· Review · Advances in Polar Science
doi: 10.13679/j.advps.2019.0028 December 2019 Vol. 30 No. 4: 362-374

Newly established autonomous adaptive low-power instrument platform (AAL-PIP) chain on East Antarctic Plateau and operation

Zhonghua XU[1*], Michael D. HARTINGER[1,2], Robert CLAUER[1], Daniel WEIMER[1], Kshitija DESHPANDE[3], Hyomin KIM[4], Stephen MUSKO[5], Anna WILLER[6], Thomas EDWARDS[1], Shane COYLE[1], Yuxiang PENG [1], Dong LIN [1] & John BOWMAN[1]

[1] Bradley Department of Electrical and Computer Engineering, Virginia Tech, Blacksburg, VA 24061, USA;
[2] Center for Space Plasma Physics, Space Science Institute, Boulder, CO 80301, USA;
[3] Department of Physical Sciences, Embry-Riddle Aeronautical University, Daytona Beach, FL 32114, USA;
[4] Center for Solar-Terrestrial Research, New Jersey Institute of Technology, Newark, NJ 07102, USA;
[5] Space Physics Research Laboratory, College of Engineering, University of Michigan, Ann Arbor, MI48109, USA;
[6] DTU Space, National Space Institute, Technical University of Denmark, Kongens Lyngby, Denmark

Received 1 August 2019; accepted 5 October 2019; published online 9 December 2019

Abstract An autonomous adaptive low-power instrument platform (AAL-PIP) chain of six stations has been newly established on East Antarctic Plateau along the 40° geomagnetic meridian, to investigate interhemispheric geomagnetically conjugate current systems, waves, and other space weather phenomena in Polar Regions. These six stations, PG0 to PG5, which host low-power magnetometers (Fluxgate and Searchcoil), dual frequency GPS receivers, HF radio experiment, and run autonomously with solar power and two-way satellite communication, are designated at the geomagnetically conjugate (based on the International Geomagnetic Reference Field) locations of the West Greenland geomagnetic chain covering magnetic latitudes from 70° to 80°. We present the development, deployment, and operation of this chain, as well as the data collected by the chain and some preliminary scientific results showing evidence of interhemispheric asymmetries, which are important to better understand Solar Wind–Magnetosphere–Ionosphere (SWMI) coupling in Polar Regions. Recent investigations focus on magnetic impulse (MI) events, traveling convection vortices (TCVs), and ultra-low frequency (ULF) waves in the coupled southern and northern hemispheres.

Keywords **magnetometers, magnetic perturbation, magnetic conjugate**

Citation: Xu Z H, Hartinger M D, Clauer R, et al. Newly established autonomous adaptive low-power instrument platform (AAL-PIP) chain on East Antarctic Plateau and operation. Adv Polar Sci, 2019, 30(4): 362-374, doi: 10.13679/j.advps.2019.0028

1 Introduction

The Earth's magnetic field, also known as the geomagnetic field, is the magnetic field that extends from the Earth's interior out into space, where it meets the solar wind, a stream of charged particles emanating from the Sun. The Earth's magnetic field serves to deflect most of the solar wind, which is crucial for protecting human, animal and plant life from direct radiation caused by charged particles originating from the Sun and interstellar space.

In general, the Earth's magnetic field looks like a

* Corresponding author, ORCID: 0000-0002-3800-2162, E-mail: zxu77@vt. edu

magnetic field produced by a bar magnet at the center of the Earth, with the North Magnetic Pole located in the Southern Hemisphere and vice versa. This dipole-like configuration leads to special conditions for the geomagnetic field in high latitudes in both Polar Regions. Magnetic field lines loop out of the South Geomagnetic Pole and into the North Geomagnetic Pole. One can define two points in either hemisphere as "conjugate" if they are on the same magnetic field line—in the remainder of this paper, we use the IGRF model to define conjugacy, though other definitions are possible. The Earth's magnetic field dominates near the surface of the Earth, but further out the magnetic field is distorted by the solar wind. Also, the magnetic field lines are divided into two parts according to their location on the sunward or tailward side of the planet. Between these two parts, at the dayside boundary of the polar cap on both hemispheres, are funnel-shaped areas with near zero magnetic field magnitude called the polar cusps. They provide an entry where solar wind particles have a direct access to the Earth's ionosphere (e.g., Reiff et al., 1977; Yamauchi et al., 1996). In addition to the solar wind particles, many types of waves and turbulent flows are able to propagate from magnetosphere to ionosphere via the cusp, such as waves from the ion foreshock, sudden impulse events, magnetosheath turbulence and waves, waves due to Kelvin-Helmholtz instability, flux-transfer events, etc.

The polar region are unique in the Earth's magnetic field configuration, and it is important to monitor the space weather phenomena in these regions. One of the most attractive space weather phenomena is the aurora, which is created by the charged particles flowing down along magnetic field lines into the polar region and hitting the atmosphere during geomagnetic disturbed periods. The charged particles that create the aurora also affect the dynamics of the ionosphere like increasing the electric density which could disrupt radio communications, and increase the ionospheric currents that in turn induces strong magnetic fields. The geomagnetically induced currents generated by the sharp change of geomagnetic field could lead to the damage on power grids (Kappenman, 2005). Hence, ground-based magnetometers in the polar region are crucial for monitoring the direct input from the solar wind, as well as for better understanding solar wind–magnetosphere–ionosphere coupling mechanisms.

While the polar region in the Northern Hemisphere is relatively well instrumented, the southern polar region is not. There are a few space weather laboratories at Antarctic stations, including Zhongshan, Syowa, Davis and other stations on the coast, the Amundsen-Scott South Pole Station, Vostok Station, and Dome C Station in the inner land. These stations are operated by wintering personnel all the year round. But there is still sparse spatial coverage, primarily because of the extreme Antarctic climate and lack of manned facilities with the infrastructure to support instrumentation. However, during the past decade, technical developments have enabled the initiation of robust measurement programs using autonomous instrument platforms that can be deployed remotely and operate unattended for extended periods of time. Examples of such systems include the low-power magnetometer (LPM) platforms operated by the British Antarctic Survey (BAS) and the Automated Geophysical Observatory (AGO) program (Lessard et al., 2009; Melville et al., 2014).

One of the recently developed autonomous low-power space weather monitoring platforms is the autonomous adaptive low-power instrument platform (AAL-PIP) chain along the 40-degree magnetic meridian on the East Antarctic Plateau (EAP) (Clauer et al., 2014). The AAL-PIP chain was established to investigate solar wind–magnetosphere–ionosphere coupling, interhemispheric asymmetries, and other space weather related phenomena from 2008 to present. It contains six AAL-PIP stations, which were designed and constructed by the University of Michigan Space Physics Research Laboratory. The stations are magnetically conjugate to geomagnetic stations along the west coast of Greenland—which are operated by the Danish National Space Institute at the Technical University of Denmark (DTU Space)—as determined by the International Geomagnetic Reference Field (IGRF) model. Its six sites cover the geomagnetic latitudes from 69.5° to 78.6°, which are under the polar cap, polar cusp, and auroral oval regions. The West Coast Greenland chain covers the same regions in the northern hemisphere. The examination of simultaneous data from both the northern and southern polar regions is very important because of the considerable asymmetries between the two hemispheres. For example, a study of conjugate geomagnetic field observations by Hartinger et al. (2017) demonstrates that solar illumination differences between the summer and winter hemispheres can produce large asymmetries in the conductance in the two polar ionospheres, and these asymmetries in turn cause asymmetries in Transient High Latitude Current Systems (THLCS).

In following sections, we will introduce the locations, instrumentation, field deployment, operations, and some of the scientific results of AAL-PIP chain. The lessons learned from our experience in the development, deployment, and operation of remote polar instrumentation are also discussed.

2 Locations

The newly developed AAL-PIP chain is located along the 40° magnetic longitude, conjugate to the West Coast Chain in Greenland, and makes it feasible to monitor the geospace environment above both polar hemispheres simultaneously. It covers almost ten degrees of magnetic latitude from 70°–80°, as shown in Figure 1. Considering that the polar region in the northern hemisphere is mostly covered by the Arctic Ocean, the locations of AAL-PIP chains and West

Greenland Chain are one of the few places on the Earth where there is land available at geomagnetic conjugate locations in both hemispheres at such high latitudes. These are the only conjugate chains available for studying mesoscale (5 km to several hundred kilometers) geospace impacts from the polar cap, polar cusp, and auroral oval regions in the high latitudes. These regions directly interact with the solar wind and Interplanetary Magnetic Field (IMF). Mass and energy can be transported into the magnetosphere and energetic particles may precipitate into the ionosphere in these areas. The unique locations of AAL-PIP ground-based magnetometer chain provide opportunities to remotely monitor phenomena occurring in these regions. The AAL-PIP station locations also provide the potential opportunity to be combined with the future Zhongshan—Dome A magnetometer chain to form a two-dimensional array in the polar cusp regions.

PG0 is located at 78.57° magnetic latitude, which is the highest magnetic latitude station in the chain. PG5 is located at 69.49° magnetic latitude, which is the lowest magnetic latitude station in the chain. PG1, 2, 3, and 4 are located between PG0 and PG5 sites. The specific locations are shown in Table 1. Each station is distributed at intervals of 150–200 km. The interaction of the solar wind and IMF with the geomagnetic field can produce magnetic variations that produce changes in the magnetic field topology and asymmetries in the locations of current systems remotely sensed on the ground. The spatial coverage is very important for investigating not only the different geospace phenomena in high latitudes, but also the inter-hemispheric symmetric and asymmetric properties. PG0 is conjugate with UPN, PG1 with UMQ, PG2 with GDH, PG3 with ATU, PG4 with SKT, and PG5 with GHB (The Automated Geophysical Observatory P03 is conjugate with STF at geomagnetic latitude 72°).

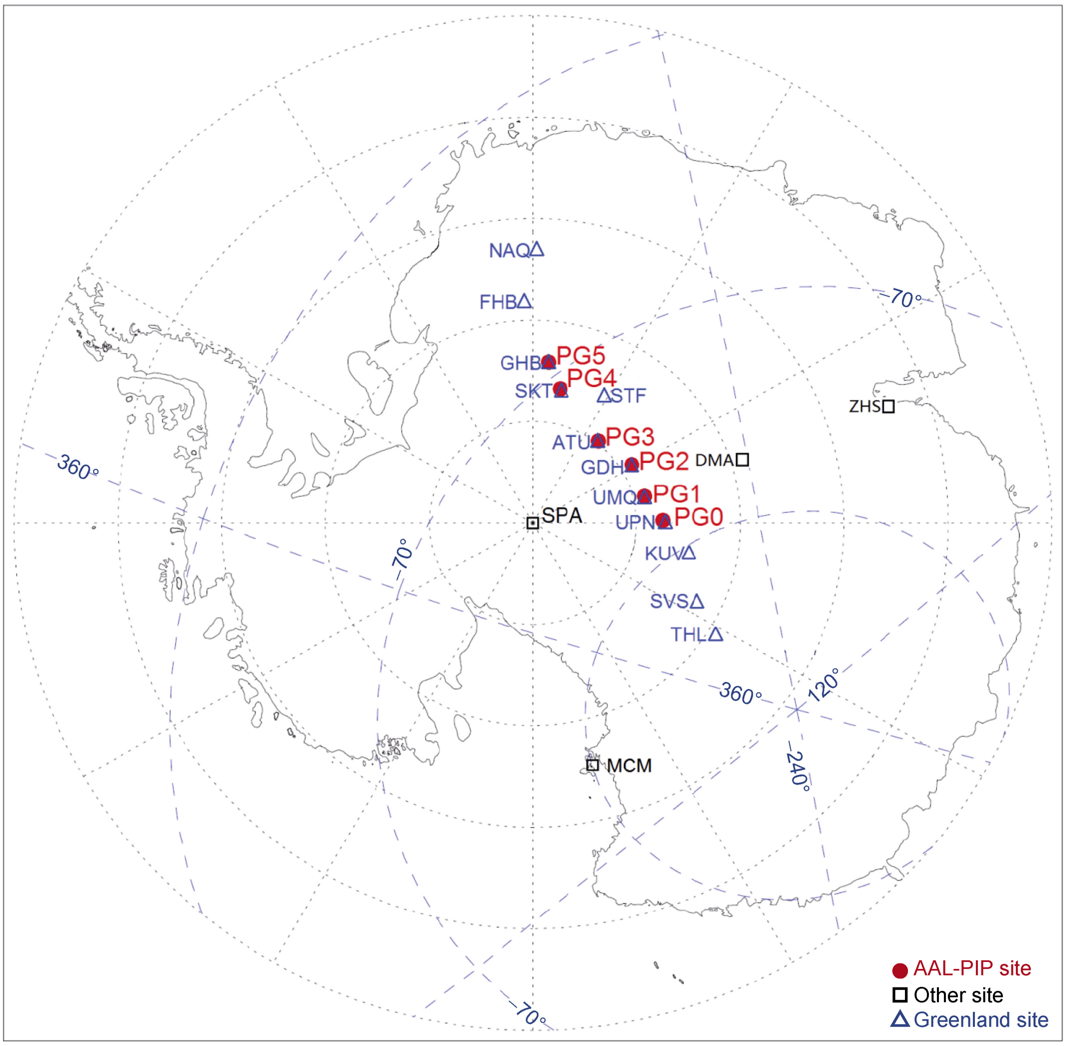

Figure 1 Locations of the AAL-PIP stations are marked with red dots here. The conjugate West Greenland stations (operated by DTU Space) are marked with blue triangles.

Table 1 The coordinates of the AAL-PIP stations and conjugate West Greenland stations

	Station code	Geodetic LON	Geodetic LAT	MagLON (IGRF2015)	MagLAT (IGRF2015)	MLT noon /(UT)	Station location
High latitude conjugate stations	**PG0**	88.68	−83.67	**38.01**	**−78.64**	14.7	Antarctic
	PG1	77.2	−84.5	**37.15**	**−77.24**	14.7	Antarctic
	PG2	57.96	−84.42	**38.95**	**−75.53**	14.6	Antarctic
	PG3	37.63	−84.81	**36.56**	**−73.79**	14.8	Antarctic
	PG4	12.25	−83.34	**36.27**	**−71.05**	14.8	Antarctic
	PG5	5.71	−81.96	**37.16**	**−69.65**	14.7	Antarctic
	THL	290.77	77.47	26.79	84.05	15.4	West Greenland
	TAB	291.18	76.54	25.25	83.19	15.5	West Greenland
	SVS	294.9	76.02	30.73	82.31	15.2	West Greenland
	KUV	302.82	74.57	39.83	79.98	14.6	West Greenland
	UPN	303.85	72.78	**38.49**	**78.18**	14.7	West Greenland
	UMQ	307.87	70.68	**41.07**	**75.59**	14.5	West Greenland
	GDH	306.47	69.25	**38.1**	**74.42**	14.7	West Greenland
	ATU	306.43	67.93	**37.05**	**73.14**	14.8	West Greenland
	STF	309.28	67.02	**39.74**	**71.77**	14.6	West Greenland
	SKT	307.1	65.42	**36.29**	**70.54**	14.8	West Greenland
	GHB	308.27	64.17	**36.99**	**69.07**	14.8	West Greenland
	FHB	310.32	62	38.29	66.47	14.7	West Greenland
	NAQ	314.56	61.16	42.37	64.78	14.4	West Greenland

3 Instrumentation

The instrumentation of the AAL-PIP systems is uniquely designed to collect geophysical data autonomously and remotely; this is because the AAL-PIP systems are deployed to the EAP which is a remote, isolated, extremely harsh environment. To fulfill the specific tasks, there are several concerns in instrumentation design.

The first concern is the low power requirement. There are no manned facilities with infrastructures to support the instrument. The power source of the AAL-PIP platform relies on the direct input from solar panels during the summer season and on the battery reservoirs during the winter season.

The second concern is the low temperature requirement. The summer high temperature reaches −14℃ there, while the winter lows can reach −70℃. Therefore, the instruments need to survive the extremely cold weather in Antarctica, while providing continuous, high quality geomagnetic field observations and other space weather monitoring data.

The third concern is the logistical challenge due to the isolated location. Due to the weather restrictions and long distance from the US and permanent stations in the Antarctic, it takes great effort to transport the instruments from the US to Antarctic, which involves ground transportation in the US, shipment by sea, and flights with LC-130 and Twin-Otter within Antarctic. The requirements for the final Twin-Otter plane flights are particularly strict; they require good weather, air-dropped-fuel supplies at the mid-way point, and limited weight according to the capacity of the Twin-Otter load, which varies according to the fuel loaded on the plane. The longer distance the site from South Pole Station, the harder to reach. Therefore, the instrument design needs to take the size and weight limitation into consideration as well as the on-site installation and maintenance.

The fourth concern is the remote communication for near-real-time data transmission. The data collected on the Antarctic Plateau are usually either retrieved by the traverse team or airplanes, which is a considerable logistic cost. Now, with improved satellite coverage, the remote system can transmit the data in near-real-time by Iridium Satellite network. In addition, due to the logistical challenges, less human intervention is preferred for system maintenance. The system is designed to work stand-alone after deployment. The system can switch itself into hibernation mode during the winter and wake up automatically during the summer.

The final concern is that the system should have the capability of future improvement and be adaptable to include other low-power instruments into the platform.

Bearing these concerns in mind, the engineers considered several aspects in the instrumentation design specially targeted at these extreme challenges, including:

(1) Instrument power consumption should be lower than or around 1 W;

(2) The electronics components should be able to work in low temperature and well insulated;

(3) Measure magnetic field variations with high sensitivity (0.2 nT resolution) and high resolution (1 Hz data resolution for fluxgate magnetometer, 10 Hz for

searchcoil magnetometer), to observe the magnetic field in the Ultra Low Frequency (ULF) range in three orthogonal components;

(4) The system should operate unattended at any location on the Antarctic Plateau for at least 5 a without on-site maintenance;

(5) Transmit data in near-real-time to the server in Virginia Tech via satellite communication during summer seasons and store data during winter seasons;

(6) The potential for adapting new low power instrumentation, such as GPS receivers, HF radio experiment transmitters.

The current AAL-PIP system has the following components:

(1) Electronic control box, including single-board-computer, fluxgate and searchcoil magnetometers data adapter, Garmin GPS receiver, CASES GPS dual-frequency receiver, Iridium modem, HF radio communication transmitter (Virginia Tech), USB flash drive, etc.

(2) Battery box, including batter reservoirs, fuses, power board, heater plates, etc.

(3) Fluxgate magnetometer sensor (LEMI-002AN, 1 Hz, 0.01 nT).

(4) Searchcoil magnetometer sensor (made by University of New Hampshire, 10 Hz).

(5) GPS antenna.

(6) HF radio antenna.

(7) Solar panel tower.

More technical details about the AAL-PIP system can be found in the article by Clauer et al. (2014).

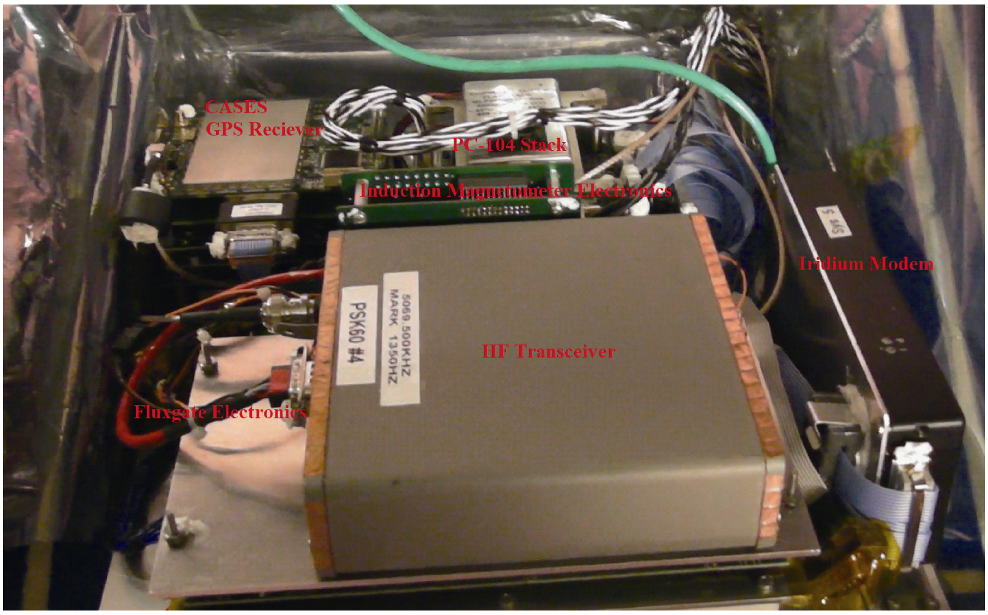

Figure 2 The electronics chassis of the AAL-PIP system.

With these specially designed features, the current AAL-PIP systems were deployed to six remote sites onto the EAP from 2008 to 2016. They have been collecting magnetic field measurements for over a decade. More recently, some stations have also collected GPS scintillation and HF radio measurements. The AAL-PIP system at PG1 has been operating without any on-site intervention since it was first installed in 2008, a remarkable record of continuous, autonomous operation for such a harsh environment. The fluxgate magnetometer at PG1 has provided reliable and high-resolution data for nearly a solar cycle, which could be considered as an outstanding record compared with other autonomous remote magnetometers. In the next section, we will introduce the system deployment and operation.

4 Field deployments and operations

The instrument will not be able to collect any scientific data until they are deployed and operating correctly. Due to the extreme conditions in Antarctica, the deployment and operation of these six systems are especially challenging. It took almost 10 a to finish deployment of the whole chain—the first system at PG1 was deployed in 2008 and the newest system at PG5 was finally deployed in 2016. The challenges to deploy and operate them on the EAP mainly come from logistic support to the deep remote field and harsh working environment under high elevations combined with cold and windy weather conditions.

The logistical support of deploying these systems starts with shipping all the equipment from the United States to McMurdo Station, then South Pole Station in Antarctica. That involves ground and vessel and air-cargo shipment and management from the US Antarctic Program (USAP) and Antarctic Support Contract (ASC) support. The most difficult part comes after the instruments arrive at the South Pole because they will all be carried via Twin-Otter airplane, and other research groups at South Pole compete for limited flights on the same planes.

The Twin-Otter airplane has the advantage of being able to land and take off on the snow covered Antarctic plateau without the need for a well-maintained runway. But it can only take 1135 kg of allowable payload over a 1430 km range, which is the maximum range that the aircraft can fly with maximum fuel. In words, the further it flies to the deep field, the more fuel it will need, and the less allowable payload it will carry. In our case, the total cargo load is 2270 kg, including both scientific equipment and camping gear. For the closest site PG3, which is located 560 km away from the South Pole, we could use the Twin-Otter flights to put in all science and camping gears since the allowable payload is about 1135 kg. But, the round trip from the South Pole to the furthest site PG5 is 1770 km, which is significantly larger than the 1430 km range of the Twin-Otter. The airplane has to take an extra fuel supply to refuel in the middle point to make a round-trip. Because the rule of allowable payload is “the further it flies, the less cargo it can carry”, it would take more than thirty Twin-Otter flights to transport all the fuel and gears to PG5 on its own. The USAP fixed-wing management has to call in the LC-130 aircraft to arrange the fuel drop of sixty barrels before the Twin-Otter flights. Thus, increasing distance adds a significant amount of logistical challenges for transportation by Twin-Otter.

After all the cargo and personnel are transported to the EAP, the installation of the system is challenging as well. The plateau is over 2750 to 3650 m in altitude, but the pressure altitude is between 3050–5500 m in altitude because of the cold weather temperature which is usually around −30℃−−40℃ during the summer season. The windy weather makes camping and installation even more difficult. The instrument was designed to use big T-bolt and push-pins and quick links to secure (1) the connections between different tower sections, (2) the solar panel installation on the tower, and (3) to hold the guy wires on the tower. This is a helpful design since work can be done without taking off gloves. Also, the big-bulk connectors with goof-proof design-wrong connectors will not match—are easy to mate the correct ends and prevent damage from wrong cable connections, which could easily occur when working with low oxygen due to the high pressure elevation and low visibility due to face covered by ski-googles and mask. The logistical challenges are shown in Figure 3.

Figure 3 Significant logistical resources are needed to deploy instruments in Antarctica, including transportation for team members and equipment, camping support, and field safety support. The left photo shows the field members working on site. The right photo shows the Twin-Otter transporting cargo to the field.

For operations, the system is designed to work autonomously with remote access and data transfer via the Iridium satellite. Since these systems are deployed and operated in such remote locations to collect data, it is hard to access the system by on-site visit and to perform maintenance. The house-keeping data (HSKP) are recorded in the system and sent back through satellite connection, including power voltage, battery temperature, sensor status, CPU loads, GPS location and time stamps, etc. These are important for monitoring the health of the system operation and diagnosis when something unexpected happens. So far, we have collected HSKP data for over a decade.

By analyzing these HSKP data, we improved our understanding of system operations, to spot and solve different issues, to adjust operation routines, and to modify the design of future systems. For example, our collaborators at the University of Michigan have solved a recurring reboot issue during the Antarctic summer season in 2013. After comparing the HSKP data from different systems, we found that reboots were caused by high CPU loads when the system was simultaneously recording multiple files, for example, from CASES GPS operation, Iridium communication and other tasks during the summer observation hours. A software update was patched to the remote systems and fixed these reboot issues.

Analyzing the HSKP data also provides information to improve the future design of the system. The HSKP data could be used to measure the charge efficiency of batteries during summer seasons, to summarize the total energy consumption, and to find the temperature limitation on battery charging. These are the key factors for extending the operation time when designing future systems, eventually to cover the whole year of operation.

5 Results

The AAL-PIP chain has been monitoring the near-Earth space environment, or geospace, gathering valuable and unique measurements from multiple instruments since the first site PG1 was installed in 2008. More sensors have been added to the adaptive platform later on. The observations are summarized in Table 2.

Survey plots and higher level data products are also available at the MIST group website (http://mist.nianet.org/), including:

(1) Daily fluxgate magnetometer data plot at individual stations. Figure 4 is an example of daily fluxgate magnetometer data plot at PG0 station on Jan 3rd, 2019. These plots are available online and usually updated within one or two weeks when Iridium connections to the remote sites are available.

Table 2 AAL-PIP system data information

Instrument	Frequency resolution	Started in year	Data access resource
Fluxgate magnetometer (PG0, PG1, PG2, PG3, PG4, PG5)	1 Hz	2008	Virginia Tech MIST website (http://mist.nianet.org/) THEMIS database (accessible via SPEDAS software and GUI) NASA SPDF CDAWeb SuperMAG (1 min data only)
Induction magnetometer (PG2, PG3, PG4, PG5)	10 Hz	2012	Virginia Tech MIST website (http://mist.nianet.org/), UNH website, Contact us directly for data requests
CASES Dual frequency GPS receiver (PG2, PG3, PG4, PG5)	Typically 1 Hz for low rate and 50 Hz for high rate data	2010	Virginia Tech MIST website (http://mist.nianet.org/), CEDAR MADRIGAL Contact us directly for data requests
HF communication experiments (PG2, PG3, PG4)	Burst transmission experiment	2011	Virginia Tech MIST website (http://mist.nianet.org/) Contact us directly for data requests

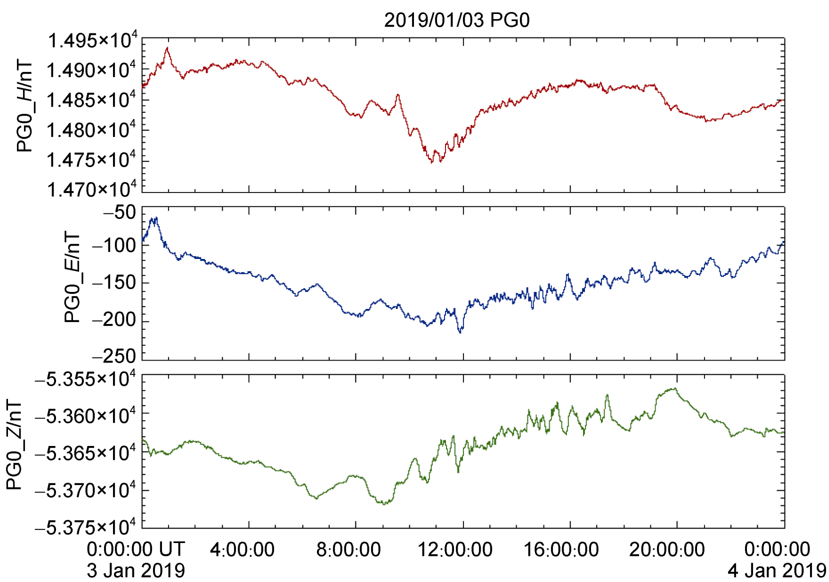

Figure 4 Daily fluxgate magnetometer data plot at PG0 station on Jan 3rd, 2019, showing three components with *H* (magnetic north) as red color, *E* (magnetic east) as blue color, and *Z* (vertical) as green color.

(2) Daily searchcoil magnetometer data plot at individual station. Figure 5 is an example of daily searchcoil magnetometer data plot at PG3 station on Jan 24th, 2018, including the original d*B*/d*t* variations and Power Spectra Density (PSD) of B_x and B_y components. The searchcoil magnetometer data are used typically for studying ULF waves including electromagnetic ion cyclotron (EMIC) waves caused by plasma particle dynamics in the magnetosphere (e.g., Kim et al., 2013, 2017).

(3) Daily conjugate station stack plots. Figure 6 is an example of daily conjugate station stack plots (*BN* as the magnetic north component) on Jan 21st, 2016, with all six AAL-PIP stations in the southern hemisphere and twelve West Greenland stations in the northern hemisphere. These inter-hemispheric comparisons of magnetic perturbations at range of latitudes are useful for sensing wave properties, investigating the effects of changing magnetic field topology, and understanding how properties vary in different regions (cusp, auroral zone, closed or open field lines) (Kim et al., 2015; Hartinger et al., 2017; Xu et al., 2017).

(4) AAL-PIP satellite conjunction survey plots. These

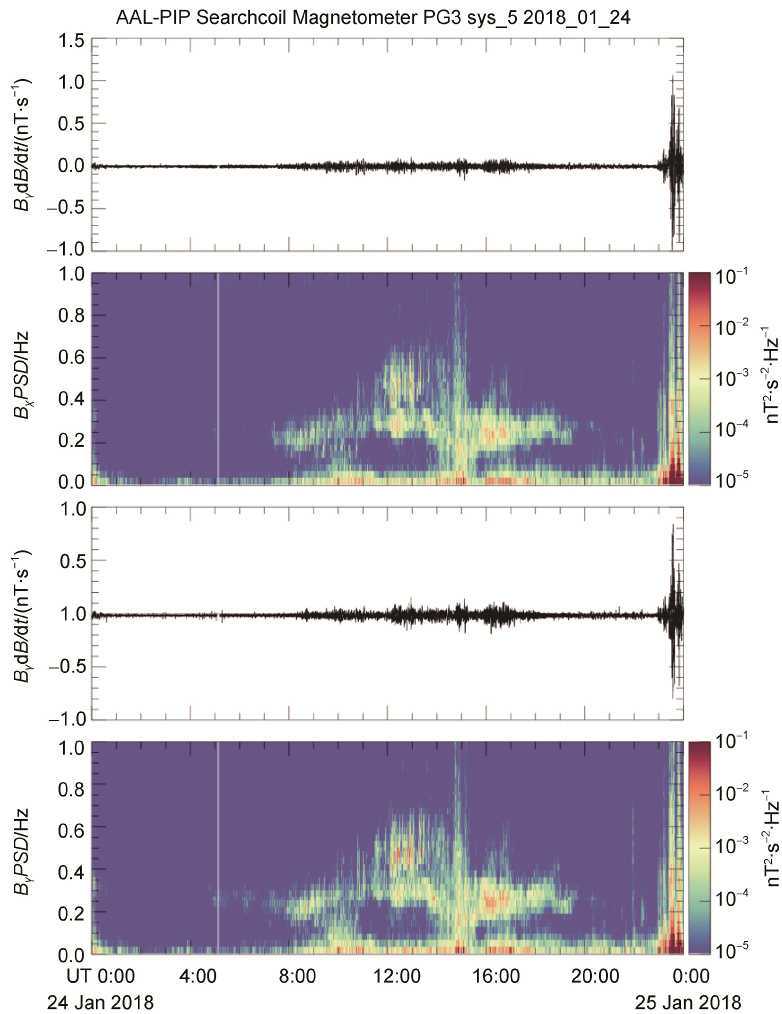

Figure 5 Daily searchcoil magnetometer data plot at PG3 station on Jan 24th, 2018, including the original dB/dt variations and Power Spectra Density (*PSD*) of B_x and B_y components. To be noted, X and Y are pointing magnetic North and magnetic East in the plane orthogonal to the magnetic field rather than orthogonal to vertical.

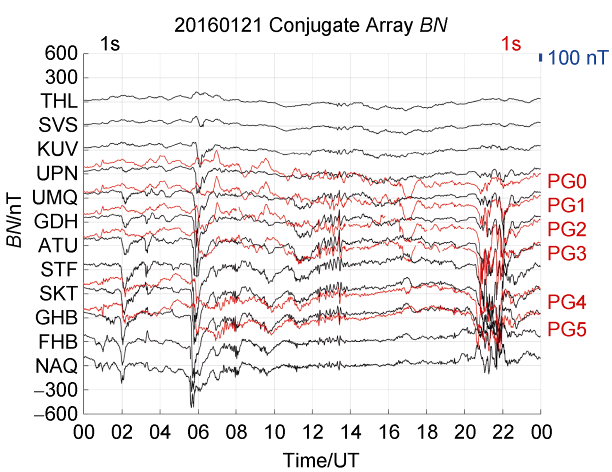

Figure 6 Daily conjugate station stack plot shows all six AAL-PIP stations in the southern hemisphere as red color and twelve West Greenland stations as black color in the northern hemisphere on Jan 21st, 2016. *BN* is the magnetic north component.

which are available at http://mist.nianet.org/Satellite_Conjunctions/, include magnetic perturbation inter-hemispheric comparisons between AAL-PIP and DTU Space ground stations along the 40° magnetic meridian. During each THEMIS satellite conjunction, 9 survey plots are generated: (1) Position of satellite in GSM *xy* plane. (2) Map showing locations of AAL-PIP stations and location of satellite footpoints in southern hemisphere. (3) Map showing locations of DTU Space stations and location of satellite footpoints in northern hemisphere. (4) The top four panels of stackplot contain (from top to bottom) THEMIS ESA ion energy flux spectrogram, THEMIS FGM GSM *x* component of magnetic field, GSM *y* component, GSM *z* component. The remaining panels contain the *H* (geomagnetic northward) component of the magnetic field measured at each DTU Space (black) and AAL-PIP (red) station. The stations are ordered according to location relative to respective magnetic poles, with stations closest to the magnetic pole at the top. (5–6) The same as four, except showing the *E* (geomagnetic eastward) and *Z* (vertical) components of the magnetic field measured by ground stations. (7–9) The same as 4–6, except showing perturbation magnetic fields. During each MMS Satellite conjunction, similar survey plots are generated accordingly. An example of the satellite AAL-PIP satellite conjunction survey plot is shown in Figure 7.

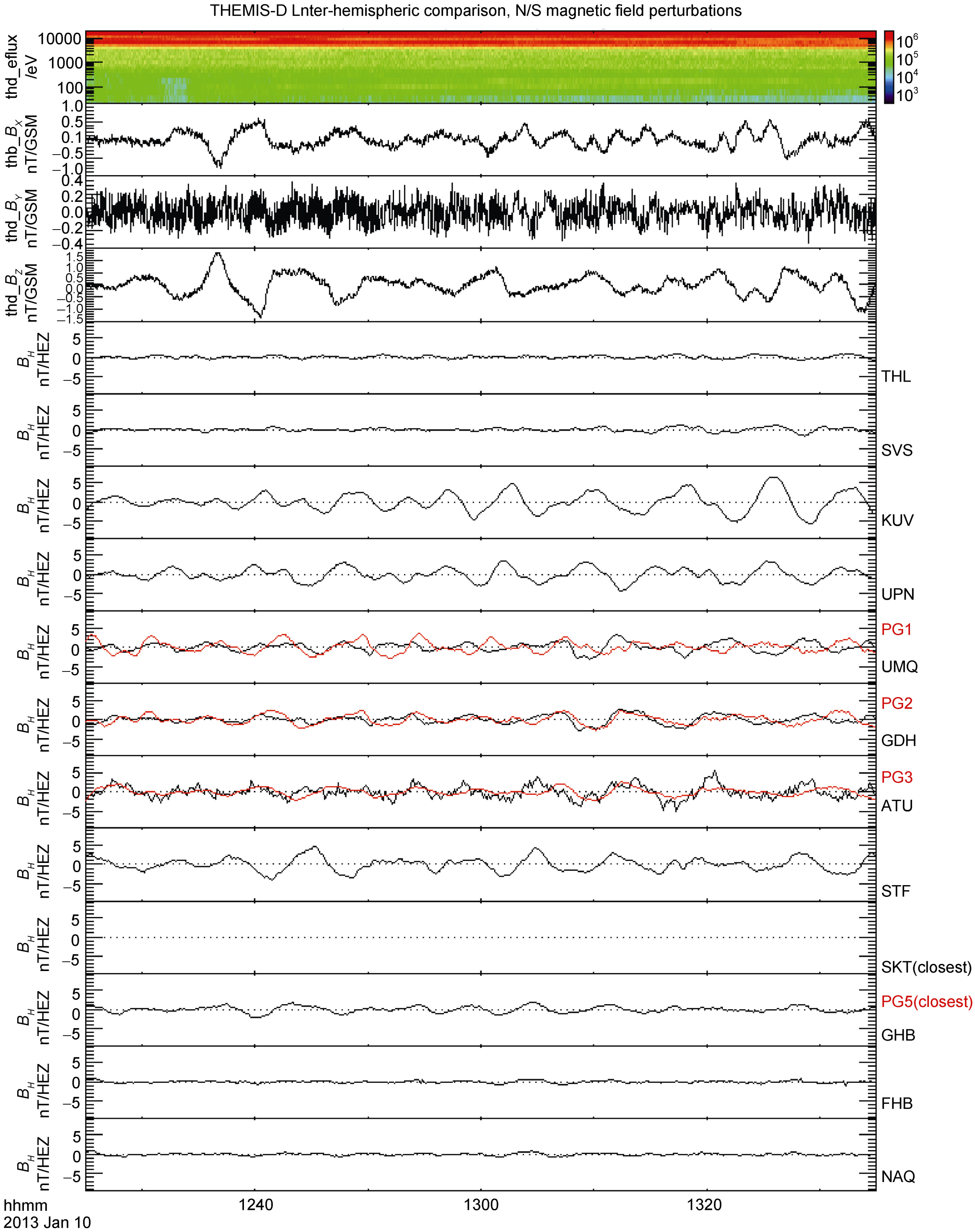

Figure 7 AAL-PIP satellite conjunction survey plots shows survey plots during conjunctions between AAL-PIP stations and the THEMIS and MMS satellites. The top four panels of stackplot contain (from top to bottom) THEMIS ESA ion energy flux spectrogram, THEMIS FGM GSM *x* component of magnetic field, GSM *y* component, GSM *z* component. The remaining panels contain the *H* (magnetic north-south) component of the magnetic field measured at each DTU Space (black) and AAL-PIP (red) station. Stations are ordered according to location relative to respective magnetic poles, with stations closest to the magnetic poles at the top.

(5) The house-keeping data from these stations are extremely essential for not only system health supervising and troubleshooting, but also for future system design. The house-keeping data provide power voltage, battery temperature, sensor status, CPU loads, GPS location, time stamps, and other parameters in Figure 8. These are important for monitoring the health of the system operation and diagnosis when something unexpected happens. So far, we have collected HSKP data for over a decade. The next generation of AAL-PIP will be developed based on the current HSKP data analysis to improve the power supply, battery system management, and signal noise reduction. Besides the instrumentation related study, the GPS location data from HSKP data could be used for glacier movement study on the EAP.

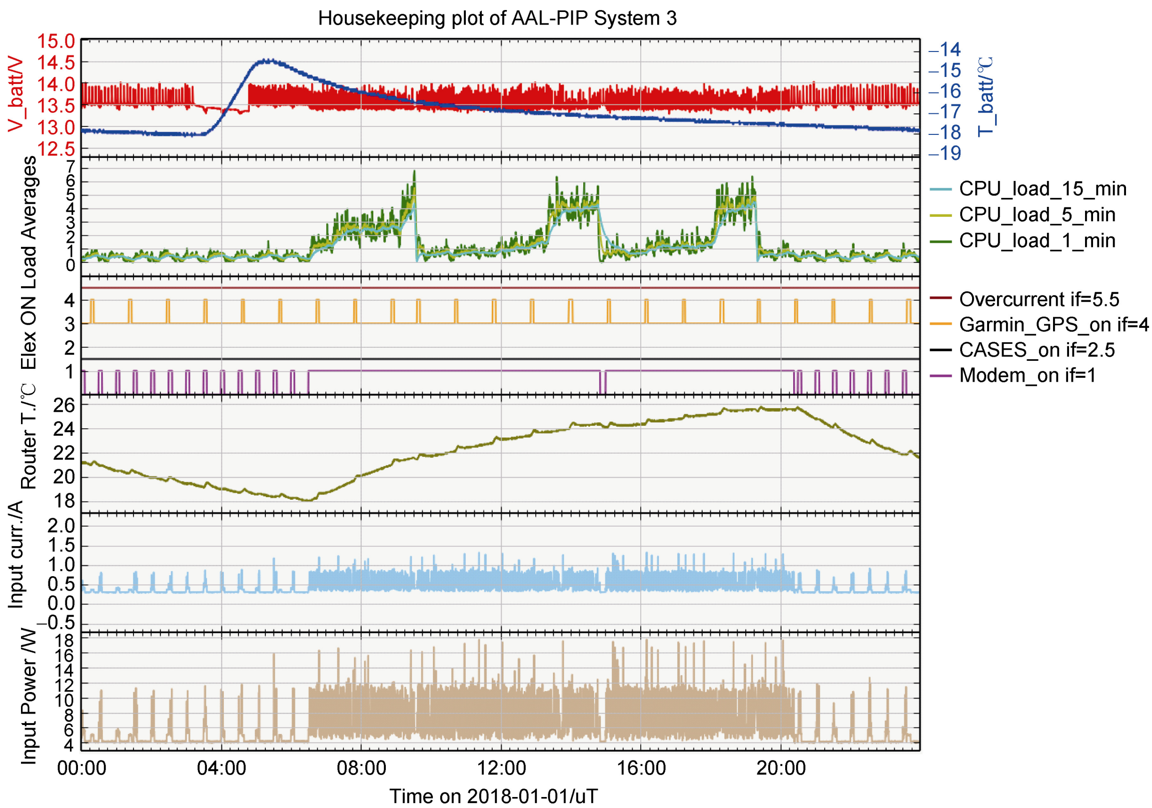

Figure 8 Example of house-keeping data from AAL-PIP system on the remote location. System 3 is at PG 2. V batt and T batt stand for the voltage and temperature of the batteries. CPU load is the measure of the amount of computational work that the single board computer system performs, averaged over 1 min, 5 min, and 10 min. The Elex ON shows which electronics are turned on, including the GARMIN GPS receiver, CASES GPS receiver, and Iridium Modem. The Router T shows the temperature measured inside the electronic control box. The Input Curr shows the input currents. The Input Power shows the input power.

Besides the survey plots and higher data products available on the MIST website, AAL-PIP CASES dual frequency GPS receiver data for GPS scintillations and GPS TEC study are available online or through request. An example of the GPS TEC analysis is shown in Figure 9. ULF Waves events were observed on January 26, 2016 by Shi et al. (2016). Ground magnetometer data Measurement from 3-station (PG2, 3 and 5) are detrended, high-pass filtered (2 mHz) and plotted in orange, where the raw carrier phase slant TEC data from PRN 25 measured by three same stations are detrended, filtered and plotted in orange. A coherence ULF wave characteristics can be found on both B_x and TEC data, among these 3 stations. Other examples can be found in Deshpande et al. (2012) and Kim et al. (2014). Also, the GPS TEC data has been processed from the GPS raw data and published in CEDAR Madrigal Database (http://cedar.openmadrigal.org/single/), which provides a global TEC map in the Antarctic region.

HF radio communication experiment shows the HF communication quality during the 2013–2014 Antarctic summertime in Figure 10. The top three panels indicate the percentage of characters received correctly as transmitted from System 3 (at PG5) to Systems 4 (at PG2), 5 (at PG3), 6 (at PG4) 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 *Kp* index, DST (nT), and proton flux over the same time period. All systems assumed nominal operations from February 2014 to March 2014.

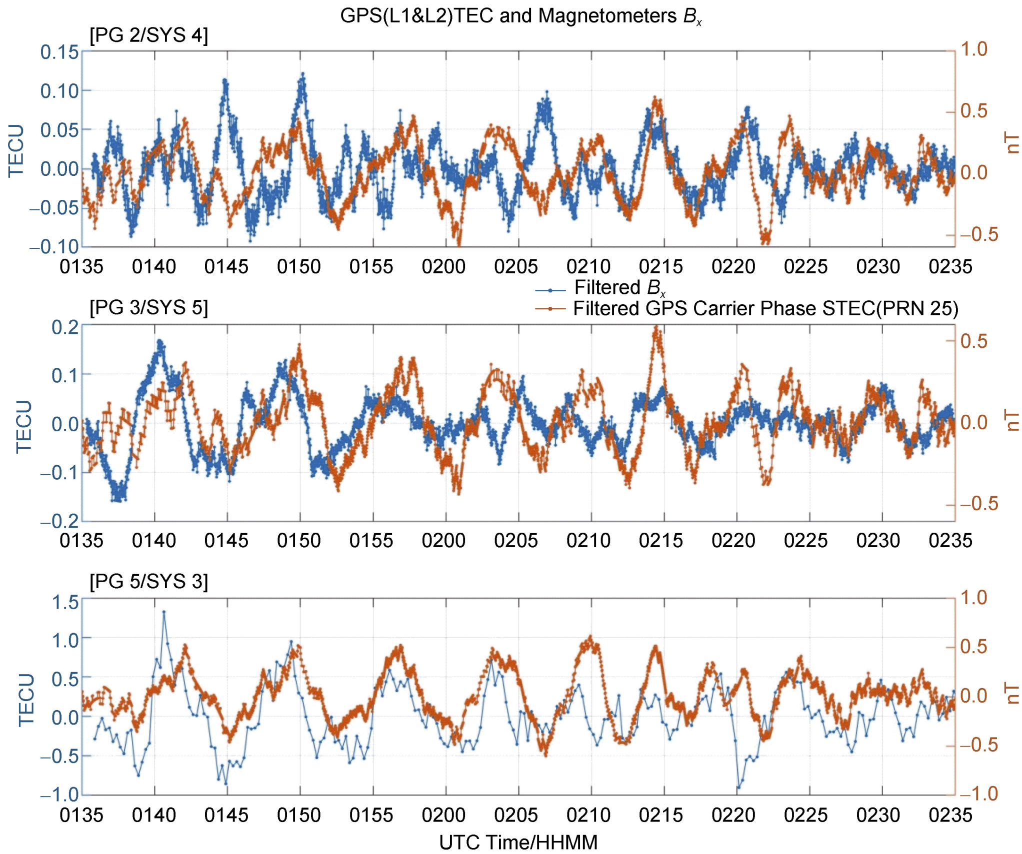

Figure 9 Example of GPS TEC data processed from CASES GPS receiver on Jan 26, 2016. Possible ULF Waves signatures found on Jan 26 2016 ground-based GPS TEC (blue color) and magnetometer data (Magnetic north component in brown color).

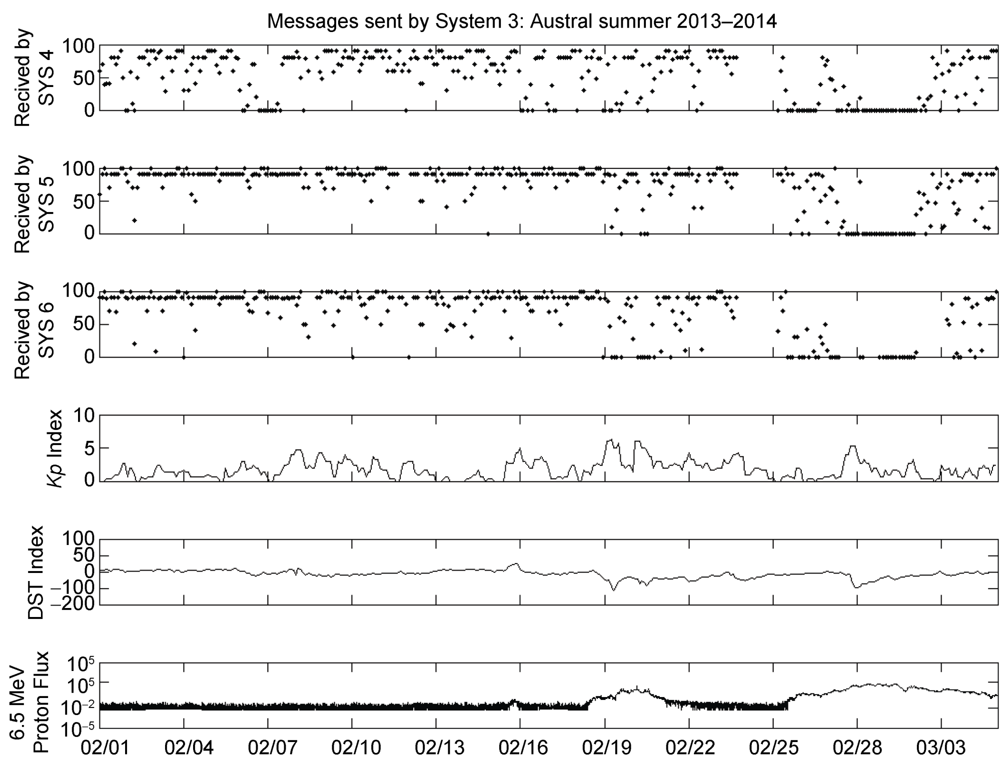

Figure 10 HF communication quality in February–March 2014 during Antarctic summertime.

The survey plots and higher level data products listed here provide valuable observations on remote sensing the high latitude electrical current systems, plasma waves, and irregularities in the ionosphere. The data are collected in near-real-time from multiple instruments at multiple locations. Combining these data with other observations, such as THEMIS or GOES satellites *in-situ* measurements and SuperDARN radar measurements, will depict an integrated picture of upper atmospheric system in the southern polar region. Combining with similar observations in the northern hemisphere in the conjugate locations will improve the understanding of global solar wind–magnetosphere–ionosphere coupling systems.

6 Summary

A new generation of AAL-PIP have been used to establish a high latitude measurement chain along the East 40° magnetic meridian that is magnetically conjugate to the existing magnetometer chain along the west coast of Greenland operated by the Danish National Space Institute at the DTU Space. These stations reach from the auroral zone to deep in the polar cap. On the dayside the chain spans the polar cusp. The first AAL-PIP station at PG1 has been in continuous operation since deployment in January 2008. In 2016, the chain of six stations was completed and is operating on the EAP. The purpose of these stations is to obtain simultaneous measurements in both hemispheres of the ionospheric electrodynamic signatures associated with the coupled solar wind–magnetosphere–ionosphere (SWMI) system. Four of the six stations support AAL-PIP instrumentation with fluxgate and induction magnetometers as well as scientific grade dual frequency GPS receivers. The instrumentation design, field deployment, and operation of these six stations are at the cutting edge stage of autonomous observatory platforms in the Antarctic. The data collected from multiple instruments at these multiple stations provide valuable observations for remote sensing high latitude electrical current systems, plasma waves, and irregularities in the ionosphere. They provide invaluable opportunities to study geospace phenomena related to the coupling of the SWMI system in Polar Regions, such as magnetic impulse (MI) events, traveling convection vortices (TCVs), ULF waves and other phenomena in the southern hemisphere.

Acknowledgments 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, USA. 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 NSF ANT-08398585, PLR-1243398, PLR-1543364 and EAR-1520864. Support at the University of Michigan was provided by NSF grant ANT-0838861. GC was supported by NSF grant PLR-1243225 to ASTRA. We thank the National Space Institute at the DTU Space for providing magnetometer data from the Greenland Magnetometer Array. We acknowledge NASA contract NAS5-02099 and V. Angelopoulos for use of data from the THEMIS Mission—Specifically: C. W. Carlson and J. P. McFadden for use of ESA data; K. H. Glassmeier, U. Auster and W. Baumjohann for the use of FGM data provided under the lead of the Technical University of Braunschweig and with financial support through the German Ministry for Economy and Technology and the German Center for Aviation and Space (DLR) under contract 50 OC 0302. We'd like to thank Dr. Yonghua Liu and another anonymous reviewer for valuable comments.

References

Clauer C R, Kim H, Deshpande K, et al. 2014. An Autonomous adaptive low-power instrument platform (AAL-PIP) for remote high-latitude geospace data collection. Geosci Instrum Methods Data Syst, 2014, 3(2): 211-227, doi: 10.5194/gi32112014.

Deshpande K B, Bust G S, Clauer C R, et al. 2012. Initial GPS scintillation results from CASES receiver at South Pole, Antarctica. Radio Sci, 47(5): RS5009, doi: 10.1029/2012RS005061.

Hartinger M D, Xu Z, Clauer C R, et al. 2017. Associating ground magnetometer observations with current or voltage generators. J Geophys Res-Space, 122(7): 7130-7141, doi: 10.1002/2017JA024140.

Kappenman J G. 2005. An overview of the impulsive geomagnetic field disturbances and power grid impacts associated with the violent Sun–Earth connection events of 29–31 October 2003 and a comparative evaluation with other contemporary storms. Space Weather, 3(8): S08C01, doi: 10.1029/2004SW000128.

Kim H, Cai X, Clauer C R, et al. 2013. Geomagnetic response to solar wind dynamic pressure impulse events at high-latitude conjugate points. J Geophys Res-Space, 118(10): 6055-6071, doi: 10.1002/jgra.50555.

Kim H, Clauer C R, Deshpande K, et al. 2014. Ionospheric irregularities during a substorm event: Observations of ULF pulsations and GPS scintillations. J Atmos Sol-Terr Phy, 114: 1-8, doi: 10.1016/j.jastp.2014.03.006.

Kim H, Clauer C R, Engebretson M J, et al. 2015. Conjugate observations of traveling convection vortices associated with transient events at the magnetopause. J Geophys Res-Space, 120(3): 2015-2035, doi: 10.1002/2014JA020743.

Kim H, Clauer C R, Gerrard A J, et al. 2017. Conjugate observations of electromagnetic ion cyclotron waves associated with traveling convection vortex events. J Geophys Res-Space, 122(7): 7336-7352, doi: 10.1002/2017JA024108.

Lessard M R, Weatherwax A T, Spasojevic M, et al. 2009. PENGUIn multi-instrument observations of high-latitude injections during the March 23, 2007 substorm. J Geophys Res-Space, 114: A00C11, doi: 10.1029/2008JA013507.

Liu Y H, Hu H Q, Yang H G, et al. 2016. Chinese Antarctic Magnetometer Chain at the Cusp Latitude. Adv Polar Sci, 27 (2): 102-106, doi: 10.13679/j.advps.2016.2.00102.

Melville R, Stillinger A, Gerrard A, et al. 2014. Sustainable energy at the 100-W level for scientific sites on the Antarctic Plateau: lessons learned from the Polar Experiment Network for Geospace Upper atmosphere Investigations-Automatic Geophysical Observatory project. Rev Sci Instrum, 85(4): 045117, doi: 10.1063/1.4871555.

Reiff P H, Hill T W, Burch J L. 1977. Solar wind plasma injection at the dayside magnetospheric cusp. J Geophys Res, 82(4): 479-491.

Shi X, Baker J B H, Ruohoniemi J M, et al. Long-lasting poloidal ULF waves observed by multiple satellites and high-latitude SuperDARN radars. J Geophys Res-Space, 2018, 123(10): 8422-8438, doi: 10.1029/2018JA026003.

Xu Z, Hartinger M D, Clauer C R, et al. A comparison of the ground magnetic responses during the 2013 and 2015 St. Patrick's Day geomagnetic storms. J Geophys Res-Space, 2018, 123(10): 8422-8438, doi: 10.1002/2016JA023338.

Xu Z, Clauer C R, Kim H, et al. 2014. Application of wavelet analysis on conjugate high latitude geomagnetic ULF Pulsations, 2014 Living With a Star (LWS) Science Meeting, November 2–6, 2014, Portland, Oregon.

Yamauchi M, Nilsson H, Eliasson H, et al. 1996. Dynamic response of the cusp morphology to the solar wind: A case study during passage of the solar wind plasma cloud on February 21, 1994. J Geophys Res-Space, 101(A11): 24675-24687.