*Cumulus Cloud Photogrammetry**

HAROLD D. ORVILLE,
Graduate Asst. in Research,
Inst. of Atmospheric Physics,
The Univ. of Arizona,
Tucson, Ariz.

ABSTRACT: *The application of photogrammetry to one aspect of cloud physics is described. Aerial cameras are fixed on the ground to provide terrestrial stereophotographs of cumulus clouds. A stereoplanimetric plotter is used to trace the outline of the cumulus clouds. Time sequences of the outlines are used to give quantitative information on the growth rates and sizes of the clouds. The stereoplanimetric plotter is described and a sample cloud tracing is illustrated. An error analysis utilizing the foreground mountains as an accuracy check is presented. Accuracies of better than 1 per cent in the 20,000 ft. heights and 10–20 mile perpendicular ranges of the clouds are expected.*

I. INTRODUCTION

FOR several years now the Institute of Atmospheric Physics at The University of Arizona has been engaged in cloud-physics research. Part of this research has involved studies of the dynamics and kinematics of cumulus clouds—the cauliflower-like cloud which in some instance heralds fair weather, or in other situations signals the beginning of a massive thunderstorm with the attendant thunder and lightning, high winds and heavy downpours. The cumulus cloud is thus as potentially dangerous as unpredictable. Certainly the meteorologist would like to be able to say, with greater certainty than he can today, when a particular cumulus cloud has a storm potential. It is hoped that more detailed knowledge about cumulus clouds will aid this objective.

Description of the phenomena of a cumulus cloud is one of the first steps toward explanation and prediction of that phenomena. Photogrammetry provides an excellent means for this description, giving quantitative information about the motion and growth of cumulus clouds, and hence providing a valuable supplemental description to the qualitative comments of the casual observer.

The Institute uses ground-based K-17 and T-11 aerial cameras to photograph clouds over the Santa Catalina Mountains 10–20 miles northeast of Tucson. This is an excellent example of terrestrial photogrammetry. Orientation of the cameras conforms to the stereophotogrammetric parallel averted case as defined by Hallert (1960). The cameras are directed parallel along a central azimuth of 34° 47; and are nearly perpendicular to a base line 3 miles long, of azimuth 123°10′ from the University camera location. The cameras are level, the cameras' horizontal fiducial marks corresponding to the earth's horizon.

The cameras are operated principally in July and August of each year. In Tucson these months are characterized by almost daily occurrence of cumulus clouds over the nearby mountains. Of extreme importance to the photogrammetric situation is the usual absence of foreground clouds, which gives a clear picture of the clouds from both camera sites.

The stereo view is usually very good. The cloud ranges of 10–20 miles dictate a slightly shorter base line for optimum stereo viewing at the shorter range, but the present arrangement has advantages in other facets of the cloud research. Of course, cloud tracings are only completed for those parts of the cloud that appear on both photos, but as implied above, this includes most of the cloud most of the time.

The horizontal orientation and 74° field of view of the aerial cameras mean that cloud growths to 40,000 feet may be pictured at the 10-mile range and growths to maximum cloud heights at the longer ranges. Pictures of the clouds are taken at 30 second, 1 minute or 10-minute intervals, the first two time intervals

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being the more suitable for cloud-growth studies since a cumulus cloud is a bubbling mass of cloudy air that rapidly changes form. An entire cumulus turret can appear and dissipate in a 10-minute interval. The cameras are electrically connected via a leased telephone line so that simultaneous exposures are made of the clouds.

II. The Measurement Technique

A record of the cloud growth can be obtained in at least two ways. One method is to identify distinctive points of a cloud and to measure the coordinates of these points from one picture to the next, using any convenient photogrammetric method. This method is time-consuming, tedious and frustrating. As mentioned above, the cumulus clouds change form rapidly, and hence it is difficult in many instances to identify the same cloud point from one minute to the next.

A more satisfactory method for following a cloud's growth is to trace the *outline* of the cloud from one picture pair to the next. Even this is not an easy job as the outline of a cumulus cloud can be rather complicated, as will be evidenced later by a sample tracing. However, the added detail and, we hope, information gained by tracing the cloud's outline make the effort worth while.

The device used for tracing the clouds is called a stereoplanimetric plotter. The idea for the device follows somewhat that of the radial planimetric plotter developed by Philip B. Kail Associates. Planimetric detail is obtained by stereoscopically observing two radial lines intersecting on the object to be plotted. The intersection performs the function of the floating dot used in the more conventional forms of stereophotogrammetry. Our device is illustrated in Figure 1. Essential elements of the plotter are the plotting table, drafting arm, radial lines, light table and stereoscope.

Operation involves orienting the two negatives on the light table by means of control points in the Santa Catalina Mountains. The negatives are taped in place and radial lines are attached to the center of each negative by means of a straight pin inserted in the light table's plexiglass top. The two radial lines intersect around a thin shaft on the drafting arm and are kept taut by a pulley and weight system. Graph paper covers the table top with its horizontal lines parallel to the horizon line determined by the centers of the two negatives. The distance between these two points uniquely determines the scale of the plot. Our 10.2-inch displacement relative to a 2.995-mile camera station displacement yields a scale of 1 inch = 1550 feet. The movement of the drafting arm displaces a radial line over each negative, and faithfully reproduces on the graph paper the (x, z) outline of the cloud when the radial lines cover the same part of the outline at the same time. A tracing of the cloud outline is obtained by observing the illuminated negatives with a stereoscope, preferably one with binoculars for close scrutiny of the clouds and radial lines. While observing the cloud stereoscopically the analyst maintains the intersection of the two radial lines on the cloud outline, and thus "traces" the cloud when moving the drafting arm. A detailed history of the cloud can then be obtained with pictures taken every minute or half-minute.

An example of the cloud photographs and

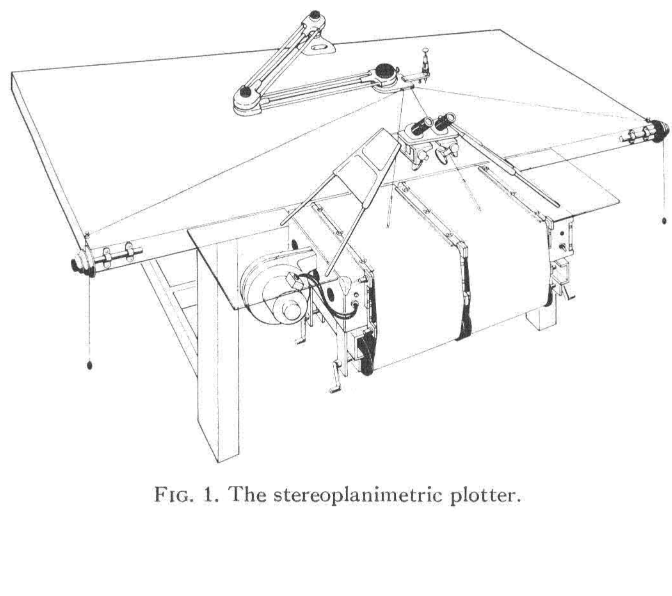

Fig. 1. The stereoplanimetric plotter.

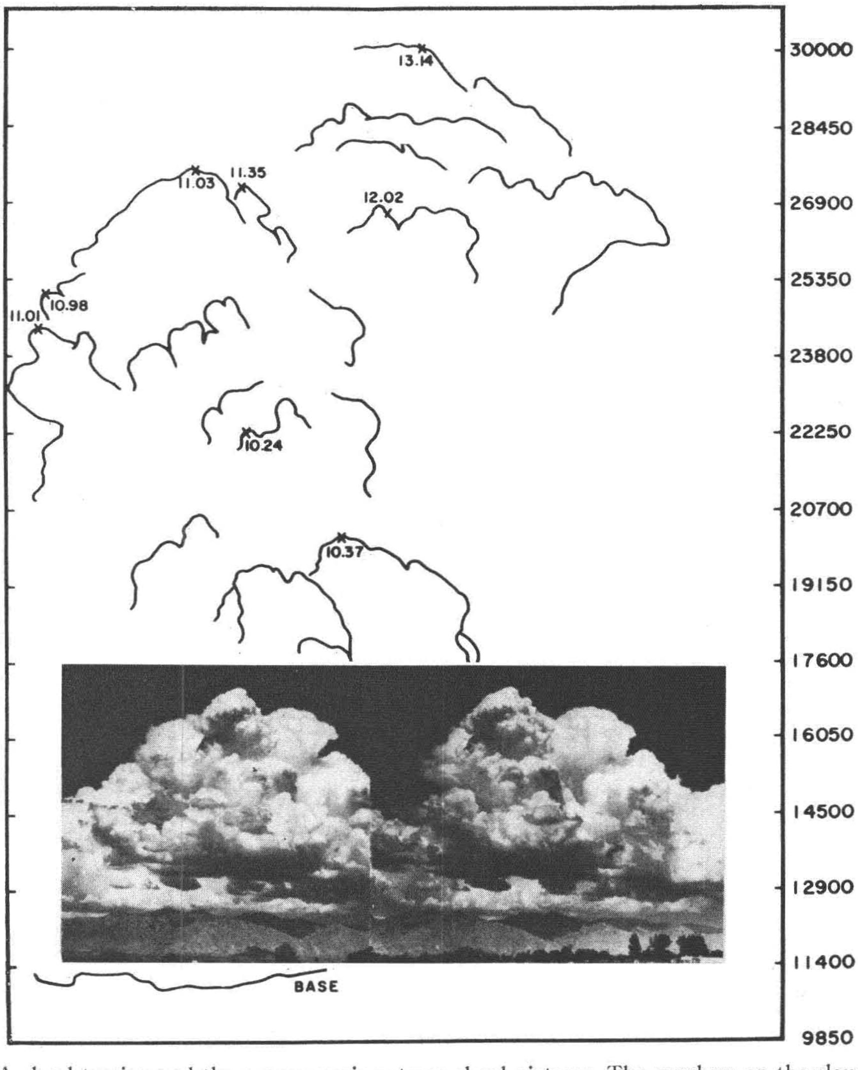

FIG. 2. A cloud tracing and the accompanying stereo cloud pictures. The numbers on the cloud outline indicate perpendicular range to the outline. Height scale is in feet above mean sea level.

the tracings made from them are shown in Figure 2. It is evident that the planimetric tracing gives a different picture than either of the photographs separately viewed. Range differences and the nearness of the cloud cause a resultant "exploded" view. Many small nodules and turrets form the outline of the cloud. It is a task of the analyst to determine the active elements and keep track of their growth.

The accuracy of the plotter depends very much on the mechanics of the system. It is desirable to have complete and instantaneous response between the drafting arm and radial lines. The radial lines should be as free from surface drag friction as possible; ideally they should make contact only at the negative's center pin and the intersecting point of the drafting arm. The lines should be thin, in the 3-mil range, to insure unambiguous stereo intersections. To accomplish this, use is made of a thin 5-inch-long plexiglass strip with a 3-mil scribed line, and attach to this fishing line of sufficient strength to support the 8-ounce weights used to keep the radial lines taut.

III. Errors

Besides serving as an excellent catalyst for cumulus clouds, the Santa Catalina Mountains provide a convenient check on the height and range errors of the photography and the stereoplanimetric plotter. Twelve mountain peaks were measured in each of the 3 years on a selected number of negatives from each year. Parallax bar measurements were made as well as the stereoplanimetric plotter measurements. It is thought the parallax bar measurements give some idea of the error present in the photography, and the stereoplanimetric plotter measurements indicate how much additional error is due to the mechanics and orientation of the plotter.

Formulae used for the parallax bar calculations are given in Hallert (1960) for the cameras parallel but averted. Partly in our notation

$$y = \frac{b \cos \delta}{p} (f - x_2 \tan \delta) \tag{1}$$

$$H_1 = \frac{Z_1}{f} y \tag{2}$$

$$H_2 = \frac{Z_2}{f} (y - b \sin \delta) \tag{3}$$

where

- y = perpendicular range
- b = base line
- δ = angle of "avertedness"
- f = focal-length
- p = horizontal parallax $= x_1 - x_2$
- x_2 = horizontal displacement on right camera negative
- H_1 = height of cloud above left camera
- Z_1 = vertical displacement of cloud on left camera negative
- H_2 = height of cloud above right camera
- Z_2 = vertical displacement of cloud on right camera negative

The focal-lengths were the same in 1959 and 1960 and within 0.008 of an inch in 1958. H_1 and H_2 must be corrected for the earth's curvature and atmospheric refraction to be compared with map heights.

Whereas the parallax bar measurements yield perpendicular range as the basic measurement, and height is derived from the range, the stereoplanimetric plotter basically gives height. Perpendicular range is derived from

$$y = \frac{H}{Z_1} f \tag{4}$$

where H is the height obtained using the stereoplanimetric plotter. This height should not be corrected for the earth's curvature or atmospheric refraction.

It is interesting to note that according to the "radial assumption" [MANUAL OF PHOTOGRAMMETRY (1952)], the height measurement is unaffected by focal-length differences and parallel avertedness, as long as both cameras are level and directed along the same axis.

Table 1 summarizes the results of the error analysis. As expected, the parallax bar provides the most accurate results. The left peaks' standard error of 0.042 mile is 0.4 per cent of the 10.6 miles perpendicular range characteristic of these peaks. The peaks to the right of camera one's optic axis aver-

TABLE 1

SUMMARY OF ERRORS

σ_e = estimated standard error $= \sqrt{n/n-1S^2}$ where s = sample standard deviation.

	No. of measurements	Average range error (miles)	σ_e (miles)	Average absolute range error (miles)	Average H_1 error (feet)	σ_e (feet)	Average absolute H_1 error (feet)	Average H_2 error (feet)	σ_e (feet)	Average absolute H_2 error (feet)
		PARALLAX BAR								
Left peaks	36	+0.016	0.042	0.034	+15.1	48	40	−9.3	47	38
Right peaks	34	−0.051	0.107	0.103	−17.2	57	56	−13.7	75	64
		STEREOPLANIMETRIC PLOTTER								
Left peaks	48	−0.23	0.16	0.23	−88	56	91			
Right peaks	37	−0.41	0.24	0.42	−106	74	112			

aged 18 miles perpendicular range so that the standard error of 0.107 mile is 0.6 per cent of their average range. The right peaks are slightly higher than the left peaks, so the standard error of the heights is about 1 per cent of the heights above the horizon, in both cases. The increased error reflects the additional measurement that must be made to obtain the heights. These measurements indicate the orientation of the cameras, and precision of the photography is good to 1 per cent or less of these range and height values. (The difference in the two height values obtained by equations (2) and (3) is noted but is thought to be mainly a result of reading errors.)

The stereoplanimetric plotter height measurements were predominantly too low (60 out of 71 measurements). This systematic error, which has approximately the same average value on the left and right peaks, can be corrected with a modification of the graph paper base values by approximately 100 feet. The standard error of the height errors of the left peaks (56 feet) is approximately 1.1 per cent and for the right peaks (74 feet) approximately 1.3 per cent of the actual heights. The range errors are 1.5 per cent and 1.3 per cent for the left and right peaks respectively. The range error follows very closely that of the height error as would be expected from eq. (4).

The average absolute error was included in Table 1 for those who prefer such a statistic, and to indicate the predominance of negative values in the stereoplanimetric plotter data.

It is suspected that such errors as are indicated above will strike terror into the hearts of the conscientious topographical map photogrammetrist. However, it is believed that the absolute magnitude of the height and range errors can also be applied to the clouds growing over the mountains, and thus the relative error is very small indeed, e.g., 200 feet or less in 20,000 feet. Also consistency is more valued than absolute accuracy in much of the work. The cloud is traced at intervals and the relative motion in the vertical is the cloud's vertical velocity. It is important that the negatives yield similar measurements on the mountains, not necessarily absolutely accurate, so that the measurements on the clouds from one minute to the next will indicate true outline change. Orienting the negatives by control points and checking the heights of these control points, gives a check on the consistency of our measurements.

The ability to obtain reproducible results has also been checked. Outlines of the same cloud at the same time have been checked several times. In general, the same analyst can reproduce a tracing within the limits of the error of the system, i.e., 200 feet or less in the areas of good stereo viewing. Different analysts trace the same form of a cloud outline but may disagree in absolute measurements. It is recognized that no two people see exactly the same stereoscopically. Hence the same analyst works one cloud history through to completion. As mentioned, the basic data are the relative movement of the clouds and not their absolute measurements. Two analysts can measure the same rate of change of outline, even though they may disagree on the absolute height of the cloud at each time interval.

IV. Summary

Measurement of the range and height of cumulus clouds is currently being done at the Institute of Atmospheric Physics with the aid of a stereoplanimetric plotter. The results are believed accurate to 1 per cent for cloud heights of 20,000 feet and ranges of 15 miles. The data are used for vertical velocities and other growth rates, which are obtained by the change in outline from one picture to the next. Here an accuracy of measurements with 200 feet per minute is expected. This is accurate enough for meteorologically significant information to be obtained from the life history of clouds. Photogrammetry has proven to be an economical and accurate data gathering method for our atmospheric physics research in the past. An even greater use is planned for it in the future.

Acknowledgment

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