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MEASUREMENT OF SURFACE DEFORMATION OF THE GREENLAND ICE SHEET BY SATELLITE TRACKING*

by

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ABSTRACT

Seven Magnavox MX1502 satellite receivers were used during the summers of 1980 and 1981 to obtain the coordinates of 22 stations in three locations on the Greenland ice sheet. Two of the receivers were located at stationary sites on the west coast of Greenland for both seasons. This allowed the short-arc method to be used to obtain relative coordinates with high precision. The stations were located at about 65°N, and positions on the ice sheet were obtained with formal accuracies of better than 0.20 m. From the coordinates, the station velocities, ice-sheet slopes, baseline lengths (between the stations) and strain-rates were calculated. Our results show that the two stations just to the east of the ice crest are not moving in the expected direction (north-east) but are moving in a direction slightly west of north. Hence, the positions of the ice crest and the ice divide do not coincide. The other stations are moving approximately as expected. No major velocity differences between neighboring flow lines are apparent. The magnitudes of the maximum strain and the velocities increase away from the ice divide and with increasing slope.

INTRODUCTION

Ice velocities can be obtained by repeated tracking of special satellites using the Doppler effect. The Doppler effect is the change in the frequency of a signal from a transmitter that is moving relative to the receiver, and a familiar example of this effect is the change in the pitch of a train whistle as it passes. It also applies to electromagnetic signals. In particular, a signal from a transmitter on a satellite will appear to change frequency when observed by a receiver on the ground. This provides a measure of the change in the distance between the satellite and receiver. This range between the satellite and the receiver must be corrected for systematic effects such as delays in tropospheric and ionospheric propagation, and other systematic errors.

The US Navy Navigational Satellite System (NNSS) was used in this research effort to obtain position data with high (geodetic) accuracy. This system is also known as the TRANSIT system. The Navy maintains a system of ground stations which make daily observations of these satellites. By means of these observations, the orbits of the satellites are predicted and the orbital parameters are injected periodically into the satellite's memory. This orbital information is the broadcast ephemeris which is transmitted by the satellite. The orbital parameters in the broadcast ephemeris provide an orbit correct to within 20 to 30 m. For several of the satellites, a precise ephemeris is also available several weeks after the relevant data have been collected. It is correct to within 2 m.

There are several Doppler satellite receivers available commercially. Magnavox model MX1502 receivers were used in this experiment; they have internal microprocessors that can calculate approximate positions. The data received by the receivers were recorded on cassette tapes. After the field season, the data were processed to obtain more accurate positions for the receiver stations. The precise ephemeris was used for the positions of the coastal stations because it increased the accuracy of the solution, even though fewer passes were available (because the precise ephemeris was available for only two satellites).

There are several techniques for obtaining the station coordinates using Doppler methods (Brown 1975). The technique used for the stations on the ice sheet was the short-arc method (Brown 1976) (Fig.1). In this method the shape of the satellite orbit is considered to be known, while its position in space is not. Satellite observations from reference positions must be made simultaneously with the observations from the stations whose positions are being sought. Thus, two receivers, as a minimum, must be operating simultaneously. Positions determined with the short-arc method are relative to the stations whose coordinates are kept fixed to otherwise determined values. The broadcast ephemeris was used with this technique because the less accurate orbit is relatively unimportant, while the added satellite passes add significantly to the accuracy of the results.

Doppler satellite observations were obtained during the summers of 1980 and 1981 as part of the Greenland Ice Sheet Project (GISP). Seven receivers were used. Two were kept throughout all observations at stationary locations on the west coast of Greenland while the

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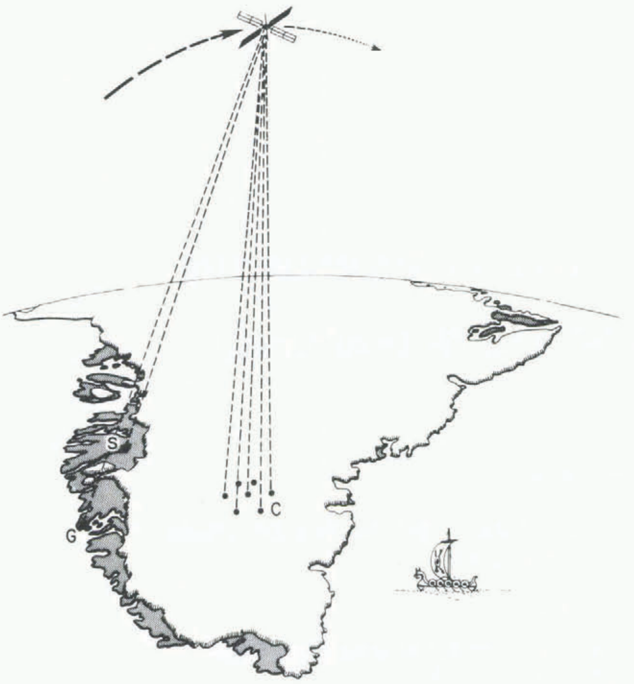

Fig.1. The short-arc method. Locations of stations G (Godthåb) and S (Søndre Strømfjord) are held fixed. Locations of stations C are calculated relative to G and S.

remaining five receivers were used for measurements on the Greenland ice sheet at 22 stations.

Figure 2 shows the station locations. The stations are located at approximately 65° N crossing the southern dome of the Greenland ice sheet. The stations comprise three large strain figures. The farthest west (at the lowest elevation) is referred to as the western cluster. The stations in this group are numbered 1001 through 1007. The middle strain figure is called the central cluster. Its stations are numbered 2001 through 2007. These two figures are hexagons, and are on the west side of the ice crest. The easternmost strain figure is approximately rectangular. It is called the eastern cluster. Its stations (numbered 3001 through 3008) are on the east side of the ice crest and it has within it the site of deep drilling at Dye 3 (near station 3003). One of the two coastal stations was located at Godthåb. The other station was located at Søndre Strømfjord.

The phase center of the antenna is the position to which the satellite tracking data refer. It was necessary to obtain the offset of the position of the antenna during the occupation of a station in the second year with respect to its position during the first year. This was done by reference to a steel wire attached to an anchor frozen into the firn below the depth of compaction. The antenna offset does not include any position changes due to the motion of the ice, but does avoid problems due to the compaction of snow into ice. The results presented here have been corrected for the antenna offset.

A version of the Doppler data reduction program GEODOP adapted to IBM computers (Kouba 1976, Archinal 1982) was used to obtain the station positions. Elevations are above the WGS66 (geocentric) ellipsoid (a = 6 378 145 m and f^{-1} = 298.25). A tropospheric correction is used to correct the Doppler counts for atmospheric pressure, temperature and humidity. This correction principally affects the elevations if the satellite passes are evenly distributed in azimuth. Meteorological data covering both periods of observations were obtained from the Dye 3 radar installation. These data were used to approximate the atmospheric pressures, temperatures and humidities at each of the stations located on the ice sheet.

For the computations of the coordinates of the stations on the ice sheet, five of the 1980 coordinates of Godthåb and Søndre Strømfjord (in an XYZ earth-centered coordinate system) were fixed to previously determined values (by setting their standard devia-

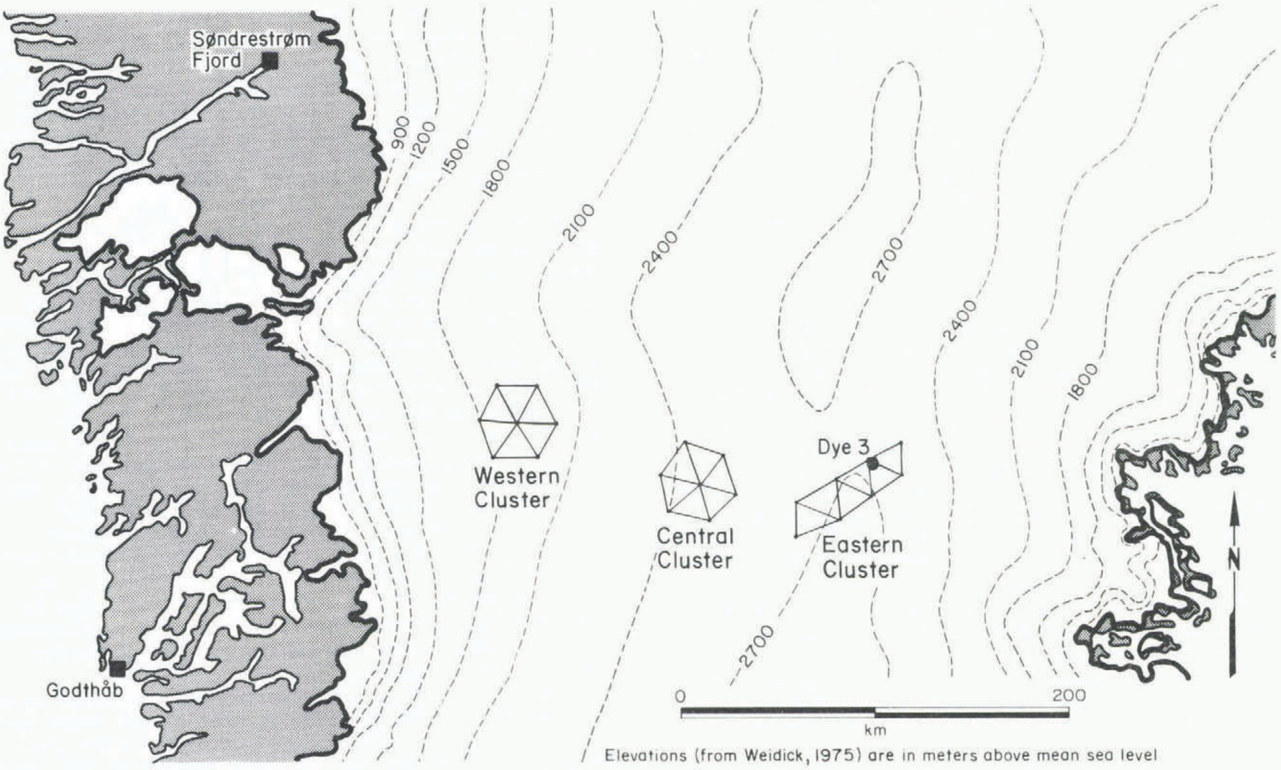

Fig.2. Stations on the Greenland ice sheet.

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tions to about 0.0002 m (Drew 1983)). The Z coordinate of Godthåb was not fixed but was allowed to vary with a standard deviation of 0.21 m. Thus, the elevation and latitude could vary while the longitude was fixed.

RESULTS

Six short-arc solutions were made (one for each cluster each year). The elevation of Godthåb changed by an average of 0.26 m in these solutions while the latitude changed by an average of 0.12 m. The changes were all within two standard deviations of the input coordinate values. Thus, these changes cannot be considered significant.

A further test was made by measuring the distance 3005-3003 by ground survey (Whillans and others 1984). The electronic distance meter (EDM) results indicate a distance 0.5 m shorter than the distance determined by satellite in 1980, and 1.0 m shorter in 1981. Better correspondence was expected and we have no clear explanation for the discrepancy. It must be due to unidentified systematic errors in either the EDM or the Doppler satellite results. This kind of problem should be investigated in future surveys.

The median date of the occupation of all of the stations in a cluster was assumed to be the date to which all the station coordinates refer (Drew 1983). Velocities were obtained by scaling the observed differences of the coordinates of the stations in a cluster by the time period between the median dates of occupation for each cluster (Table I and Figs.3, 4 and 5). Because only five coordinates were fixed, the coordinate systems of the solutions were undercon-strained. The unconstrained rotation was around an axis through the two fixed stations. Such a rotation would affect the stations in each cluster by virtually the same amount. There do not, however, appear to be consistent differences in vertical velocities between clusters and this effect does not seem to have been important.

Strains were calculated from the changes in the distances between stations (Livieratos 1980). These were then converted to strain-rates using the elapsed time between surveys. The distances used for this are base-line lengths on the ellipsoid. They were calcu-lated using the Gauss mid-latitude formulae (Rapp

TABLE I. STATION VELOCITIES

Station	Horizontal velocity (1σ) (m a^{-1}) (m a^{-1})	Azimuth (1σ) (° ') (° ')	Vertical velocity (1σ) (m a^{-1}) (m a^{-1})
1000+	(WESTERN CLUSTER)		
1	35.76 (0.12)	288 6 (0 8)	-0.02 (0.12)
2	30.04 (0.14)	289 10 (0 11)	-1.20 (0.13)
3	36.07 (0.15)	290 17 (0 10)	0.37 (0.14)
4	42.08 (0.14)	287 17 (0 18)	-0.21 (0.15)
5	46.50 (0.12)	288 33 (0 6)	-0.10 (0.11)
6	44.05 (0.24)	285 0 (0 14)	1.17 (0.21)
7	33.99 (0.20)	287 3 (0 13)	0.21 (0.16)
2000+	(CENTRAL CLUSTER)		
1	9.32 (0.12)	297 40 (0 33)	-0.55 (0.11)
2	7.55 (0.11)	309 20 (0 47)	-0.15 (0.13)
3	8.58 (0.13)	298 14 (0 40)	0.50 (0.13)
4	11.38 (0.13)	292 48 (0 27)	0.04 (0.12)
5	11.56 (0.13)	294 53 (0 25)	0.55 (0.11)
6	10.95 (0.14)	301 44 (0 35)	-0.22 (0.13)
7	8.21 (0.14)	306 46 (0 51)	0.08 (0.13)
3000+	(EASTERN CLUSTER)		
1	27.43 (0.16)	68 18 (0 15)	-0.53 (0.16)
2	23.20 (0.16)	62 37 (0 18)	-1.84 (0.16)
3	13.44 (0.14)	63 49 (0 27)	-0.42 (0.14)
4	13.65 (0.12)	55 35 (0 26)	0.86 (0.14)
5	7.57 (0.11)	52 29 (0 44)	-0.05 (0.14)
6	6.81 (0.15)	49 21 (1 11)	-0.11 (0.16)
7	2.42 (0.11)	339 10 (3 33)	-0.82 (0.15)
8	3.06 (0.10)	348 6 (2 54)	-0.19 (0.14)

The date assigned to the calculated position was the median date of the occupation.

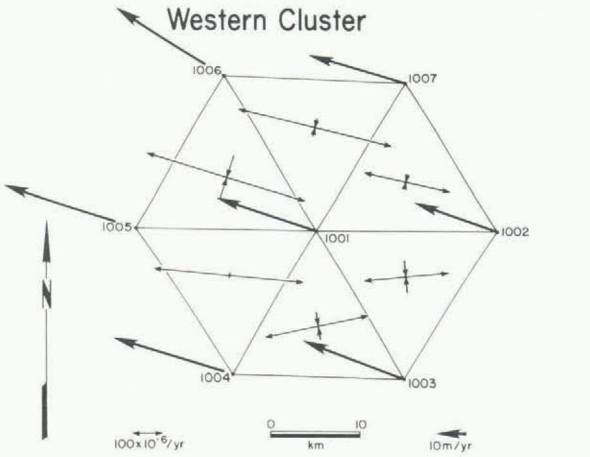

Fig.3. Velocities and strain-rates of the western cluster.

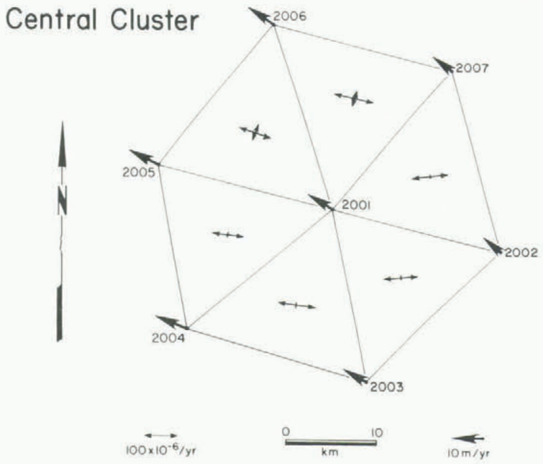

Fig.4. Velocities and strain-rates of the central cluster.

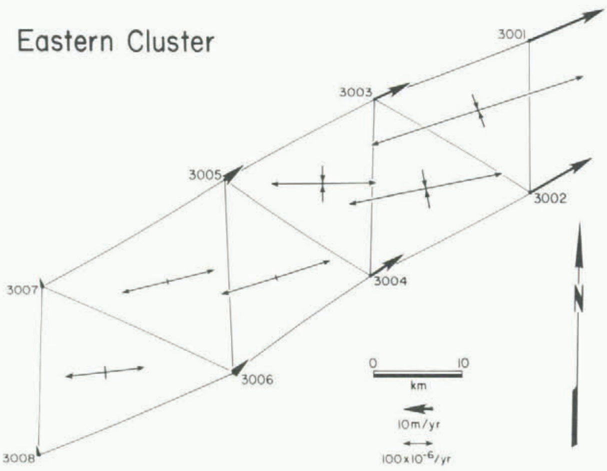

Fig.5. Velocities and strain-rates of the eastern cluster.

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1979). Strain-rates for the small triangles are listed in Table II and plotted in Figures 3, 4 and 5. As can be seen from the plots, the velocities tend to be more northerly than the directions of maximum strain. Both the velocities and the strain-rates increase away from the ice crest. However, the velocities and the maximum strain-rates east of the ice crest increase more rapidly than those to the west.

The velocities of the western cluster stations are nearly parallel (Fig.3), and the directions of maximum strain-rates diverge in the direction of flow. The ice is flowing about 12° north of the average direction of maximum extension. The minimum strains are almost all negative. Thus, the ice in this cluster is expanding more or less along the flow of the ice and contracting perpendicular to it. Several stations show anomalously large vertical velocities.

The velocities of the central cluster stations have a much smaller magnitude than those of the western cluster (Fig.4) and are not as close to parallel. The strain-rates at the central cluster are also smaller than those of the western cluster. The pattern of divergence of the maximum strain-rates at this cluster is similar to that of the western cluster and their average direction is the same. Thus, the ice is moving nearly 25° from the direction of maximum strain. However, unlike the western cluster, the minimum strain-rates are all positive. In other words, the ice in this cluster is expanding in all horizontal directions. While none of the elevation differences is as large as in the western cluster, several are well outside the expected range.

The two stations in the eastern cluster that are nearest the ice crest (3007 and 3008) are moving in a distinctly different direction than the other stations in this cluster (Fig.5). They are moving slightly west of north while those farther from the ice divide are moving more nearly east. The two westernmost stations in this cluster are west of the ice divide (the line of ice-flow divergence) but on the east side of the ice crest (the line of the highest elevations). The ice crest was determined by closely spaced observations by pressure altimeter. There is a rotation in the velocity vectors over the cluster. The strain-rates at this cluster do not show this rotation. They also do not show the same type of diverging pattern as the strain-rates at the other clusters, but are more nearly parallel. As in both the western and the central clusters, the ice movement is north of the direction of maximum extension. The minimum strains are all compressive. Again, as in the other clusters, several of the stations have anomalous vertical velocities.

TABLE II. STRAIN-RATES AND SLOPES FOR SMALL TRIANGLES OF STATIONS

Station	Maximum strain-rate[1]	Minimum strain-rate[1]	Azimuth of maximum strain (°)	Maximum slope[2] (%)	Azimuth of maximum slope (°)
1000+ (WESTERN CLUSTER)					
1-2-3	278.4	-111.5	264.1	-0.73	286.4
1-3-4	349.1	-94.3	259.0	-0.74	285.7
1-4-5	498.8	12.5	275.8	-0.83	287.3
1-5-6	547.7	-149.2	287.0	-0.82	284.3
1-6-7	528.2	-61.2	284.3	-0.67	298.2
1-7-2	290.5	-47.8	282.8	-0.80	298.4
2000+ (CENTRAL CLUSTER)					
1-2-3	125.4	19.2	265.0	-0.36	298.7
1-3-4	126.1	9.5	276.0	-0.39	294.9
1-4-5	114.5	20.1	276.6	-0.39	294.8
1-5-6	113.7	60.9	287.6	-0.40	297.9
1-6-7	138.8	56.8	283.1	-0.37	301.6
1-7-2	128.3	12.7	263.5	-0.37	301.5
3000+ (EASTERN CLUSTER)					
1-2-3	756.2	-124.1	70.9	-0.61	53.9
2-3-4	526.9	-119.7	78.9	-0.40	66.6
3-4-5	357.7	-109.7	79.5	-0.36	62.8
4-5-6	394.0	-26.3	71.5	-0.48	54.5
5-6-7	318.8	-7.8	75.7	-0.34	36.5
6-7-8	268.7	-44.5	84.5	-0.25	41.3

Notes:

[1] Strain is in 10^{-6} a^{-1}. Positive strain indicates expansion.

[2] Slope is calculated from 1980 coordinates.

CONCLUSIONS

The locations determined for the 22 stations on the Greenland ice sheet were found with average (RMS) standard deviations of 0.066 m in latitude, 0.105 m in longitude and 0.096 m in elevation. These are the formal errors as calculated in the program GEODOP. Formal error is the precision or the internal accuracy of the results. The formal error can also be considered the repeatability of the results, given the same kind of data and using the same data reduction method. Accuracy is the relationship of the results to the unknown true values. The accuracy of these results is not as good as the formal error because of unmodeled systematic errors. These systematic errors include unmodeled higher-order atmospheric effects, errors associated with the satellite receivers and antennae, and other systematic errors (Drew 1983). We do not know the magnitudes of these errors. However, we believe that most of these sources of error affect principally the station elevations. Thus, the vertical velocities obtained cannot be considered significant. Because the horizontal coordinates are much less affected by these systematic errors, and because the horizontal motions are large relative to these errors, the horizontal velocities and strain-rates are significant.

Elevation contours from this work are shown in Figure 6. They are somewhat different from those on previously available maps (Fig.2). As expected, ice velocities generally are in the direction of maximum slope and increase with increasing slope. Near the ice crest, however, slope-associated stresses are much smaller and longitudinal stresses dominate. These longitudinal stresses must be responsible for the component of flow across the ice crest.

The magnitude of the strain-rates are about as expected, based on accumulation rates measured in the clusters (Bow 1983) and on radar-determined ice thicknesses (S Overgaard personal communication, 1980). Surface-based radar data have not been fully reduced.

Deviations of the direction of principal strain from that of the velocity vectors arise because ice in neighboring flow lines is moving at different velocities. (The direction of strain is to the right if the flow is faster to the right.) Our results indicate that ice velocities increase to the south in the area of the studied transect. A possible explanation for this is the pattern of ice flow away from the southern dome of the ice sheet. The transect crosses the north end of the southern dome which is a north-south ridge dipping to the north. Flow east and west of the ridge is nearly parallel and approximately perpendicular to the ridge. But flow at the northern limit has a large northern component and is slower because of lateral divergence.

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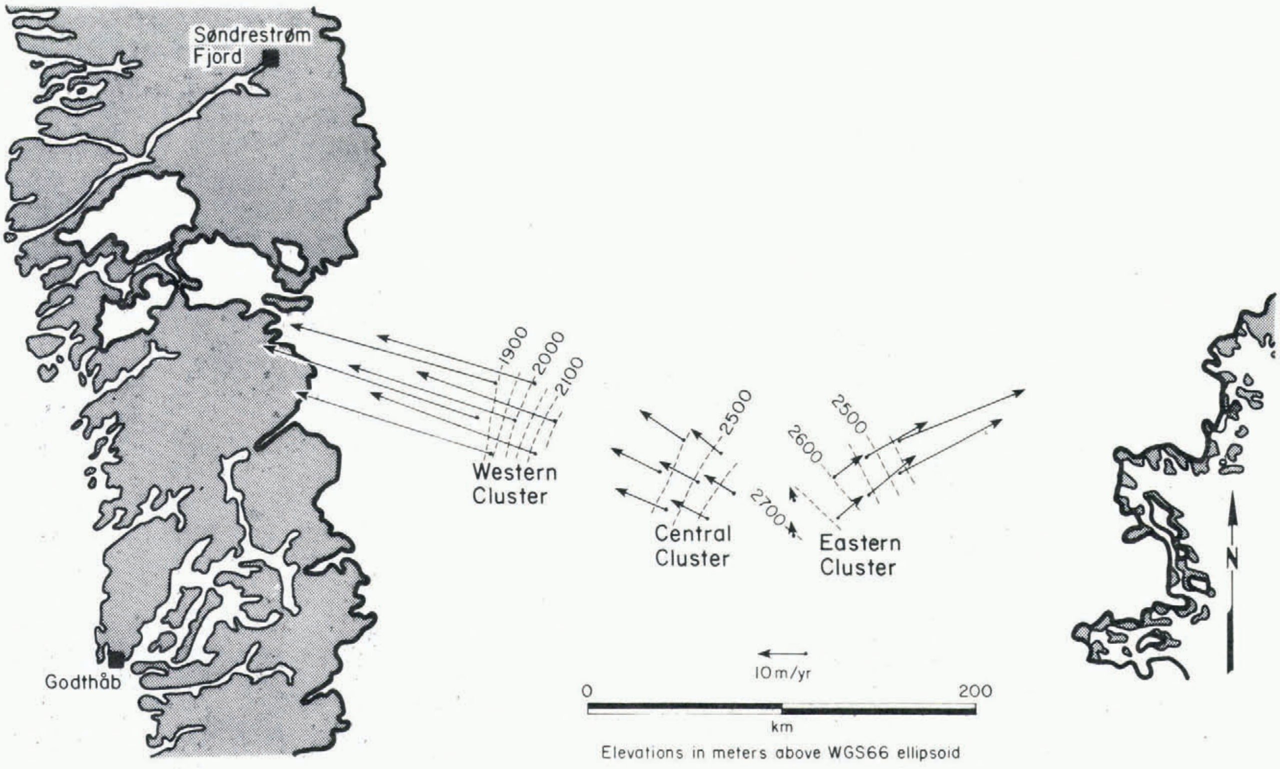

Fig.6. Velocities of stations on the Greenland ice sheet, 1980-81.

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