Photogrammetry from Aircraft Nose Camera Movies

CHARLES WARNER

University of Virginia, Charlottesville 22903

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ABSTRACT

Equations for photogrammetry from an aircraft nose camera movie are based on angles from a fixed point on the horizon toward which the aircraft is flying. The positions and dimensions of an arc of clouds occurring on day 261 of GATE are presented as an example. The accuracy of such measurements is a few kilometers in the horizontal and about 500 m in the vertical.

1. Introduction

The Atlantic Tropical Experiment of the Global Atmospheric Research Program (GATE)—which was centered near 8°N, 23°W during the summer of 1974—yielded an abundance of photographs of clouds over the tropical Atlantic, recorded as time-lapse movies from side and nose cameras mounted aboard aircraft, from the geosynchronous satellite SMS-1, and from all-sky cameras mounted aboard ships. To understand the convection, it is necessary to find ways of reducing these data to describe the patterns of the clouds. A very small percentage of the available photographic data from GATE has been exploited; most of the analysis to date has been by hand, a tedious procedure at best. The purpose of this note is to present a method for the use of aircraft nose camera movies to describe mesoscale features of clouds. The method is not new in principle, but it has never before been applied to cloud patterns (to the author's knowledge). As presented here it is relatively quick; a limited program of cloud mapping can be accomplished in weeks rather than months.

With aircraft subject to irregular movements of roll, pitch and yaw, the precision of photographic measure-

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ments is limited to some hundreds of meters. The approach is different from the case of stereo-pair time-lapse movies made from ground-based cameras at carefully surveyed sites (Warner *et al.*, 1973), in which locations and velocities of clouds may be followed quite precisely. Aircraft quickly pass over extensive areas, allowing one to record cloud positions at the times of encounter, but not generally to follow the details of behavior of any one cloud unless the aircraft circles nearby. One looks to aircraft movies for the delineation of mesoscale features of clouds.

Meteorological photogrammetry has recently been reviewed by Holle (1978). Much aircraft photogrammetry using side camera and nose camera movies has been done using the approximate graphical methods of Ronne (1959). In the former case, for straight and level flight, the distance of a cloud from the aircraft track is related to the time taken—or the number of frames of film—for the cloud to pass across the field of view. The plan position of the cloud is found by triangulation. The height of the cloud then follows from a measurement of its angle of elevation referred to the direction of view or principal axis of the camera, and a knowledge of the location of this axis at the time of measurement.

For the case of a nose camera pointing forward along the flight direction, Ronne made use of the fact that any object will double its size if the distance between the camera lens and the object is halved. One can again obtain the horizontal position of the cloud by triangulation, and then its height after measuring its elevation.

To be rigorous, photogrammetry can proceed only as a series of angular measurements referred to the principal axis of the camera. When pointing to the side of an aircraft, this axis moves across the clouds both with steady translation, and with small irregular up, down and lateral movements as the attitude of the aircraft continuously changes. Care is necessary in dealing with this motion. When pointing along the direction of flight, the camera axis corresponds closely with the direction toward which the aircraft is heading. If the view contains many cloud features, the corresponding point in projected images of the movie is readily recognized; cloud images move radially away from the point as the aircraft travels forward. Angular measurements may be referred to this point seen in every frame of the movie, irrespective of minor changes in attitude of the aircraft. With the approximation that the camera axis corresponds to the point toward which the aircraft is seen to be heading, the following method is rigorous.

The nose camera used here, with a lens of effective focal length about 10 mm, was flown at altitude 5.7 km aboard NOAA's US-C130 aircraft, and recorded clouds at all levels within roughly 20 km on either side of the flight track. For clouds more distant than about 20 km, use of a side camera is preferable.

A nose camera has the advantage that penetrated clouds are photographed beforehand.

2. Photogrammetry

Illustrating the method, an example is given from day 261 (18 September 1974) of GATE. On this day, five aircraft flew twice around a box circuit of side 150 km (defined by the latitudes 8°34′ and 9°56′ N, and longitudes 21°2′ and 22°23′ W), around a cloud cluster as it was growing. Some description of this activity has been given by Warner *et al.* (1977). Here we consider an arc pattern of clouds in the lower troposphere, seen from the US-C130 aircraft as it flew westward along the north side of the box. With a ground speed of about 136 m s^{-1}, and an exposure every 5 s, views were obtained at intervals of about 680 m along the flight track.

The arc formation is shown in the foreground of Fig. 1, a photograph taken by Joanne Simpson at 1522 GMT from a side window of the aircraft. Preceded by many tiny cumulus, the arc was composed of cumulus clouds leaning backward (in a manner which corresponded with the shear of the wind). Behind the arc the air was clear. Here we examine the shape of this particular arc. Documentation of other such features on this day is in preparation, with an ample exploitation of many of the other sources of data in GATE, with a view to elucidating the principal features of the convection.

FIG. 1 (right): 1522 GMT 18 September 1974. Composite of photographs looking north from US-C130 flying at altitude 5.7 km, from location B in Fig. 2.

FIG. 3 (left): 1521.45 s GMT 18 September 1974. Frame from C130 movie looking west from location A in Fig. 2, showing clear air behind the arc.

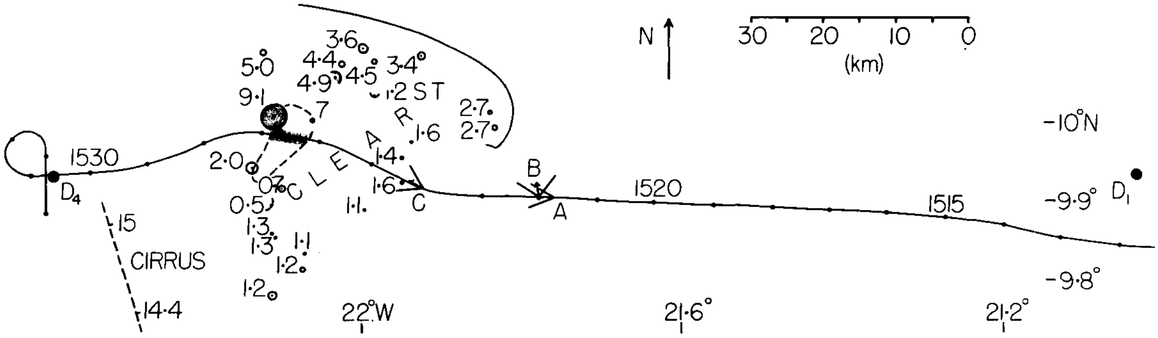

FIG. 2. 1520 GMT. Plan view of clouds mapped by nose camera photogrammetry. The US-C130 flew westward along the track shown, marked at minute intervals, between D₁ and D₄ (the north side of the box circuit). Measured clouds are represented by a dot, with a circle of diameter equal to the measured width. Numbers are heights in kilometers above sea level. Dashed line partly delineates westward extent of cirrus. Curved solid line, drawn in by hand, marks the approximate boundary where tiny cumulus fractus gave way to cumulus mediocris. Fields of view for Figs. 1, 3 and 4 are denoted by B, A and C, respectively.

The first step in analysis was to plot the track of the aircraft as a function of time on a plan view map of scale 1 inch = 4 n mi (Fig. 2), using data on microfilm provided by NCAR. These include the position and attitude of the aircraft at intervals of 1 s. The 16 mm color movie was then put into a projector having a frame counter, and after zeroing the frame counter at a recognizable frame, the frame number was found as a function of time. This was done by plotting for selected intervals the roll of the aircraft as a function of time and as a function of frame number, and comparing the two plots. With rapid changes in roll occurring at turns, a precision of 1 or 2 s was obtained for the time of any chosen frame. Frame numbers of the film could then be put on the map of the aircraft track.

Two photographs looking forward along the flight track are shown in Figs. 3 and 4. Fig. 3 is reproduced from the 16 mm nose-camera movie (see location A in Fig. 2). It shows clear air southwest of the arc, behind other clouds in the foreground. Over it was a tall cumulus, later penetrated. From a 35 mm slide taken near location C in Fig. 2, Fig. 4 shows this cumulus shortly before penetration. It had a sloping base, at altitude 3 km in the center of the picture. Hatching along its track shows where the aircraft passed through this cloud, giving a good opportunity to check the photogrammetry.

Analysis proceeded on the following basis, from measurements within the interval 1518.30 s to the turn at 1523.30 GMT (with a few from beyond the turn). For a case of straight and level flight, the image of a cloud element moves radially away from the point where the optical axis of the projector appears on the projection screen (or principal point). This is shown in Fig. 5, in which measured quantities are indicated. As the film is advanced from frame n_i to frame n_j, the distance of the cloud image from the principal point increases from d_i to d_j, while the radial along which the image moves remains at constant angle ϵ to the horizontal. The approximate width w_j of a cumulus tower was measured at a height judged to be a few hundred meters below its top. (For cloud elements above flight level, ϵ was negative. For clouds to the right of the aircraft track, an indicator k was set $=1$; for clouds to the left, $k=-1$.)

These data were fed to a computer program designed to output the following results for a given cloud element:

FIG. 4. 1524 GMT. Photograph from cockpit of US-C130 looking west-northwest from location C in Fig. 2, at cloud about to be penetrated.

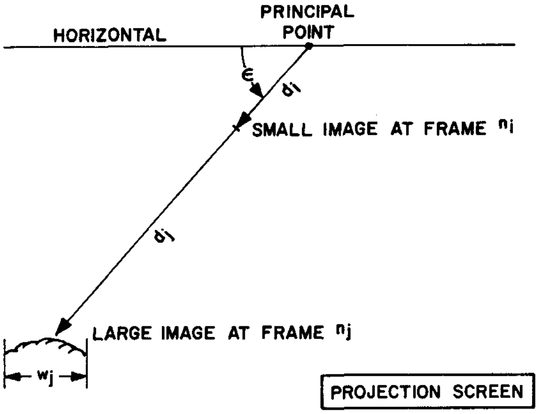

FIG. 5. Positions on a vertical projection screen of first and last images (recorded on frames n_i and n_j, respectively).

n_x, the frame number of the film at which the element was directly to the side of the projected track of the aircraft; y, the range of the element normal to the flight track; z, the height above the sea of the element; and w, the width of the element. The results were plotted on the plan view map Fig. 2 as dots in appropriate locations (from outputs n_x and y). A circle of diameter w was centered on each dot, and labeled with the height z.

Parameters built into the computation were f the effective focal length of the camera multiplied by the magnification due to projection (the latter being the ratio of a linear dimension of the projected image of the film gate in the projector, to its actual dimension); the distance s traveled per frame; and the altitude h of the aircraft above the sea.

To show how output results are obtained, the location of the cloud in a vertical plane normal to the flight track is shown in Fig. 6. The distance a in this figure is given by

$$a=(n_x-n_i)s(d_i/f)=(n_x-n_j)s(d_j/f), \qquad (1)$$

where d_i/f (or d_j/f) is the tangent of the angle between the ray to the cloud element and the principal line or heading direction at frame n_i (or n_j). (In this formulation, the curvature of the aircraft track around the earth's center is taken as zero.) Eq. (1) immediately yields

$$n_x=(n_jd_j-n_id_i)/(d_j-d_i). \qquad (2)$$

This equation shows that the position of the element along the flight track is found independently of the focal length f, and the angle ϵ. The frame number n_x is best obtained by making the run of frames n_i to n_j as long as possible.

From Fig. 6 one has

$$a=y\ \sec\epsilon. \qquad (3)$$

Using Eq. (1), this leads to

$$y=(s/f)d_jd_i(\cos\epsilon)(n_j-n_i)/(d_j-d_i). \qquad (4)$$

For the height z of the element, from Fig. 6,

$$h-z=y\ \tan\epsilon. \qquad (5)$$

Allowance for the earth's curvature is inappropriate here. Heights may be underestimated by the additive quantity $r^2/2r_E$, where $r_E\approx 6337$ km is the local radius of curvature of the earth's surface and r is the range. This correction equals 100 m at $r=36$ km. For the small ranges involved in this work, uncertainties arising from the measurements exceeded this curvature effect.

From Eqs. (5) and (4)

$$z=h-(s/f)d_jd_i(\sin\epsilon)(n_j-n_i)/(d_j-d_i). \qquad (6)$$

The cloud element shown in Fig. 5 is to the left of the aircraft track: $k=-1$. (Had it been to the right, $k=1$.) The range y is multiplied by k before printing the output.

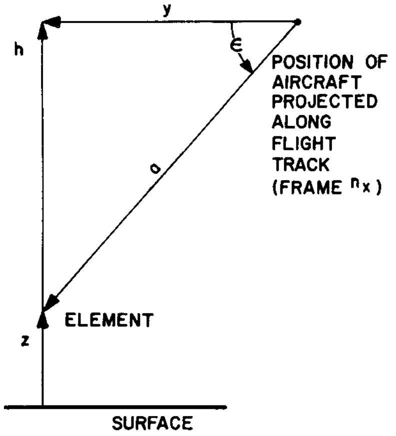

FIG. 6. Positions related to the cloud element on a vertical plane through the element and normal to the flight track.

The approximate angular width measurement of the cloud, $w_j(f^2+d_j^2)^{-0.5}$[rad], is converted to width in linear units by the equation

$$w=w_j(n_x-n_j)s/f. \qquad (7)$$

Here the angular width of the element, measured at frame n_j, is multiplied by the distance of the camera from the element at frame n_j.

When making the measurements uncertainties were estimated. Different combinations of measurements within these limits of uncertainty were punched on to separate computer cards. The computer processed each card in turn, and so produced a range of output for any one cloud element. A choice of appropriate output was made subjectively, the choices for all cloud elements being mutually consistent and compatible with other available information, as described below.

The map of the cloud arc appears in Fig. 2. The knowledge of penetration of one of the mapped clouds gave a good opportunity to check horizontal positions, better than any other information. The derived position of this cloud should be close to the hatching indicating the penetration. It is; it might be a little too far west. The only permissible adjustment to the fixed parameters of the computation was f, of nominal value 9.5 mm multiplied by the magnification used (48.8). To obtain the present results f was increased by 5%. This is within the limits of uncertainty, due primarily to the unknown effect of the aircraft window through which the camera was pointed. The adjustment had no effect on distances parallel to the aircraft track [f being absent from Eq. (2)], but did reduce displacements sideways from the track [through Eq. (4)] and differences of height from that of the aircraft [through Eq. (6)]. The adjustment to f was chosen on the basis of heights. At the nominal value of f, the tops of the lowest clouds would have been several hundred meters lower (within a few hundred meters of sea level), and the cirrus edge would have been several hundred meters higher.

Descending southward to the NOAA ship *Oceanographer* at 1615 GMT, the US-C130 passed tops of low clouds (like those shown here) at 2.7 km; ascending again a few minutes later, tops were encountered at 2.2 km. Photogrammetry by the technique described yielded tops of similar nearby clouds of 2–3 km. The map in which these clouds appear will be presented separately, along with much other information. Photogrammetry from a C-130 side camera (Warner *et al.*, 1977) put the cirrus at 12.5 or 13 km at 1434 GMT, at an early stage of development; at 1620 GMT it was at about 14 km. In Fig. 2 we have 14.4 and 15 km, the former probably more accurate. The tropopause was at about this altitude, not clearly defined. Radio soundings also indicated a stable layer at 2.3 km; the map Fig. 2 shows most of the small clouds below this level, as expected.

The agreement between various analyses gives confidence that the technique yields horizontal positions accurate to a few kilometers, and heights to about 500 m.

Fig. 2 shows a number of cumulus towers growing in an arc pattern. A line has been added to the figure to indicate approximately the boundary where tiny cumulus fractus gave way to larger cumulus mediocris. This boundary is seen clearly in Fig. 1. Toward its west end, a series of cumulus elements were found, with heights increasing southward, culminating in the tower which was penetrated. The base of this tower rose toward the south, reaching 3 km under the line of penetration. Southwest of the arc the air was clear. A fairly full discussion of these phenomena is in preparation.

3. Conclusion

A technique of photogrammetry has been described, for use with time-lapse movies made with aircraft nose cameras. In straight and level flight, the camera axis is pointed approximately along the direction toward which the aircraft is headed. If the view ahead is crowded with cloud features, the heading direction can be recognized in the series of projected images of the film, as a principal point. Then angular measurements can be made from this principal point, without regard to small irregular changes in the attitude of the aircraft from frame to frame. This situation is inherently better than that of a side camera movie, where the camera axis both translates across the cloud field, and moves irregularly with the aircraft.

Experience with the technique indicates that for a camera lens of focal length 10 mm and field of view of about 55°, horizontal positions can be obtained with an accuracy of a few kilometers and heights to about 500 m. Such accuracies are useful for examining patterns of clouds on the mesoscale.

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