Stereo photogrammetry of cumulonimbus clouds

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SUMMARY

A technique is described for stereo photogrammetry of clouds. Movie cameras are set up on a ground baseline 5-6 km long. Time-lapse films are made with a frame interval of 3 s. The analysis involves the superimposition of stereo pair images of the cloud, with advantages over methods previously used.

Measurements are presented of an Alberta hailstorm, and estimates are made of horizontal divergence near the cloud tops, and mass flux. Measurements and calculations imply that the ring vortex model of the circulation in small cumulus tops is applicable to some large hail-bearing storms, and that little or no net mass transfer occurs through the caps of rising cloud towers.

1. INTRODUCTION

In this paper a technique of stereo photogrammetry is described, for examining the behaviour of cumulonimbus clouds, using a pair of ground based time-lapse movie cameras. After outlining the measurements and computations, details of behaviour in one particular hailstorm are examined.

The technique was developed by Renick in 1965 as part of the Alberta Hail Studies project, and has been used in Alberta during recent summer seasons. The time-lapse films yield information on the dynamics of storm updraughts: they show the outlines of cloud towers rising at the top of a storm. On projecting these films at normal speeds the cellular nature of storm tops, and the smoothness of storm inflow at cloudbase, are revealed clearly.

Time-lapse photography has been used in meteorology since the beginning of the century. By this means it has been shown that storms build up as a succession of cloud towers of increasing height (Brown 1966). The tops of these towers show pulsations with periods of a few minutes (Anderson 1960, Orville and Kassander 1961); they expand as they rise (Saunders 1961), and on their tops a radial outflow occurs (Vonnegut and Atkinson 1958).

Methods for stereo photogrammetry have been described by Kassander and Sims (1957), Shaw (1969) and others. All methods must involve the matching of features in the two photographs of a stereo pair, so that detailed analyses are laborious. The present system involves the superimposition of stereo pairs, projected simultaneously on to a translucent screen. This facilitates unambiguous identification and matching of common cloud features, and rapid measurement.

2. MEASUREMENTS

(a) Outline of the technique

Pictures are taken simultaneously, every 3 s, with two Bolex H16 movie cameras, on Kodachrome II film. The cameras are located 5-6 km apart on a north-south baseline. Each camera site is surrounded by marker poles stationed at 10° intervals of azimuth, on a circle of radius 11 m centred on the camera pedestal. On each pole orange marks indicate the horizontal, and + 1° elevation.

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From corresponding frames of the films from each camera, measurements are made for the same time \( t \) of the azimuth \( \phi \) and elevation \( \theta \) of cloud elements. The measurement geometry is shown in Fig. 1, with subscripts \( C \) and \( R \) referring to the 'centre' and 'remote' sites. In order to determine precisely the range \( R \) in the base triangle, the azimuth difference \( a = \phi_R - \phi_C \) must be measured precisely; but this angle must be little more than 10° if fine structural detail in the cloud is to be identified unambiguously in both members of a stereo pair. With superimposition of images of the two photographs, \( a \) may be measured directly, in terms of the displacement of images of the marker poles (Fig. 2).

![Figure 1](image.png)

Figure 1. Measurement geometry. \( R \) refers to range on the tangent plane through the centre site, and \( R_s \) to slant range. \( \phi_B \) is the azimuth of the baseline. The other angles are described in the text.

![Figure 2](image.png)

Figure 2. Superimposition of two cloud images. Poles A and B mark the same azimuth in the two photographs: \( a \) is measured directly.

This can be done very precisely. To achieve superimposition, pairs of corresponding frames on the two films are projected simultaneously on to a plane translucent screen. The two projectors are placed on a table facing one another, at a distance of 2 m, with the translucent screen midway between them (Fig. 3). The translucency permits the viewing of the image from either projector from either side of the screen. The film in one projector is reversed so that the two cloud images are compatible.

The screen is marked with a grid of lines of constant azimuth and elevation, at 1° intervals. To obtain the grid, appropriate horizontals and verticals were drawn on a large
plywood panel, which was bent to a cylindrical shape of radius 2 m and photographed with a camera set up normally, with the front nodal point on the axis of the cylinder. After development, the film was projected in the normal way, and the image of the grid traced on to the screen. This procedure yielded automatic compensation for standard lens and film distortions.

Cameras and projectors are fitted with lenses of the same focal length, and tilted at the same angle to the horizontal. Thus lines of constant azimuth in the grid are vertical, and a projector may be rotated about a vertical axis through its front nodal point in order to obtain superimposition of cloud images on the screen.

The projectors are placed on complex mounts, to permit compensation for small distortions, such as variations in shrinkage of the film, by adjusting a projector so as to fit the separation of a pair of adjacent marker poles to the azimuth scale on the screen.

Optimum precision in the measurement of the angles is obtained by using alternative sets of lenses for the cameras and projectors. Lenses of focal length 25 or 12.5 mm are used, for clouds at ranges respectively greater or less than 30 km. With the axes of the cameras tilted at respectively 7° or 10° upwards from the horizontal, the field of view is 22° horizontally by 15° above the horizontal, or 42° by 26°.

(b) Measurement uncertainties

For the particular occasion described in Section 4, measurement uncertainties are given in Table 1. The largest uncertainties are systematic, in azimuth, incurred in setting up the cameras, for we are not able to build permanent installations. The marker poles are mounted in metal buckets and surveyed with a transit every two weeks during a season. Occasionally one of them shifts by as much as 0.03°, and then an alternative pole is used, or a distant landmark, if available. Image superimposition is accomplished with a random

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<td>Baseline azimuth, $\phi_B$</td>
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<td>Time ($t$) Uncertainty in measurement of intervals: $\pm2.8$ s</td>
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</table>
uncertainty of ± 0.02°. The time of any frame in the films can be read from a watch included in the field of view.

Generally it is difficult to follow a particular cloud element over a measurement interval. A large cloud tower is composed of many small elements, and often the direction of the point of highest elevation shows discontinuous changes, comparable in size with the measurement uncertainties. About 40 per cent of these irregularities, and of the random uncertainties, are removed by smoothing, which is described below.

3. Computations

The two sets of values of azimuth (Φ) and elevation (θ) define two 'rays' from each camera. With perfect measurements these rays intersect at the cloud element. In practice there are slight inaccuracies, so that the rays do not intersect. For any given pair of rays in three-dimensional space a unique 'short line' may be found which represents the shortest distance between the two rays (Fig. 4). The method of computation involves finding the mid-point of the short line, and taking this as the best estimate of the location of the cloud. The procedure follows that devised by Thyer (1967).

![Figure 4. The 'short line' of closest approach of two rays. Note that the two 'rays' and the 'short line' are not co-planar.](image)

The method was found necessary only in rare cases where the two elevation angles (θ) differed by an amount substantially greater than the measurement uncertainty: when the cloud was off to one side of the normal to the baseline, and at close range. In normal circumstances θR can be ignored, because generally it is close to θc (see Fig. 1).

Computations are performed on the measurements of Φ and θ after smoothing by taking running means. This smoothing consists of applying the following formula twice in succession to equally time-spaced measurements (xₙ):

\[ xₙ = 0.25 (xₙ₊₁ + xₙ₋₁) + 0.5 xₙ. \]

Values (x₁) at the beginning of sequences are modified to

\[ x₁ = (5x₁ + 2x₂ - x₃)/6; \]

a similar function is used for the end points. After the calculation of positions, a further pair of passes of running means is applied: then velocities are calculated, by finite differencing over two measurement intervals.

A discussion follows of the uncertainties in calculated positions and velocities. The range (R) of the cloud in the tangent plane from the centre site may be described in terms of the baseline (B) and the azimuths ΦB, ΦC and ΦR which are measured quantities (see Fig. 1):

\[ R = B \sin (\phi_R - \phi_B) / \sin a. \]
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By logarithmic differentiation, uncertainties (prefix d) are related as follows:

$$\frac{dR}{R} = \pm \frac{dB}{B} \pm \cot(\phi_R - \phi_B)d(\phi_R - \phi_B) \pm \cot a da.$$

The fractional range uncertainty is expressed in terms of the uncertainty in the length of the baseline and the uncertainties in differences in azimuth. For the storm described in Section 4, at 65 km range and with $a \sim 5^\circ$, the three terms respectively yield a total systematic uncertainty of

$$\pm 0.5 \pm 0.07 \pm 4.6 \sim \pm 5.2\%, \text{ or } \pm 3.4 \text{ km at 65 km;}$$

and a total random uncertainty of

$$0 \pm 0.01 \pm 0.09 \sim \pm 1.0\%, \text{ or } \pm 0.7 \text{ km at 65 km.}$$

The uncertainties in $a$ (in $\phi_R$ and $\phi_B$) predominate; and this angle, subtended by the baseline at the cloud, is at nearly a minimum acceptable value. Comparison of cloud with radar data indicated that on this occasion the systematic uncertainty was within $\pm 1.5$ per cent.

The height ($H$) of the cloud approximately is equal to the product of range and elevation. Then

$$\frac{dH}{H} \sim \pm \frac{dR}{R} \pm \frac{d\theta}{\theta},$$

in which the range term predominates. Differentiating the height equation yields an expression for uncertainties in vertical velocity ($w$):

$$d(w) \sim \pm Rd\left(\frac{\Delta \theta}{\Delta t}\right) \pm \left(\frac{\Delta \theta}{\Delta t}\right)d(R) \pm \theta d\left(\frac{\Delta R}{\Delta t}\right) \pm \left(\frac{\Delta R}{\Delta t}\right)d(\theta).$$

For the storm described, with $\Delta t = 40s$,

$$d(w) \sim \pm (0.9 + 0.4 + 3.6 + 0.01) \sim \pm 5 \text{ m s}^{-1}.$$}

The major contribution to this possible uncertainty arises from the term $d(\Delta R)$, here 1.2 km, which is related closely to the magnitude of the random component of $\cot a da$ in the equation for the range uncertainty. The ideal baseline would be about 9 km in length.

4. **An Alberta hailstorm**

   (a) Cloud top measurements

   On 15 July 1968 data were obtained on an evening storm which consisted of a small number of distinct cells, reminiscent of the descriptions by Byers and Braham (1949). Fig. 5 is a photograph of the storm taken at 1929 MST (0229 GMT). The two cells are 65 km to the east of the cameras. The cell on the left is labelled NW, that on the right SE. Soft hail of diameter up to 1 cm, in a shaft about 800 m wide, was encountered by a Hail Studies mobile sampling vehicle at 1930, under cell NW. Hailstone diameters reached 1.5 cm twenty minutes later.

   For the period 1924 to 1933 MST, stereo measurements were made of all those small elements on the cloud tops which could be followed in the films for one minute or more. A time step of 20 s was used, roughly commensurate with the measurement resolution. Besides the measurements of elevation and azimuth of the tops, an approximate measurement of the width of each element was made, close to the level at which it merged with the cloud mass.

   Measurements of sufficient density were obtained to make possible the drawing of height contour maps. The map for 1929 MST is shown in Fig. 6, with a height analysis, done by hand, for levels from 7 to 9.5 km. Eighty-nine elements were involved here. This view of the cloud may be compared with the photograph.
Figure 5. 1929 mst. Cells NW and SE, 65 km away to the east of the camera.

Figure 6. 1929 mst. Plan view of cloud tops, with constant altitude contours at 500 m intervals drawn in by hand. Each of the 89 measured elements indicated by a semi-circle of diameter equal to its width. Cloud tops NW₁, NW₂, NW₃, SE₁ and SE₂ are identified.

On Fig. 6 locally higher parts of the cloud are identified as cloud tops NW₁, NW₂ and NW₃ (collectively NW), and SE₁ and SE₂. The contouring was affected by the difference in height between the tops of the small elements and the levels at which they merged into the cloud mass; the contours shown are based on the top heights. Stereo
viewing (Fraser 1968) of the photographs indicated that the contours were less smooth than those drawn.

Widths were measured of 560 cloud top elements, and visual lifetimes were determined to the nearest 20 s. The minimum discernible width was 50 m (subtending an angle of 0.05°). Relative frequencies diminished, for both widths and lifetimes, for values increasing towards a few hundred metres and 4 min; median values were about 150 m and 1.3 min. The large cloud tops 2 km across were visible for roughly 8 min. In Fig. 6 the measured widths of the elements are indicated by semicircles.

Vertical velocities averaged over 3 min were obtained with an uncertainty of about ±1 m s⁻¹. Details of the height-time trajectory of cloud tops NW₁ are shown in Fig. 7. This cloud was made up of small elements appearing in succession at the rising top, as indicated by the different symbols. While each element individually rose while visible with velocities decreasing from about 5 m s⁻¹, the cloud as a whole rose quite steadily at 7 to 10 m s⁻¹. It is inferred that while still invisible within the cloud mass, the elements rose at speeds faster than 10 m s⁻¹, decelerated abruptly on reaching the top, and were replaced by others closely following. This behaviour, shown clearly by irregularities in sequences of measured elevations, has been seen on all of many cloud tops.

![Figure 7](image)

Figure 7. Detailed height-time trajectories of top NW₁, showing how it was made up of a succession of small elements (each represented by a different symbol).

(b) Estimates of horizontal divergence and mass flux

From the contour analyses (Fig. 6), it was possible to measure widths (D) of clouds NW and SE₁ as a function of height and time. These appear in Table 2. Included also in parentheses are the expansions in area (2/D) (ΔD/Δt), calculated over intervals Δt of 20 s. These are identified as horizontal divergences. In the right-hand column the height of the cloud is given. The calculated divergences exceeded 10⁻² s⁻¹ near the cloud tops. From satellite observations, Sikdar, Suomi and Anderson (1970) found divergences at storm tops of about 0.05 × 10⁻² s⁻¹. They show a maximum value near 10⁻³ s⁻¹, close to the values calculated here.

Under an assumption of zero net mass transfer across the caps of the clouds, mass fluxes were obtained from the width measurements. First, each width measurement was
TABLE 2. Widths (km) of rising towers, and (divergences) \((10^{-2} \text{ s}^{-1})\)

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<th>7.5</th>
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converted to a mass of air \((M)\):

\[
M = \rho(\pi D^2/4)k.
\]

\(\rho\) is the air density and \(k\) the thickness of the layer for which the area measurement was made: from 250 m below to 250 m above the nominal level \((k = 500 \text{ m})\) – except for the highest level where \(k = 250 \text{ m}\). Thus each cloud tower was treated as a stack of discs. In Figs. 8 and 9 the masses are shown plotted against time for the two towers. Then for the
family of different heights a family of matching curves was drawn by hand to represent the change with time of mass at each height, bearing in mind that the stereo time-lapse films showed that the clouds grew smoothly. There is considerable scatter in the points, so that these families of curves might have been drawn differently, and the deductions must be viewed with caution.

From the slopes of the matching curves, mass fluxes \( \frac{\Delta M}{\Delta t} \) were evaluated over each 20 s interval; the values are written in on each height curve. Then these values were summed in order of decreasing height, obtaining the total mass flux at each level \( h \) at each time (working upwards in columns in the figures):

\[
\left( \frac{\Delta M}{\Delta t} \right) (h - 1/2), \quad t = \sum_{h=\text{h=top}}^{h=\text{h}} \left( \frac{\Delta M}{\Delta t} \right) h, t.
\]

Values of 4 to 20 \( \times 10^7 \) kg s\(^{-1}\) were obtained for the upper middle troposphere, in good agreement with those found mainly from photographic data by Brown (1966). Inflow air fluxes at cloud base in other storms have been measured from aircraft. The values found here are comparable with the overall mean value of 23 \( \times 10^7 \) kg s\(^{-1}\) given by Auer and Marwitz (1968) for hailstorms on the high plains; and with a median value, 12.5 \( \times 10^7 \) kg s\(^{-1}\), given by Dennis, Schock and Koscieslki (1970) for hailstorms of western South Dakota.

(c) Comparison of measured rise rates with horizontal divergences

As it penetrated the tropopause at 8.3 km, each cloud tower was rising at about 7 m s\(^{-1}\). Such apparent uniformity on a given occasion has been noted by Craddock (1949)
and Scorrier and Ludlam (1953). Over periods of about one minute the motion was irregular, and the measurements of rise rate showed considerable scatter. The maximum rate, measured over 40 s, was 12 m s⁻¹. A downward return flow occurred on the flanks of the rising towers: five cloud elements which were followed for 1.5 min or more moved at about −4 m s⁻¹. The circulation in the cloud tops appeared similar to that of a ring vortex, and the numbers obtained here correspond quite well to those for laboratory thermals given by Woodward (1959). She found that if the cap of a thermal moved at velocity $W$, the velocity on the flanks was $-0.6 W$, and the velocity of fluid in the core of the thermal was about 2.2 $W$. Thus, rise velocities in the cores of the updraughts in this storm probably reached 15 to 20 m s⁻¹.

This result may be compared with the measurements of horizontal divergence. If there is zero net mass transfer across the cap of a cloud, then as the rise velocity ($w$) in the updraught diminishes towards zero at the cloud top, its decrease with height ($-\Delta w/\Delta H$) approaches the local horizontal divergence: the units m s⁻¹ km⁻¹ translate to $10^{-3}$ s⁻¹. Near the cloud tops, calculated horizontal divergences exceeded $10^{-2}$ s⁻¹. If the assumption of zero net transfer is correct, then $-\Delta w/\Delta H$ in the updraughts exceeded 10 m s⁻¹ km⁻¹. If there was a net flux downwards into the caps, then values of $-\Delta w/\Delta H$ were smaller. The updraught core velocity of 15 to 20 m s⁻¹ at the level of the tropopause, suggested above, would yield a value of $-\Delta w/\Delta H$ near the cloud tops exceeding about 10 to 13 m s⁻¹ km⁻¹. Thus in this case, the ring vortex model for the circulation in the cloud tops is consistent with the occurrence of little or no net mass transfer through the caps of the clouds.
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(d) Summary

Time-lapse films showed that the circulation in the cloud tops of this large hail-bearing storm was similar to that of a ring vortex. The caps of the clouds rose through the level of the tropopause at about 7 m s⁻¹, with downward motion on the flanks near 4 m s⁻¹. It is inferred that velocities in the cores of the updraughts reached 15 to 20 m s⁻¹. Expansions in horizontal area of the cloud tops exceeded 10⁻² s⁻¹, and this result was found consistent with the inferred core velocities and an assumption of zero net mass transfer through the caps of the clouds. The latter assumption yielded values of mass flux near 10⁸ kg s⁻¹ in the upper middle troposphere. All of the numbers obtained are consistent with the results of previous work, and therefore it seems that the assumption of zero net mass transfer through the caps of the clouds is approximately correct.

Acknowledgments

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