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# Autonomous Adaptive Low-Power Instrument Platform (AAL-PIP) for remote high latitude geospace data collection

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## Abstract

We present the development considerations and design for ground based instrumentation that is being deployed on the East Antarctic Plateau along a 40° magnetic merid-  
ian chain to investigate interhemispheric magnetically conjugate geomagnetic coupling  
and other space weather related phenomena. The stations are magnetically conjugate  
to geomagnetic stations along the west coast of Greenland. The autonomous adap-  
tive low-power instrument platforms being deployed in the Antarctic are designed to  
operate unattended in remote locations for at least 5 years. They utilize solar power  
and AGM storage batteries for power, two-way Iridium satellite communication for data  
acquisition and program/operation modification, support fluxgate and induction mag-  
netometers as well as dual-frequency gps receiver and an HF radio experiment. Size  
and weight considerations are considered to enable deployment by a small team us-  
ing small aircraft. Considerable experience has been gained in the development and  
deployment of remote polar instrumentation that is reflected in the present generation  
of instrumentation discussed here. We conclude with the lessons learned from our  
experience in the design, deployment and operation of remote polar instrumentation.

## 1 Introduction

Improvement in the quality and resolution of data for use in scientific analysis and dis-  
covery is a major driver in the advancement of geophysical science. Improvements are  
accomplished by increasing the spatial distribution of measurements and by increas-  
ing the quality and temporal resolution of the samples. This is particularly true in space  
science and in the investigation of space weather – the dynamic variation of electri-  
cal currents and energetic charged particle populations around the Earth and in the  
upper atmosphere that are produced by interactions of the supersonic solar wind with  
the geomagnetic field. The solar wind flows around and distorts the geomagnetic field,  
forming the magnetospheric cavity in the flow. The magnetic field is compressed on

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(AGO) program supported by the National Science Foundation (Lessard et al., 2009; Melville et al., 2014). The BAS LPMs are simple, yet robust systems that use only solar power and batteries to support the data acquisition system. They store data in solid state memory and must be visited each year to acquire the data. During these visits, the electronics box with memory and acquisition system are simply swapped with a new system, so the service is simple and rapid. The US AGOs are more complex systems supporting multiple instruments and utilizing both wind and solar power. They also utilize satellite communications (Iridium) to acquire data and monitor the health of the system. Nevertheless, they often require maintenance visits during the summer field season. In the appendix, we provide Web resources for various autonomous polar system designs taken from the *Autonomous Polar Observing Systems Workshop Report*.

Another example of remote autonomous system development is the evolving low-power magnetometer platforms developed originally for use on the Greenland ice cap and later for deployment in Antarctica. We report here on the most recent development and deployment of this platform that now supports multiple low-power instruments and is designed to operate unattended for at least 5 years. Designated as an Autonomous Adaptive Low-Power Instrument Platform (AAL-PIP) it is a relatively simple, yet robust, system using only solar power and storage batteries for winter operation. A two-way satellite data link provides data acquisition, system engineering data, and provides the ability to load new software to modify the operation of the system. While any cluster of low-power instruments can be supported, the present systems deployed on the East Antarctic Plateau support: (1) fluxgate magnetometer, (2) induction magnetometer, (3) Connected Autonomous Space Environment Sensor (CASES), a new software-defined dual-frequency Global Positioning System (GPS) receiver, and (4) a High Frequency (HF) radio experiment.

We have a long history of developing and deploying small autonomous instrument systems beginning in 1990 through the present. A review of this history is given by Musko et al. (2009). Here we will focus our attention on the specific design

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requirements, and changes that have led to the present AAL-PIP. The 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 laboratories at the University of Michigan and Virginia Tech. During the summer, the photo voltaic (PV) panels provide abundant power. During the dark of winter, power is provided only by a bank of lead-acid absorbed glass mat (AGM) batteries. Therefore, during the winter, data are stored in memory and only engineering information is transmitted via the Iridium satellite so that, while using less power, we can still monitor the health of the system. Since the Iridium communication link is two-way, it is possible to command the station to send winter data if there is a special event or time interval needed. When the sun comes up again and power becomes abundant, the current data plus the archived data are transmitted.

The CASES dual-frequency GPS receiver requires more power and produces more heat in the electronics box than the other instruments. Therefore, it is not run continuously, but rather scheduled to run for specific time intervals. Thus, it does not provide continuous data. The GPS signals are being examined primarily to investigate signal scintillation (variations in amplitude and phase of the signal) with the goal to understand the associated plasma irregularities that produce the scintillations. The two-way communication with the platforms using the Iridium link enables the capability to modify the operation of the system and schedule the operation of the instruments in different modes as desired. In general, the fluxgate and induction magnetometers are operated in a standard data collection mode, while the GPS and HF radio can be scheduled to operate during specific time intervals, or during specific conditions in the magnetometer data that can be monitored by the system itself, and/or in various modes of operation.

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 and wait in this hibernation state until power is detected from the PV panels. When the sun comes up, power from the PV panels is initially used to heat the batteries to a temperature that will



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4. Measure magnetic field waves in the ultra low frequency (ULF) range (0.1–5 Hz) with the resolution of tens of  $pT/\sqrt{\text{Hz}}$  over the frequency response in two orthogonal horizontal components.
5. Support a newly developed low-cost, software-defined, science-grade, dual-frequency GPS receiver for exploratory scintillation measurements.
6. Be able to store at least 1 year of science and engineering data in internal non-volatile memory.
7. Transmit stored and near-real-time data to our laboratories at the University of Michigan and/or Virginia Tech via satellite communication link.
8. Time-tag stored data with coordinated universal time (UTC)  $\pm 40$  ms.
9. Include an HF radio experiment to explore radio propagation characteristics between the deployed stations (over ranges of a few hundred to several hundreds of kilometers).

Considerable attention was also devoted to facilitating the deployment of these systems under difficult cold conditions. For example, most of the system can be assembled with gloves on. There are no nuts and bolts to be manipulated and no tools are required. Instead, pins are inserted to secure the tower sections and T-bolts are used to secure the solar panels to the tower. This is illustrated in Fig. 3 showing a close-up view of the tower assembly with solar panels. The T-bolts secure the solar panels to top and bottom frames and this assembly is winched to the top of the tower after the tower is raised and secured by guy wires.

The following sections describe the present generation of AAL-PIP design using the specifications described above.



### 3 System and thermal design

The main consideration in the thermal design of the AAL-PIP is the desire to not have to revisit the site for maintenance. This consideration outweighs the desire for a 100 % duty cycle. This requires a system that can automatically shut down when conditions are poor and restart when conditions improve. The thermal design minimizes power usage during the austral winter. This, in turn, reduces the number of batteries that must be transported to the field site (a major consideration). The overall strategy is to prepare an electronics enclosure that is heavily insulated and minimizes the volume that requires heating for the electronics such that the electronics themselves provide sufficient heat. The measurement sensors are operated at the ambient exterior temperature.

A separate battery box is insulated with 10.1 cm of polystyrene panels and heated to between  $-15$  to  $-20^{\circ}\text{C}$  during the austral summer for battery charging. The battery box is not heated during the winter to reduce power consumption. This is a chosen design consideration between degrading the capacity of the batteries at cold temperatures and using power to heat the batteries to achieve greater capacity. In this simple design, as the batteries cool while the system continues to draw several Watts, the voltage will gradually drop. When the battery voltage drops below 11.2 V, a low-voltage cutoff is activated and the system shuts down for the remainder of the winter. When, or if, this occurs depends upon the power used by the system (instruments, communications, and internal computer control) and the number of batteries. Increasing the number of batteries extends the operation of the system, but requires additional transport. Since lead-acid batteries are very heavy, this is a significant trade-off consideration because of weight limits for the small aircraft used in the deployment. As it is, for the more distant deployment sites, several flights are required and fuel caches must be deployed to support the AAL-PIP installation.

The electronics box, illustrated in Fig. 4, is insulated using a combination of 10.1 cm vacuum panels and 10.1 cm of polystyrene panels. The actual box is shown in Fig. 5.

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convinced that wind generators can be relied upon for long-term reliable operation in remote Antarctic conditions.

Figure 7 shows a block diagram of the power system. The power system is designed around a bank of 16, 100-amp-hour 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 earlier Greenland and Antarctica systems, and because they retain a significant amount of their rated capacity at low temperatures. In laboratory tests at the University of Michigan, Power-Sonic 100 amp-hour batteries at  $-55^{\circ}\text{C}$  retained 48% of their rated capacity when powering a 1.4 Watt load. This allows us to power the system using unheated batteries during the austral winter, when the batteries cannot be charged 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  $-20^{\circ}\text{C}$  to accept a charge, the batteries are heated to between  $-15$  and  $-20^{\circ}\text{C}$  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. Our earlier design Low Power Magnetometer (LPM) system, which uses the same batteries and charge/discharge strategy, is in its 9th year of Antarctic operation with no signs of battery degradation.

Figure 8 shows the top layer of two layers installed in the battery box. Battery handling under Antarctic conditions (high altitude and cold) can be hazardous due to battery weight and possibility of electrical shorts. We minimize the danger by using the following components and procedures. The batteries are shipped with Delphi automotive connectors prewired to the battery terminals. The battery terminals are also coated with a silicone caulk before shipment to prevent electrical shorts. At the field site, the batteries are moved one at a time from the battery shipping containers to the battery box. They are then connected to the power control electronics using a single wiring harness. The wiring harness is built using Arctic Ultraflex wire (Power Wire Products, Inc.) and is fitted with mating Delphi connectors. The connection is made by snapping the

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two connectors together. No tools are required for the battery installation or connection, and it can be accomplished wearing gloves. Figure 9 shows the power electronics box and fuse panel installed on top of the batteries in the battery box (left) and the power electronics printed circuit board inside the power electronics box (right).

Except for the PV panels and system power switch, the power system is contained entirely within 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 for shipping and deployment, the batteries are shipped to the field site in separate foam-lined plywood shipping crates, each containing two batteries. For shipment, the battery box contains PV panels and other lightweight and fragile items. The batteries are moved from their shipping crates to the battery box at the deployment site. In addition to the batteries, the battery box 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 printed circuit board that contains the battery heating, charging and low-voltage disconnect (LVD) circuits. A custom design was selected over an off-the-shelf solution for three reasons: low parasitic power losses, the need to control battery temperature, and the extremely low operating temperature range. Since the AAL-PIP system depends on stored battery power for up to six months per year, parasitic power losses must be minimized. Off-the-shelf battery charge controllers have significant parasitic power losses and cannot control battery temperature. They also cannot operate down to  $-70^{\circ}\text{C}$ .

The power electronics board performs the following functions:

1. Sends all the PV power to the battery heaters when the batteries are too cold to charge.
2. Sends all the PV power to the batteries when the batteries are warm enough to charge and are not fully charged.

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3. Disconnects the PV panels when the batteries are warm and the batteries are fully charged.
4. Disconnects the load (the electronics box) from the batteries when the battery voltage drops below 11.2 V. Reconnects the load when the battery voltage rises above 11.8 V.

We note also that the PV panels never power the load directly. PV power is only used to heat and charge the batteries. The AAL-PIP system does not use mechanical relays or any other moving parts. Solid state switches are used throughout. The heater control, charge control, and LVD circuits all employ hysteresis to eliminate unnecessary switching cycles when voltages and temperatures approach threshold values.

### 3.2 Computer control

The control subsystem consists of a three board PC-104 stack, an Iridium modem and antenna. It is contained, except for the Iridium antenna, in the electronics box. Figure 10 shows the PC-104 stack that comprises the core of the control system.

The PC-104 stack consists of a Technologies TS-7260 single board computer (SBC), a Technologies TS-Ser4 quad serial port board and custom I/O board. The TS-7260 SBC has many features including a Cirrus 200Mhz ARM9 32 bit CPU, 64 MB RAM, 128 MB flash memory, Ethernet, two USB ports, three serial ports, digital I/O, 12 bit A/D converter, watchdog timer and battery-backed real time clock, and an operating temperature range of  $-40$  to  $+85^{\circ}\text{C}$ . It runs the Linux operating system. A four gigabyte flash drive connected to one of the USB ports provides mass storage for instrument and housekeeping data. A Garmin GPS receiver is used to provide an accurate time standard.

The only significant TS-7260 SBC deficiency for our application is inadequate system oscillator stability. This causes the system time to drift at a rate that varies strongly with the oscillator temperature. AAL-PIP is required to time-tag data with UTC  $\pm 40$  ms, but uncorrected system time can drift several seconds per hour. System time stability

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could be improved by continuously powering the Garmin GPS receiver and synchronizing frequently, but in order to save power, we use a different method. The Garmin GPS receiver is powered up once per hour to synchronize system time to UTC. While synchronizing the system time, the system time error and drift rate are measured using the GPS Pulse per Second (PPS) signal. The system clock rate is then adjusted, using Linux kernel functions, to compensate for the error and drift rate. Using this method, the system time is consistently maintained at UTC  $\pm 5$  ms.

The custom I/O board contains:

- Solid state switches that control the Iridium modem, electronics box heater and instrument power.
- A Garmin GPS15H GPS receiver which transmits serial time messages to the TS-7260 SBC once per UTC second. It also transmits the digital PPS signal that is used to synchronize system time and measure time error and drift rate. The PPS signal is connected to one of the TS-7260 SBC interrupt inputs.
- Temperature, current and voltage sensors that are used to monitor battery voltages, battery temperatures, electronics temperature and electronics current.
- Warm up thermostat which diverts power to a 5 W heater until the PC-104 stack reaches operating temperature. The stack is then powered up and a second software-controlled heater is used as needed to maintain the electronics temperature.
- GPS antenna power and signal splitting circuitry that powers the antenna and routes its RF output to the Garmin and the CASES GPS receivers.
- Connectors and on-board interconnections that connect off-board instruments and peripherals to each other and the PC-104 stack.



### 3.4.1 Fluxgate magnetometer

The system supports a low-power, 3-axis vector fluxgate magnetometer (LEMI-022AN) produced by the Laboratory for Electromagnetic Innovations (under the direction of Dr. Valery Korepanov), Lviv Centre of the Institute of Space Research, National Space Agency of the Ukraine. It was specifically prepared to acquire stable 3-component measurements of the Earth's magnetic field in the Antarctic region. The magnetometer consists of an electronic unit that is located in the super-insulated electronics box and a sensor with a connecting cable that is approximately 15 m in length. The main technical specifications of the instrument are given in Table 1.

### 3.4.2 Induction magnetometer

Induction magnetometers are widely used for space science research to measure magnetic field waves in space and on the ground. The magnetic field frequencies of interest in space physics typically falls into the ULF range (a few mHz to a few Hz). Induction magnetic sensors are copper wires wound around a highly permeable ( $\mu$ ) metal core. A voltage is induced across the coil when magnetic field through the sensor changes over time ( $dB/dt$ ). Since induction magnetometers are sensitive to the magnetic field direction, it provides vector magnetic field information.

Each induction magnetometer deployed with the AAL-PIP system consists of two orthogonally mounted magnetic sensors with preamps, a cable of  $\sim 200$  m, and a main analog circuit. The 2-axis magnetic sensor configuration provides measurements of wave activity in the geomagnetic north-south and east-west directions. The sensor is located approximately 200 m away from the AAL-PIP system to minimize interference from the electronics. Signals detected by the magnetic sensors are filtered and amplified by the main analog circuit, and archived in the AAL-PIP data acquisition system with 12 bit digitization at the rate of 10 samples/sec/axis. The main analog electronics include amplifiers and band-pass filters so the magnetic field variation in the ULF range of interest can be detected. The magnetometer measures magnetic field wave activity

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### 3.4.4 HF radio experiment

At distances beyond a few kilometers HF radio propagation is an ionospheric phenomenon (Hunsucker and Bates, 1969; Blagoveshchensky et al., 2008). In the lower HF band a critical frequency can exist where a wave launched vertically is reflected. Frequencies near that critical frequency are useful for communication at distances to several hundred kilometers. Under normal propagation conditions signal levels are typically strong and consistent. Propagation is enhanced by strong F region ionization. Strong ionization in the D region, however, attenuates the signal so that the optimum signal frequency varies toward higher frequencies during daylight hours but is reduced during night. This effect is further enhanced during geomagnetic storms when particle precipitation and X-ray flux levels increase (Warrington et al., 2012). An interesting aspect of this propagation mode is that it is enhanced when the antenna is designed to direct the maximum energy at high (nearly vertical) angles rather than toward the horizon. This mode is sometimes referred to as Near Vertical Incidence Sky wave (NVIS) propagation. High latitude statistics on HF propagation over distances of hundreds of kilometers, particularly in the polar Antarctic region, are not well developed so we include a HF radio experiment to collect information about propagation statistics between our array of stations (Collin, 1985).

The HF radio system (shown in Fig. 12) consists of three major modules: antenna, radio transceiver and modem. The antenna is a  $1/2$  wavelength horizontal dipole antenna designed to operate at 5 MHz frequency. The antenna is constructed of wire supported approximately 1.5 m above the ice. Since the ice is relatively transparent to electromagnetic radiation at this frequency, the antenna height is not critical. Additionally, as the propagation is by way of sky wave (reflected from the ionosphere), the horizontal dipole best facilitates the high angle radiation direction required for relatively short distance HF propagation. The transceiver is a fixed frequency SSB radio which converts the radio frequency to and from the audio tones of the modem. The radio transmissions are very low power at approximately 3 W. The modem is a DSP based

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device capable of numerous modes of operation. The modem interfaces with the AAL-PIP system control computer which controls radio operation and handles data through a serial data link.

The normal modulation mode is frequency shift keying (FSK) at 100 Baud. The protocol is SITOR-B which is a maritime HF communication standard using forward error correction (FEC). The relatively low data rate is designed to provide maximum effectiveness in the presence of HF noise and fading. Narrow bandwidth filters (approximately 300 Hz) in the modem and transceiver provide a high signal to noise ratio which, along with the FEC, offsets much of the disadvantage of the low power transmitter.

During operation of the HF antenna, the AAL-PIP computer applies a lookup table according to the system temperature to maintain the transceiver frequency within 50 Hz of the correct channel frequency. The frequency correction process is implemented by shifting the frequency of the modem audio tones since this may be done in small increments. The transceiver and modem have been tested for operation over a temperature range of  $-40$  to  $50^{\circ}\text{C}$  with a cold soak below  $-50^{\circ}\text{C}$ .

While SITOR-B provides excellent communications in the radio system, FEC serves to mask some errors in the communication link. The modem provides several additional communication modes, some of which do not provide any error correction. The use of non-error corrected modes can allow experiments which better indicate the channel characteristics. Selection of mode, protocol and data rate and transmitted power level are under software control so many experiments are possible.

The locations of the AAL-PIP systems in Antarctica as of January 2014, is shown in Fig. 13. In current experiments, the HF radio system is briefly turned on at two hour intervals for test transmissions. Each station transmits in turn with the other stations receiving. The transmission consists of several repetitions of a telegraphic test symbol (vuv) and the station identifier in plain text. Since the exact transmitted pattern is known a character error rate can be found for each transmission. Initial results for tests between a site on the Antarctic plateau and the South Pole station (a distance of approximately 600 km) indicate very high communication reliability except during periods

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of high D region absorption due to proton events. During significant proton events the signal reliability drops rapidly to zero as the 5 MHz signals are highly attenuated while passing through the D region. This suggests that the absence of signals is a good indicator of a significant event.

5 An example of D-region attenuation during geomagnetic storm periods in the 2011–2012 austral summer is shown in Fig. 14. Two major storms were evident during this season. The first occurred towards the end of January 2012 and the second occurred the first part of March 2012. In both storm cases, the HF communication links between the installed systems was severely affected, with periods of total communication  
10 “blackout” witnessed during the height of the storms. There are also periods of communication disruption evident during minor storm events occurring in the same season. With the completion of the 2013–2014 summer season, many of the systems have been aligned along the geomagnetic field line, creating a much improved geometry for the study of HF communication impacts during geomagnetic storm time conditions in  
15 Antarctica.

## 4 Data handling

Because the AAL-PIP systems are extremely remote, maintaining Iridium communications is the highest software priority. Loss of communications means an expensive and time-consuming field trip. The communications software processes are well-tested, mature and independent of the other processes. Any of three different watchdog timers  
20 can force a hard reset if the Linux kernel crashes or communications are lost for a predetermined length of time. This scheme has proven reliable. We have never lost communication with an AAL-PIP system due to a software bug.

25 In previous systems, we used Iridium modem-to-modem connections for communications. We now use an Iridium protocol known as RUDICS which is a combination of a single Iridium modem and the Internet to provide communication between a remote

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then erased from the AAL-PIP flash drive. The download program can also be configured to download data for any subset of instruments and range of dates.

Iridium communications are subject to intermittent data corruption and dropped connections so an error detection and retransmission protocol is required for automated file downloading. We are using a custom protocol to maximize performance over the relatively slow, unreliable Iridium link. Large blocks of data are transmitted to minimize protocol overhead and communications line turnarounds. Using this custom protocol, file download throughput approaches the link speed of 2000 bits s<sup>-1</sup>.

Following the acquisition of the raw telemetry data by the operations center computer at (UM), the data files are transferred to the Virginia Tech web server that is hosted on a desktop computer. Here the files are converted into formats that are more readily accessible for scientific analysis, plotted, archived, and made available on the web and for file transfers. These tasks are accomplished by a combination of Unix Bash shell scripts, Python programs, and IDL programs.

A shell script that starts the processing is executed automatically at fixed intervals, twice per day. A Python program connects to the SFTP server at UM, checks the data directory contents, and downloads any new data files that are not already on the local file system. Sometimes there are no new files, such as when the data transfers are suspended during the Antarctic winters and no solar power is available. If new files are found then, following their download by SFTP, the list is handed off for further processing by IDL programs.

The first step in the processing is conversion of the files into a “flat file” format, that in principle can be accessed on any computing platform in any language. As the raw AAL-PIP data do not contain fixed time intervals, there are multiple files from each instrument for each day (approximately 24 per day), and these files need to be sorted and concatenated in the proper sequence to obtain a new, one-day file.

Traditionally, flat files up through Version 3 have used two separate files to hold an ASCII text “header” and binary data. A newer, Version 4 format is now used in which the text header and binary data are combined into one file. The header contains

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a description of the data contents, in a standardized format that is both human readable and can be used by programs for further processing. The binary data begin at a fixed offset from the start of the file; this offset value is included in the text header, but is normally 4096 bytes, which allows adequate space for most headers. The byte-order of the data may be either big- or little-endian, and is specified in the header. Programs that read flat files should be able to handle both formats. The flat files are stored in a database having subdirectories for each year and month, but with all magnetometer sites combined together.

Following the conversion to flat files, the new data are graphed, with the results saved in both PDF and PNG formats. The data are also converted to the Common Data Format (CDF). A web page (<http://mist.nianet.org>) shows the most recent plots, and also has links to the archived plots and access to the CDF data files via HTTP. FTP access to the flat files is also available to the research group and collaborators. Due to the risk to hacker attacks that could result from “anonymous” FTP access, our FTP server requires a user name and password. These are made available to collaborators. Copies of the CDF data files are also available in the THEMIS database (Angelopoulos, 2008; Mende et al., 2008). The THEMIS project obtains these files automatically through FTP.

Backups of the data files and processing programs are maintained on a redundant, RAID system (the present capacity is 2 TB). All programs are also backed up on another system, normally through the use of DropBox. As the computer system that does the final processing and archiving of the data is accessible over the internet for HTTP and FTP transfers, there is some exposure risk to malicious attacks (the firewall log shows multiple attempts daily). For this reason the RAID backup file system is not continuously connected to the host computer, ensuring that it would not be affected by a successful attack; backups to the RAID file system are done manually.

Figures 15 and 16 shows example events from the data obtained by the AAL-PIP systems located in the East Antarctic (PG1, PG2, and PG3). See the map in Fig. 13 for the locations of the remote field stations. Geomagnetic disturbances are clearly seen in





in the GPS signals (Fig. 16d and g). It should be noted that the GPS receivers were turned on from 22:00 to 03:00 UT. Similar results have been reported by Kim et al. (2014) showing a possible connection of ionospheric irregularities to a substorm event using simultaneous observations of ULF waves and GPS scintillations.

## 5 Conclusions

We have learned a number of lessons over the years through our engagement in remote polar measurements. With regard to the AAL-PIP system described here, the glove-friendly, tool-free deployment design has proved to be very well thought out and highly valued by the members of the deployment teams. This is one of the most innovative and valuable features of this new design.

The support of multiple instruments has increased the demand for power with the consequence that the system spends a longer time in winter hibernation mode than with previous designs. New strategies for instrument operation, or supplying additional batteries could help to reduce the hibernation period. The system has been designed such that the battery box is a modular unit and it is simple to add more battery boxes to the system. The limitation, however, is the ability for logistical support to accommodate the weight and transport of the batteries to the remote sites.

The system, as it is deployed now, provides no outputs for the deployment team to monitor, other than to see that the power is on. The orientation of the magnetic sensor is done by using an Iridium phone to talk with a person in the laboratory at Virginia Tech who is monitoring the data transmitted by the station. The magnetic sensor is rotated to place the  $x$  axis along the magnetic field by nulling the  $y$  axis ( $x$  and  $y$  lie in the horizontal plane and  $z$  is positive vertical in the down direction). This has been satisfactory for the deployment of the magnetometer and gives a good end-to-end test of the system. However, if odd readings are obtained from any of the instruments or other components of the system do not operate as expected, it is difficult for the deployment team to undertake any simple diagnostic steps – checking cables, connectors, voltages, etc.

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It would be useful to have some type of diagnostic system output available to the deployment team for such purposes.

Our concern for operating in the cold environment using the super-insulated electronics box provided a surprise when the temperature of the electronics got above 40 °C during summer time with extended operation of the CASES GPS receiver. The result has been that we have needed to limit the operation of the receiver because of temperature considerations within the electronics box. We are able to heat the volume containing the electronics, but we have no way of actively cooling the volume. More thought must be given to this problem.

*Acknowledgements.* Support for the development and testing of this system has been provided through a Major Research Infrastructure (MRI) Grant ATM-922979 to Virginia Tech from the National Science Foundation. Additional support has been provided by the National Science Foundation for the operation and scientific investigation of data from the deployed AAL-PIP stations along the Antarctic 40° magnetic meridian by Grants ANT-08398585 and PLR-1243398. Support at the University of Michigan was provided by NSF grant ANT-0838861. GC was supported by NSF grant PLR-1243225 to ASTRA.

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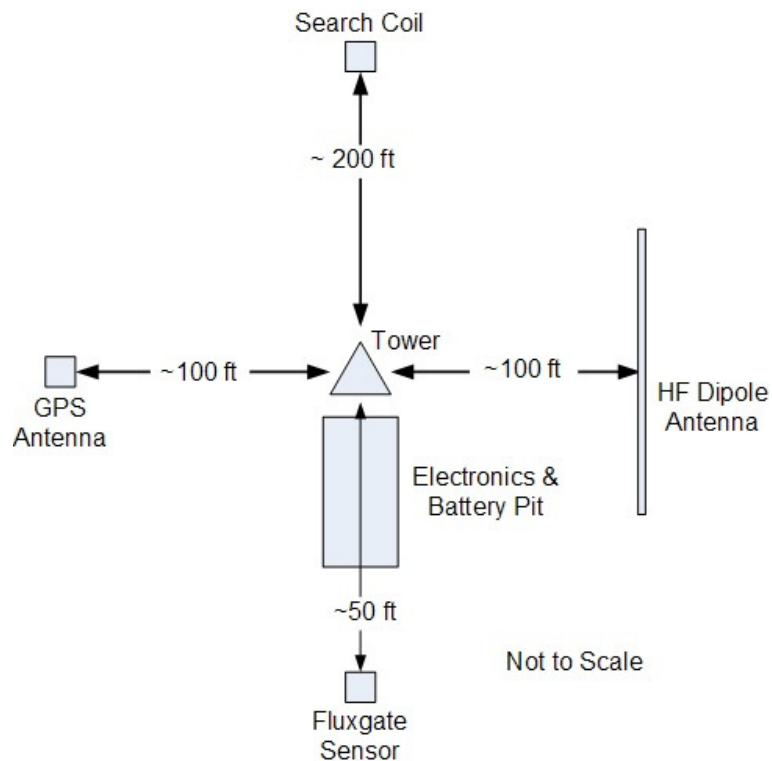
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**Figure 1.** Schematic diagram of the site plan for the deployment of an AAL-PIP system supporting fluxgate magnetometer, search coil (or induction) magnetometer, CASES dual-frequency GPS receiver and HF transceiver experiment.

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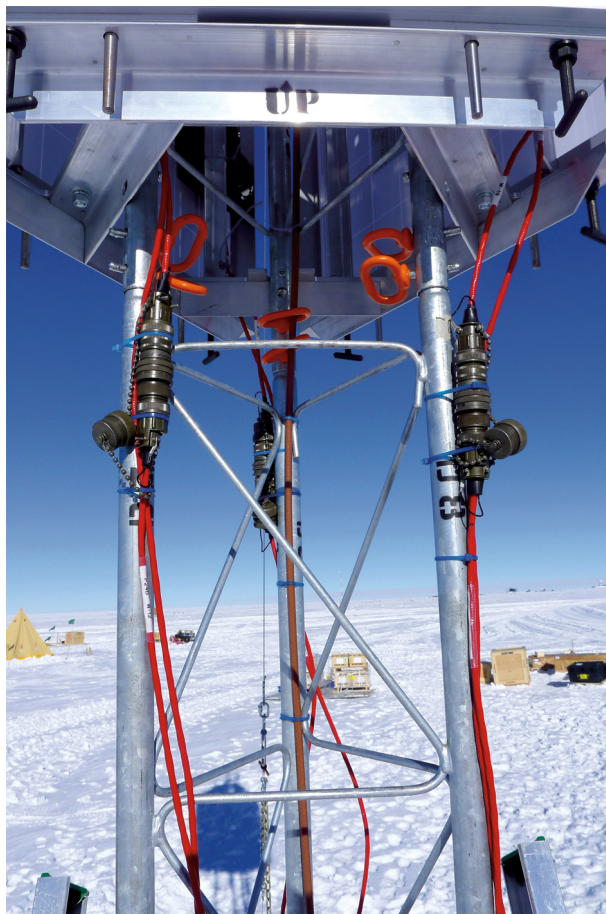
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**Figure 3.** Tower close-up view showing orange pins used to secure tower sections and T-bolts at top securing the bottom of the PV panels.

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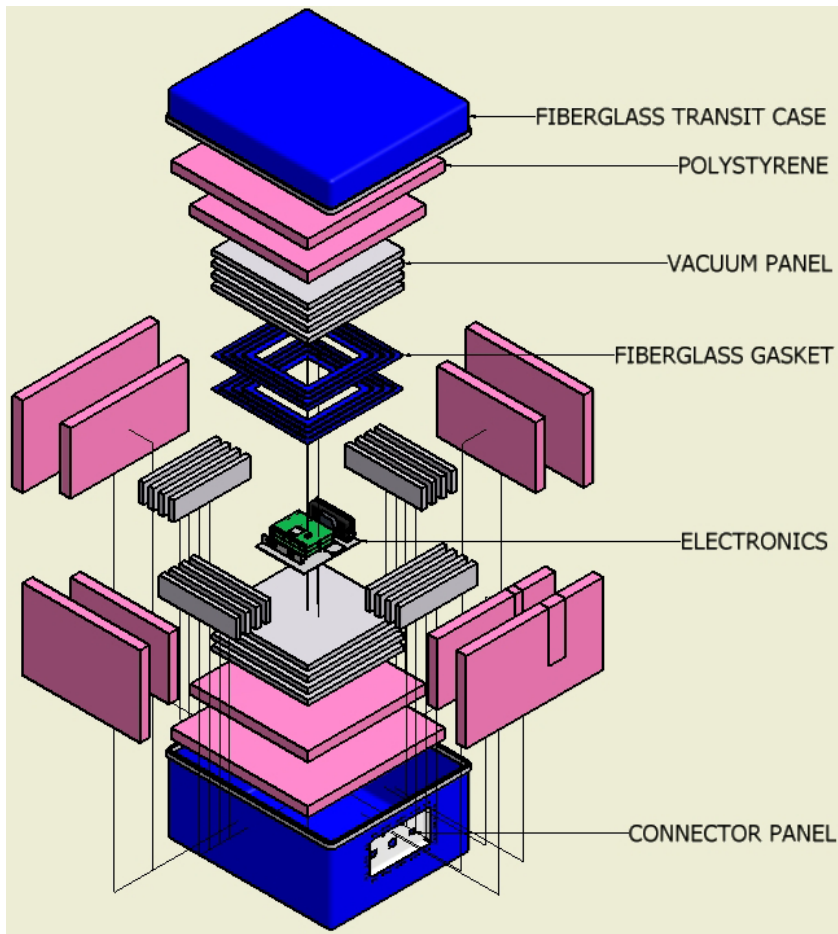
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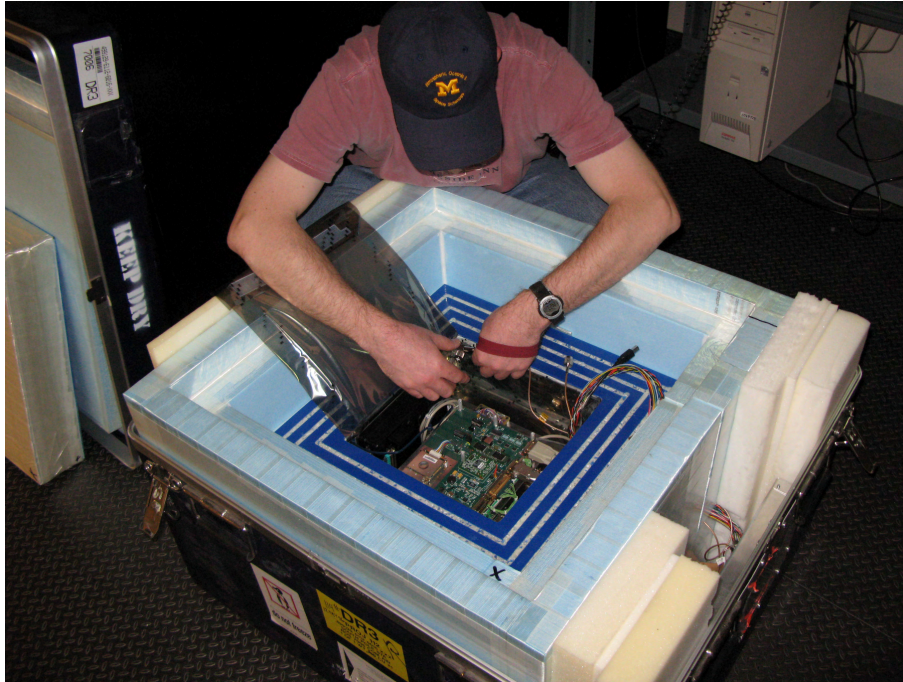
**Figure 4.** The super-insulated electronics box exploded view.

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**Figure 5.** The super-insulated electronics box.

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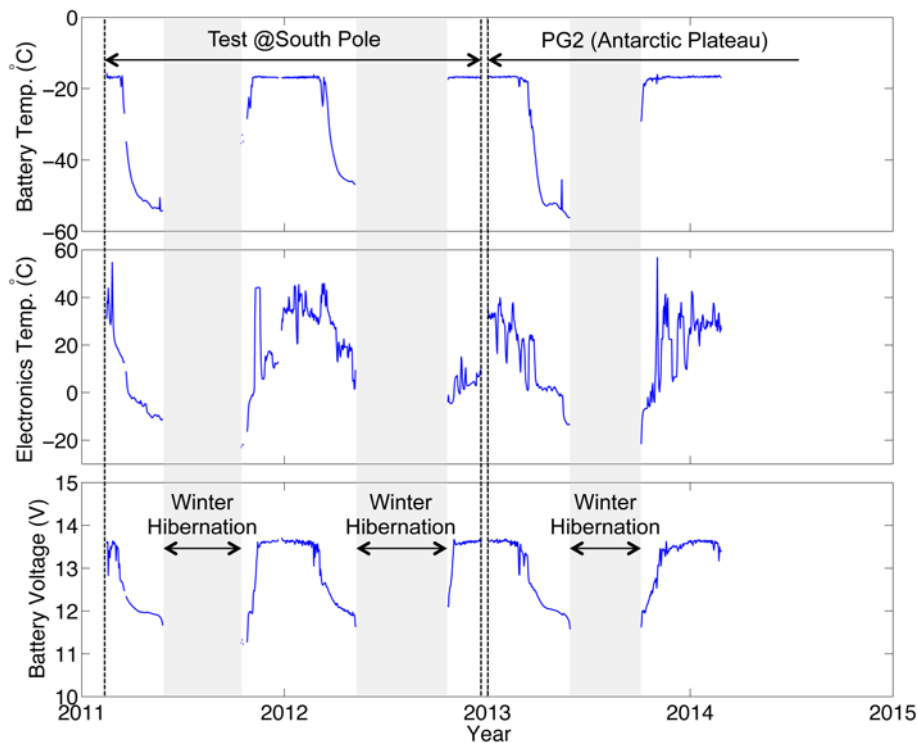
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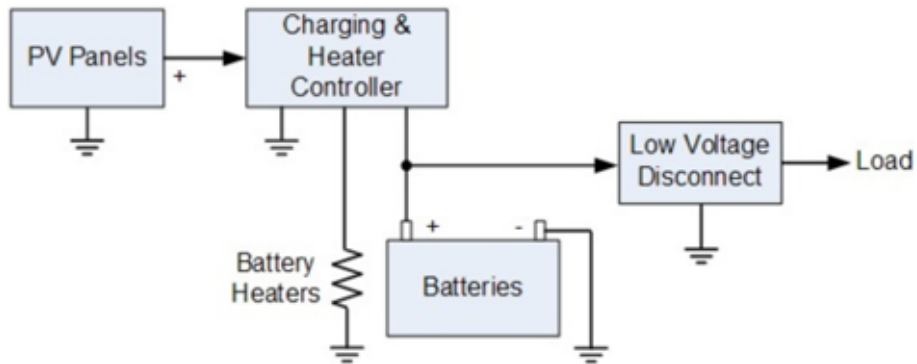
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**Figure 6.** Measured temperature in the battery box (top), temperature in the electronics box (middle) and battery voltage (bottom) from 2011 to end of February 2014. The AAL-PIP system was designated SYS4 during testing at South Pole station and renamed PG2 after deployment on the East Antarctic Plateau.



**Figure 7.** Power system block diagram.

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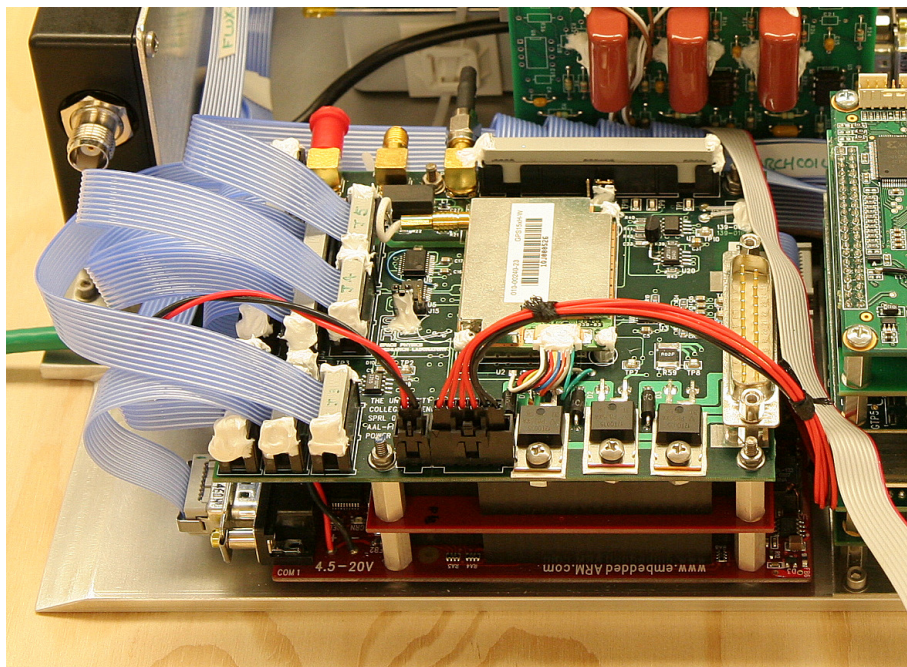
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**Figure 10.** The PC-104 stack mounted on the electronics chassis. The custom I/O board is on the top.

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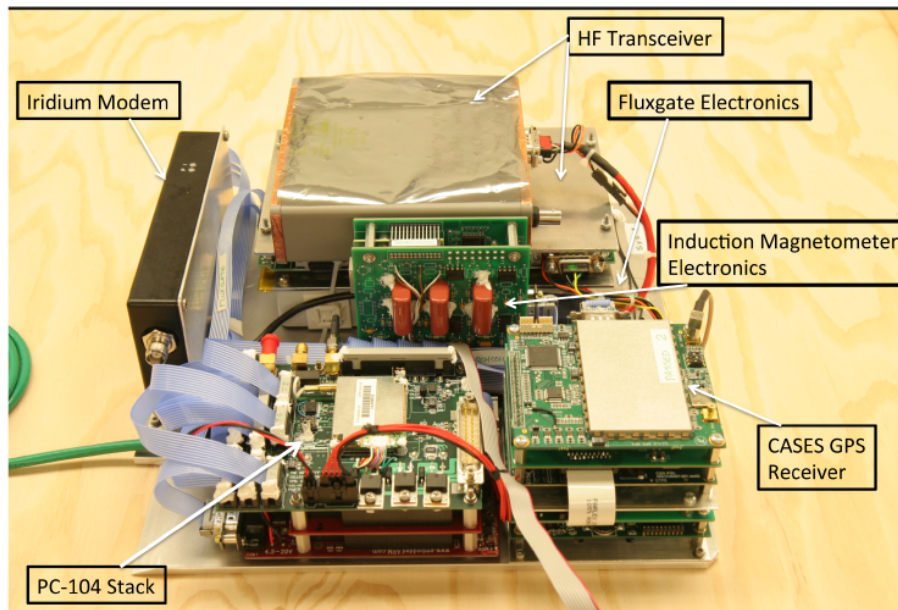
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**Figure 11.** Electronics chassis.

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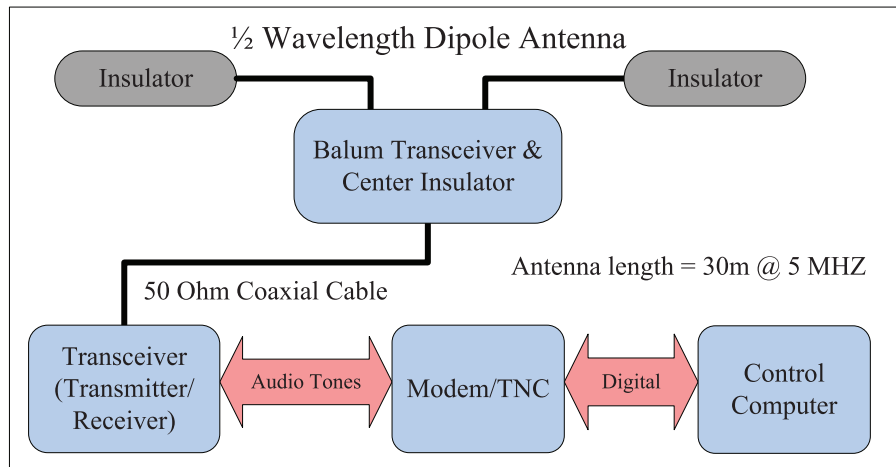
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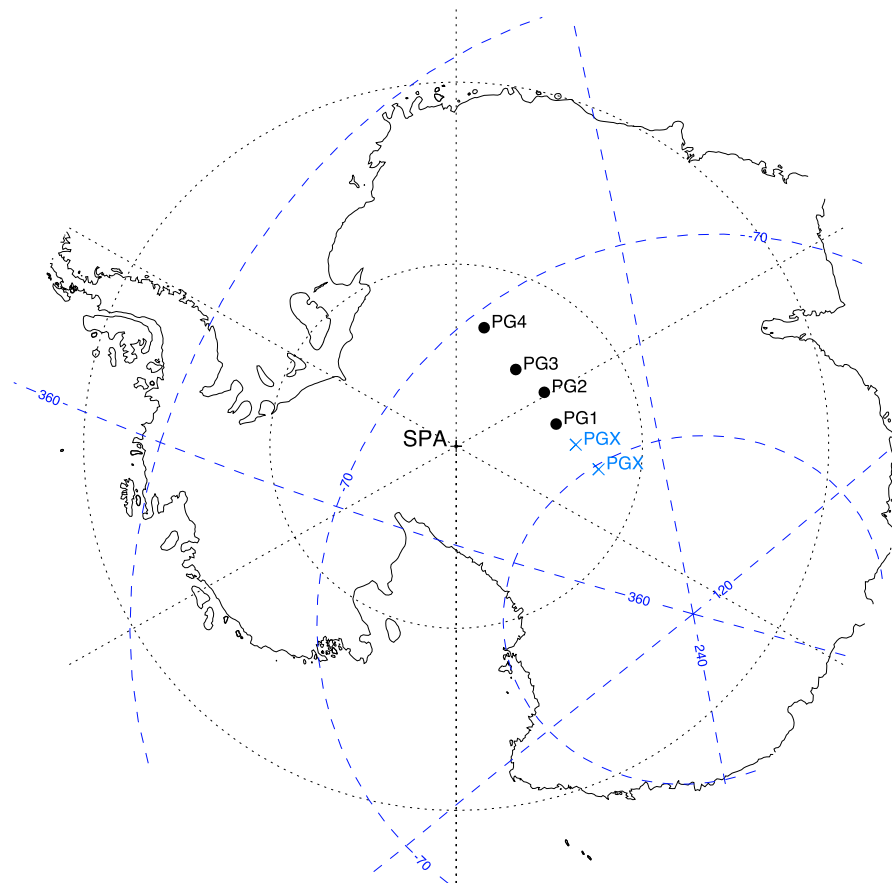
**Figure 12.** HF Radio System.

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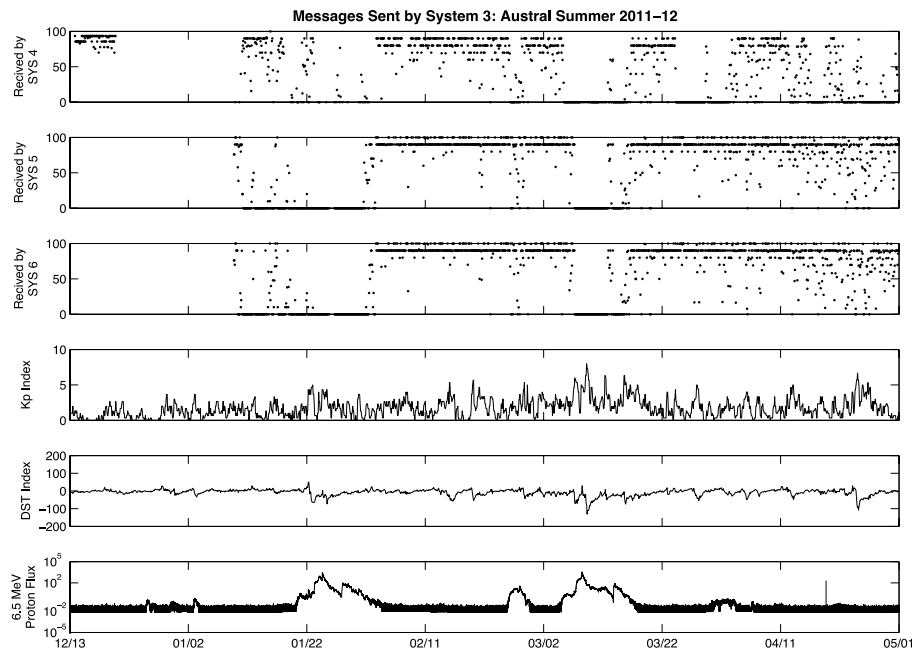
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**Figure 13.** Map showing the locations of the AAL-PIP systems deployed in Antarctica since January 2014.

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**Figure 14.** HF communication quality during the 2011–2012 summertime period. The top three panels indicate the percentage of characters received correctly as transmitted from System 3 to Systems 4–6 (see Fig. 13 for a map of the location of the varying systems during this time frame) vs. time. A level of 100 indicates that all receptions were error free. A level of 0 indicates that all of the receptions included a complete distortion of the transmitted file character set. The bottom three panels plot the  $K_p$  index,  $D_{ST}$ , and proton flux ( $\# \text{s}^{-1} \text{cm}^{-2} \text{sr}^{-1}$ ) over the same time period. All systems assumed nominal operations from 10 January 2012 until the end of the season (May 2012).

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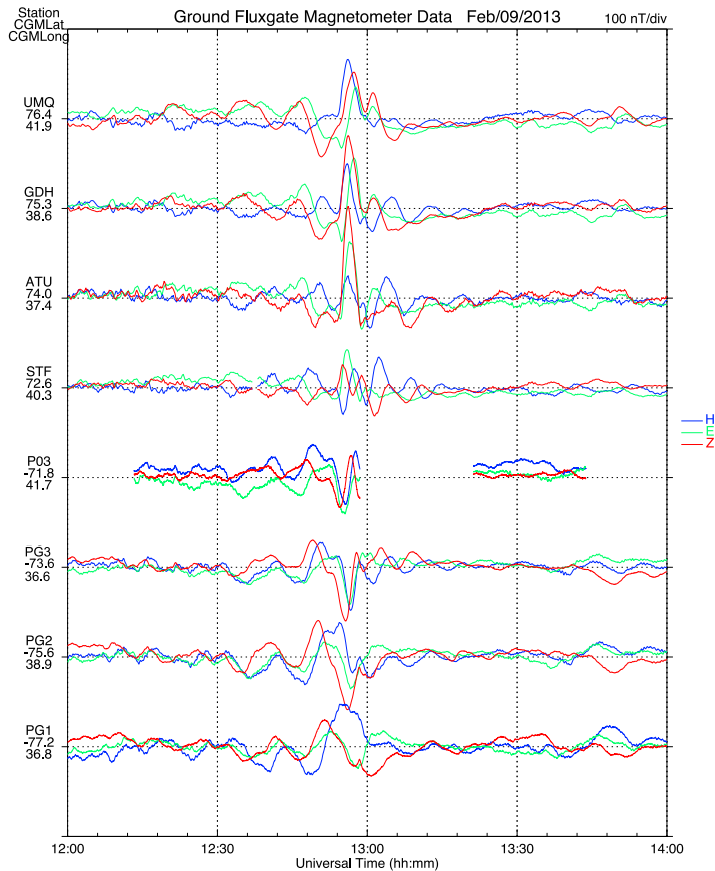
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**Figure 15.** Geomagnetic impulse events observed by the fluxgate magnetometers at four station pairs in magnetically conjugate hemispheres (UMQ-PG1, GDH-PG2, ATU-PG3, and STF-P03) starting approximately at 12:45 UT on 9 February 2013.

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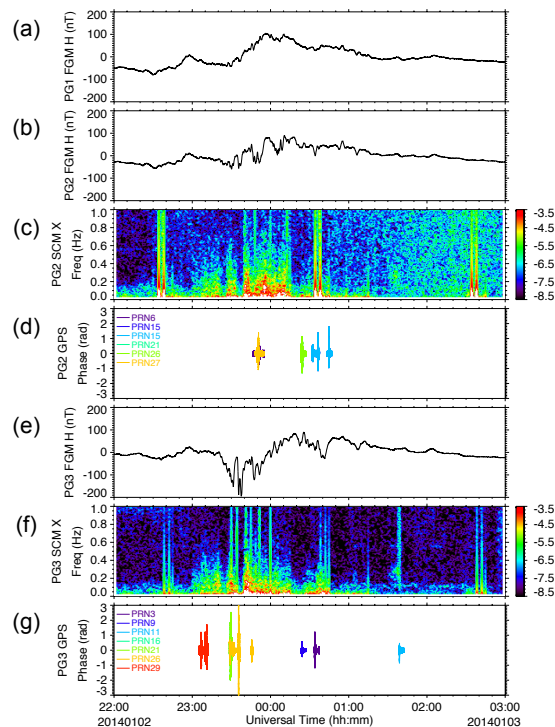
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**Figure 16.** Measurements at the three remote field stations (PG1, PG2 and PG3) from 22:00 UT on 2 January 2014 to 03:00 UT on 3 January 2014 showing magnetic field disturbances and associated with GPS signal scintillations observed by **(a)** PG1 fluxgate magnetometer, **(b–d)** PG2 fluxgate and induction magnetometers, and GPS scintillation monitor, and **(e–g)** PG3 fluxgate and induction magnetometers, and GPS scintillations monitor. Note that the magnetic field data are measured from the  $H$  (fluxgate magnetometer) and  $X$  (induction magnetometer) components, both of which are aligned along the horizontal local magnetic field line.