Photogrammetric Map Accuracy

L. L. FUNK, Photogrammetric Engineer, California Division of Highways

Highway engineers using large-scale photogrammetric mapping for detailed design work require certain standards of horizontal and vertical accuracy for both the control surveys and the mapping. Vertical accuracy of mapping, as represented by contours, is the most difficult to attain and is generally the greatest source of trouble.

The California Division of Highways is making a statistical analysis of the vertical accuracy of photogrammetric mapping obtained under contract. The information is derived from a comparison of field elevations with elevations interpolated from contour maps. Field elevations generally consist of a profile of the final line as staked on the ground. The data as developed for each project include the arithmetic mean, standard deviation, calculated C-factor, and a comparison of the error frequency distribution with the theoretical error or probability curve. The C-factor is calcuated from the theoretical contour interval which would comply with the 90 percent specification requirement as determined from the error frequency distribution.

This study is not a test of a particular type of plotting equipment under carefully controlled or ideal conditions. It is, rather, an evaluation by the map user of the accuracy of photogrammetric mapping obtained by contract under normal working conditions. For this reason the effect of the allowable horizontal shift is discussed but is not included in the results.

Analyses have been completed on several projects mapped for 2-ft contours at flying heights of from 1,500 to 2,100 ft. Results in most cases indicate close agreement between the error frequency distribution and the theoretical curve. The calculated standard deviations agree remarkably well with the 90 percent spread, indicating the validity of the statistical approach. In two cases values of the arithmetic mean indicate systematic errors in the mapping. The results show that C-factors of 1,000 or more should be used with extreme caution in planning for 2-ft contour mapping, particularly if the horizontal shift is not included in the specifications.

Study of the data has led to investigation of the more common types of map errors, their distribution, probable cause, and methods of prevention. The checking and investigation of photorammetric mapping by means of a Kelsh plotter have also developed data on spot height accuracy attainable under controlled conditions with this instrument.

THE PAST few years have seen widespread acceptance of photogrammetry as a means of obtaining large-scale topographic maps for the design of major highway facilities. To be suitable for this purpose the maps must have sufficient horizontal and vertical accuracy that the facility, designed from the terrain as depicted by the maps, will fit the actual terrain when staked in the field.

The highway engineer planning to use such maps for computation of earthwork quantities is particularly interested in their vertical accuracy as represented by the contours. This type of accuracy is the most difficult to attain and is generally the greatest source of trouble. Attempts to obtain information concerning the probable accuracy of large-scale mapping, reveal the almost total lack of data on the subject.

Many engineers believe that photogrammetric mapping should be considered as a professional service with methods and equipment limitations left to the mapping contractor. The question of negotiation versus competitive bidding is outside the scope of this paper. The fact remains that a large volume of photogrammetric mapping for highway design is being obtained by competitive bids. The matter of price is also the controlling factor in many negotiated contracts.

At the present time photogrammetric mapping is a rapidly expanding, highly competitive field. There is a shortage of trained personnel particularly at the higher levels. New firms are entering the field, many of them without realizing the technical knowledge and experience required. These conditions frequently result in equipment ratios being stretched to the limit and field control reduced to a minimum in order to obtain work at a reasonable profit.

Many firms actually know very little about the accuracy of the maps they are producing. Acceptance by the contracting agency is frequently assumed to be proof of the specified accuracy. It is questionable whether satisfactory mapping can be assured under such circumstances without specifications which limit equipment ratios and require a definite amount of photo control. Development of factual data is needed so that highway engineers will know more about map accuracies actually being obtained and the specifications required to assure the desired accuracy.

The California Division of Highways is making a statistical analysis of the vertical accuracy of photogrammetric mapping obtained under contract. The information is derived from a comparison of field elevations with elevations interpolated from contour maps. The data as developed for each project include the arithmetic mean, standard deviation, calculated C-factor, and a comparison of the frequency distribution with the theoretical error or probability curve. The calculated C-factor is derived from the theoretical contour interval which would comply with the 90 percent specification requirement as determined from the error frequency distribution.

Data developed at the time the maps are checked for acceptance are generally insufficient to form an adequate statistical base. For this reason the analysis is generally not made until field elevations from a profile or slope stakes of the final line are available. The study is intended as an evaluation of the accuracy of photogrammetric mapping obtained by contract under normal working conditions. It is not a test of the absolute accuracy limits of a particular type of stereoplotter or photogrammetric system under carefully controlled conditions.

OBJECTIVES OF THE STUDY

Some of the broader aspects of the study include: adequacy of the present 90 percent within one-half contour interval specification; need for the horizontal displacement in determining contour accuracy; practical C-factor limitations for planning large-scale mapping for compilation in a Kelsh plotter; and the causes of map errors and possible methods of prevention.

Are Present Mapping Specifications Satisfactory?

National Map Accuracy Standards, which are the basis for most photogrammetric mapping specifications, require that: "Vertical accuracy, as applied to contour maps on all publication scales, shall be such that not more than 10 percent 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 maps at scales of larger than 1:20,000 this permissible error is 0.033 in. It is generally assumed that error frequency distribution of photogrammetric mapping, within the limits of plus and minus one-half contour interval, follows the theoretical error or probability curve (1).

It is contended, however, by some writers (2, 3) that standard deviation, which is a measure of dispersion of the entire range of errors, would be a better method of specifying map accuracy. Information concerning the actual distribution of errors in mapping obtained under present specifications is needed to determine their adequacy.

Effect of the Horizontal Shift

The allowable horizontal shift of contours has the effect of lowering vertical accuracy as the steepness of slope increases. It is troublesome to apply, and the engineer using the map wants the same accuracy throughout. A recent memorandum of the U.S. Bureau of Public Roads states that the horizontal shift tolerance is not applicable to contours on large-scale topographic maps and should be omitted from the specifications. It is desirable to determine the effects on the accuracy and cost of photogrammetric mapping before eliminating the horizontal shift from the specifications.

Practical C-Factors for Large-Scale Mapping

The accuracy of photogrammetric mapping is closely related to the flying height. The relationship is frequently expressed by the term "C-factor" which is defined as the flying height divided by the contour interval. It should be understood that the C-factor is dependent not only on the type of stereoplotter but on many variables (5). However, with other conditions being equal, it is customary to consider that each type of stereoplotter has a certain C-factor. As over 90 percent of the design mapping for the California Division of Highways is compiled on a Kelsh plotter with a 6-in. focal length, it is the only instrument considered in this study.

There is little if any data available as to the C-factor attainable for contour intervals as small as 2 ft compiled in a Kelsh plotter under actual working conditions. Altenhofen (6) has stated that Geological Survey experience in small-scale mapping has indicated a C-factor range of from 850 to 1,000 for the Kelsh plotter. Struck (7) gives a value of 1,100 to be decreased 30 percent under poor conditions and increased 30 percent under favorable conditions. Based on tests of spot heights in a single model, Trorey (8) estimates a range of 1,000 to 1,500. Pennington (9) states that tests indicate a value of approximately 1,200. Pryor (10) has listed 1,200 as the value customarily employed.

It is believed that all of the above writers except Pryor had contour intervals of 5 ft or greater in mind. Harman (5) has stated that: "The C-factor of any plotting system will increase when the flight height decreases." This view is shared by most photogrammetrists. There is some reason to doubt that this opinion takes into account the effect that minor irregularities in ground surface and light growths of grass or weeds will have on the accuracy of 2-ft contours as compared to their effect on 20-, 10-, or even 5-ft intervals.

Present mapping specifications of the California Division of Highways do not directly specify a C-factor. However, the specified plotting ratio of 1 to 5 for a 6-in. Kelsh plotter has the effect of requiring a C-factor of 750 for 2-ft contours mapped at 1 in. = 50 ft. Many photogrammetric mapping organizations are optimistic about their ability to produce accurate maps at C-factors of 1,200 and even 1,500. The Kelsh Instrument Co. now makes a plotter with a ratio of 1 to 7 from photo scale to map scale. This instrument would allow a flying height of 2,100 ft for 1 in. = 50 ft mapping, with a resulting C-factor of 1,050 for 2-ft contours.

If greater flying heights can be used without sacrifice of accuracy it would result in fewer photographs with more width, less photo control, fewer models to compile and a lower resultant cost. Data on this subject are needed so that highway engineers will have a sound basis for planning large-scale mapping projects.

Types and Causes of Map Errors

Inaccuracies in any system of measurement can be classed as either random errors, systematic errors, or blunders. Random errors can be expected to follow error theory as to size, frequency and distribution. In photogrammetric mapping random errors,

TABLE 1

SUMMARY OF ANALYSIS OF TWELVE MAPPING PROJECTS

Figure	ASC NO.	Points Tested	Flying Height (ft)	Within ½ C.I (%)	Arithmetic Mean (ft)	Standard Deviation (ft)	Calculated C-Factor	90% Error Range (ft)	3.3 Std. Deviations
1	119 Loc. II	433	1,500	92.6	-0.09	0.58	800	1.9	1.9
2	90 Loc. III	472	1,500	88.8	-0.09	0.66	700	2.2	2.2
3	90 Loc. I	605	1,500	80.5	+0.62	0.65	600	2.0	2.1
4	150	224	1,500	88.1	-0.10	0.72	700	2.3	2.4
5	174	339	1,800	86.5	-0.40	0.62	800	1.9	2.0
6	169	185	2,100	76.5	+0.01	0.98	700	3.1	3.2
7	127	326	2,100	83.7	+0.19	0.79	800	2.4	2.6
8	159	528	1,500	83.0	-0.07	0.83	600	2.5	2.7
9	165	760	1,500	79.0	+0.09	0.98	500	2.9	3.2
10	146	356	1,500	91.5	-0.21	0.60	800	1.9	2.0
11	108	409	1,500	94.0	+0.13	0.52	950	1.6	1.7
12	172	484	1,500	91.5	0.00	0.61	750	1.9	2.0

together with small systematic errors which may be impossible to eliminate, determine the basic accuracy of the system. It follows that most of the larger and more troublesome inaccuracies are due to either large systematic errors or blunders.

Fortunately these two types of inaccuracies can generally be isolated and can frequently be traced to assignable causes. The investigation of types, distribution and causes of major inaccuracies is an important phase of this study.

METHODS AND RESULTS

Figures 1 to 12 illustrate the results of an analysis of twelve projects which were mapped at a scale of 1 in. = 50 ft with 2-ft contours A summary of the data is shown in Table 1. These projects represent the work of eight different mapping firms. Although no final conclusions can be drawn at this stage of the study, it is hoped that presentation of these data will stimulate thought and discussion on the subject of map accuracy.

Adequacy of Present Specifications

To test the conformity of the mapping to error theory the frequency distribution of errors has been compiled for each project. The standard deviation has been calculated on the basis of deviations from the arithmetic mean or average error. The horizontal shift, permitted by California specifications, has not been allowed in determining the size of errors. Points in areas of dashed contours where the ground was obscured by cover have not been used.

Frequency distributions have been plotted in cumulative form on arithmetic probability paper. They are plotted so that for any minus error the percent shows in error "more than" and for any plus error it shows "equal to or less than." For example, Figure 1 shows 6.7 percent of the points tested were in error by more than -1.0 ft and that 99.3 percent were in error by +1.0 ft or less. The difference between the two, or 92.6 percent is the percentage in error by not more than ±1.0 ft. The straight lines in Figures 1 to 12 represent the normal law of error distribution. This theoretical probability curve is plotted with 5 percent at -1.0 ft and 95 percent at +1.0 ft or, in other words, the 90 percent tolerance limits of mapping specifications. Various points on the theoretical curve are shown in detail in Figure 13.

Conformity of the mapping to error theory can be judged in several ways, one of which is by visual inspection of the curves. Another method is from the values of the arithmetic mean and the standard deviation. Statistically the value of the arithmetic mean should fall within certain limits dependent on the size of the sample (4). The range of sample sizes for the projects analyzed is from 185 points tested on the mapping shown in Figure 6 to 760 in Figure 9. For such sample sizes the arithmetic mean should be within the limits of ±0.1 ft. Seven of the twelve projects have an arithmetic mean within this range indicating the statistical validity of the approach. Where values are greater than ±0.1 ft the presence of blunders or systematic errors should be suspected. With the theoretical curve fixed by the 90 percent within one-half con-

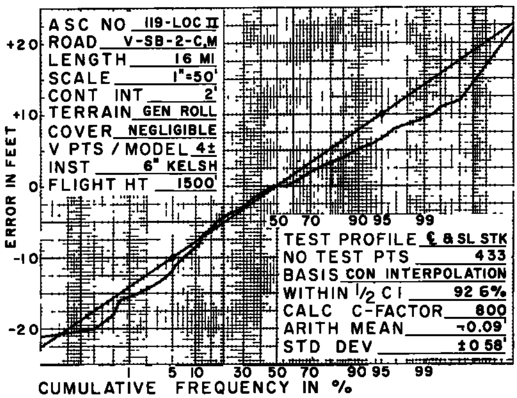

Figure 1.

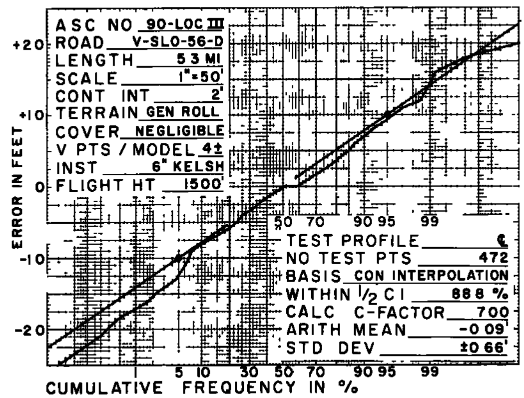

Figure 2.

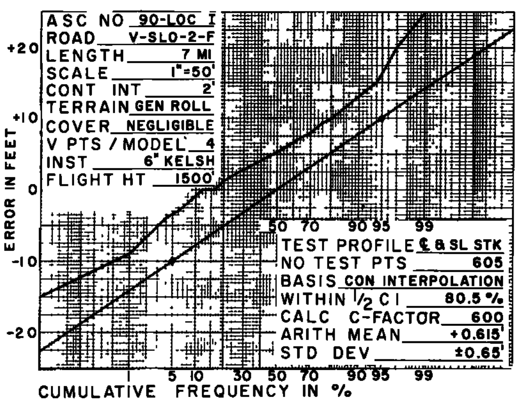

Figure 3.

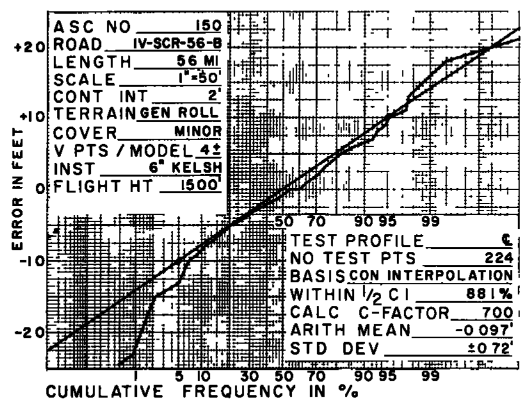

Figure 4.

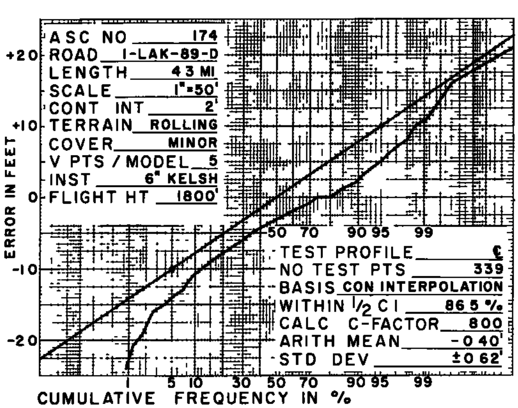

Figure 5.

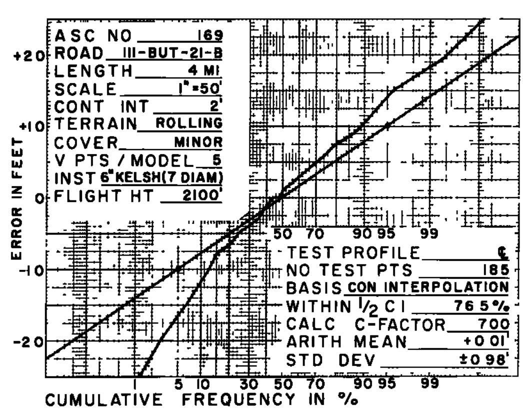

Figure 6.

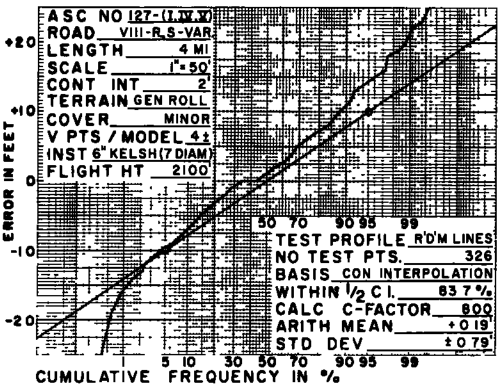

Figure 7.

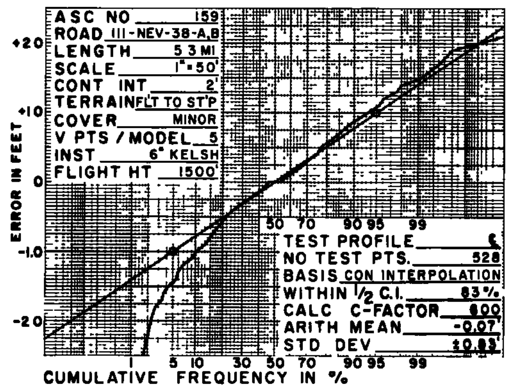

Figure 8.

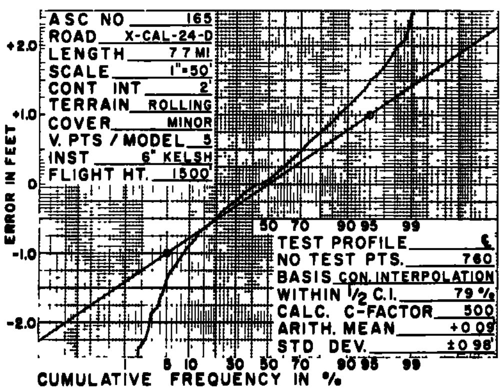

Figure 9.

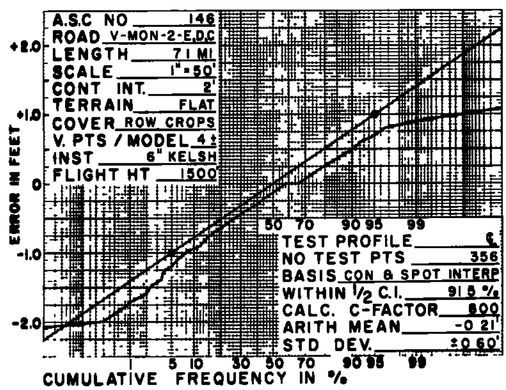

Figure 10.

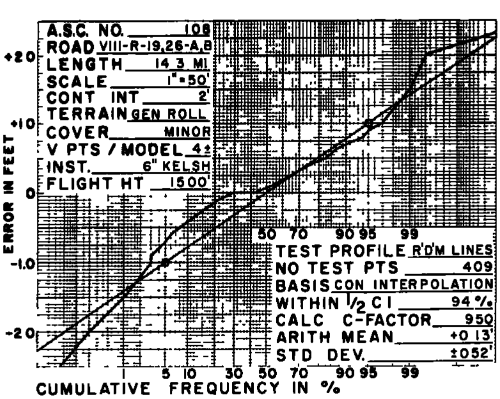

Figure 11.

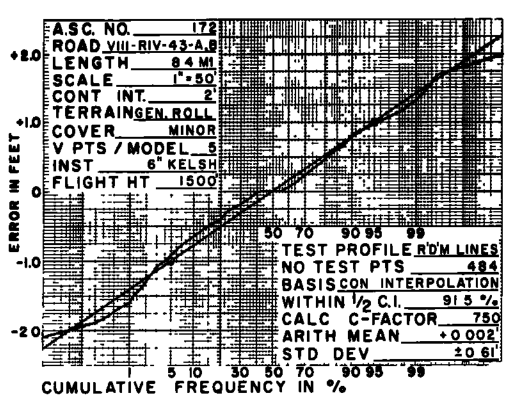

Figure 12.

tour specification, the value of the standard deviation should be 0.3 contour interval. Thus for 2-ft contour mapping it should be 0.6 ft.

Most of the projects show fairly good general conformity. There is a tendency (Figs. 6, 8, and 9) to deviate in the lower portions of the curve due to a disproportionate number of errors in excess of -1.0 ft. This is also shown by the relatively high values of the standard deviations. The mapping shown in Figure 3 follows error theory very closely but on a parallel curve due to a systematic error. The curves are approximately 0.60 ft apart measured vertically, which is the approximate amount of the arithmetic mean. The slope of the frequency distribution curve in Figure 6 is steeper than the theoretical curve for a 2-ft contour interval. It actually approximates the theoretical curve for 3-ft contour interval mapping very closely. This is also indicated by the high value of the standard deviation.

Compilation of the mapping shown in Figures 6 and 7 was done with a Kelsh plotter modified to enlarge seven diameters from photo scale to plotting scale. The flying height was 2,100 ft as compared to 1,500 ft on most of the other projects. California specifications no longer permit use of a plotting ratio of over 1 to 5 for Kelsh plotters.

The poorest conformity to error theory (Fig. 9) is due to the large number of errors in excess of ±2.0 ft. This is best shown by a comparison of the last two columns of Table 1. From error theory the value of the 90 percent point on the curve is 1.65 standard deviations (4). Therefore the 90 percent error range should theoretically equal 3.3 standard deviations. The actual error ranges and the values of 3.3 standard deviations are shown in the last two columns of Table 1. For example, on the frequency distribution curve of Figure 9, the 5 percent point is at -1.4 ft and the 95 percent point is at +1.5 ft or a 90 percent error range of 2.9 ft. This is a variation of 0.3 ft from the value of 3.3 standard deviations. All other projects show a variation of 0.2 ft or less between these values.

Analysis of these twelve projects shows general conformity to error theory and indicates that present specifications are adequate from the practical standpoint. There is, nevertheless, strong reason to question their basic soundness. To illustrate this statement a possible, although highly improbable, frequency distribution is shown on the lower portion of Figure 13. If a map with an error distribution such as this were delivered to a highway engineer he would be forced to accept it under present mapping specifications even though many would consider it entirely inadequate for the computation of earthwork quantities. Although such an extreme case as this might never occur, it cannot be considered good engineering practice to use a specification which could result in a product as unsatisfactory as this.

The standard deviation, by itself, would be equally unsatisfactory as a specification for map accuracy if the statistically correct method of computing it on the basis of deviations from the arithmetic mean were followed. This is illustrated by the values of the standard deviation for the mapping shown in Figure 3 and for the possible error distribution shown in Figure 13. The highway engineer is in a different position from most map users in that he is particularly concerned with the balance between plus and minus errors. It is probable that the most satisfactory specifications from this standpoint would embody both the arithmetic mean and the standard deviation.

Effect of the Horizontal Shift

From the fifth column of Table 1 it is apparent that only four of the twelve projects analyzed complied with the 90 percent within one-half contour interval tolerance. However, the percentages listed do not take into account the horizontal shift which is permissible under California specifications. To determine its effect, the allowable shift was applied to all points in error by more than ±1.0 ft on five of the projects. The effect on the one-half contour interval percentages was as follows:

Figure 5 increased from 86.5 to 93.4 percent
Figure 6 increased from 76.5 to 83.0 percent
Figure 7 increased from 83.7 to 87.7 percent
Figure 8 increased from 83.0 to 90.7 percent
Figure 9 increased from 79.0 to 87.3 percent

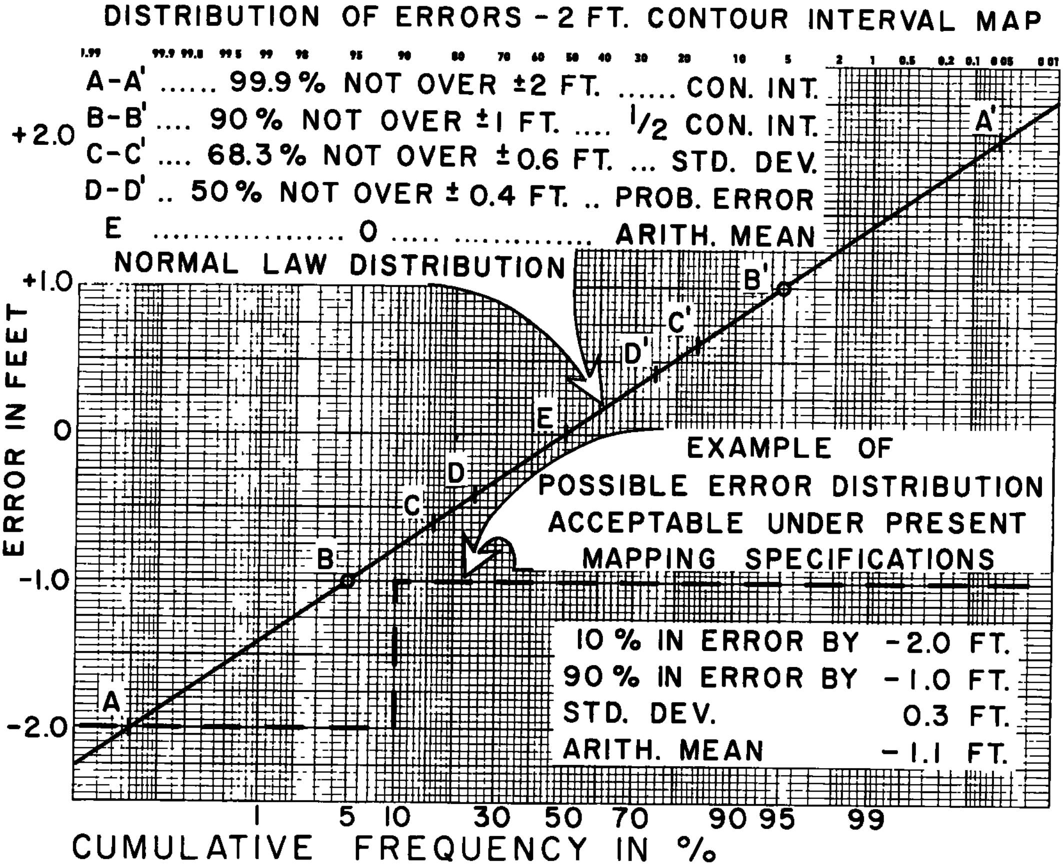

Figure 13.

From this comparison it is apparent that the effect of the horizontal shift in percentage of points within one-half contour interval ranged from 4 percent to 8.3 percent. As might be expected, the amounts varied with the steepness of the terrain. Thus the horizontal shift brought two of the projects within specification limits and would undoubtedly have done the same for the projects shown in Figures 2 and 4. With the effect of the horizontal shift taken into consideration, eight of the twelve projects thus complied with the 90 percent requirement and two more were over 87 percent which might be considered a tolerable variation.

The fact remains however, that many highway engineers want greater accuracy than is afforded by specifications which permit the horizontal shift. The principal causes of map errors in steep terrain as compared to those on flatter slopes are inaccuracies in drafting and generalization of contours by compilers and draftsmen. It is probable that the desired accuracies can be attained by using greater care in compiling and drafting, provided realistic C-factors are used in flight planning.

C-Factor Study

As a means of determining the C-factors actually being attained under working conditions the indicated C-factor has been calculated for each project. The method used is the same as that of the U.S. Geological Survey in their unpublished C-factor studies for small scale mapping. It consists of determining, from the frequency distribution curve, the contour interval which would have resulted in compliance with the 90 percent within one-half contour interval specification. The flying height is divided by this

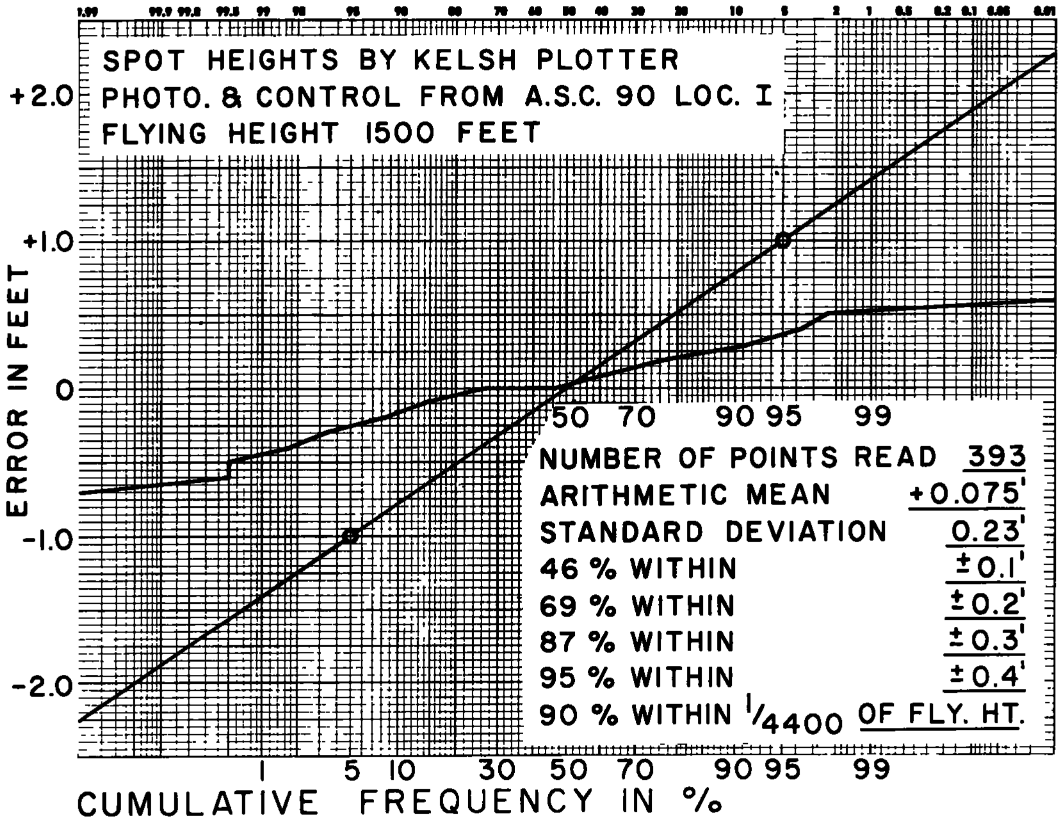

Figure 14.

contour interval to determine the calculated C-factor. The horizontal shift has not been applied to the individual points to determine errors for this study.

The resulting calculated C-factors as listed in Table 1 are considerably lower than those frequently used. As previously mentioned there is little if any published data to support the use of C-factors of 1,200 or 1,500 for mapping with a 2-ft contour interval to be compiled in a Kelsh plotter. Although values such as these can undoubtedly be attained in controlled tests or under ideal conditions, they do not provide any margin for systematic errors or blunders. Sound, conservative practice would indicate use of an operating cushion or factor of safety of at least 1.5 resulting in working C-factors of from 800 to 1,000. The data developed in this study confirm early experience of the California Division of Highways in contracting for large-scale mapping with no limitation on flying height.

Causes and Prevention of Map Errors

In discussing this phase of the study systematic errors will be considered first. Excellent examples of this type of errors are shown in Figures 3 and 5. The systematic error of approximately 0.6 ft on the project illustrated in Figure 3 caused an imbalance of approximately 90,000 cu yd in earthwork quantities. The errors were not disclosed in field checking the maps prior to acceptance, but were found at the time of running the centerline profile immediately prior to construction. The necessary changes in grade line made during construction were both troublesome and costly.

In studying the pattern of errors by comparing centerline and slope stake elevations with map elevations it was found that over one-half of the errors occurred in a 2-mi section. The pattern in individual stereomodels disclosed that errors were largest near the model centers. The general range was from + 1.0 ft to +1.5 ft near the model centers tapering down to +0.2 ft at the photo centers. Several models were set up in the Division of Highways Kelsh plotter and the elevations of 393 points, on which field elevations were available, were read. Diapositives furnished by the mapping contractor were used. Models were set up on the contractor's control without recourse to the additional field data available.

The results of the Kelsh plotter spot height readings as shown in Figure 14 were in close agreement with the field elevations with 95 percent being with ±0.4 ft. This indicated that both the photography and field control were satisfactory. In view of these facts and the intermittent pattern of the systematic errors it was concluded that they were due to malfunctioning of the distortion correction devices in the plotter at the time of compilation.

Present specifications of the California Division of Highways for mapping to be used in highway design require a minimum of three horizontal and five vertical field control points in each stereomodel, with the fifth vertical point located near the model center. Had this specification been in effect at the time the mapping in Figure 3 was undertaken the map errors would have been greatly reduced, if not entirely eliminated. The errors might have been found during field checking if it had been realized that model centers are areas of potential weakness in the mapping.

A less serious but more complex example of systematic errors, possibly combined with blunders, is shown in Figure 5. In this case the mapping complied with specifications after application of the horizontal shift. Three models were set up in the Division of Highways plotter. Spot height readings in these models failed to show consistent agreement with the field profile. Further investigation indicated that several causes contributed to the map errors. The flying height of 1,800 ft above average terrain required plotting ratios of over 1 to 6 in the lower areas. This resulted in reduced illumination and sharpness of focus and in magnification of any calibration errors. The mapping contractor also reported difficulties due to warping of the glass table top during compilation. A third source of possible error was the use of diapositives from distortion-free photography with the emulsion side up, even though the cams were disconnected. Future specifications will require compilation with the emulsion side down when distortion-free photography is used. In this case the centerline was staked in the field and a centerline profile run as soon as the projection was completed and the line calculated. The earthwork quantities can be readily corrected to a close approximation of their true value by raising or lowering the ground line of each cross-section to agree with the field centerline elevation.

In the analysis of blunders the control chart method (4) based on the number of defects per sample was used. Points in error by more than one-half contour interval were considered defects. Individual stereomodels were considered as samples. There is some doubt as to the statistical validity of this approach due to the small number of observations per sample. It is possible that the same results could be achieved by visual inspection. However, the grouping of defects by models is a sound procedure that will afford a clue to blunders in photo-control, photography, and compilation.

The control chart method was applied to errors of over ±1.0 ft on five projects. The following tabulation shows the percentage of total errors of over ± 1.0 ft which were outside the control chart limits and the percentage of the total number of models in which they occurred.

Figure 1:	81 percent of errors occurred in 10 percent of models.
Figure 5:	36 percent of errors occurred in 12 percent of models.
Figure 6:	21 percent of errors occurred in 6 percent of models.
Figure 8:	36 percent of errors occurred in 13 percent of models.
Figure 9:	40 percent of errors occurred in 17 percent of models.
Total:	40 percent of errors occurred in 13 percent of models.

The fact that on these five projects 40 percent of the errors outside the 90 percent specification tolerance occurred in only 13 percent of the models is strong evidence

TABLE 2

COMPARISON OF EARTHWORK QUANTITIES

Project	Contour Interval	Year Mapped	Total Exc. Quantity (Cu Yd)	Difference Between Field Survey and Map Quantities. Excavation (%)	Embankment (%)
I-Hum-1-G	5	1954	1,100,000	3[a]	3[a]
I-Men-15-A	5	1953	1,000,000	2[a]	c
II-Sha-3-C	5	1948	733,500	0.3	c
II-Sha-3-D,C	5	1948	1,750,000	0.8	4 4
III-But-21-B	2	1956	381,400	3.5	0.8
III-But-21-B	5	1954	1,849,200	1.1	1 4
IV-Mrn-1-C,D	5	1951	1,216,500	2.0	1.7
V-SLO-2-A	5	1951	764,400	0.1[b]	c
V-SB-2-J	2	1951	309,500	0.8	c
V-SLO-2-D,C	2	1952	1,013,000	1.9	0.03
V-SLO-2-F	2	1952	538,200	0.9	c
V-SB-2-M,L	2	1953	1,019,000	1.1	c
V-SLO-2-F	2	1955	784,000	2.9	7.6
V-SB-2-F	2	1953	349,200	5.4	3.8
V-SLO-2-PsRs-A	2	1951	935,600	0.9	3.7
V-SB-2-Q,G,F	2	1953	1,733,100	2.3	3.1
VI-Ker-140-D	5	1954	350,000	2.5	c
VII-LA-4-H,I,J	5	1947	1,150,000	1	c
VII-LA-4-LA,F	5	1947		1.5	c

[a] Contour map cross-sections were adjusted to conform to field centerline profile.
[b] Five-ft contours were supplemented by field profiles in level areas.
[c] Not available.

that blunders have a serious effect on the inherent accuracy of photogrammetric mapping. If blunders could be eliminated all measures of map accuracy including the calculated C-factors would be greatly improved.

The mapping shown in Figure 1 is an outstanding example of this. If the one poor model were disregarded the remainder of the mapping on this project would have had 98.2 percent of the points tested within one-half contour interval and a calculated C-factor of 1,100. Investigation of this model showed that it was difficult to get a satisfactory scale solution in the plotter due to sparsity of horizontal control. This was undoubtedly the major cause of error. Present specifications requiring three horizontal control points per model reduce the likelihood of this type of errors.

Two of the poorer models from the mapping shown in Figure 9 were also investigated. They contained 20 points in error by more than ±1.0 ft. Using the contractor's photography and control, the plotter operator read 87 percent of the points within ±0.6 ft of their field elevation and all but one within ±1.0 ft. This eliminated photography and control as a cause of the more serious errors and indicated that they occurred during compilation. In one of the models the errors appeared to be due to poor interpretation, by the compiler, of the height of a 1.5 ft to 3.0 ft growth of weeds or grass.

Checking Photogrammetric Mapping

The frequency of blunders as a major cause of map errors and the distribution of errors by models have an important bearing on map checking. They indicate that effective checking must include tests in every model. Unguided field checking is frequently a guessing game as to how much or what portion of the map to check. Experimental work by the California Division of Highways during the past few years has indicated that checking with a stereoplotter might be the most satisfactory solution. A Kelsh plotter was obtained in September 1956, and has been used for this purpose with results that have far exceeded expectations. It has proven to be the only feasible method of checking every model with a minimum expenditure of time and manpower.

By using the mapping contractor's diapositives, photo control and map manuscripts, an experienced operator can quickly determine how well the control fits and whether or not a satisfactory model setup can be made. This makes it possible to evaluate thoroughly the quality of the mapping. In many cases it is possible to analyze the underlying causes of substandard mapping such as misidentification, improper spacing or incorrect values of photo control, poor photography, poor plotter calibration or unsatisfactory compilation. This type of analysis and evaluation makes it possible to work with the mapping contractors to improve their techniques and will result in better quality of mapping on future projects.

In several instances plotter checking has disclosed serious errors which the contractor has corrected without the necessity for a field check. In other cases it has indicated areas of possible weakness for verification by field checking.

Special mention has been made of the investigation of errors in the mapping shown by Figures 1, 3, 5, and 9. Had a stereoplotter been available for map checking at the time these projects were completed the more serious errors would have been disclosed at once and the map sheets returned to the contractors for correction. The costs due to the difficulties encountered during construction, by reason of map errors, on the project illustrated by Figure 3 were alone more than enough to pay for a Kelsh plotter and a year's operation.

Earthwork Quantity Comparisons

No discussion of map accuracy would be complete without mention of earthwork quantity comparisons, as they are of particular interest to highway engineers. It is obvious that a comparison by percent of error in quantities, while of interest, is not a good test of actual map accuracy. Consider, for example, the frequency distribution of errors shown in the lower portion of Figure 13. If the arithmetic mean of -1.1 ft were applied to a 100-ft roadbed with 2:1 slopes and an average cut of 2.0 ft the resulting error would be 23,000± cu yd per mile, or approximately 56 percent of the quantity. If, however, the average cut was 10 ft, the error would be 30,000± cu yd per mile, but would only be approximately 13 percent of the quantity.

Table 2 shows quantities from photogrammetric mapping, as compared to quantities from field cross-sections. Only two of these projects are among the twelve analyzed for map accuracy. The mapping shown in Figure 3 is for the project shown on the 13th line of Table 2. The mapping in Figure 6 covered a portion of the project shown in the fifth line of Table 2. The total excavation quantity for the portion of the project in Figure 6 was 300,000 cu yd. The excavation differed by 9,000 cu yd, or 3 percent. Embankment quantities differed by only 90 cu yd. This close agreement, even though the mapping was relatively poor, was undoubtedly due to the low arithmetic mean of the errors.

Detailed breakdowns of quantity comparisons by individual cuts and fills were available for several of the projects listed. In most cases the discrepancies in individual cuts and fills were greater than for the entire project. This tends to confirm the evidence that a large proportion of the serious errors in photogrammetric mapping are due to blunders.

CONCLUSIONS

The most important phases of map accuracy discussed in this report are the C-factor study and the investigation of the types, distribution, and causes of map errors. Factual data concerning accuracies actually attained in photogrammetric mapping are needed to develop realistic C-factors for use in planning future mapping projects. Investigation of map errors should lead to methods of preventing them and result in increased map accuracy. Specifications defining methods to be used may be necessary to obtain the desired accuracy due to present conditions in the photogrammetric mapping industry.

As projects designed from photogrammetric mapping are staked for construction they afford a convenient, inexpensive source of information concerning map accuracy. Highway engineers should take the lead in the development of data on map accuracy as a means of increasing the usefulness of photogrammetric mapping.

ACKNOWLEDGMENTS

The writer wishes to acknowledge the contributions to this study made by Rex H. Fulton, Senior Highway Engineer and George P. Katibah, Supervising Photogrammetrist, of the California Division of Highways. Over a period of several years Mr. Fulton has been responsible for many of the improvements in California mapping specifications as well as for the use of the stereoplotter in map checking. Mr. Katibah has supplied the technical knowledge and supervision necessary for map accuracy investigation and plotter checking.

REFERENCES

1. Sharp, John V., "Photogrammetric Engineering." p. 358 (June 1951).
2. Thompson, Morris M., and Davey, C. H., "Surveying and Mapping." p. 40 (January-March 1953).
3. Thompson, Morris M., "Surveying and Mapping." p. 164 (April-June 1956).
4. A.S.T.M. Manual on Quality Control of Materials, Special Publication 15-C
5. Harman, William E., Jr., Manual of Photogrammetry, p. 262
6. Altenhofen, Robert E., "Photogrammetric Engineering." p. 370 (June 1951)
7. Struck, Luis, "Photogrammetric Engineering." p. 84 (March 1952).
8. Trorey, Lyle G., "Photogrammetric Engineering." p. 831 (December 1951).
9. Pennington, John T., Manual of Photogrammetry, p. 639.
10. Pryor, William T., Highway Research Board Bulletin 157, p. 23.

Appendix

The basic information necessary for an analysis of map accuracy consists of field elevations and photogrammetric elevations of a number of points. For a valid analysis the measurements should be made in a uniform manner and under similar conditions. The analysis should include as many points as are available and should represent all portions of the mapping.

Minimum criteria for the selection of points require that the field elevations be determined by spirit level and that the ground is not completely obscured by brush and trees as would be evidenced by dashed contours.

Three types of comparative measurements are recognized and are generally tabulated and presented separately:

1. Points with field elevations available are plotted on the map and the photogrammetric elevations interpolated from the contours. The occasional points which fall directly on a contour are not segregated. This type of measurement is presented in Figures 1 to 9, inclusive, and Figures 11 and 12.
2. Points whose field elevations can be compared directly with photogrammetric spot height readings of the same point. The data in Figure 14 are based on this type of measurement.
3. Points with field elevations available are plotted on the map and the photogrammetric elevations interpolated from spot heights such as cross-sections. A portion of the data in Figure 10 was obtained in this manner. This portion was tabulated separately and compared with other data obtained by the first type of measurement. The two tabulations were in such close agreement that they were combined for presentation.

Data processing equipment is utilized in making the analysis. Information furnished the tabulating section for processing includes the identification, field elevation, and photogrammetric elevation of each point. The identification consists of the centerline station and, in the case of cross-sections, the distance right or left. Field elevations are generally supplied by the field notebook with the points to be used circled or checked.

The first step in data processing is to keypunch the identification, field elevation, and photogrammetric elevation of each point on a single card. In some cases where

TABLE 3

1 Error in feet	2 No. of Points	3 Cumulative Total	4 Cumulative (%)
+2.0	1	472	100
1.8	1	471	99.8
1.7	2	470	99.6
1.6	1	468	99.2
1.4	1	467	98.9
1.3	1	466	98.7
1.2	7	465	98.5
1.1	6	458	97.0
+1.0	7	452	95.8
0.9	11	445	94.3
0.8	10	434	92
0.7	11	424	90
0.6	13	413	87
0.5	17	400	85
0.4	20	383	81
0.3	21	363	77
0.2	30	342	72
+0.1	37	312	66
0.0	33	275	58
0.0		242	51
-0.1	33	209	44
0.2	35	174	37
0.3	24	150	32
0.4	27	123	26
0.5	15	108	23
0.6	20	88	19
0.7	22	66	14
0.8	19	47	10
0.9	10	37	7.8
-1.0	4	33	7.0
1.1	4	29	6.1
1.2	5	24	5.1
1.3	2	22	4.7
1.4	7	15	3.2
1.5	4	11	2.3
1.6	3	8	1.7
1.7	3	5	1.1
1.8	2	3	0.6
1.9	1	2	0.4
2.1	1	1	0.2
-2.6	1		0.0

5	6	7	8	9	10	11
Error in feet	No of Points		Algebraic Σ [(6)+(7)]x(5)		Numerical Σ (6)+(7)	$n(e)^2$ $(10)x(5)^2$
	+	-	+	-		
0.1	37	33	0.4		70	0.7
0.2	30	35		1.0	65	2.6
0.3	21	24		0.9	45	4.0
0.4	20	27		2.8	47	7.5
0.5	17	15	1.0		32	8.0
0.6	13	20		4.2	33	11.9
0.7	11	22		7.7	33	16.2
0.8	10	19		7.2	29	18.6
0.9	11	10	0.9		21	17.0
1.0	7	4	3.0		11	11.0
1.1	6	4	2.2		10	12.1
1.2	7	5	2.4		12	17.3
1.3	1	2		1.3	3	5.1
1.4	1	7		8.4	8	15.7
1.5		4		6.0	4	9.0
1.6	1	3		3.2	4	10.2
1.7	2	3		1.7	5	14.5
1.8	1	2		1.8	3	9.7
1.9		1		1.9	1	3.6
2.0	1		2.0		1	4.0
2.1		1		2.1	1	4.4
2.6		1		2.6	1	6.8
Total +119 -52.8					$\Sigma e^2 = 209.9$	

Arithmetic Mean $= \frac{+11.9 - 52.8}{472} = \frac{-40.9}{472} = -0.09$ ft

Std. Dev. $= \sqrt{\frac{209.9}{472} - (0.09)^2} = \sqrt{0.445 - (0.09)^2}$

$= \sqrt{0.437} = 0.66$ ft

Calc. C-factor

88.8% = ±1.0 ft
90.9% = ±1.1 ft
90.0% = ±1.06 ft

$\frac{1500}{2 \times 1.06} = 708$ Say 700

either field or photogrammetric elevations have been previously used for earthwork computations they are gang punched into the card. The elevation difference, computed on IBM Machine Type 604, is punched into each card with a credit overpunch to indicate the direction of error. If the photogrammetric elevation is greater the error is considered plus, and if less, minus.

Two tabulations are produced by the data processing equipment:

1. A frequency distribution of calculated differences between field and photogrammetric elevations. The differences are expressed to the nearest 0.1 ft (for 2-ft contour mapping) and plus and minus differences are tabulated separately in ascending order. A sub-total of the number of points is furnished for each 0.1-ft group.
2. A list, in order by station, of all points having a difference of 1.0 ft or more.

Both tabulations show the identification, field elevation, photogrammetric elevation, and difference for each point.

The cards are sorted by elevation difference and the frequency distribution listing is produced on the IBM accounting machine Type 402. All points of the contour elevations whose difference is 1.0 ft. or more are interpolated. Points which have a difference of 3.0 ft or more are examined particular care for gross errors. If there appears to be any possibility of the field elevation being in error, the point is rejected. Also determine the effect of the horizontal shift on points whose difference is greater than 1.0 ft. and study the distribution of large errors by models.

The detailed method of making the analysis for the mapping is illustrated in Table 3. The error groups, to the nearest 0.1 ft, as shown by Table 1 are entered in Col. 1,

Table 3, in descending order from the largest plus error. The number of points in each error group is also taken from Table 1 and is entered in the Col. 2, Table 3. A cumulative total of these points is calculated and entered in Col. 3. It will be noted that the largest minus error of 2.6 ft is not entered opposite -2.6, but rather in the next error group, or opposite -2.1. This indicates that one point is in error by more than -2.1 ft. At the top of this column the total number of points, 472, is in error by +2.0 ft or less.

The cumulative total for each error group is converted to percent and entered in Col. 4. The cumulative percentages in Col. 4 provide an easy means of determining the percentage of the points within any desired error range. For example, 62 percent of the points (85 percent - 23 percent) are in error by not more than ±0.5 ft and 88.8 percent are in error by not more than ±1.0 ft. The percentages shown in Col. 4 are plotted on arithmetic probability paper to show the frequency distribution.

The error groups, without regard to sign, are entered in descending order in Col. 5. The number of plus points in each error group is entered in Col. 6 and the number of minus points in Col. 7. The algebraic sum of Col. 6 and 7 for each error group is multiplied by the size of the error and the result entered in either Col. 8 or Col. 9 depending on the sign. The algebraic sum of the totals of Col. 8 and 9 divided by the total number of points is the arithmetic mean or average error.

The numerical sum of Col. 6 and 7 for each error group is entered in Col. 10. Each numerical sum is then multiplied by the square of the error in feet and the result entered in Col. 11. If the total of Col. 11 were divided by the number of points and the square root extracted the result would be the standard deviation from zero error. However, to provide a true measure of dispersion the standard deviation must be calculated on the basis of deviations from the arithmetic mean. This can be readily done by dividing the total of Col. 11 by the number of points and subtracting the square of the arithmetic mean from the result. The square root of the resulting number gives the standard deviation from the arithmetic mean.

The calculated C-factor for contour mapping is determined by finding the error range in feet which includes a total of 90 percent of the points. Col. 3 is used to determine the 90 percent range. In this case ±1.0 ft includes 88.8 percent of the points (95.8 percent - 7.0 percent). Also ±1.1 ft includes 90.9 percent (97.0 percent - 6.1 percent). By interpolation ±1.06 ft includes 90 percent of the points. The flying height divided by twice this error range is the calculated C-factor. In other words it is the theoretical contour interval which would have complied with the 90 percent specification requirement. In the case of spot heights the fraction of the flying height which includes 90 percent of the points is calculated rather than the C-factor. This method of presentation is illustrated in Figure 14.

After a sufficient number of projects mapped at the same scale and under generally similar conditions have been analyzed, the calculated C-factors will be plotted as a cumulative frequency distribution. This will provide a means for predicting the probability of attaining any selected C-factor for mapping to be undertaken under comparable conditions. It should be a valuable guide in planning future mapping projects.

Statistical terminology and methods of computing the arithmetic mean and standard deviation have been based on A.S.T.M. Manual on Quality Control of Materials, Special Technical Publication 15-C. Particular reference is made to pages 13 and 14. Characteristics of the normal law distribution of errors are given in Table 1. The design of arithmetic probability paper is explained in the discussion of a paper by Allen Hazen published in Volume LXXVII of the Transactions of the American Society of Civil Engineers, December 1914, page 1666.