Let's Optimize Stereo Plotting[*]

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ABSTRACT: *The first portion of this paper concerns accuracy criteria and quality control for stereo plotting. It describes and compares several commonly used criteria for judging the vertical accuracy of stereo plotting. Concluded is that the C-factor has been our best guess regarding the potential accuracy of contouring. Also concluded is that the C-factor (as commonly used) does not provide a reliable criterion. Finally shown is how we can improve the reliability of our stereo plotting, and of the conventional C-factor.*

The second portion of this paper describes several practical but somewhat unconventional proposals for optimizing stereo plotting. Emphasis is placed on the development of practical criteria for optimizing camera design, aerial photography, and stereo plotting equipment and techniques.

The third portion of this paper gives some conclusions, recommends appropriate development goals, and raises some questions for further research.

PART I: ACCURACY CRITERIA

IN PHOTOGRAMMETRY there is a tendency to compile maps near the practical limit of our ability to make significant measurements from photographs. In the second portion of this paper proposals will be made for stretching these limits in every possible way, in order to achieve the best compromise between accuracy and compilation costs. As a result, quality control in our daily work would then have critical importance. The first part of this paper is therefore concerned with accuracy criteria and quality control for stereo plotting. Emphasis will be placed upon the rather uncertain statistical probabilities involved in working near the practical limits of our photographic and photogrammetric techniques.

Accuracy criteria are essential in making plans for a mapping project, and in maintaining production standards in our daily work. In other words, we need to predict how accurately we can compile maps under given circumstances. Also, we should know if we are actually achieving this accuracy in our daily work. If we lack confidence in our accuracy criteria, we will then protect ourselves by flying the photographs at a relatively low altitude and/or utilizing an excessive amount of ground control. *We would thus greatly increase our compilation costs simply because we lack dependable accuracy criteria for use in project planning and quality control.*

Incidentally, experience has shown that the positional errors of a stereo model are less important than its heighting errors. It has therefore become customary to regard heighting errors as the yardstick for predicting the accuracy and quality of a proposed photogrammetric map compilation. For this reason, a discussion of horizontal plotting errors will not be given in this paper.

A. STATISTICAL CRITERIA

The "mushiness" of a stereo model is a general term which refers to the operator's visual and mechanical difficulties in finding the elevation of any point on its surface. In other words, mushiness represents the mean *accidental* errors of heighting throughout a stereo model. The "flatness" of a stero model is a general term which refers to the mean *systematic* residual errors of heighting throughout a stereo model due to lack of flatness of the model's imaginary plane of zero elevation. These systematic and accidental errors of heighting in a stereo model are caused by optical, mechanical, visual and photographic limitations of the stereo procedure. The absolute accuracy of spot eleva-

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[*] Prepared for delivery at the 1963 Annual Meeting of the American Society of Photogrammetry. Approved for publication by the Commander, Aeronautical Chart and Information Center. The views expressed herein are those of the author and do not necessarily reflect the views of the U. S. Air Force or of the Department of Defense.

tions in a stereo model is usually stated in terms of the standard deviation of heighting, *dh*, after a least squares fit to ground control. (In other words, *dh* indicates all those mean residual heighting errors normally caused by mushiness and lack of model flatness.)

If we could draw contours with a standard deviation of *dh* at every point, the smallest possible contour interval would then be 3.3 times *dh*—if the contours are to meet U. S. Map Accuracy Standards (1). In other words, we could obtain spot elevations from the stereo model and the corresponding map with identical accuracies. Actually, however, we cannot draw contours with this accuracy on a production basis. In this dynamic situation we can't afford to plot and check carefully each of the infinitely many points that constitute a contour line. Instead, we move the floating mark at a rapid rate along the surface of the stereo model. Whenever the floating mark loses contact with the ground we then move it sideways to re-establish this contact. Meanwhile, we have traced a line that wanders back and forth across the true contour line in our search for it. This hunting process occurs continuously and more or less automatically. It results from our constant need to correct for errors due to muscular tremors, visual errors, and the inevitable carelessness caused by the operator's urgent need to achieve acceptable production rates. The resulting accuracy is further reduced because of irregularities in the slope of the terrain and by variations in the appearance of the terrain, which may range from light to dark, from barren to heavily wooded, and from smooth to coarse textured. As a result, we can draw contours from a stereo model with an accuracy of only about 4*dh*, after a least squares adjustment of the model (or some portion of it) to previously established control. Incidentally, *dh* is by definition the best standard deviation of abolute heighting that can be achieved throughout any given stereo model. It makes adequate allowance for the lack of model flatness and errors of absolute orientation.

The approximate potential accuracy of a mapping system is often given in terms of a figure of merit called the "*C-factor*." A C-factor is an empirical ratio between the flying-height and the minimum contour interval that can be achieved with a given photogrammetric system consisting of a camera, film, plotter and operator. A specified contour interval times the C-factor will give the maximum flying height that will yield topographic maps which meet U. S. Map Accuracy Standards. Also, the flying-height divided by the C-factor gives the smallest possible contour interval which will just barely meet U. S. Map Accuracy Standards. (Incidentally, it is assumed that the C-factor applies solely to the map manuscript and not to the printed maps derived therefrom. It is thus independent of drafting and printing errors in the published maps.) The significance of the C-factor has been thoroughly discussed in the literature (2).

As conventionally used, the C-factor is our best guess regarding the accuracy with which such a photogrammetric system can be used to draw contours under certain specified conditions. The magnitude of the C-factor depends upon the accuracy achieved by a given organization over a long period of time as established by field checks of its compilation manuscripts. This magnitude depends not only upon the equipment but also upon the quality of the photography, the skill of the operators, topographic relief, ground cover, established production rates, and the amount and distribution of photo-identifiable ground control.

The C-factor is frequently used to describe the relative accuracy of stereo plotters, where all of these variable factors have been conveniently ignored. As a result, various authorities differ substantially as to the C-factors of various stereo plotters. For example, in a recent issue (3) of PHOTOGRAMMETRIC ENGINEERING Colner gave the Kelsh Plotter a C-factor of only 512 while Tewinkel gave it C-factors ranging from 1,200 to 1,700. No doubt these accuracy criteria are equally reliable under the assumed conditions. Nevertheless, it is obvious that these C-factors do not provide other organizations with reliable accuracy criteria for stereo plotting. As a result, this term now has very little useful meaning under general conditions.

What can we do about this lack of adequate accuracy criteria? Certainly we cannot make the most effective use of a sophisticated photogrammetric system unless we can confidently predict what its ultimate accuracy really is. Neither can we be sure that we are currently achieving this predicted accuracy in our daily practice. *For urgent economic reasons we therefore need an accuracy criterion that will allow us to use our equipment to best competitive advantage.* This accuracy criterion should have a reliability of 90 per cent in order to be consistent with U. S. Map Accuracy Standards.

B. INSTRUMENTAL CRITERIA

Under favorable conditions in a stereo plotter we can just barely see (or visually detect) with 90 per cent confidence:

A. Well-defined low-contrast point images if their diameter equals one line-plus-space of resolving power on the aerial negatives.
B. Local differences in elevation, if the corresponding parallax differences equal at least one line-plus-space of resolving power on the aerial negatives.

This limiting precision is achieved only under optimum conditions of enlargement and magnification, where the operator's visual image is so large as to appear slightly fuzzy. Nevertheless, it provides for the detection and measurement of any such images with maximum confidence *in terms of ground units.* (See Figure 3.)

Under these conditions we can *measure* local elevation differences with a limiting *accuracy* that corresponds to a parallax difference of about two-fifths* of one line-plus-space of low-contrast resolving power with 90 per cent confidence. In other words (at negative scale, and with 68 per cent confidence) the standard deviation of parallax differences throughout a stereo model equals

$$dp = (3/5)(2/5r) = 6/25r \qquad (1)$$

where r equals low-contrast lens-film resolving power, in lines/mm.

After some thought it appears that our need for a reliable easy-to-use accuracy criterion can be satisfied by a figure of merit called the "coverage-contour factor" (or CC-factor), which is here defined as the neat ground coverage of a stereo model for a given limiting contour interval. When stated as a function of the maximum permissible flying-height *or a given* contour interval, the coverage-contour factor equals (with 90% confidence):

$$CC = KH^2 = K(b4dh\cos^2 T/4dp)^2 \qquad (2)$$

where:

K = Coverage factor of neat stereo model
H = Maximum permissible flying height
dp = Standard deviation of absolute x-parallaxes
dh = Standard deviation of absolute heighting
b = Photo base of equivalent vertical photo
T = Convergent tilt, in degrees

and where b and dp are in millimeters, and H and dh are in meters. Several authorities have proposed similar equations of considerable technical interest (4). However, they seem overly sophisticated for the purposes of this elementary discussion.

Equation 2 is an empirical modification of the well-known classical parallax equation* and assumes that:

A. The term H equals the maximum permissible flying-height in meters that can be achieved with any given camera-film-plotter-operator combination for a given contour interval (with 90 per cent confidence).

B. The term K represents the area of the neat stereo model, as a function of the flying height squared, H^2.

C. The accuracy coefficient of 4 approximately equals the mathematical product of the following three factors:

   1.64, which statistically converts our standard of reliability from 68 to 90 per cent;
   2.00, which converts our standard of accuracy from one-half the contour interval to the full contour interval;
   1.22, which allows for the operator's inability to draw contours with the same accuracy that he measures well-defined spot elevations.

   For example, in a first-order stereo plotter we can expect to measure absolute elevations from aerial photographs with a standard deviation of $H/5{,}000$ after a least-squares fit to ground control. As a result we can expect to draw contours (that meet U. S. Map Accuracy Standards) with an interval of $H/1{,}250$—one-fourth of our heighting accuracy. Incidentally, 3.3 (the product of 1.64 and 2.00) is the limiting accuracy coefficient and cannot be closely approached in practice.

D. The term dp is the standard deviation of absolute x-parallaxes in the stereo model at negative scale.

E. The term dh is the standard deviation of

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* $dp/dh=(f/H)(B/H)=b/H$, so that $H=b(dh/dp)$.

absolute heighting in the stereo model at negative scale, and $4dh$ equals the minimum permissible contour interval that can be used with U. S. Standard Map Accuracy. (The term dh represents the limiting accuracy with which we can measure the elevations of all well-defined, low-contrast, images in the stereo model. The factor of 4 makes full allowance for the residual errors normally involved in the contouring process, as noted above.)

F. The term b is the photo base.

G. The term $\cos^2 T$ corrects approximately for the degrading effect of tilt on image resolution.

H. Residual y-parallaxes in each model are normally distributed, are accidental in character, and do not exceed tolerable values as established by well-known mathematical formulas.

I. Adequate horizontal accuracy can also be achieved simultaneously.

The use of this new CC-factor assumes that we will standardize the quality of each stereo model by the use of the following techniques:

A. Use one, and only one, vertical control point in each corner of each stereo model. (In actual practice all available vertical control should be used. However, this fact should be clearly stated in any subsequent proclamations about the CC-factor.)

B. Before initiating map compilation, calibrate the stereo plotter in terms of dh—using calibrated stereo grids. (Over a period of time this will establish a predictable relation between dh for a grid model and dh for low-contrast aerial photographs.)

C. Before plotting the topography from each stereo model, and after its absolute orientation, verify that the root-mean-square value of the residual y-parallaxes does not exceed ten or fifteen microns at negative scale. In this connection Hallert (4) concludes that "The simplest method for determining if the expected accuracy is really obtained in connection with the measurements, is testing of residual y-parallaxes in the models after finishing the absolute orientation. The geometrical quality to be expected can then be determined from the formulas within the corresponding confidence limits. . . . " Incidentally, Schermerhorn (5) agrees that "Measurements of y-parallax in connection with restitution should be regularly performed (in particular the residual y-parallaxes after finishing the relative and absolute orientation) . . . "

D. Before plotting the topography from each stereo model, and after its absolute orientation, verify that the standard deviation of spot heighting does not exceed twelve per cent of the specified contour interval. (See Table 1. If the standard deviation of spot heighting does not meet this criteria, the stereo model should then be appropriately magnified and/or enlarged, as explained subsequently.)

From Equation 2 we see that the maximum permissible flying height for *vertical* photographs and a given contour interval equals

$$H = b(4dh/4dp) \tag{3}$$

where $4dh$ equals the desired contour interval, I. If we substitute Equation 1 in Equation 3 we find that

$4dd = I$

$$H = rbI \tag{4}$$

and

$4dp \times \frac{25}{6r} = \frac{1}{r}$

$$CC = K(rbI)^2. \tag{5}$$

C. PHOTOGRAPHIC CRITERIA (6)

The accuracy criteria described above depend for their validity upon certain statistical and geometrical concepts, as we have explained. However, they also depend upon that rather intangible factor called "*resolving power*." Unfortunately, resolving power is not a fundamental property of a photographic emulsion or a camera lens, and varies widely with respect to the texture, contrast and illumination of the terrain. Nevertheless, this term is commonly used and, for lack of something better, provides a useful interim criterion within the context of this paper.

The limiting relation between resolving power and the resulting ground resolution has not been scientifically established. However, by geometrical proportion it appears that ground resolution in meters equals, with 90 per cent confidence

$$R = H/fr \tag{6}$$

where:

H = Flying height, in meters
f = Principal distance of camera, in millimeters
r = Low-contrast lens-film resolving power, in lines/mm.

If b/f equals the base-height ratio of the stereo model, it is then evident that one line of resolving power permits the visual detection of relief (with 90 per cent confidence) at threshold values equal to

$$V = R/(b/f) = H/rb. \qquad (7)$$

It is evident from Equations 4 and 7 that I (the limiting contour interval) equals V (the visual limit of relief perception).

Equation 6 is commonly used in the R&D community. Nevertheless, some authorities do not approve. For example, Macdonald notes that "Resolution and scale are not interchangeable at parity.* . . . It is obvious . . . that other factors play a most significant role and that resolution by itself can be a misleading criterion. . . . Interpretability improves as resolution improves, but the gain in interpretability is always a lesser factor than the gain in resolution." As a further example, Bousky states that "careful examination of (certain) data indicates that in the region of low contrast, recognition and detection are related more nearly to the square root of resolution than the first power, as might be expected. . . . "

D. U. S. NATIONAL MAP ACCURACY STANDARDS

U. S. Map Accuracy Standards (1) state that "Vertical accuracy, as applied to contour maps on all publication scales, shall be such that not more than 10 per cent of the elevations tested shall be in error more than one-half the contour interval. In checking elevations taken from the map, the apparent vertical error may be decreased by assuming a horizontal displacement within the permissible horizontal error for a map of that scale."

The commonly accepted meaning of this specification is this: The elevations of 90 per cent of all well-defined planimetric features interpolated from the contours of a *published* map will be correct within one-half the contour interval. Incidentally, it is the author's opinion that the "horizontal shift," mentioned above, was originally intended to compensate for drafting and printing errors. For this reason, it should not be used in evaluating the accuracy of the original map manuscript.

TABLE 1

LIMITS ON HEIGHTING IMPOSED BY ACCURACY CRITERIA

Confidence Level, Per Cent	*50*	*68*	*90*
Limiting precision	0.08	0.12	0.20
Limiting accuracy	0.17	0.25*	0.42
Interpolated elevations on map	0.20	0.30	0.50

* This value corresponds to dh in Equation 1, so that $4dh$ equals the minimum contour interval that can be achieved with 90 per cent confidence by a first-order stereo plotter in normal practice.

E. SUMMARY

The above discussion is summarized by Table 1, where the decimal quantities are fractions of the smallest contour interval that can be achieved with U. S. Map Accuracy.

The 50, 68 and 90 per cent confidence levels in the first row of this tabulation are three different ways of representing exactly the same degree of accuracy. (These three confidence levels are statistically related in the proportions of 2/3/5.)

The data in the second row reflect the maximum permissible accidental errors of sensing the model's surface, and thus represent its "mushiness."

The data in the third row equal the absolute vertical errors at all well defined image-points, and thus includes errors of "mushiness" and lack of model flatness.

The data in the bottom row equal the errors of absolute spot heighting plus errors of sensing and plotting the contours, drafting errors, and errors of interpolating check points from the published contours.

The data within each of these three columns are only empirically related, and do not necessarily represent the experience of any specific organization. Nevertheless, they appear to conform closely to customary commercial practice, although some other authors seem to disagree (6). In any event, under ideal conditions of enlargement and magnification, we see from the 90 per cent column of Table 1 that:

A. The limiting *precision* of sensing the model's surface (its "mushiness") equals $4dh/5$ or $H/5rb$.
B. The limiting *accuracy* of spot elevations

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* In other words, Equation 6 is a geometrical limit to ground resolution that cannot be achieved in practice.

throughout a model equals $8dh/5$ or $2H/5rb$. (This corresponds to dh with 68 per cent confidence.)

C. The limiting contour interval (and the *visual* limit of relief detection) equals $4dh$ or H/rb. (See Equations 4 and 7).

PART II: EQUIPMENT AND TECHNIQUES

According to recent literature, it is evident that substantial improvements are being made in stereo plotters, cameras, aerial films, and related techniques. These improvements are not likely to produce optimum results until they are all used together in one carefully integrated photogrammetric system. Such a system is apt to be somewhat more difficult to use than our present systems, and might require a greater capital investment. However, this development would be consistent with the historical tendency in photogrammetry to use our stereo techniques *near the limit* of our practical ability to make reliable measurements. It therefore seems desirable to take a fresh "unbiased" look at this situation in an attempt to find the best compromise between compilation costs and compilation accuracy.

Compilation costs of a given map vary primarily with the number of photographic flight lines and the amount of available ground-control. Ultimately, these costs tend to vary with the flying height and ground coverage of the photographs. In this connection Theis (9) has noted that "... one of the goals of photogrammetrists everywhere is to devise means of increasing the altitude of the photographic aircraft without decreasing the accuracy of the map.... This goal is a significant economic consideration because, by doubling the altitude, there is obtained four times the ground area." Hallert (4) agrees that "... the flying altitude is of fundamental importance for the economy of the entire mapping project." *This paper is therefore devoted to the subject of increasing the ground coverage of a stereo model without reducing its potential contouring accuracy.*

We intuitively conclude from Equation 2 that the coverage-contour factor is limited in magnitude by visual resolution, mechanical precision of both the camera and the plotter, and the format, overlap, altitude, tilt, resolution and base-height ratio of the photographs.

In order to overcome these limits (*and thus optimize the coverage-contour factor of the stereo model*) it is now proposed that we utilize the following practical but somewhat unconventional photo-mapping techniques. Most of these methods are well known and commercially feasible, but they have never been combined into one system.

A. Use an optimum lens design.
B. Use a camera with a calibrated reseau grid.
C. Use an optimum base-height ratio.
D. Use high-resolution aerial film with optimum exposures and development.
E. Reproduce negatives on films at optimum enlargements, using a precision projection printer and electronic dodging techniques.
F. Use optimum viewing magnification in stereo mensuration.
G. Avoid photogrammetric triangulation by flying the photographs at maximum altitudes and with maximum ground-coverage for a given contour interval.
H. Plot topography in a simple stereograph, or contour finder, equipped with special computing devices for removing residual dimensional errors of the stereo model.

These topics will now be discussed in more detail in the following subordinate paragraphs.

A. OPTIMUM LENS DESIGN (8)

In a stereo model, wide-angle photographs give strong intersections of poorly-resolved perspective rays, while normal-angle photographs give weak intersections of well-resolved rays—comparatively speaking. In order to optimize the coverage-contour factor we must therefore determine the relative merits of various camera configurations in terms of the camera's focal length, resolving power, and field angle.

It is clearly evident from Equation 5 that the CC-factor is a function of the lens parameters K, r^2 and b^2. Incidentally, this figure of merit, $K(rb)^2$, is improved with an increase in its numerical value. Since the focal-length does not appear in Equation 5, it obviously does not affect the coverage-contour factor. The eighth column of Table 4 lists values of K for representative lenses, while the last column lists values of $K(rb)^2$—in other words KH^2.

B. OPTIMUM BASE-HEIGHT RATIO (9)

One method of improving the coverage-contour factor is to increase the ratio between the air-base of a stereo model and its altitude.

This makes the intersections of corresponding perspective rays more obtuse and thus increases our ability to perceive small differences of relief. Two methods can be used to achieve this objective. Under certain limited conditions we can decrease the overlap of vertical photographs, or we can use convergent-oblique cameras. In this paper, it is assumed that the ideal base-height ratio equals 1.00, if the flying-height is at least ten times the maximum differences in topographic relief in any stereo model. (The resulting flying height will thus be large enough to prevent substantial "dead spots" in the photo coverage.) This optimum B/H ratio will facilitate optimum visual and geometrical resolution of small local differences of relief.

A *decrease* in endlap causes a corresponding *increase* in the photo base. However, it is evident from Equation 5 that the *CC*-factor is increased in direct proportion to the square of this increased photo-base until we reach 50 per cent endlap; thereafter it is decreased towards zero with a further increase in the photo base. In vertical photography we normally use 60 per cent endlap. The photo-base (and our accuracy of heighting) can be increased by 50 per cent if we fly the photography with 70 per cent endlap, and then use alternate photographs in stereo plotting. These alternate photographs would thus have an endlap of 40 per cent, while successive stereo models would have ten per cent endlap.

The net effect of *convergent tilt* upon the coverage-contour factor is illustrated by Equation 2. Here we see that convergent tilt affects the *CC*-factor in three ways. First, it degrades the mean resolving power of the stereo model somewhat in proportion to $\cos^2 T$. Second, it permits a substantial increase in the base-height ratio of the stereo model. Third, it allows a substantial increase in the coverage factor K, as noted in the eighth column of Table 4.

C. OPTIMUM CAMERA DESIGN

We have already demonstrated the practical importance of using a camera with a high resolution lens that has a wide-angle field. In order to overcome the effects of lens distortion and differential film shrinkage we further recommend the use of a camera equipped with a precisely calibrated reseau grid. The Zeiss RMK AR 15/23 illustrates a commerically available camera of this type.

The use of such a reseau grid permits us to do two important things in stereo plotting: *First*, we can use enlarged and segmented film positives as proposed in Section E, below. *Second*, we can use a stereo plotter with an electronic memory which will remove all known model errors, as proposed in Section *H*. *It is here assumed that the camera's focal plane would be located for maximum micro-contrast rather than for minimum lens distortion!*

D. OPTIMUM FILM, EXPOSURE AND DEVELOPMENT (10)

Our goal here is to produce excellent negatives, *in terms of interpretability* (or visual acuity at threshold values of image contrast). Figure 1 illustrates the probable relation between interpretability and image density for a typical aerial film, as determined by Barrow. In this connection Bousky states that "Barrow used randomly arranged squares and circles of equal area to evaluate the capability for recognition of detail. He determined the contrast threshold and used the reciprocal of this contrast value as a 'recognition index.'" Figure 1 indicates a relationship between Barrow's recognition index and high-contrast resolution as a function of density. The maximum in high-contrast resolution which is usually used as the criterion for determining image quality, does not correspond to the maximum point for his recognition index.

"Barrow's data also may be compared with that of Kardas for low-contrast resolution. Figure 2 shows comparisons of recognition index and resolution at a contrast of 0.03, as a function of gamma for two different developers. Here again the resolution maximum is different from the recognition index maximum for each developer. *This indicates that both high and low-contrast resolution may fail as a quality parameter in terms of interpretability.*"

It therefore seems evident that we should make effective use of fine-grain films that are optimized for low-contrast images.* We should also seriously consider proposals by Kasper (9) and Meier (10) to use infrared film as a further means of increasing the potential ground resolution.

The camera-emulsion (photographic) system can achieve near-maximum resolution only at exposures located near the bottom end of the linear portion of the characteristic curve. A change in exposure from this opti-

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* In this connection please see the dramatic illustration on page 57 of the SOCIETY'S MANUAL OF PHOTOGRAPHIC INTERPRETATION.

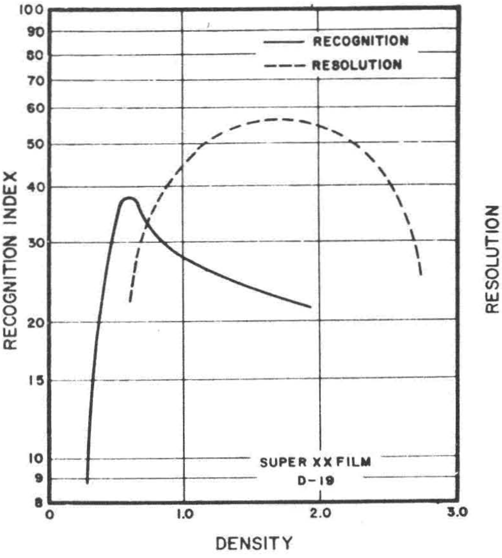

FIG. 1. Density versus Resolution and Recognition. (Credit: Samuel Bousky.)

mum value will substantially degrade the mean resolution of the resulting images. We should therefore make each exposure in accordance with theoretical criteria for optimum resolution.

The processing of photographic films is seldom considered to be an important function in practice, and is therefore usually performed by the lowest paid technician in the photo lab. We pay for this policy where it hurts the most—in the mushiness of the stereo model. We should therefore use only our best photographers and techniques in developing and printing our aerial negatives.

E. OPTIMUM DIAPOSITIVE ENLARGEMENTS (11)

Berg reports that great improvements have been made recently in the quality of aerial negatives. We can now achieve 30 to 40 lines/mm. in the air, and may double this figure by 1970. However, if we use conventional techniques of making diapositives, we will throw away at least one-third of this resolving power in the photographic laboratory. (For example, see the data in the third column of Table 3.)

In order to capture most of the resolving power in our aerial negatives it is therefore obvious that we must reproduce them at favorable enlargements through a good projection lens. Unfortunately, only a small increase in definition results from a 4× enlargement; a really large increase in definition requires an 8× enlargement, according to Berg. It is therefore now proposed that we make enlarged and segmented film positives to capture the resolving power currently available in our best aerial negatives.

For example, 4× enlargements of the overlap between two 9″×9″ negatives would yield sixteen prints of 10″×11″ format—four segmented models on each side of the flight line. Incidentally, the geometrical accuracy of the camera would be retained at such enlargements, since all measurements would then be automatically referred to a common reseau grid. These enlarged and segmented diapositives would also allow us to overcome the mechanical errors normally encountered in even the best stereo plotters. Only in this way can the inherent accuracy of the negatives be physically recovered in the stereo plotter itself.

Table 2 illustrates the practical significance of this proposal. The limiting unit dp's in the second column are assumed to equal a standard deviation of $1/4r$ on the negatives. (See Equation 1.) It is further assumed that the parallax measurements of the stereo plotter have a standard deviation of 12 microns with low-contrast images at optimum magnification. In order to achieve a standard deviation of 17 microns in practice, the diapositives must therefore be enlarged in the amount indicated by the third column. As a result of this enlargement the diapositives all have a nominal resolving power of 20 lines/mm. However, in order to allow for the inevitable loss of visual contrast with increased negative

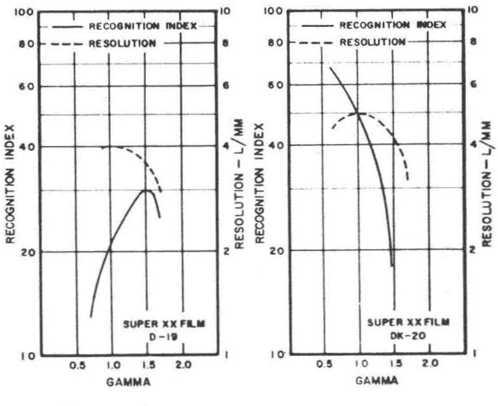

FIG. 2. Gamma versus Resolution and Recognition. (Credit: Samuel Bousky.)

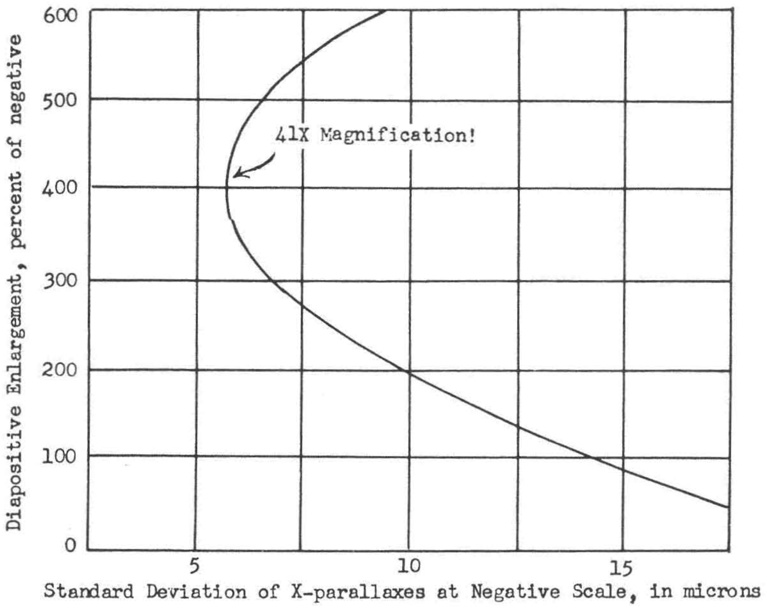

FIG. 3. Standard deviation of x-parallaxes versus optimum diapositive enlargement in a Wild A7 Autograph, when H/f at model scale equals 3.00, and the viewing magnification equals ten diameters at low contrast.

resolution, the operator's viewing magnification should be increased as indicated in the fourth column of Table 2. In the last column the C-factor is the product of the negative's resolving power and its photo base of 92 mm. (See Equation 4.)

F. OPTIMUM VIEWING MAGNIFICATION (11)

The low-contrast resolving-power of the human eye equals about five lines/mm. at a normal reading distance of ten inches. In order to fully use the resolving power of our aerial negatives, it is therefore necessary to view the diapositives with a magnification such that the resolving power of the resulting image equals the observer's visual resolving power.

Figure 3 illustrates an empirical relation that exists between viewing magnification and the resolving power of aerial negatives. It represents data obtained from four stereo pairs of a given area appearing on two overlapping negatives. These diapositives were made at nominal scale factors of 75, 150, 300 and 600 per cent of negative scale. They were all viewed at a magnification of ten diameters in a Wild A7 Autograph. As a result, the stereo images were viewed at magnifications of 7.5, 15, 30 and 60 diameters with respect to the original negatives. A nominal base-height ratio of six-tenths was used for all tests. Fourteen identical, well-defined point images were selected in the overlap common to the four pairs of diapositives. The x-parallaxes of these fourteen points were measured ten times each in each model at maximum model scale and with good illumination.

From Figure 3 it appears that the smallest standard deviation of x-parallaxes at negative scale (i.e., 6.5 microns) would have been achieved with 4× diapositives. It might be well to mention that the resulting stereo image would be too large to be considered as a "hard" model. *The magnification was not chosen to give a hard model, but rather to give the smallest standard deviation of heighting.*

TABLE 2

ENLARGEMENT, MAGNIFICATION AND RESOLVING POWER

Resolving Power in Lines/mm.	*Limiting* Parallax Measurement*	*Minimum Diapositive Enlargement*	*Optimum Viewing Magnification*	*Limiting C-factor rb*
10	25u	50%	2×	920
20	12u	100%	4×	1,840
40	6u	200%	8×	3,680
80	3u	400%	16×	7,360

* The limiting parallax measurement of the stereo plotter is assumed to equal a standard deviation of 12 microns on the diapositives.

Eden has recently published data which tend to support the above conclusions. Table 3 summarizes Eden's work, where we see that an enlargement of 30 diameters is necessary to read a high-contrast ground resolution diagram imaged on an aerial negative taken from 3,000 feet. The image of this resolution diagram indicated that a resolving power of 68 lines/mm. was achieved at a relatively good image density difference of 0.33. It is evident from Table 3 that the resulting diapositive had a resolving power of 42 lines/mm. *at contact scale*, while the corresponding paper print had a resolving power of 31 lines/mm. *at contact scale*. In this connection Eden notes that we are still using the same magnification in stereo viewing that we used with the old coarse-grained films of the 1930's. (Incidentally, the practical relation between optimum magnification and resolving power can be observed most dramatically with a Zoom microscope.)

G. Optimum Image Contrast (12)

The acuity (or resolving power) of the human eye varies with the visual angle, illumination and contrast. In stereo plotting, visual acuity largely depends upon density differences (or micro contrast) between point images and their background. For example, our eyes will just barely resolve *high-contrast* point images separated by *one* minute of arc. This visual acuity corresponds to a resolving power of about ten lines/mm. at a normal viewing distance of 10 inches. However, our *low-contrast* resolving power may be as poor as *seven* minutes of arc, or two lines per millimeter. This poor acuity is achieved at a limiting contrast (density-difference threshold) of about 0.03 to 0.04 for point images at a gamma of one under favorable illumination and visual aspect angle.

Unfortunately, the micro contrast of point images on aerial negatives approaches our limiting value of visual contrast—especially in the light and dark areas. It therefore appears likely that we could nearly double the potential CC-factor of a given system by improving the mean micro-contrast of the diapositives. This improvement can now be partially achieved in practice by the use of commercially available (13) automatic electronic dodging printers or by the use of the un-sharp masking technique developed in England (14). Incidentally, high contrast may explain much of the improved accuracy that is achieved by Halbrook and others with rectangular grids in stereo plotters (9).

H. Optimum Stereo Plotter (15)

The above discussion implies that heighting accuracies of about five microns at negative scale can now be economically achieved with relatively simple equipment and techniques. However, we are required to use enlarged and segmented film positives in order to achieve this accuracy and simplicity. This author therefore concludes that the optimum stereo plotter of the near future will consist of a stereograph equipped with special computing devices for removing residual dimensional errors of the stereogram. These devices would correct for errors due to film distortion, the reseau grid, lens distortion, earth's curvature, displaced principal points, image-motion compensation, and erroneous principal distances. Also, they could greatly simplify relative and absolute orientation of the segmented models, and change plotting scales as desired.

The parallax bar and viewing mechanism of this new stereograph would be attached to a simple parallel-motion mechanism. The stereo images would be observed under optimum

Table 3

Eden's Comparison ov Viewing Procedures

Viewing Procedure	*Ground Resolution in Inches*	*Per Cent Loss Due to Print*	*Per Cent Loss for Magnification*	*Resulting Resolving Power*
Optimum viewing of the negative (30×)	3.6	0	0	68
Optimum viewing of diapositive (25×)	5.6	38	0	42
Contact diapositive when viewed at 18×	5.9	38	6	38
Diapositive when viewed at 10×	7.7	38	16	31
Optimum viewing of paper print (16×)	7.9	54	0	31
Contact paper print when viewed at 8×	10.6	54	14	22
Paper print when viewed at 4×	15.8	54	24	15
Paper print when viewed at 1×	32.8	54	35	7

illumination, enlargement and magnification. A pencil, attached to a simple coordinatograph or pantograph, would be used to draw topography in the usual manner. A comparatively simple analog computer (electronic or mechanical) would drive step or servo motors attached to the drawing pencil, and to the micrometer screw on the parallax bar. This computer would remove residual y-parallaxes from all points in the stereo image. It would also remove all known errors from the vertical datum, and from the position of the drawing pencil at any location within each segmented model. This computer need not compute absolute positions or absolute elevations of any points within the model; *it would only be concerned with removing small residual errors* by means of electrical voltages. We thus *minimize* the use of electronic circuits and their overwhelming maintenance problems.

The resulting stereo plotter would accommodate vertical photographs of any focal length and any convenient format—including super-wide-angle photographs. By using rectified film positives this same plotter could also make optimum use of convergent-oblique photographs.

I. OPTIMUM CONTROL EXTENSION

In this paper it has been assumed that aerial photographs will be obtained at the highest possible altitudes as set by the coverage-contour factor. As a result, there will be no surplus geometrical accuracy that could be expended in conventional photogrammetric triangulation of vertical control. Nevertheless, an elementary form of control extension is required if we are to use segmented stereo models, as proposed herein. In this case, each pair or triplet of overlapping photographs would be absolutely oriented to ground control in each corner of the overlap. Supplementary control points would then be located in each corner of each segmented model. For example, if one overlap is broken up into eight segmented stereo models, then at least eleven supplementary control points would be required—or a total of fifteen points in the one overlap.

This limited form of triangulation should be performed by numerical techniques using the independent model method, where measurements of the control points would be obtained directly from the segmented film positives. It is likely that appropriate intersections of the reseau grid would be used as pre-marked and pre-measured supplementary control points. Incidentally, it should be understood that the smallest permissible contour interval would be at least four times the standard deviation of this supplementary vertical control, as previously explained.

J. SUMMARY

Table 4 summarizes much of the above discussion. The last column in this table compares the relative efficiency of representative photogrammetric systems in terms of the converage-contour factor and low-contrast resolving power. The next-to-last column

TABLE 4

PARAMETERS OF REPRESENTATIVE PHOTOGRAMMETRIC SYSTEMS, ALL HAVING THE SAME CONTOURING ACCURACY, I

Camera System Number	*Focal Length in mm.*	*Negative Format in cm.*	*Mean Resolution Lines /mm.*	*Photo Base in mm.*	*Per Cent Endlap*	*Conv. Tilt*	*Cover. Factor K*	*Ground Resolution $(H/fr)I$ in Meters*	*Optimum Altitude rbI, in Meters*	*Optimum Coverage KH^2 in $Km.^2$*
1	610†	23×23	97	—	100	10°	0.095	0.37I	21,825I	$45.3I^2$
2*	610	23×23	100	138	40	zero	0.034	0.23I	13,800I	$6.5I^2$
3	610	23×23	100	92	60	zero	0.046	0.15I	9,200I	$3.9I^2$
4	300†	23×23	45	—	100	19°	0.460	0.80I	10,845I	$54.1I^2$
5*	300	23×23	50	138	40	zero	0.141	0.46I	6,900I	$6.7I^2$
6	300	23×23	50	92	60	Zero	0.188	0.31I	4,600I	$4.0I^2$
7	152†	23×23	40	—	100	20°	1.130	1.00I	6,080I	$41.8I^2$
8*	152	23×23	45	138	40	zero	0.540	0.91I	6,210I	$20.8I^2$
9	152	23×23	45	92	60	zero	0.730	0.61I	4,140I	$12.5I^2$
10	88.5	23×23	25	92	60	zero	2.162	1.04I	2,300I	$11.4I^2$

* The length of the corresponding neat stereo models equals one-half of their air base.

† This is a duplex (convergent-oblique) camera installation.

indicates the maximum permissible flying height for a given contour interval. For example, if the desired contour interval is ten feet, the flying height would then be ten times the indicated altitude-contour ratio. The coverage-contour factor (in the last column) assumes that aerial photography would be obtained at maximum permissible altitudes consistent with the desired contour interval. The amount of essential ground control would thus be reduced to an absolute minimum in each case.

Camera systems 2, 5 and 8 would require the use of photogrammetric triangulation in the form of stereo triplets, where consecutive photographs overlap 70 per cent. Camera systems 1, 4 and 7 involve the use of convergent-oblique cameras. It should be understood that, for purposes of easy comparison, all of the stereo models referred to in Table 4 are assumed to have equal contouring accuracy in terms of ground elevations. Table 4 seems to illustrate the relative superiority of super-wide-angle photographs in terms of the flying height and coverage-contour factor, when we consider the difficulties of flying photography at high altitudes.

The following outline describes the new map compilation procedure proposed by the above discussion:

A. Expose aerial negatives at maximum permissible altitudes for a given contour interval.
B. Develop negatives and make segmented film positives, at enlargements of at least four diameters.
C. Identify and mark ground-control points on the film positives. Also select and mark supplementary control points (reseau intersections).
D. Measure the x- and y-photo coordinates of all control points and fiducial marks on film positives.
E. Compute position and elevation of the supplementary control points in each overlap, using the independent model method.
F. Plot map-projection and control points on the map manuscript.
G. Plot topography on the map manuscript at considerable visual magnification.

This procedure requires the use of a precision enlarging printer, a stereo point marker, a simple 10-micron comparator, a small electronic computer, and a new type of stereograph. All of these devices are commercially available except the stereograph.

PART III: CONCLUSIONS AND RECOMMENDATIONS

It is the author's conclusion that the use of the standardized CC-factor in mission planning should give us increased confidence in the accuracy to be ultimately achieved in stereo plotting. As a result, we would be justified in flying our aerial photographs at higher altitudes and thus substantially reduce compilation costs.

It appears that we can greatly improve the efficiency of stereo map compilation in the near future. Hallert (9) has reached a similar conclusion, for he says ". . . it seems possible to arrive at a more rational method . . . for photogrammetric work. . . . It is probable that too low flying altitudes have frequently been used for the aerial photography and that, consequently, the most economical results have not been obtained." (Plotting with a Kelsh at a C-factor of 512, as reported by Colner (3), seems to illustrate Hallert's contention.)

We should now be able to at least double or triple our present compilation accuracies for a given altitude. However, it should be clearly understood that this improved accuracy could be justified on an economical basis only if we would fly our mapping photography at relatively high altitudes. If the operating ceiling of the aircraft imposes a practical limit on the flying height, it is then important to achieve the largest possible coverage-contour ratio from that height.

Compilation costs probably would vary inversely with the coverage-contour factor. When this CC-factor is increased, costs would then be reduced—mostly because we would need fewer flight lines and much less ground control. Nevertheless, it is recognized that this conclusion may not be valid when a large amount of photo identifiable ground control is available within a project area. In this special case we could fly the photographs at lower altitudes and then use less precise plotting equipment and techniques for a net savings.

Much has been said in the literature about the relative merits of vertical and convergent-oblique photographs (9). As noted above, the outstanding advantage of convergent-obliques is the very large coverage-contour ratio. Against this one big advantage we have the following somewhat minor disadvantages:

1. Aerial triangulation is more difficult and less accurate.

2. It is relatively difficult to remove errors of y-parallax from the stereo model.
3. The base-height ratio is too large for good stereo perception at low altitudes. (At low altitudes local differences of topographic relief will then exceed the operator's stereoscopic field of clear vision.)
4. At relatively low altitudes complete stereo coverage may not be achieved in areas of rugged relief.
5. The base-height ratio is fixed by the need to achieve 100 per cent overlap in the stereo models.
6. Mean resolving power of the stereo model is reduced by $\cos^2 T$.
7. Contact prints of convergent obliques cannot be directly viewed stereoscopically.
8. Relief displacements are relatively great in photo mosaics made from such photographs.
9. It is difficult to achieve satisfactory endlap between exposures due to narrow tolerances.

However, as Schermerhorn (5) notes "... at present a fully justified comparison of convergent and vertical photography is impossible. ... Nevertheless, it must be considered an important problem to find out which are the real qualities of the convergent photography in order to determine in which cases its application will have advantages above vertical photography."

At this point you may wonder if we should include automated plotters (16) in our current development goals for civil mapping. We should make way for these instruments whenever they promise a substantial reduction in our total compilation costs. Their primary contribution will be in the drawing of contours and drainage, and probably will require a substantial reduction in flying height. Nevertheless, this is a complex subject and is entirely beyond the scope of this present paper. Whether or not automatic plotters are practical is irrelevant to this current proposal to minimize compilation costs by covering the largest possible area on the ground with each aerial photograph.

It appears that the optimization of stereo plotting will depend upon three important factors. *First*, upon increasing the information capacity of the aerial photographs at threshold values of image-contrast. *Second*, upon increasing the geometrical precision of the camera and plotter. *Third*, upon devising a more reliable and efficient figure of merit for low-contrast "interpretability." The author therefore recommends that our minimum procure-goals for 1970 should include the commercial development of the following equipment and techniques:

A. Cameras with better resolving power at low image-contrasts. (Perhaps we could achieve the essential resolving power with focal-plane shutters—and remove the resulting distortions in the electronic memory of the stereo plotter.)
B. Improved automatic-dodging projection printers.
C. Improved plotters (stereographs) with better resolving power and an improved standard deviation of heighting.
D. Improved low-contrast resolution targets.

All of these developments are well within the current state of the art. The resulting photogrammetric systems apparently would provide the best compromise between equipment costs and compilation costs for the civil mapping of large areas.

In closing let me quote Professor Schermerhorn's (9) concluding remark in a similar situation: "The sense of this paper is ... to show how poor the position of research in photogrammetry still is at present, notwithstanding all the theory of errors published in the past 20 years." So I leave you at this point with a few of the many questions for which I have no answers:

A. What confidence level is normally implied by the term "photographic resolving power"?
B. How does the standard deviation of heighting in a give plotter vary with illumination, viewing-magnification, image-density, contrast resolution, and base-height ratio of the diapositives, and the size and brilliance of the floating mark?
C. Under the conditions described immediately above, what is the ultimate precision with which we can superimpose the floating mark on a stereo image?
D. How does the standard deviation of heighting vary with diapositive enlargement? (See Figure 3, above.)
E. How does the standard deviation of heighting in a given plotter vary with the base-height ratio, when the model is formed by the use of calibrated reseau grids?
F. What is the optimum relationship be-

tween resolving-power (or ground-resolution) and the resulting map-scale or contour interval?

G. How can we best improve the net ground resolution of the stereo (plotter-observer) system for a given angular field, where losses in resolving power of 30 to 50 per cent are now common?

H. Would we achieve best results in stereo plotting by using smaller cameras as Eden suggests and *then* making enlarged prints, or by using large cameras as Katz (8) suggests?

I. When will high altitude (jet) aricraft be commercially available for aerial photography?

J. What is the relation between model flatness tests using reseau grids and real photographs? Are these differences predictable? Could they be removed from terrain models by the use of an analog computer?

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