Monitoring Isostatic Rebound in Antarctica with the Use of Continuous Remote GPS Observations

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A solar-powered GPS receiver has been installed near Beaver Lake, Antarctica, to monitor postglacial isostatic rebound that may be occurring as a result of ice thinning near the Lambert Glacier since the last glacial maximum. The equipment is 400 km from the nearest Australian Antarctic base and is completely automated. It is expected that there will be sufficient solar power to operate the equipment from January 1998 to May 1998, but the data will not be recovered until the following summer season. The scatter in height computed from the first 25 days of data is ±7.5 mm. If such precision is representative of the accuracy of the height estimates, isostatic rebound of < 1 mm/yr will be able to be detected after a few years of observations at the site. © 1999 John Wiley & Sons, Inc.

INTRODUCTION

The Global Positioning System (GPS) has been used for measuring tectonic deformation on the surface of the earth for more than ten years. There are many articles that have reported deformation due to earthquakes, motion across active faults, and subduction at collision zones (e.g., Feigl et al., 1993; Hudnut et al., 1996; Tregoning et al., 1998). The continued improvement in modeling of physical processes in GPS analyses (e.g., orbit modeling, antenna phase center variations, earth tides, earth rotation parameters) and the increase in the number and distribution of global tracking sites has led to increases in the accuracy of GPS coordinates. As a result, GPS technology is being applied to an increasing number of geophysical problems.

One such application is the monitoring of (postglacial) isostatic rebound. When large ice caps melt, the lithosphere (or crust) of the earth rises in response to the removal of the weight of the ice in the same manner in which a boat will float higher in the water if a load is removed from its deck. The rate of uplift varies depending on the shape of the ice cap and both the amount and timing of the melting that has occurred. Isostatic rebound has been detected with the use of Very Long Baseline Interferometry (VLBI) (Argus, 1996) and GPS (Davis, 1997) by estimating the long-term uplift rate of geodetic stations. To achieve this, one must observe at the same site for many years in order to create a time series of height estimates from which the uplift rate over the period of the observations can be deduced.

On January 9, 1998, we installed a GPS system near Beaver Lake, Antarctica, to monitor the uplift rate near the Lambert Glacier (Figure 1). This is a pilot project for a future transect of GPS sites stretching from the coast to rock outcrops up to 800 km inland. Measuring the uplift rates on such a transect will make it possible to

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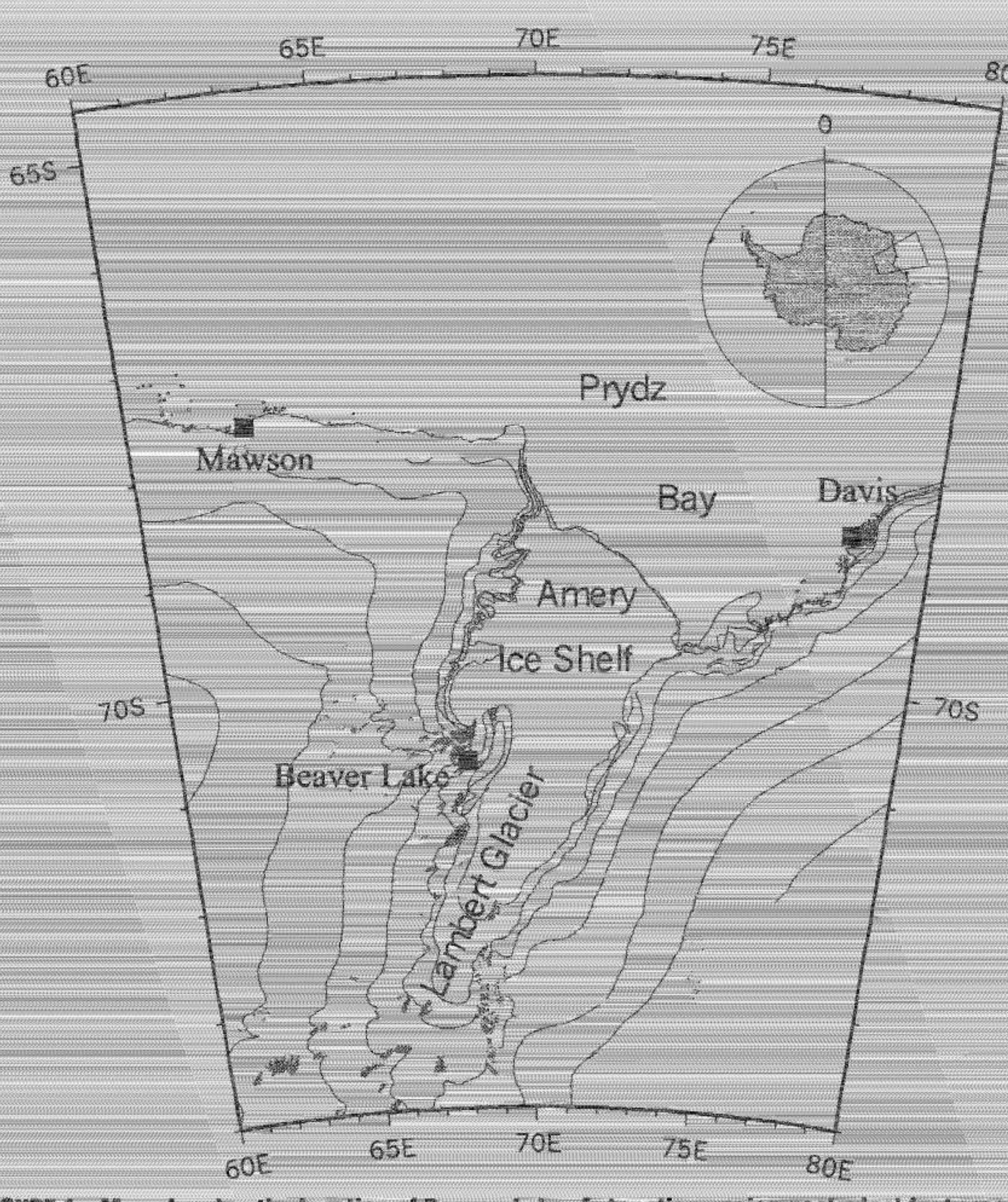

FIGURE 1. Map showing the location of Beaver Lake, Antarctica, major geological features and nearby GPS tracking sites. One hundred-meter ice contours are shown on the Lambert Glacier and surrounding plateau.

distinguish between different models of ice melting and will provide valuable climatic information regarding the history of ice melting. Predicted uplift rates at Beaver Lake range from 2 to 3 mm/yr (Zwartz et al., in preparation) with the use of ice models of Nakada and Lambeck (1988), Huybrechts (1990), and a standard model of earth viscosity derived from sea-level studies in northern Europe. James and Ivins (1998) predicted an uplift of ~2 mm/yr, whereas Adamson, Mabin, and Luly (1997) claimed that there is no geomorphologic evidence to support any relative change in sea level at Beaver Lake during the mid-Holocene.

A major difficulty associated with making continuous GPS observations in this region is the lack of facilities within 400 km of the site. Consequently, we cannot rely on any operator involvement for the running of the equipment, nor is there any power or heating available from any facilities. In addition, because of the short Australian Antarctic field program in the 1997/1998 season, the equipment was last inspected on February 5 1998 and it is no longer possible for anyone to return to the site until the next Antarctic spring/summer season in October 1998. The system must be self-sufficient in terms of power generation, data storage, and resistance to the Antarctic environment. In this article we outline the means by which our equipment is powered as well as the internal monitoring systems employed so that we can determine how the equipment functions during the 1998 Antarctic autumn. We also present the results of the data recovered from the receiver.

EQUIPMENT

The GPS receiver used for this project is an Ashtech Z-12™ (10 Mb internal memory), which is housed inside an insulated plastic suitcase also containing two 28 amphour (Ah) gelcell batteries, a laptop computer, and a small data logger. Power is generated from four 53-W solar panels wired in parallel and is fed into the batteries via two voltage regulators, one for each battery. The batteries are wired in parallel (with isolating diodes to prevent one battery feeding charge into the other) and provide power to both the GPS receiver and the computer. The antenna cable and the power cable from the solar panels pass through a small hole in the case that is sealed with silicone. The suitcase is lined with insulating foam and provides a waterproof, airtight environment for the equipment.

The GPS antenna mount was designed so that a highly stable mark could be installed very quickly with the use of a limited amount of equipment and materials. A 200-mm-deep hole was drilled into a sandstone outcrop with the use of a battery-operated drill, modified with attachments for vertical drilling. A 200-mm threaded bolt was glued into the hole, and a nonmagnetic steel plate was screwed onto the bolt as close to the ground surface as possible. The plate was leveled with the use of three additional rods, also glued into holes drilled into the sandstone. The installation of the mark took one person about 45 min to complete.

The antenna is an Ashtech choke-ring, and the preamp of the antenna is approximately 50 mm above the ground. Although this may introduce errors due to near-field scattering of signals reflected off the ground (see, e.g., Elósegui et al., 1995), it is more likely that we can maintain a consistent local multipath environment for long periods. The system as installed must be able to withstand Antarctic environmental conditions without any maintenance; replacing absorbent microwave material that has deteriorated because of weathering is not possible. Kenneth, Jaldenhag, Johansson, Davis, and Elósegui (1996) have shown that up to 40 mm of error in height can be introduced by snow accumulation on the antenna radome and the surface below the antenna. Beaver Lake is a windy location and, although some windblown snow is likely to accumulate on or near the antenna, we chose to leave the space between the antenna and the ground exposed. This allows the snow to blow beneath the antenna rather than accumulate on the leeward side of the antenna. We have protected the antenna with the use of an Ashtech radome antenna cover. Our tests have shown that these radomes can affect the absolute height estimate by up to 15 mm; however, the height bias introduced by the radome will remain constant and so will not affect the long-term estimate of the rate of change of height. Figure 2 shows the configuration of the equipment as installed near Beaver Lake.

Operation

The GPS receiver has been programmed to record continuously at a sampling interval of 60 s and an elevation cutoff angle of 10°. Each day at 0130 UT the computer automatically downloads the file created on the previous day and then deletes it from the receiver. When there is no storage space available on the computer hard disk it will cease to communicate with the receiver, which will then continue to record data until the 10 Mb storage is also filled. We can store about 90 days of data in the computer and a further 30 days in the receiver—a time interval which will almost certainly exceed the time for which solar power is available in Antarctica.

The SmartReader7™ data logger is a self-powered unit that monitors the ambient temperature inside the case as well as the voltage at seven locations in the

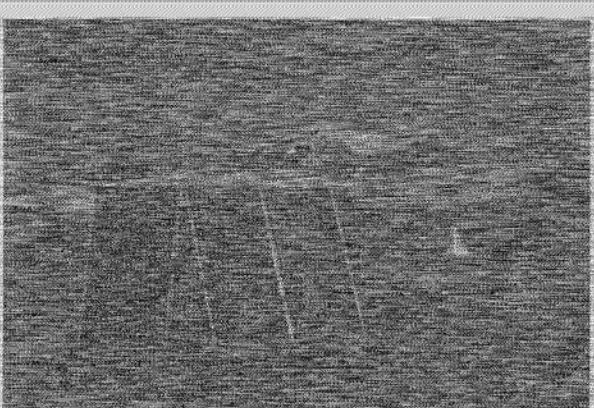

FIGURE 2. Setup of equipment as installed at Beaver Lake. The GPS receiver and laptop computer are located immediately behind the solar panels with the antenna and protective cone visible at ground level in the background.

electronic circuitry. This allows the recharge current flowing into the batteries and the voltage drop across the GPS receiver and computer to be measured; thus, we will be able to determine how much solar power was generated and when the level was insufficient to maintain operation of the equipment.

Power

Each solar panel has the potential of generating a current of up to 3.3 A when exposed to direct sunlight. Ideally, one would like to move the solar panels such that they track the position of the sun (both in azimuth and elevation) in order to maximize the amount of solar power generated. This cannot be done in a remote location, and so we have faced the panels to the north, tilted 20° from vertical. On March 23 (the spring equinox) the sun reached a maximum elevation of 20° when viewed from Beaver Lake and so was normal to the solar panels. We varied the azimuth of the two outer panels by only 20° (Figure 2) in order to increase the possible power production in the early morning and late evening without compromising the production at noon when the sun intensity is a maximum.

The GPS receiver draws 12.5 W continuous power and the computer requires 8 W continuous power. A single battery in a fully charged state (at 20 °C) can provide enough power to operate both the receiver and the laptop for about 20 h. The equipment ceases to operate when the battery voltage falls below 11 V. Hence, about 400 Watt-hours of power must be generated each day in order to keep the system operational.

Temperature Constraints

Because the capacity of a battery to provide power decreases with temperature, the ambient temperature within the case must be above 0° C in order to achieve 90% power capacity from the batteries. In addition, the nominal operating temperature range for the laptop computer requires that the temperature remains above 0° C. Tests inside a refrigeration unit, carried out prior to deployment in Antarctica, showed that for an outside air temperature of −20° C the heat generated by the equipment was sufficient to maintain an internal temperature of about 4 °C. The temperature at Beaver Lake is not likely to fall below −20° C before the end of April, beyond which the lack of solar power will have terminated the operation of the equipment.

PRELIMINARY RESULTS

The first 25 days of data were retrieved and returned to Australia. Because the power capacity of the batteries is only sufficient to operate the receiver for 2 days, it is clear that sufficient solar power is being generated to operate the system. Unfortunately, logistical constraints prevented the SmartReader7™ data logger from being downloaded, so we will not know the actual power budget of the equipment until the data logger is retrieved at the start of the next Antarctic season in about October 1998.

We analyzed the retrieved data with the GAMIT/GLOBK software package (King and Bock, 1997; Herring, 1997). We processed the data from Beaver Lake simultaneously with all available IGS sites in the southern hemisphere, using a 60-s sampling rate and an elevation cutoff angle of 10°. These solutions were then combined with the global solutions computed at the Scripps Orbit and Permanent Array Center (Bock et al., 1993) with the terrestrial reference frame imposed by constraining the ITRF94 coordinates (Boucher, Altamimi, Feissel, and Sillard, 1996) of the 13 core IGS sites. Figure 3 shows the repeatability of the coordinate estimates of Beaver Lake from the first 25 days of data.

Simulated Uplift Rate Precision

Zhang et al. (1997) analyzed 19 months of data from 10 continuously operating GPS stations in California, and

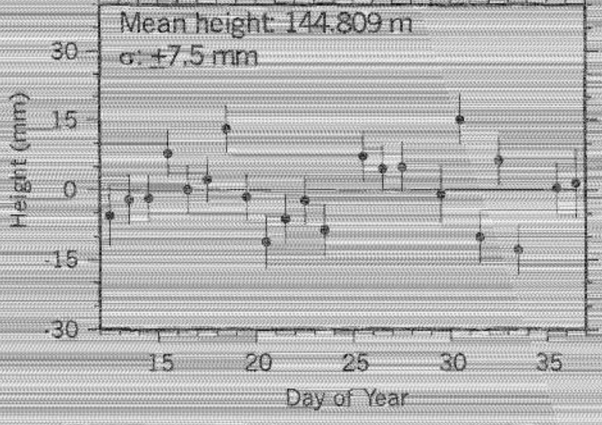

FIGURE 3. Daily height estimates of BVLK from the analysis of the first 25 days of observations in 1998. The mean height and one-sigma uncertainty of a single observation are shown. Data from days-of-year 024 and 028 were irretrievable.

showed that continuous GPS daily coordinate estimates do not display white-noise characteristics. They claimed that there is significant temporal correlation in the time series of positions that is not reflected in a weighted RMS calculation, rendering this statistic unsuitable for describing long-term precision of GPS coordinate estimates. From an analysis of the stochastic properties of the time series, they concluded that a noise model comprised of white noise and flicker noise fits the data better than a pure white-noise model. This model increases the uncertainty of a velocity estimate by a factor of 1.5–3.5 over the white-noise model for annual or weekly sampling of positions over a 5-year period. Sites with well-anchored monuments (bedrock or deeply anchored) showed much lower levels of stochastic noise than poorly anchored sites.

We can simulate the expected precision of rate of uplift by computing a linear regression through data points, assigning a level of uncertainty to each data point according to the expected accuracy based on the analyzed data. The uncertainty of the slope is affected by the uncertainty of each height estimate and the time interval between them rather than by the actual value of the height. We should obtain data until April 30, 1998 from our deployed GPS equipment and, for the purposes of simulating the expected uplift precision, we will also assume that we will be able to obtain data for the same period each year until 2003. We model the noise characteristics as both white noise and white noise plus flicker noise, with the additional flicker noise uncertainty due to possible temporal correlations being approximated by scaling our white-noise uncertainty by a factor of 3. Assuming that the errors associated with the first 25 days of data have the characteristics of white noise, we compute from the daily scatter of height estimates that the (one sigma) uncertainty of a single height observation at Beaver Lake is ± 7.5 mm, but we use values of ± 5 mm and ± 10 mm in the simulations. Table 1 shows the expected precision of estimated uplift rates for different durations of the experiment with the use of models of white noise only and white noise plus flicker noise. An isostatic uplift rate of 1 mm/yr or greater will be able to be detected after 2 years assuming white noise only, or after 4 years assuming some stochastic noise is present in the GPS position time series.

TABLE 1.

Expected precision of rate of uplift from GPS height estimates

		Duration of Observations (years)				
Noise Model	σ	*1*	*2*	*3*	*4*	*5*
WN	10	1.3	0.7	0.4	0.3	0.2
WN+FN	10	3.9	2.1	1.2	0.9	0.6
WN	5	0.7	0.3	0.2	0.1	0.1
WN+FN	5	2.1	0.9	0.6	0.3	0.3

Simulated precision of uplift rates in mm/yr for white noise (WN) and white noise plus flicker noise (WN+FN). Uncertainty of a single observation is set to be ±10 mm and ±5 mm.

FUTURE PLANS

It is feasible to create a small, compact, solar-powered GPS system that will operate in remote locations for long periods. Our installation near Beaver Lake, Antarctica, operated during the first few months of 1998, but would have failed when the level of sunlight decreased with the onset of the Antarctic winter. We will not be able to access the remaining data from the first summer period until about October 1998. We are investigating other power-generation possibilities (e.g., fuel cells, wind generators) in order to continue operation throughout the winter months when solar power is unavailable. Continuous operation throughout the year will require a better data storage system and we are developing a low-powered (i.e. < 500 mW) data logger with 85-Mb flash-card memory for this purpose. The initial 1998 occupation of the site will provide information regarding the feasibility of installing solar-powered remote GPS systems in Antarctica, as well as three months of GPS observations to commence the time series of height estimates.

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Adrian Nell (The Energy Shop, Goulburn, Australia) constructed the solar panel array, and Andrew Welsh (RSES) assembled the electronic components. ■

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BIOGRAPHIES

Paul Tregoning received a Ph.D. from the University of New South Wales, Sydney, Australia, 1995. He is presently a post-doctoral Research Fellow. His responsibilities include the organization of field work and the analysis of GPS data to study crustal motion in Papua, New Guinea, the Solomon Islands, and Antarctica, and the estimation of precipitible water vapor with the use of GPS observations. During 1995 he participated in software development (GAMIT) at MIT.