of errors associated with camera calibration and their effect on the accuracy of the calibration (10, 11, 12, 13).

The calibration data with which the photogrammetrist is mainly concerned are the resolution, distortion pattern, and the focal length. A "high performance lens" is one which exhibits high resolving power and low distortion. These terms imply that a high performance lens is capable of producing photographs of exceptional clarity and detail, and at the same time can be used for photogrammetric measurements without correcting for displacement of images caused by deviations in the light rays passing through the lens. Because all lenses exhibit distortions, however small, no lens can be labeled "distortion-free," and the effect of the residual distortions must be analyzed to verify the ultimate effect on the stereomodel. The focal length, of course, is necessary to correctly adjust the principal distance of the projectors in order to recover the proper perspective geometry of the exposures.

## RESULTS OF INVESTIGATIONS

### Diapositive Glass

Kelsh plotter procedure normally requires only two lens components in completing the optical path from the exposure of a ground area to the projection of it onto the platen. The lenses involved are the camera lens and the projection lens. It is currently normal procedure to make the diapositives by contact printing through the film base, using a point-source light, in order to register a reverse image. This permits the diapositives to be placed emulsion-surface down in the projectors. This produces the same results as a one to one ratio projection printer, but eliminates an optical step.

If the diapositive is made emulsion to emulsion in a contact printer the photo-image will have to be projected through the glass. This procedure introduces an optical step because the glass is actually a lens, each surface being of infinite radius. The light rays transmitting the image through the glass will be refracted, causing a distortion which will result in model deformation. Distortion values can be readily determined for glass of any particular thickness considering the angular distance from the axis of the lens system according to the tabular values on page 47 of the "Manual of Photogrammetry" (2).

Printing diapositives emulsion-side up on 0.06-in. thick glass is still in practice, mostly because of the lower costs of materials and the facility of conventional printing methods. The 0.06-in. thick glass does not measure up to the quality of the thicker glass currently available for diapositive materials, as indicated in the brochures of the commercial outlets. Experience shows that it requires support in the middle to revent sag, and there is the possibility of wedge effect caused by the lack of parallel-sm between the two planar surfaces.

The distortion values for 0.06-in. thick glass are given in Table 1. Using these istortion values, 16 points distributed in 52 locations in the stereomodel can be comuted, yielding results in terms of vertical errors, or deviations from a truly plane urface. Computational results are given in Table 2 at model scale in millimeter units, nd in equivalent feet at a scale of 1 in. = 50 ft, the usual design mapping scale required y the California Division of Highways. he location of the points in relation to 25-mm grid model (5-mm diapositive rids enlarged 5 diameters) is shown in igure 1. The contours have been in-erpolated between computed values to epict the expected model deformation, hich is a "dished" effect approaching ft in equivalent value at the model enter.

The close agreement between comuted and actual values demonstrates the alidity of the computational approach, nd of course is a tribute to the skill-ulness of the instrument operator inas-uch as he had no prior knowledge of the omputed values. The biggest spread etween computed and actual values ccurred at points H and S, both far out-ide the neat model area within about ½ . from the margin of a corresponding otograph. Point P was so far outside the neat model area that it was beyond the phy-cal limitations of the instrument, and therefore could not be read. Inasmuch as

TABLE 1

DIAPOSITIVE GLASS DISTORTION[a]

| Angle Off Axis (deg) | Distortion (mm) |
|---|---|
| 5 | 0.000 |
| 10 | 0.002 |
| 15 | 0.005 |
| 20 | 0.013 |
| 25 | 0.026 |
| 30 | 0.048 |
| 35 | 0.081 |
| 40 | 0.130 |
| 45 | 0.202 |

[a]Emulsion surface up on 0.06-in. thick glass.

TABLE 2

VERTICAL ERRORS IN MODEL[a]

| Point | Comp. Vert. Error (mm)[b] | Comp. Vert. Error (ft)[c] | Actual Average Reading (ft)[d] |
|---|---|---|---|
| A | -0.415 | -0.82 | -0.85 |
| B | -0.320 | -0.63 | -0.75 |
| C | -0.180 | -0.36 | -0.55 |
| D | -0.015 | -0.03 | 0.00 |
| E | -0.465 | -0.92 | -0.90 |
| F | -0.330 | -0.65 | -0.60 |
| G | -0.145 | -0.29 | -0.10 |
| H | -0.040 | +0.08 | +0.55 |
| M | -0.360 | -0.71 | -0.70 |
| N | -0.195 | -0.38 | -0.45 |
| O | 0 | 0.00 | 0.00 |
| P | -0.170 | -0.34 | - |
| Q | -0.175 | -0.35 | -0.45 |
| R | +0.015 | +0.03 | +0.05 |
| S | +0.230 | +0.45 | +0.75 |
| T | -0.485 | -0.95 | -0.95 |

aused by 0.06-in. thick glass, emulsion surface up.
t model scale = 5 times scale of diapositive.
t model scale = 1 in. = 50 ft.
t 1 in. = 50 ft in grid model as set up in Nistri-Photomapper.

parallax is cleared at point O, the datum plane for the measurements is established as passing through these four points, which are the corners of the neat model. Withir this area the biggest spread in readings is 0.2 ft, which is actually 0.1 mm.

Although it may be physically possible to compensate for the large distortion value: exhibited by 0.06-in. thick glass, the use of thicker plates with emulsion down is generally considered to produce noticeably improved results. The latter plates eliminate an optical step in the projection system as well as remove for all practical purposes the possibility of variations caused by sag, wedge, and glass quality.

## Projection Lenses

Hypergon. —The conventional Kelsh plotter uses a Hypergon lens for projection. These lenses have a nominal focal length of 127 mm, or 5 in. When set with a princip distance of 6 in. in the projector, the optimum focal plane is formed at a projection distance of 30 in. The magnification factor of the lens in this specific situation is 5 diameters, and will vary directly with a change in projection distance. Thus, if the relief in a model, such as a high hill, causes a projection distance of 27 in., the resulting magnification will be 4.5 diameters.

There is considerable variation in Hypergon lenses with respect to focal length and distortion patterns. A variation in focal length does not alter the geometry of projection, therefore has no influence on model deformation. It is desirable, however, to incorporate matched lenses in a plotter, in order to assure satisfactory model definition. For instance, a variation of 0.05 in. in focal length produces a change of almost 2 in. in optimum projection distance. The important consideration is that eac of the two lenses have essentially the same focal length.

The variation in distortion patterns of Hypergon lenses directly influences expecte model deformation. It is customary to separate Hypergon lenses into two groups, relative to results in the model. The first group includes lenses which produce mode with little or no measurable deformation, whereas the second group includes lenses which do produce models of measurable deformation. A calibration report similar to those associated with aerial cameras would be inconclusive because of the construc tion and assembly of the projector unit.

The distortion pattern of a Hypergon lens is typically negative; that is, light rays are distorted inward radially toward the principal point. As an example, Table 3 gives the values of a lens which would produce a model of measurable deformation.

TABLE 3

POSSIBLE HYPERGON DISTORTION

| Angle Off Axis (deg) | Distortion (mm) |
|---|---|
| 5 | 0.00 |
| 10 | 0.00 |
| 15 | 0.00 |
| 20 | 0.00 |
| 25 | -0.01 |
| 30 | -0.01 |
| 35 | -0.01 |
| 40 | -0.03 |
| 45 | -0.03 |

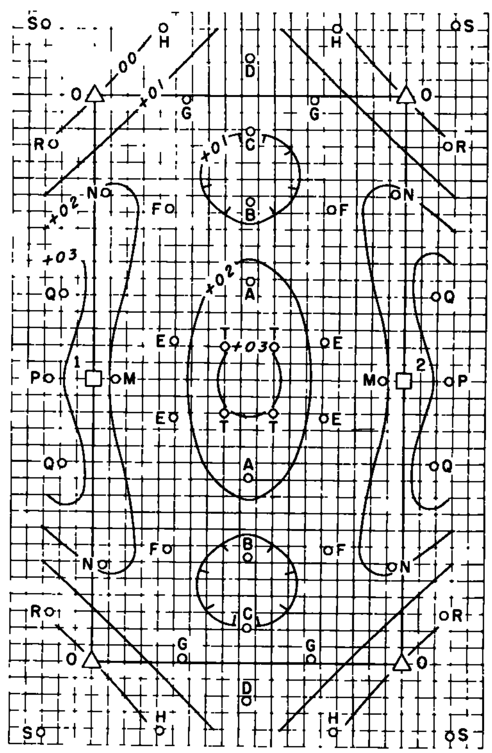
A combination of two Hypergon lenses characterized by the distortion values given in Table 3 would produce a stereomodel as shown in Figure 2. The undulat configuration of this deformed surface generally rises above the ideal datum plane.

Not all Hypergon lenses produce a model surface as illustrated in Figure 2. As previously mentioned, it is impractic to attempt calibration of a Kelsh projecto in the same manner that a camera is cali brated. The distortion of a Hypergon ler must therefore be determined by optical bench procedures for the unmounted lens In the final analysis, the only important consideration is model deformation and not lens distortion: rather than rely sole ly on lens calibration, a more practical solution is the test of over-all performance by the grid model method.

Omigon. —The Omigon lens is a wide-angle type of nominal 6-in. principal distanc used in the Nistri-Photomapper. The entire projector cone is an integral unit, with the lens permanently mounted and the fiducial marks designed to establish the focal plane. The projector unit is virtually a camera, and therefore can be calibrated ike a camera. Principal distance setting is accomplished at the focal plane by adjusting the micrometers at each iducial mark.

The Omigon lens must be essentially listortion-free for use with nominally listortion-free photography, because here is no provision for any distortion compensation. The Division of Highways as one Nistri-Photomapper, and it is apable of producing an unusually flat nodel by the grid model test. In fact, his was the instrument used in the grid nodel test associated with Table 3. The eport accompanying the instrument tated simply that the "cameras were ractically distortion-free."

Figure 3 shows the distortion curve of typical Omigon lens. This curve was ncluded in a calibration report for an nstrument belonging to a private conern. The curve data made it possible o compute the projected model, as shown n Figure 4. Grid model test data are ot available for comparison with the omputed data, but a close agreement ould be expected. The computed model s very flat by comparative standards ith other models, and also compares ery favorably with grid model test reults of the instrument belonging to the alifornia Division of Highways.



Assumptions: Camera lens distortion-free
Diapositives emulsion down

Instrument: 5X projection plotter
Model Scale: 1 in. = 50 ft
Contour Interval: 0.1 ft
B/H = 0.62  W/H = 1.12
25 mm grid at model scale

Figure 2. Model deformation caused by possible Hypergon distortion.

## amera Lenses

The four camera lenses commonly sed in this country for mapping photoraphy are all of nominal 6-in. focal length, and are considered to be wide-angle lenses r use with the 9- by 9-in. format size. Each of the four designs have individual

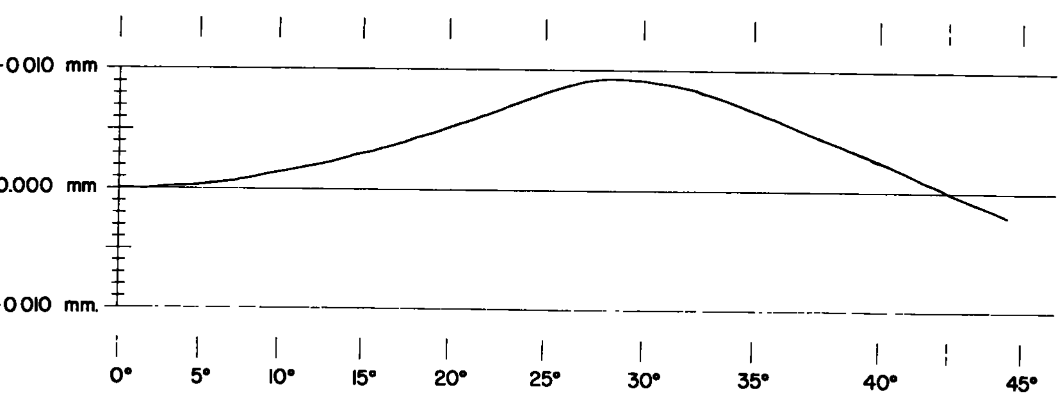
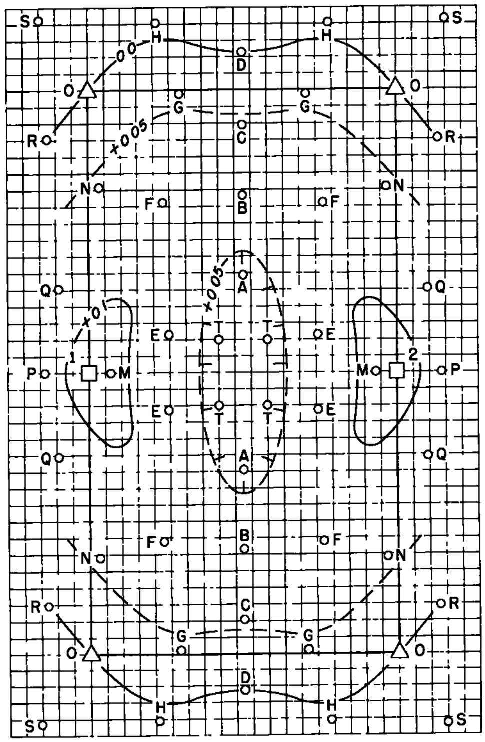



Figure 3. Omigon distortion curve.



Assumptions: Camera lens distortion-free
Diapositives emulsion down

Instrument: 5X projection plotter
Model Scale: 1 in. = 50 ft
Contour Interval: 0.1 ft
B/H = 0.62 W/H = 1.12
25 mm grid at model scale

Figure 4. Model deformation caused by typical Omigon lens.

characteristics with respect to radial distortion. The four designs are discussed separately.

Metrogon. —The Metrogon is probably the oldest design of mapping lens currently in use. The distortion characteristics follow a general curve as shown in Figure 5. Considering that this is a mapping lens, the distortion pattern is quite extreme and must be compensated for in the restitution of a reliable stereomodel. Figure 6 shows the expected model configuration if Metrogon distortion is not compensated. Not all lenses will duplicate this nominal or average curve. As an actual curve departs from the average curve, model deformations will result from the lack of compensation of the residual distortion. Aspheric cams in the Kelsh Plotter for compensation of Metrogon distortion are usually ground for the average curve but may be ground specifically for an individual lens or a group of lenses if each lens in the group exhibits a similar distortion pattern.

Planigon. —The Planigon lens is a post-World War II design of American manufacture considered to be nominally distortion-free. The alternate name of Cartogon is used for the commercial version of the Planigon, and the two terms are used interchangeably.

Photogrammetrists have been aware for many years that distortion characteristics of Planigon lenses vary considerably (8). Examples of the variations are shown in Figure 7, where each of the curves was derived from calibration data for three different cameras. The dissimilarity of the three curves makes it virtually impossible to arrive at an average curve for the purpose of distortion compensation. Compared with Metrogon distortion

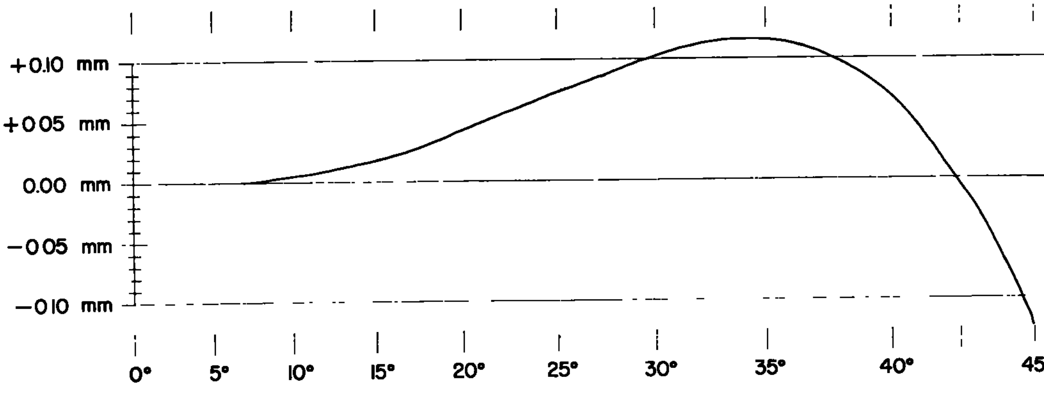



Figure 5. Nominal Metrogon distortion curve.

?lanigon distortion does not cover a wide ange and individual lenses may not even equire compensation. The nominal Metrogon distortion curve shows a maxi-num value about 10 times greater than he maximum value of Planigon curve C.

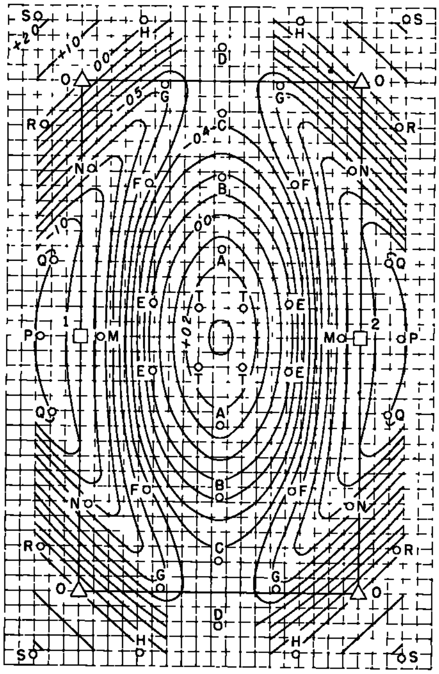
Model surfaces resulting from curves ., B, and C are shown in Figures 8, 9, nd 10, respectively.

Aviogon. —The Aviogon lens is an ex-mple of a nominally distortion-free de-ign of Swiss manufacture, and is assoc-ated with the Wild RC5A and the Wild RC8 ameras.

The pattern of Aviogon distortion is articularly consistent, as indicated in 'igure 11-a showing curves for three ifferent lenses. Aviogon distortion haracteristically produces "humped" iodels (Figs. 12, 13, 14) derived from urves D, E, and F in Figure 11-a. This haracteristic "hump" suggests the pos-ibility of compensation using an average viogon distortion curve.

Pleogon. —The Pleogon lens is a Ger-ian contribution to the list of nominally istortion-free lenses, and is associated ith the Zeiss RMK 15/23 cameras.

Pleogon distortion is shown in Figure 5-a. It is noted that Pleogon distortion ends to be consistent, at least as in-cated by curves G, H, J, and that the eneral shape of the curves is opposite the general shape of the Aviogon curves Figure 11. Pleogon models exhibit a ightly "dished" effect as illustrated in Figures 16, 17, and 18 which have been com-ited from the distortion values taken from curves G, H, J, respectively, of Figure 15-a.



Assumptions: Projection lens distortion-free
Diapositives emulsion down

Instrument: 5X projection plotter
Model Scale: 1 in. = 50 ft
Contour Interval: 0.1 ft
B/H = 0.62 W/H = 1.12
25 mm grid at model scale

Figure 6. Model deformation caused by nominal Metrogon distortion.

## amera Calibrator Tests

The foregoing computational results pertaining to Metrogon, Planigon, Avio-on, and Pleogon lenses are based entirely on calibration data derived from

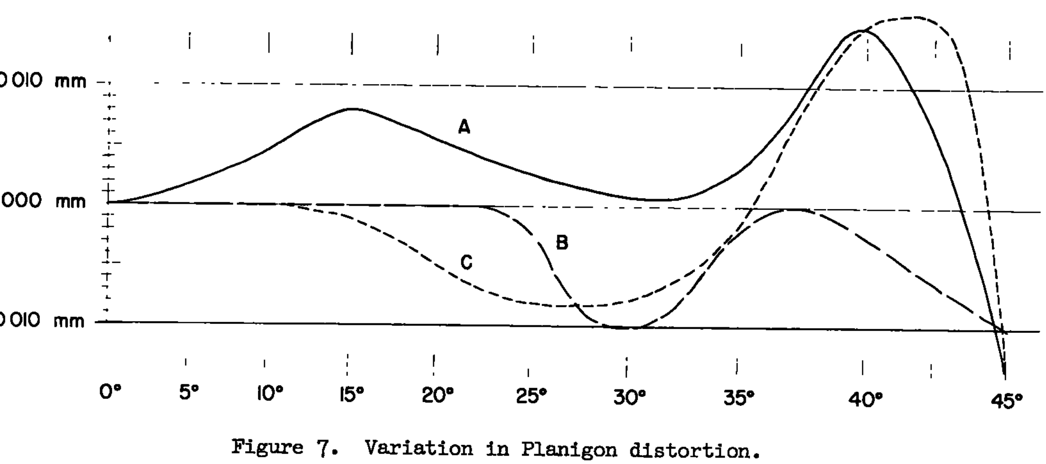
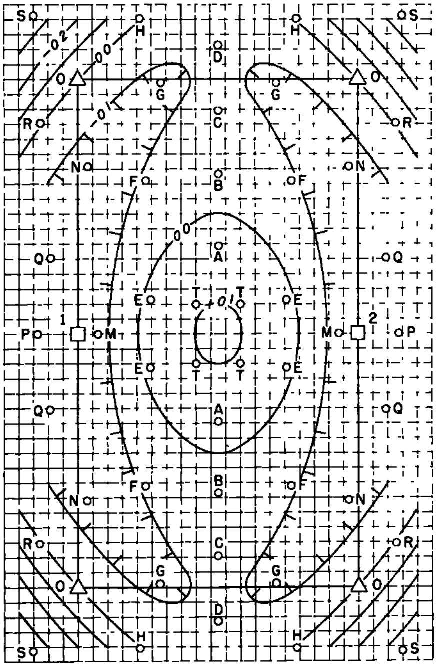


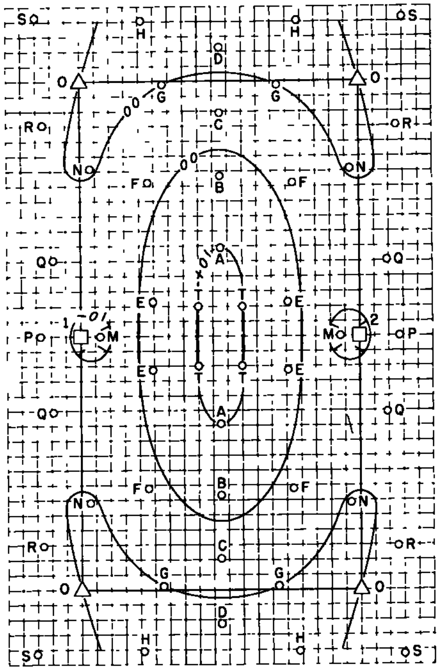

Figure 7. Variation in Planigon distortion.



Assumptions: Projection lens distortion-free
Diapositives emulsion down

Instrument: 5X projection plotter
Model Scale: 1 in. = 50 ft
Contour Interval: 0.1 ft
B/H = 0.62 W/H = 1.12
25 mm grid at model scale

Figure 8. Model deformation caused by Planigon curve A.



Assumptions: Projection lens distortion-free
Diapositives emulsion down

Instrument: 5X projection plotter
Model Scale: 1 in. = 50 ft
Contour Interval: 0.1 ft
B/H = 0.62 W/H = 1.12
25 mm grid at model scale

Figure 9. Model deformation caused by Planigon curve B.

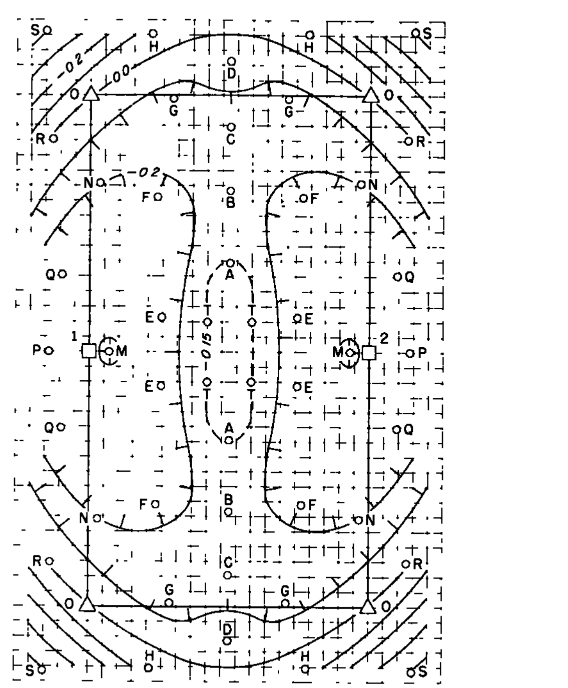
camera reports. The distortion values tabulated in a camera report are merely averages of values taken at specified radial points along four radii within the format area, using the point of symmetry for center, as obtained from camera calibrator tests (14). The resultant distortion curve is presumably representative of the distortion curve along any radii. This is a basic assumption and produces symmetric deformations in the computed model. Thus, the foregoing figures depicting model deformations are somewhat idealized. Deviations of computed values from actual value at any point in the model are directly related to the magnitude of residual distortion resulting from curve averaging. For the purpose of computing aspheric surfaces as a means of distortion compensation, the average curve representing the lens must be the starting data, just as it is the starting data for computing model deformations.

A camera calibrator test procedure developed by the U. S. Geological Survey eliminates the derivation of distortion data by analysis of comparator measurements. In this calibrator the collimators are arranged so that nine of them will be combined to produce conjugate images for stereomodel testing. The arrangement of the nine discrete points in the model is shown in Figure 19. The real advantage of the USGS method is that the optical performance of a camera can be translated directly in tern of model deformation. Any camera can be rapidly tested for acceptance or rejection for use with a particular plotting instrument.

The values shown in Figure 19 apply to the same camera analyzed in Figure 14. Note the lack of symmetry in the deformation pattern in the stereo-performance test data, undoubtedly due to asymmetric distortion distribution of the camera lens. As ın average curve is used in mathematical ınalysis, computational results will not ndicate asymmetric characteristics.

## Combinations of Optical Components

The investigation of individual optical components can be extended to include combinations of components in the over-ıll photogrammetric system. If the performance of the plotting instrument by the grid model method has been deter-nined, and assuming other things being equal, vertical errors may be attributable entirely to the projection lenses. The compatibility of a particular camera with he plotting instrument can be ascertain-d by combining grid model results with computed results of the camera lens at each discrete point in the neat model area. The total errors represent the expected nagnitudes of model deformation. In-erpolated contours in any desired unit nay be drawn in order to visualize the nodel surface.



Assumptions: Projection lens distortion-free
Diapositives emulsion down

Instrument: 5X projection plotter
Model Scale: 1 in. = 50 ft
Contour Interval: 0.1 ft
B/H = 0.62 W/H = 1.12
25 mm grid at model scale

Figure 10. Model deformation caused by Planigon curve C.

The discussion on diapositive glass provides an example. When the deforma-ion (Fig. 1) caused by 0.06-in. thick lass, emulsion up, is combined with ypical Aviogon deformation (Fig. 12) he total expected deformation is shown n Figure 20. Note that vertical errors re relatively equalized along the line etween principal points, but the total eformation describes a dished model. n similar manner, a combination of Iypergon (Fig. 2) with Aviogon (Fig. 14) will aggravate the hump in the model center, pproximating +0.6 ft at model scale of 1 in. = 50 ft.

## nalysis of Errors Under Operational Conditions

Photography obtained under operational conditions is not a particularly reliable nedium for camera testing. The analysis of errors in routine mapping projects often ırns out to be an illusive job of detective work with inconclusive results. The photo-rammetrist seldom has time to make a systematic analysis, and even if he did, many lind alleys would be encountered. He may decide that if a test area were located on ıe ground, all the necessary data could be gathered with two overlapping exposures, a imple remedy for innumerable frustrations.

With this thought in mind, an area within a routine mapping project near Sacramento as premarked with a general distribution of limed points just prior to the taking of ıe photography. The resulting model area showing the point distribution is illustrated ı Figure 21. The premarked points shown as crosses had been established by the ıapping contractor in conformance with the contract specifications. The premarked oints shown as dots had been established by Division of Highways personnel, with the levation of each point determined by spirit levels.

The four corner points, A, B, C, and D, were used to level the model, and the levations of all other points read accordingly. The model was actually set in four ifferent instruments, with each instrument operated by a different individual. The esulting errors were averaged and compared with the known field elevations. These

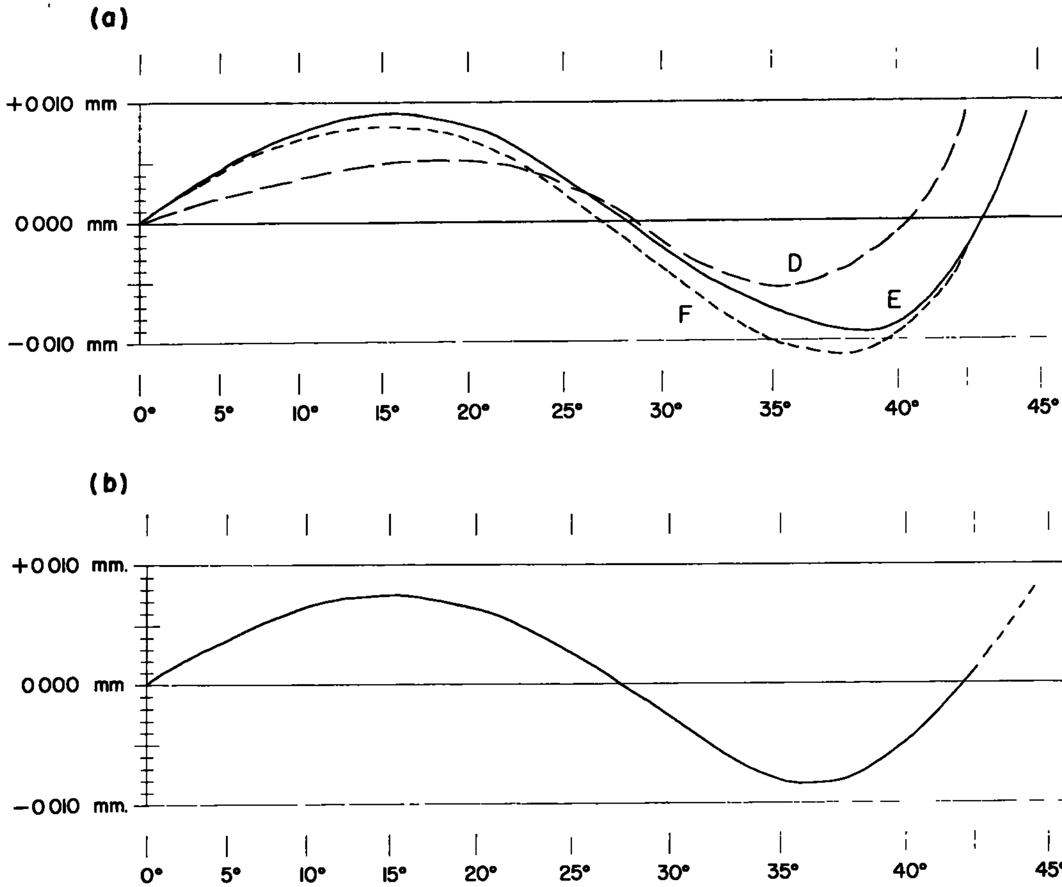
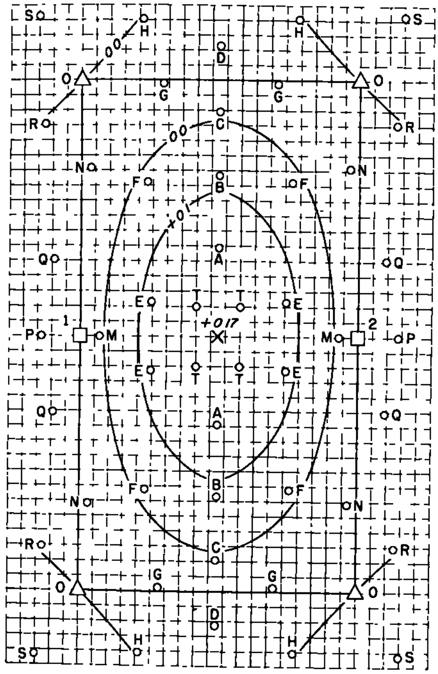



Figure 11. (a) Variation in Aviogon distortion. (b) Average of Aviogon curves D, E, F

average errors are noted along side the individual points in Figure 21.

The camera used in this test was a Wild RC8 with an Aviogon lens, in fact the same camera analyzed in Figure 14 and in Figure 20. The observed errors in the operational test model do not duplicate either of the other two test results point for point, but do show the trend of deformation and the asymmetric distribution. Some unexplainable variations exist in the operational model. For instance, a test point happened to fall adjacent to the lower left-hand corner point D, but an error of 0.2 ft was observed in the photogrammetric elevation. Other examples of this anomaly are evident. Photogrammetric elevations of premarked points are frequently difficult to determine, probably due to variations in image quality. Among the possible reasons for variation are: premarked images tend to halate; the premarking may be on sloping ground; surrounding ground cover may obscure part of the premarking.

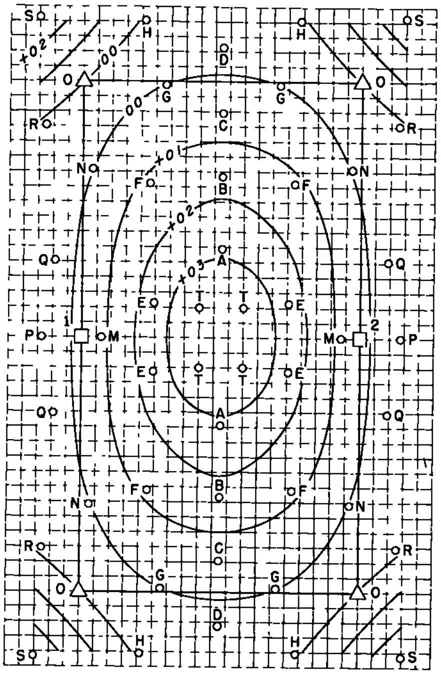
Observed errors under operational conditions may not agree with computed errors based on distortion data for reasons other than image quality. It was previously point out that certain assumptions were made relative to the geometry of the overlapping photographs, as follows: the base-height ratio and width-height ratio was assigned to determine the size of the neat model; both photographs comprising the stereo pair had identical scale values; both photographs were tilt-free. It is obvious that these specifications cannot be applied to operational photography, and it follows, therefore, that the geometry of actual exposure probably will differ from the assumed geometry used in mathematical analysis. Because varying geometric conditions are bound to occur,



ssumptions: Projection lens distortion-free
Diapositives emulsion down

Instrument: 5X projection plotter
Model Scale: 1 in. = 50 ft
Contour Interval: 0.1 ft
B/H = 0.62 W/H = 1.12
25 mm grid at model scale

igure 12. Model deformation caused by Aviogon curve D.



Assumptions: Projection lens distortion-free
Diapositives emulsion down

Instrument: 5X projection plotter
Model Scale: 1 in. = 50 ft
Contour Interval: 0.1 ft
B/H = 0.62 W/H = 1.12
25 mm grid at model scale

Figure 13. Model deformation caused by Aviogon curve E.

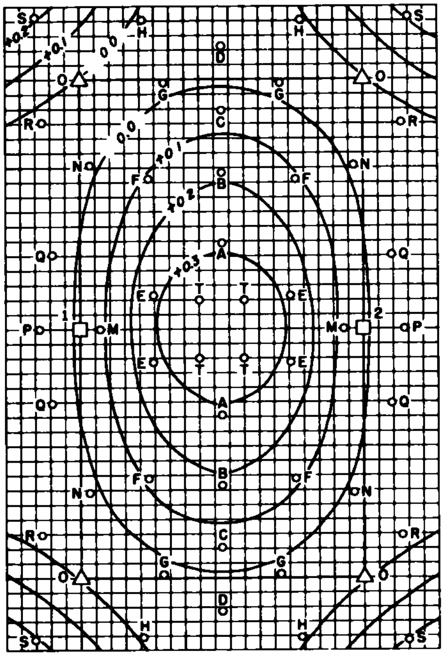
omparison of observed results with computed results will only verify the trend of iodel deformation. One cannot hope to definitely repeat point for point the identical rrors.

The operational test introduces other variables not related to the distortion charac- ›ristics of the various lens components. It must be remembered that each variable ontributed to some extent, however small, to model deformation. These considera- ons are beyond the scope of this paper, but are mentioned here as a reminder that perational testing will not always produce the concrete evidence the photogrammetrist esires.

## DISTORTION COMPENSATION

### tandards for Compensation

The standards for compensation of distortion in the photogrammetric system depend a large extent on photogrammetric measurement requirements. The tolerances for erotriangulation throughout many models demand a different standard than for com- lation of individual models. Tolerances for compilation of highway design maps emand a different standard than compilation of military maps. Standards for com- ensation are not well defined and are usually resolved according to the best that can e done, because it is virtually impossible to compensate all the distortion in the sys- m. The "best that can be done" is dependent not only on the ability of the optical esigner and the machinist, but also on the type of plotting instrument and the ability the individual operating it.



Assumptions: Projection lens distortion-free
Diapositives emulsion down

Instrument: 5X projection plotter
Model Scale: 1 in. = 50 ft
Contour Interval: 0.1 ft
B/H = 0.62 W/H = 1.12
25 mm grid at model scale

Figure 14. Model deformation caused by Aviogon curve F.

A logical starting point is the plotting instrument, specifically the direct projection 5X Kelsh-type plotter. As indicat in Table 2 by the close correlation betwee computed values and values determined wi a Nistri-Photomapper, the direct projection instrument is capable of very satisfac tory results. Within the neat model area the largest discrepancy is 0.2 ft at 1 in. = 50 ft, or 0.1 mm, which when compared to the optimum projection distance of 760 mm represents an accuracy of $\frac{H}{7,600}$ in terms of flying height. Grid model tests with this instrument using 0.250-in. thick diapositives, emulsion-surface down, indicate that the neat model area is flat with in 0.05 mm, or $\frac{H}{15,000}$. Readings small than this cannot be made with any degree of certainty even by the sharpest sighted operators.

The value of 0.05 mm, defining the plane of grid model flatness, has been us by the California Division of Highways as a specification for a Kelsh plotter ordere from the Kelsh Instrument Company. Th delivered instrument was carefully tested by two operators, with the joint conclusio that the projected model did not exceed th specified tolerance. This value is sugges ed as a standard for 5X projection instruments.

The second consideration is the aerial camera. Because all camera lenses exhibit some distortion, a decision must be made as to whether or not the camera is compatible with the plotting instrument. For this purpose the computed model will quickly reveal the expected vertical errors. In the foregoing section on camera lense a total of nine Planigon, Aviogon, and Pleogon lenses were analyzed. The greatest deformations are shown in Figures 10, 13, and 14, amounting to 0.3 ft at 1 in. = 50 ft, or $\frac{H}{5,000}$. Assuming that an operator can level on the control within 0.1 ft, residual model errors attributable to camera lens distortion will occur, but will not be detected unless control is arranged to locate the maximum range of errors. The Nistri-Photomapper has no provision for compensation and, therefore, the residual erro represent "the best that can be done." (The Nistri-Photomapper is also available wit projectors designed to accommodate nominal Metrogon photography.) At this time it is not definitely known whether or not these residuals can be compensated by the customary procedures associated with Kelsh plotters. This is discussed later in this paper.

## Compensation Methods

There are, in general, three possible ways to compensate distortion: (a) compensation in diapositive printing by optical means, (b) compensation in projection by optical means, and (c) compensation in projection by mechanical means.

The first method would be applicable if diapositives were made with a 1 to 1 ratio printer. It would be possible to locate an aspheric glass corrector plate in the optica path within the printer, designed to introduce distortion values equal to the camera lens but opposite in direction. The resulting diapositive would be free of distortion. This method is incorporated in the reduction printer for making of ER-55 diapositives from Metrogon photography. Ratio printers for contact size diapositives are not commercially available.

The second method suggests the use of aspheric glass corrector plates located in the projectors, similar to the arrangement in the Wild Autographs. As cost of the corrector plates undoubtedly would be out of proportion to the initial cost of the projection plotter, this does not appear to be a practical solution. It is also possible to design the projector lens to compensate for the camera lens distortion, in the manner associated with the Nistri-Photomapper designed to accommodate nominal Metrogon distortion. Cost of the projector units is approximately the same as for aspheric glass plates, which is about $1,000 for one pair.

The third method is employed in the Kelsh plotter. It offers a practical, low-cost solution, and is described in the following section.

## Theory of Distortion Compensation by Aspheric Cams

Figure 22 represents the geometry of distortion compensation for 5X Kelsh-type plotters. The ray 1, which emanates from some object A on the ground, is directed toward the perspective center of the camera lens and incident to it at the angle $\alpha$ measured from the axis of the lens system. In the ideal lens, the refracted ray 2 would emerge likewise at the angle $\alpha$, recording the image in the undistorted position a'. However, in the event of distortion the refracted ray 3 emerges at the slightly different

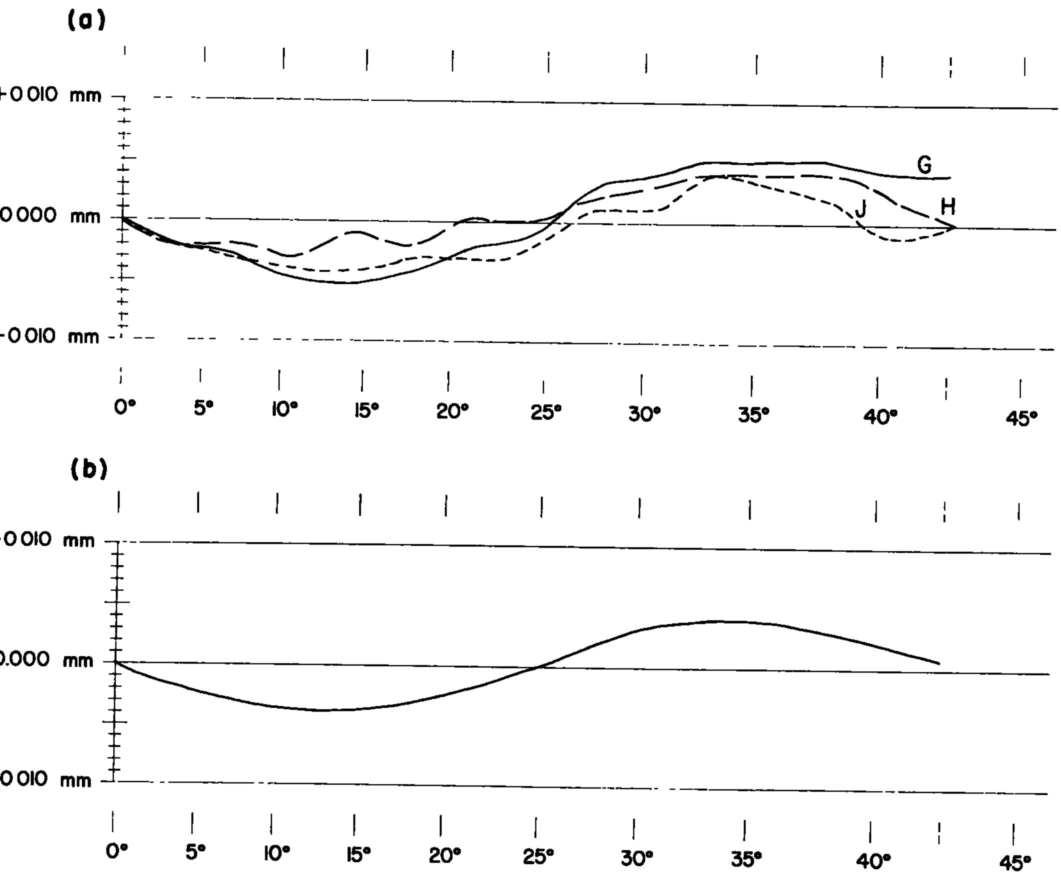



Figure 15. (a) Variation in Pleogon distortion. (b) Average of Pleogon curves G, H, J.

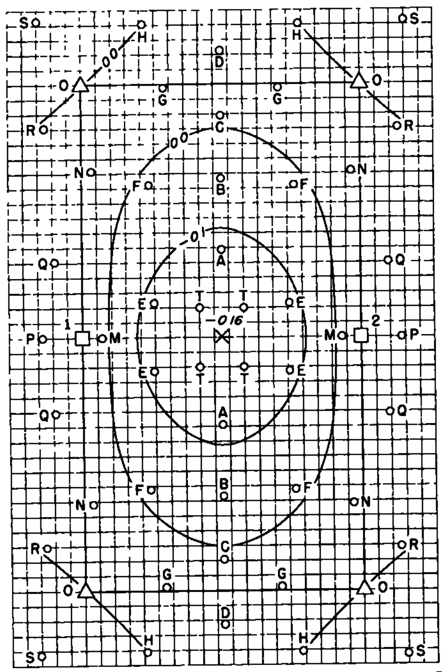
angle β, recording the image in the distorted position a. The difference between a' and a is a measure of radial distortion D on the negative. The distorted point a will be recorded in turn on the diapositive and ultimately projected through the projection lens. Assuming the projection lens is distortion free, point a will emerge along ray 4, coming to focus at A'. Because the lens has a magnification factor of 5 diameters, point A' will be displaced 5D from the correct position A. The next step would be to attempt to compensate for the distortion by changing the principal distance of the projector; that is, by moving the lens vertically the amount D (cot α). Point a would be projected along ray 5 parallel with the original ray 1, coming to focus at A''. In this position it is displaced from position A by the amount D. In order to make point a focus at position A, the principal distance is varied by 5/6 D(cot θ). This can be verified by inspection of the geometry illustrated in Figure 22.

Because the magnitude of distortion in modern camera lenses is very small, the difference between the angles α and θ is also very small. Sufficient accuracy will be attained by substituting α for θ, modifying the expression for change in principal distance, accordingly:

$$\Delta P.D. = 5/6\ D(\cot \alpha)$$

This equation serves as a basis for computing the aspheric surface of the distortion correction cam, which actuates the mechanical linkage imparting vertical movement ΔP.D. to the projection lens.

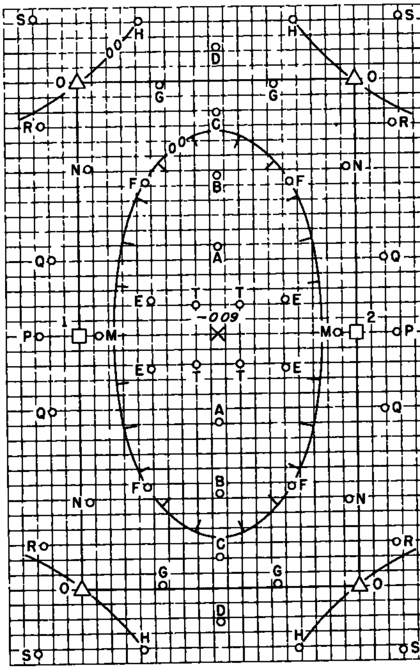
Figure 23 is a diagram of the lens assembly showing the linkage between the cam




Assumptions: Projection lens distortion-free
Diapositives emulsion down

Instrument: 5X projection plotter
Model Scale: 1 in. = 50 ft
Contour Interval: 0.1 ft
B/H = 0.62 W/H = 1.12
25 mm grid at model scale

Figure 16. Model deformation caused by Pleogon curve G.

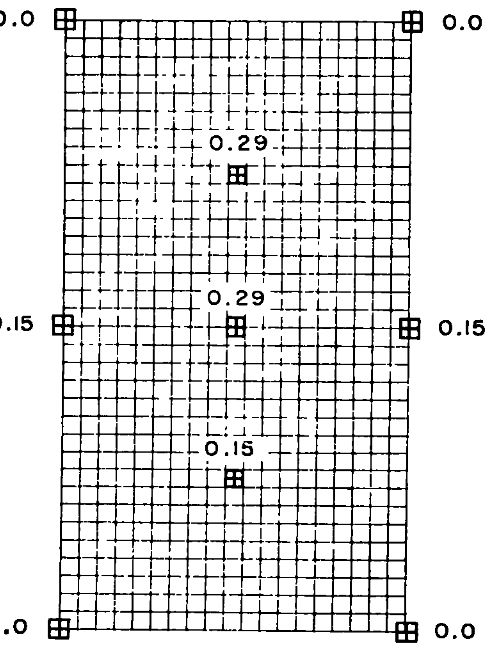



Assumptions: Projection lens distortion-free
Diapositives emulsion down

Instrument: 5X projection plotter
Model Scale: 1 in. = 50 ft
Contour Interval: 0.1 ft
B/H = 0.62 W/H = 1.12
25 mm grid at model scale

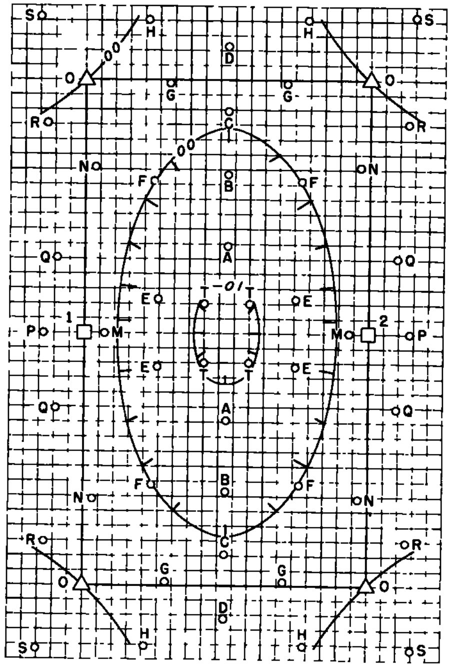
Figure 17. Model deformation caused by Pleogon curve H.

and the lens barrel. The design of the plotter permits the orientation of the cam stem to be made parallel with any ray projected from the perspective center of the lens. For example, if the projected ray defines an angle of 22 deg, the cam stem also defines an angle of 22 deg. In this way the cam is rotated in the bracket so that the cam follower moves up or down as it rides the aspheric surface. The force applied to the lever at the cam follower transmits a reaction to the pin fixed to the lens barrel. In most commercial models of the Kelsh plotter the lever ratio is 3.5:1 (Fig. 23), thereby making the vertical motion of the cam follower 3.5 times greater than the vertical motion of the lens barrel. The lens barrel is actually encased in a sleeve rigidly fixed to the bracket. The spring applies a constant downward force to the pin in the lens barrel, which in turn is applied to the lever to assure positive contact between the cam follower and the cam surface.




Approximate locations of test points in relation to 25 mm grid. Readings in ft at model scale of 1 in. = 50 ft, converted from mm readings by ER-55

Figure 19. USGS stereo-performance test model.



Assumptions: Projection lens distortion-free
Diapositives emulsion down

Instrument: 5X projection plotter
Model Scale: 1 in. = 50 ft
Contour Interval: 0.1 ft
B/H = 0.62  W/H = 1.12
25 mm grid at model scale

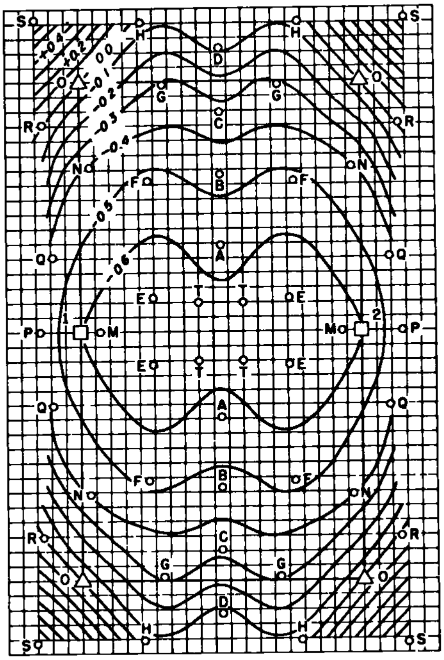
Figure 18. Model deformation caused by Pleogon curve J.

The surface of the cam is expressed in terms of the vertical movement of the cam follower:

$$\text{Cam follower drop} = (3.5)\ 5/6\ D(\cot \alpha)$$

This is simply 3.5 times greater than ΔP.D. It also represents a variation in length of selected radii to describe an aspheric surface of revolution (Fig. 24).

The value of the distortion D in the formula for "cam follower drop" is the algebraic sum of all the known distortions in the system. As an example, assume photography taken with a Metrogon lens, diapositives printed emulsion up on 0.06-in. thick glass, and projected with a Hypergon lens. A ray passing in turn through each optical component receives some degree of deviation from its original path. The distortion introduced by each component will contribute to model deformation. Rather than treat each independently,



Assumptions: Projection lens distortion-free
Diapositives emulsion up

Instrument: 5X projection plotter
Model Scale: 1 in. = 50 ft
Contour Interval: 0.1 ft
B/H = 0.62 W/H = 1.12
25 mm grid at model scale

Figure 20. Model deformation, Aviogon curve F plus 0.06-in. thick glass.

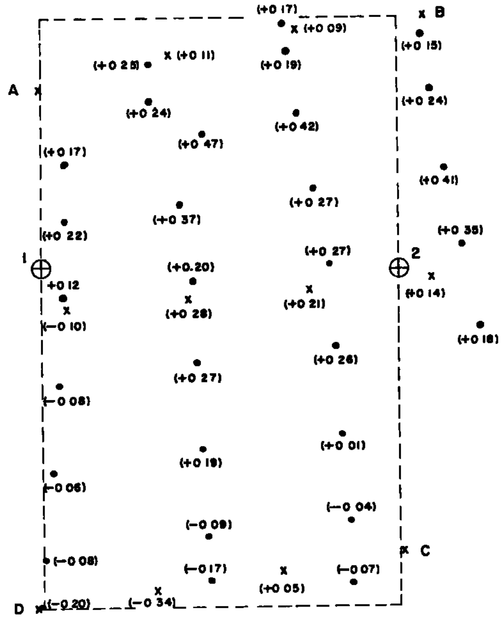


Figure 21. Stereo-performance test results under operational conditions (readings in ft at model scale of 1 in. = 50 ft).

their total distortion is used in cam computations. A typical computation is given in Table 4 showing how the data is handled.

Relief in a model also has an effect on cam performance (9). Because the cam is designed and computed to compensate at the optimum plane of focus, or 30 in. (760 mm) from the lens, a departure from this plane will introduce a vertical error in the model. This error may be evaluated, for any point, from the approximate equation:

$$\Delta Z = \frac{(Z)\,(\Delta P.D.)}{\text{Optimum Projection Distance}}$$

in which $\Delta Z$ is the vertical error, and Z is the departure from the optimum plane of focus. It is possible, therefore, to predict a systematic error under certain circumstances. As an illustration, suppose flat valley land was photographed with a Metrogon lens, and that the flying height was too great, causing the projection distance to be about 36 in. The optimum projection plane will be 6 in. above the terrain in the model, or 152 mm. From Table 4, the maximum $\Delta$P.D. is 0.222 mm at 35 deg. Then

$$\Delta Z = \frac{152\ (0.222)}{760} = +0.044\ \text{mm.}$$

At the model scale of 1 in. = 50 ft, this error amounts to +0.09 ft. In ordinary situations this can be safely ignored, but it is present and could conceivably be added to other deformations existing at that point in the model. With the diapositives printed emulsion down, maximum $\Delta$P.D. would be 0.126 mm, ultimately making $\Delta Z$ equal to 0.05 ft at 1 in. = 50 ft for the same point.

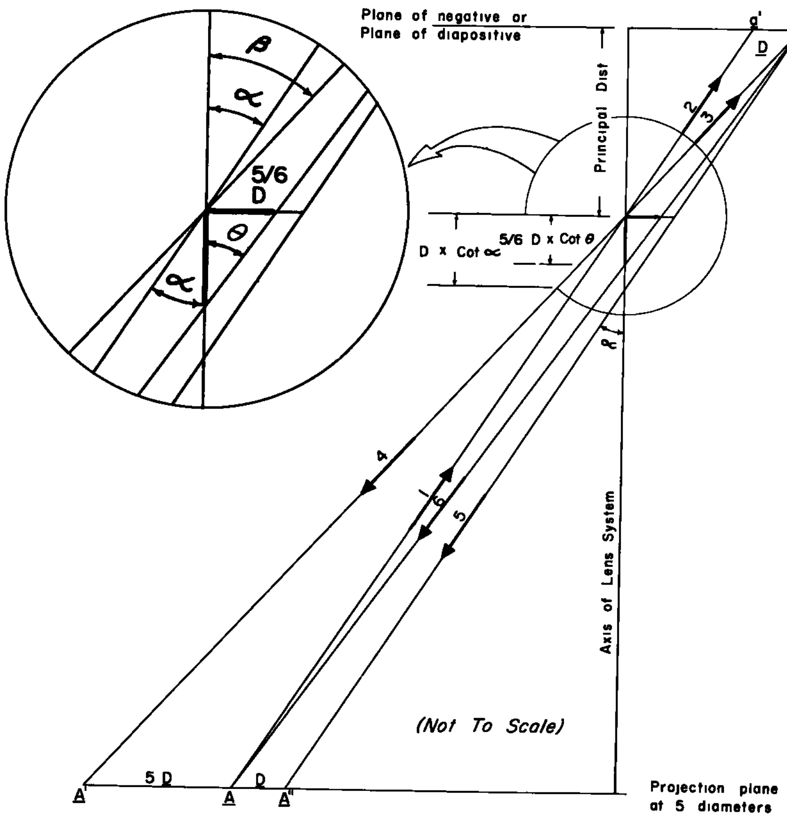


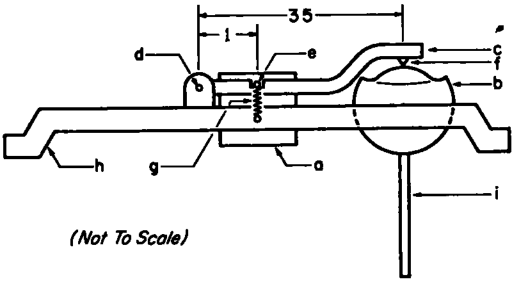

Figure 22. Geometry of distortion compensation, 5X Kelsh Plotter.

pplication of Cams

Kelsh plotters come equipped with cams for compensation of Metrogon distortion. /ithout the cams Metrogon photography would not be usable in the Kelsh, just as it s not usable in the distortion-free Nistri-Photomapper. A cam surface may be round to compensate distortion of a particular Metrogon, or it may be ground to com- ensate a group of Metrogons exhibiting distortion patterns within a specified tolerance f an average curve. As demonstrated by the sample computation (Table 4), known dis- ›rtion other than Metrogon may be compensated by the cam.

The application of cams to Planigon, Aviogon, or Pleogon photography is not stand- rd practice. A provision is made in the recent models of the Kelsh plotter to dis- ıgage the cam follower whenever low distortion photography is to be used, with the resumption that the residual distortions will not adversely affect the model datum. or most mapping requirements this procedure is justified and the resulting accuracies ill be well within usual specifications. The new demand for photogrammetric data s a basis for deriving final pay quantities for earthwork makes it necessary to in- ıire into the possibility of using cams to correct the existing distortions in the nomin- ly distortion-free lenses.

Aviogon lenses exhibit fairly uniform and consistent distortion patterns causing easurable deformations in Kelsh models. A cam computation correcting for the erage Aviogon distortion (Fig. 11-b) is given in Table 5. The average curve is lected in this example with the idea that any of the three cameras may be used to




a - Lens barrel in fixed sleeve
b - Aspheric correction cam
c - Lever
d - Fulcrum of lever
e - Pin fixed to lens barrel
f - Cam follower
g - Spring
h - Bracket
i - Cam stem

Figure 23. Diagram of lens assembly.

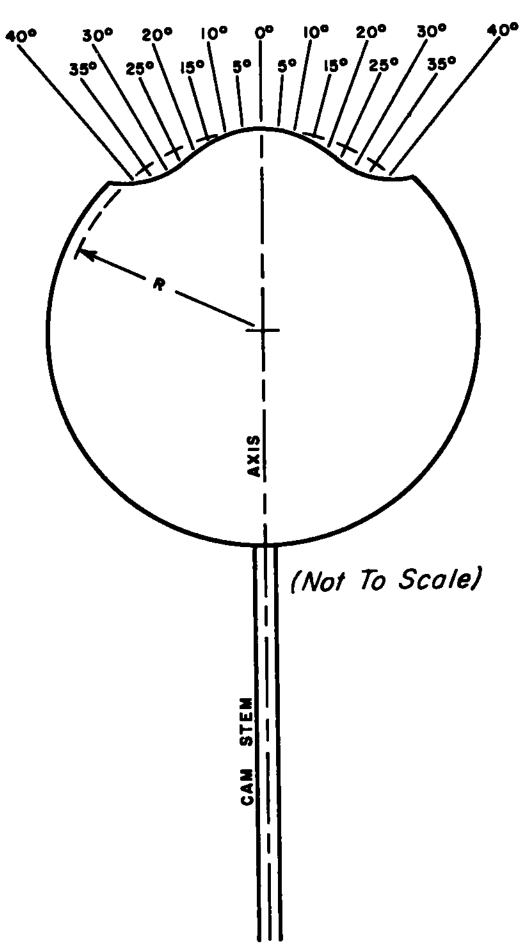



Figure 24. Vertical section of aspheric cam (cam follower drop is the difference along selected radii between dashed surface (radius R) and aspheric surface).

photograph a mapping project. Departure of an actual curve from the 3-curve average will leave residual distortions. Table 6 gives the computed vertical errors, due to residual distortion, for each of the three Aviogon cameras. In no instance does any value exceed 0.1 ft, which demonstrates that from a purely academic standpoint cam compensation based on the average curve should be adequate. The column listing cam follower drops (Table 5) reveals that the cam surface requires a very high degree of machining quality.

Pleogon distortion curves follow a fairly uniform and consistent pattern (Fig. 15-a). The average curve (Fig. 15-b) provides the necessary data for cam computations. At this point it must be decided whether or not compensation is actually justified because of the small model errors caused by the Pleogon lens. The average curve indicates that Pleogon distortion may be expected to be less than 0.004 mm. Models from photography with distortion values not exceeding this should be flat within 0.05 mm, or 0.1 ft at 1 in. = 50 ft. It does not seem feasible to attempt compensation of errors which cannot be definitely read in the Kelsh model.

Planigon distortion does not follow a uniform and consistent pattern (Fig. 7) and m[ay] or may not require compensation. With the cameras currently available for furnishin[g] mapping photography, it may be difficult to group them according to similarity of distortion curves. If distortion compensation is desired for any particular camera, a separate set of cams would have to be made specifically for it.

## Limitations of Cams

Photogrammetrists are not in agreement concerning the virtues of cams as a mea[ns] of distortion compensation. In recent years there has been a definite trend towards their elimination from Kelsh plotters, especially since low distortion photography ha[s] been readily available. It would appear, that the suggestion of returning to cams at this late date is an anachronism.

TABLE 4

SAMPLE CAM COMPUTATIONS

| Angle off axis, α (deg) | 5 | 10 | 15 | 20 | 25 | 30 | 35 | 40 | 45 |
|---|---|---|---|---|---|---|---|---|---|
| Metrogon[a] | 0.001 | 0.003 | 0.018 | 0.042 | 0.071 | 0.103 | 0.116 | 0.073 | -0.116 |
| Hypergon[a] | 0.000 | 0.000 | 0.000 | 0.000 | -0.010 | -0.010 | -0.010 | -0.030 | -0.030 |
| Total lens | 0.001 | 0.003 | 0.018 | 0.042 | 0.061 | 0.093 | 0.106 | 0.043 | -0.146 |
| 0.06-in. glass | 0.004 | 0.009 | 0.013 | 0.020 | 0.028 | 0.048 | 0.081 | 0.130 | 0.202 |
| Σdistortion[a] | 0.005 | 0.012 | 0.031 | 0.062 | 0.089 | 0.141 | 0.187 | 0.173 | 0.056 |
| Cot α | 11.43 | 5.67 | 3.73 | 2.75 | 2.15 | 1.73 | 1.43 | 1.19 | 1.00 |
| Total distortion D | 0.005 | 0.012 | 0.031 | 0.062 | 0.089 | 0.141 | 0.187 | 0.173 | 0.056 |
| Dx cot α | 0.057 | 0.068 | 0.116 | 0.171 | 0.191 | 0.244 | 0.267 | 0.206 | 0.056 |
| Lens drop 5/6 D x cot α | | | | | | | | | |
| mm | 0.047 | 0.057 | 0.097 | 0.142 | 0.159 | 0.203 | 0.222 | 0.172 | 0.047 |
| in. | 0.0019 | 0.0022 | 0.0038 | 0.0056 | 0.0063 | 0.0080 | 0.0088 | 0.0068 | 0.0018 |
| Cam follower drop 5/6 Dx cot α | | | | | | | | | |
| mm | 0.166 | 0.198 | 0.338 | 0.499 | 0.557 | 0.712 | 0.779 | 0.601 | 0.0163 |
| in. | 0.0065 | 0.0078 | 0.0133 | 0.0196 | 0.0219 | 0.0280 | 0.0307 | 0.0237 | 0.0064 |

[a]All distortion values in millimeters.

TABLE 5

CAM COMPUTATIONS[a]

| Angle Off Axis, α (deg) | Cot α | Average Distortion D (mm) | DxCot α | Lens Drop 5/6DxCot α | | Cam Follower (3.5)5/6Dx Cot α | |
|---|---|---|---|---|---|---|---|
| | | | | (mm) | (in.) | (mm) | (in.) |
| 5 | 11.43 | 0.0035 | 0.040 | 0.033 | 0.0013 | 0.117 | 0.0046 |
| 10 | 5.67 | 0.006 | 0.034 | 0.028 | 0.0011 | 0.099 | 0.0039 |
| 15 | 3.73 | 0.007 | 0.026 | 0.022 | 0.0009 | 0.076 | 0.0030 |
| 20 | 2.75 | 0.006 | 0.017 | 0.044 | 0.0006 | 0.050 | 0.0020 |
| 25 | 2.15 | 0.025 | 0.005 | 0.004 | 0.0002 | 0.015 | 0.0006 |
| 30 | 1.73 | -0.003 | -0.005 | -0.004 | -0.0002 | -0.015 | -0.0006 |
| 35 | 1.43 | -0.008 | -0.011 | -0.009 | -0.0004 | -0.032 | -0.0013 |
| 40 | 1.19 | -0.005 | -0.006 | -0.005 | -0.0002 | -0.017 | -0.0007 |
| 45 | 1.00 | - | - | - | - | - | - |

[a]For average Aviogon distortion curve, Figure 11-b.

The vertical motion of the lens (lens drop) in Table 5 covers a very small range of travel from -0.0004 in. to +0.0013 in., a total distance of 0.0017 in. Within this distance the lens barrel must travel freely without binding and without lateral play. Any resistance to free travel will tend to cause stress in the mechanical linkage (Fig. 23), resulting in wear. It is very easy to overstress the bearings between the lens barrel and the sleeve, ultimately making grooves in the lens barrel. This could cause the lens to "hang-up," or at least "chatter" in the sleeve. The adjustment of the bearings at the fulcrum of the lever is also critical.

The machining tolerance for grinding the surface of the cam is particularly demanding. The maximum difference in cam radii, according to cam follower drops, is from +0.0046 in. to -0.0013 in., or a total of 0.0059 in. This difference can be increased by using a lever ratio greater than 3.5:1. A lever ratio of 4:1 will increase the difference to 0.0068 in. Adoption of a new lever ratio would require modification of the lens assembly to accommodate the new relative positions of the fulcrum, lens, and cam.

There are undoubtedly other reasons which tend to offset the effectiveness of cams, but the main point is that mechanical compensation is not always reliable enough to be depended on. The Kelsh operator must be constantly alert to the possibility of malfunction of the mechanism, and he should also be aware that projector calibration is directly affected by the adjustment of the entire lens assembly.

## CONCLUSIONS

From this study some conclusions can be drawn and some opinions offered. First of all, one should realize that the question of lens distortion is not by any means the "weakest link" in the photogrammetric system. The principal concern is that it does contribute to systematic vertical errors which may or may not be significant depending

TABLE 6

RESIDUAL MODEL ERRORS[a]

| Point | Aviogon D (mm) | Aviogon D (ft) at 1 in. = 50 ft | Aviogon E (mm) | Aviogon E (ft) at 1 in. = 50 ft | Aviogon F (mm) | Aviogon F (ft) at 1 in. = 50 ft |
|---|---|---|---|---|---|---|
| A | -0.032 | -0.06 | 0.036 | 0.07 | 0.033 | 0.06 |
| B | 0.002 | 0.00 | 0.027 | 0.05 | 0.014 | 0.03 |
| C | -0.008 | -0.02 | 0.012 | 0.02 | 0.010 | 0.03 |
| D | 0.000 | 0.00 | 0.015 | 0.03 | 0.005 | 0.01 |
| E | -0.020 | -0.04 | 0.039 | 0.08 | 0.027 | 0.05 |
| F | -0.025 | -0.05 | 0.024 | 0.05 | 0.022 | 0.04 |
| G | -0.008 | -0.02 | 0.021 | 0.04 | 0.011 | 0.02 |
| H | 0.002 | 0.00 | 0.001 | 0.00 | -0.002 | 0.00 |
| M | -0.015 | -0.03 | 0.024 | 0.05 | 0.022 | 0.04 |
| N | -0.010 | -0.02 | 0.028 | 0.06 | 0.016 | 0.03 |
| O | 0.000 | 0.00 | 0.000 | 0.00 | 0.000 | 0.00 |
| P | 0.000 | 0.00 | 0.031 | 0.06 | 0.013 | 0.03 |
| Q | 0.000 | 0.00 | 0.026 | 0.05 | 0.013 | 0.03 |
| R | 0.000 | 0.00 | -0.002 | 0.00 | 0.000 | 0.00 |
| S | - | - | - | - | - | - |
| T | -0.045 | -0.09 | 0.042 | 0.08 | 0.037 | 0.07 |

[a]After compensation of average distortion of Aviogon D, E, F.

on the purpose of the measurements. The magnitude of errors under consideration would not be important in a reconnaissance map or in a general purpose map of any type. These errors may possibly influence earthwork quantity calculations, especially in flat terrain, and for this reason they are significant in large-scale highway design maps.

At this point the photogrammetrist is at a crossroads. If he is working under the customary specification for vertical accuracy; namely, that 90 percent of contour elevations shall be correct within one-half contour interval, he is relatively certain that by following established procedures the maps will meet the specifications. On the other hand, if he is working under specifications also requiring that 90 percent of all spot elevations be within one-quarter contour interval, and that the mean error shall not exceed a certain value, he is not at all certain that the routine established procedures will produce the additional accuracy requirements. He is forced to re-evaluate all the procedures step by step, and to determine the possible effect that variations on procedure will have on map accuracy, substantiated by a program of accuracy testing.

The following steps are recommended as a starting point in an over-all inspection program:

1. Carefully check calibration of the plotting equipment in order to account for and eliminate mechanical sources of error.
2. Arrange for the printing of diapositives on glass which is at least 0.130 in. thick with the emulsion surface down.
3. With the use of precise grids as diapositives, analyze the projected grid model for vertical errors, with cam action disengaged. A suggested standard is 0.05-mm maximum error. If errors larger than this are observed, the cause may be found in the projection lenses.
4. If cams are used, the grid model should also be analyzed for the effectiveness of cam compensation with cam action engaged.

The foregoing steps provide an adequate check on the geometry of projection and in no way involve other sources of error which occur prior to projection. These steps are entirely within the control of the photogrammetrist.

The calibration data furnished with the various camera lenses provide information relative to operational planning procedures. Distortion values for Aviogon and Pleogon enses are seldom given beyond 140 mm radially from the indicated principal point, which describes a cone of coverage of about 85 deg at the perspective center of the ens. The model deformation diagrams for the various lenses show that beyond the assigned limits of the neat model the variations in model datum tend to change rather suddenly, expecially on the extreme edges away from the flight line. The reading of grid models also indicates that plotting instruments tend to produce unreliable elevations at the extreme edges of projection. These facts confirm that the compilation unit should be the neat model area. For a 60 percent overlap the dimensions of this area on the photograph are 3.6 by 7 in. This area presumes a cone of coverage of 80 deg, or 40 deg off axis, which allows a margin of safety because overlaps are bound o vary, thereby affecting the dimensions of the neat model. If the 7-in. dimension s held constant, then the cone of acceptable coverage must be allowed to vary with hange in overlap. For instance, with an overlap of approximately 54 percent the imensions of the neat model would be about 4.1 by 7 in., and would be equivalent to cone of 85 deg, or 42.5 deg off axis corresponding to the calibration limits of the amera lens. Inasmuch as highway design mapping ordinarily covers a strip of terrain f uniform width, it is reasonable to limit this width to a fixed dimension on the photograph. This will insure that the optical limitations of the photogrammetric system re not exceeded.

The model deformation diagrams also serve as a guide to the planning of vertical ontrol. The datum of the models illustrating Planigon, Aviogon, and Pleogon deformaion remain fairly constant within the neat model in the immediate vicinity of the corers, with the greatest deviation tending to occur at the model center. The characeristics of model datum lead to the conclusion that:

1. Vertical control should be planned so that at least one point is located in the pproximate center of the neat model and the wing point control located within the ounds of the neat model, one near each of the four corners.

2. Vertical control should not be planned beyond the limits of the neat model, esecially on the extreme edges away from the flight line. It is a safe rule to restrict e outer limits of the control so that no point is nearer than 1 in. from the edge of e photograph.

The planning and selection of vertical control points as a function of operational lanning within the limitations of the photogrammetric system are very important ctors influencing map accuracies. The effectiveness of cams designed to compensate w distortion values needs to be investigated, because it is not a foregone conclusion at cams will be successful in eliminating systematic errors. Furnishing the inrument operator with a well-planned project, and with definite control data, is the ositive approach to the solution of the map accuracy problem, for the success of the apping is ultimately a product of his training and ability.

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