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Surface Ice Flow Velocity and Tide Retrieval of the Nivlisen Ice Shelf from GPS Observations

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ABSTRACT

Using a Global Positioning System (GPS) receiver, 19 days of continuous GPS data were collected from January 23 to February 10, during austral summer of 2005, in the frontal zone of Nivlisen ice shelf (NIS) of central Dronning Maud Land (cDML), East Antarctica. GPS data were analyzed to estimate the diurnal and semi-diurnal variations. We constrained the shelf DG GPS site co-ordinates with the base station MAITRI set up at Schirmacher Oasis and nearby International GNNS Service (IGS) stations. The Ice shelf motion in both cases was caused by a combination of ocean tidal effect, wind stress and ocean currents. The estimated horizontal velocity at DG GPS site was 0.72 m/day towards north-north-east with an azimuth of 20.27^{o}. Major constituents of the oceanic tide have been delineated subjecting the hourly time series data (for five days) to Fast Fourier Transform (FFT) analysis. The amplitudes of the diurnal and semi diurnal were ~1.25 m and 0.5 m, respectively. The result showed not only the expected vertical tidal displacement but also a significant variation in the horizontal velocity. The maximum forward velocity occurred about 3-4 hours after the maximum tidal height, a phase relationship that suggests the role of ocean currents also as one of the driving forces for the ice shelf movement. Further more, this type of precise observations of diurnal and semi-diurnal tidal constituents can be assimilated in tide models.

Keywords: Antarctica, Nivlisen Ice Shelf, Schirmacher Oasis, GPS, Tide, Velocity

INTRODUCTION

The Polar Regions are important components of the global environment. The floating ice shelves and glacier tongues surrounding Antarctica are the source of most of the mass loss from the Antarctica ice sheet (Jacobs et al., 1992), and fast responding components to climate warming in the Antarctic Peninsula. Hence knowledge of the surface velocity field and strain rate of ice shelves and continental ice are important in determining their present kinematical states and detecting any changes.

Much of the Antarctic coastline is fringed by floating ice shelves which range in area up to 500,000 km^2 and in thickness up to 2 km or more (Doake et al., 2002). There are many large ice shelves surrounding Antarctica. Some of the important ones are Amery Ice Shelf, Filchner-Ronne Ice Shelf, Ross Ice Shelf and Nivlisen ice shelf etc. The ice shelves are usually considered to have a similar horizontal and vertical movement and the former is much less than the latter during a 24 hour period (Rommelaere and Ritz, 1996). Strain induced by the weight of the ice shelf or increased basal melting and ocean tides and currents are the major responsible forces for time varying horizontal and vertical changes of these ice shelves. Generally, for the ocean tidal effect, ice shelves respond like a free floating object and maintain in phase with the tide (schematic diagram of ice shelf is shown in **Fig. 1**).

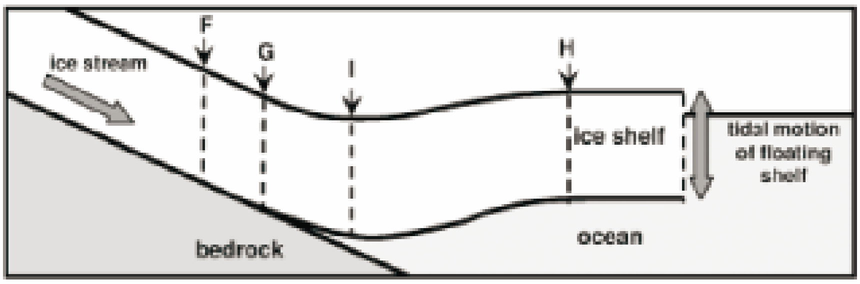

Fig. 1 : Schematic diagram of an ice shelf (after Vaughan (1994); Fricker and Padman (2006)). F, G, I and H indicate limit of ice flexure, limit of ice flotation, and inflexion point and the inshore limit of the hydrostatic zone of free-floating ice shelf, respectively

There are many techniques by which, tide-induced effect on floating ice shelves can be monitored. Interferometric Synthetic Aperture Radar (InSAR) (Bindschadler, 1998), Global Positioning System (GPS) (Manson et al., 2000 and Horwath el al., 2006), Gravity meters (Williams and Robinson, 1980), bottom-mounted tide gauges, tilt meters etc. From a combined analysis of ice thickness, ice surface height and ice-flow observations, one can obtain a new description of the complex glaciological regime, and can generate models of ice thickness, ice-flow velocity, mass-flux and mass-balance parameters on a local and integrated scale (Horwath et al., 2006). In this paper we report on the preliminary study to access whether GPS data from floating ice shelf can provide useful information for the NIS, which floats on the Lazarev Sea, East Antarctica (looks like funnel shaped, **Fig. 1, Fig. 6**). Both horizontal and vertical movements of the NIS are particularly important to observe, as both provide valuable data for mass balance calculations.

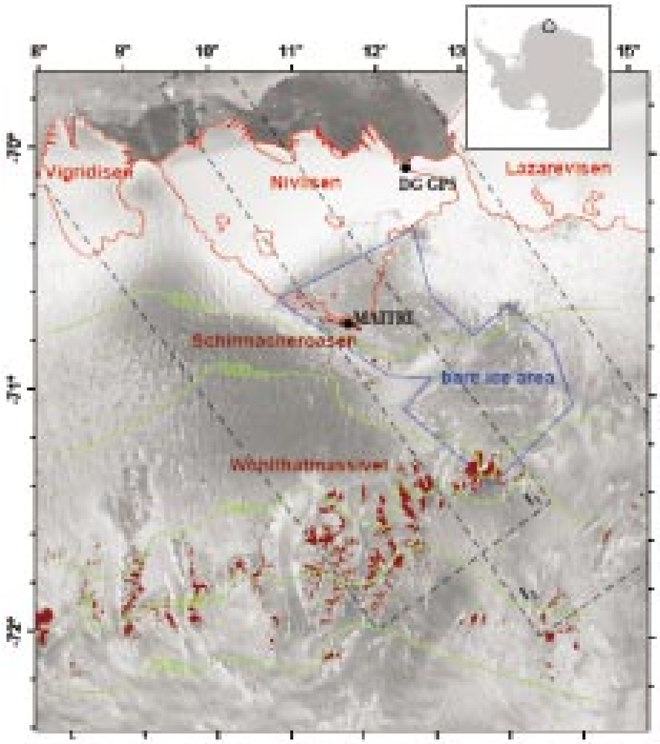

Fig. 2 : The region of Scirmacher Oasis with Nivlisen Ice Shlef (NIS). The background image is the RADARSAT amplitude image. The contours indicates the 500m elevation interval (after Horwath et al., 2006). The GPS site near Dakshin Gangotri (DG GPS) and MAITRI are indicated as closed black circles

GPS Data Collection and Processing

NIS, is one of the number of small ice shelves bordering the Antarctica's Atlantic sector **(Fig. 2)**. The ice shelf extends over about 80 km in south-north and 130 km in west-east direction. Ice thickness varies from about 700 m in south-east to 150 m at the ice front. Dynamics of the NIS from a combination of InSAR and GPS data have previously been presented by Horwath et al., (2006). In the present study, dual frequency Trimble 4000 SSi Receiver with choke ring antenna was installed near to the Dakshina Gangotri (DG) site (latitude 69°58' 5.06"S and longitude 12°23' 46.36"E), which is the first Indian station established during 1983 **(Fig. 2)** and abandoned later as it got submerged in ice. The antenna was fixed on a 1.5 cm diameter threaded steel bolt screwed on a wooden block of 0.5 m × 0.5 m, embedded to a depth of 0.75 m in ice **(Fig. 3)** (Sunil et al., 2007). The logistic support was availed from lone geomagnetic observatory that was set up in container near to the GPS point and maintained by Indian Institute of Geomagnetism (IIG). The data collection started from January 23, 2005 until February 10, 2005 (with 30 sec sampling interval and 15° elevation angle) . In double-difference GPS positioning, the GPS positions (and hence velocities) are traditionally measured relative to stationary sites using static GPS positioning techniques. To enable relative positing, the GPS data from permanent GPS site set up on bedrock at Scirmacher Oasis (MAITRI) (latitude 70°38’50.34"S and longitude 11°44’08.61"E, ~80 km away from the DG GPS site) has been used.

Fig. 3 : GPS antenna mounted on wooden platform which is embedded in the glacier at DG GPS location. The ship used in the expedition is moored on the shelf is seen at the background

Generally, for the static positioning, we organized the GPS data into 24 hours segments, covered a Universal Time Coordinated (UTC) day and process. The GPS data on floating ice is bit complicated due to the presence of vertical tidal signal with periodicities and large enough to contaminate the static positions. Here we splitted the GPS record into one hour segment and processed each segment separately to minimize the motion effects of the GPS receiver on the ice shelf (Fricker et al., 2002). In order to estimate the precise positioning in diurnal and semi-diurnal conditions, the international GNSS Service (IGS) precise orbit and precise satellite clock products were taken as known data. The data were processed by GAMIT and GLOBK software by King and Bock (2002) and Herring (2002), respectively. We considered Maitri base station and nearby IGS stations OHI2, MAW1, SYOG and VESL to constrain the daily ice shelf velocity in International Terrestrial Reference Frame 2005 (ITRF2005) (Altamimi et al., 2007). Additional parameters that were adjusted included a zenith troposphere delay as constrained random walk, carrier phase biases, and the receiver clock. Models for solid earth tides, including the pole tide were considered.

Surface Horizontal and Vertical Movement

The daily positions for total horizontal flow has been inferred by integrating the NS and EW component velocities. The initial inspection of the result in a longitude and latitude showed that the ice flow was predominantly in north direction with an average speed of 0.67 m/day and east direction with a speed of 0.25 m/day. The total horizontal component movement of the shelf showed the speed of 0.72 m/day towards north-north-east with an azimuth of 20.27°. A map view of the result from the entire 19 day data set is shown in **Fig. 4**, which shows that it follows nearly linear trend. If the velocity of 0.72 m/day is uniform throughout the year, the NIS will move about 263 m/year.

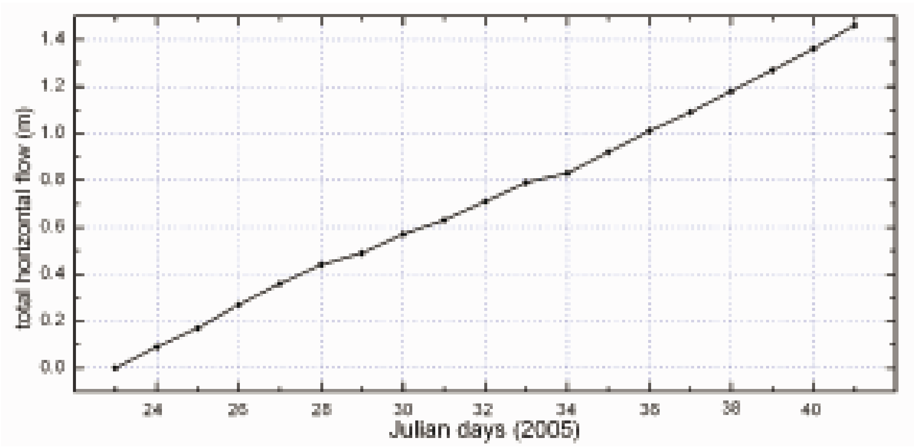

Fig. 4 : Map view of the path of DG GPS site on Nivlisen Ice Shelf over a 19-day period. Axes indicate Julian day and total horizontal displacement respectively

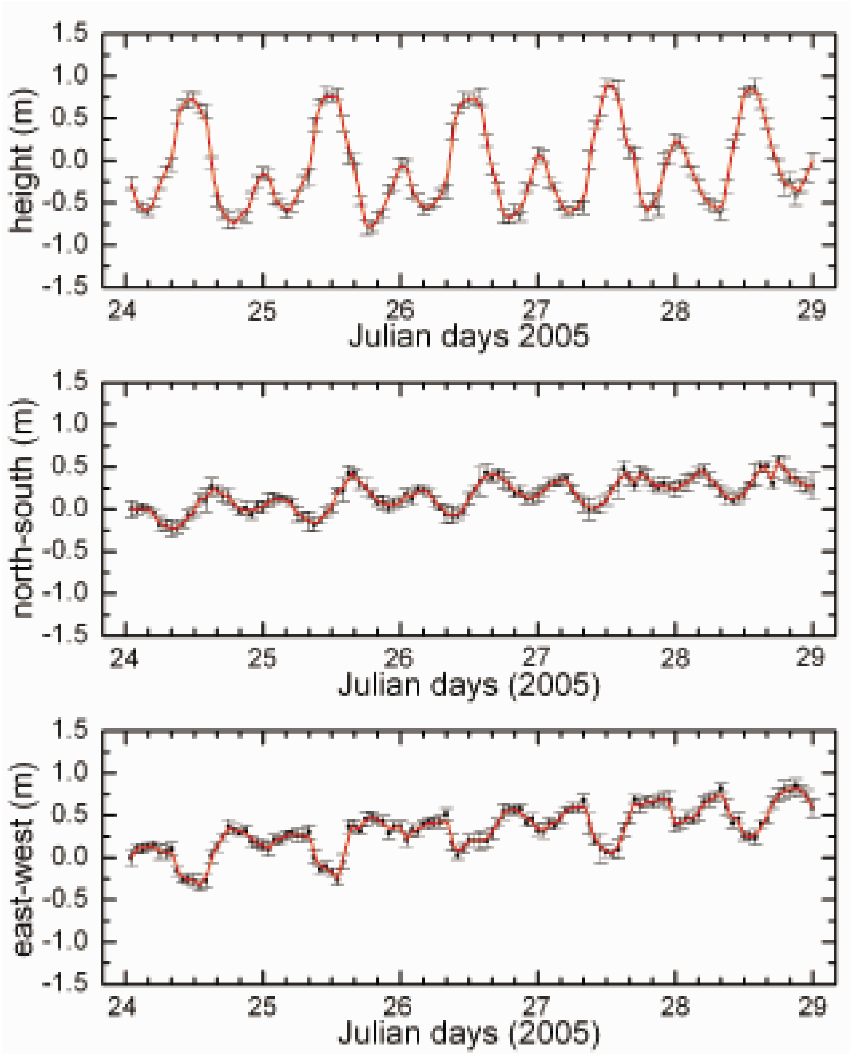

Fig. 5 : Gives the hourly time series of the position co-ordinates considering 5 days of data. The sinusoidal variation represents true ice shelf response to the tides. The associated error is shown as error bars. Tide gauge observation would have facilitated excellent comparison. Unfortunately, we could not procure these data. However, fairly good comparison can be made with regional tidal model (e.g. Robertson et al., 1998)

Subsequently, hourly estimated position data were differentiated to give tidal modulated velocity in horizontal and vertical directions. During a day, though the sea tides caused detectable displacements on horizontal motion (Doake et al., 2002), they were much less than vertical motion (i.e. 40-50% of the amplitude of the vertical signal) (King et al., 2003). **Fig. 5** shows the hourly ice flow measurements of NIS in vertical, north-south and east-west direction. The horizontal axis is the UTC time of the day. The periodic elevation variation of the NIS front has been isolated, with a solution computed epoch-by-epoch. The surface height of an ice shelf varieed in time due to ocean tides, wind stress, atmospheric pressure, ocean dynamics, snow loading, ablation or accretion of ice at the ocean/ice interface, as well as ice dynamics. However, Figure 5 clearly shows the isolated tidally related signal over the 5 days of observation, with the range between the highest and lowest tide to be about 1.5 m whereas, cross correlation of the horizontal and vertical components showed that the maximum horizontal displacement occurring after 3 to 4 hours after the high tide, suggesting the involvement of ocean currents, which also contributed to the horizontal movement of the NIS.

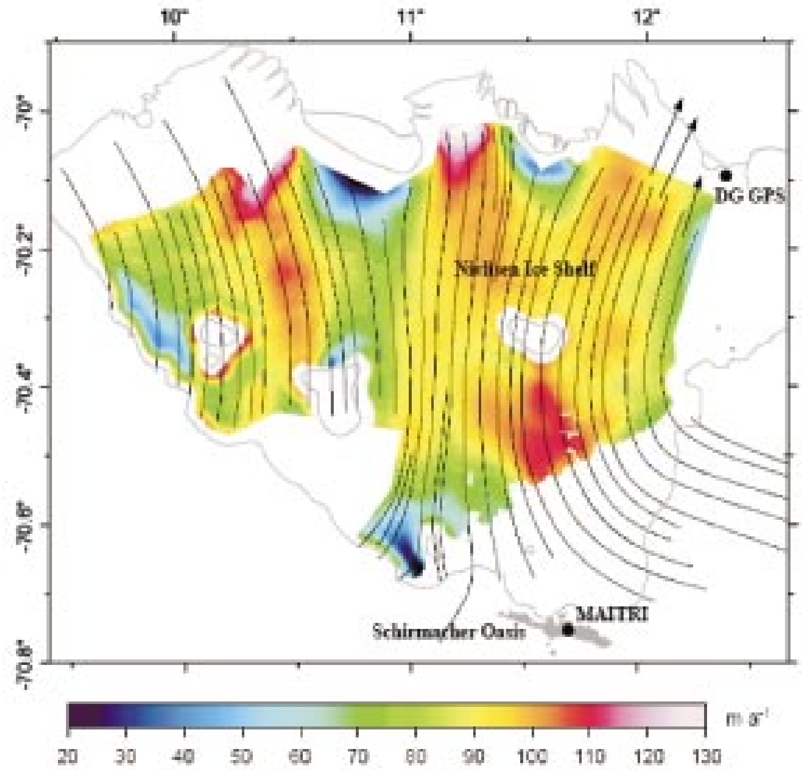

Fig. 6. Horizontal velocity field of Nivlisen derived from interferometric SAR processing. Black lines are flow lines deduced from the amplitude image and used to delineate the flow direction. Arrows show the GPS measurements used for the calibration (Horwath et al, 2006)

CONCLUSIONS

GPS established as one of the most convenient tools for the measurement of tidal signals in remote areas, and one of the better ways to derive ice shelf tidal movement (King et al., 2005). Full interpretation of GPS data from a single point can be well studied by corroborating the result with InSAR data. King and Aoki (2003) showed that, it is possible to measure ocean tide signals using only a single GPS receiver with the precise GPS data processing approach. Among the ice shelves along Antarctica's coast, NIS is one with a peculiar glaciological regime, a long history of exploration, and a wealth of observations. At NIS, despite logistic difficulties, we collected 19 days of GPS data near DG site (on frontal part NIS) during austral summer of 2005 January 23 to February 10. We adopted conventional static mode processing though kinematic and sequential processing was feasible. It was found that horizontal velocity of the NIS is 0.72 m/day and if the velocity of 0.72 m/day is uniform throughout the year, the NIS will move about 263 m/year towards north-north-east direction. We have compared our result with the GPS result of Amrey Ice Shelf (AIS). AIS shows a daily movement of 2.25 m/day (Zhang and Andersen, 2006), which is three times higher than the NIS velocity. And with SAR results of Horwath et al (2002) (shown in Fig. 6) where the SAR derived velocity is around 90 m/yr, much less than our result. Low velocity of SAR may due to not accounting for atmospheric effects properly.

We have estimated the possibility of GPS derived height to determine the individual diurnal (amplitude ~ 1.25 m) and semi-diurnal (amplitude ~ 0.5 m) tidal constituents close to the NIS front. From the sub-daily data analysis, we have presented evidence to show that, ice shelves can experience horizontal motion associated with ocean tide as well as ocean currents. Mainly during semi-diurnal tidal variations, the horizontal velocity of the ice shelf is getting affected after 3 to 4 hours of maximum high vertical tide. This sub-daily periodic activity throws light not only to the involvement of tidal activity for the lateral movement of floating ice but also to sources like ocean currents which also may actively be involving as a driving force. It is very likely that there can be some spurious motions due to the processing of the unmodelled, tidally induced vertical signals in the GPS data (King et al., 2003). When we go for sub-daily GPS position estimates, Larson et al. (2001) showed that ambiguity resolution improves these spurious variations in horizontal motions.

Further, we compared our results with the ocean tide models (e.g. FES2004, TPXO6.2, NAO99 or GSFC00) and found it comparable. However, these models rely heavily on assimilated TOPEX/ Poseidon (T/P) satellite altimeter data. Accurate tidal models are also important for correction of remote sensing signals designed to measure ice shelf topography from ERS, ENVISAT and ICESAT. It is, therefore, interesting to investigate if GPS observations can provide a supplement to the tidal observation for possible future assimilation into ocean tide models.

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