NERC GEOPHYSICAL EQUIPMENT FACILITY LOAN 847 SCIENTIFIC REPORT

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Basal conditions on Pine Island Glacier, West Antarctica

Abstract

Two Leica 1200 GPS receivers from NERC Geophysical Equipment Facility were used alongside two British Antarctic Survey GPS receivers. This allowed coverage between 55 km and 171 km along the centreline of Pine Island Glacier (PIG), West Antarctica and on one of its tributaries. Velocity, acceleration and elevation changes were measured. We demonstrated with a simple force-balance model that the section of PIG, 55 to 171 km inland, is steepening at a rate which provides an increase in driving stress of sufficient magnitude to produce the observed acceleration. If the perturbation causing this acceleration originated at the downstream end of the glacier it is likely that it has been transmitted rapidly upstream, by a diffusion process, faster than 10 years per 100 km. Current rates of thinning and acceleration are greater than any previously measured on PIG. A paper outlining these findings has been published online in discussion format and if successful under open review an edited version will be published in The Cryosphere journal.

Background

Two Leica 1200 GPS receivers from NERC Geophysical Equipment Facility (GEF) were required for use alongside two identical British Antarctic Survey GPS receivers on Pine Island Glacier, West Antarctica (Figure 1). This enabled us to place three receivers along the central flowline of the glacier at separations of around 50 km in order to detect changes in acceleration along this flowline. A fourth GPS receiver allowed the measurement on another tributary of the glacier. Pine Island Glacier (PIG; Figure 1) and its catchment basin comprise 10 % of the West Antarctic Ice Sheet and have the potential to contribute 50 cm to sea level rise. It is undergoing significant change that affects the whole basin, but is concentrated in the outlet glaciers. Initial analysis of the first ground-based GPS measurements on this glacier, taken in the previous season (2006/2007), revealed that the glacier was accelerating much further upstream than satellite measurements have previously been able to demonstrate using Interferometric Synthetic Aperture Radar (InSAR) techniques. A question to be answered was whether the acceleration of PIG is due to ocean influences or originates inland.

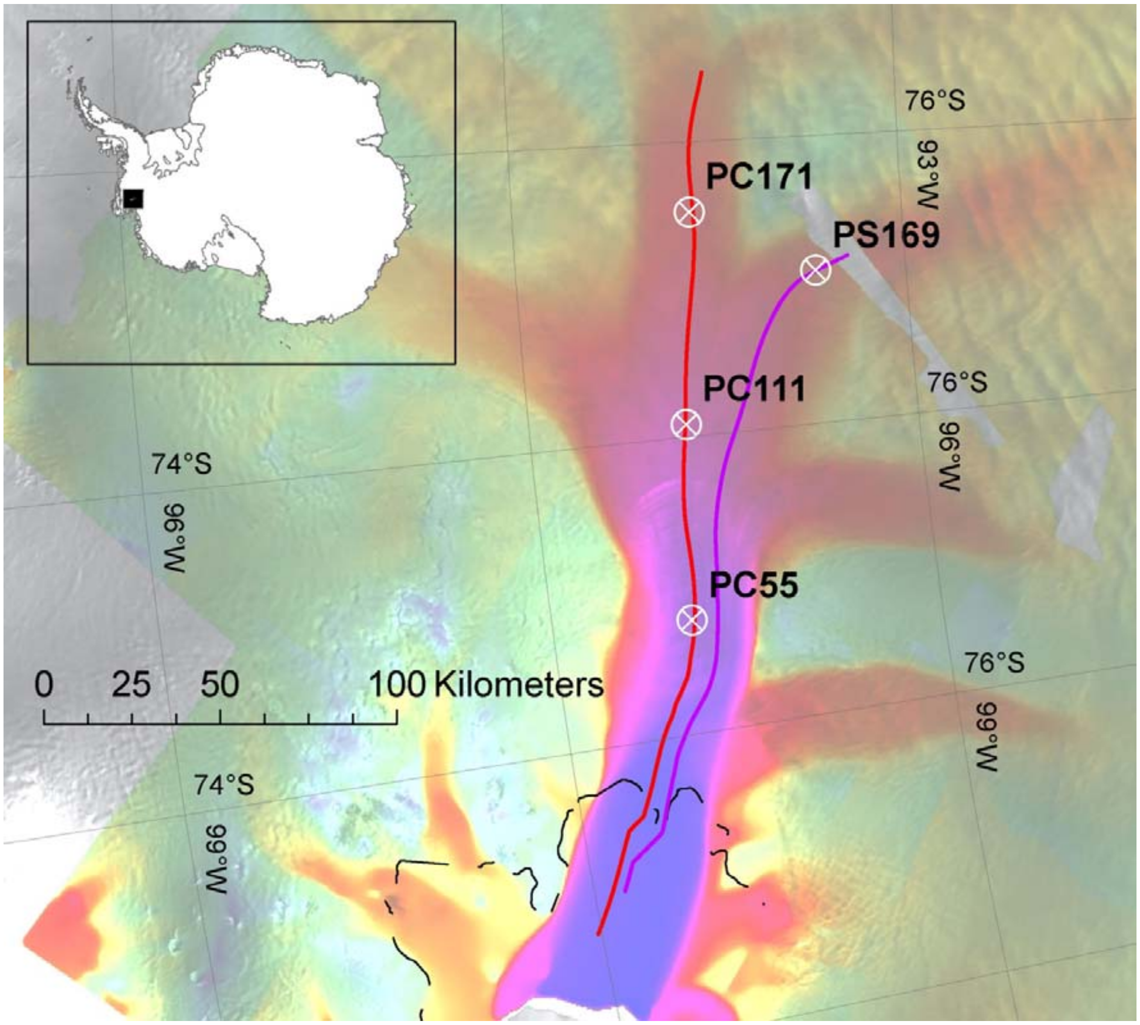

Figure 1. Map of Pine Island Glacier. With the four GPS locations marked. Flowlines in red and purple; grounding line (2000) in black. Background is velocity magnitude (blue is fast – green is slow) from ERS-1/-2 data overlaid on a RADARSAT-1 mosaic (Rignot, 2006). Current satellites only cover approximately the lower 100 km of the glacier.

Survey procedure

Between mid-November 2007 and early-February 2008, three GPS receivers were sited close to the central flowline of PIG (Figure 1) at sites 55, 111, and 171 km upstream from the grounding line. The same geographic sites (hereafter PC55, PC111 and PC171 respectively), were previously occupied between early-December 2006 and early-February 2007. A further GPS station, PS169, was placed on a tributary to PIG, 169 km upstream from the grounding line (Figure 1). Each GPS was run from a battery connected to a regulated solar panel so that it could work continuously for up to three months. GPS observations were recorded at 10 s intervals onto our own 1 Gb Compact Flash cards. At the beginning and end of the 2007/2008 season, further GPS measurements were made to derive the strain rates in a 1 km radius around each site. The surface profile along the central flowline was also measured by kinematic GPS, along with net snow accumulation at PC55 and PC111.

Data quality

Data recovery was 100% at all stations. The NERC equipment appeared to work faultlessly for the full deployment period. The only problem encountered was with the power supply, as one solar panel was blown over in high winds. The processed positions had a precision of around 1 cm which was the desired quality. The diurnal GPS noise in the data can be seen in Figure 2.

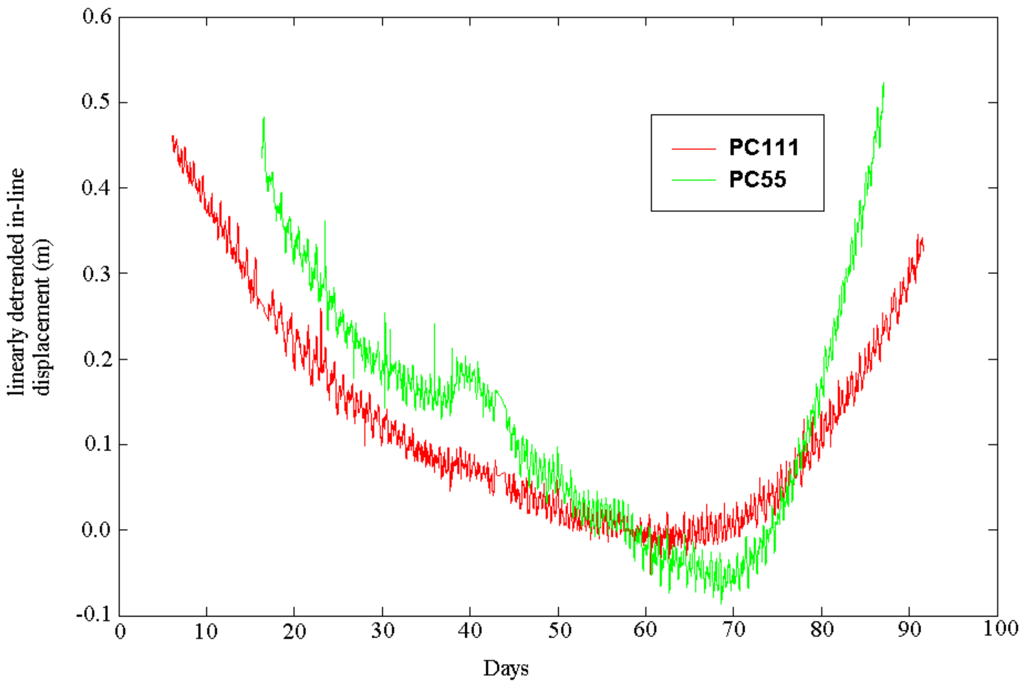

Figure 2. GPS displacement along the direction of flow with a linear trend (constant velocity component) removed. For two of the GPS stations (Figure 1). The quadratic nature of these curves reveals acceleration at both locations.

Processing and modelling

The 10 s interval GPS data were processed to give kinematic precise point position solutions every 30 s. This processing was done on each station separately using the Bernese software with precise ephemeris and was the same as the processing method used by Gudmundsson (2007). With this method it is possible to detect variations in horizontal position to around 0.01 m. A more detailed analysis of the processing method and the associated uncertainties is given by Dach et al. (2008). Velocities and accelerations shown in Table 1 were calculated by fitting a quadratic function of time to in-line displacements for each measurement period. The uncertainty in the quadratic fit is the largest error in the calculation of the acceleration, these errors are given in Table 1. Acceleration was nearly constant, although some residuals between measured and fitted displacements indicate short-term changes of velocity. Although it was not possible to get an accurate acceleration during the season for every GPS location the velocities obtained at each station can be compared to the last velocity available at the site from 1996 satellite measurements. These sites are too far inland for current satellite coverage. Using the strain grid around each station along with snow accumulation measurements and the surface slope measurements it was possible to calculate the thinning rate of the glacier at each location (Table 1).

Station	Mean velocity, u (2007/2008 season)	Mean acceleration between seasons (2006/2007 and 2007/2008)	Mean acceleration during 2006/2007 season	Mean acceleration during 2007/2008 season	Rate of elevation change during 2006/2007 season	Rate of elevation change during 2006/2007 season
PC55	2075 ± 2 ma^{-1}	115 ± 2 ma^{-2}	137 ± 20 ma^{-2} (26 Dec–15 Jan)	131 ± 20 ma^{-2} (21 Nov–31 Jan)	-3.5 ± 0.5 ma^{-1}	-3.6 ± 0.6 ma^{-1}
PC111	907 ± 2 ma^{-1}	41.5 ± 2 ma^{-2}	49 ± 10 ma^{-2} (14 Dec–5 Feb)	51 ± 10 ma^{-2} (11 Nov–4 Feb)	-2.0 ± 0.4 ma^{-1}	-2.8 ± 0.5 ma^{-1}
PC171	325 ± 2 ma^{-1}	12.7 ± 2 ma^{-2}	11.6 ± 2 ma^{-2} (19 Dec–3 Feb)	No value (30 Nov-20 Dec)	-1.2 ± 0.1 ma^{-1}	-1.0 ± 0.1 ma^{-1}
PS169	319 ± 2 ma^{-1}		Not deployed	No value (1 Dec-30 Dec)	Not deployed	-1.7 ± 0.2 ma^{-1}

Table 1. Velocities, rates of acceleration and elevation change measured at the GPS stations.

Interpretation and Preliminary findings

The GPS measurements reveal that the rates of acceleration experienced in 2007, which are higher than any previous measurements have shown on PIG, extend far inland. At the downstream end of PIG, the acceleration reached at least 6.4 % a^{-1} in 2007, but it was also 4.8 and 4.1 % a^{-1} at distances of 111 and 171 km, from the grounding line, respectively. This upstream acceleration is at a greater percentage rate than any estimates prior to 2006 for the downstream end of the glacier (Rignot, 2006). Therefore, if the perturbation causing this acceleration originated at the downstream end of the glacier it is likely that it has been transmitted rapidly upstream, by a diffusion process, faster than the 10 years per 100 km suggested by the model of Payne et al. (2004). The reduction in the percentage velocity increases, with distance upstream, suggests that the perturbation could originate at the downstream end of the glacier, but modelling is needed to verify this.

Current rates of thinning are higher than over the previous two decades. If the exceptionally high thinning rates continue they could contribute to ungrounding of the weakly grounded ice plain and further acceleration (Payne et al., 2004). The section of PIG, 55 to 171 km inland, is steepening at a rate which provides an increase in driving stress of sufficient magnitude to produce the observed acceleration, we show this using a simple force-balance model

$$\partial_t u = D u^{(n-1)/n} \partial_t \alpha \quad (1)$$

where *u* is the centreline velocity, *α* the slope and D and n are constants. The fit to this relationship (Equation 1) is given in Figure 3 (for n=3, the standard ice flow law value). Although based on only four data points, the good fit of the model to the data indicates there does not necessarily need to have been a sustained increase in longitudinal stress gradient or reduction in basal drag over this region of the glacier to explain the current force imbalance. However, we have measured changes in the longitudinal stress gradients that are transmitted rapidly along the glacier causing fluctuations in the acceleration over short periods at sites 56 km apart. It is likely that perturbations transmitted initially by longitudinal stress gradients cause the acceleration inland (Payne et al., 2004).

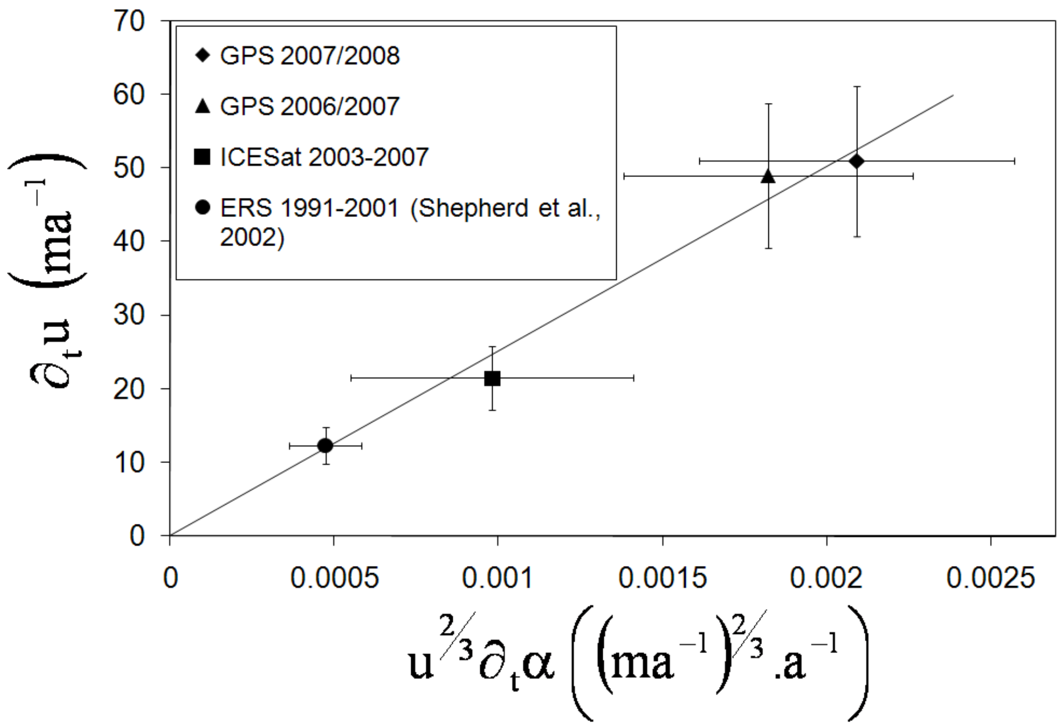

Figure 3. Graph of acceleration, $\partial_t u$, against speed and slope change $u^{2/3}\partial_t\alpha$. Average slope changes for 1991-2001 from ERS satellite altimetry and for 2003-2007 from ICESat satellite altimetry. With December 2006 – February 2007 and November 2007 – February 2008 calculated from GPS measurements. The black line is the best fit to the data.

Conclusions and recommendations

The GPS measurements on PIG augment those obtained from remote sensing. They demonstrate that rates of thinning and acceleration are both increasing and that this extends at least 171 km inland. Acceleration is highly correlated to slope increase and no sustained increase in longitudinal stress gradient, or decrease in basal drag, is needed to explain the force balance. Transmission of the acceleration inland has been exceptionally fast at less than a decade for 200 km. The results are consistent with the hypothesis that changes in PIG result from changes at the downstream end, including the grounding area and floating ice shelf. It appears that PIG is not only out of balance but continues to move further out of balance. If there is a feedback process, where downstream thinning causes further ungrounding and acceleration, then this could result in a major retreat of the ice stream. With the submission of a paper the current section of this work is complete. The results will be used in the future alongside more recent data from our GPS stations we have maintained on the glacier.

Publications

An article has been published in the online discussion journal, The Cryosphere Discussions (see below). If favourably reviewed an edited version of this article will be published in the journal The Cryosphere.

Scott J.B.T., Gudmundsson G.H., Smith A.M., Bingham, R.G., Pritchard H.D. and Vaughan D.G., 2009. Increased rate of acceleration on Pine Island Glacier strongly coupled to changes in gravitational driving stress. *The Cryosphere Discuss.* **3**, 223-242. http://www.the-cryosphere-discuss.net/3/223/2009

Results have been presented at the following international conferences:

Bingham, R.G., Scott, J.B.T., Smith, A.M., Gudmundsson, G.H., Vaughan, D.G. & Hindmarsh, R.C.A., 2008. In situ glacial geophysical investigations on Pine Island Glacier. FRISP/WAIS Workshop, Derbyshire, UK, 18-20 September 2008.

Scott, J., Bingham, R. & Smith, A., 2008. Recent flow history of Pine Island Glacier. WAIS Workshop, 8-10 October 2008, Sterling, Virginia, USA.
http://neptune.gsfc.nasa.gov/wais/pastmeetings/abstracts08/Scott.pdf
http://neptune.gsfc.nasa.gov/wais/pastmeetings/PPT08/Scott.ppt

Scott, J., Smith, A., Bingham, R. & Gudmundsson, G.H., 2008. Pine Island Glacier inland flow increases: Causes and longevity from new ground-based GPS and radar results, EOS Trans. AGU 89(53), Fall Meet. Suppl., Abstract C11D-0546. http://www.agu.org/cgi-bin/wais?mm=C11D-0546

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Gudmundsson, G. H.: Tides and the flow of Rutford Ice Stream, West Antarctica, J. Geophys. Res., 112, F04007, doi:10.1029/2006JF000731, 2007.

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Rignot, E.: Changes in ice dynamics and mass balance of the Antarctic ice sheet, Phil. Trans. R. Soc. A, 364, 1637-1655, doi:10.1098/rsta.2006.1793, 2006.