Movement determination of the Ross Ice Shelf, Antarctica

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ABSTRACT

Horizontal movements of very large ice sheets and ice shelves can be determined by astronomical positioning, by satellite triangulation, aerial photogrammetric triangulation, or geodetic traversing. A geodetic method is discussed in detail. Because of their dependency upon time, all originally "incoherent" measuring quantities must be reduced to a reference time. Two possible reduction methods involving either time reduction of observations or time reduction of positions, are compared. Some problems which occurred during the movement determination along the Ross Ice Shelf Studies (RISS) traverse, surveyed in 1962–63 and 1965–66 are discussed together with the results (field of velocity vectors, strain rates) and an error analysis.

The purpose of this paper is to show (1) how the surface movement of large ice shelves or ice sheets can be determined, and (2) that a geodetic method can provide most reliable and precise results. The results of the Ross Ice Shelf traverses 1962–63 and 1965–66 are later discussed. All methods have one factor in common, viz. that a certain configuration of well marked points on the ice surface must be surveyed at least twice, the time interval being determined by the size of the ice movement and the accuracy of the method applied. Where points are located close enough to fixed ground to be visible, absolute movements can be determined easily by intersection or resection methods. On very large ice sheets, however, other methods must be applied. These include *astronomical positioning*, by which the geographical co-ordinates of a point can be determined absolutely. Good results are obtained only if a larger number of stars can be observed at the same zenith distance and not too close to the horizon. Although bright stars are visible through highly magnifying telescopes during the day it is usual to use only the sun as a target in polar regions. However, because of the generally low elevation of the sun in polar regions rather large systematic errors can occur due mainly to the unknown atmospheric refraction. The sun, however, is an excellent target for azimuth determinations of horizontal angles in conjunction with geodetic observations. Passive or active *satellites* will possibly be used in the near future for accurate positioning in polar regions. Recent preliminary results of the U.S. Coast and Geodetic Survey's world satellite triangulation net show absolute position errors of ±6 to ±10 m. The instrumental equipment, however, is very heavy, expensive and not too portable. A few satellite observation stations are being installed presently on the Antarctic continent.

Ice movements can be determined *photogrametrically* by means of aerial triangulation or "bridging" methods. After having established a chain of well marked and signalized points on the ice surface, sequentially overlapping aerial photographs are taken from the proper altitude. The photogrammetric strip should be tied at both ends to fixed points on the ground. Major disadvantages with this method are that it is difficult to fly along a fixed but invisible line above a featureless terrain and that it is very difficult to identify marked points in the photographs, thereby decreasing the efficiency of the actual triangulation procedure on a stereo plotting instrument or with analytical photogrammetry.

With *geodetic* methods, relative movements can be determined by measuring distances, angles, or azimuths, of planimetric figures on, e.g. a succession of triangles or quadrilaterals extending across the ice surface. The simplest arrangement of points and the one that was used on the Ross Ice Shelf is the traverse. Ideally, this consists of a set of equally spaced points situated more or less on a straight line. With this method distances between two adjacent points and angles between three adjacent points are measured. If one or both ends of the traverse are tied to fixed ground, the absolute movements can also be obtained.

As each set of observations takes time to accomplish, considerable time may elapse before measurements of the entire network can be completed. During this period of observation, the ice is still moving and the movement is not necessarily the same at all points. Therefore all observations are incoherent quantities with respect to time, and cannot be related to each other directly. The data can be treated adequately only if they are reduced to a fixed reference time. This "reduction to epoch" problem was first realized by C. W. M. Swithinbank during his movement studies at Maudheim, Antarctica (Swithinbank, 1958). It was also investigated by W. Hofmann on his 1959 Greenland traverse of EGIG (Hofmann and Nottarp, 1964 [a]).

Two reduction methods are available for traverses measured at least twice: (1) both sets of observations are reduced directly to two corresponding reference times, which results in two fictitious "time-reduced traverses". All subsequent computations follow simple geodetic routines. The movement can be measured by comparing the results of the two fixed and independent traverses. (2) the positions of the traverse points, taken at the time of actual measurement, are adjusted to slightly different positions along a predetermined approximation of their flow line, according to the slightly different times of observation of the adjacent traverse quantities. The traverse must then be computed twice but simultaneously by a complicated interpolation algorithm. The movement ensues from the comparison of two dependent "terraced traverses".

The second method is much more flexible if the traverse is measured more than twice. Besides, there is less reduction of data, although all determined ice displacements refer to different dates. A rigorous treatment of all originally incoherent quantities leads to rather complex relations and practical solutions can be obtained only by intensive use of high speed computers. If a traverse is observed twice, only linear movements can be assumed to have occurred in the intervention period. Depending on the amount of curvature of the flow lines and the amount of change of the ice velocity, systematic deviations from the actual positions will be introduced.

The RISS-traverse extends over a total length of over 900 km. It consists of an E-W leg parallel to the Ross Ice Shelf, and a N-S leg near Roosevelt Island (see Fig. 1). The traverse comprising 100 observation points was established during the austral summer 1962–63 (Hofmann, *et al.*, 1964 [b]). A resurvey was carried out three years later (Dorrer, *et al.*, 1969) with the same kind of instruments. Distances were measured with modified tellurometers and angles with a precision theodolite. As a result of this work, a field of velocity vectors was computed (Fig. 1). This field was characterized by increasing velocities between McMurdo and the Ross Ice Shelf, a uniform, parallel movement in the middle of the shelf (maximum velocity 935 m yr^{-1}) and a systematically increasing divergence of the flow lines towards both ice margins. Along the southern leg, a distinct decrease of velocity can be noted; also a change of movement direction due to the flow of ice around the western side of Roosevelt Island. In addition to these vectors, strain rates for all traverse distances were computed. These indicate no lateral deformation on that part of the shelf with maximum velocity, i.e. the ice at these locations moving as if it were a rigid body. Along the N-S profile, which

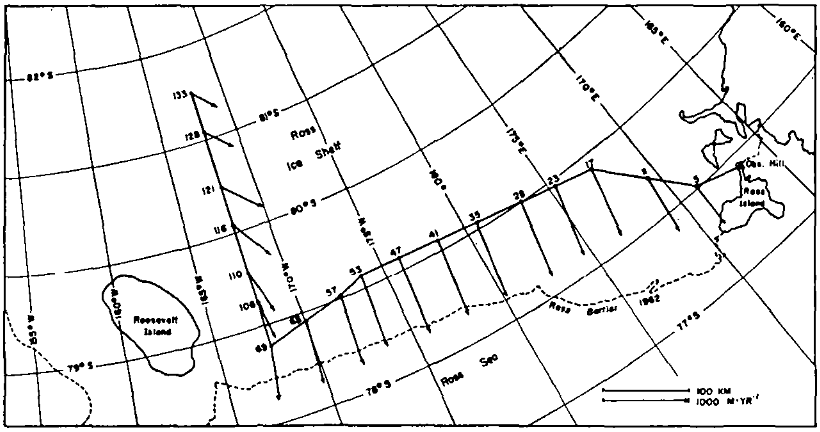

FIG. 1. Field of velocity vectors along the R.I.S.S. traverse determined between 1962–63 and 1965–66.

followed a light zig-zag course, these strain rates are highly dependent upon the azimuth of their corresponding traverse distance. This is caused by a compression of the ice south and south-west of Roosevelt Island.

For all traverse points with angles considerably different from 180°, the strain rate tensor ellipses could be derived as well as a quadratic correction to the linear movement. Finally the field of velocity vector changes along the traverse was determined which also shows considerable dependency upon the azimuth.

Since all traverse quantities were measured more than once for each observation period an error analysis was carried out with *a priori* errors. The traverse was tied to fixed ground only at one end. This was at Observation Hill in McMurdo Sound. Due to error propagation of an endfree traverse the accuracy for traverse points decreases rapidly with increasing distance from Observation Hill. This is demonstrated in Fig. 2 with standard error curves of a few individual traverse points.

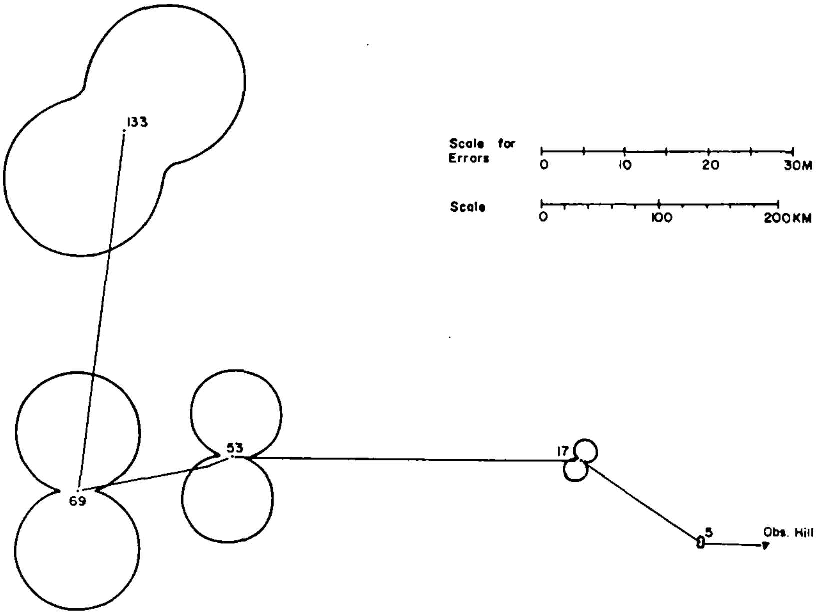

FIG. 2. R.I.S.S. traverse. Relative standard (pedal) curves for one observation epoch with respect to Obs. Hill.

These curves indicate the standard position error as a function of the azimuth for one observation period. Since a velocity vector is the difference between the same traverse point determined independently at different times, its error is identical to the corresponding position error parallel and perpendicular to it, multiplied by $\sqrt{2}$.

TABLE 1

SOME VELOCITY VECTORS AND THEIR STANDARD ERRORS

Point No.	Velocity	Azimuth (true North)
5	539·6 ± 0·3 m yr^{-1}	2° 29′ 39″ ± 49″
17	811·8 ± 1·1	12° 31′ ± 1′
69	620 ± 6	10° 08′ ± 14′
133	323 ± 4	315° ± 1°

In order to obtain a final control and to check the reliability of the traverse method, a sun azimuth was measured at the last observation point on the traverse, point 133. Comparison of this astronomical azimuth and the propagated traverse azimuth shows a closing difference of 23 seconds of arc. This difference not only contains all observation errors but also errors in the co-ordinates of Observation Hill and the initial azimuth on Ross Island. If all traverse angles were adjusted accordingly the location of point 133 would change by about two meters, which still is within the corresponding error curve. Considering this and the independently determined astronomical and traverse azimuths, it is likely that the given standard velocity vector errors (Table 1) are about 50 per cent too large. The geodetic method has therefore proved to be a very efficient method for determining movement on very large ice sheets.

If similar work is to be conducted in the future then the following recommendations may be useful. Both ends of a traverse or triangulation chain should be tied to fixed points on land, as this provides an important check on all observations. Astronomical control azimuths should be measured at various points along the traverse including the fixed points at both ends.* If more information is desired on the horizontal deformation conditions of the ice surface, either the traverse should follow a distinct zig-zag course or a triangulation or trilateration chain should be utilized.

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* This was done during the remeasurement of the EGIG profile across Greenland in 1967.