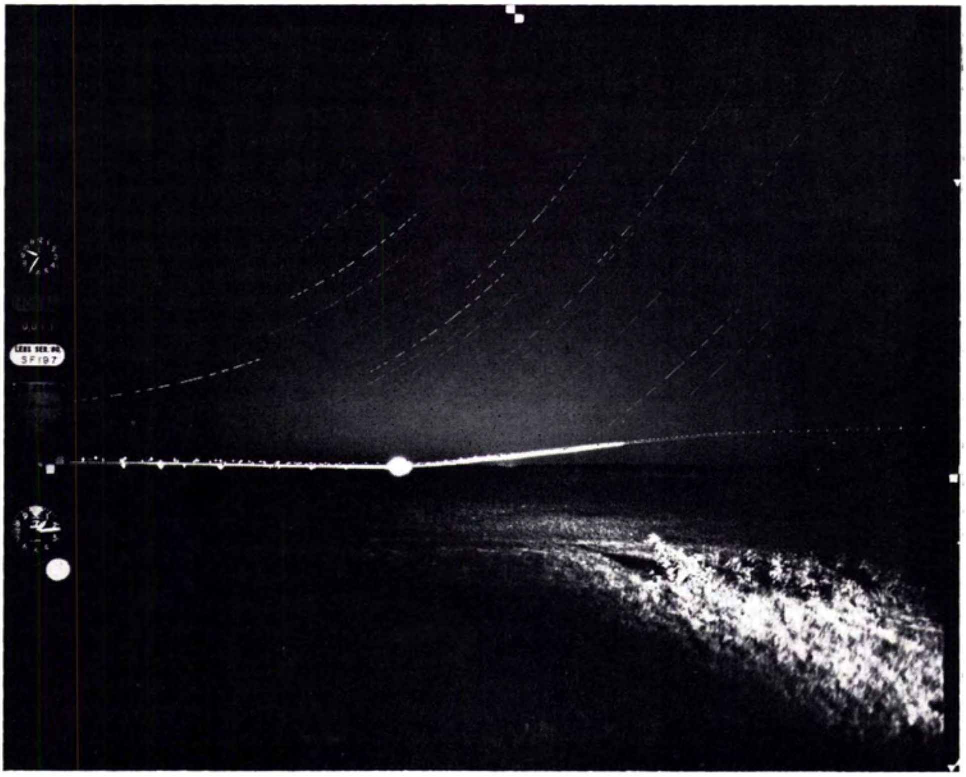

FIG. 1 Star photograph: time exposure of the northeast sky in Northern Minnesota in late summer, begun shortly after sunset. The bright star in the lower left is the first magnitude star Capella. Exposure time: 83 minutes.

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Camera Orientation for Cloud Measurements

Stellar images are used in a field method to align terrestrial stereo cameras for finding the heights and locations of cloud formations.

INTRODUCTION

THE CLOUD PHYSICS LABORATORY of the University of Chicago uses star photographs to orient a pair of permanently mounted T-11 cameras to an acceptable approximation of the normal case for terrestrial stereophotogrammetry (Hallert, 1960) and to estimate the systematic errors in measurement of distance and height due to inexact orientation.

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ABSTRACT: *Stereoscopic photographs are used to measure height and distance of points on convective clouds. The problem is to orient a pair of cameras to the normal case for terrestrial stereophotogrammetry without permanent ground objects common to both camera fields to serve as control points. The bearing (azimuth) perpendicular to the line joining the cameras is determined. Measurements from star photographs are used to place the camera axes on this bearing at zero elevation angle with minimum swing. The systematic errors in height and distance measurement due to imperfect camera orientation are determined using error equations and values of elevation angle error and x-parallax error measured on a stereoscopic pair of star photographs. An example is shown where maximum errors due to camera orientation are 1.2 percent for distance and 0.8 percent for height for an object twenty miles from the reference camera.*

As part of a field research program the Cloud Physics Laboratory uses serial stereoscopic photographs of convective clouds to obtain measurements of cloud height, position, and cloud top growth rate. Data analysis relates cloud size and its rate of change to the development or non-development of precipitation within the cloud. Precipitation information is obtained by scanning clouds with a 3-cm height-finding radar having a receiver gain such that the radar detects only precipitation-size particles.

The stereoscopic cloud photographs are provided by a pair of T-11 cameras, one camera mounted next to the radar antenna and the other approximately two miles away. To provide the simplest method for data reduction the cameras are mounted with their axes horizontal, parallel to each other, and perpendicular to the base line joining the camera sites—the normal case.

Our research period is seasonal and the research sites are remote from our laboratory. Consequently it is necessary to mount and position the cameras annually at the beginning of the research period and to remove and store them at the end of the period. The research sites are in relatively flat, forested terrain. No ground objects are common to both camera fields to serve either as control points or as points of known distance and height with which to test the accuracy of camera orientation.

Our stereoscopic camera arrangement is much the same as that employed by other meteorologists who use aerial mapping cameras on a base line distance of the order of one to three miles for research in cloud physics and cloud dynamics. Kassander and Sims (1957) were among the first to make use of serial photographs of this type for the purpose of measuring clouds. Variations of their technique have been used by Orville and Kassander (1961), Orville (1961), Glass and Carlson (1963), and others. None of these authors adhere strictly to the normal case.

The clouds studied in the above references were orographic in origin. The peaks of the mountains with which the clouds were associated appeared in both photographs of a stereoscopic pair and served as control points for positioning the photographs for measurement. In addition independent measurements of the distances and heights of the peaks could be compared with distance and height values obtained from the photographs to indicate orientation error. With no terrestrial features common to both camera fields, our technique is to use measurements from a star photograph to place the camera axis as closely as possible on a selected bearing, at zero elevation, with minimum swing (the angle in the focal plane between camera vertical and gravitational vertical). When a satisfactory orientation has been achieved for both cameras measurements from a stereoscopic pair of star photographs are used to estimate errors in distance and height due to imperfect camera orientation.

Initial Camera Placement

The choice of camera sites determines the direction toward which the cameras point. Having selected the camera sites we measure the length and bearing of the base line joining them using surveying methods and celestial observations. The bearing perpendicular to the base line is then computed. This is the bearing to which we orient the camera axes. In practice the perpendicular bearing is computed for one of the camera sites and both cameras are oriented to this value. Because our camera axis bearing has a component toward north, perfectly positioned camera axes, rather than being parallel, will converge at an angle of approximately one minute of arc.

The problem of proper camera placement is one of mounting the cameras so that they are level with their axes pointing toward the computed bearing. For fine adjustment the cameras are mounted in a yoke which is joined to a leveling table by a pivot bolt. The leveling table permits sensitive adjustment of the elevation of the camera axis and the swing around the camera axis. A set screw gives sensitive azimuth adjustment around the pivot bolt.

The initial setting of the camera to the proper bearing requires that an object whose bearing has been measured appear in the camera field. It is then a relatively simple matter to place the camera axis on the desired bearing to an accuracy of one minute of arc. The horizontal angle between the camera axis and the object is measured on a photograph. Any deviation of this angle from the desired value is corrected using the azimuth adjustment on the camera mount.

A first approximation to a level camera is attained with the aid of a spirit level placed on top of the camera. The level tube is first placed parallel to the camera axis and the bubble centered using the adjustable screws of the leveling table. The tube is then placed perpendicular to the axis and the process repeated.

Final Camera Adjustment

Final adjustment of the camera is made by using measurements from a series of star photographs. The stars' bearing and elevation angles are computed using their ephemerides for the time of the photograph. The stars' bearing and elevation angles are also computed using measurements of their positions in the photograph. The differences between the computed and measured values of elevation and bearing angles are used to correct the camera orientation and another star picture is taken. This procedure is repeated until an acceptable camera orientation is attained.

The star photograph is a time exposure. The time is recorded when the shutter is tripped at the beginning of the exposure. With the shutter open the lens is covered and uncovered periodically and the times of these actions are recorded. Thus a star's track appears in the photograph as a series of dashes (Figure 1). The elevation and bearing angles of the end points of the dashes are determined from their measured positions in the photograph. Independent computations are made of the stars' elevations and bearings at the times corresponding to the end points.

The T-11 camera exposes four fiducial marks on each photograph, one at the center of each margin. Lines connecting opposite fiducial marks are perpendicular and intersect in the photograph at the camera axis. These fiducial lines serve as cartesian coordinate axes for locating points in the photograph. The camera exposes two additional pairs of marks on the photograph, one pair in the bottom margin and the other pair in the right hand margin. The distance between each pair corresponds to the calibrated focal length of the camera (the camera constant). Thus the focal length may be measured in each photograph, providing a correction for film shrinkage.

Let us consider a point in a photograph taken with a perfectly oriented camera. The coordinates of the point are x and y with respect to the fiducial lines as a cartesian system. The bearing of the point is

$$B = \beta + \epsilon \qquad (1)$$

where

B = bearing angle, measured east or west from north

β = horizontal angle between the point and the camera axis

ϵ = computed bearing to which the camera axis should point.

From Figure 2

$$\tan \beta = \frac{x}{f} \qquad (2)$$

and the elevation angle of the point is given by

$$\tan h = \frac{y \sin \beta}{x} = \frac{y \cos \beta}{f} \qquad (3)$$

where

f = camera focal length

h = elevation angle.

The measured elevation angle of a star is corrected for atmospheric refraction using standard stellar refraction tables, for example the tables appearing in the Nautical Almanac.

The true elevation and bearing angles of a star are computed from the expressions

$$\sin h = \cos d \cos \phi \cos t + \sin d \sin \phi \qquad (4)$$

$$\sin B = \frac{\cos d \sin t}{\cos h} \qquad (5)$$

where

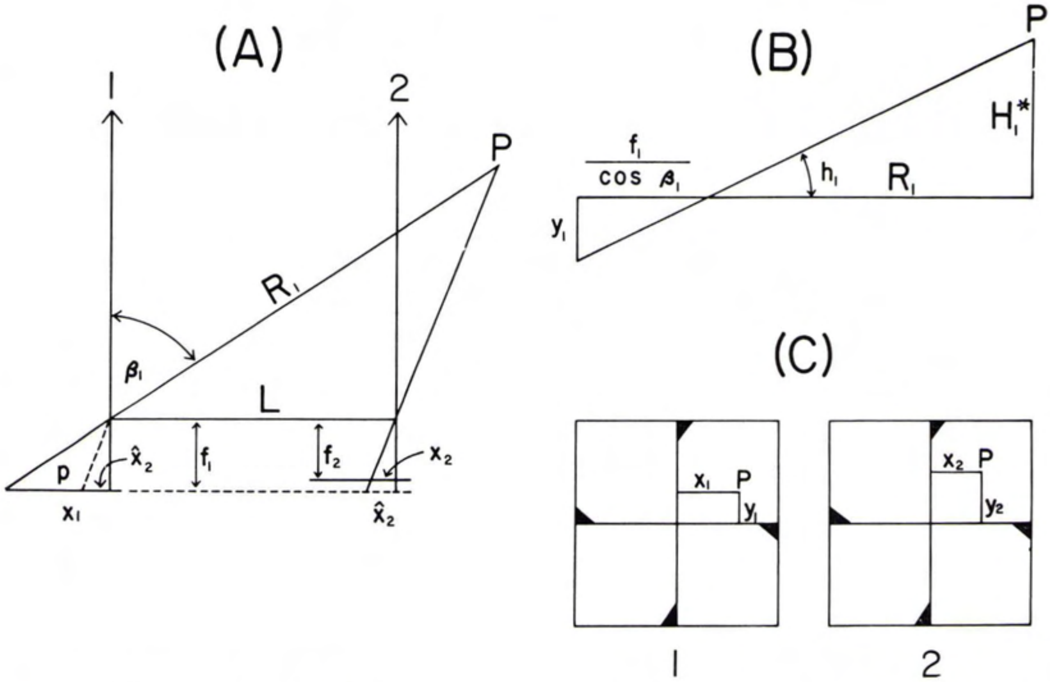

FIG. 2 Geometry for obtaining the height and range of point P from a stereoscopic pair of photographs. A, plan view; B, the vertical plane through Camera number 1 and P; C, schematic diagram of P in a pair of photographs.

d = declination of the star
ϕ = latitude of the camera site
t = angle between the star's meridian and the meridian of the camera site.

The meridian angle t is the algebraic sum of the Greenwich Hour Angle of the First Point of Aries, the Sidereal Hour Angle (SHA) of the star and the longitude of the camera site. The Greenwich Hour Angle of Aries for the observation time and the star's declination and SHA are obtained from the Nautical Almanac if the star is a navigational star. If a star is not a navigational star, one must refer to either *The American Ephemeris* or a star catalog for declination and SHA and correct the ephemeris or catalog values to the date of observation. Latitudes and longitudes of the camera sites are measured from United States Geological Survey quadrangle charts.

In practice we determine true and measured values of bearing and elevation angles for a few points near the edges of the photograph where the discrepancies due to camera swing are the largest. A subjective examination of the distribution in the photograph of the differences between measured and true values is generally sufficient to suggest camera orientation corrections. It has been our experience that the first star photograph shows maximum elevation and bearing errors of about five or six minutes of arc. Given sufficient time, it is possible to reduce the errors to approximately one minute. As time is a factor when we mount and orient the cameras, our goal is two-minute accuracy, but if necessary we accept error of three or four minutes on an occasional star near the edge of the photograph. We usually attain acceptable accuracy with three star photographs.

Albritton et al. (1962) describe a computation whereby measurements of star points in a photograph yield directly the bearing and elevation angles of the camera axis and the angle of swing around the axis. (These authors use *tilt* to describe what we call swing, the angle in the focal plane between the vertical fiducial line of the camera and gravitational vertical.) We find our method faster and more suitable for field work where, pressed to meet a deadline, we must take advantage of all clear nights for star photography and, occasionally, must perform the calculations by hand.

We observed above that our two camera axes oriented to a common bearing will converge at an angle of approximately one minute of arc. In addition, if both cameras are perfectly level their vertical fiducial lines will diverge upward at an angle equal to the arc joining the camera sites on the earth's surface. This arc is approximately a minute and a half for our field sites. In making measurements from the photographs using the normal case for stereophotogrammetry, these deviations from perfect orientation introduce an error in p, the x-parallax (Figure 2). The parallax error dp due to converging camera axes is barely measurable (0.002 inch on T-11 photographs) for targets at a distance of 50 miles and is less for closer targets. Divergence of the vertical fiducial lines introduces values of dp of 0.002 inch near the top of a photograph and less for lower elevation angles.

Calibration

Consider an object appearing in both photographs of a stereoscopic pair. From Figure 2 the height of a point on the object above Camera 1, the reference camera of the pair, is

$$H_1^* = \frac{Ly_1}{p} \qquad (6)$$

and the distance to the point from Camera 1 is

$$R_1 = \frac{H_1^* f_1}{y_1 \cos \beta_1} \qquad (7)$$

where

$$p = x_1 - \hat{x}_2 \qquad (8)$$

$$\hat{x}_2 = \frac{f_1}{f_2} x_2 \qquad (9)$$

L = the distance between the cameras

and the subscripts designate the respective cameras. H^* is uncorrected for the curvature of the earth and atmospheric refraction.

Differentiating Equations 3, 6, and 7 and substituting, we obtain the error equations

$$\frac{dR_1}{R_1} = \tan \beta_1 d\beta_1 - \frac{dp}{p} \qquad (10)$$

$$\frac{dH_1^*}{H_1^*} = \frac{dR_1}{R_1} + \frac{dh_1}{\sin h_1 \cos h_1}. \qquad (11)$$

Measurements from a stereoscopic pair of star photographs are used to determine distance error dR_1 and height error dH_1^* using Equations 10 and 11. For this purpose a longer exposure is used for the star picture than is needed for positioning the cameras. We have found that an exposure of 90 minutes gives quite thorough coverage of star points throughout the photograph. Stars may be considered to be an infinite distance from the cameras. Any measurement of parallax p at a star point then is in fact a measurement of the parallax error dp due to camera orientation. Elevation error dh_1 is the difference between true star elevation and the elevation measured in the photograph from Camera 1. Likewise bearing error $d\beta_1$ is the difference between measured and true bearing in Photograph 1. We have always been able to keep $d\beta_1$ sufficiently small so that the term $\tan \beta_1 d\beta_1$ in Equation 10 could be neglected.

A sufficient number of star points are evaluated to indicate the distribution pattern of dp and dh_1 throughout the photograph. Such a distribution pattern of dp and dh_1 is shown in Figure 3. The data from which this pattern is derived were taken from a pair of star photographs obtained during the Cloud Physics Laboratory's 1966 field operation at Bemidji, Minnesota. From this figure it is possible to use Equations 10 and 11 to determine height and distance orientation error at any point in the camera field. The results of such a determination are shown in Figure 4. The figure shows the maximum values of dR_1 and dH_1^* for distance and height ranges likely to be encountered in cloud measurement.

Some comparison may be made of the errors shown in Figure 4 with those of other authors. Glass and Carlson cite errors of about 0.5 percent in target location for targets 15 miles from the cameras. Measuring mountain peaks Orville finds an error of 0.4 percent for targets at 10.6 miles, and 0.6 percent for targets at 18 miles. Our maximum error in range (distance) is 0.5 percent at 10 miles, and 1.2 percent at 20 miles, and for most measurements the error will be less than these values. Both Orville and Glass

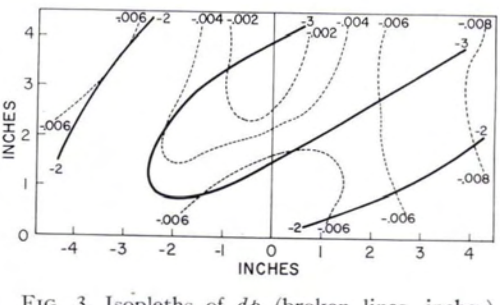

FIG. 3. Isopleths of dp (broken lines, inches) and dh_1 (solid lines, minutes of arc) computed for the 1966 camera orientation. The horizontal and vertical scales give position in the upper half of the photograph with the camera axis as the origin.

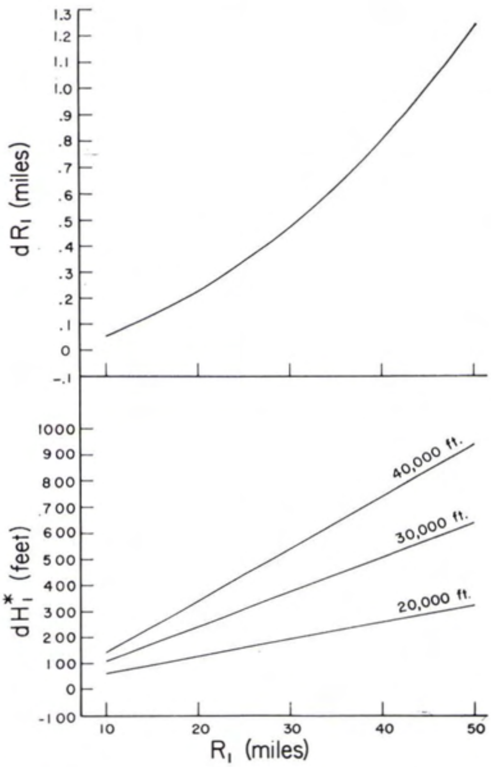

FIG. 4. Maximum values of dR_1 and dH^*_1 derived from the errors shown in Figure 3.

and Carlson measure range perpendicular to the camera base line whereas our range R_1 is the distance to the target from the reference camera. Orville's height errors are about 1 percent of the height above the cameras for heights of 6,500 feet or less. Our maximum height errors from Figure 4 are 0.4 percent at 10 miles, and 0.8 percent at 20 miles for heights of 20,000 feet and higher.

SUMMARY AND CONCLUSIONS

Star photographs serve as a valuable tool for orienting cameras to desired bearing, elevation, and swing angles. For the normal case for terrestrial stereophotogrammetry, swing and elevation angles should be zero and the bearing angle of the camera axis should be perpendicular to the bearing of the base line joining the two cameras. By noting differences between star elevations and bearings measured from photographs and star elevations and bearings computed from the stars' ephemerides one may correct for deviations from perfect camera orientation. With sufficient time it is possible to place the camera axis within one minute of arc of the desired bearing and zero elevation. Because of the difficulty in eliminating the swing angle about the camera axis, elevations and bearings of objects removed from the center of the photograph usually cannot be obtained at this accuracy.

Systematic error dp in the x-parallax is measured directly from a stereoscopic pair of star photographs. The systematic error in elevation angle measurement dh_1 is found by subtracting star elevations, measured on the reference camera photograph, from computed true star elevations. If values of dp and dh_1 are inserted in the error equations, height and range errors due to imperfect camera orientation can be determined.

The Cloud Physics Laboratory has used the star photograph technique to position cameras for cloud measurement during four summers of field research, the summers of 1962 and 1963 at West Plains, Missouri, 1965 and 1966 at Bemidji, Minnesota. The measurement errors calculated for the 1966 operation are representative of those for the other years and compare favorably with errors cited by scientists who positioned their cameras by other methods.

ACKNOWLEDGEMENTS

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