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# PHOTOGRAMMETRY APPLIED TO AVALANCHE STUDIES

*By* M. C. van Wijk

(Photogrammetric Research, Division of Applied Physics, National Research Council, Ottawa 7, Ontario, Canada)

Abstract. Stereophotogrammetric techniques were used for a study of snow avalanches. The contour lines of the avalanche slope were mapped from stereo-photographs taken before and after the occurrence of the avalanche. The outline of the avalanche front at certain time intervals and the contours of the snow cloud were also plotted. A relative accuracy for the different maps of 0·7 m. on the terrain was established.

The volume of the snow cloud at four different stages of the avalanche was determined from the maps. These volumes were also computed independently from coordinate readings that were made in the stereo models. The standard errors of both methods of volume determination were estimated to be 450 m.$^3$ and 290 m.$^3$ respectively, representing errors of 5 per cent and 3 per cent of the average cloud volume.

The photographs were taken with an accurately determined time interval. Therefore, the velocity of the avalanche front could be determined from the photogrammetric measurements.

Résumé. *Application de la photogrammétrie a l'étude des avalanches.* Des techniques photogrammétriques furent utilisées pour une étude d'avalanches. Les contours de la pente d'avalanche ont été levés avec des stéréo-photographies prises avant et après l'avalanche. On a aussi dessiné la ligne extérieure du front d'avalanche à certains intervalles de temps et les contours du nuage de neige. Pour les différentes cartes, l'erreur relative est de 0,7 m sur le terrain.

A partir de ces cartes, on a déterminé le volume du nuage de neige à quatre stages différents de l'avalanche. Ces volumes ont aussi été obtenus indépendamment à partir des coordonnées lues dans les modèles stéréoscopiques. L'erreur standard pour les deux méthodes a donné respectivement 450 et 290 m$^3$, soit une erreur de respectivement 5% et 3% du volume moyen du nuage.

Les photographies ont été déterminées avec un intervalle de temps déterminé d'une manière précise. Il en résulte que la vitesse du front d'avalanche put être déterminée par les mesures photogrammétriques.

Zusammenfassung. *Anwendung der Photogrammetrie in der Lawinenforschung.* Für eine Untersuchung von Schneelawinen wurden stereophotogrammetrische Methoden angewandt. Die Höhenlinien des Lawinenhanges wurden aus Stereobildpaaren kartiert, die vor und nach dem Abgang der Lawine aufgenommen wurden. Weiter wurden der Umriss der Lawinenfront und die Höhenlinien der Schneewolke in bestimmten Zeitabschnitten ausgewertet. Für die verschiedenen Pläne wurde eine relative Genauigkeit von 0,7 m erreicht.

Aus den Plänen wurde das Volumen der Schneewolke in 4 verschiedenen Stadien der Lawine bestimmt. Eine unabhängige Bestimmung dieser Volumen ergab sich aus der Koordinatenmessung in den Stereomodellen. Die mittleren Fehler beider Methoden wurden zu $\pm 450$ m$^3$ und $\pm 290$ m$^3$ abgeschätzt, was einen Fehler von 5% bzw. 3% des mittleren Wolkenvolumens entspricht.

Die Messbilder wurden in genau bestimmten Zeitabständen aufgenommen. Deshalb konnte auch die Geschwindigkeit der Lawinenfront aus den photogrammetrischen Messungen ermittelt werden.

## 1. Introduction

The determination of geometric and dynamic characteristics of snow avalanches presents an important problem in the study of avalanches and in particular, their destructive power. These characteristics cannot be determined with any degree of accuracy by the visual and motion-picture methods often used.

A technique that may be applied in this respect is terrestrial photogrammetry, sometimes used in topographical mapping of mountain areas. Besides maps of the avalanche slope, this technique can provide information on the volume of snow that is moved by the avalanche, the avalanche velocity and the volume of the snow cloud. These data are of great importance to the avalanche expert and are indispensable for designing defence structures.

A joint project by the National Research Council and McGill University was begun in 1964 to study the various aspects of snow avalanches and the use of terrestrial photogrammetry in this respect. The investigations that are described here were carried out on avalanches that were artificially released in Banff National Park, March 1965. More advanced experiments were planned for Alta, Utah in 1966. However, as a result of very unusual snow conditions during this winter, no avalanche could be released.

This paper covers the photogrammetric part of the project for which the N.R.C. assumed the responsibility.

## 2. Preparations

Ideally the cameras designated for the application of photogrammetry to avalanche studies should satisfy the following requirements:

At least two photogrammetric cameras of stable dimensional characteristics should be used.

The camera's elements of interior orientation, i.e. the focal distance, the principal point and the lens distortion should be accurately known.

The cameras should be equipped with a fast "between the lens" shutter.

Accurate synchronization of the cameras should be assured.

Accurate determination of the location of the camera stations and the orientation of the cameras is desirable.

The film transport should be fast. A time interval between successive photographs of about one second would be desirable.

Relatively light cameras are preferable because of their transportation to the avalanche site.

The lenses should be of high optical quality.

The existing terrestrial or aerial survey cameras do not usually fulfill these requirements. Since designing and building of special cameras could not be justified at this stage of the project, compromises had to be accepted. Consequently two older Williamson Photogrammetric Cameras, type O.S.C., that were available to us, were used. These film cameras have a 23 cm. × 23 cm. photoformat and a 152 mm. focal distance. The shutter is mounted inside the objective and exposure times of 1/100 sec., 1/200 sec. or 1/300 sec. can be selected. A disadvantage of this camera is its weight, approximately 90 kg. Motor vehicles, therefore, must be provided to transport the cameras to the avalanche site.

The time interval between consecutive exposures depends on the speed of the film transport. For the O.S.C. camera, this interval is approximately 3 sec. However, after changing the gears of the film transport mechanism in the camera magazine, this time was shortened to a minimum exposure interval of 1·8 sec. An intervalometer was used to control the interval of the exposures for both cameras. Synchronization of the shutters was accurate to 0·01 sec. under the prevailing temperature conditions at the avalanche site.

Camera supports were built to use the cameras with their optical axes in an approximately horizontal position (Fig. 1). Means for accurate orientation of the cameras were not provided; the orientation of the camera axes parallel to each other and perpendicular to the base was possible to an accuracy of approximately one degree.

## 3. Field Operations

The slope selected for the experiments described in this report, was located in the Mount Temple area of Banff National Park. It has an average incline of approximately 45 degrees. The cameras were installed at both ends of a 127·9 m. base line on a small rise at the foot of the mountain, 300 m. below the top. The horizontal distance between the base line and the top of the mountain was approximately 500 m.

Five control points to be used for the orientation of the stereophotographs in the plotting instrument were established around the avalanche path. They were clearly defined details in the rocky parts of the slope in the area of the photographic overlap and were determined by theodolite intersection from the camera stations.

The avalanche was released by members of the Warden Service and Ski Patrol of Banff National Park on 2 March 1965 at 12.15 M.S.T. The light conditions at this time proved very favourable for photographing the avalanche. Kodak Super XX Aerographic film was used. The cameras were equipped with minus blue filters and the exposure time was 1/200 sec. at f:11. Three different stages of the avalanche are represented in Figures 2, 3 and 4.

## 4. Plotting Operations

Differences in the distances from the camera station to points on the avalanche resulted in large scale variations in each photograph. For relative orientation, a method for oblique photographs (Schwidefsky, 1950) was therefore followed. The absolute orientation of the stereo-models was based on control points located directly around the avalanche path.

A Zeiss C-8 Stereoplanigraph was used for the plotting operations. A plotting scale of 1:500 and a contour interval of 1·5 m. were selected. The plotting was done on dimensionally stable, transparent material for comparing the maps of the various stages of the avalanche.

The section of the avalanche that was within 250 m. of the cameras could not be stereoscopically observed because of the large base ratio. Plotting of this section was therefore not possible.

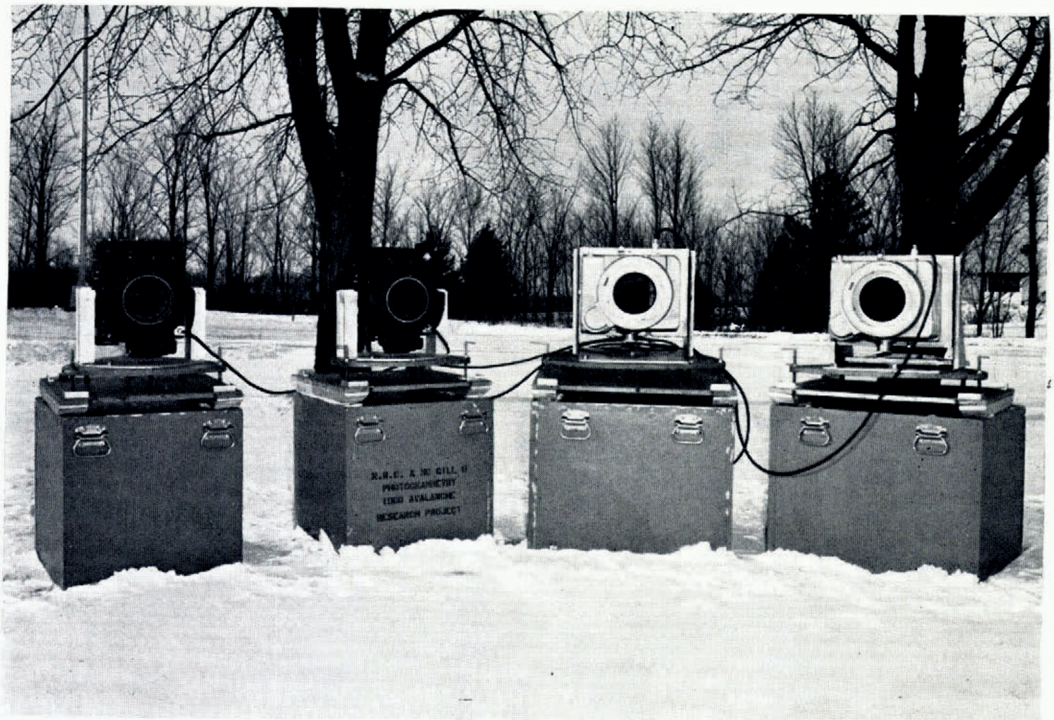

*Fig. 1. Photogrammetric cameras mounted on special supports used in avalanche research*

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*Fig. 2. Release of the avalanche*

*Fig. 3. Avalanche 18·4 sec. after its release*

*Fig. 4. Avalanche 29·2 sec. after its release*

The following maps and profiles were made:

(a) A map of the slope before the avalanche was released (Fig. 5). This map was plotted from the stereo-photographs taken before the avalanche. On some photographs, the photographic image of the camera's instrument dials interfered with the image of the slope due to an error made when unloading the magazine. This accounts for the blank area in the lower right corner of the map.

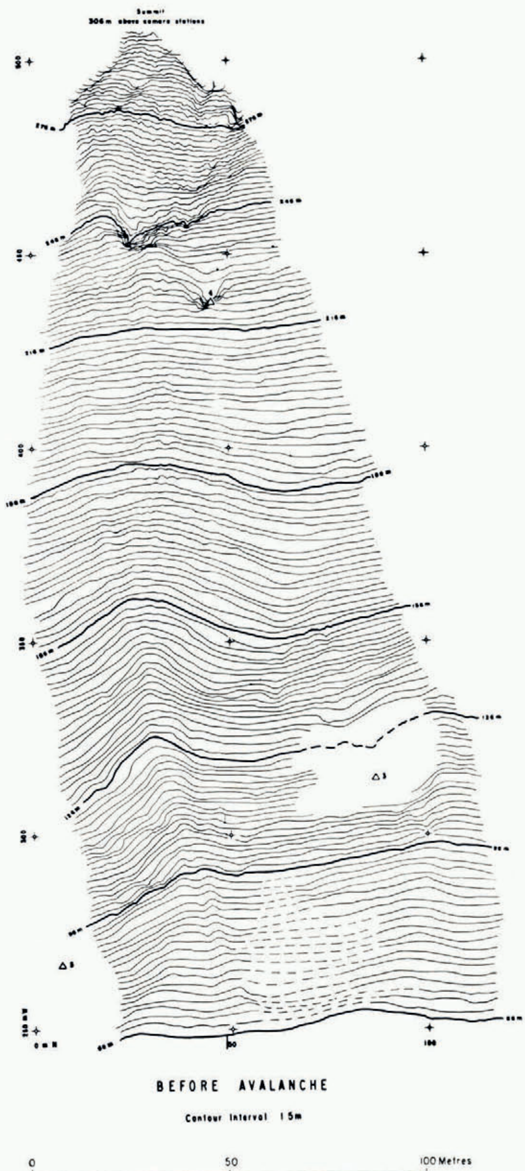


*Fig. 5. Map of the slope before the release of the avalanche*

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(b) Maps of different stages of the avalanche. The map in Figure 6 was plotted from the photo pairs that were made at 4·0 sec., 11·2 sec. and 18·4 sec. after the avalanche was released. Contour lines of the snow cloud at these instants are shown. This map was used in conjunction with the map in Figure 5 for determining the volumes of the snow cloud.

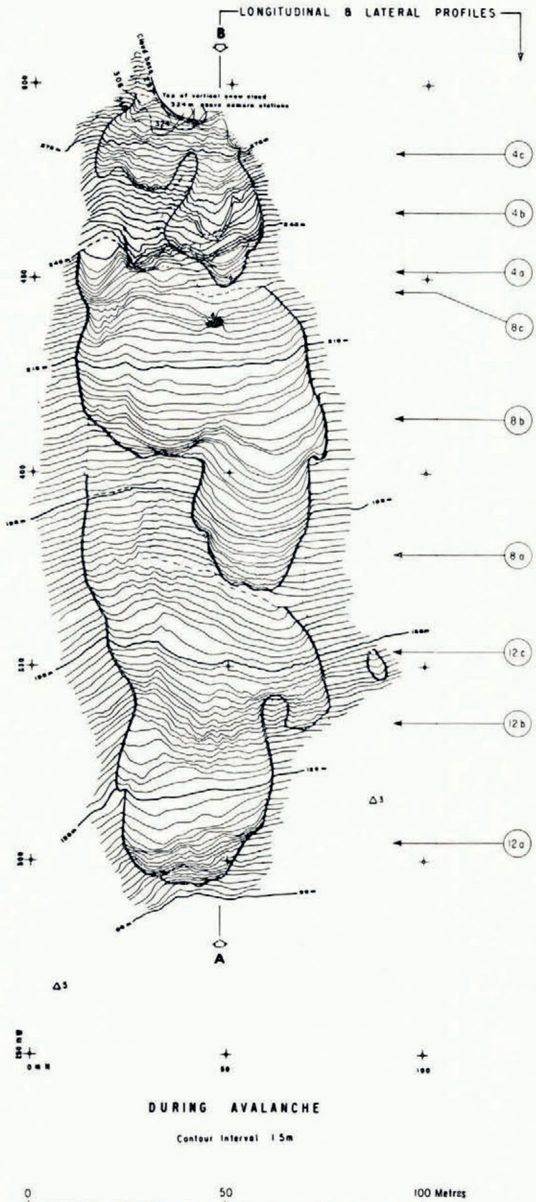


*Fig. 6. Map of three different stages of the avalanche*

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(c) A map of the slope after the avalanche (Fig. 7). This map was plotted from stereo-photographs taken after the avalanche. Phenomena such as rocks, snowball tracks and outline of the avalanche path, which could be of interest in avalanche studies were plotted as well as the contour lines of the slope.

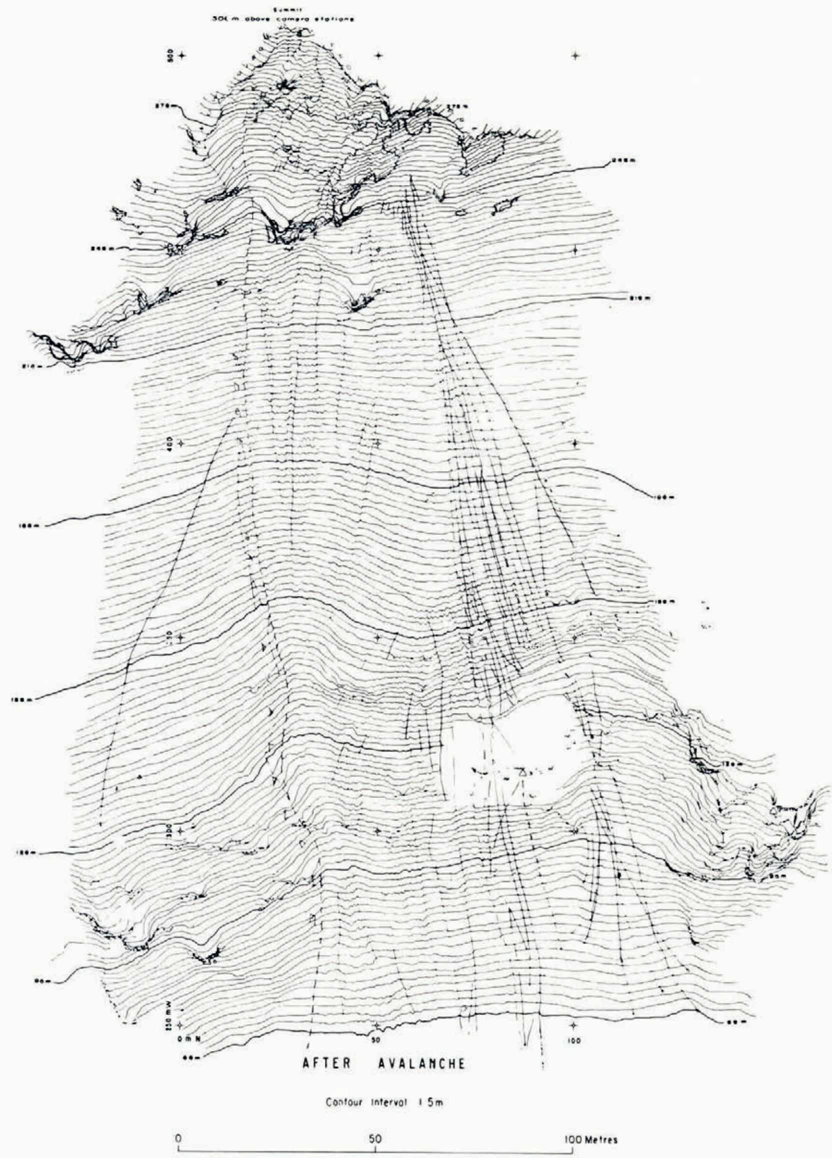


*Fig. 7. Map of the slope after the avalanche*

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(d) A map of the outlines of the avalanche front (Fig. 8). This map represents the position of the avalanche front at 1·8 sec. intervals between 4 sec. and 22 sec. after the release of the avalanche. It was used to determine the velocity at different stages of the avalanche.

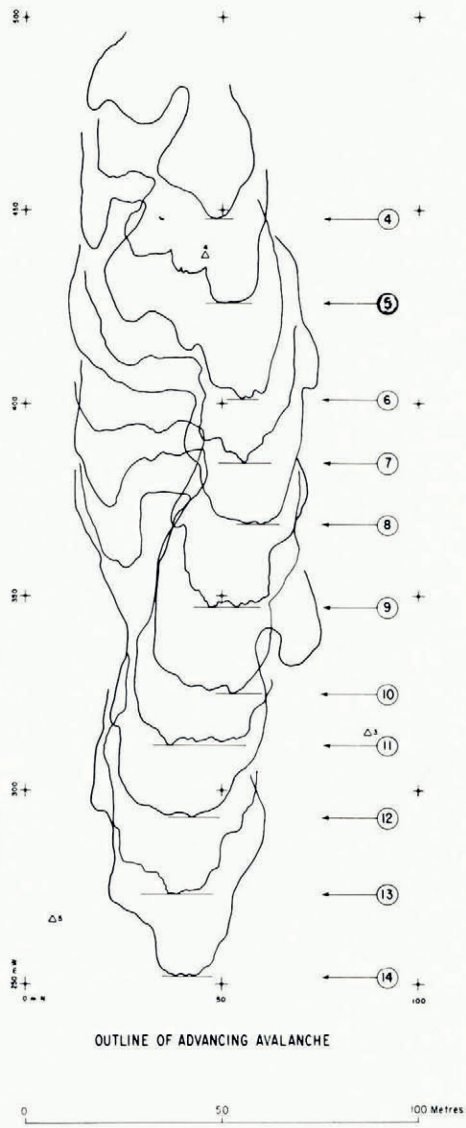


*Fig. 8. Map of outlines of the avalanche front*

(e) A longitudinal profile and nine lateral profiles (Fig. 9). The maps of Figures 5, 6 and 7 were used in plotting these profiles. Besides the slope before and after the avalanche, the outline of the snow cloud at 4·0, 11·2, and 18·4 sec. following the release of the avalanche is shown. The horizontal location of the profiles is given in Figure 6.

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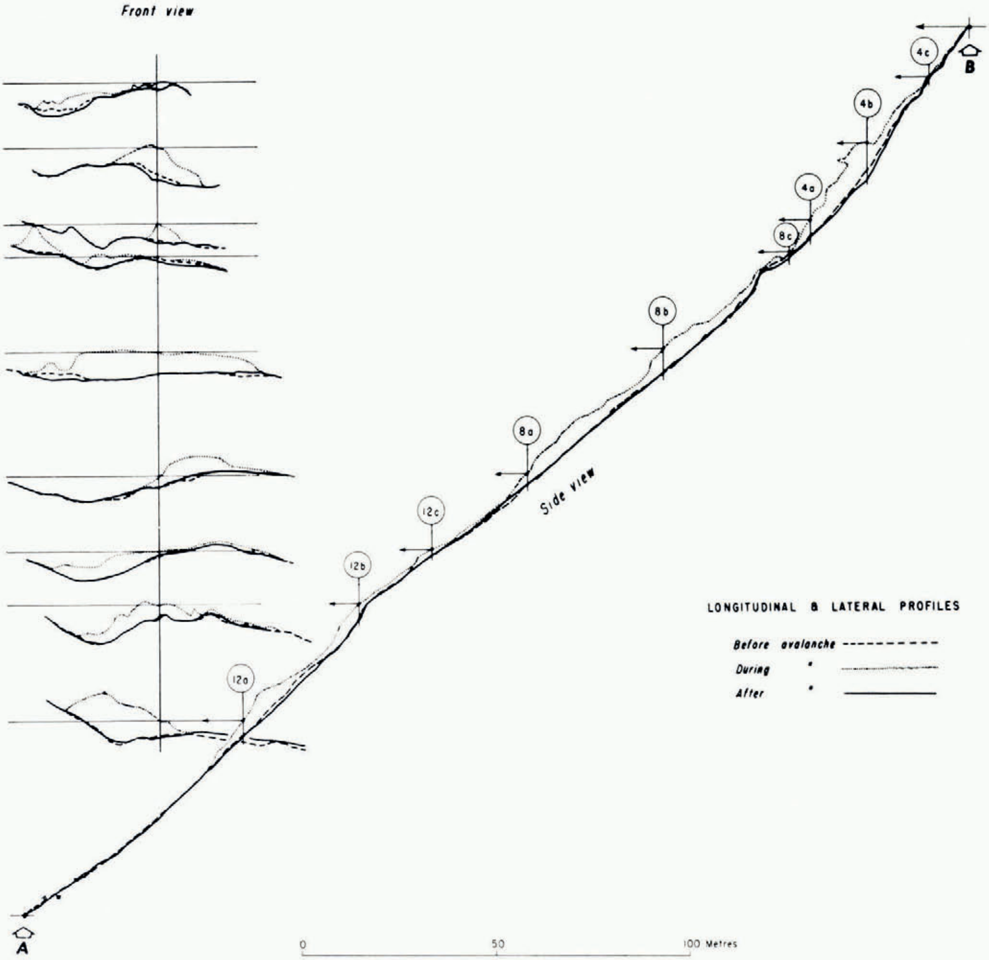


*Fig. 9. Longitudinal and lateral profiles*

## 5. Accuracy

The main error sources that affect photogrammetric mapping are limited accuracy in the formation of the stereoscopic model and errors in the actual plotting.

The discrepancies between terrestrial and photogrammetric coordinates of the control points are an indication of model deformations. Maximum errors of 1·4 m. in horizontal position and 0·8 m. in elevation were found. These deformations affect the accuracy of the maps. However, for volume and velocity determination comparative measurements are made in the different stereoscopic models and model deformations have limited effect when they are similar for these models.

It was not possible to control model deformations beyond certain limits. An attempt was therefore made to improve the relative accuracy of the stereo-models by making use of the fact that the orientation of the cameras remained unchanged while the avalanche was photographed. Similar orientation elements could therefore in principle be accepted for the different stereo-models. These elements were determined by absolute orientation of the first model by means of the ground control data. For the following models only small corrections to the orientation elements were required to compensate for parallaxes, introduced by differences in centering the diapositives on the plate carriers.

The relative accuracy of the different models was determined from coordinate readings of the snow surface that was not disturbed by the avalanche. For positions with selected $x$- and $y$-machine coordinates the elevation of the snow surface at both sides and in front of the avalanche was recorded for the different stereo-models. An average number of 47 of these points were measured in each model. After compensating for small systematic shifts of one model in relation to another, a standard error $m_h = 0 \cdot 69$ m. was found.

The precision of the plotting process was investigated by a repeatability test. The profiles shown in Figure 9 and constructed from contour lines of the snow surface and the outline of the snow cloud were used for this test. The plotting precision was determined by measuring the elevations of the snow surface and the cloud along these profiles in the stereoscopic model. These elevations were compared with the profiles and from the discrepancies the following standard errors computed: for the snow surface $m_h = 0 \cdot 15$ m., for the snow cloud $m^h = 0 \cdot 65$ m.

They correspond with, respectively, $0 \cdot 3$ mm. and $1 \cdot 3$ mm. at the scale of the maps.

## 6. Velocity Determination

Velocities can be determined by photogrammetric techniques when a moving object is recorded in different photo pairs that are taken with a known time interval.

In the case of a loose snow avalanche, it is generally not possible to identify certain details of the moving snow mass in successive photographs. By comparing the position of the avalanche front in different stereo-pairs, its velocity can be computed. However, this is not a true velocity as it is not at all sure whether the same snow mass is measured in the different photographs. This velocity is sometimes referred to as apparent speed. It was computed by measuring the distances between the most advanced parts of the avalanche front at different stages of the avalanche. These distances were measured in the main direction of the snow movement. Velocities were computed for the part of the avalanche that was mapped. The horizontal, vertical, and slope components are shown in Figure 10. Their numerical values are given in Table I. It appears that the apparent speed of the avalanche shows a wave-like fluctuation despite the almost constant slope angle.

The accuracy of the velocities, is affected by the relative accuracy of the stereo-models and the accuracy of the time interval between the exposures. The differences between the stereo-models, described in Section 5, result in a standard error of the avalanche speed $m_s = 0 \cdot 4$ m./sec.

The time interval of two successive exposures was computed from the time recorded for the first and the last of a series of exposures taken with a constant time interval. This time was recorded to the nearest second. A total of 31 exposures were made and a time interval of $1 \cdot 80$ sec. was found, with an accuracy of approximately $\pm 0 \cdot 06$ sec. An error of $0 \cdot 06$ sec. in the time interval results in an error of $0 \cdot 6$ m./sec. for the maximum velocity that was measured for this avalanche.

## 7. Volume Determination

### 7.1. *Graphical method*

Volumes can be determined from the maps of different stages of the avalanche (Wild, 1954). The volume of the snow cloud at four different stages was determined from the maps of the snow cloud and of the snow surface prior to the avalanche. When one of these maps is superimposed over the other, it will be noticed that the contour lines of the snow cloud

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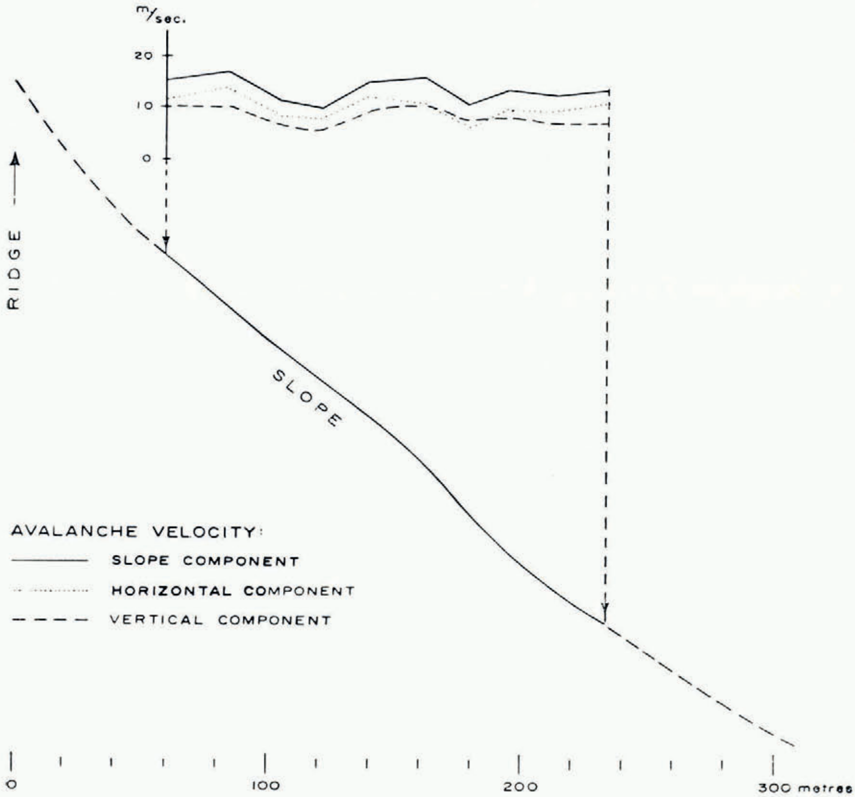


*Fig. 10. Avalanche velocity for the central section of the slope*

TABLE I. RESULTS OF AVALANCHE VELOCITY DETERMINATIONS

| *Model no.* | *Time after release of avalanche* sec. | *Time interval* sec. | *Avalanche velocity* *Horizontal component* m./sec. | *Vertical component* m./sec. | *Slope component* m./sec. | *Slope angle* deg. |
|---|---|---|---|---|---|---|
| 4 | 4·0 | | | | | |
| | | 1·80 | 11·8 | 10·4 | 15·7 | 42 |
| 5 | 5·8 | | | | | |
| | | 1·80 | 14·0 | 10·8 | 17·7 | 39 |
| 6 | 7·6 | | | | | |
| | | 1·80 | 9·2 | 7·1 | 11·6 | 39 |
| 7 | 9·4 | | | | | |
| | | 1·80 | 8·5 | 6·2 | 10·5 | 37 |
| 8 | 11·2 | | | | | |
| | | 1·80 | 12·4 | 10·0 | 15·9 | 35 |
| 9 | 13·0 | | | | | |
| | | 1·80 | 11·9 | 11·7 | 16·7 | 45 |
| 10 | 14·8 | | | | | |
| | | 1·80 | 7·6 | 8·3 | 11·3 | 44 |
| 11 | 16·6 | | | | | |
| | | 1·80 | 10·4 | 9·6 | 14·2 | 43 |
| 12 | 18·4 | | | | | |
| | | 1·80 | 10·8 | 8·4 | 13·7 | 41 |
| 13 | 20·2 | | | | | |
| | | 1·80 | 12·1 | 8·2 | 14·6 | 33 |
| 14 | 22·0 | | | | | |

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and the corresponding ones of the snow surface enclose a certain area. The cloud volume is then given by

$$V_{1n} = h \sum_{i=1}^{n-1} \tfrac{1}{2}(S_i + S_{i+1}) \tag{1}$$

where $V_{1n}$ is the volume in map scale, $S_i$ the surface enclosed by two corresponding contour lines, and $h$ the contour interval in map scale. For the determination of the areas $S_i$, a planimeter can be used.

The average $\frac{1}{2}(S_i+S_{i+1})$ is used for the volume determination. Consequently, Equation (1) is only an approximation as a linear interpolation is made to define the snow surface between the contour lines. The contour interval has therefore to be sufficiently small in order to achieve a reasonable accuracy.

The volume of the snow cloud at 11·2, 14·8, 18·4 and 22·0 sec. after the release of the avalanche is given in Table II.

Table II. Volume of the Snow Cloud Determined by Two Independent Methods

| Model no. | Time after release of avalanche sec. | Volume of cloud: Graphical method m.$^3$ | Numerical method m.$^3$ |
|---|---|---|---|
| 8 | 11·2 | 10 100 | 8 600 |
| 10 | 14·8 | 6 800 | 6 000 |
| 12 | 18·4 | 7 000 | 7 400 |
| 14 | 22·0 | 12 700 | 13 400 |

The amounts of snow that are moved by the avalanche can be determined by similar methods, using the contour maps of the slope before and after the occurrence of the avalanche. As a result of the fact that the avalanche used for our investigations was relatively small, only limited amounts of snow had been transported by the avalanche. Limitations upon the accuracy of the method of volume determination meant that the volume could not be determined with a sufficient degree of accuracy. These volumes are therefore not presented.

### 7.2. *Accuracy of graphical volume determination*

Graphical volume determination is affected primarily by errors in the position of the contour lines. An error in the position of the contour lines will influence the computed volume as follows:

$$m_v = hdn^{\frac{1}{2}}m_c \tag{2}$$

where $m_v$ is the standard error in map scale of the volume, $m_c$ the standard error in map scale of the contour line position, $h$ the contour interval in map scale, $d$ the average width in map scale of the avalanche path, and $n$ the number of contour lines used for volume determination. The standard error $m_c$ depends on the deformation of one stereo-model in relation to another and on the errors made during the actual contouring process.

The model deformations were determined and discussed in section 5; they amounted to a standard error $m_h = 0{\cdot}69$ m. (1·5 mm. in the map scale). For an average slope angle of 45 degrees this error affects the horizontal position of the contour lines by the same amount.

The plotting precision was established for the snow cloud contours by means of a repeatability test. A total of eleven different snow cloud contours was plotted ten times in both directions for this purpose. From the discrepancies for the same contour a standard error of 0·7 mm. in the plotting scale was found.

The total effect of both the model deformations and the plotting accuracy is represented by a standard error $m_c = 1{\cdot}6$ mm. This value was used in Equation (2) and with $h = 3$ mm. $d = 92$ mm. $n = 66$, a standard error in map scale $m_v = 3590$ mm.$^3$ was found for the snow cloud volume. This error corresponds with 450 m.³ in the terrain or 5 per cent of the average cloud volume given in Table II.

3.7. *Numerical method*

A disadvantage in using the graphical method of volume determination is that maps of every stage of the avalanche have to be produced before the volumes can be determined. This time-consuming operation can be avoided by a more direct numerical method of volume determination. When spot elevations are determined according to a grid pattern that is similar for the photographs taken before and during the avalanche, the volume of the snow cloud is expressed by:

$$w_{m,n} = s_x s_y \sum_{x=0}^{m-1} \sum_{y=0}^{n-1} \tfrac{1}{4}(\Delta z_{x,y} + \Delta z_{x+1,y} + \Delta z_{x,y+1} + \Delta z_{x+1,y+1}) \qquad (3)$$

where $w_{m,n}$ is the volume in scale of stereo-model over a block $x = m$, $y = n$, $s_x$, $s_y$ the grid interval in the scale of the stereo-model in $x$- and $y$-directions respectively, and $\Delta h_{x,y}$ the difference of the elevation readings in the scale of the stereo-model of a grid intersection in two different stereo-pairs. A grid pattern that was parallel to the $x$, $y$ coordinate axes of the stereo-plotter was used to determine the snow cloud volume from photographs taken before and during the avalanche. A grid interval of 3·33 mm. in the scale of the stereo-model (5 m. on the terrain) was selected.

The grid pattern was extended to the undisturbed snow layer on both sides and in front of the avalanche. Elevation readings of the undisturbed snow surface could therefore be compared for the different stereo-models and used to adjust for shifts of one model in relation to another.

The volumes that were computed for the snow cloud at different stages of the avalanche are recorded in Table II. The differences between the results of the graphical and numerical methods of volume determination are not larger than three times the combined standard error found for the two methods.

7.4. *Accuracy of the numerical method*

The standard error of the snow cloud volume as determined by numerical methods was estimated from the discrepancies found in the spot elevations taken around the avalanche path in different models ($m_h = 0{\cdot}69$ m.). The following equation was used to compute the standard error of the volume as a result of these discrepancies.

$$m_w = s_x s_y n^{\frac{1}{2}} m_z \qquad (4)$$

where $m_w$ is the standard error of the snow cloud volume in the scale of the stereo-model as a result of model deformations, $m_z$ the root-mean-square value in model scale of the discrepancies between different models, $n$ the number of grid squares, and $s_x$, $s_y$ the grid interval in $x$- and $y$-directions in the scale of the stereo-model.

An average of 275 grid squares was used for the determination of cloud volumes from photo pairs 8, 10, 12 and 14. Using Equation (4), the standard error in the scale of the stereo-model of the snow cloud volume was found to be $m_w = 85{\cdot}7$ mm.³. This error corresponds with 290 m.³ on the terrain and represents an error of 3 per cent of the average cloud volume.

The effect of errors in setting the floating mark on the snow and snow cloud surfaces was also investigated. For the snow cloud, which was the most difficult for pointing, a standard error of 40 $\mu$m. in the scale of the stereo-model was determined. The effect of the pointing accuracy on the volume determination can be computed using Equation (4). A standard error of 25 m.³ representing 0·3 per cent of the cloud volume was found. This error is very small compared with the error that is caused by the discrepancies of the different models and its effect on the volume accuracy can be neglected.

## 8. Discussion

The information on snow avalanches that is presented in this report demonstrates that the photogrammetric technique has certain potential in this field of research.

The different stages of the avalanche were mapped and information on velocity and volume was extracted from the photogrammetric measurements.

The accuracy that was obtained in this first experiment is somewhat limited. Generally the numerical methods of volume determination were found to be more accurate than the graphical methods. Apart from the fact that the photographic quality and the choice of cameras are of particular importance, we expect therefore that analytical photogrammetry will offer certain advantages, both in accuracy and in time. The analytical plotter may prove to be a particularly useful instrument in this kind of study.

More experiments have to be carried out to obtain a more complete picture of the possibilities of photogrammetry in avalanche research. In particular, the following points should be investigated.

(a) *Photographic emulsions.* Although a good photographic definition was obtained using a black and white emulsion, the characteristics of other emulsions such as color and false color should be investigated. From experiments that were made in Alta in 1966 it was found that a very good photographic definition for the snow surface was obtained when these emulsions were used. It is therefore expected that color and false color emulsions offer certain advantages in the interpretation of the stereo-photographs. In particular, the precision of the contouring process will be improved.

(b) *Study of the final stages of the avalanche.* It was not possible to plot the parts of the avalanche that came within a distance of 250 m. from the cameras. This was a result of the cameras being used at a large relative distance in order to obtain a high accuracy for the initial stages of the avalanche. Depending on the accuracy required and the dimensions of the avalanche, the use of a combination of more than two synchronized cameras should be considered. The initial stages of the avalanche could then be plotted from the photographs taken by the cameras that are placed a large distance apart. Photographs taken by cameras installed at a shorter relative distance, would be used to plot the later stages of the avalanche.

(c) *Information on air turbulence.* The study of air turbulence in and around the avalanche cloud is of extreme importance in avalanche research. This turbulence contributes significantly to the destructive power of avalanches. Photogrammetry has been applied successfully to air velocity determination in wind tunnel tests. In avalanche studies also, the photogrammetric technique may offer important information in this respect.

To record air movements on the photographs, it is necessary that artificial objects be carried by the air stream. A certain photographic penetration into the avalanche cloud is required for the proposed study. Consequently, the use of flares was examined for the experiments in Alta. In order to obtain a true picture of the air turbulence, these flares have to be extremely light or to be attached to balloons or parachutes.

It was not possible to provide flares with a sufficient long burning time that were light enough to be carried with the air stream. It was therefore decided to use parachutes. A container was prepared for each individual flare–parachute combination. These containers were installed on the avalanche slope at heights ranging from 1·5 m. to 2 m. above the snow surface by means of poles. A small charge was placed in the container so that upon ignition the flare and parachute would be injected into the air stream. Ignition of this charge and the flare was done electrically by means of a special power supply.

The burning time of the flares amounted to approximately 5 sec. which was sufficiently long to record the burning flare on at least two different photo pairs. When a flare is identified in different photo pairs that are taken with a known time interval, its velocity and direction of motion can be determined from its position in each photo pair.

As a result of unusual snow conditions which prevented the release of an avalanche during the field period in 1966, no final results are available for this experiment. We hope that the proposed technique will create interest among avalanche experts and photogrammetrists and that further development of this idea may be seen in the near future.

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