including the aerial photography, is on glass, and the Brock process is capable of work of great accuracy, approaching or exceeding the accuracy of the better automatic instruments."

We have a high regard for the Kelsh Plotter and find that it too fits into our needs in topographic mapping work. We have not explored the full range of flying height—contour interval ratios for various types of mapping areas with this instrument. We see the need for slight modifications, improvements and expansions of the basic Kelsh ideas, and we look with interest upon the instruments which have been displayed at this meeting.

Moderator Sharp: The next speaker is Mr. Robert E. Altenhofen.

ACCURACY AND ADAPTABILITY OF STEREOPLOTTING INSTRUMENTS AS REVEALED BY U. S. GEOLOGICAL SURVEY PRACTICE

Robert E. Altenhofen

THE U. S. Geological Survey utilizes a variety of stereophotogrammetric plotting instruments in its topographic mapping program. This agency practices a policy of combined production and research in the field of photogrammetry. Long experience in topographic mapping has proved the wisdom of such a course. Photogrammetric research creates the tools for map production which in turn proves the efficacy of research. This reciprocity of benefits has led specifically to the development and improvement of certain stereoplotting instruments, and generally to the production of better maps at lower costs.

The map production methods practiced by the U. S. Geological Survey have a direct bearing on the subject under discussion by this panel. The plotting instruments used by the Survey in order of increasing accuracy as revealed by experience are the Multiplex, Kelsh, Wild Autograph A-6, Autograph A-5, and the Stereoplanigraph.

It is prudent to preface this discussion by admitting the controversial character of the subject of instrument accuracy. Comparisons of accuracy inevitably lead to heated discussion which frequently descends to argument. Pride seems to be the cause of much debate. Pride of invention and ownership, national pride, or just plain bias often lead to overenthusiastic claims for a specific instrument.

We of the Survey can only say, in the vein of the late Will Rogers, that all we know relative to the performance of stereoplotting instruments is what the photogrammetrist reads on the height counter of the plotter, or what the engineer finds in his field check of the topographic map. The performances of these instruments have been determined by the practical procedure of checking their end product, the map. Thus, all operational components of the photogrammetric process are considered in the appraisal of an instrument. Inherent instrumental accuracy as a function of design and manufacturing skill is the principal component; but we find other factors combined with it, perhaps detrimentally, when facing the realities of map production. Some of these components are instrument calibration, quality of the aerial photography, ease of operation, skill of the average operator, and work schedules. Therefore, from a production standpoint, instrument accuracy and adaptability are most comprehensively determined by weighing all factors in the photogrammetric process.

Although map accuracy tests assume the greater importance in determining instrument performance, the observation of test models for the purpose of checking aerial camera operation also furnishes the means of measuring instrumental accuracy. The designer and research worker particularly are interested in the test model. Fortunately for them an artificial grid model of infinite contrast and ideal geometry frequently serves their purpose. Unfortunately the photogrammetrist requires a natural model, and nature has yet to produce anything approximating the grid. Like Diogenes in his search for an honest man, the practicing photogrammetrist continues to seek the reliable test model.

Before briefly outlining the photogrammetric methods employed by the Geological Survey, it is proper to mention the aerial camera lenses used in combination with the instruments previously listed. Normal-angle lenses include the 206 mm. Zeiss Orthometar covering a format of 18×18 cm. and the 8¼ inches Goerz Aerotar covering a format of 9×9 inches. These lenses produce photography used principally for mosaic assembly and planimetric base compilations over areas abounding in detailed culture. Wide-angle photogrammetric lenses which expose most of the topographic mapping photography include the Metrogon series of focal lengths 4, 5.2, and 6 inches, all focused on a 9×9 inch format, and the 100 mm. (4 inches) Topogon covering an 18×18 cm. format.

As the normal-angle lenses are considered distortion free, no compensation is required in the stereoplotting process. Compensation for distortion present in wide-angle aerial photography is accomplished in a variety of ways: by a compensating diapositive printer for the Multiplex and the Autograph A-5; by compensating plates in the A-5 and A-6; by application of the Porro-Koppe principle in the Stereoplanigraph; and by use of a cam which varies the principal distance in the Kelsh Plotter. It is beyond the scope of this discussion to consider the relative merits of these distortion compensating systems. It may be said in passing, however, that essentially we are appraising the accuracy of compensation when we appraise the accuracy of an instrument utilizing wide-angle coverage. Perhaps the advent of distortion-free wide-angle photography, eliminating the need for compensation, will permit us to resolve the long standing debate occasioned by the mechanical, as opposed to the optical solution of the stereophotogrammetric problem.

Map compilation scales in the case of the direct projection instruments such as the Kelsh Plotter used without the pantograph and the Multiplex are a function of flight height; or to use a much abused expression, they are a function of the C-factor. This factor is defined as the ratio of flight height to contour interval. It is not intended to defend this oversimplified artifice for denoting instrument accuracy. The following C-factors simply result from dividing the contour interval into the flight height found by Geological Survey experience to give photo coverage which will yield in a given plotter topographic maps meeting national accuracy standards:

Instrument	*C-factor*
Multiplex	600 to 800
Kelsh	850 to 1,000
Autograph A-6	900 to 1,100
Autograph A-5	1,000 to 1,200
Stereoplanigraph	1,200 to 1,250

The range in the C-factor is an interesting phenomenon and will be discussed later. These factors have been enumerated simply to give a basis for the following map compilation scales which have been adopted by the Geological Survey:

Instrument	*Quadrangle Size*	*Contour Interval (ft.)*	*Plotting Scale*
Multiplex and Kelsh	All	10	1: 6,000 or 1:7,200
Multiplex and Kelsh	All	20	1:10,000
Multiplex	All	40	1:15,840
A-6, A-5, Stereoplanigraph	$7\frac{1}{2}'$	All	1:15,840 or 1:20,000
A-6, A-5, Stereoplanigraph	15′	All	1:31,680

In grouping the Multiplex and Kelsh it is assumed that the latter is operated with the pantograph set at a reduction of 1 to 2.1. This tabulation of compilation scales demonstrates instrument characteristics which assume importance when discussing adaptability. It should be noted in the case of the direct projection instruments that the compilation scale is a function of contour interval, whereas with the other instruments the compilation scale is a function of quadrangle size or drafting scale. The A-6, A-5, and Stereoplanigraph afford a greater freedom in the selection of model scales which may be altered in transmission to the plot sheet. Therefore, when compiling $7\frac{1}{2}'$ sheets, these instruments are operated at the color separation drafting scale of 1:20,000. Similarly a 15′ quadrangle is plotted at 1:31,680 which is convenient for field checking, and permits a reduction to the drafting scale of 1:40,000.

Production methods adopted by the Survey require combinations of instruments which exploit the capabilities of each and yield maximum efficiency. The Multiplex is utilized to establish pass point control, and to compile the planimetric base which is contoured by means of the Kelsh Plotter with pantograph set at 1 to 2.1 reduction. Similarly the Stereoplanigraph or Autograph A-5, when not operating on projects specifically designed for them, are used for aerotriangulation and compilation of planimetry which is contoured on the A-6. This combination may serve to enlighten those who have been confused by the debate between proponents of tracing table operation (as with the Multiplex, Kelsh, and A-6) as opposed to those favoring hand wheel operation which is characteristic of the Stereoplanigraph and A-5. Objections to hand wheel operation usually come from those whose experience has been limited to the tracing table and never from those who have operated both. Note that one manufacturer is redesigning an instrument to replace the "pushing" technique with hand wheel control. Geological Survey operators having experience with both types heartily approve. Another instrument combination of limited application consists of aerotriangulation by the Stereoplanigraph for altimetric data to fix the absolute orientation of Multiplex models. The Geological Survey generally relies on the greater accuracy of field survey elevations to establish the absolute orientation of stereoscopic models. Where accessible, spot heights are fixed in the corners of every model by spirit, fly, trigonometric or barometric leveling in the field.

This brief outline of Survey stereophotogrammetric methods serves to establish the relative accuracies of 5 types of instruments, as revealed by field checking the final topographic map. One could dismiss the subject of accuracy by pointed reference to the tabulation of C-factors. On the other hand a brief analysis of the figures might prove enlightening. The range in the value of "C" for a given instrument is caused primarily by the range in photographic quality. But this is an unknown factor in the planning stage of a project. However, the seasonal and local characteristics of the atmosphere throughout the country are known, and these in turn affect photo quality. Here we have a tangible factor which might dictate a Multiplex flight height of 600×CI in the Atlantic Region, whereas the Central or Rocky Mountain Regions could tolerate an altitude of $800\times$CI.

It is probably true that contouring alone by stereoscopic methods would permit a direct application of the C-factor rule; that is, the flight altitude is proportional to the contour interval. However, in areas of high cultural density, planimetry may limit flight height to a value which will insure delineation of all map-worthy planimetric detail. The influence of planimetric detail upon flight height is even more marked in the case of large-scale cadastral maps, where close horizontal position tolerances must be maintained. Note the scale of 1:15,840 used for the Multiplex compilation of a 40′ contour interval. This scale fixes the flight altitude at approximately 19,000 feet above terrain, and the C-factor at 475. Experience has shown that at altitudes above 18,000 or 19,000 feet, available aerial mapping camera lenses will not produce negatives adequate for the delineation of the required planimetric detail. One other characteristic of the C-factor may be stated in quasi-mathematical form; namely, that it is some inverse function of flight height. Simply stated, the lower the altitude, the higher the precision of reading spot heights in the stereoscopic model.

This statement leads to a consideration of the accuracy of spot height readings in the various instruments. It is assumed that the elevations of the vertical control points in the model must be read with errors not to exceed $\pm 1/5$ of the contour interval, if elevations interpolated from the stereoscopically drawn contours are to fulfill national map accuracy standards. Applying this tolerance to the minimum values of the C-factors previously listed yields the following maximum spot height reading errors expressed as a fraction of the flight height: Multiplex, $\pm 1/3000$; Kelsh, $\pm 1/4250$; A-6, $\pm 1/4500$; A-5, $\pm 1/5000$; Stereoplanigraph, $\pm 1/6000$. If the Multiplex constant is multiplied by the optimum projection distance of 360 mm., spot heights may be read within ± 0.1 mm. This figure is the basis of the Multiplex practice of contouring at a model scale for which the contour interval is 0.5 mm.; that is, $5\times$the maximum permissible error of spot height readings by the average operator in an average model. Since the Kelsh Plotter projection distance is 30 inches or approximately 760 mm., the ability to read a model elevation to ± 0.1 mm. might lead one to conclude that spot heights observed with this instrument are accurate within $\pm 1/7600$ of the flight height. Actually the effect of the distortion compensating and optical components of this instrument is to increase the maximum error of a spot height reading to the figure mentioned above.

The expression, spot height, used in this discussion of the altimetric accuracy of the model deserves definition. So, at the risk of being called naive, we define the ideal elevation point as one which possesses infinite contrast and high resolution. Terrain of this earth exhibits no such beauty marks. Therefore, every spot elevation in a test model has its weight which is a function of the contrast and definition of its image point. Even if all the points were ideal, their weights would diminish from the maximum at the model center, as demonstrated by *Professor Hallert* of Sweden in his application of error theory to the analysis of the model. All this leads to the conclusion that the photogrammetrist must take liberties with error theory when rejecting test model observations. Large deviations are attributed to mis-identification either by the field engineer or by the instrument operator. Also, there is always the charge of camera vacuum failure or non-homogeneity of film available as legitimate alibis for a breakdown in the photogrammetric process. Only when a definite warpage pattern is noted can the observer consider the test model as an indicator of failure rather than an aggregation of uncertain spot heights. Although the application of error theory is beyond the scope of this discussion, it is pertinent to remark that theory cannot be applied rigorously to the observation of test models consisting of aggregations of spot heights of varying photographic character. Nevertheless, test models when observed with judgment in properly calibrated equipment have confirmed the stereoplotting instrument accuracies previously stated.

How does plotting instrument accuracy effect adaptability? It is almost axiomatic that the most accurate instrument is the most adaptable. The "almost" of this statement implies exceptions which arise from the many connotations of the word, adaptable. Is the instrument adaptable to the operating skill of available personnel; to the photographic materials supplied; to the capacity for capital outlay; to the scale requirements of the final map? Instruments can be graded differently in each of these adaptability categories.

One important factor contributing to adaptability is the plotting scale range. The following tabulation is based on 6″ Metrogon photography and gives the ranges for Survey instruments expressed as multiples of aerial negative scale:

Instrument	*Plotting Scales* (×*Negative Scale*)
Multiplex	2.4
Kelsh without pantograph	5
Kelsh with pantograph	½ to 5
A-6	⅕ to 3
A-5	⅓ to 20
Stereoplanigraph	¼ to 30

The large Multiplex and Kelsh plotting scales make advance copies of their compilation manuscript particularly useful for planning and engineering purposes. Although the A-5 and Stereoplanigraph can accommodate similar scales, the physical limitations of the coordinatograph confine plotting to one strip per plot sheet. However, when the expedient and direct production of the topographic map is desired, these heavier instruments permit plotting at the smaller field checking or drafting scales. Adaptability in this case is dependent upon the desirability of an interim large scale print of the stereocompilation before publication of the final topographic map.

Other aspects of stereophotogrammetric mapping could be cited to make a case for the adaptability of each of the instruments employed by the Geological Survey. Such an elaboration would lead probably to the conclusion that the mapping task of a particular organization will determine the instrument most suited to its needs. In fact, finances might take preference over task, and the most adaptable plotter will be the cheapest.

Adaptability, in the purest sense, is measured in terms of capacity to utilize a variety of materials. Here are the instruments arranged according to their scope of operation:

Instrument	*Plottable Stereopairs*
Stereoplanigraph	Vertical, High and low oblique, Terrestrial
A-5	Vertical, Low oblique, Terrestrial
Multiplex, Kelsh, A-6	Vertical

This arrangement can be altered if the ingenuity of the photogrammetrist is given full sway and map standards are lowered. Witness the experiences of World War II military mapping which required the Multiplex to be almost as versatile as the stereoplanigraph. Acceptable maps of remote uncharted areas were produced with the vertical type Multiplex utilizing trimetrogon obliques. There was nothing that the protagonists of this instrument would not attempt except, perhaps, to use it for terrestrial stereophotogrammetry.

So, adaptability of stereoplotting instruments depends upon the skill of the photogrammetrist. The wise photogrammetrist will not rank stereoplotters in their order of accuracy and adaptability, without weighing all factors including capital outlay, ease of operation, quality of the photographic materials, operator skill, map accuracy standards, and work schedules. The Topographic Division of the Geological Survey cannot overlook these factors, for to do so would be to ignore the realities of map production which is its chief responsibility.

Moderator Sharp: I am sure there is a lot of meat in Mr. Altenhofen's paper.

Our next speaker is Professor Schermerhorn. I believe his biography has been presented twice before at this meeting, so I will only say, that we felt that, with his outstanding background, Professor Schermerhorn seemed the ideal person to summarize, discuss and possibly suggest avenues of approach for the improvement of our ideas on the very important subject which we are discussing.

DISCUSSION AND SUMMARIZATION

Professor Ir. W. Schermerhorn

I HOPE that you will take my remarks for what they are worth as expressions of impressions I have gotten from this discussion and my former partly prewar experience.

I feel a little bit as I did many times in the years between 1936 and the outbreak of World War II, when we in Delft were one of the few places on earth where we had the different plotting machines, especially the stereoplanigraph and A-5. How many times did it happen that colleagues and technicians asked me my idea of the kind of instrument I would prefer for our future work? I remember answering that I felt that the major problem was not in the plotting machine, but in both ends of the instrument; on the one end, the film, and on the other end, the operator and perhaps the staff behind the operator. I have given that answer many times and I give it again today. They were the major problems before World War II; they are still the major problems.

Comparisons of instruments based on the data available now is a very dangerous thing. Listening to the figures given in the excellent paper of Mr. Altenhofen, I am inclined to ask what is the mean square error of his figures.

I have another impression. I know by experience that each one of these plotting instruments has its own qualities and lack of qualities. In Delft we had two stereoplanigraphs and two A-5's. These instruments were both of the same type, but they were not equal and have never been equal. The explanation of these small differences of the order of 1 in 5000 to 1 in 6000 is very difficult to make.

That makes me a little afraid to give too clear-cut statements about the capacity of special instruments. Naturally, there is apparatus that fall into the first, second and third order. I have a certain impression, also based on experience, about the results of comparing the multiplex against the stereoplanigraph and that kind of instrument. It is very difficult to give figures that have 100-per-cent reliability. Not only are there differences in the behavior of each of the instruments, but there are also differences in circumstances. In many cases, instruments I should not like to use are useful for certain purposes and under special circumstances.

The fact stated by the representative of Aero Service Corporation about the