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ICE-MOTION DETERMINATION BY MEANS OF SATELLITE POSITIONING SYSTEMS

by

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ABSTRACT

The satellite positioning systems, NNSS or Transit system and NAVSTAR-GPS, are used successfully for the determination of ice motion. The ice motion is derived from the change in the coordinates of a station between at least two measurement epochs. Simultaneous satellite observations on solid-ground-based and on ice stations yield precise relative or local coordinates between the stations. The ice motion can be determined very accurately from the variation in these coordinates. The field observations and post-processing steps, which differ slightly for the two positioning systems, are outlined. Results for several examples are presented. Ice-motion solutions are discussed for data from Anvers Island (NNSS), from Filchner-Ronne Ice Shelf (NNSS, GPS), and from Ekström Ice Shelf (NNSS, GPS). Slow velocities of a few dm/d could be estimated in the course of one field season and the velocity values found are confirmed by annual station displacements.

1. GEODETIC SATELLITE POSITIONING SYSTEMS FOR GLACIOLOGICAL RESEARCH

Currently two satellite-based positioning systems can be applied worldwide for on-line coordinate determination. Over more than a decade the Navy Navigation Satellite System (NNSS or Transit system) had proved to be a powerful tool in Antarctic field expeditions, not only as a method of positioning but also for the determination of ice motion. Since 1986 the Global Positioning System (GPS) has also been used for glaciological research.

After a brief introduction to the principles of both positioning systems, the method for ice-motion determination is presented in section 2. In section 3, examples from field seasons will then demonstrate the potential of geodetic satellite positioning.

1.1 **Transit system (NNSS)**

The space segment of the NNSS or Transit system consists of five satellites in operational mode, which circulate the Earth every 107 min in near-polar orbits at about 1100 km altitude. Whenever a satellite passes above the horizon, a position fix can be obtained. Each satellite is a self-contained navigation beacon, which transmits two frequencies (150 and 400 MHz), timing marks, and a navigation message; its position can then be calculated as a function of time. By receiving and measuring the range difference (doppler count) between these positions during a single satellite pass, the position of the combined receiver/processor equipment can be obtained.

The number of passes per day is low in the equatorial region and increases towards the poles. This advantage is reduced by interference effects between two or more simultaneous passes. For geodetic purposes, a certain number of passes is necessary. A position-fix precision of about 30 m will be reached by at least 20 passes with an elevation of 15° or more above the horizon at the point of closest approach.

Generally the pass geometry should be symmetrical, in order to reduce the influence of systematic effects upon geodetic point positioning, e.g. satellite orbit errors and inadequately modelled ionospheric refraction effects. The measured data of stations which are observing the same satellite pass are influenced by the same effects, which cause a systematic error in the absolute coordinate positioning.

The post-processing of the data received at two or more stations enables a recalculation of the satellite orbit to be made. Each orbit is allowed to shift in a parallel manner into a new position, such that the inter-station vector ΔX between the stations involved, as determined from the whole series of orbits, best represents all the observations. Increased accuracy is provided by this technique, which is called translocation (see Fig. 1). If the differences in the absolute coordinates of all the stations are taken into account, high precision in these relative coordinates is obtained.

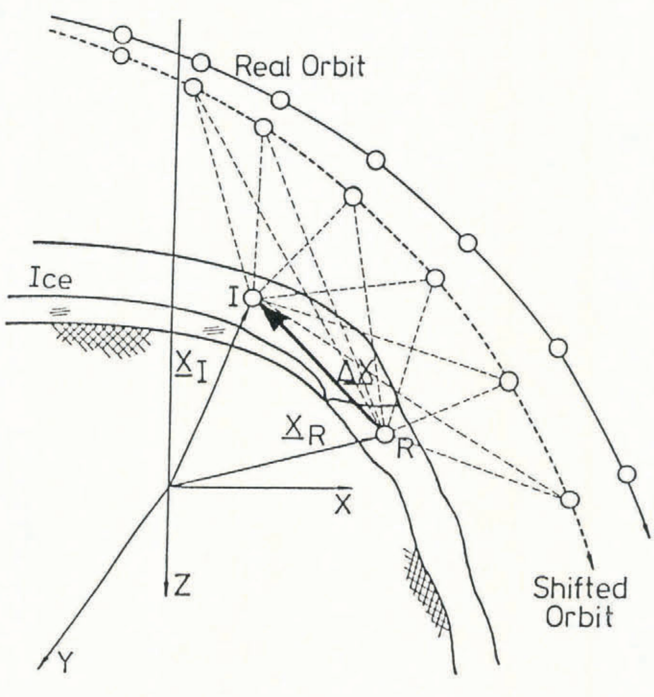

Fig. 1. The rationale of Transit translocation.

A local coordinate system is then defined by relative satellite observations from one or more reference stations on the receiver network. Translocation can achieve a precision level of up to 0.2 m in ΔX from about 20 passes. The advantages of relative positioning for glaciological applications have also been described by McDonald and Whillans (1988, this volume).

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The absolute coordinates of the reference stations which were tracking the satellites for the main period covered by the observations are post-processed from more precise satellite orbital data and will reach the 1 m accuracy level in all three coordinates. The combination of relative station coordinates and absolute station coordinates then yields a network accuracy of about 1–2 m (Ellmer and others 1987).

1.2 Global Positioning System (GPS)

The NAVSTAR–GPS (Navigation System with Time and Ranging – Global Positioning System) will consist, when it is complete (probably at the end of 1989), of 18 satellites in orbits 20 200 km above the Earth. Unlike Transit, GPS will have at least four satellites constantly within view, worldwide, so that three-dimensional real-time positioning will be possible. Currently only nine satellites are available; several hours' coverage daily can be provided by four satellites. Consequently, GPS is already in use in a limited way (see Fig. 2).

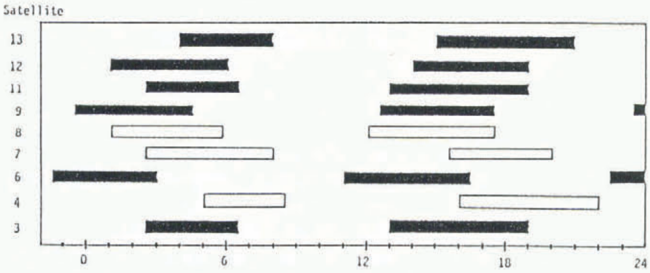

Fig. 2. Radio visibility of GPS satellites at Neumayer Station on 1 February 1987. Favorable observation conditions (four satellites) occurred between 14.00 and 18.00 GMT, dilution of precision occurred in the night coverage block. Satellites 4, 7 and 8 are not suitable for positioning.

The basic positioning mode is realized by the measurements of so-called pseudo-ranges between the user and four satellites. These ranges are determined by cross-correlating a coded navigation signal, transmitted from the satellite, with an identical signal generated in the receiver. The measurement of pseudo-ranges requires prior knowledge of the signal codes. The P-code (precise or protected code) allows real-time positioning with an accuracy of 10–15 m in the GPS broadcast-ephemeris system. The less accurate S-code (standard code or C/S-code — coarse/acquisition or clear/access code) has an accuracy of 30–50 m in the broadcast system. As in the case of Transit, the predicted broadcast ephemeris is of limited accuracy, so that the position in an absolute coordinate system will be worse than the one in the broadcast system.

The GPS satellites transmit the orbital data elements and information about satellite clock behavior within the data signal. These messages are code-modulated on the carrier frequency. Two frequencies are used: the signal L1 (1.6 GHz), containing P- and S-codes, and the signal L2 (1.2 GHz), containing only the S-code. Consequently, reduction of the mean-positioning error, by refraction correction from measurements on both carrier frequencies, can only be computed by those users who have access to the L2 carrier. Currently both codes are free, but after completion of the GPS, the P-code will probably be classified and will not be made available to non-military users. The accuracy of S-code positioning will then limit the absolute coordinates to 100 m.

The basic concept of GPS measurements by pseudo-ranges is used for on-line positioning (navigation) and may provide a real-time position accuracy of 10 m (which is not sufficient for geodetic purposes) within the broadcast-ephemeris reference system. A higher accuracy is available by using differential techniques (like translocation with Transit) and by measurements of the signal-carrier phase. For the application of phase measurements, the carrier must be reconstructable in the

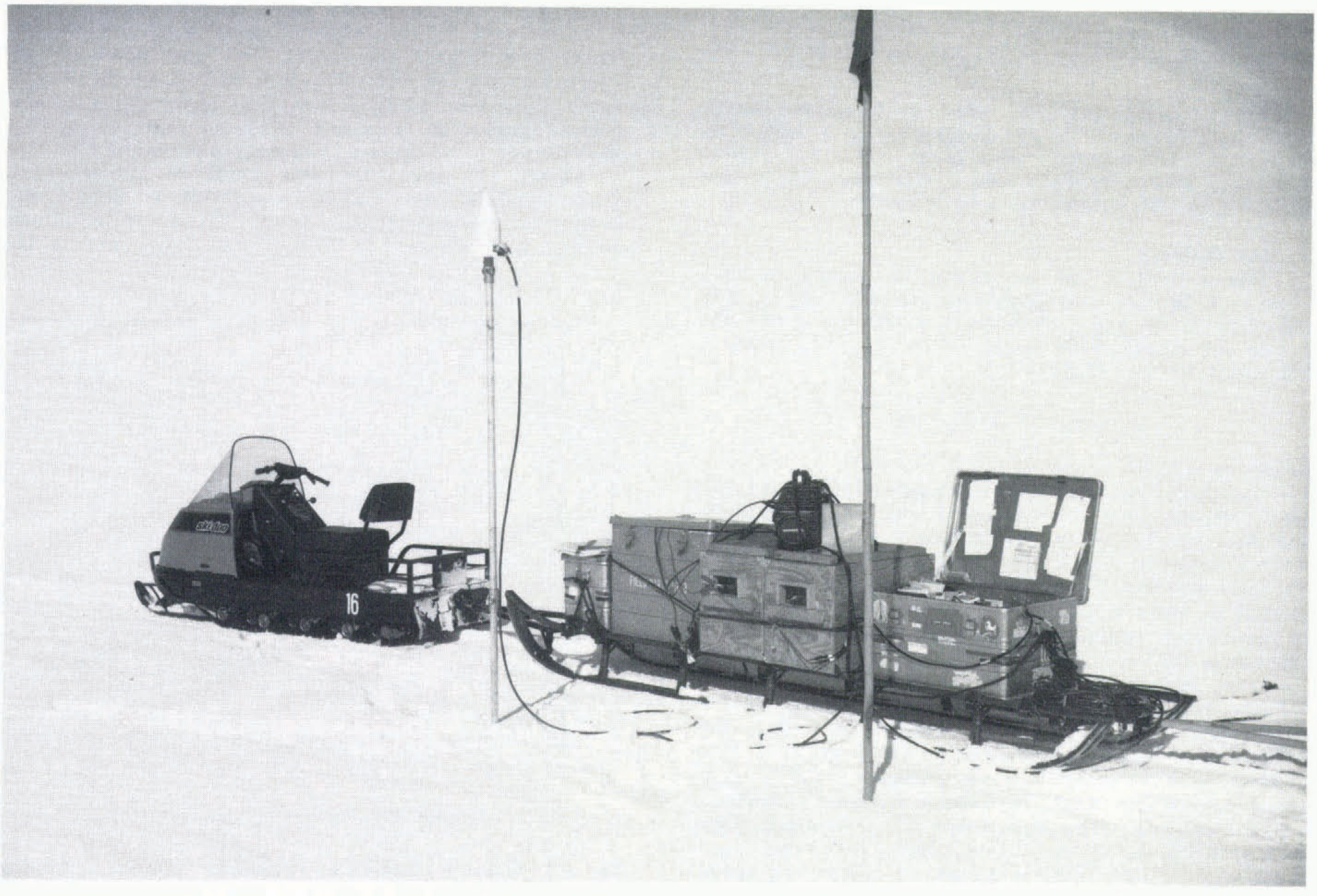

Fig. 3. TI 4100 receiver transport and measurement sledge on Ekström Ice Shelf, 1987.

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receiver. This can be done (e.g. with the TI 4100 receiver) if the code is known. If the phases and phase differences of the carrier wave are measured, the resolution is better than with code measurements only and allows an extremely precise resolution to be obtained at the centimeter level.

In Antarctica, two field expeditions have been made with TI 4100 GPS-receivers from Texas Instruments. The system is ruggedized, quite light-weight, and portable. In Figures 3 and 4 the equipment is shown in action on Ekström Ice Shelf. The TI 4100 is a multiplex receiver; it switches within 20 ms between four satellites, which operate on both frequencies. By this carrier phase, the pseudo-ranges and doppler shift of the satellites can be measured quasi-simultaneously. For precise geodetic positioning with the TI 4100, code availability is essential. The satellite message is decoded and allows real-time positioning, with updates every 4 s. The result is displayed on a hand-held input/output unit. All data can be transferred to an external recording device.

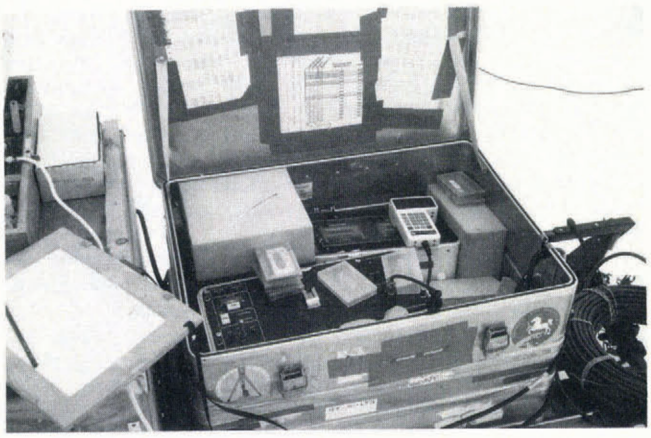

Fig. 4. TI 4100 equipment: receiver/processor unit, control display unit, dual tape-drive recorder.

2. ICE-MOTION DETERMINATION

Between 1982 and 1984, field work on the Anvers Island ice cap resulted in the development of a method for ice-motion determination by means of the Transit positioning system. However, the concept developed is also applicable to GPS positioning (see Hinze 1986).

2.1 The principle

The velocity of an ice station is assumed to be a linear one between two positioning times t_1 and t_2. The difference in the local coordinates L at the two epochs (L_1, L_2) is the displacement vector $\Delta L = L_2 - L_1$, which is normalized for the velocity

$$v = (L_2 - L_1) / (t_2 - t_1)$$

in m/a or m/d.

The necessary time interval between the observation epochs depends upon the accuracy of the station coordinates and the velocity of the ice motion. If it is fast, the interval might be shorter than in the case of slow-moving ice. Low accuracy of coordinates is acceptable if the time interval is immense. On the other hand, the ice motion can be determined within quite a short time interval if the coordinates are very accurate.

The relative coordinates ΔX between a stationary receiver and an ice station are most precise in the simultaneous observation mode (the translocation and differential modes respectively). This enables short observation times and reduces the necessary interval to the second observation epoch. The relative Cartesian coordinates, ΔX_1 and ΔX_2, should be transformed into a local geographic coordinate system, L_1 and L_2, to correspond to the overall situation. L is then given in latitude, longitude and height, or in northing, easting and height. Figure 5 shows the principle of ice-motion determination.

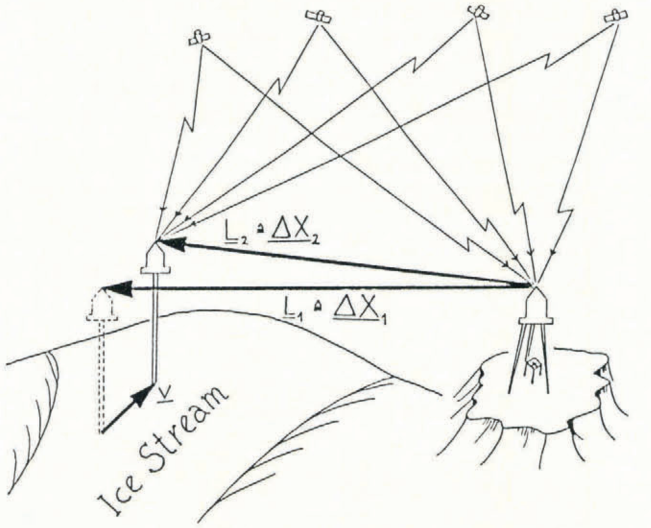

Fig. 5. The principle for ice-motion determination in the GPS differential mode.

2.2 Observation epoch and reference epoch

If the observation period is long enough to divide the satellite data into several groups, where each group represents one observation epoch, the ice motion can be determined from these data. On the one hand the epoch has to be long enough to provide a precise station position, on the other hand it has to be short enough to cancel out any effects of the station motion. For both systems the motion is determined by geodetic positioning software packages which assume a stationary receiver network. Navigation programs are not applicable, because they require a motion orders of magnitude greater than the ice motion (with the exception of the fast sea-ice floes). Figure 6 demonstrates the relation between the station position-fix error and the proper motion for the Transit translocation mode. To achieve a precision of 0.2 m, about 25 satellite passes have to be accepted by the sequential adjustment program for Transit doppler data (GEODOP). This corresponds to an observation time of 24 h. If, within this time, the station moved more than 0.2 m, the position determination is less precise, because the true and calculated positions do not coincide, due to the geodetic stationary software model.

Ideally, the observation data should be distributed at regular intervals over the entire observation period. By dividing the observation span one gets observation epochs of identical data quality. In reality, some data have to be

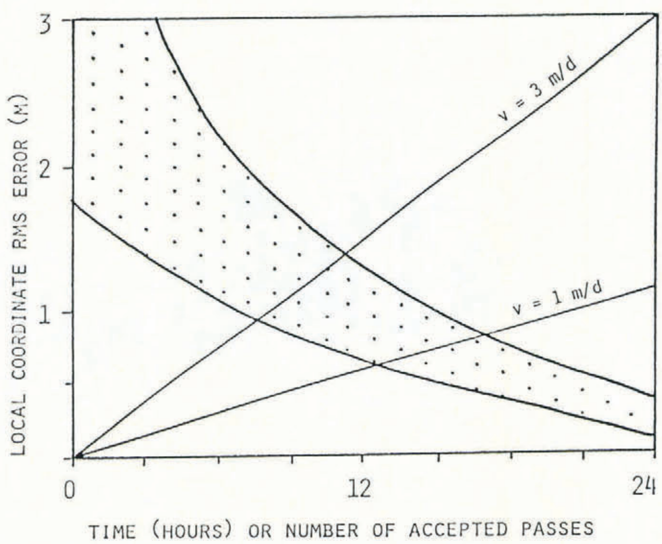

Fig. 6. Relation between coordinate error (Transit translocation) and station motion, assuming one pass per hour.

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rejected if they are separated from the main data block, or some data have to be used in two consecutive epochs in order to increase the amount of data to what is required (a blow-up of observation data). Most important for the arrangement of Transit doppler data into several epochs is the option of a uniform time span for all the epochs. The GPS data-processing software which was used (TIPOSIT) provides a solution for each data span, which terminates when the satellite constellation changes or an irrecoverable cycle slip occurs.

Because the ice motion is estimated by a linear fit of the variation in the local coordinates *L* of the ice station, the determination of the reference time to which the solution of the observation epoch refers is essential. The center of the observation epoch is sometimes chosen as the reference epoch for the coordinates (see, e.g., Gerdau and Schenke 1984). In a sequential adjustment model the reference time is the time of the last observation data set, if the proper motion of the ice station is slow. Any remaining errors in the determination of the reference epoch do not affect the linear motion fit as long as the conditions within the epochs are uniform.

3. EXAMPLES AND RESULTS FROM ANTARCTIC FIELD SEASONS

Here, results of horizontal ice-motion determination are displayed for different data arrangements. The ice motion is separated into horizontal and vertical components, because in the horizontal the motion of an ice cap or ice shelf is at least one-tenth power faster than in the vertical. The results presented are from Transit, from Transit and GPS, and from GPS positioning.

The task of the field projects was to study the possibilities of short-time positioning for ice-motion determination and to apply the methods which have been developed. The motion derived from short-time position changes (day-by-day or daily solution) can be compared with those computed in monthly or annual time intervals.

Because the vertical motion is so much less, it cannot be detected within a short time interval. The noise level of absolute and relative vertical coordinate precision will cover any small vertical motion. Therefore a larger time interval between the observations is needed in order to obtain vertical velocity values.

3.1 **Marr Ice Piedmont, Anvers Island**

Between 1982 and 1984, Transit data was recorded on Marr Ice Piedmont, Anvers Island. Simultaneous observation epochs of several days on ice-camp stations, and permanent satellite tracking on the reference-station base camp Biscoe, were scheduled to provide day-by-day relative positions in the translocation mode. Re-observations 1 year later were used to check the short-time motion results (Hinze 1986).

The change in the local coordinates *L* = (north, east, height) for Camp 1 in 1982 is shown in Figure 7, with the standard deviation (1 σ) of each coordinate component. The horizontal position variation is obvious and it is determined as 0.27 ± 0.01 m d^{-1} with an azimuth of 214 ± 2° (SSW). Within a 3 σ level the changes in height are statistically insignificant. However, from re-observations a vertical

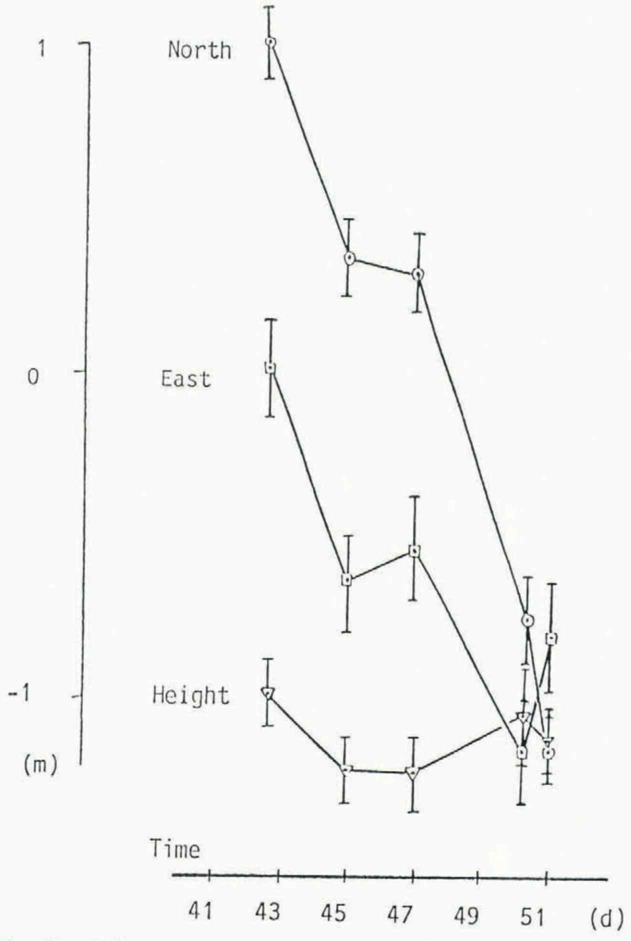

Fig. 7. Daily variations in local coordinates at Camp 1 in 1982, from Transit translocation.

TABLE I. ANNUAL AND SHORT-TIME HORIZONTAL ICE MOTION, ANVERS ISLAND. Parameters given for each station: horizontal velocity *v* (in m d^{-1}), azimuth of motion *a* (°N) and standard deviation (1 σ)

Solution	Station							
Data source / Field season	Camp 1 *v*	Camp 1 *a*	Camp 2 *v*	Camp 2 *a*	Camp 3 *v*	Camp 3 *a*	Camp 4 *v*	Camp 4 *a*
Day-by-day / 1982	0.27 ±0.01	214 ±2	0.13 ±0.06	191 ±15	(1)		(1)	
Day-by-day / 1983	0.30 ±0.01	205 ±2	(2)		0.09 ±0.01	189 ±9	(1)	
Day-by-day / 1984	0.28 ±0.01	204 ±1	0.14 ±0.01	215 ±4	(1)		0.09 ± 0.02	350 ±9
Annual / 1982–84	0.26 ±0.01	202 ±3	0.12 ±0.01	215 ±3	(1)		(1)	
Interpolated data from Rundle (1973)	(2)		0.12 ±0.02	241 ±3	0.13 ±0.05	230 ±5	(2)	

(1) No observations
(2) Insufficient data for this estimate

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displacement was estimated which corresponds to 0.02 m d^{-1} (downward).

In three field expeditions, motions were derived from daily satellite positioning data for Camp 1. These results do not differ if statistical criteria are applied (see Table I). The field data prove that the slow ice-motion results can be repeated even if the 1984 local coordinates have a large root mean square error (larger than normal by a factor of 2) due to instrument-oscillator instabilities. The velocities from annual satellite-data comparison and interpolated data from a terrestrial survey (Rundle 1973) verify these results.

The observation time span for relative positions was generally between 1.2 and 2.0 d for Transit pass tracking, with a mean data-registration span for each solution of about 1.6 d. This observation span will be slightly shorter if the ice-station velocity is higher.

3.2 Filchner–Ronne Ice Shelf

Horizontal ice-shelf motion determination by short-time Transit translocation processing is demonstrated for two stations on Filchner–Ronne Ice Shelf. In 1984, translocation between the Anvers Project reference station Biscoe and site 140, near Filchner Station, was possible (Seeber and Hinze 1984). In 1984, Transit observations were made simultaneously between receivers on Filchner–Ronne Ice Shelf and two reference stations, Belgrano II Station on Bertrab Nunatak (Coats Land) and base camp Biscoe (Anvers Island). For details of relative positioning and absolute coordinates, see Ellmer and others (1987). Figure 8 displays the local horizontal coordinate variations of the translocation Belgrano II – Filchner (point 140), with error ellipses at the 95% confidence level (or 5% error).

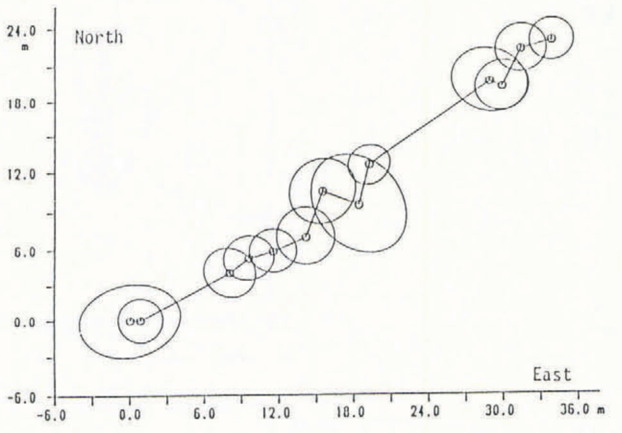

Fig. 8. Daily variations in local horizontal coordinates at Filchner Station in 1984, from Transit translocation.

The Biscoe–Filchner results are influenced systematically by the geometric situation of the two stations (station separation: 1400 km), therefore the results with a long inter-station vector are less weighted. However, they demonstrate the feasibility of very long translocation positioning.

The time span for data registration of the passes per group varied in the relative-position mode between 0.7 and 1.2 d, with an average of 0.9 d for the epochs. The day-by-day changes in the local coordinates indicate a motion of 2.8 m d^{-1} to 53° (NNE) (see Table II). These results can be compared with those of the changes in annual position over several field seasons.

At site 230 field work in 1984 allowed motion to be determined from the day-by-day positioning. Here the average observation time span per epoch is 0.6 d. Results of 3.5 m d^{-1} and 41° have been confirmed by the 1986 re-observations. Motion of 3.27 m d^{-1} at 40° was derived from the changes in position between 1984 and 1986.

Other sites on Filchner–Ronne Ice Shelf had been positioned in 1984 by Transit, in 1986 by Transit and GPS, and in 1987 by GPS. These results are preliminary and are shown in Figure 9 as contour lines of velocity (in m a^{-1})

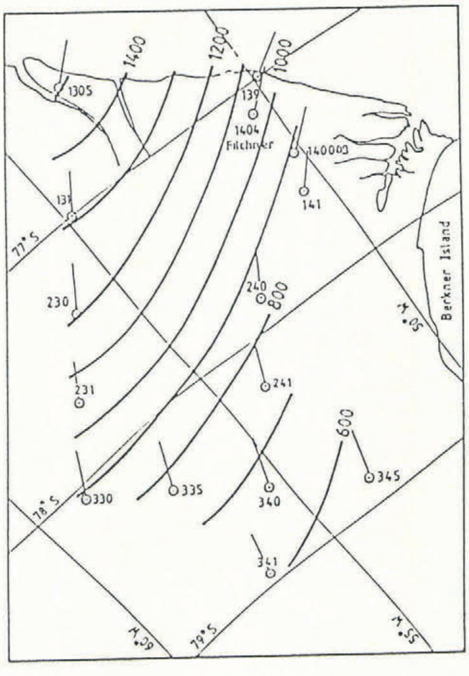

Fig. 9. Contour lines of the velocity and direction of ice-shelf motion in the area of Filchner Station in 1984. Partly preliminary results from on-line positions (Transit and GPS).

TABLE II. HORIZONTAL MOTION OF FILCHNER–RONNE ICE SHELF AT FILCHNER STATION (SITE 140) AND AT SITE 230 FROM SHORT-TIME AND ANNUAL VARIATIONS IN COORDINATES

For parameters, see Table I

Solution		Site			
Data source Field season	Remarks	140		230	
		v	a	v	a
Day-by-day / 1980	Transit single-point positioning	2.9	56	(1)	
Day-by-day / 1982	Transit translocation with base camp Biscoe	2.8	52	(1)	
Day-by-day / 1984	Transit translocation with base camp Biscoe	2.8	52	(2)	
Day-by-day / 1984	Transit translocation with Belgrano II	2.9	54	3.5	41
Annual / 1980–84	Transit	2.82	53.4	(1)	
1984–86	Transit, GPS	2.79	53.5	3.27	40.3
1986–87	GPS on-line	2.85	53.9	(1)	

and bars of motion direction. The increase in velocity towards the ice front is about $3.0 \times 10^{-3}\, a^{-1}$ along the section of profile 30 (330–1305) and about $1.5 \times 10^{-3}\, a^{-1}$ along profile 40 (341–139). The form of the contour lines in the central part of Figure 9 might vary because of the lack of data. In addition, the ice-surface features (flow lines, crevasses) from the glaciological map of Filchner–Ronne Ice Shelf (Swithinbank and others 1987) were not taken into account for contour-line interpolation. The direction of the ice-shelf motion is changing continuously and fits very well with the linear ice-surface forms (flow lines, ice-stream margins) of the glaciological map.

3.3 Ekström Ice Shelf

On Ekström Ice Shelf, Queen Maud Land, position data for Georg von Neumayer Station (station code GVN) and its vicinity have been recorded since 1980. The velocity values derived from Transit or GPS positioning within an area of $20 \times 25\, km^2$ are about $170\, m\, a^{-1}$ or less. The velocity at the ice front is not uniform, because there are ice rumples in the north-west.

For two years, 1982–83 and 1986, a Magnavox MX1502 Transit receiver was operated continuously by the geophysicists at Neumayer Station in order to obtain single-point position data throughout the year. This allows the calculation of absolute positions and the monitoring of changes within time intervals of several days, weeks and months. The 1982–83 data did not provide any evidence of seasonal variation (see Lindner and Ritter 1985).

Simultaneous observations in the GPS differential mode and in the Transit translocation mode had been carried out on Ekström Ice shelf in 1987 (stationary reference station: Grunehogna Station). The 1987 Ekström field season covered the central ice-shelf area of about $125 \times 45\, km^2$ in order to determine ice motion. For details of the combined GPS and Transit positioning work, see Ehrhardt and others (1987). Re-observation of the Ekström stations was carried out in the 1987–88 field season.

The 1987 satellite data are still (September 1987) in the post-processing stage, so a preliminary result will be given as an example. At site 504 (K53: 71°03'40"S, 8°56'09"W) GPS relative positions are available for four observation periods with different geometric satellite constellations and data-registration times. In Figure 10 the local horizontal coordinates of the very first GPS processing are displayed. In the computer calculations of these results, cycle slips have not yet been recovered and all the solutions of each registration time are combined. The first solution is from less than 0.5 h observation time during night-time satellite coverage and is not so precise. The other three solutions are from more than 1 h registration time. These horizontal coordinates indicate a displacement over 14 d which corresponds to a velocity of $170\, m\, a^{-1} \pm 18\%$ in the NNW direction (322° ± 15%). The satellite data for all the observations still have to be edited and corrected for multi-path or cycle-slip effects.

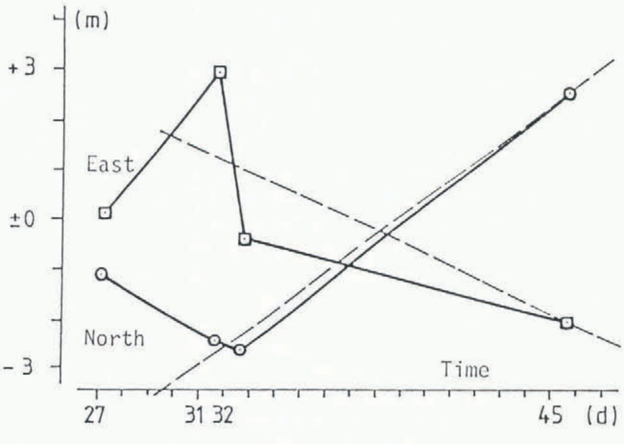

Fig. 10. Variation in local horizontal coordinates at station K53 (504) in 1987, from differential GPS.

CONCLUSIONS

The satellite-positioning systems and calculation methods applied and presented here prove their great effectiveness for the determination of absolute ice motion. The observation schedule has to take into consideration the positioning system used, GPS or Transit, and measurement and post-processing conditions. In the simultaneous-observation mode, the Transit translocation observation epoch should last at least 1 d, and differential GPS should last 30 min or longer under favourable conditions. The fixed reference station could be several hundred kilometers away from the operation area (the use of a reference station which has moved will be studied from the 1987 Ekström Ice Shelf data).

The time interval Δt between the observation epochs depends on the ice motion; as a rule of thumb it should be of the order of

$$\Delta t = 0.2\ m / (v \cdot 5\%)$$

or longer. Multi-receiver campaigns and aircraft transport facilities enable the determination of slow ice motion in the course of one field season.

In particular, the reference station has to be maintained carefully to withstand any disruption from the receiver, e.g. oscillator instabilities, because these affect the local coordinates and reduce the accuracy of all the results.

In the post-processing stage all observation data have to be checked for their use in the simultaneous relative-positioning mode before they are used to form different observation epochs. Ice-motion determination by linear regression then has to take into consideration the varying accuracy of the epochs.

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