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# Autonomous low-power magnetic data collection platform to enable remote high latitude array deployment

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A major driver in the advancement of geophysical sciences is improvement in the quality and resolution of data for use in scientific analysis, discovery, and for assimilation into or validation of empirical and physical models. The need for more and better measurements together with improvements in technical capabilities is driving the ambition to deploy arrays of autonomous geophysical instrument platforms in remote regions. This is particularly true in the southern polar regions where measurements are presently sparse due to the remoteness, lack of infrastructure, and harshness of the environment. The need for the acquisition of continuous long-term data from remote polar locations exists across geophysical disciplines and is a generic infrastructure problem. The infrastructure, however, to support autonomous instrument platforms in polar environments is still in the early stages of development. We report here the development of an autonomous low-power magnetic variation data collection system. Following 2 years of field testing at the south pole station, the system is being reproduced to establish a dense chain of stations on the Antarctic plateau along the 40° magnetic meridian. The system is designed to operate for at least 5 years unattended and to provide data access via satellite communication. The system will store 1 s measurements of the magnetic field variation (<0.2 nT resolution) in three vector components plus a variety of engineering status and environment parameters. We believe that the data collection platform can be utilized by a variety of low-power instruments designed for low-temperature operation. The design, technical characteristics, and operation results are presented here. © 2009 American Institute of Physics. [DOI: 10.1063/1.3108527]

## I. INTRODUCTION

Many of the advances in geophysics are driven by the acquisition of more and better data. This is accomplished by increasing the spatial distribution of measurements and increasing the quality and resolution of the samples. This is particularly important in space science and the investigation of space weather—the dynamic variation in electrical currents and energetic charged particle populations around the Earth that are driven by interactions of the geomagnetic field with the variable supersonic solar wind plasma. A fundamental tool for these investigations is measurements of the ground magnetic field that are produced by electrical currents that flow in space and in the upper atmosphere (ionosphere) around the Earth. Due to the dipole nature of the geomagnetic field, large regions of the magnetosphere project into the polar regions and auroral and magnetic variations observed in the polar regions can be used to provide context to observations from satellites in space. Measurements in the polar regions are also vital to validating global numerical models that may be used to describe and forecast space weather phenomena. Thus, it is increasingly important to deploy arrays of geophysical instruments in polar regions to advance our understanding of the complex electrodynamic interactions that comprise space weather. The examination of

simultaneous of data from both polar regions is very important because of the considerable asymmetries in the northern and southern polar regions. For example, the solar illumination differences between the summer and winter hemisphere produce large conductivity differences in the two polar ionospheres. The magnetic field in the southern hemisphere is significantly weaker and therefore tends to experience larger amounts of energetic particle precipitation into the ionosphere, producing localized channels of high conductivity.

Measurements from the southern polar regions have historically been very sparse due to the lack of manned infrastructure to support scientific measurement programs. During the past decade or so, technical development has enabled the initiation of measurement programs based on autonomous instrument platforms that can be deployed remotely and operate unattended for extended periods of time. Examples of these are the low-power magnetometer (LPM) platforms operated by the British Antarctic Survey (BAS) (Ref. 1) and the Automated Geophysical Observatory (AGO) program supported by the United States National Science Foundation.<sup>2</sup> The BAS LPMs are robust, simple systems that use only solar power and energy stored in batteries to support the data acquisition system. These systems store data in solid state memory and must be visited each year to acquire the data. The Japanese National Institute for Polar Research utilizes the BAS system with the addition of iridium satellite communication for data retrieval. The U. S. AGOs are more com-

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plex and utilize both wind and solar power. They also utilize satellite communication to acquire data and monitor the health of the systems. Nevertheless, they generally require annual visits for maintenance during the summer season. We report here on the development of a low-power magnetometer platform that is designed to operate unattended for at least 5 years. It is a simple system that utilizes only solar power and storage batteries for winter operation. A two-way satellite data link is utilized to acquire data and monitor the health of the system. The system is also designed to support additional low-power instruments and could be utilized to support any low-power geophysical instrument that requires remote unattended deployment in cold polar locations.

Design of our first autonomous LPM system for remote deployment on the Greenland ice cap near the summit began in 1990. Our first system utilized meteor burst radio technology for data communication to a base station in Sondre Stromfjord, Greenland. This system, however, failed and we subsequently adopted a simple data logger that would store the data locally at the remote site and required that the site be visited each year to retrieve the data. Since it was not possible to revisit the ice cap station, the source of the meteor burst failure was not known until the following year. The system made one transmission and there was no further contact. The failure was caused by destruction of the transmit/receive switch in the radio of the ice cap station. This failure occurred because of the excess power provided by the solar panels due to the high altitude and very clear sky, and inadequate protection for the switch.

The system that was developed during 1990–1992 was very simple, utilizing solar panels to charge lead-acid batteries (about 16–20 100 A/h batteries), a Danish Meteorological Institute fluxgate magnetometer, and solid state data logger using EEPROM. The system acquired 1 min vector samples and worked reliably for several years, both summer and winter. A variety of science papers were published utilizing this data (e.g., Refs. 3–17).

Based on this early, simple design, several subsequent generations of magnetic data collection platform were developed, each providing incremental improvement with the utilization of newer technology. Higher temporal resolution was gradually achieved. We tried to reduce the number of lead-acid batteries through the use of a hybrid power system that utilized both solar panels and wind turbines, with mixed success.

We have been operating remote magnetometer systems in Greenland and in the Antarctic in one form or another continuously to the present day. Our first attempt to utilize the Greenland system in the Antarctic was only partially successful—the Antarctic presents a much colder environment. The first deployment was accomplished using the Russian Antarctic Expedition traverse from Mirny to Vostok station, so a system that utilized a large number of lead-acid batteries was feasible. However, for remote deployments that rely on small aircraft such as the twin otter, the volume and weight of the system become critical parameters.

We report here the results of our recent redesign and testing effort that has produced a robust and reliable data collection platform that will support a low-power fluxgate

magnetometer or other low-power geophysical instrument. This system is designed for remote deployment by small aircraft onto the Antarctic plateau and to operate unattended for at least 5 years. Data are stored in solid state memory but are also transmitted via iridium satellite telemetry to the laboratory at the University of Michigan. During summer, the solar panels provide abundant power. During the dark winter, power is supplied only by the batteries. Therefore, during the winter, the magnetic data are stored in memory and only engineering information is transmitted via the iridium satellite so that, while using less power, we can monitor the health of the system. Since the iridium communication link is two-way, it is possible to command the station to send back winter data if there is a special event or time interval needed. When the sun comes up again and power is abundant, the current data plus the archived data are transmitted. The stored winter data is currently manually downloaded and takes several weeks to fully retrieve.

In the event that the system detects a sufficiently low charge state in the batteries during the winter operation, the system will gracefully shut down to await power from the solar panels. When the sun comes up, power is initially used to heat the batteries to a temperature that will permit them to accept charging. The batteries are charged and the system resumes operation.

Our prototype system was deployed at the south pole during the 2005–2006 austral summer field season for a year-long test. Figure 1 shows the installation at south pole. The system utilizes an Acuña<sup>18</sup> fluxgate magnetometer that requires only 700 mW of power. The initial testing of the system identified several small software and hardware problems that were corrected during the 2006–2007 field season. The second year of operation was completely successful and the system was deployed to a remote field location on the plateau during the 2007–2008 summer field season where it has been operating to the present without problems. A second system was deployed on the plateau during the 2008–2009 summer field season and we anticipate successful continuous operation. Both systems have entered into their winter operation mode in early March 2009 and continue to operate according to their design.

## II. SYSTEM SPECIFICATIONS

The Antarctic plateau is an extremely harsh environment, having summer high temperatures that only reach  $-14\text{ }^{\circ}\text{C}$ , while having winter lows that can reach  $-70\text{ }^{\circ}\text{C}$ . The infrastructure on the continent is extremely limited, with the south pole station being very crowded and only being open for deployment a couple of months per year. It is necessary to be able to deploy the system within a few days in the field by a small team of two or three people utilizing small aircraft. Finally, the sun is not available as a power source for a large portion of the year.

Given these issues, the LPM system requirements in a rough order of importance, established by the science team, were the following:

1. Operate autonomously year around at any location on

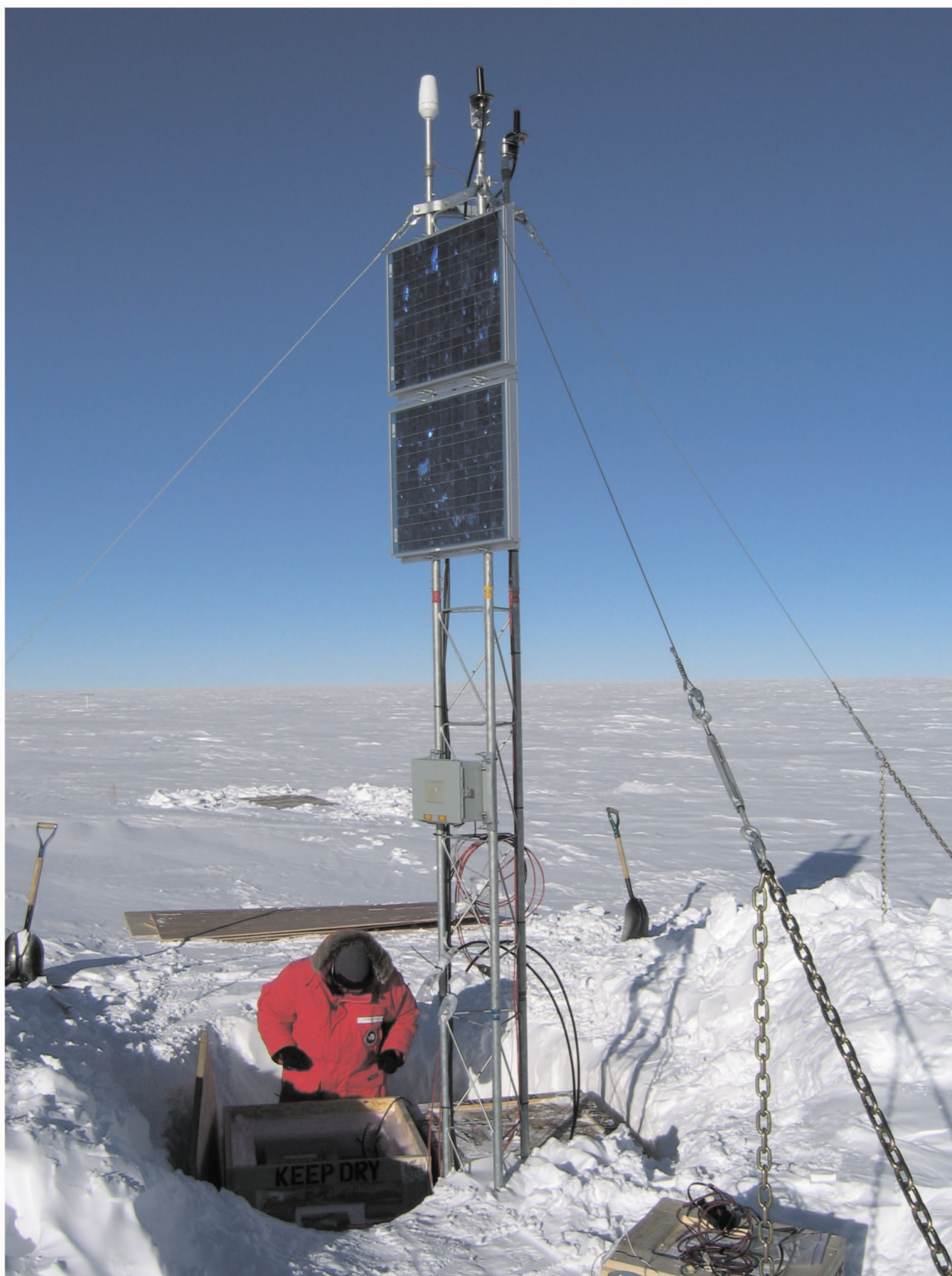


FIG. 1. (Color) Installation of prototype LPM at the south pole for field test. Tower holds solar panels, iridium antennas, and GPS antenna. Electronics box and battery box are buried at the base of the tower and the sensor is located 20 m from the tower in the background of the picture.

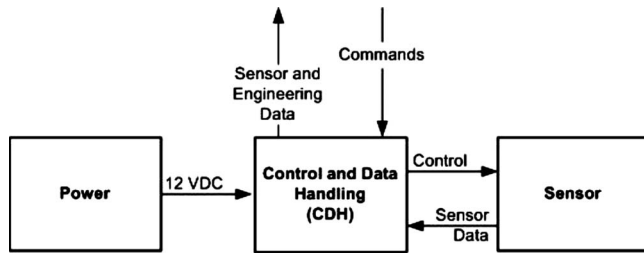


FIG. 2. LPM functional block diagram.

the Antarctic plateau for at least 5 years with no maintenance.

2. Require only the use of a small aircraft for deployment.
3. Transmit stored and near-real-time data off continent via satellite communications.
4. Achieve 0.2 nT magnetic field strength resolution in three orthogonal components and one second temporal resolution.
5. Store at least 1 year of science and engineering data in internal nonvolatile memory.
6. Time-tag stored data with coordinated universal time (UTC)  $\pm 40$  ms.

With these specifications, the present generation LPM was designed as follows.

### III. SYSTEM DESIGN

The LPM is divided into three functional subsystems:

- **Power:** The power system receives power from the photovoltaic (PV) panels, heats and charges the batteries, protects the batteries from over discharge, and provides power to the control and data handling (CDH) subsystem.
- **Sensor:** The sensor is a three-axis flux gate magnetometer and associated data conditioning electronics. It receives

power and control signals from the CDH subsystem, converts magnetic field strength readings into digital sensor data and sends them to the CDH.

- **CDH:** The CDH is a custom microcontroller-based printed circuit board (PCB). It controls the sensor, stores sensor and engineering data, controls the thermal system, and handles data communication.

The LPM functional block diagram is shown in Fig. 2, and consists of four major mechanical assemblies:

- **Tower:** The tower provides mechanical support for the PV panels, rf antennas, and system power switch.
- **Battery box:** The battery box contains the batteries, heaters, charge controller, and low voltage disconnect.
- **Electronics box:** The electronics box contains the CDH electronics, iridium modem, and sensor electronics.
- **Sensor head assembly:** The sensor head assembly consists of the three-axis flux gate magnetometer sensing coils secured to a mechanical mounting which is rotated and leveled to orient the sensor.

The mechanical assemblies as assembled on site are shown in Fig. 3. The sensor head is not shown, and would be located (buried) approximately 20 m away from the tower. The sensor is enclosed in a cube measuring approximately 10 cm on each side, made of a clear polycarbonate material.

### IV. THERMAL DESIGN

The main consideration in the thermal design of the LPM was the desire to not have to revisit the site for maintenance. This consideration outweighed having a 100% duty cycle, allowing the design of a system that was simple, and could automatically shut down and restart when conditions became bad and when conditions improve, respectively.

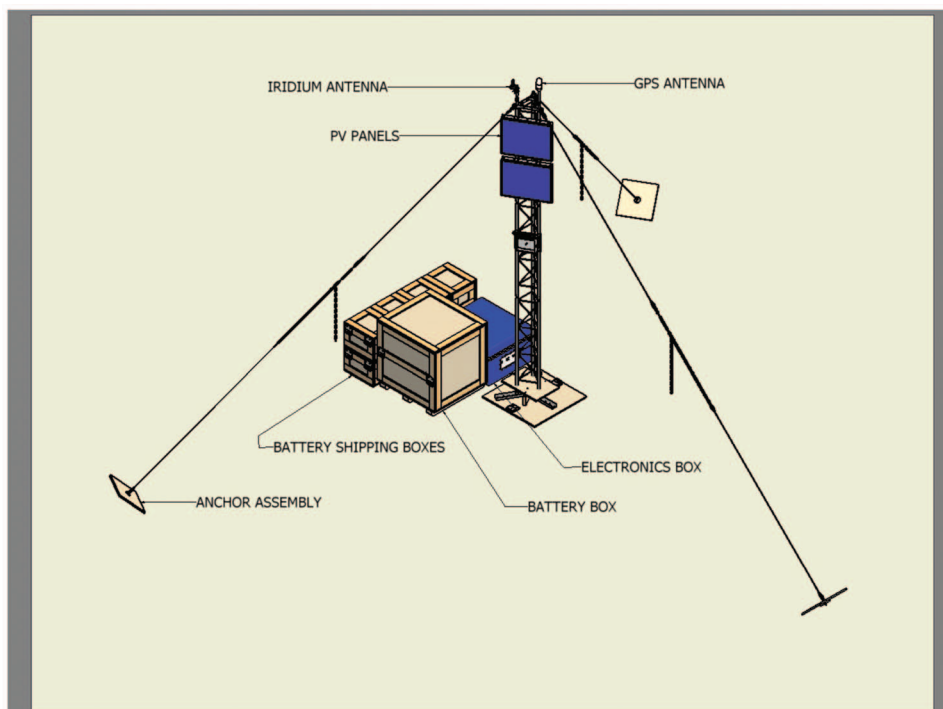


FIG. 3. (Color) The assembled system at the field site. Note that the battery box, electronics box, and empty battery shipping boxes are buried. The magnetometer sensor would sit about 20 m away from the tower and is not shown.

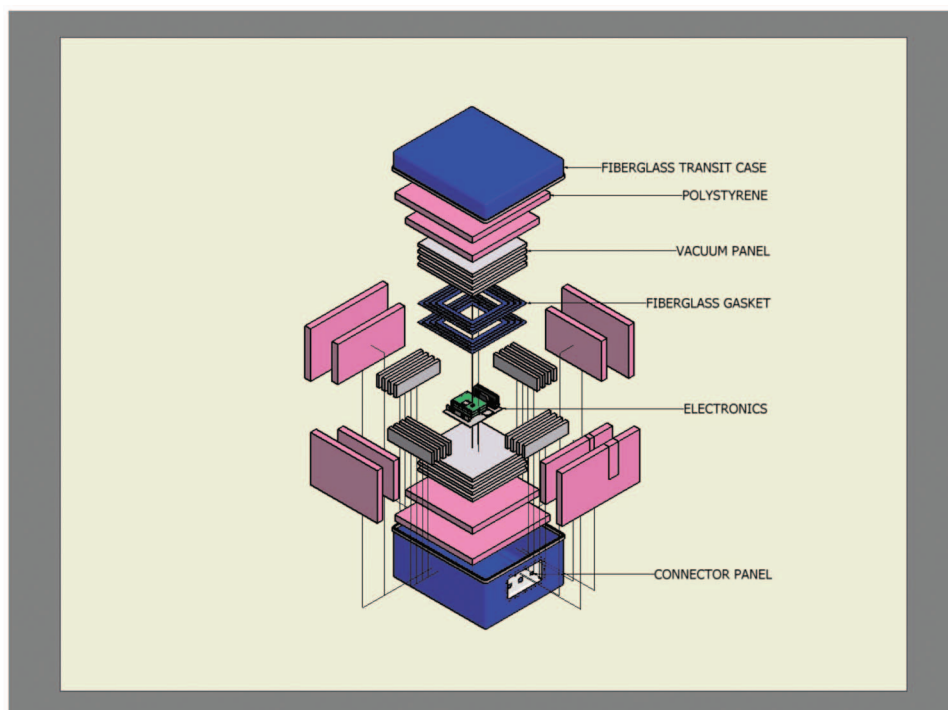


FIG. 4. (Color) The electronics box exploded view.

The thermal system is designed to minimize power usage during the austral winter. This in turn minimizes the number of batteries that must be transported to the field site. Our overall strategy is to heavily insulate and to minimize the size and temperature of heated volumes. During the austral winter, only a single 9.4 l super insulated volume inside the electronics box is heated. The sensor head assembly is not insulated or heated.

The battery box is insulated with 10.1 cm of polystyrene panels and heated to  $-15$  to  $-20$  °C during the austral summer for battery charging. The battery box is not heated during the austral winter to save on power. This is a chosen design consideration between degrading the capacity of the batteries at cold temperatures and using power to heat the batteries to maintain a higher capacity. The more simple design sacrifices capacity for the heating power, which is how the system was designed. Therefore, as the batteries cool and the system continues to draw approximately 2 W of power, the voltage drops. When the battery voltage drops below 11.2 V, the low voltage cutoff is activated and the system shuts down for the winter.

The electronics box is insulated with a combination of 10.1 cm of vacuum panels and 10.1 cm of polystyrene panels, as is shown in Figs. 4 and 5. The insulated volume in the electronics box is heated year round to  $-27$  °C. The measured thermal resistance of the electronics box is  $0.07$  W/°C allowing the electronics box to maintain its interior temperature at 30 °C above ambient by dissipating 2.1 W in the insulated volume.

When PV power is again available at the end of winter, the batteries are slowly heated to charging temperature. As the batteries warm up, their remaining stored energy once again becomes available and their voltage rises. When the voltage rises to 11.8 V (typically around  $-45$  °C) the low voltage detection (LVD) circuit reconnects the load and the

system starts up. A thermostat in the electronics box diverts power to a heater until the electronics reach operating temperature. In practice, the heater is powered only once during initial start up. After that, the iridium modem and global positioning satellite (GPS) receiver are power cycled to control the electronics temperature.

Figure 6 shows the battery temperature and voltage over 3 years of operation. The gaps during the winter periods occur because the battery voltage dropped below the threshold value. During the first 2 years, the system was located at the south pole, but during January of 2008, the system was relocated to a remote camp on the plateau, AGAP-S (85.5S, 77.2E), which is much colder than the south pole. During January 2007, the electronics box was improved (as described below), allowing the system to run longer into the winter, as is shown by the shorter down-time during winter

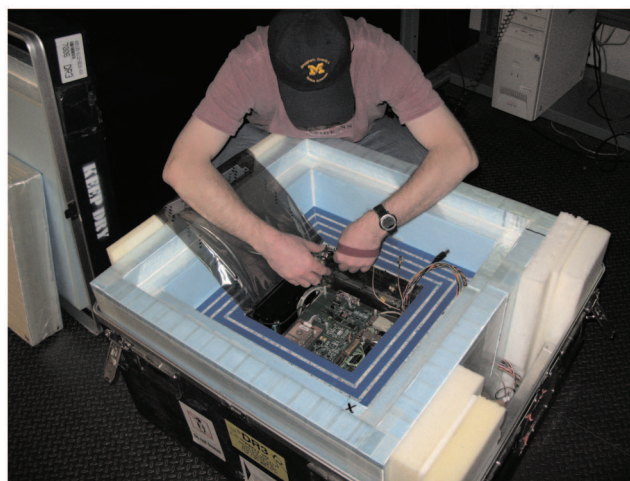


FIG. 5. (Color) A photo looking down into the electronics box.

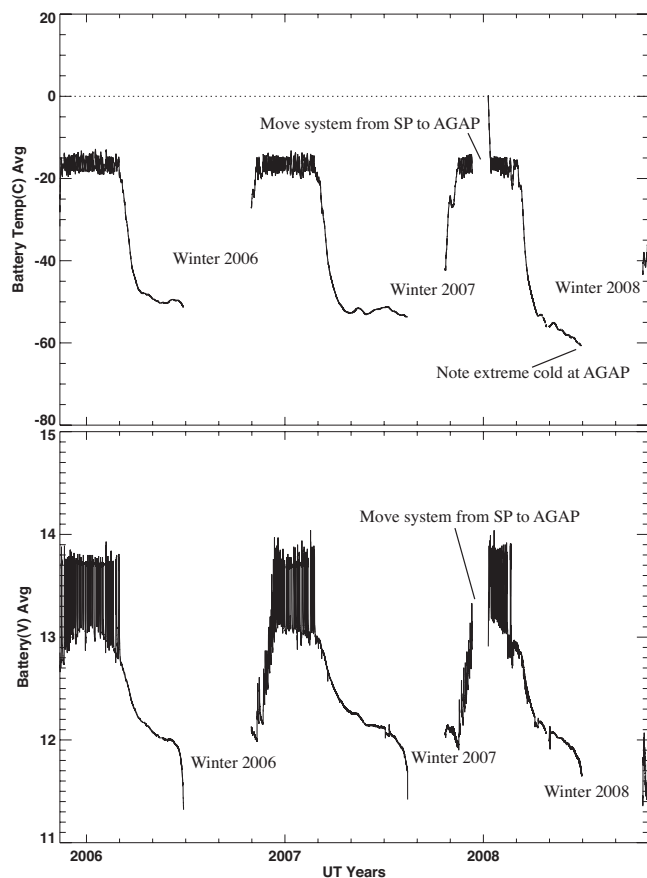


FIG. 6. Housekeeping data from 3 years of operation on the Antarctic plateau. The top plot shows the temperature within the battery box, while the bottom plot shows the voltage being generated by the batteries.

in 2007 compared to winter in 2006. Once the system was moved to AGAP-S, the system once again shut down relatively early, since the temperature in the battery box became significantly colder than previous winters and the capacity of the batteries was diminished.

The insulated volume measures  $30.5 \times 30.5 \times 10.1 \text{ cm}^3$ . To reduce vacuum panel manufacturing set up charges, only two different size vacuum panels are required:  $51 \times 51$  and  $40.6 \times 10.1 \text{ cm}^2$ . The electronics box is assembled and sealed using a silicone room temperature vulcanizing (RTV) adhesive. The G10 fiberglass gaskets provide a flat air tight seal. All air gaps between insulation panels are filled with RTV adhesive. The molded fiberglass case serves as its own shipping container.

To minimize heat loss from the cables running from the interior to the exterior of the electronics box, the number and diameter of wires that lead out from the insulated space are minimized. The wires are laid in a flat serpentine pattern between layers of insulation from the inside to the outside of the box. This is done to maximize the length of the wire for minimal heat conduction through the wire and to maximize the length of the path for air circulation, if any exists.

## V. SUBSYSTEM DESIGN

### A. Power system

In past systems in Greenland and Antarctica, we found small wind turbines unreliable unless they were maintained

or replaced yearly. This was mainly due to seizure of the bearings, caused by lack of grease. Since the LPM is required to run at least 5 years without maintenance, the use of a wind turbine was ruled out, even though wind power is available year round in Antarctica, while solar power is not.

The power system is designed around a bank of 12, 100 A/h Power-Sonic absorbed glass mat (AGM) lead-acid batteries connected in parallel. Power-Sonic AGM batteries were selected because they have a proven track record of reliability and ruggedness in our previous systems in Greenland and Antarctica, and because they retain a significant amount of their rated capacity at low temperatures. In laboratory tests at the University of Michigan, Power-Sonic batteries at  $-55 \text{ }^\circ\text{C}$  retained 48% of their rated capacity when powering a 1.4 W load. This allows us to power the system using unheated batteries during the austral winter (i.e., when the batteries cannot charge due to lack of sunlight.) The batteries are charged during the austral summer when PV power is plentiful. Since the battery temperature must be higher than  $-20 \text{ }^\circ\text{C}$  for charging, the battery bank is heated to  $-15$  to  $-20 \text{ }^\circ\text{C}$  while charging during the summer. Because the batteries operate at low temperatures, and because they undergo only one full charge/discharge cycle per year, we expect battery life to exceed 10 years.

Except for the PV panels and system power switch, the power system is contained entirely in the battery box, which is a heavy duty plywood shipping crate lined with 10.1 cm of polystyrene insulation panels. To reduce the weight of the battery box during deployment, the batteries are shipped to the field site in separate plywood shipping crates, each containing two batteries. The battery box is used to ship solar panels and other light weight fragile items to the field site. The batteries are moved from their shipping crates to the battery box upon installation of the system. The battery box additionally contains the power electronics board, fuse panel, and battery heaters. The battery heaters are commercial power resistors mounted on an aluminum panel that is located in the center of the battery bank.

The power electronics board is a custom designed PCB that contains battery heating, battery charging and LVD circuits. A custom design was selected over an off-the-shelf solution for two reasons: lower parasitic power losses and the need to control battery temperature. Off-the-shelf charge controllers and LVDs have significant parasitic power losses and cannot control battery temperature. Since the LPM depends on stored battery power for up to six months per year, parasitic power losses must be minimized.

The power electronics board performs the following functions:

- (1) Connects the PV panels to the battery heaters when the batteries are too cold to charge.
- (2) Connects the PV panels to the batteries when the batteries are warm enough to charge and less than fully charged.
- (3) Disconnects the PV panels when the batteries are warm and the batteries are fully charged.
- (4) Disconnects the load from the batteries when the battery

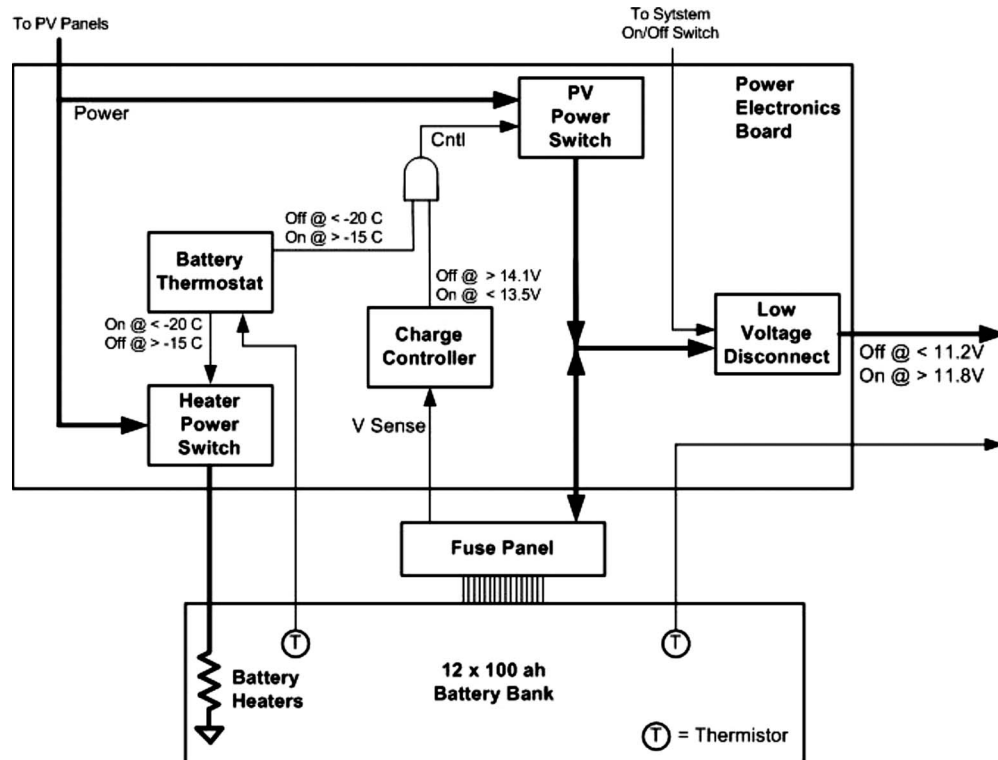


FIG. 7. Power system.

voltage drops below 11.2 V. Reconnects the load when the battery voltage rises above 11.8 V.

It should be noted that the system operates off the batteries all of the time so there is no switching between power sources. Figure 7 shows a diagram of the power system and Fig. 8 is a photo looking down into the power electronics board that sits in the battery box above the batteries.

The power electronics board (and the LPM in general) uses no relays or other moving parts. Solid state power

switches are used throughout. The heater control, charge control, and LVD circuits all use hysteresis to eliminate unnecessary switching cycles when voltages and temperatures are near threshold values.

## B. CDH system

The CDH system consists of a custom controller board, an iridium modem and a GPS receiver. Except for the GPS and iridium antennae, the CDH system is contained entirely in the electronics box.

A custom made controller board is utilized because we needed to minimize size and power consumption and support several nonstandard peripheral devices. We also wanted to provide a breadboard area on the circuit board to accommodate unforeseen and future needs. The controller board is designed around a Z-World RCM3110 (Rabbit) microprocessor plug-in core module. It has a microprocessor, real-time clock, memory, and I/O interfaces. The Rabbit module controls the peripheral devices on the controller board. We selected this module because it has sufficient processing power and I/O control capability, more than enough memory and comes with an integrated C-language software development system. We had used the RCM3110 in previous projects and had confidence that it would perform well in this application. A schematic diagram of the controller board is shown in Fig. 9.

The only significant RCM3100 deficiency for our application is excessive real-time clock drift at low temperature. The LPM is required to time-tag magnetic data with UTC  $\pm 40$  ms. The source of UTC is the GPS receiver. If the receiver was powered continuously, the time-tagging accu-

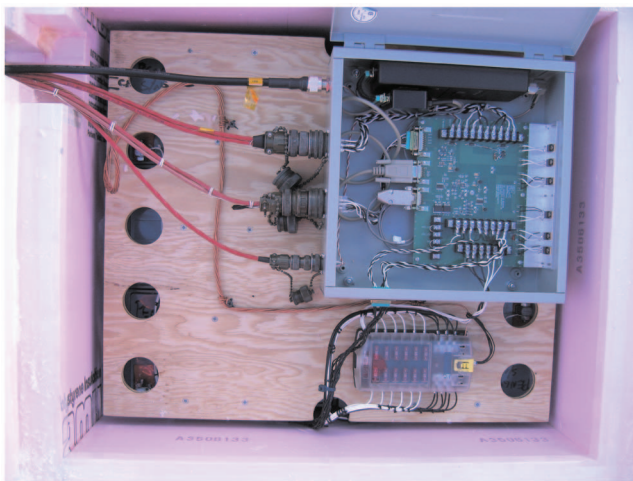


FIG. 8. (Color) Looking down into the battery box. The batteries are beneath the plywood panel. Note that the wires are not spiraled outwards as in the electronics box. This is mainly because there is no heat source within the battery box during the winter, which means that once the PV system stops operating, the temperature drops rapidly to the ambient temperature, as is shown in Fig. 6.



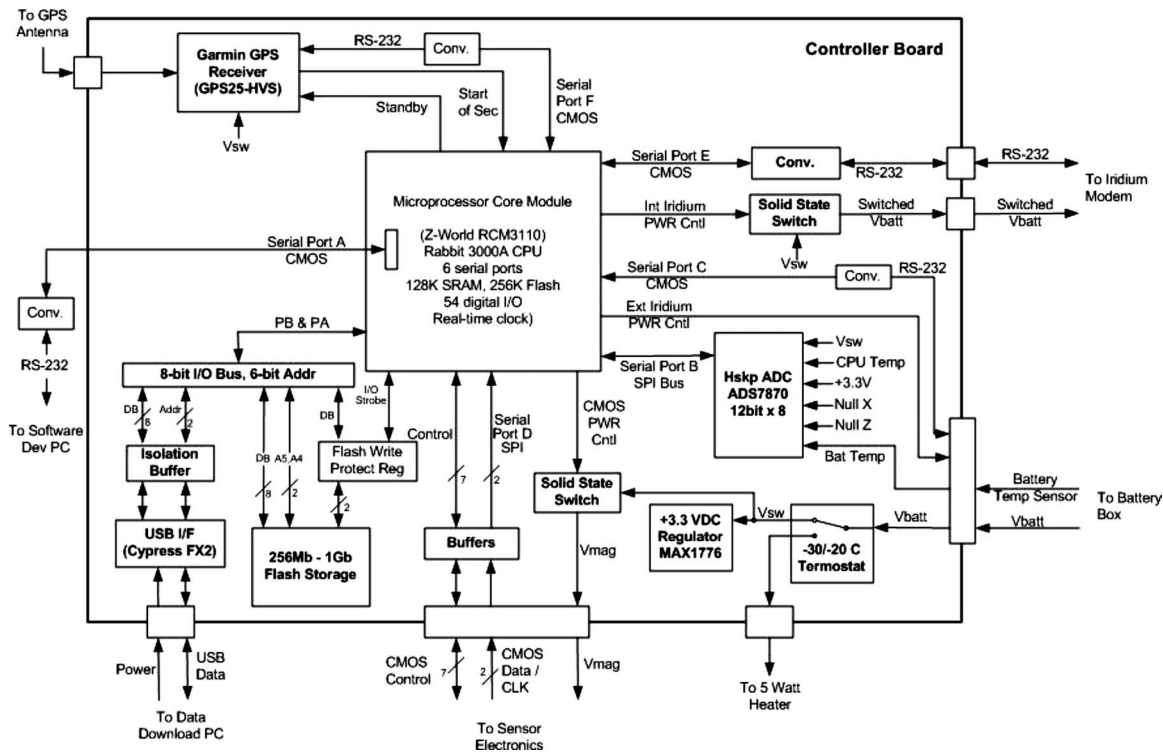


FIG. 9. Schematic diagram of the controller board.

racy requirement could easily be met. But in order to save power, the GPS receiver is turned on only once per hour to set the real-time clock to UTC. Between hourly UTC synchronizations, the value of the real-time clock is used as the time tag. When running at  $-27\text{ }^{\circ}\text{C}$  the real-time clock can drift up to 300 ms per hour.

The clock drift problem was solved by adding temperature compensation code to the real-time clock interrupt service routine. A temperature-dependent number of clock ticks are added or removed to compensate for the crystal time drift. Using this technique, the compensated real-time clock drift does not exceed  $\pm 30$  ms per hour.

The peripherals on the controller board include the following:

- A Garmin GPS25-HVS GPS receiver. The receiver transmits a serial time message once per UTC second. It also outputs a digital start-of-second signal that is used to synchronize the RCM3110 real-time clock with UTC. The receiver is powered up once per hour and typically remains on for less than a minute.
- Solid state switches to control the iridium modem and sensor electronics power. The GPS receiver power is controlled using its standby control input.
- A solid state thermostat diverts battery power to a 5 W heater until the electronics board warms up to operating temperature. The heater is only used when coming up after a winter shut down. After the initial warm up, the controller board temperature is maintained in software using the GPS receiver and iridium modem as heaters.
- A 12-bit, eight input analog to digital converter that is used to monitor battery and controller board supply voltages,

battery and controller board temperatures, and the sensor X and Z axis nulling voltages.

- 256 Mbyte of flash memory used for nonvolatile data storage.
- A Cypress FX2 USB interface used for bench testing and high speed data transfers.

A  $5.1 \times 10.1\text{ cm}^2$  grid of plated through-holes on the controller board, known as the breadboard area, is reserved for future expansion. The breadboard area can be used to add additional peripherals and interfaces.

The CDH, including sensor and sensor electronics, requires 1.02 W. The GPS receiver requires 1.04 W. The iridium receiver in standby mode requires 0.9 W. Its active power averages between 3 and 4 W. By controlling the GPS receiver and iridium modem duty cycles, winter power consumption is minimized. The GPS receiver and iridium modem are only powered up for UTC synchronization, or when needed for heat to maintain the electronics temperature.

The controller board software is written in the Dynamic C language using an integrated development environment (IDE) supplied by Z-World. The IDE runs on Windows PCs and is nicely integrated with the microcontroller core module using a serial interface. The IDE provides a full featured C library, quick compile and download times, and symbolic debugging.

In addition to the typical C library, Dynamic C includes several nonstandard C constructs that support cooperative multitasking. The LPM software is structured as a set of independent tasks that use messages to communicate with each other. This architecture allows the LPM to take data continuously regardless of what other tasks are active. There

are separate tasks that control the GPS receiver: control temperature; sample, average and store magnetic data; handle commands; handle the iridium modem; upload data; and handle the USB interface.

The LPM uses NAND flash memory because of its non-volatility, high density, and low-power requirements. There are two drawbacks to using high density flash memory in this application: (1) limited number of erase cycles and (2) bad blocks.

Each flash memory chip is divided into blocks of 131 072 data bytes. Each block is further divided into 64 individually writable pages. Each page has 64 spare bytes associated with it. The first four spare bytes contain a software generated page checksum that is stored when the page is written. Each block is individually erasable, but the number of erase cycles for each block is limited to 100 000. While this does not seem like much of a limitation, the usual file and directory structure must be avoided because the directory blocks would fail long before the file blocks.

The LPM levels flash wear by organizing the flash blocks into a single circular buffer. As data become available they are written to the next unused block in the buffer. When all the blocks are in use, the block containing the oldest data is erased and reused. The flash memory can hold about 500 days of data so each data-block is erased once every 500 days.

It is the nature of NAND flash that bad blocks can develop at any time, so the software must be able to detect and retire bad blocks to prevent data loss. A block is declared bad if it fails an erase operation or any page in the block fails a write operation. The flash chip contains the logic to detect both of these failures. If checksum verification fails during a page read, the error is considered transient and the data ignored. If the error is due to a genuine bad block, the bad block will be detected and retired when it is next erased and written.

The list of bad blocks is stored in a special flash block, known as the end of list (EOL) block. The EOL block is located directly following the newest data in the circular buffer. It is uniquely identified by a 32 byte signature that is stored at the start of the block. Every time a new flash block is needed for data storage, the contents of the EOL block is moved to the next block creating a new EOL block. The old EOL block is then erased and used to store the newest data.

The EOL block is also used to mark the current beginning and end of the circular buffer. Since the loss of the EOL block would result in data loss, it is moved using a write-verify-erase algorithm to avoid corruption due to power loss. The new EOL block is written and verified before the old EOL block is erased ensuring a valid EOL block exists at all times.

Stored data are downloaded to a PC using an iridium modem to iridium modem connection or a direct USB connection. There is a significant cost savings with having an iridium modem on each side of the call, as opposed to having the field iridium call a land-line. This is due to the calling plan provided by the National Science Foundation, as opposed to any design constraints. The USB port is typically used only for bench testing and high speed data transfers. Data downloads are initiated by PC command. The PC can

request either science or engineering data for any date range stored in flash memory.

Engineering data are stored hourly and include: latitude, longitude, real-time clock drift, X and Z axis null voltages, battery temperature, controller electronics temperature, power supply voltages, heater duty cycles, iridium signal strength, flash memory usage, and bad blocks. Voltage and temperature hourly minimums, maximums, and averages are stored.

Iridium modem communications are subject to frequent data corruption and dropped connections so an error detection and retransmission protocol is utilized. The protocol was tailored to the LPM to minimized code size and complexity. The PC requests one 512 byte packet at a time. When received, the packet checksum is verified. If the checksum is valid, the PC requests the next packet. Otherwise the PC requests a packet retransmission. If the connection is dropped, the PC waits for a short period, reestablishes the connection and picks up the data download where it left off. Using this simple protocol, the system averages 2000 bits/s of error-free downloaded data.

Because of a quirk in the iridium system, a modem must attempt to make a call periodically or it becomes invisible to the system and will not accept incoming calls. Because of this, the LPM modem calls the PC modem once a day. The PC modem is not required to answer the call and usually does not. The LPM modem is powered up periodically during the day and waits for incoming calls from the PC modem. A single PC modem can download data from several LPM systems.

During the summer, when the system has sufficient power, the data are downloaded once daily utilizing automated scripts. Once the sun has set, and the iridium modem is not utilized in transmit mode often, since it is the most power-hungry peripheral. Therefore, only engineering data are downloaded during this period. If the batteries run into low voltage, the system will shut down and wait for power from the solar panels. When the system powers on again, data are manually downloaded from the winter season. It can take about 40 min to download a day's worth of data, therefore it can take up to a few weeks to fully download all of the winter data.

The downloading strategy is scalable up to about five systems per iridium modem in the laboratory at the University of Michigan. This is primarily due to the downloading of the winter data.

### C. Sensor

The sensor is a three-axis fluxgate magnetometer built by Acuña<sup>18</sup> at the NASA Goddard Space Flight Center. It derives from a series of spacecraft magnetometers designed and built by Acuña.<sup>18</sup> The primary sensor specifications are:

- resolution of 0.17 nT;
- dynamic range of  $-4000$  to  $+4000$  nT, allowing for all but the most extreme magnetic perturbations to be recorded;
- analog antialiasing filters of 3 Hz;
- commandable electronic nulling for X and Z axis; and

- power usage of 700 mW continuously.

The sensor output is sampled at 14 Hz. All the samples taken during a UTC second are averaged to produce a 1 Hz reading which is stored in flash memory.

## VI. FIELD TEST RESULTS

The LPM was deployed for field testing at the south pole in November 2005. Initial performance was as expected except for the following problems: (1) unreliable iridium communications; (2) insufficient battery capacity; and (3) late spring wake up. The sources of all three problems were determined by November 2006 and fixed during a south pole site visit in January 2007. The LPM has operated normally since then. In January 2008 the LPM was moved to the AGAP camp at  $-85.4^\circ$  lat,  $77.2^\circ$  long.

### A. Unreliable iridium communications

Starting in December 2005, contact with the LPM iridium modem became sporadic, dropping out for several days and weeks at a time. The problem was eventually traced to two causes: a quirk in the iridium system whereby a modem must attempt to make a call periodically or it becomes invisible to the system, and excessive rf power losses in the iridium antenna cable. The solution to the first problem was to force the LPM modem to call the PC modem at least once a day. The solution to the second problem was to replace the iridium antenna cable that runs through the electronics box insulation with a shorter, lower loss cable. The iridium modem specification limits antenna cable attenuation to 3 dB. The calculated attenuation of the replaced iridium cable was 4 dB.

### B. Insufficient battery capacity

In March 2006, the battery voltage dropped faster than expected. By the third week in June, the LPM had run out of power and shut down. Analysis of the engineering data revealed that the electronics box was losing 40% more heat than expected. We believe this was due to a punctured vacuum panel and/or a leaking box air seal.

We redesigned the electronics box and built a replacement, using the design described in this paper. The new design included additional polystyrene insulation and a flat fiberglass air seal. We also reduced power requirements by decreasing the electronics box temperature from  $-20$  to  $-27^\circ\text{C}$ . After the modifications, the LPM ran almost two months longer into the winter at the south pole, but still ran out of power on August 10, 2007, as is shown in Fig. 6. The battery capacity problem will be eliminated in future LPM systems by increasing the number of batteries from 12 to 16 and by lowering the electronics temperature from  $-27$  to  $-37^\circ\text{C}$ . It is expected that the system will run through the winter with these modifications.

### C. Late spring wake up

After shutting down in June 2006, the LPM did not power up until October 30. This was about three weeks later than expected. The problem was traced to the LVD reconnect

voltage level being set too high. The reconnect level for a typical solar powered system is 12.8 V. But the LPM has a much larger battery capacity to PV power ratio than a typical solar powered system. This causes the battery voltage to rise slowly in the spring. The problem was fixed by changing the LVD reconnect voltage from 12.8 to 11.8 V. The new lower reconnect voltage still provides sufficient hysteresis to prevent unnecessary switching cycles.

### D. Lessons learned

The following is a list, in no particular order, of lessons we have learned during the design and construction of several generations of autonomous polar systems.

- Use connectors that are rated for cold temperatures. Insist on gold contacts. Good connectors are expensive and worth it. Inexpensive connectors fail and cause intermittent problems.
- Use a grounding bus. Use a single point ground that is connected to the negative battery terminal. All metallic cases and mechanical items (tower, PV panel frames, etc.) should be grounded. Blowing snow can charge ungrounded items to very high levels, sometimes causing electrical discharge through electronic components.
- The system must be deployed by people wearing gloves or mittens. Large hardware should be utilized whenever possible. Big connectors spaced well apart are a must. It is almost impossible to operate with bare hands in the Antarctic.
- Limit shipping container size and weight so they can be handled by two people. Fork lifts are typically not available at field sites.
- Eliminate moving parts if regular maintenance cannot be performed. Unmaintained moving parts eventually wear out and fail.
- Be skeptical about manufacturer temperature ratings. Test low-temperature performance before designing a component into the system.
- Design cables and choose connectors so that they cannot be connected incorrectly.
- Color code cable ends, connectors, and all parts of an assembly.
- Measure actual iridium antenna cable attenuation. Limit it to less than 3 dB.
- If a cable needs to flex in the field, test it for low-temperature flexibility in the laboratory. Some cable types rated for low temperature become very stiff at low temperature.

### E. Magnetic field data recovered

Figure 10 shows magnetic perturbation measured by the system after it was moved to AGAP-S and woke up for the summer 2008–2009 season. The data are recorded every second. The  $Y$ -component should be centered around zero, but the magnetometer is not oriented exactly along the magnetic meridian, so there is a slight offset to the values.

Figure 11 shows power spectra of the data from each of the three magnetometer axes for the time interval from 10 to

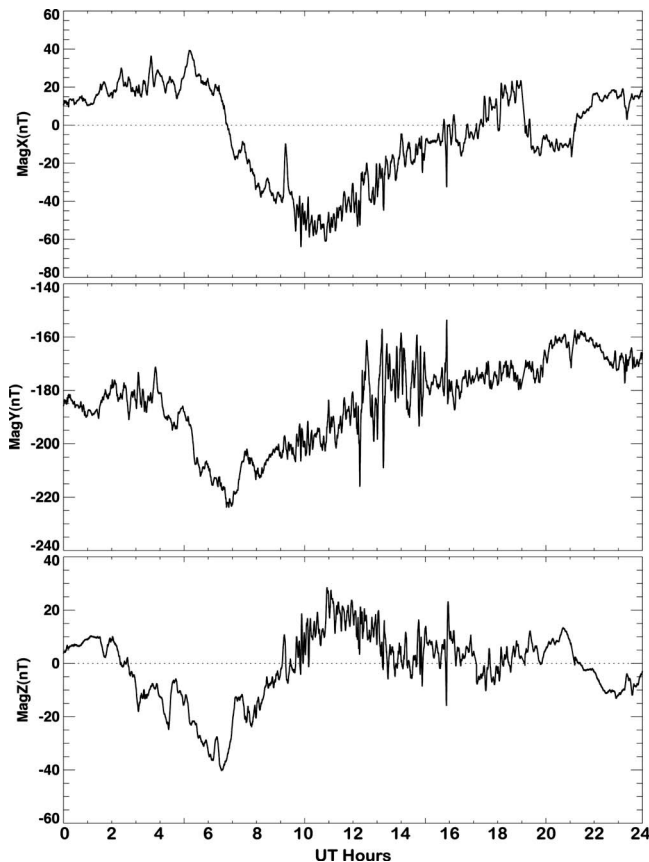


FIG. 10. Magnetic perturbations in the northward, eastward and vertical direction (from top to bottom) measured on November 6, 2008 by the autonomous LPM at the AGAP-S camp ( $-84.5S, 77.2E$ ).

14 UT on November 6, 2008, shown in Fig. 10. The data have first been detrended to remove the mean and auto spectra are computed from the residuals. The most obvious feature is a spectral peak at about 1.5 mHz present in all three components. Another feature is a broad hump centered just above 10 mHz (100 s period). The flattening of the spectrum at low frequency is an artifact of detrending. The nearly flat

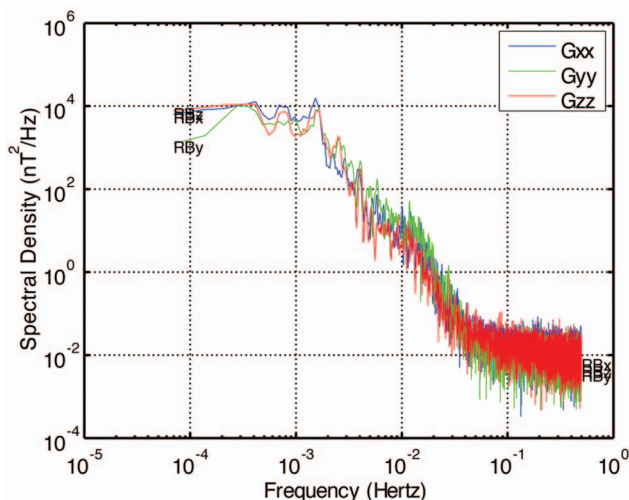


FIG. 11. (Color) Superposed auto spectra of the three magnetic components computed from the data on November 6, 2008 between 10 and 14 UT shown in Fig. 10.

spectrum at frequencies above 10 mHz is most likely digitization noise.

## F. Future improvements

Several improvements to the system are planned in order to achieve a network of autonomous and dynamically adaptive low-power geophysical measurement stations. At present, we use a simple Garmin GPS receiver to provide the time signal for data acquisition. We plan to replace this unit with a newly available low-cost, next generation dual-frequency GPS receiver known as the CASIS GPS receiver. This GPS receiver is specifically designed as an ionospheric space weather sensor that can measure both amplitude and phase scintillations in addition to total electron content (TEC). The receiver is a development of faculty at Virginia Tech and Cornell and is based on previous and ongoing research on embedded software-defined radios for scientific applications. This will permit the platform to provide additional ionospheric measurements for little additional cost. The CASIS size and power requirements are also consistent with our design concept.

Since the CASIS GPS receiver can be operated with a variety of receiving modes, our present plan is to operate the GPS receiver at a low cadence to obtain TEC. On-site examination of the signal, however, will determine if the signal shows scintillation characteristics that would indicate ionospheric plasma instabilities that are of scientific interest. Such a detection would cause the GPS data collection to increase to capture information about the scintillation event. Since our plan is to form a chain of stations along the  $40^\circ$  magnetic meridian in the Antarctic, we plan to develop an interstation communication system so that the station detecting ionospheric GPS scintillation could alert the adjacent stations to also change the GPS data collection mode in order to capture the spatial growth of the instabilities if that occurs. Since this is primarily a summer time phenomena, power should be sufficient to support this operation mode.

To facilitate the addition of different low-power instruments to the system, the data logger will have multiple undedicated serial ports. Each port will be connected to an interface adapter module (IAM) which is, in turn, connected to an instrument. The IAM is a small circuit board that has a serial port, microprocessor, and undedicated electronics breadboard area. The IAM will condition, serialize, and transmit the instrument output to the data logger. The IAM can also convey commands from the logger to the instrument and provide power to the instrument.

For different instruments, the basic IAM design remains the same. Only the IAM firmware and breadboard electronics area need to be customized for each instrument. The breadboard area is typically used for (but not limited to) analog to digital conversion, level shifting, buffering, and isolation.

## VII. SUMMARY

In this report, we have outlined a system that is specifically designed to accurately measure high-time-resolution magnetic field variations in the Antarctic continent. This sys-

tem could be easily modified to incorporate other low-powered instruments in addition to, or instead of, the magnetometer.

One of the largest considerations in the design was the desire to not have to make annual maintenance trips to the system. This requirement pushed toward the design of a system that could automatically power cycle as the external conditions changed through the year. Valuable lessons were learned the first year of deployment, and the system was modified to lose less heat during the winter and deal with the iridium modem. During the last year, the system has operated flawlessly.

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<sup>1</sup>Information available on the web at [http://www.sos.siena.edu/antarctic/PENGUIn\\_Program/](http://www.sos.siena.edu/antarctic/PENGUIn_Program/).

<sup>2</sup>Information available on the web at [http://www.antarctica.ac.uk/bas\\_research/instruments/lpm.php](http://www.antarctica.ac.uk/bas_research/instruments/lpm.php).

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