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CPS: Computed Photo Scale

A guide to choosing the optimum photo scale for contouring

Introduction

There are many users of photogrammetric maps such as engineers, developers, Federal government, and State technical representatives, who are perhaps unaware of many of the possible causes of errors in contour mapping. Many of these users have not received adequate map products, sometimes because of bad performance and sometimes because of bad planning either on their part or the contractor's. This article will attempt to describe briefly the potential sources of error in the mapping process, and point out some of the misconceptions which still persist in parts of the mapping community. The article will deal only with vertical accuracy, and attempt to develop a simple formula which could serve as an approximate guide for calculating the best photo scale for a given contour interval, knowing beforehand many of the different parameters.

Abstract: *An attempt is made to produce a simple formula for computing the optimum photographic scale for a project which has a given contour interval by using those variables which affect the accuracy of contours. The assumptions have been extremely generalized in order to come up with a usable formula which can be easily applied, the parameters of which, with the exception of the C-factor, have been assigned values based only on the author's professional judgement. No theoretical attemmpt is made to justify these values, but a short analysis of each parameter is given. The author does not claim that the parameters in the formula are theoretically founded, or that they are correct.*

The C-Factor

The C-factor of a particular make and model of stereoplotter is an empirical measure of its inherent contouring accuracy. It is defined by the formula

$$\text{C-factor} = \frac{\text{Flying Height}}{\text{Contour Interval}}$$

For example, the Kelsh plotter commonly uses a photographic scale of 1:6000 taken with a 6-inch focal length camera, for mapping at 1:1200 with 2-foot contours. A photo scale of 1:6000 for photography exposed with a 6-inch lens infers a flying height above ground elevation of 3000 feet. Therefore, the Kelsh C-factor = 3000 feet/2 feet = 1500.

1500 is a commonly accepted value for a Kelsh C-factor in the commercial sector, but the C-factor as a measure of a calculation of the flying height for a given contour interval is used extensively only in the United States. In Europe there are serious objections to its use, and theoreticians there prefer to express precision in terms of standard errors which are closely linked to the written specifications for firstly, spot height accuracy, and secondly, contour accuracy. These last two factors are rated two to one in the United States, i.e., spot height accuracy is reckoned to be twice as good as contour accuracy. Argumentatively, this is not necessarily a true assumption.

C-factors of some instruments are sometimes stretched in order to justify an extremely high flying height for economic reasons, but on the whole the C-factors listed later are accepted in the commercial sector as being reasonable. What is not generally accepted is that, in order for these C-factors to work, the conditions have to be well-nigh perfect. The C-factor is a most useful tool in the planning of a specific contouring project if properly used, but it has some severe limitations due to some common misconceptions.

Some Common Misconceptions

It is a misconception that a C-factor can be applied with only average operators and with instrumentation in only average calibration.

It is a misconception that a C-factor can be applied when using superwide-angle photography. (A

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modified C-factor for superwide photography could be derived.)

It is a misconception that a C-factor can be applied when the photogrammetric control has been acquired from analytical aerial triangulation.

In the author's opinion, a C-factor should be used only under the following conditions:

- 6-inch focal length camera
- Instrument in good calibration
- Good, experienced operator
- Full vertical ground control
- Sharp, clear diapositives
- Smooth-sloped terrain
- Terrain unobscured by vegetation

Computed Photo Scale

The author's suggested formula to be used for the computed photo scale is

$$CPS = CI \times CF \times CA \times FL \times AN \times IN \times OP \times \frac{(20\text{-}MB)}{20} \times 2$$

where CI = contour interval to be used, in feet;

CF = C-factor of the instrument;

CA = 1.0 for a camera whose maximum mean radial distortion is less than 5 micrometres,
0.95 for a camera whose maximum mean radial distortion is between 5 and 10 micrometres, or
0.9 for a camera whose maximum mean radial distortion is more than 10 micrometres;

FL = 1.1 for a $3^{1}/_{2}$-inch camera,
1.0 for a 6-inch camera,
0.75 for a $8^{1}/_{4}$-inch camera, or
0.5 for a 12-inch camera;

AN = 1.0 for full ground control,
0.9 for simultaneous bundle adjustment analytics with additional parameters,
0.85 for simultaneous bundle adjustment analytics without additional parameters,
0.8 for independent model analytics, or
0.7 for polynomial adjustment analytics;

IN = 1.0 for instrument in excellent calibration, or
0.9 for instrument in average calibration;

OP = 1.0 for excellent operator, or
0.9 for average operator;

MB = Maximum number of models bridged, i.e., consecutive models containing no vertical control in the neat model area; and

CPS is the reciprocal of the natural scale. For example, if CPS is 7200, then the photo scale is 1:7200.

EXAMPLES

(1) Project is to be mapped with a 2-foot contour interval using a 6-inch focal length camera having less than 5-micrometres radial distortion, with mapping on a Kern PG2 in excellent condition with an average operator, using full ground control.

$$\begin{aligned} CPS &= 2 \times 2000 \times 1.0 \times 1.0 \times 1.0 \\ &\quad \times 1.0 \times 0.9 \times \frac{(20\text{-}0)}{20} \times 2 \\ &= 7200 \end{aligned}$$

Photo scale is 1:7200.

(2) Project is to be mapped with a 2-foot contour interval using a 6-inch focal length camera having maximum 8-micrometres radial distortion, with mapping on a Kelsh plotter in average condition with an excellent operator, using analytics developed from a polynomial adjustment method, bridging over three models.

$$\begin{aligned} CPS &= 2 \times 1500 \times 0.95 \times 1.0 \times 0.7 \\ &\quad \times 0.9 \times 1.0 \times \frac{(20\text{-}3)}{20} \times 2 \\ &= 3052 \end{aligned}$$

Photo scale is 1:3052.

Note that the same project with full control, where AN = 1.0 instead of 0.7 and MB = 0 instead of 3, CPS would be 5130 and the photo scale would be 1:5130.

(3) Project is to be mapped with a 2-foot contour interval using a $3^{1}/_{2}$-inch focal length camera with maximum 4-micrometres distortion with mapping on a Jena Stereometrograph plotter in average condition with an excellent operator, using analytics developed from a simultaneous bundle adjustment method with additional parameters, bridging over three models.

$$\begin{aligned} CPS &= 2 \times 2400 \times 1.0 \times 1.1 \times 0.9 \\ &\quad \times 0.9 \times 1.0 \times \frac{(20\text{-}3)}{20} \times 2 \\ &= 7270 \end{aligned}$$

Photo scale is 1:7270.

(4) Project is to be mapped with 2-foot contours using a 6-inch focal length camera, distortion less than 5-micrometres, with mapping on a Wild AG1 plotter in excellent condition with an excellent operator, bridging over one model using a bundle adjustment method without additional parameters.

$$\begin{aligned} CPS &= 2 \times 2000 \times 1.0 \times 1.0 \times 0.85 \\ &\quad \times 1.0 \times 1.0 \times \frac{(20\text{-}1)}{20} \times 2 \\ &= 6460 \end{aligned}$$

Photo scale is 1:6460.

(This example refers to much of the work done by the author's company. For convenience in sectionalized terrain, the acutal CPS chosen is 5100 to allow for control at quarter-section corners at half-mile intervals. This allows for a significant margin of error).

(5) The following example is typical of the more conservative approach taken in many other countries.

Project is to be mapped with a 1-meter (3.281-feet) contour interval using a 6-inch focal length camera with maximum 4-micrometres distortion, compiling on a Wild A8 plotter in average condition with an average operator, using analytics developed on an independent model adjustment method, bridging over one model.

$$\begin{aligned} CPS &= 3.281 \times 2000 \times 1.0 \times 1.0 \times 0.8 \\ &\quad \times 0.9 \times 0.9 \times \frac{(20\text{-}1)}{20} \times 2 \\ &= 8079 \end{aligned}$$

Photo scale is 1:8079.

It is fairly common practice in other countries to use 1:8000 scale for 1-metre contours whereas here in the United States that scale is commonly used for 2-foot contours. Those other countries commonly use a 1:4800 scale for 2-foot contours, using equipment which may be of higher quality than the average used in the United States.

Explanations

C-Factors

The following list is not totally comprehensive, and some instrument manufacturers will no doubt take issue with the author over them! The CPS formula is based on a commercial list which is commonly accepted in the commercial sector, but other factors are listed for comparison which are acceptable by some Federal agencies, and it is interesting to note that they are substantially lower.

Instrument	C-Factors Commercial	C-Factors Federal Agencies
All Analytical Plotters	3000	2500
Zeiss Planimat	2400	2100
Wild A10	2400	2100
Wild Aviomap	2400	2100
Santoni IV	2400	2100
Kern PG3	2400	2100
Jena Stereo-metrograph	2400	2100
Wild AG1	2000	1800
Wild A8	2000	1800
Santoni III	2000	1800
Santoni IIC	2000	1800
Galileo G7	2000	1800
Galileo G6	2000	1800
Kern PG2	2000	1800
Zeiss Planitop	1800	1500
Wild B8	1800	1500
Jena Topocart	1800	1500
Kelsh	1500	1200

Camera Radial Distortion

The U.S. Geological Survey in Reston, Virginia provides an excellent service to aerial camera operators in the United States by providing detailed camera calibrations. For radial distortion, the four semi-diagonals are measured and the average taken for mean radial distortion. Asymmetric radial distortion shows up in the difference between the semi-diagonals, and this certainly has an effect on contouring as it causes a warped stereo-model, but for the sake of simplicity its effect has not been included in the CPS formula.

The CPS formula is based on the performance of a good 6-inch focal length camera with average radial lens distortion of less than 5 micrometres at any point. Older cameras, often very good ones, have distortion ranging up to 10 micrometres. Any camera having maximum mean radial distortion of more than 10 micrometres should be considered inadequate for precision mapping tasks, unless the mapping is done using an analytical plotter where distortion corrections can be applied.

The values of CA reflect a degradation in accuracy, assumed by the author, of about 5 percent for each of the categories.

Camera Focal Lengths

The geometry of the $3^1/_2$-inch super-wide angle lens, with its greater base/height ratio would seem to result in much greater vertical accuracy from the same flying height, thereby allowing a much smaller photo scale with each photograph covering a larger area. However, practice has proved that this is not the case, and that the improvement in accuracy is minimal. The reason for this is probably due to unflatness of the camera vacuum plate, which could easily result in deviations from a perfectly flat plane of 30 micrometres or more. In the $3^{1}/_{2}$-inch camera the image point resulting from rays of light coming in at a much flatter angle (30° instead of 45° in the corners) would be displaced radially to a greater extent, causing greater vertical errors in the stereo-model.

In addition, it is more difficult to design a distortion-free lens for a focal length of $3^{1}/_{2}$ inches, so usually some accuracy is sacrificed in favor of higher resolution. It is also common to find a greater variance between the distortion curves on the four semi-diagonals of a $3^{1}/_{2}$-inch camera, although the mean distortion curve may look good.

The values of FL which have been assumed credit the $3^{1}/_{2}$-inch lens with 10 percent more accuracy than a 6-inch lens for the same photo scale (Note: Not for the same flying height).

Because of poorer base/height ratios of the $8^{1}/_{4}$-inch and 12-inch lenses, and because less time has been spent by manufacturers on improving these lenses over the past ten years, the values of FL have been assessed by the author at factors roughly proportional to their base/height ratios, for the same photo scale.

Photographic Quality

An important parameter which effects the accuracy of contouring is the quality of the photographic film and the diapositives. However, the influence of this parameter cannot be predicted in advance, so its effect has been omitted from the CPS formula.

Analytical Aerial Triangulation

Clearly there is a difference in vertical accuracy resulting from different adjustment methods, and equally clearly there are other factors involved such as control patterns and distributions. But the objective in this paper has been to generalize, and it has been assumed by the author that the methods differ by about 10 percent in the vertical accuracy obtainable from them. The use of additional parameters in the bundle adjustment method improves accuracy when systematic errors are present, and this applies more to high altitude than to low altitude photography.

Ground Control

The CPS formula assumes that the vertical ground control is error-free. As a rough guide, "error-free" could be defined as having maximum errors of less than 10 percent of the contour interval. It should be noted that, for a two-foot contour interval, a vertical ground control accuracy of better than 0.2 feet can in general only be achieved by differential levelling, or by simultaneous reciprocal vertical angles observed using two single-second theodolites over short distances.

Instruments and Operators

The quality of these two variables has a great effect on contour accuracy, and it would be unusual to be able to apply an "excellent" factor in both cases to the calculations.

Definition of an "excellent" operator might be a conscientious person with at least three-years experience. It is not essential that an operator have any formal training, but it is interesting to note that in parts of Canada, for instance, the majority of operators have had a two-year technical course in photogrammetry.

Definition of an "excellent" instrument (the longevity of instruments, or the rate at which they wear out and can hold a calibration for a long time, varies widely among different manufacturers) might be an instrument less than five years old which has been calibrated within the past three months.

In the author's opinion, a contracting officer trying to assess bids from aerial survey contractors should value both these categories at 0.9 (average) unless he or she has good reason to decide otherwise.

Models Bridged

Vertical errors, usually systematic in nature, tend to be cumulative and therefore will increase with the distance bridged no matter what method of adjustment is used. It is assumed by the author that there will be a decrease of 5 percent in accuracy for every model bridged (no vertical control in that model). This is a linear decrease whereas the propagation of errors will be quadratic or cubic in effect, but once again, a simple factor has been chosen. (This may be more applicable to large and medium scale photography than to small scale photography.)

Terrain

Other factors affecting contouring accuracy are the smoothness of the terrain and the degree to which it is obscured by vegetation. These factors are very difficult to define accurately and, therefore, are not included in the CPS formula. It is probably true that in broken terrain the contour accuracy is not as important as in smooth terrain, and in obscured areas the contours should be compiled with broken or dashed lines to indicate lack of confidence in those areas.

Automatic Contour Interpolation

Contours interpolated by a computer from digital terrain models (DTM) are becoming more commonplace, especially in countries other than the United States. The accuracy of these contours can be better or worse than conventionally plotted contours, depending on the spacing of the DTM points, the digitizing of break lines, and the software used for the interpolation. This is a new field of expertise, and the implications are not included in the CPS formula.

Conclusion

There can be little doubt that aerial survey companies in the United States often fly too high for the specified accuracies, and the reason has been the highly competitive nature of the marketplace. This tendency has been encouraged by some government agencies who have been offered misleading advice by some commercial companies and by some instrument manufacturers who have claimed very high C-factors for their instruments.

Unfortunately, this tendency has resulted in some poor work being done, and many users of contour maps have lost faith in photogrammetry and so do not use it to its full potential. This state of affairs has been encouraged by the lack of field checking of mapping by clients. The implementation of a field checking system would have two benefits. The immediate benefit would be an accurate project due to the enforcement of the technical specifications; the longer term benefit would be a greater knowledge of project planning resulting from the results of the checking. Eventually there would be a greater acceptance of photogrammetric mapping for engineering design rather than its relegation to a role for initial planning. When field checking is done, it should be implemented in areas remote from the ground control points, and not in their immediate vicinity.

Commercial companies need to return to a more conservative approach to mapping accuracy, an approach where they have a margin for error, an approach where they can regain better credibility with their clients.

Government agencies could help by writing specifications based on some of the principles outlined here, but some level of self-policing within the private mapping community is also needed.

The CPS formula could be used by Contracting Officers' Representatives to assess the qualities of technical proposals which are often submitted by aerial survey contractors under the "Request for Proposal" type of procurement, which is fairly common in the United States.

The author once again wishes to emphasize the simplicity of the CPS formula, acknowledging its lack of theoretical foundation. A specific investigation by some independent research organization supported by practicing photogrammetrists would be most worthwhile to the aerial survey community.

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