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Determination of the Velocity vector of Schirmacher glacier (Dronning Maud Land, Antarctica) using Global Positioning System

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Abstract: Global Positioning System (GPS) has proved to be one of the most effective methods to measure glacier velocity. To give insight into the kinematics and quantitative understanding of the Schirmacher glacier (central Dronning Maud Land, Antarctica), two GPS campaigns were made during the austral summers of 2003 and 2004. GPS data were collected at 21 sites and have been analysed to estimate the site co-ordinates, baselines and velocities in ITRF2000. All the GPS points in the glacier have been constrained with the base station established at MAITRI, the Indian Antarctic Research Station and the nearby IGS stations, viz. VESL and SYOG. Displacement measurements were made from the GPS sites in Schirmacher glacier, parallel to the Schirmacher Oasis. The velocity of the sites is found to lie between 2 - 11 m yr^{-1} in NNE direction and the average velocity of the ice stream over the study region is 6.2 m yr^{-1}. The site velocity distribution is spatially correlated to the surface undulation gradients, crevasses, and blockage of Schirmacher Oasis. In this paper, we report the glacier velocity vector derived from GPS and dynamic nature of the Schirmacher glacier.

Keywords: GPS, ice sheet, Schirmacher glacier, glacier dynamics, surface velocity, Antarctica

Introduction

Antarctic ice which contains 90% of the world's total ice and 70% of world's fresh water, has an active role in global climatic change (Meir, 1993; Zwartz et al., 1999). Monitoring of surface mass balance of Antarctica is one of the key parameters to estimate the glacier dynamics. The Antarctic region is mostly covered by thick glaciers, surface velocity vector of which can provide useful information on phenomena such as glacier surges, icefall and the effect of global warming. Ninety percent of the discharge from the Antarctic ice sheet is drained through a small number of moving ice streams and outlet glaciers fed by relatively stable and inactive areas. Since these outlet glaciers play a vital role in Earth's geodynamics and climate systems, understanding of the complex dynamics of the glacial system requires fundamental information such as mass balance, depth and temperature of the ice, meteorological conditions, surface velocity vectors, strain rates, surface gradients, changes in the surface elevation, etc. To facilitate these studies, critical areas of the outlet regions through which most of the continental ice is discharged to the coast are required to be monitored. Some of such important outlet glaciers have already been studied, e.g. Shirase glacier (Pattyn and Naruse, 2003), Lambert basin glacier (Manson et al., 2000), Dronning Maud Land (Scheinert, 2001), etc.

The coastal region of Antarctica is the most sensitive part of the Antarctic ice sheet. Schirmacher glacier is one such important outlet glacier in central Dronning Maud Land (cDML), playing a major role in the drainage of East Antarctica. In the 1980s, glaciologists from the then East Germany explored some classical ice caves in Schirmacher Oasis, created by water flow. They are outflow conduits draining internal glacier water. With the availability of this vast amount of different types of data for the past two decades, it has become a valuable site for observing the changes in the movement of the Antarctic ice sheet caused by global warming.

With advancement in airborne and spaceborne geodetic techniques, it is now feasible to monitor the dynamics of Antarctic glaciers. With high spatial coverage there are several well-established space-borne geodetic techniques for this purpose, e.g. Very Long Baseline Interferometry (VLBI), Satellite Laser Ranging (SLR), Synthetic Aperture Radar (SAR), Global Positioning System (GPS), etc. Amongst these, the GPS has become the geodetic method of choice for studying the wide range of geophysical phenomena very precisely with the instrument being cost-efficient, low power consuming, containing high memory, portable and requiring minimum logistic support. GPS has become a standard and indispensable tool for determination of ice kinematics to a precision of few mm/yr. Scheinert (2001) outlines a variety of geodetic observation techniques, which were applied to investigate geodynamic phenomena in Schirmacher Oasis region. In this paper, we describe two GPS campaigns undertaken in Schirmacher glacier during 2003 and 2004 and present the velocity distribution over the region.

Regional Geological Setting

The studied glacier is situated in Schirmacher region of cDML, East Antarctica, - part of the Antarctic rift system that has evolved in different stages since the Gondwana break-up in the Jurassic time (Lawver et al., 1992). The study area covers inland plateau, marginal oasis and coastal shelf-ice and bounded by longitude from 11°15′E to 12°15′E and latitude from 70°30′S to 71°00′S . The region of Schirmacher glacier is blocked by the exposed landmass of Schirmacher Oasis, a low-lying nunatak in north (ice-free rocky exposure). The Oasis exposes rocks of granulite to amphibolite facies comprising charnockites, enderbites, garnet-sillimanite gneiss, garnet-biotite gneiss, dolerite, etc. and covers an area of 34 km^2. Elevation of Schirmacher Oasis varies from 0 to 228 m above the msl and it is located 100 km south of Lazarev Sea and Nivlisen shelf ice (Sengupta, 1986 and Hermichen, 1995). In the south, Schirmacher glacier is bounded by Wohlthat mountain range.

The study area is divided (elevation ranges from 0 to 1000 m) topographically into three distinct units, the southern continental ice sheets, rocky hill slopes and northern undulatory shelf ice (Ravindra et al., 2001). This outlet glacier is characterised by steep gradient surface slopes, crevasses and NE-SW- to NNE-SSW-trending criss-crossed fractures near Schirmacher range (south of Oasis) and relatively gentle slope in the inland area near the nunataks, viz. Tallaksenvarden, Hauglandtoppen, Pevikhornet, etc. (Fig. 1). The north of Schirmacher Oasis comprises shelf ice with pressure ridges, fractures and crevasses. The contact between shelf ice and eastern rocky slopes is marked by a prominent 3-km-long, NNE-SSW-trending lineament.

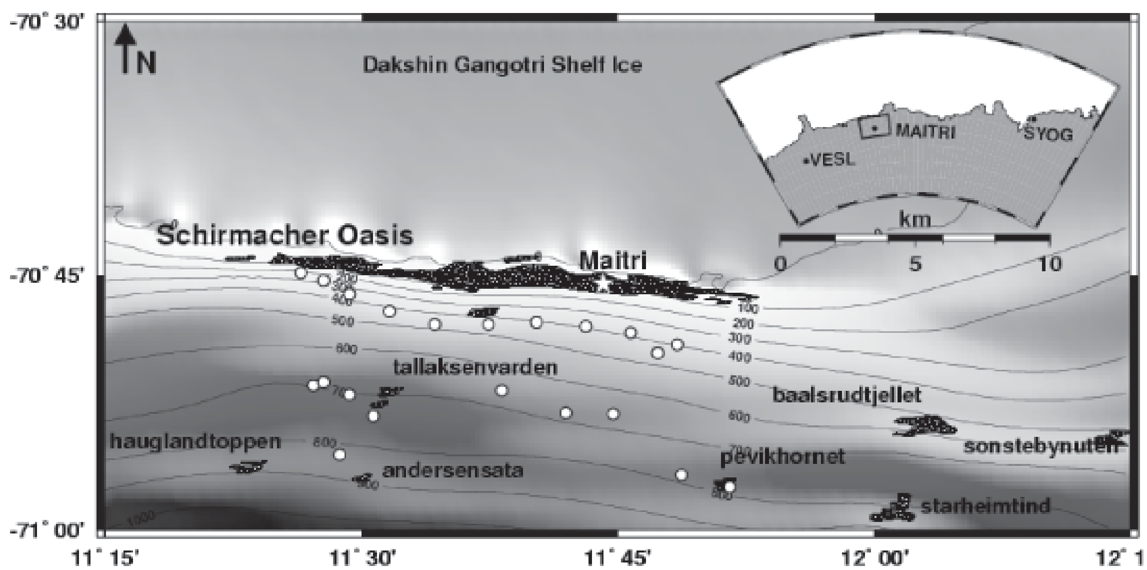

Fig. 1. Network of 21 GPS sites in Schirmacher glacier superposed on shaded relief map of GTOPO30 topographic data with 100- m contour interval. The GPS locations in glacier are shown as open circles and various coastal nunataks including Schirmacher Oasis are shown as black patches. In the inset, the rectangle indicates the study region near Indian research station MAITRI and the IGS stations VESL and SYOG.

Survey Description and Data Processing

Figure 1 shows the network of 21 sites with ~5-km inter-station spacing, spread over an area of 25 × 50 sq km. The coordinates of these sites are given in Table 1. For GPS data collection, dual frequency (L1/L2) geodetic Trimble 4000SSi receivers with choke ring antenna were used. Each antenna was fixed on a 1.5-cm diameter threaded steel bolt fixed on a wooden block of 1 × 1 × 1 ft which is embedded in the ice to a depth of 1.5 ft (Fig. 2). The first and second campaigns were made during January - March, 2003 and January - March, 2004 respectively. At each site the data were collected for about 48 hours with 30-seconds sampling interval and 15°-elevation mask by Indian Antarctic expedition. The survey region lies ~15 km away from the Indian Antarctic Research Station, Maitri that was established in 1989. Near to Maitri one permanent GPS site is set up (shown with star symbol in Fig. 1) on exposed bedrock. The GPS receivers were transported from Maitri to field sites by helicopters and snow vehicles. The GPS receivers were powered by specially sealed 12V, 72AH charged batteries enclosed in non-conducting boxes. During the second GPS campaign, the data were collected at only 15 sites (out of 21

Table 1. Geodetic co-ordinates of the GPS monuments set up on the Schirmacher glacier and their averaged horizontal flow rates with associated errors

Glacier Points	Latitude (South)	Longitude (East)	No. of Observation(s)	Horizontal velocity (m yr^{-1})	Precision (m yr^{-1})
GL01	70° 37′ 37.89″	11° 26′ 28.73″	1	—	—
GL02	70° 38′ 04.60″	11° 27′ 46.22″	2	2.37	5.65
GL03	70° 38′ 51.21″	11° 29′ 16.42″	1	—	—
GL04	70° 39′ 53.82″	11° 31′ 37.99″	2	4.33	6.63
GL05	70° 40′ 40.66″	11° 34′ 14.99″	2	6.56	7.54
GL06	70° 40′ 43.06″	11° 37′ 28.16″	2	6.97	7.77
GL07	70° 40′ 35.14″	11° 40′ 16.12″	2	7.82	7.92
GL08	70° 40′ 48.52″	11° 43′ 08.30″	1	—	—
GL09	70° 41′ 10.39″	11° 45′ 48.45″	2	8.81	8.26
GL10	70° 41′ 54.68″	11° 48′ 27.63″	1	—	—
GL11	70° 42′ 22.63″	11° 47′ 18.84″	2	10.79	6.55
GL12	70° 44′ 51.26″	11° 29′ 18.22″	2	4.85	6.41
GL13	70° 44′ 12.84″	11° 27′ 10.29″	2	4.47	6.46
GL14	70° 44′ 08.71″	11° 27′ 46.94″	1	—	—
GL15	70° 46′ 00.43″	11° 30′ 38.03″	1	—	—
GL16	70° 48′ 24.76″	11° 28′ 42.56″	2	2.84	8.38
GL17	70° 44′ 32.64″	11° 38′ 13.44″	2	7.18	7.37
GL18	70° 45′ 57.62″	11° 42′ 00.89″	2	10.88	9.48
GL19	70° 45′ 59.94″	11° 44′ 47.75″	2	8.7	7.49
GL20	70° 49′ 37.86″	11° 48′ 42.89″	2	4.69	8.4
GL21	70° 50′ 13.90″	11° 51′ 31.19″	2	1.89	7.03

Fig. 2. GPS antenna mounted on wooden platform and GPS receiver being set for the collection of GPS data at Schirmacher glacier.

sites) due to logistic problems. Data have been downloaded to the Notebook PC and converted to Receiver Independent Exchange (RINEX) format at each site.

The GPS data obtained during the two campaigns were organised into 24-hour segments covering a UTC day to facilitate the processing relative to nearby IGS (International GNSS Service) network sites VESL and SYOG (Fig. 1). As a first step, we analysed all pseudorange and phase GPS data using GAMIT post-processing software developed by Massachusettes Institute of Technology and Scripps Institution of Oceanography (King and Bock, 2000). To produce estimates and an associated covariance matrix of station positions, we solve for satellite state vectors, tropospheric zenith delay parameters and phase ambiguities using doubly differenced GPS phase measurements. Thus, for each session, a "loose solution" (Feigl et al., 1993) defined in the International Terrestrial Reference Frame 2000 (ITRF2000) (by using precise orbits from anonymous ftp site 'lox.ucsd.edu') has been obtained and then passed to a Kalman filter (Herring et al., 1990). In the second step, these loosely constrained solution files (h-files) were combined with the global solution files (IGS h-files) from the IGS daily processing routinely done at Scripps Institute of Oceanography (SIO) by using the GLOBK software (Herring et al., 1990; Dong et al., 1998). We then impose the ITRF2000 reference frame using this combined solution by minimising the position and velocity deviation of IGS core stations SYOG and VESL with respect to the ITRF2000 for the estimation of consistent set of coordinates and velocities of each GPS site.

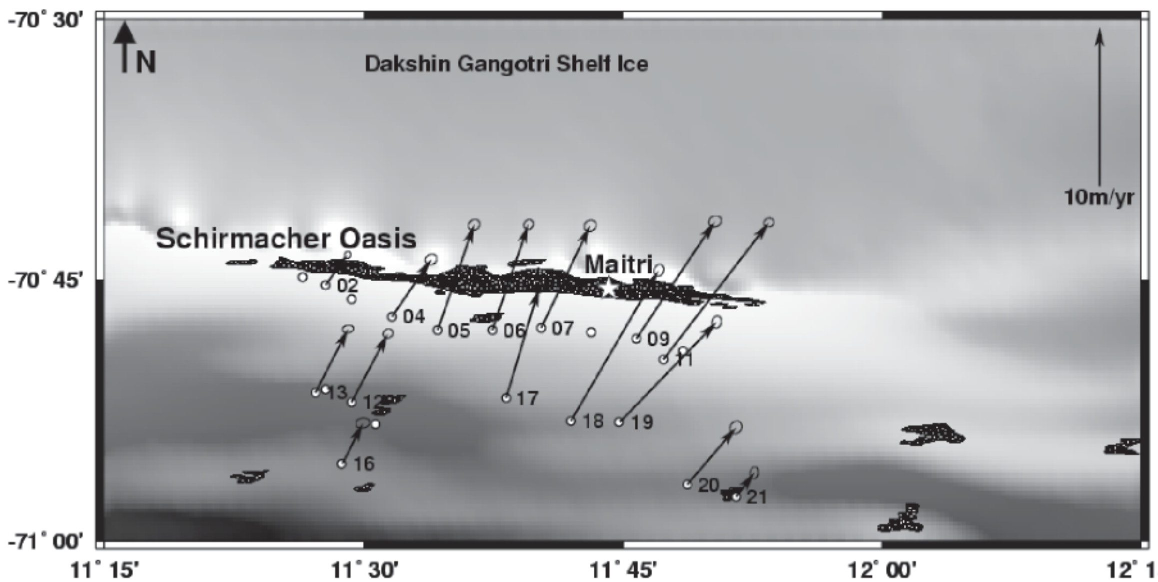

Fig. 3. Horizontal velocity vectors (with 95% confidence ellipses) for the GPS network in Schirmacher glacier, superposed on shaded relief map of GTOPO30 data.

Results and Discussions

Table 1 gives the magnitudes of surface horizontal velocity estimated at each site of Schirmacher glacier, and the velocity vectors are shown in Fig. 3 (for 15 sites out of 21 sites). The maximum and minimum velocities are 10.88 ± 0.009 m yr^{-1} and 1.89 ± 0.007 m yr^{-1} seen in the northeastern and southern parts of the study area respectively. The average velocity of the glacier is 6.21 ± 0.007 m yr^{-1} in NNE direction. In general, higher velocity is recorded at the sites located at maximum steepness of the glacier or/and away from the blockage of Schirmacher Oasis.

The maximum velocity of other glaciers in East Antarctica, e.g. Shirase (1200 m yr^{-1}) (Pattyn and Naruse, 2003) and Lambert Glacier (2500 m yr^{-1}) (Manson et al., 2000) is far higher compared to ~11 m yr^{-1} of Schirmacher glacier. The reason for the low velocity might be due to the friction offered by undulated bedrock. The Schirmacher Oasis and other nunataks exposed in the study region which are extended along the grounding line also offer resistance significantly to the flow of this glacier.

The surface-velocity contour map with 1 m yr^{-1} interval is presented in Fig. 4. This map clearly shows the high-velocity region (fast-zone) which contains GPS sites 09, 11, 18 & 19, (as shown in Fig. 2). Though the elevation gradient of this region is gentle, the velocity is maximum because the blockage of the Schirmacher Oasis is minimum. The shear stress of gravitational driving force (with extension strain rate of ~400 micro strains per year) is caused due to the number of steep crevasses noticed during the field observation along this zone. GPS sites 02, 05, 06 & 07, despite being situated over the steep gradient region, have relatively low velocity because of the blocking by Schirmacher Oasis. The velocity of site 02 is very low i.e. 2.37 m yr^{-1}, as this site is very close to the Schirmacher Oasis. In the

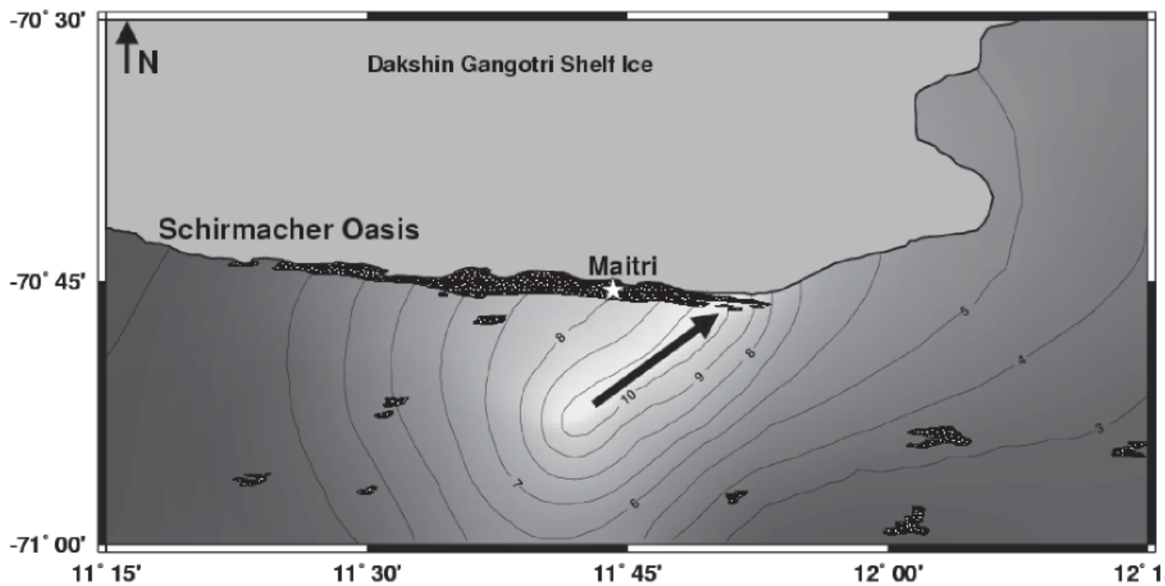

Fig. 4. The magnitude of the horizontal surface velocity contoured with 1- m interval. Arrow indicates the direction of glacier outlet movement.

region away from the Schirmacher Oasis (SE and SW part), the points are away from the marginal ice shelf and the surface undulation is gentle compared to the northern part. The points in this part show the minimum velocity of 1.89 m yr^{-1} and a maximum of 4.85 m yr^{-1}. The results from this study correlate very well with the previous geodetic investigation (Scheinert, 2001) done in this area and show that the major outlet and downstream area of the Schirmacher glacier is through the eastern end of the Schirmacher Oasis.

The campaign data are not adequate to study the secular (at time scale of years) velocity variations and influence of the atmospheric conditions on the velocity vector. To accomplish these, continuous recording of GPS data (with MET package) at selected sites on the Schirmacher glacier has been planned. To model the glacier dynamics and estimate the mass balance changes, in addition to the rheology of the ice, the knowledge of glacier geometry, boundary conditions, deformational and basal components of the glacier velocity is required.

Conclusions

To study the kinematics of Schirmacher glacier in East Antarctica, GPS data has been collected for two campaigns during 2003 and 2004 and analysed using GAMIT/ GLOBK. The results show that the magnitude of the horizontal velocity (in ITRF2000) is in the range of 2 m yr^{-1} to 11 m yr^{-1} with an average of 6.21 m yr^{-1} in NNE direction. The distribution of velocity is spatially correlated to the surface undulation gradients, crevasses (coinciding with the fast-zone), and influenced by the blockage due to presence of Schirmacher Oasis. Another technique InSAR is extensively used for the measurement of glacier velocity, e.g. Rutford Ice Stream in Western Antarctica (Goldstein et al., 1993) and suitable SAR scenes are being acquired for Schirmacher region. The InSAR results with good vertical resolution can supplement the GPS results with good horizontal resolution.

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