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CLOUD PHOTOGRAMMETRY WITH GROUND-LOCATED

K-17 AERIAL CAMERAS

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ABSTRACT

A technique is presented in which a pair of ground-located K-17 aerial cameras are used on a 1.30 mile baseline to determine cloud ranges to one mile accuracy at 40 miles and cloud height measurements to within 500 feet at this range. Details of the power supply, vacuum supply, and camera synchronization requirements are discussed as well as methods used in analysis. In particular, a detailed discussion is given of the theoretical and practical errors encountered in such a photogrammetric technique.

1. Introduction

One of the basic requirements in researches in cloud physics is the ability to make dimensional measurements of the clouds. This problem arises in many ways in the field of cloud dynamics, in cloud "census" studies, in seeding studies, in comparison of cloud growth rates and precipitation as determined by radar methods, and in simple descriptive studies.

In the past such measurements have been made in a number of ways, examples of which are double-theodolite determinations of Braham et al. (1951), panoramic camera and theodolite measurements of Bigler and Changnon (1954), and from aircraft reports and comparisons of cloud motion with upper level winds by Plank et al. (1955).

Each of these methods suffers certain disadvantages. In the case of theodolite observations, it is necessary for one observer to describe to the other observer the point he is looking at under transient conditions so that correct triangulation measurements can be obtained. This is a difficult procedure and, as a result, a limited number of accurate cloud measurements can be made on any given day. In the case of panoramic cameras, or any camera using only standard high quality optics, in order to get sufficient accuracy at ranges of several tens of miles, base lines of several miles must be used, thus making recognition of particular cloud points difficult when viewed from substantially different

angles. In addition, the associated analysis problem can become quite unwieldy. Airplane measurements are excellent but not always possible for all research groups.

In an attempt to overcome these difficulties it was decided to try to use K-17 aerial cameras with 6-inch focal length lenses. These would give a 74 degree field on a 9x9 inch contact print. This is a very large field of view by camera standards and a print of this size has excellent resolution properties. In addition, all of the well-established, accurate stereogrammetric analysis equipments and techniques could be used, making analysis substantially easier and faster.

It was decided that one mile range resolution at 40 miles and 500 foot height resolution would be required. Since one minute of arc of angular resolution is well within the specifications of the camera presentation this would require a base line of the order of one mile and such a camera separation would not introduce sufficient parallax error to make recognition difficult.

Since all of these considerations made these cameras seem ideal for the purpose, they were set up within the city of Tucson, Arizona and used during the summer of 1955 by the Institute of Atmospheric Physics in connection with radar measurements, panoramic camera pictures, lapse-time movies of the clouds, rain gauge networks, airplane flights, and all of the other types of observations which go along with a well-integrated attack on the problem of basic precipitation mechanisms. In all, some 3000 pairs of pictures were taken with the K-17 cameras. After the data reduction and evaluation began it became apparent, as is usually the case, that the technique was not as simply ideal as preliminary investigations indicated. Many pitfalls evinced themselves which were not obvious in preliminary considerations or from the best technical advices immediately available.

The technique is basically good and will be extensively used in the future but it is to the consideration of those hard-won pieces of information that enable the technique to be successful that this paper is largely devoted.

2. Description of the Equipment

The K-17 camera and its mounting is shown in fig. 1. A Paillard-Bolex 16 mm. movie camera with lapse-time actuating mechanism and wide-angle base is seen in the foreground and the power and vacuum supply for the camera are in the background. The camera mounting is of the altazimuth type built around a standard Chevrolet front axle spindle assembly. Precision machinists' levels were mounted on the camera. The mounting must be rugged as well as carefully built since the camera plus loaded magazine weighs of the order of fifty pounds.

The magazine holds 200 feet of $9\frac{1}{2}$ inch width film, producing 250 pictures. The camera is entirely automatic in firing and film advance, and may be actuated by either manual or electrical control. A 24 volt D.C. supply is required capable of producing 30 amperes instantaneous current although only a few amperes are actually required during the winding cycle. A vacuum supply of approximately two inches of mercury is also required to hold the film against the camera focal plane plate during the actual moment of exposure.

The camera was used pointing skyward at an angle of 30 degrees with the horizontal. The standard red filter was used although the diffusion pattern was ground off since it appeared to introduce more difficulties than it was designed to eliminate. A four inch metal disc was used as a sun-shade, supported on a stand about three feet in front of the lens. Since aerial photographic film does not have anti-halation backing, this is very necessary.

Fig. 1. Photograph showing K-17 camera and mount with power and vacuum supply in background and 16 mm. lapse-time camera in foreground.

The two cameras were placed 1.30 miles apart and for synchronization purposes were connected by a leased telephone pair. This could be done equally well with radio control but the telephone line is much simpler. Since it was desired to operate the vacuum pump only immediately prior to an exposure and only one wire pair was available to control the exposure, a little more than the simply obvious wire connection had to be used.

The wiring diagram for the vacuum system, power supply and camera control circuit is shown in fig. 2. The timing of the cameras is accomplished by use of inexpensive A.C. synchronous timers set to the desired interval. The cameras are fired at the end of a ten second pulse, during which time the vacuum pumps have brought the system to equilibrium at approximately $3\frac{1}{2}$ " of mercury. If for some reason the system does not reach a minimum of at least 3" of Hg, the vacuum relay, S_2 is not actuated and the cameras do not fire. This insures against exposure with the film not correctly located against the focal plane plate. On the other hand, if the vacuum exceeds 4" of Hg there may be danger in distorting or "etching" the film along the vacuum grooves in the focal plane plate. A bleeder valve and a surplus altimeter are used to adjust and regulate the vacuum supply.

The "master unit" contains the intervalometer while the "slave" unit contains a relay actuated by the intervalometer through the telephone pair. The film is advanced when the vacuum pump stops at the end of a cycle and the vacuum relay makes it normally-off contact. Exact synchronism between cameras is maintained by firing the shutter when the intervalometer or manual control is released. Firing the cameras when the intervalometer or manual control is closed could introduce inaccuracies in timing since the two pumps would take slightly different times to close their respective vacuum relays.

Fig. 2. Circuit diagram of camera and vacuum control unit.

The "input or output" rotation refers to the fact that the two control units are connected at these points and S_1 may be the contacts of the sensitive relay in the "slave" unit or the intervalometer of the "master" unit. "BAT." and "INT." refer to those plugs so-labeled on the K-17.

R_2 is a latching type relay which permits the camera shutter to operate only on the release of S_1 when the magazine has a vacuum on it as indicated by S_2 .

3. Basic Geometry of the System

The whole field of photogrammetry, particularly using aerial cameras, is very well presented in considerable detail in such standard references as that of the American Society of Photogrammetry (1952). Normally, stereo pairs of aerial photographs are compared and the differences of parallax between the object of interest and one or more known points are measured on the pictures. Then, knowing the length of the base line between successive pictures, standard parallax formulas may be used to determine the distance from the camera to the unknown point. If "tip" or "tilt" of the camera has occurred during flight standard "rectification" formulas or appropriate mechanical adjustment of the analysis equipment can be made. This was the technique originally chosen for this investigation. However, in order for the ground analog of two cameras on a fixed base to be identical to two pictures taken with one camera in a moving airplane, the focal lengths of the two cameras must be identical. The assumption that the error in distances computed would be just the percent difference in focal lengths proved to be completely erroneous. In the final analysis, the mathematical correction to be applied to the difference of parallax measurement involving aparaallelism of the cameras, difference in focal lengths, and differential tilt proved to be entirely

too unwieldy for practical consideration. Moreover, analysis equipments suitable for the job involve the expenditure of several tens of thousands of dollars which was impossible to consider.

Therefore, it was necessary to fall back on standard triangulation measurements in which the azimuths and altitudes to the unknown point are measured from the two pictures. This is sometimes called the "single-picture" method but the reader is, of course, not to infer that any distance to an unknown point can be measured from one picture unless some linear dimension involving that point is independently known.

Basically the technique is illustrated in fig. 3. If θ_1 , and θ_2 are the azimuth angles of the point A from camera positions C_1 , and C_2 with respect to the perpendiculars to the line $C_1 C_2$, whose length is L, then

$$R_1 = \frac{L \sec \theta_1}{\tan \theta_1 - \tan \theta_2} \quad (1)$$

where R_1 is the horizontal range from C_1 to A, and $\tan \theta$ must carry the appropriate algebraic sign. Then, if β_1 is the altitude angle from C_1 to A,

$$h = R_1 \tan \beta_1 \quad (2)$$

where h is the elevation of A. If there is a difference of elevation between C_1 and C_2 these simple relations must be modified.

The cameras were pointed skyward at an angle of 30° with the horizontal since it was desired to photograph as much of the sky as possible. However, it was correctly assumed that it would prove absolutely essential to have the horizon in the picture to provide a check on the altitude and azimuth angles of the axes of the cameras. To have depended on graduations on the camera mounts to maintain one minute angular accuracies would have proved impossible, even though the mounts were built with all of the care consistent with practical considerations.

Fig. 3. Drawing showing parallax relationships for two cameras at ends of a base line, L .

In an oblique photograph vertical lines and lines of constant angular altitude appear as is shown in fig. 4. In particular, if the camera is pointed upward the vertical lines converge at a "zenith point," "Z," whose distance above the picture center, "O," is given by

$$OZ = f \cot \phi \quad (3)$$

where f is the focal length of the camera and ϕ is the angle of elevation of the camera above horizontal. The picture center is accurately determined in an aerial camera by fiducial marks shadowed on the film during exposure.

If θ' is the angle between the vertical line, as determined by the fiducial marks and the line from the zenith point to the unknown point, then the true azimuth, θ , is given by the relation

$$\tan \theta = \tan \theta' \csc \phi \quad (4)$$

The height of the cloud above station 1 is given by the relation

$$h = R \cos \theta, \left(f_1 \frac{\csc^2 \phi - \cot \phi}{AZ \cos \theta'} \right) \quad (5)$$

where AZ is the length shown in fig. 4.

4. The Analysis Technique

Since many data recording systems ultimately prove valueless because the reduction of the data is too cumbersome, particular attention was paid to the analysis scheme. It was decided to analyze the picture negatives on the basis of convenience of handling, considerable economy, and a gain in resolution.

Two light-boxes were constructed, as shown in fig. 5, each having four twelve-inch fluorescent tubes in them. A sheet of 1/8-inch flashed opal glass was mounted above the tubes and a sheet of 1/4-inch plate glass was mounted over the flashed opal. This latter was added because it proved difficult to scribe index marks on the rather brittle flashed opal.

Fig. 4. Drawing showing appearance of lines of equal azimuth and equal angular elevation on photograph with camera tilted 30° upward from the horizontal.

Fig. 5. Photograph of picture analysis equipment.

Also the additional strength of the plate glass seemed desirable. The boxes were ventilated with centrifugal blowers. Each box was equipped with rollers and holders for the 200 foot film rolls. The plate glass sheets were very carefully scribed with a pair of perpendicular lines for locating the picture center from the fiducial marks. This was surprisingly easily done by the use of glass etching compound found in most hobby supply stores. The lines are scribed with a needle in black asphaltum which has been previously painted on the glass and allowed to dry. The etching compound is then applied and after the prescribed length of time it is washed off with water and the asphaltum removed with gasoline or any other appropriate solvent.

One-minute draftsman's protractors were mounted on the boxes by means of wing nuts and bolts through slots in the protractors so that it was possible to make adjustments to accommodate variable tilt angle, ϕ , and also variable focal length, f . The need for the latter adjustment will be discussed later. Good quality draftsman's scales were screwed to the protractor arms so that the protractor centers could be set at the appropriate OZ distances of equation (3) and the distance AZ of equation (5) could be measured.

In practice, the negatives were very carefully taped to the plate glass lining up the fiducial marks with the scribed lines on the glass. The cloud points and horizon check points were then pricked with a needle to make measurement easier. A simple stereoscope, shown in fig. 5, very often helped in this operation. The protractor position was then checked and the θ' and AZ distances to each point measured and recorded.

Tables had previously been prepared for $\cos \theta'$, $\cos \theta$, and θ as a function of the measured θ' for different values of ϕ . These values together with AZ and cloud identification numbers were immediately

punched into IBM cards. The computations were then done very quickly on the Institute's IBM 602A calculator and tabulated. Auxiliary radar data and coded comments are also included in the final tabulated summaries. If such punched card equipment is available, the usually tedious computing job becomes very painless indeed. This particular analysis, including constructing the initial conversion tables, proved quite amenable to the punched card technique.

5. Error Analysis

Since the range depends on the difference between measured angles, whereas the height depends directly on one angle, it is to the range equation that we must look for greatest errors.

If one combines equations (1) and (4) and logarithmically differentiates, the following rather formidable equation results for the error in range:

$$\begin{aligned} \frac{dR}{R} = & \frac{-1}{\frac{\tan \theta'_1}{\sin \phi_1} + \frac{\tan \theta'_2}{\sin \phi_2}} \left[\frac{\sin \phi_1 \sec^2 \theta'_1 d\theta'_1 - \tan \theta'_1 \cos \phi_1 d\phi_1}{\sin^2 \phi_1} \right. \\ & \left. + \frac{\sin \phi_2 \sec^2 \theta'_2 d\theta'_2 - \tan \theta'_2 \cos \phi_2 d\phi_2}{\sin^2 \phi_2} \right] \\ & + \left(\frac{1}{1 + \frac{\tan^2 \theta'_1}{\sin^2 \phi_1}} \right) \left[\frac{\sin^2 \phi_1 \tan \theta'_1 \sec^2 \theta'_1 d\theta'_1 - \tan^2 \theta'_1 \sin \phi_1 \cos \phi_1 d\phi_1}{\sin^4 \phi_1} \right] \end{aligned}$$

As a sample calculation in the above expression, consider for $R = 30$ miles, $\phi = 30^\circ$ and $\theta = 35^\circ$, $d\theta$ to be 3' and $d\phi$ to be 6' and in particular the $d\theta$ and $d\phi$ for the two camera measurements to be in such a sense as to reinforce rather than to cancel each other. The result of

this calculation gives a range error of about 4%. It was found that the initial specification of one mile range accuracy at forty miles could barely be met by extreme care in setting the pictures and protractors. This was verified by checks on photographs showing the moon. Star photographs might also be helpful although the camera shutter linkage must be detached to permit time exposures. Of course, greater accuracy can be obtained if a longer base line or longer focal length cameras are used.

It should be reemphasized that it is imperative to have fixed points or recognizable horizon discontinuities in the picture to maintain sufficient azimuth and tilt accuracy.

One pitfall that must be avoided is the assumption that topographic base aerial film has no shrinkage. Due to several causes such as variations in temperature and humidity, age, and processing techniques the film can show distortions of as much as a few tenths of a percent in its overall dimensions. Such distortions can not be tolerated in relation to the errors previously discussed. Fortunately, however, the distortion can be assumed uniform to the degree of accuracy demanded so that the correction for shrinkage can be handled mathematically as a variation in the focal length of the lens associated with the film in which the shrinkage occurs.

The shrinkage problem was handled by exposing glass spectrograph plates in the camera magazines to get an accurate measure of the distance between fiducial marks. This distance is then measured on all of the films and the percent difference then becomes directly the percent variation to be applied to the focal length. It was found that the equivalent focal length marked on the camera lens was sufficiently accurate for these measurements.

In practice it is felt that azimuth errors can be held to within the three minute error of the foregoing example and that elevation angle errors can be held to within one-half the six minute error of the example.

A check of horizon points yielded an average error of 0.25 miles at 20 mile ranges and an average height error of 260 feet at 4700 feet. It should be pointed out that percentagewise the height error is large because the horizon points are most unfavorable for best accuracy. It is felt that this absolute error would still be representative at cumulus cloud top heights.

Fig. 6 shows a typical stereo-pair of cloud photographs. The individual pictures have been cropped somewhat for ease of mounting. As can be seen, a clock and date card is mounted in front of the cameras for identification purposes.

6. Conclusions

Several hundred cloud measurements have now been made using the techniques described. The meteorological inferences of these measurements will be published later. Although the method did not prove as simple or foolproof as first considerations indicated, the results are gratifying and making use of the hard-won experience, it is expected that this technique will prove very useful in many future cloud census and cloud dynamics studies. The detail and contrast obtainable using the aerial cameras is remarkable and since one has a very large negative to start with, enlargements of very large size are attainable without objectionable graininess. With great care cloud ranges can be measured to one mile at 40 miles and clouds can be measured to a few hundred feet with a base line of the order of one mile. Accuracy is greatly increased as the ratio of range to base line is decreased.

Fig. 6. A typical stereo pair of cloud photographs.

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REFERENCES

Braham, R. R., Jr., Reynolds, S. E., and Harrell, J. H., Jr., 1951:

Possibilities for cloud seeding as determined by a study of
cloud height versus precipitation. J. Meteor., 8, 416-418.

Bigler, Stuart G. and Changnon, Stanley, A., 1954: A study of

relationships between visual clouds and radar echoes on 24 and
25 August, 1954. Unpublished report prepared by Illinois
State Water Survey under Sub-Contract No. 1 with University of
Chicago, Prime Contract AF 19(604)-618.

Plank, Vernon G., Atlas, David and Paulsen, Wilber H., 1955: The

nature and detectability of clouds and precipitation as
determined by 1.25-centimeter radar. J. Meteor., 12, 358-378.

American Society of Photogrammetry, 1952: Manual of Photogrammetry.

George Banta Publishing Company, 876 pages.