A low cost GPS system for ice movement studies

Matt King, Christopher Watson, Richard Coleman, Anthony Sprent, Antoine Guichard, Guy Williams - 2001

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Abstract

An inexpensive GPS system has been designed to operate autonomously in Antarctica for a period of three months or more during the Antarctic summer. The system may be installed in the field in less than two hours and costs less than US$1500 per installation. Such a system is useful for a wide variety of ice movement surveys, such as ice shelf tidal response, grounding zone dynamics and rift formation studies. The system has been successfully deployed over a 6-10 week period on the Amery Ice Shelf during the 2000-01 austral summer. Preliminary results from this campaign are presented, highlighting the value of such a modular GPS system.

1. BACKGROUND

Long-term continuous measurements of ice movement are required to advance the understanding of ice dynamics in a number of research areas. These include studies on ice shelf tidal motion, rift formation and grounding zone dynamics. These studies require high precision measurements (preferably three-dimensional) that are made on a continuous basis for extended observation periods. Such a measurement system must be autonomous and be able to withstand the harsh polar environment. Logistical constraints typically require the system to be quick and easy to assemble and install in the field. An inexpensive and multi-purpose system is also of considerable benefit.

Ice movement has previously been measured by a number of techniques: EDM (Thomas, 1970), triangulation (Naruse, 1978), optical levelling, tilt meters (Stephenson and Doake, 1979), gravity (Doake, 1992), GPS (Manson et al., 2000), satellite image feature tracking (Bindschadler and Scambos, 1991) and InSAR (Joughin et al., 1996). Brief summaries of each of these measurement types, including the spatial resolutions and limitations of each technique, are shown in Table 1. GPS is particularly useful in determining ice movement since it can determine three-dimensional position and velocity to a high precision and is the easiest technique to use in the field.

Long-term measurements of ice movement are essential in order to understand many of the glaciological, oceanographic and atmospheric forces acting on continental and floating ice. For example, current numerical ocean tide models perform poorly in the sub-ice shelf regions due to a lack of bathymetric data and water column thickness information, although more importantly from having an inadequate time series of tidal measurements. The lack of accurate, high-resolution tidal models has consequences for the tidal correction of remote sensing measurements, such as those from InSAR or the forthcoming

GLAS laser altimeter mission. Away from the ice shelves, ocean loading corrections are required for remote sensing measurements (Yi et al., 2000) and for geophysical studies including measurements of post-glacial rebound (Donnellan and Luyendyk, 2000; Tregoning et al., 2000). The accuracy of numerical ocean tide models has a direct effect on the accuracy of derived ocean loading corrections. While short-term observations will resolve the semi-diurnal and diurnal constituents, longer-term measurements are required for the fortnightly and long-period constituents. GPS has been shown to be a convenient and cost-effective way of making such tidal measurements on ice shelves (King et al., 2000).

With the aim of constructing an ice movement measurement system that was capable of making long-term ice movement measurements, the Centre for Spatial Information Science at the University of Tasmania began design work for such a system during July-October 2000. The system was designed to be low cost, capable of operating unassisted for greater than ten weeks, simple to install in the field and delivering high precision three-dimensional measurements using a dual-frequency carrier phase GPS receiver. The components of our system are described in the following section. We demonstrate the usage of our GPS system by presenting results in Section 3 of a tidal motion study on the Amery Ice Shelf, East Antarctica, from our first deployment season during the 2000-01 Antarctic summer. Future versions of the system can, with little modification, be operated for up to one year and the necessary alterations are described in Section 4.

2. System Components

The system is comprised of five distinct components: (1) power supply and its management, (2) data acquisition, (3) equipment housing, (4) support frame and (5) the in-situ reference mark. Each of these components is described in detail below, followed by a costing of the system.

2.1 Power Source

The measurements of ice motion in the system are made using a dual-frequency GPS receiver with on-board data storage capacity. In terms of power consumption, modern GPS receivers consume 6-8W on a continuous basis, although some recent GPS units use as little as 2W (e.g., Javad Navigation Systems JNSbox-GD). However some GPS units, such as the one implemented in our system, may consume as much as 15W. Power requirements for the other electronic components in the system (charge regulator, voltage cut-off) are negligible.

To meet the requirements of continuous operation of the GPS units for up to 6-10 weeks, four options are available as a power source. The options are: large battery banks, solar panels, wind turbines or fuel cells. The first option is impractical. Assuming ten weeks of continuous operation of a 15W GPS receiver, this would require approximately 25kWh of storage capacity, the equivalent of about 20 batteries (215Ah/6V) instead of the two batteries eventually used! As an aside, this option also creates transportation problems since 20 batteries would weigh approximately 600Kg. The use of fuel cells in Antarctica is still experimental and potentially too expensive for most research projects (Tregoning *et al.*, 2000). However, the generation of power from fuel cells is independent of weather (unlike wind and solar power generation) and they provide a potential solution for continuous measurements over very long time periods.

Of the two remaining options, solar power is the most proven in Antarctic conditions. In particular solar panels are frequently used for powering remote scientific instrumentation such as Automatic Weather Stations (I. Allison, personal communication, 2001) or GPS receivers (Tregoning *et al.*, 2000). For the last option, it is difficult to manufacture wind turbines that are capable of surviving high wind speeds whilst also operating efficiently at low wind speeds. Some level of maintenance (e.g., blade replacement) would also be typically required. Additionally, significant portions of the Amery Ice Shelf, for example, experience very low average (<10 knots) summer-time wind speeds (King, 2001). These conditions may however surge during blizzard conditions, recording wind gusts greater than 80 knots. On the other hand, if the system is to be capable of year-round operation, solar power is insufficient. For the purposes of this initial summer-time experiment, we adopted solar panels as the power source linked to a set of batteries. Future year-round models require the use of a hybrid wind-solar system to provide power to maintain continuous operation.

We have estimated the power generation and storage requirements of the system based on the fixed system parameters shown in Table 2. These values were determined for three locations at different latitudes along the Amery Ice Shelf (69.1°S, 71.0°S and 73.25°S). The expected power generation levels were calculated using solar radiation intensity, azimuth and elevation time series at each site as determined by the Solar Energy Management and Assessment Scheme (SEMAS) model. The SEMAS is a model developed by Latitude Technologies to assess solar power potential at the Australian Antarctic stations (Williams and Magill, 2000). A "cloud cover" attenuation factor was applied to the SEMAS model, corresponding to the average attenuation factor measured at Davis Station (68.6°S, 78.0°E) during the period December 15, 1998 to February 15, 1999. The average cloud cover during this period was 4.21 oktas. The cloud cover at the front of the Amery Ice Shelf is expected to be similar to that at Davis since they are at similar latitudes and both are affected by coastal cloud. It is also expected that these values would be quite typical for many other Antarctic coastal sites. Further inland, however, the atmospheric water vapour is significantly less and hence these values will be pessimistic, providing additional system redundancy.

To determine the optimal solar panel position at each location, several solar radiation time series were generated using SEMAS for various panel azimuths and elevations. The 3-hourly time series for the optimal position (facing True North and 50° elevation angle for all three sites) were then used in a spreadsheet simulating power generation and storage level time series over the three month summer period (December 15 to February 15) at each site, starting with fully charged batteries. This simulation is a function of two variables: (1) solar panel area and (2) number of batteries. Based on the simulation, values were chosen for the two variables at each of the three locations. Table 2 summarises the system parameters used. The operational efficiency terms used in the calculations are slightly conservative values for this type of equipment operating at cold temperatures.

For our three sites, the average radiation levels received on the panels over the three-month summer period were estimated at 0.26 to 0.28kW/m^2. Given a solar panel with an area of 0.6m^2 along with the other operational parameters, the long-term average production is 15.75 to 16.95 W.

With the choice of solar/battery power, a charge regulator is required to regulate the current from the solar panels to the two 215Ah 6V deep cycle batteries connected in series (equivalent to one 215Ah 12V battery). Our system also implements a low-voltage cut-off system to cut the power to the GPS receiver when the battery bank voltage is less than ~11.1-11.2V and reconnects at ~12.4-12.5V. This is to overcome a limitation with the receivers we use and may not be required in all systems.

2.2 Data acquisition

Two distinct data sets were required for our tidal investigations: GPS and meteorological data (in the form of atmospheric pressure and temperature measurements). The GPS measurements were made at intervals of thirty seconds with a satellite elevation cut-off of 10° above the horizon. Dual frequency (L1 and L2) carrier phase and pseudo-range measurements and their signal-to-noise ratio values were stored along with the broadcast satellite ephemeris. The data were stored within the GPS receiver on a 60Mb PCMCIA ('flash') card. Most geodetic dual-frequency receivers require 500-800Kb of data storage capacity per 24 hour period when recording at 30 second intervals. The variation is due to the respective proprietary data formats of each receiver manufacturer. For ten weeks of measurements, this equates to a total storage capacity of 35-56Mb. Further data compression may be achieved by converting to the RINEX format (Gurtner, 1994) and applying compression techniques such as the widely used Hatanaka method (Gurtner, 1997). However, the extra effort to utilise data compression requires the use and integration of a computer into the data acquisition system. This is considered an unnecessary complication for our low-cost system.

Atmospheric pressure at each site was required for tidal studies in order to correct for the so-called "inverse barometer" effect due to the ice surface being loaded by atmospheric pressure. Hourly measurements were made using a self-powered (lithium battery) pressure meter (Microdaq PT-210) with onboard storage capacity of ~12 weeks

(2048 readings) at this data rate. Temperature readings are also made on the same instrument since the pressure readings are temperature dependent.

2.3 Equipment Storage

The efficiency of the system, and hence its ability to operate for up to 12 weeks, is dependent on the equipment remaining within standard operating temperatures and not being exposed to the harsh Antarctic environment. The batteries, in particular, begin to lose efficiency below +15-20°C. Our entire system depends on the equipment operating for the most part well above 0°C. To ensure this, we stored the equipment (other than the antenna and solar panels) inside a ~0.3m^3 (~1.0x0.55x0.55m) black, high density plastic box. The outside temperatures at each site could be as low as about -25°C overnight and as high as about 0°C during the day. Consequently, we required sufficient insulation in the box to allow a ~30-40°C temperature differential between the outside air temperature and the contents of the box. In our current system, we used a combination of Polystyrene and domestic fibreglass insulation batts to provide a constant temperature environment, leaving less than 1% of the box volume as unfilled space. The heat source is the GPS receiver and to a lesser degree, the other electrical components. Basically, all power consumed by the equipment is recycled as a heat source for the box. Despite shading of the box caused by the solar panel when the solar radiation is at a maximum, a black coloured box was selected to maximise heating from solar radiation at other times of the day. The internal layout of the box is shown in Figure 1.

To ensure that the pressure meters were measuring actual outside air pressure, two small holes (~10mm diameter) were drilled in opposite corners of the box and covered with Teflon vent spots. These vent spots allowed air to pass through while preventing snow from entering the box. They also allowed any gas by-products of battery charging to be safely vented out of the system. The holes were drilled near the base of the box to reduce heat loss. Antenna and power cables were passed through a standard cable gland that was clamped down onto the cables. Rubber foam was wrapped around the cables to ensure that no snow passed through any small hole in the gland.

2.4 Support Frame

An aluminium frame was needed to support and elevate the plastic box and solar panels. The frame consisted of four side brackets that fitted into four legs, such that when assembled they locked together without requiring any screws or bolts. These legs were fabricated from standard aluminium angle section (see Figure 2). The horizontal sections of the frame were constructed of slightly smaller width aluminium section than the legs. This allowed two horizontal sections to fit loosely but firmly inside each leg. The frame gained rigidity and strength by the addition of a high-strength ratchet compression strap that was tightly clamped horizontally around the frame and box. The rigidity of the box is thus used to provide rigidity to the structure as a whole. In order to avoid problems of frame components being assembled in the wrong combinations, each component is colour coded with its associated matching components allowing rapid erection. This frame design is the key to quick field installations - on typical snow surfaces, the system was assembled and GPS measurements commenced within 90-110 minutes of arrival at the site. Only four bolts are fitted during the field installation. The only tools required for the frame construction on site are a soft rubber hammer and a single spanner to bolt on the solar panel. A snow shovel for digging holes for the feet of the frame and snow/ice drill for placing the reference pole or frame feet are also required for the frame installation.

The entire system is shown in plan view in Figure 3 and in elevation in Figure 4. The frame was designed so that snow would blow under the box, preventing a snow build-up on the leeward side (most often the northern side in the AIS region, and hence in front of the solar panel). Once constructed, the entire frame was orientated with the solar panel facing True North. The frame was held in place by the four legs buried approximately 300mm into the snow. In the case of an ice surface, the legs were placed in holes drilled to ~100mm depth. The weight of each of the legs was distributed onto four flat platforms (feet), thereby preventing the frame sinking into the snow. There were also two tie-down points on the frame, used to attach ropes to four ‘deadmen’ snow anchors that are buried in the snow at approximately 45° to the frame (i.e., northeast, northwest, southeast and southwest).

2.5 Reference Mark and Antenna

For the measurements to be of the highest accuracy, it is important that the GPS antenna is stable relative to the ice shelf. Any unknown vertical motion from compaction or melting-in of the reference mark will consequently bias the coordinate time series. To minimise these effects, we mounted the GPS antenna on top of an aluminium pole via a short aluminium/stainless steel sleeve with the same internal dimensions as the pole. The base of the pole was buried more than 2m below the snow surface. The pole was also held in place by a cable connected to a 'deadman' anchor buried in the snow. For the highest precision results for the vertical component, "Coffee-can" style observations (Hamilton *et al.*, 1998) are required. The top of the aluminium pole becomes the reference mark for future reobservations. A solid wooden or fibreglass insert was used to join the sleeve to the pole and the antenna was attached to the sleeve via a standard 5/8th inch Whitworth thread at the top of the sleeve.

In terms of the choice of antenna, we chose a choke-ring antenna to reduce signal multipath as much as possible. Snow settling on a GPS antenna is known to have an adverse effect on the GPS signals, affecting the vertical coordinate by up to 100mm (Jaldehag *et al.*, 1996). Snow is prevented from accumulating in the choke rings by mounting a standard hemispherical radome on the antenna. The signal delay/refraction caused by such domes is known to effect the vertical coordinate by 1-2mm, however this does not concern us in this project since this delay can be assumed to be a constant bias.

2.6 Costing

The GPS receiver and antenna dominate the cost-budget for this system. Since it is assumed that most research bodies already have access to this equipment, we exclude this equipment from our costing although an approximate cost would be US$15000. Furthermore, the cost of labour is also excluded from our budget since our system was built using University of Tasmania personnel and it is expected that most other research institutions would have similar personnel and workshop facilities.

The cost breakdown of the system is shown in Table 3. As can be seen, the total cost of our system is approximately US$1500. Costs will vary depending on the type and quality of the purchased components, but our components were of good quality.

For the purposes of transportation, volume and weight information is important. Since many of the smaller components may be packed inside the storage box, the volume for one system is less than 1m^3. The aluminium (30Kg) and batteries (30Kg each) dominate the weight of the system, which totals approximately 120-150Kg.

3. Results

Six ice movement systems were deployed on the Amery Ice Shelf during December-January 2000-01 as part of a tidal motion/grounding zone study. A photograph of one of these sites shortly after installation is shown in Figure 5. Three of the units were retrieved during mid-March 2001. The remaining three systems could not be retrieved due to logistical problems (no clear weather for helicopter support). GPS data retrieved from the three recovered GPS units, spanned 6, 9 and 10 weeks respectively at the three locations (TS1, TS3, TS4). It is thought that the GPS receiver from site TS1, where only six weeks of data was retrieved, operated significantly longer than this period and the remaining data was lost due to data corruption on the flash card. Hourly pressure and temperature measurements were successfully made at two of the three locations – one sensor only recorded a single measurement.

The GPS data was processed by segmenting the data into one hour blocks using the technique described by King *et al.* (2000). The horizontal and vertical motion of one site (TS3; 69.2°S, 70.4°E) is shown in Figure 6 along with the measurements of external atmospheric pressure and internal box temperature. External temperatures measured by a nearby Automatic Weather Station (AWS) are also shown. The time-series of vertical motion shows a clear tidal signal in the data. Observations were nearly continuous until late February 2001 when a power failure occurred. This event was anticipated, since the power levels to the GPS would not be maintained as the daylight hours reduced due to the lower levels of solar radiation. For our system, this occurs when average solar radiation drops consistently below approximately 0.25kW/m^2. Our simulation (Section 2.1) suggested that the power would fail on February 12, although we used conservative values in the simulation. Note that the internal box temperature dropped to almost zero at the same time as the failure, i.e., as soon as the receiver stops there is no longer any heat source. From the temperature profile, it appears that the receiver restarted within a day of stopping due to the battery charge increasing to the point where the power supply was reconnected, at approximately 12.4-12.5V. However, there is no GPS data available for this period, suggesting that some data was lost due to the flash card corruption that occurred at this site.

The temperature profile shows that the internal box temperature quickly rose from around zero at the time of installation to a peak of approximately 45°C. The temperature then slowly decreased with time before the sudden drop in temperature attributed to the turning-off of the GPS receiver. The temperature profile contains a diurnal cycle of 4-10°C (peak-to-peak), with the daily maxima at approximately 12:00 (local solar time, approximately GMT+4.5hrs). Temperature measurements made at the nearby AWS exhibit a similar, although slightly larger, diurnal range. The lower diurnal range inside the box is most likely due to the box insulation. This shows that while the internal temperature does increase with external air temperature, direct solar radiation on the box is having little impact. The slow decline in the box temperature also shows that the insulation was adequate, and the internal temperature was well maintained by the heat generated by the GPS receiver.

Due to the last-minute recovery of these units from the field, only the GPS receiver, antenna, pressure/temperature meter, regulator and the low-voltage cutoff could be retrieved. Although a thorough inspection was not possible, the condition of the frames, batteries, solar panels and other components appeared normal at this time (mid-March 2001). Therefore, the system described in this paper has operated successfully at these three sites. The tidal measurements from this campaign will be assimilated into future versions of regional tide models, such as the Antarctic CADA model (Padman *et al.*, 2001). This will result in significant improvement in these models, and the consequent ocean loading parameters, both in the AIS region and further afield.

4. Year-round Operation

A number of studies ideally require longer-term measurements than those afforded by the present system. For example, >1 year of tidal data is required to determine the annual tidal constituents. Long-period observations are also required to better understand the three-dimensional strain rates involved in ice shelf rift formation. Extension of the GPS system described above to year-round operation requires additional complexity and cost. The risk of a system not performing to specification is also high given the inability to test and evaluate it thoroughly in typical field conditions. Weather conditions in Antarctica are significantly more severe on equipment during the winter period compared to the summer. Such conditions will tend to test even the most well designed systems. Due to logistical difficulties caused by poor weather, three of the Amery Ice Shelf systems are experiencing an unscheduled winter on the ice shelf during 2001. The durability of the system will be tested in early 2002 when these systems are retrieved! GPS data spanning 12-13 weeks and temperature and pressure data spanning 12 weeks should be retrieved from these sites.

The following additions/changes would be required for the ice movement system to operate on a continuous basis across an austral winter.

Power source:

To operate for longer periods the system needs additional power input. The best way to achieve this, using our low-cost philosophy is to add:

- Two wind turbines – one operating as a backup in case of blade or generator failure.
- A more sophisticated power management system for shutting down and restarting (in an appropriate order) the receiver, internal heaters within the box and a computer in the event of low battery voltage.

Data Acquisition:

- A temperature/pressure logger capable of logging more than one year of data, or otherwise some means of automatically downloading the data to an independent logger with higher storage capacity.

- A low-power computer to download the GPS receiver at regular intervals with ~300-500Mb storage capacity.

Equipment storage:

- Small heaters (2 x 2-4W) with temperature sensitive start/stop.

Support Frame:

- Increased frame rigidity by the addition of bolts to the frame.
- Longer frame legs in regions of high snow accumulation.
- Improved support for the solar panel frame.

Reference Mark:

- A longer antenna reference pole in regions of high snow accumulation.

Conclusions

An inexpensive system for high precision GPS measurements of ice shelf motion has been described. The system is autonomous in terms of power generation across the austral summer and can be installed in the field in less than two hours. The system cost is less than US$1500, not including the cost of the GPS antenna and receiver and labour. Year-round operation is possible with the addition of wind turbines, low-power computer and data storage device, power management, heaters and some other minor modifications. This would increase the total cost to approximately US$4000-5000.

Six to ten weeks of tidal motion measurements were made at three locations on the Amery Ice Shelf, East Antarctica, during December 2000-March 2001 demonstrating that our system worked exactly as predicted. It is hoped that the description of this system will encourage others to undertake measurements of long-term ice movement. In particular, significantly more observations of tidal motion on ice shelves is required if present and future remote sensing measurements, from instruments such as GLAS, are to reach their full accuracy potential.

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TABLES

Technique	Precision (mm)	Limitations	Measurement Spatial Resolution	Motion measured
Bottom-mounted tide gauge	~5-10	Difficult to install, retrieve and download	Point	1d (vertical)
Optical Levelling	~5-15	Short distances from coastline for tidal studies; Manual operation; Line-of-sight required (50-200m separation)	Relative	1d (vertical)
Gravity meters	~10-50	Knowledge of water density required for tidal studies	Point	1d (vertical)
Tilt Meters	~10-50	Difficult to monument; most useful in grounding zone locations	Point	1d
EDM/total station (slope distance and angles)	~5-200	Manual operation; line-of-sight required (up to 20km separation)	Relative	3d
GPS	~10-50	Heavy reliance on maintaining power supply; Data storage	Point/Relative	3d
Satellite Image Feature Tracking	>500	Calibration required (need coherent images)	Large areas (swath width ~500km, pixel resolution ~25m)	2d (horizontal)
InSAR	~5-100	Current satellite orbital periods are in phase with semi-diurnal tides at high latitudes; Calibration required	Large areas (swath width ~500km, pixel resolution ~25m)	3d

Table 1: Examples of ice movement measurement techniques.

Parameter / Variable	Parameter state	Value
Solar panel area	Variable (Value is final design value)	$0.6m^2$
Solar panel azimuth	Fixed parameter	True North
Solar panel elevation angle	Fixed parameter	50°
Solar panel efficiency	Fixed parameter	10%
Regulator efficiency	Fixed parameter	95%
Battery capacity (215Ah@12V)	Fixed parameter	2580Wh
Number of batteries	Variable (Value is final design value)	1
Batteries round-trip efficiency	Fixed parameter	80%
GPS system power consumption	Fixed parameter	15W

Table 2: Power supply and storage sizing parameters.

System Components		Cost ($US)
Power Source		
	Solar Panel (80W)	330
	Charge Regulator	75
	Batteries (2x 220Ah 6V)	195
	Low Voltage Cut-off	20
	Wiring	30
Data Acquisition		
	Pressure & Temperature Meter	300
Equipment Storage		
	Storage Box (~0.3m^3)	190
	Insulation	15
	Miscellaneous (cable gland, Teflon vent spots)	10
Support Frame		
	Aluminium	135
	Miscellaneous (High-strength ratchet compression strap, nuts, wing nuts, rope, 'deadmen' anchors, frame feet)	120
Reference Mark		
	Aluminium pole	20
	Adapter sleeve for antenna	20
	Wooden/fibreglass pole joiners	5-30
Total		**~1500**

Table 3: GPS System Costing.

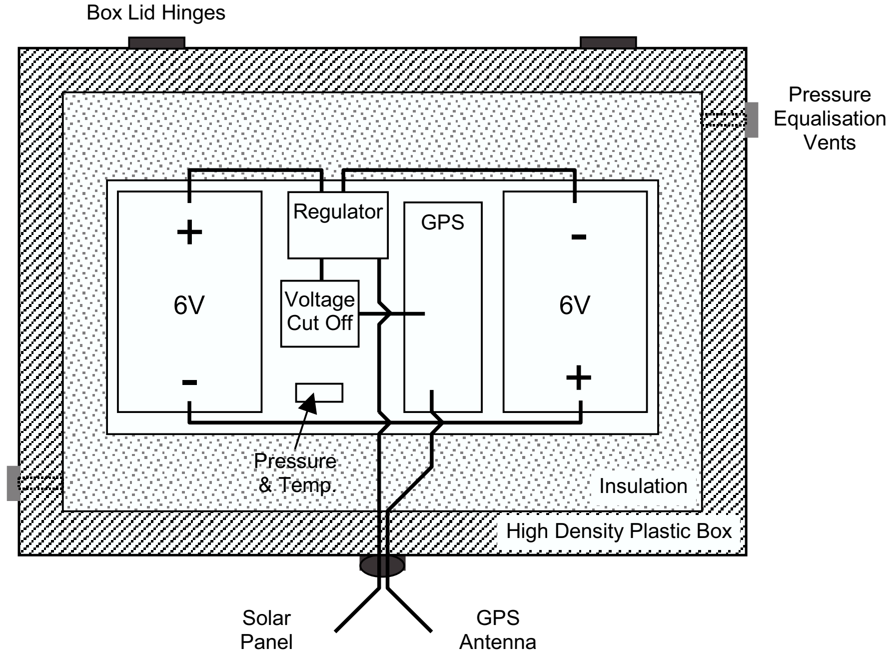

Figure 1: Internal system box components and layout.

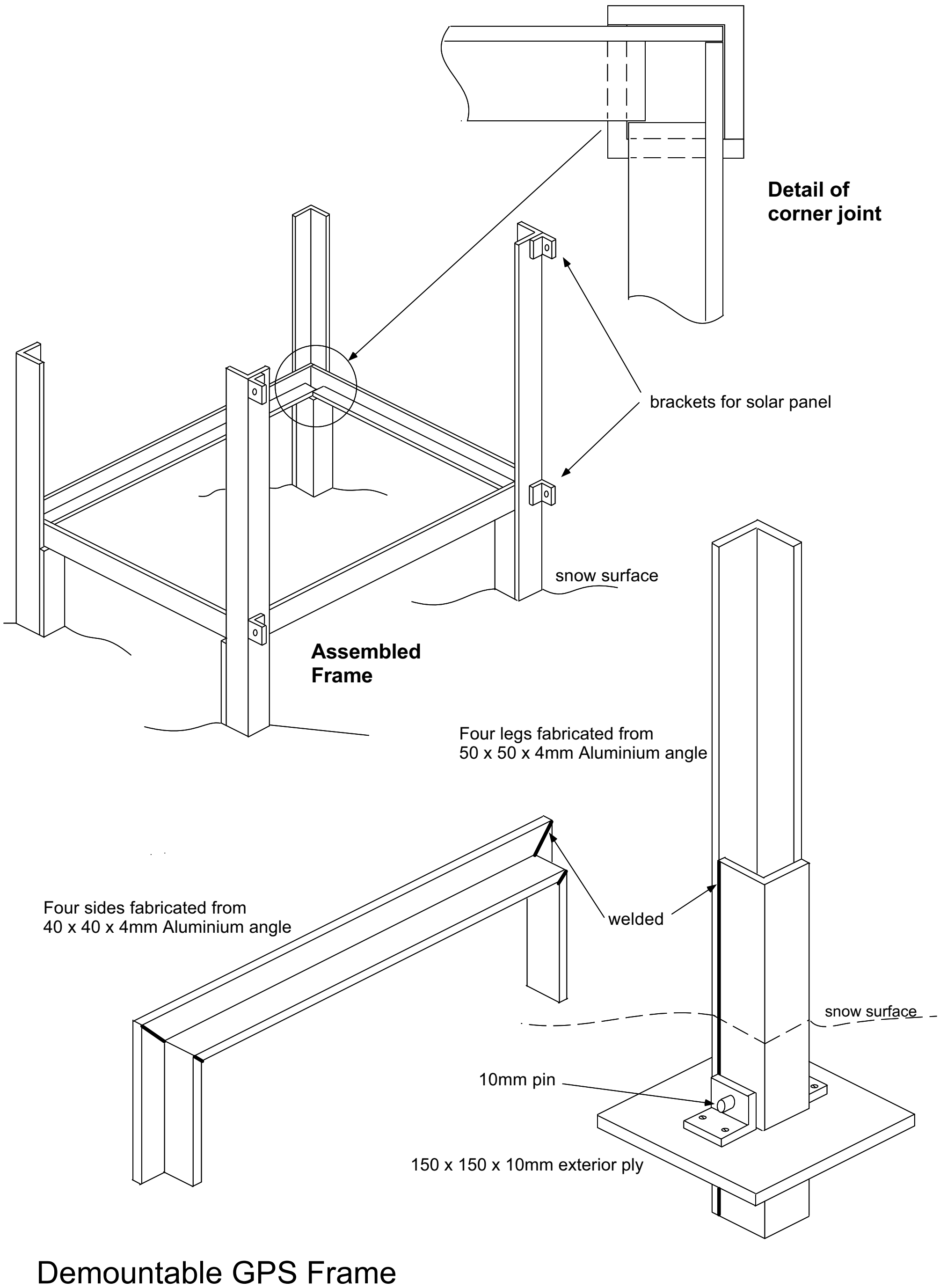

Figure 2: Detail drawing of construction of the GPS support frame.

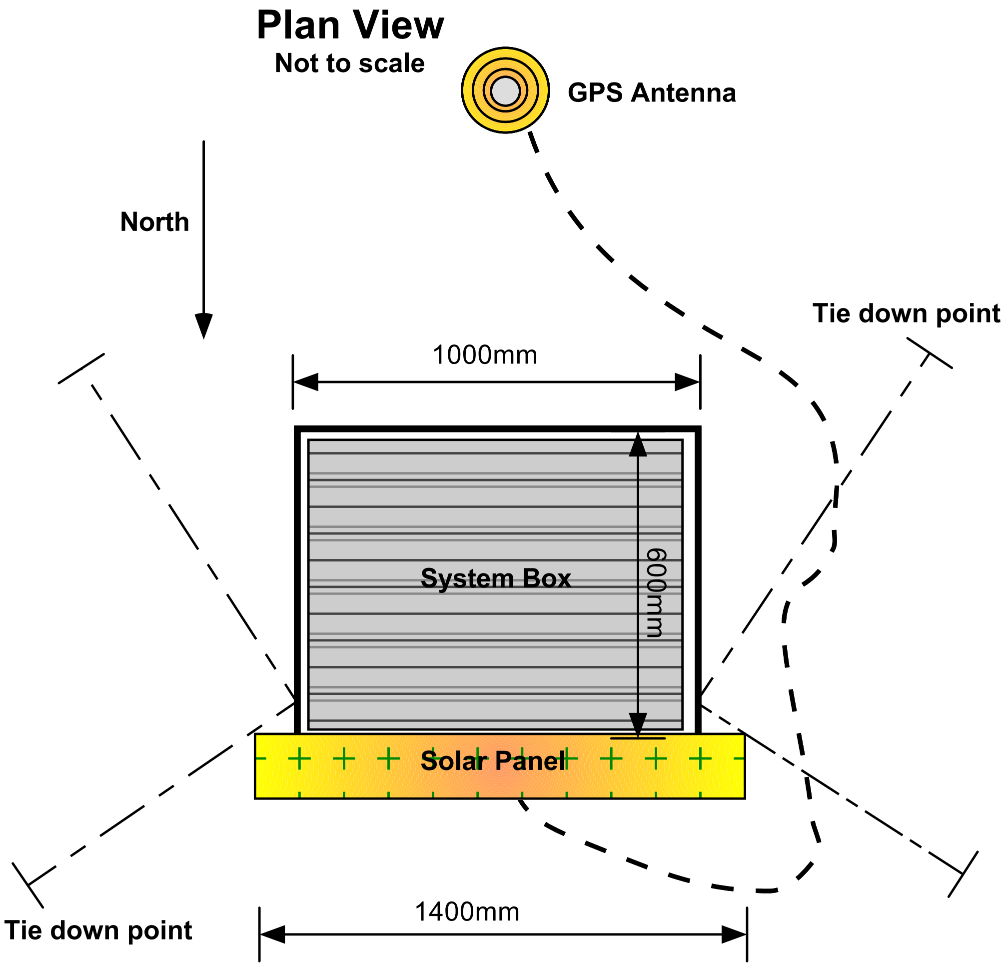

Figure 3: Plan view of the GPS system. Dimensions are approximate and will vary depending on the storage box dimensions.

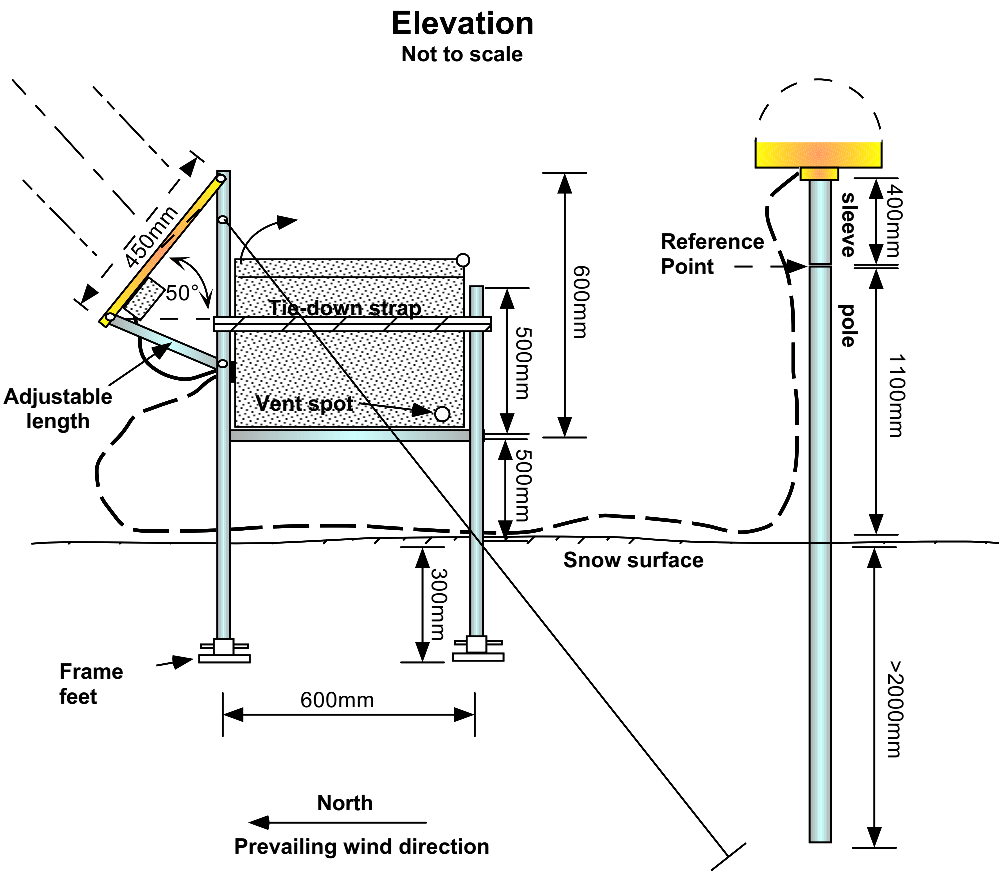

Figure 4: Elevation of the GPS system. Dimensions are approximate and will vary depending on the storage box dimensions

Figure 5: Site TS2 (~71.1°S, 69.6°E) shortly after installation on the Amery Ice Shelf. Photo courtesy of Volker Janssen.

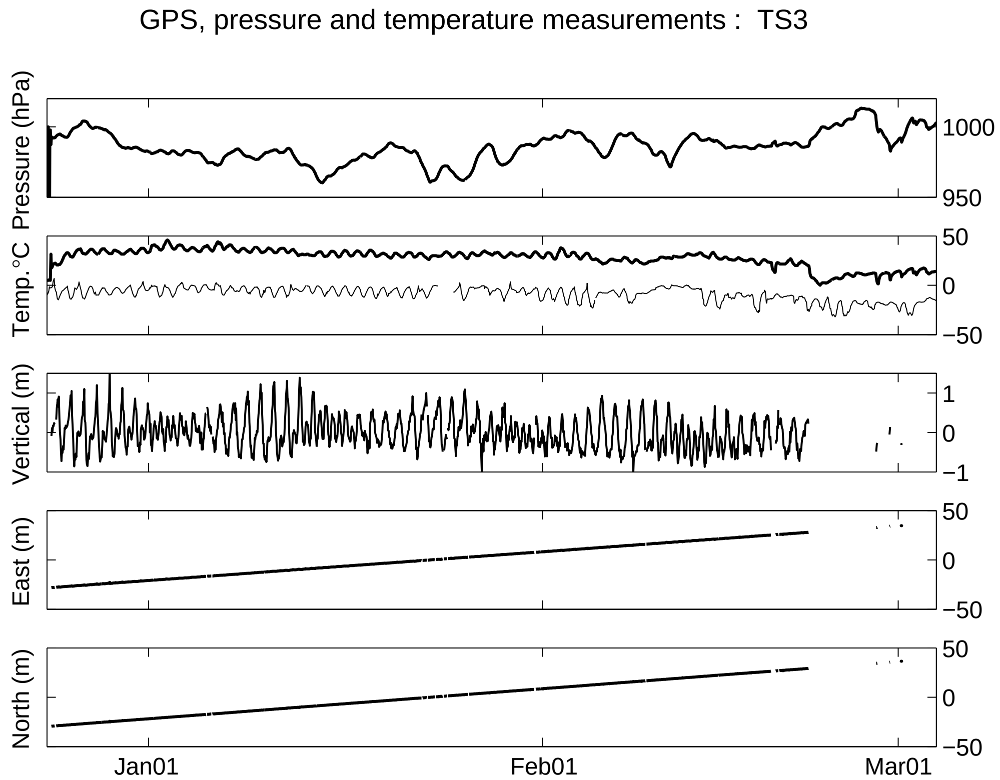

Figure 6: Pressure, temperature and the north, east and vertical components of motion as determined using the GPS data at TS3. The two temperatures shown are the air temperature inside the box (thick line) and the external air temperature measured by the nearby AWS (thin line).