Observations of Earth space by self-powered stations in Antarctica

S. B. Mende,[1] W. Rachelson,[1] R. Sterling,[1] H. U. Frey,[1] S. E. Harris,[1] S. McBride,[1] T. J. Rosenberg,[2] D. Detrick,[2] J. L. Doolittle,[3] M. Engebretson,[4] U. Inan,[5] J. W. Labelle,[6] L. J. Lanzerotti,[7] and A. T. Weatherwax[8]
[1]*Space Science Laboratory, UC Berkeley, Berkeley, California 94720, USA*
[2]*University of Maryland, Maryland 20742, USA*
[3]*Lockheed Advanced Technology Center, Palo Alto, California 94304, USA*
[4]*Augsburg College, Minneapolis, Minnesota 55454, USA*
[5]*Stanford University, Stanford, California 94305, USA*
[6]*Dartmouth College, Hanover, New Hampshire 03755, USA*
[7]*New Jersey Institute of Technology, Newark, New Jersey 07102, USA*
[8]*Siena College, Loudonville, New York 12211, USA*

(Received 3 September 2009; accepted 19 October 2009; published online 17 December 2009)

Coupling of the solar wind to the Earth magnetosphere/ionosphere is primarily through the high latitude regions, and there are distinct advantages in making remote sensing observations of these regions with a network of ground-based observatories over other techniques. The Antarctic continent is ideally situated for such a network, especially for optical studies, because the larger offset between geographic and geomagnetic poles in the south enables optical observations at a larger range of magnetic latitudes during the winter darkness. The greatest challenge for such ground-based observations is the generation of power and heat for a sizable ground station that can accommodate an optical imaging instrument. Under the sponsorship of the National Science Foundation, we have developed suitable automatic observing platforms, the Automatic Geophysical Observatories (AGOs) for a network of six autonomous stations on the Antarctic plateau. Each station housed a suite of science instruments including a dual wavelength intensified all-sky camera that records the auroral activity, an imaging riometer, fluxgate and search-coil magnetometers, and ELF/VLF and LM/MF/HF receivers. Originally these stations were powered by propane fuelled thermoelectric generators with the fuel delivered to the site each Antarctic summer. A by-product of this power generation was a large amount of useful heat, which was applied to maintain the operating temperature of the electronics in the stations. Although a reasonable degree of reliability was achieved with these stations, the high cost of the fuel air lift and some remaining technical issues necessitated the development of a different type of power unit. In the second phase of the project we have developed a power generation system using renewable energy that can operate automatically in the Antarctic winter. The most reliable power system consists of a type of wind turbine using a simple permanent magnet rotor and a new type of power control system with variable resistor shunts to regulate the power and dissipate the excess energy and at the same time provide heat for a temperature controlled environment for the instrument electronics and data system. We deployed such systems and demonstrated a high degree of reliability in several years of operation in spite of the relative unpredictability of the Antarctic environment. Sample data are shown to demonstrate that the AGOs provide key measurements, which would be impossible without the special technology developed for this type of observing platform. © *2009 American Institute of Physics.* [doi:10.1063/1.3262506]

I. INTRODUCTION

The investigation of how electromagnetic effects from the sun control the Earth's magnetosphere and ionosphere requires high latitude observations. At high latitudes the Earth's magnetic field lines extend to large distances from the Earth where the weak field interacts with the magnetic field of magnetized plasma clouds emanating from the sun traveling radially outward, constituting the solar wind. Solar variability as experienced on Earth is highly dependent on high latitude solar wind magnetospheric interactions. These processes can be observed directly by using satellite platforms and measuring the particles and fields directly *in situ*. However, satellites are expensive and have inherent disadvantages. For example there is the difficulty of separating spatial or temporal variability when observing from a fast moving single satellite platform. To overcome this limitation in recent years satellite missions using multiple satellites, such as the CLUSTER or THEMIS missions, have become fashionable.[1,2]

We can only make remote sensing observations of Earth space from the ground but each ground station provides a reliable time series data from a known fixed geographic location. The relatively economical nature of ground observations compared to satellites allows the use of multiple ground station networks. A network of stations is a relatively straightforward way of obtaining the spatial and temporal scales of the phenomena. It is not surprising therefore that as far back as the 1950s ground-based high latitude networks of magnetometers and optical auroral cameras were operated, e.g., Akasofu and Meng.[3] This is mostly so in the northern hemisphere where the access to polar regions is relatively easy.

There are several advantages in performing high latitude space research on the Antarctic continent rather than in the northern Arctic. The lack of population centers minimizes the light and radio wave pollution in the Antarctic continent. For optical remote sensing there are several factors which specially favor the Antarctic continent. In Antarctica the larger offset of geographic and geomagnetic poles allows optical observations at a large range of magnetic latitudes during the winter darkness.[4] In fact, near the southern geographic pole it is possible to view the aurora continuously for >3 months. In the northern hemisphere the region for maximum viewing of the high latitude region is in the Arctic Ocean and the closest suitable land base is in the relatively small islands of Svalbard (Spitsbergen). The high altitude Antarctic plateau is a continent size region and ideally situated for optical viewing because of the dry climate, which provides minimal cloud cover and unparalleled visibility. The operation of a year round manned station in Antarctica is expensive, therefore the idea of operating instruments remotely and automatically has a great appeal.

The idea of operating unmanned geophysical observatories in Antarctica has been around for a long time. In the late 1960s an experimental Unmanned Geophysical Observatory (UGO) was field tested at a manned Antarctic site.[5] The first unmanned geophysical observatory was operated by the Australians on the Antarctic ice sheet and it used on-site data recording of geophysical parameters.[6] These early remote systems had limited success often due to the failure of moving parts in very cold conditions.

In 1990s and almost simultaneously with our own effort the British Antarctic Survey (BAS) funded a program to develop instrument platforms, also called AGOs in Antarctica.[7] These were intended for deployment in the vicinity of the British manned station near Halley Bay. Their scientific justification was that, in combination with the instruments at Halley Bay, these AGOs were useful satellite stations expected to identify the equatorial and poleward auroral boundaries. The British AGO at location, shown as A77 in Fig. 1, was deployed and functioned with wind and solar power in the winters of 1992 and 1993. At the same time they operated a test bed AGO at Halley Bay. The British AGO instrumentation consisted of magnetometer, VLF receiver, and LF/MF/HF receivers. A single wavelength (630 nm) photometer was run at the test bed in Halley Bay. They also planned on incorporating a multiwavelength photometer with plans to eventually operate an imager.[8]

There were several programs serving other science disciplines that recognized the advantages of operating automatic observatory networks in Antarctica. Instruments that operate on minimal power can be accommodated in unattended stations through the Antarctic winters using only batteries. The Automatic Weather Stations (AWS) program uses this technique. As early as World War II the Germans operated automatic weather stations in Greenland and Spitsbergen. Automatic stations using HF radio transmission of data were tried in the Antarctic (e.g., by the Australians on Chick and Lewis Islands from 1958). During these early days data gathering was limited by on-site generally magnetic (tape) recording necessitating the use of moving parts that easily failed in very cold conditions.

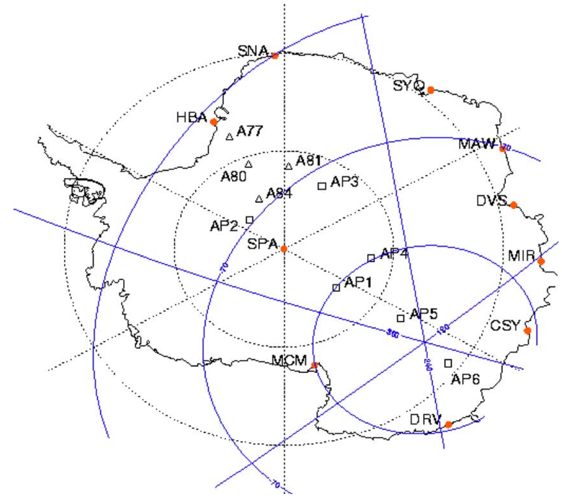

FIG. 1. (Color online) The AGO array, AGO-1 to AGO-6 (shown here as AP1 to AP6), as was installed in the PENGUIN program. Geomagnetic coordinates are illustrated in blue. The main objective was to study the polar cap, the region in the vicinity of the magnetic pole. The array consisted of two meridian arrays consisting of AP5-AP1-South Pole Station (SPA)-AP2 and of AP5-AP4-AP3. AP6 was intended to be at the opposite geomagnetic longitude of AP5 at the apex of the two arrays. We have also included some of the British stations from A77 to A84. For reference manned Antarctic stations are also shown: McMurdo (MCM), Dumont d'Urville (DRV), Casey (CSY), Mirny (MIR), Davis (DVS), Mawson (MAW), Syowa (SYO), Sanae (SNA), and Halley Bay (HBA).

By the 1970s improvements in satellite technology made possible the transmission and collection of data from AWSs and hence the availability of real or near-real time meteorological data from remote locations. The ARGOS system, designed by the French and carried by the U.S. NOAA near-polar orbiting satellites, made this routinely possible. Using two of the NOAA satellites it was possible to obtain direct observations almost every 52 min in the polar regions, even without data storage in the AWSs.

The development of AWSs for use in Antarctica was carried out independently by several nations. The first U.S. stations were built under the leadership of Dr. A. M. Peterson of Stanford Research Institute.[9] The program was later transferred to the University of Wisconsin, where it has been located since then under the leadership of C. R. Stearns.[10,11] The earlier Australian stations built within the Australian Antarctic Division are described by Allison and Morrissy.[12] Subsequently these stations have been considerably improved.[13] While the design of the stations originating in the different countries differ somewhat, all stations measure air temperature, atmospheric pressure, wind speed, and direction. Some stations have additional sensors, measuring also snow temperature at different depths, atmospheric humidity, solar radiation, and snow accumulation/ablation, as well as several "housekeeping" parameters. The stations are powered with an array of batteries, which are recharged in summer by solar photovoltaic panels.

Another effort of unattended operations of scientific instruments in Antarctica was undertaken by the Astronomy community in the PLATO project. To take advantage of the unparalleled good astronomical viewing conditions on the Antarctic plateau the Plateau Observatory (PLATO) remote field site power system was field tested.[14] PLATO is a third-generation self-powered robotic Antarctic observatory developed at the University of New South Wales. The first generation of these was the Automated Astrophysical Site Testing Observatory (AASTO).[15] The fist generation AASTO was intended as a test bed for remote Antarctic power generation systems and as a control and communication platform for a number of instruments. The AASTO power system was built by the Lockheed Palo Alto Research Laboratories in California and was closely similar to the design of the U.S. Automated Geophysical Observatory (subject of this present paper). It was deployed and operated in 1996 at the permanently manned South Pole Station.

The second generation facility leading toward the PLATO system was the Automated Astrophysical Site Testing International Observatory (AASTINO).[16] It was operated at Dome C station from 2003 to 2005 and fully remotely during the 2003 and 2004 winter seasons.[17,18] Recognizing that astronomical instruments would eventually require more power, a system was needed that had higher efficiency than the AASTO, therefore the AASTINO utilized a hybrid Stirling engine power electrical generation system, which was assisted with solar during the summer months. This system produced 200 W of electrical power and 3.5 kW of heat. A further advantage of the AASTINO and subsequently PLATO was that they use the fuel Jet A-1, which is much easier to transport and store in Antarctica than propane. The demand for yet more electrical power, and the need to operate PLATO at an even higher altitude, led to the decision to replace the Stirling engines with diesel engines for PLATO.

The PLATO system[14] was designed to provide power, 800/1600 W during winter and 400/1200 W during the summer, for a number of individual instruments and for heating. The electrical power source in this system is based on two banks of three diesel engines up to 1.8 kW per engine burning Jet A-1 aviation fuel. The engines are located in an engine module separate from the instruments. To supplement the diesel power two external solar panel arrays can provide a total of up to 1 kW when sunlight is available. These engines charge a 320 Ah lead-acid battery bank (28 V), which provides 1 day of battery backup for recovery procedures in case the engines shut down.

Although diesel engines have been and are the primary power sources at manned stations in Antarctica, traditionally they were not considered suitable as primary energy source for unmanned stations because of the required servicing interval of every 200 h. Otherwise they have several advantages, their high electric power generating efficiency (~30%) and the relative ease of the storage and transportation of diesel fuel in Antarctica. To solve the service interval problem each engine in the PLATO system is equipped with its own bulk oil filtration and recirculation system in order to extend the required servicing interval to 2000 h (83 days). This requirement still necessitates deployment operation of multiple engines to last through the winter period. Another innovation is the use of ultracapacitors for starting the engines instead of conventional batteries because they can operate to temperatures below −40 °C, providing ideal charging behavior without the need for temperature compensation and they maintain extremely high discharge current capacity even at very low temperatures. The PLATO fuel tank capacity is 4000 l of aviation fuel.

In January 2008 PLATO was deployed to Dome A, the highest point on the Antarctic plateau and it ran successfully in the Austral winter for a total of 204 days before communication was lost in early August 2008. In summary PLATO is a self-powered observatory with a multiply redundant, hybrid (diesel in winter and solar in summer) power generation system, designed to provide heat, power, control, and communications for a suite of automated astronomical and other science instruments to realize the superb astronomical viewing conditions offered by this Antarctic site. The size and capabilities of PLATO were designed for the operation of a more complex set of high power astronomical instruments. The larger scale and presumably larger costs associated with the PLATO design make it less suitable for housing a multistation network of modest size geophysical instruments.

In this paper we will review the technical aspects of the development program for the US unmanned Automatic Geophysical Observatories (AGOs)[19,20] from their original prototype to the current system. We will concentrate on the history of solving the most crucial problem: the development of a reliable power and thermal system that can operate unattended in the harsh Antarctic environment. This development started in the 1980s and provided a working system that was operational in the mid-1990s. The stations were powered by propane fuelled thermoelectric generators. The high cost of the fuel air lift and some remaining technical issues necessitated the development of a new type of power unit. This new one uses renewable energy operating with a simple wind turbine during the winter and solar cells during the summer. We will describe the new system and show its suitability for geophysical and other measurements from the Antarctic plateau.

II. SCIENTIFIC CONSIDERATIONS

Continued progress in understanding the Sun's influence on the structure and dynamics of the Earth's upper atmosphere will depend on knowledge of the electrodynamics of the polar cap and surrounding auroral regions. These regions play key roles in coupling the solar wind with the Earth's magnetosphere, ionosphere, and thermosphere. Measurements that are critically needed include the high latitude electric field convection patterns across the polar cap, the energy inputs in the form of waves and particles and the response of the atmosphere to these energy inputs. To make the desired progress an array of multistation Geophysical

TABLE I. Location of the U.S. Automatic Geophysical Observatories (AGOs) and two manned stations.

AGO	Date established	Geographic Lat.	Geographic Lon.	Geomagnetic Lat. (100 km reference)	Geomagnetic Lon. (100 km reference)	Elevation (m)
AGO-1	January 1994	S 83.86	E 129.61	S 80.14	E 16.75	2813
AGO-2	December 1992	S 85.67	E 313.62	S 69.81	E 19.21	1859
AGO-3	January 1995	S 82.75	E 28.59	S 71.78	E 40.17	2845
AGO-4	January 1994	S 82.01	E 96.76	S 80.00	E 41.56	3597
AGO-5	January 1996	S 77.24	E 123.52	S 86.73	E 29.39	3519
AGO-6	February 1997	S 69.51	E 130.03	S 84.92	E 215.32	2343
South Pole station		S 90.00	E 000.00	S 74.02	E 18.35	2910
McMurdo station		S 77.85	E 166.67	S 79.94	E 326.82	200

Observatories was developed and fielded as part of the Polar Experiment Network for Geospace Upper-atmosphere Investigations (PENGUIn) program.[20,21]

The imagers measure the auroral light which can be converted into the total energy of precipitation and the mean energy of the precipitating auroral electrons. These two quantities can be used to estimate the resultant ionospheric conductivities due to the electron precipitation. The magnetometers can measure the magnetic field produced by overhead ionospheric currents driven by the magnetosphere. These currents are largely horizontal currents driven by the electric fields that are responsible for the plasma convection. Thus the ionospheric currents that are derived from the magnetometer measurements are the result of the applied electric fields in the ionosphere and the ionospheric conductivity according to Ohm's law. Combining the two wavelength optical imaging with the imaging riometer (relative ionospheric opacity meter) data the ionospheric conductivity can be estimated. The riometer measures radio wave absorption that is created as a result of the precipitated electrons. Since the absorption preferentially occurs at lower altitudes the riometer provides additional data about the more penetrating higher energy component of the precipitation. The measured current and conductivity yield an electric field which can be compared to measurements of ionospheric electric fields obtained from radar measurements. There are SUPERDARN radar observatories in Antarctica that measure ionospheric drift and allow an independent estimation of the electric fields.

Wave instruments are useful in observing the electric and magnetic field fluctuations that are produced either in the magnetosphere or in the ionosphere. The AGOs have three different wave instruments looking at different parts of the magnetic spectrum: a search coil magnetometer covering ULF, a receiver covering VLF, and an LF/MF/HF band receiver that operates in the 30–5000 kHz range.

The layout of the AGO observatories for the PENGUIN program is illustrated on Fig. 1 and the station locations are tabulated in Table I. AGO-1, AGO-4, AGO-5, and AGO-6 are located in the so called polar cap, the region near to the magnetic pole, distinct from the oval shaped region circling the pole where visible auroras most frequently occur. The main emphasis was toward having arrays that span a large latitude range. The South Pole magnetic meridian with stations AGO-5, AGO-1, South Pole, and AGO-2 is optimum for studying particle precipitation patterns by observing optical aurora in the Austral winter. Because of the long polar night it is possible to observe auroras 24 h a day thus capturing auroras that occur during magnetic midday. AGO-1 was well located to observe the poleward boundary of the aurora when the aurora is at the poleward edge of the South Pole field of view. The second meridian chain was about 1 h local time ahead of the other chain and it consists of AGO-5, AGO-4, and AGO-3. The two chains provide information about longitudinal or local time variability of the phenomena.

III. SCIENTIFIC INSTRUMENTS

An optical instrument such as an auroral all sky imager is difficult to accommodate in the AGO because it requires a very large data storage, it can only operate during night conditions where the availability of power is limited, and it requires a viewing port which has to be kept clean. At the outset of the program it was agreed that if the imager can be accommodated then the AGO should support a full set of remote sensing Earth space observing instruments. We therefore planned the AGO around a combination of instruments consisting of a two channel all-sky auroral imager, an imaging riometer, a fluxgate magnetometer, a search coil magnetometer, ELF/VLF, and an LF/MF/HF radio receiver. This complement would constitute the correct baseline payload for the PENGUIn Geophysical measurements. In addition various weather related measurements such as outside temperature and wind speed were also incorporated.

A. Dual channel monochromatic all-sky imager

Low energy auroral electrons cascading into the atmosphere from the magnetosphere interact with atmospheric oxygen and excite the parent state of an oxygen line emission at 630 nm. The lifetime of the parent state of 630 nm is long (110 s) and the emission takes place only if the excited atom avoids collisions during this time. Therefore, 630 nm emission occurs only at altitudes of 180 km or higher where collisions are relatively infrequent. Since most (not all) auroral electrons stop around 100 km one can argue that almost all electrons cascade through the regions above 180 km, and therefore the 630 nm emission is a good proxy for the electron number flux. The 427.8 nm emission is an emission of the ionized state of the N_2 molecule. It is a permitted transition with extremely short lifetime generated in the regions from 90 to about 120 km where most electrons stop and N_2 is abundant. Therefore this emission is an excellent proxy for the total energy deposited into the atmosphere by each electron. Measuring the two emissions therefore provides a proxy for the electron number flux, total energy of the precipitating electron, and the comparison of the two yields a mean energy of precipitation.

A special purpose dual wavelength low light level auroral all-sky imager[22] was developed for the AGO application by Stephen Mende and Jack H. Doolittle at the Lockheed Palo Alto Research Laboratories. The AGO imagers incorporate a two-channel intensified charge coupled device (CCD) camera with a single all-sky optical channel and a single detector and are capable of acquiring images in two different wavelengths (630.0 ± 3.0 and 427.8 ± 5.0 nm) simultaneously. They are optically identical to an imager installed at South Pole Station. Imager data, recorded at a rate of 1 image/min, have 10 km geographic resolution over most of the field of view, ranging to 30 km at the edges. Imager sensitivity is 20 Rayleighs in an 8 s exposure and with exposure bracketing, the dynamic range covered auroral intensities from 20 Rayleighs to 10 000 Rayleighs. Images are digitized using an 8-bit quasilogarithmic scheme and compressed to minimize the data volume.

The specially developed all-sky imager instrument for the AGO is illustrated in Fig. 2. The camera is hermetically sealed under a double dome (1) and a conventional "all-sky" fish eye lens (2) is used to form a 3 in. intermediate image near the special dual band interference filter (4). The filter has two narrow ~4 nm wide passbands at 427.8 and 630 nm. This filter is located at the telecentric space provided by lens (3) that ensures that all central rays of the F/4 convergence beams are essentially parallel with the optic axis. The intermediate image is reimaged on the photocathode of the image intensifier (7). A set of blocking filters (5) constructed from two separate semicircular half filters and a prism (6) are included in collimated space between two field lenses The prism is included to bend each half size image away from the image intensifier optic axis and thus two separately filtered images of the same sky are produced side by side on the image intensifier photocathode. The image intensifier (7) amplifies the images and they are reimaged on the CCD (8). The electronics consist of a single frame digital memory and a low-power computer, which is capable of compressing the images about 20:1 and transmitting them to the AGO data system. The domes are kept clear because of wind scouring and perhaps through the benefit of some waste heat which passes from the AGO through the camera port and the dome. Since the AGO station power is limited the camera was power cycled between scans to achieve an average power consumption of less than 5 W. These cameras have worked reliably for several years in the unattended, unmanned environment.

Individual all-sky images can be produced for analysis, but in addition they may be combined from contiguous AGO sites (and South Pole) or processed to generate large area mosaics (see discussion later), conventional latitude-UT keograms,[23] or clock-dial keograms.[24]

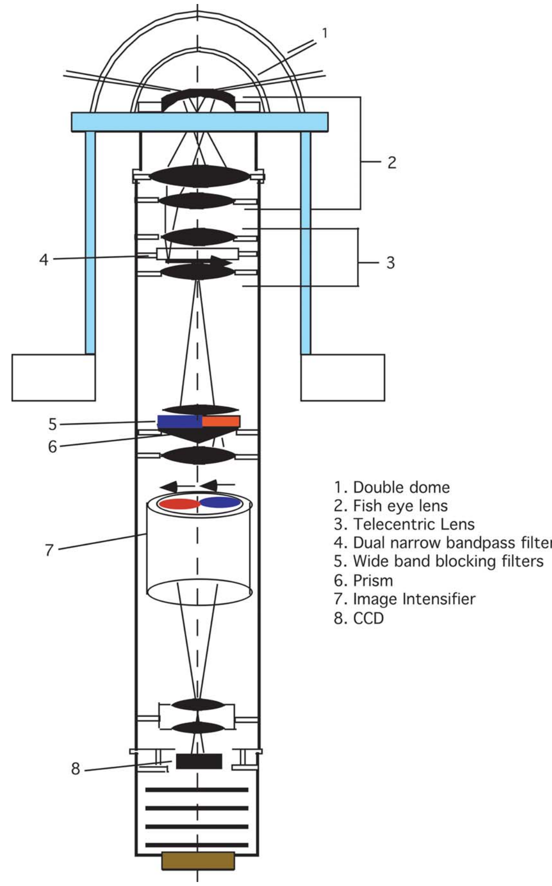

FIG. 2. (Color online) The AGO all-sky imager. The dual channel narrow wavelength band all-sky camera has been in field service duty in the AGO stations since the early 1990s.

B. Imaging riometers

The University of Maryland under the direction of author Dr. T. J. Rosenberg, provided 38.2 MHz imaging riometers for each PENGUIn AGO. A riometer is an instrument that measures the opacity of the Earth's ionosphere/atmosphere to cosmic radio noise, which is used as a constant background against which small changes in the electron density of the ionosphere can be examined. The ionospheric plasma attenuates high-frequency (HF) radiowave energy that passes through it, so the riometer operates at frequencies particularly susceptible to this attenuation, in the range from 20 to 50 MHz.

The electron density changes that the riometer is used to examine are primarily caused by the precipitation of energetic electrons from the magnetosphere into the atmosphere. The riometer is most sensitive to incident electrons that deposit energy at 55 km altitude; an electron needs energy of the order of 1 MeV to reach this low in the atmosphere. However, the sensitivity of the riometer enables it to measure the effects of electrons below 10 keV energy, corresponding to altitudes above 110 km. The auroral precipitation events of most interest to riometry generally have electron energies in the few tens of keV, so the most significant effects occur near 90 km altitude.

Zenith-viewing riometers were the first to be used to provide a single measurement of the absorption above the station. In order to examine the spatial scale of regions of energetic electron precipitation, which are coincident with cosmic radio noise absorption activity, the use of antenna arrays producing multiple narrow beams is necessary. By using such beams and introducing appropriate phase delays it is possible to "steer" these beams and form an image of the patterns of radio absorption above a station. The imaging riometer provides good spatial and temporal resolutions for examining auroral precipitation events. It complements the optical all-sky camera and operates year round since it is not affected by sunlight and cloud cover. Although the imaging riometer has a lower spatial resolution than the all-sky camera it operates with higher time resolution than the all-sky camera without taxing the data recording capability of the AGO.

The PENGUIn imaging riometer system was based on the 64-element phased array instrument deployed at South Pole Station in 1988. However, such a large array requires considerable effort in field installation. Therefore, a smaller array was designed for the remote sites, as discussed in Ref. 25. The new imaging riometer consists of a 16-element phased array antenna and requires only 4–5 W. The system employs two riometers for redundancy and to double the rate of data recording. The 12-bit analog-to-digital converter produces 24 bytes of data for one complete scan (in 12 s) of the 16 beams for each riometer, resulting in a complete riometer image of the radio sky every 6 s.

C. Fluxgate magnetometer

Bell Laboratories—Lucent Technologies, under the direction of Dr. Louis Lanzerotti, has provided fluxgate magnetometers for each PENGUIn AGO. Each instrument measures and records the three dc vector components of the geomagnetic field at 1 s intervals. Each component of these systems has a noise level of typically 0.01 nT rms between 0 and 1 Hz. Similar magnetometers are deployed at South Pole Station and McMurdo, Antarctica.

Magnetic field values and variations are considered some of the most basic of diagnostics for ground-based observations of ionospheric and magnetospheric processes. Although they are now complemented in the PENGUIn AGOs and elsewhere by other types of instruments, they remain a basic and necessary component of most studies of these phenomena.

D. Search coil magnetometer

Professor Hiroshi Fukunishi of Tohoku University has provided search coil magnetometers for each PENGUIn AGO. Variations in magnetic fields are measured along three orthogonal components (N-S, E-W, and vertical) by individual coils which are buried at a depth of 1 m from the snow surface with a distance of at least 5 m between sensors. Each search coil has a linear frequency response from $\sim$0.001 to 2 Hz and is equipped with a low pass filter with a cutoff frequency of 2 Hz. The output signals of each coil are sampled simultaneously at 0.5 s intervals and are digitized using a 12-bit A/D converter, providing a dynamic range from $\pm$1.6 pT to $\pm$3.2 nT at 1 Hz and $\pm$160 pT to $\pm$320 nT at 0.01 Hz.

E. ELF/VLF measurements

Professor Umran Inan and his team at Stanford University have developed an ELF/VLF receiver for use on the PENGUIn AGOs which consists of one digital broadband snapshot system (BBS) that collects data in the range of 300 Hz–5 kHz, eight frequency-banded channels (500 Hz–1 kHz, 1–2 kHz E-W, 1–2 kHz N-S, 2–4 kHz, 4–8 kHz, 8–16 kHz, and 30–40 kHz), and one additional narrowband channel tuned to the frequency of a powerful U.S. Navy operated VLF transmitter (NAA at 24.0 kHz).[26]

Electromagnetic and electrostatic waves play an important role in the transport and acceleration of magnetospheric and ionospheric plasma, and particle precipitation driven by these waves constitutes a significant form of energy deposition into the Earth's ionosphere. Because many of these waves follow magnetic field lines down to the ionosphere, measurements of ELF/VLF waves (300 Hz–30 kHz) at multiple sites provide a powerful means of remotely sensing magnetospheric processes. In the context of the PENGUIn program, ELF/VLF measurements complement other observations primarily targeted toward documenting the spatial and temporal distributions of precipitation activity via optical and riometer measurements, and the measurement of magnetic activity.

Low resolution data on overall ELF/VLF activity usually consist of the recordings of the detected signal amplitude in selected frequency-banded channels, sampled relatively slowly (e.g., $\sim$2 Hz). However, since a diverse range of different types of waves are commonly observed, including discrete emissions such as chorus, steady and structureless emissions such as hiss, and other signals originating in lightning discharges, wideband measurements of the signal waveform are necessary to identify the nature of the waves. At manned stations, large data volume continuous digital broadband measurements can be made and typically can accommodate up to 50 kHz bandwidth in real time.

A complicating aspect of ELF/VLF measurements on the ground is the fact that waves of magnetospheric origin that penetrate the lower ionosphere may propagate to long distances in the Earth-ionosphere waveguide and be detectable at distances of many hundreds of kilometers from their points of entry. Thus, simultaneous multiple-site measurements are necessary to determine the spatial extent of ionospheric and magnetospheric regions within which the wave activity resides.

Since the early 1980s, Stanford University has maintained and operated an ELF/VLF system at South Pole Station, Antarctica. In the context of the PENGUIn program, ELF/VLF observations at South Pole are crucially important for two reasons: (i) SP is part of the meridional and latitudinal chains constituted by the PENGUIn sites and (ii) continuous and synoptic wideband (30 Hz–50 kHz) ELF/VLF measurements at South Pole, not possible at AGO sites due to data limitations, provide key information on the diverse range of wave types the intensity of which are registered in the narrowband channels.

The nine frequency-banded channels and the BBS in the PENGUIn ELF/VLF receiver system share a common power system and line receiver, and the banded channels each have separate detector/integrators in a common module. A separate dual-channel low-noise preamplifier unit is deployed outside near the sensors, which consist of two 4.9×4.9 m^2 square loop antennas deployed in orthogonal directions, magnetic N-S and E-W. The sensitivity of the ELF/VLF receiver system is 1.89×10^{-4} μV m^{-1} Hz$^{-1/2}$. Two of the frequency-banded channels cover the same frequency range (1–2 kHz) with two different antennas (N-S and E-W) to allow the extraction of direction of arrival information during postprocessing. All frequency-banded channels are sampled and recorded continuously at 2 Hz.

The PENGUIn ELF/VLF receiver system incorporates a single-board computer, with operating program stored on EPROM so it can be replaced annually as requirements (such as snapshot frequency and duration) change. Wideband signals from the line receiver for the N-S and E-W antenna are sampled simultaneously at 10 kHz with 16-bit resolution for 2 s several times per hour (typically at 5, 20, 35, and 50 min after the hour).

F. LF/MF/HF radio receiver

Professor Jim Labelle of Dartmouth has provided LF/MF/HF radio receivers for deployment on the PENGUIn AGOs. The lower part of the LF/MF/HF radio bands (30 kHz–30 MHz) are of geophysical interest because several key ionospheric resonance frequencies lie in this band; namely, the electron cyclotron frequency (approximately 1.5 MHz) and its harmonics, and the electron plasma and upper hybrid frequencies (approximately 1–10 MHz). Therefore, several types of spontaneous emissions occur in this frequency range in the presence of free energy sources such as auroral electron beams reviewed in Ref. 27. These emissions are indicative of electron precipitation and can provide information about plasma density and irregularities and their variation with altitude, e.g., discussion in Refs. 28 and 29.

The Antarctic is an especially good location for monitoring these emissions both because it lies under the polar aurora and also because of the relative absence of local man-made interfering transmissions. The AGOs included an LF/MF/HF receiver covering 0.03–5.00 MHz. The sensor is a 10 m^2 magnetic loop antenna with active preamp located approximately 100 m from the observatory. The receiver is a single-conversion superheterodyne type with a 10 kHz bandwidth defined by a crystal intermediate-frequency filter. The detected frequency is defined by a tunable local oscillator whose frequency is controlled by code stored in and read out sequentially from an erasable programmable read-only memory (EPROM). Therefore, the frequency resolution, sweep duration, and range can be changed by replacing the EPROM. Due to the modest data storage in the original AGOs, the first version of the LF/MF/HF receiver included a delta data-compression scheme, implemented in discrete digital electronics, whereby only changes in signal levels at each frequency are stored as 4-bit words, allowing 20 frequencies to be measured each second. The standard mode was a 116-frequency sweep lasting 5.8 s, composed of two 58-frequency sweeps lasting 2.9 s with interleaved frequencies. Resolution varies over the spectrum, with frequencies concentrated to give higher resolution in frequency ranges of natural phenomena such as auroral hiss or roar; resolution is as good as 10 kHz in these ranges.

In recent years, as data storage has increased by a factor of ~1000, the added complexity of the data compression is not required, and the receivers have been cycled out of the field and replaced by modified units lacking the data compression. The data rate can be increased by up to a factor of 20 by adjusting jumpers on the board, as further data storage improvements allow a higher data rate and corresponding increase in frequency and time resolution.

IV. REQUIREMENT SUMMARY

To accommodate a set of instruments suitable for remote sensing Earth space measurements the Automatic Geophysical observatories had to satisfy a number of requirements. In the low temperatures and inclement weather environment of Antarctica the most important requirement is to provide heat and power for operating the instruments and for recording a large enough data set for making optical imaging observations.

Data recording has gone through the most significant transformation since the early 1980s when the original concepts of the AGOs were developed because of the huge changes in the technology of data storage. At the start of the AGO program the data recording system was based on onsite recording only using two redundant digital tape drives and being able to record only a few hundred kilobytes of data represented by the onsite annual data storing capacity. Today several hundred gigabytes of flash memory can be used which is a thousand fold increase. Quite early on the AGO system was equipped with an ARGOS transmitter and the stations could telemeter health and status data which were collected and reviewed daily. Later on iridium satellite modems were also added to provide approximately 20 Mbytes/day per station data retrieval through digital modem transmission; a separate paper detailing the iridium modems is in preparation.

In this article we will not deal with the development of the AGO data system. It is sufficient to say, however, that the original data storage and instrument data handling capabilities required a benign thermal environment of temperatures in the range of 0–30 °C. The total AGO electrical power usage including all instruments is shown in Table II. Including a good reserve and leaving some room for expansion the design requirement was defined to be about 50 W average. It should be mentioned that instruments other than the all-sky imager and the VLF/ELF receivers require relatively little data volume, and therefore they could be accommodated by stations requiring much less power and thermal support. In fact, the scale of the AGOs was defined by the all-sky camera and ELF/VLF requirements.

Conditions in the Antarctic polar plateau are harsh to say

TABLE II. PENGUIn/AGO power budgets. P1 (1 February 2002).

Instrument	Power (W)
Data acquisition unit (DAU)	4.60
Flux gate magnetometer	3.50
Search coil magnetometer	
ELF/VLF receiver(s)	7.64
LF/HF receiver	1.26
Imaging riometer	4.56
All-sky camera (standby)	3.11
Total	26.41

the least, at places the temperatures drop to −100 °C in the winter and get up to −10 at times during a summer "heat wave." So the system has to be designed to be able to cope with this huge change in exterior temperature while maintaining the electronics and data recording systems between 0 and 30 °C.

So the big question has been how to generate the heat and power required to run these stations. Jenny and Lapson[1] selected a radiothermal generator (RTG). RTGs contain a large block of radioactive element such as strontium 90 and the radiation produced heat is used to generate electricity by a built in thermal electric generator. Such units, with their exterior lead shielding, weigh a great deal. Because of their radioactivity they must be retrieved according to the Antarctic Treaty. For this reason and their radioactive health hazard, it was decided early on that other forms of power generation should be considered first. The experience held that conventional diesel generators would not run unattended for a year at a remote site. Thermoelectric generators without moving parts seemed the most reliable and attractive proposition for the AGO power source. Propane was chosen because it is a much cleaner burning than any other fuel which would be otherwise practical.

V. PHASE 1: PROPANE FUELLED POWER GENERATION

In the early 1980s the Lockheed Palo Alto Research Laboratories were funded to develop a prototype Automatic Geophysical Observatory based on the propane fuelled thermo electric generator principle. This phase of the development was directed by Stephen Mende and the lead engineer was S. E. Harris at the Lockheed Laboratories.

The prototype AGO was a relatively small insulated enclosure approximately 12×7×7 ft in length, width, and height (Fig. 3). The thermoelectric generator was a Teledyne model using 6 TEG modules in series. In order to solve the temperature control problem the modules were each connected to a heat pipe each of which had their condensers above the enclosure roof venting heat directly to the outside. The principle of operation was simple: in each heat pipe the working fluid was under pressure so that its boiling point was reached at the desired inside set temperature, e.g., 10 °C. Below this temperature the heat pipe was not operational and the TEG heat stayed inside the enclosure and was vented to air by appropriate fins attached to the TEGs. When the temperature reached the set temperature or went above it then the working fluid started boiling and the heat conductivity of each heat pipe went up enormously thereby venting the heat of the TEG outside.

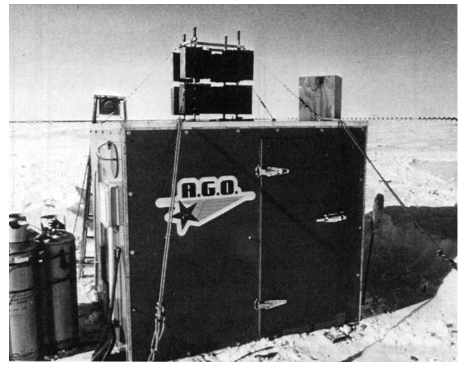

FIG. 3. Prototype Automatic Geophysical Observatory at the South Pole ca. 1983.

The prototype was fielded at South Pole station for several Austral winters (Fig. 3). There were several practical problems with the prototype unit; the most important was the frequent failure of the solder joints of the large heat pipes. Nevertheless the prototype testing was sufficiently successful to convince the parties involved that the program was ready to develop six new identical AGO units and field them in Antarctica. About this time the project management was taken over by Dr. Jack Doolittle also at the Lockheed Palo Alto Laboratories.

The six production AGOs were designed from the ground up. They were intended for deployment as shown in Fig. 1 according to the PENGUIN science requirements. Each station was to be delivered by a Lockheed ski equipped LC-130 aircraft with an "open field" landing. Because of the large carrying capability of this aircraft it was decided (wrongly in hindsight) that it was preferable to build an enclosure that had sufficient volume to provide overnight accommodation to the annual visiting party as well as the instrument electronics recording and satellite modem transmitters. The resulting enclosures were 16×8×8 ft (length×width×height). They were built with a polystyrene foam core with a fiber glass skin on the inside and outside. Since the so-called ultralight sailing boats use the same construction technique the enclosures were built by Moore Sailboats in Santa Cruz, California.

The system is illustrated in Fig. 4. The power generation was provided by a Teledyne Telan type TEG. In this version the six catalytic burner modules were assembled in line. This unit was capable of delivering the required 50 W of electric power at nominal 24 V dc. The efficiency of thermoelectric generators is about 5% at best. In order to generate the 50 W it had to produce about 2000 W of heat. Propane produces 19.8 MJ/l (Table III).

The power units were modified and the cooling fins were removed and a coolant fluid reservoir/evaporator was sandwiched between the fins and the TEG burner boxes. The propane fuel was kept outside of the AGO enclosure in a tank "farm" shown on the left of Fig. 4. At the temperatures encountered in Antarctica propane is in liquid form and it

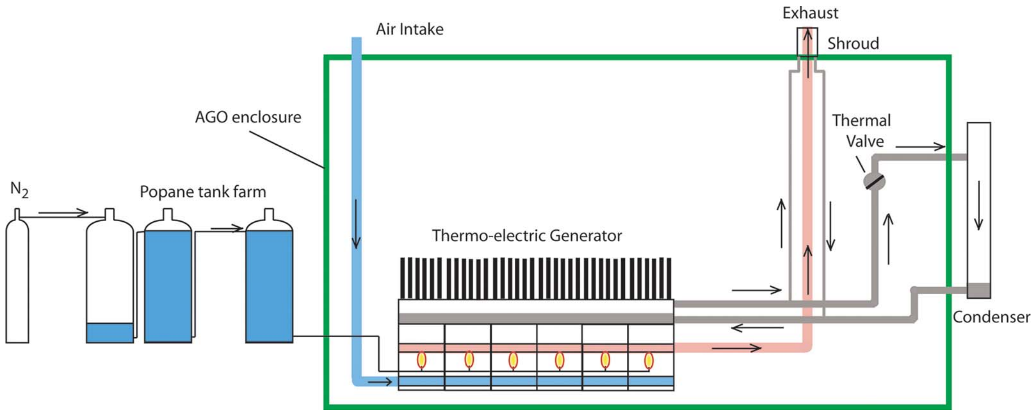

FIG. 4. (Color online) Propane fuelled AGO schematic diagram including the power generation and thermal system.

had to be actively driven into the TEG. This was accomplished by a few cylinders of high pressure N_2. These cylinders were included at the far end of all the serially connected fuel tanks. Each tank was connected with the inlet pipe at the top and the outlet at the bottom and the nitrogen pressure drove the propane into the TEG. While this system was ingenious and worked very well, it also introduced many single point failures into the system because each joint was a potential single point failure for the system as a whole. The tanks had to be U.S. Department of Transportation (DOT) certified airplane flight worthy containers, and therefore they had to be relatively small requiring the annual delivery of many small tanks annually for each observing season. Although the tanks were palletized and interconnected before loading on the airplanes, the final connection had to be made in the field and leak tested in the field usually in −30 °C weather.

A novel temperature control system was designed for the AGO "production" models. As mentioned a coolant fluid reservoir was incorporated into the TEGs. The working fluid was boiling at the operating temperature of the TEG and the vapor was led to an outside condenser through a thermal valve as shown in Fig. 4. This valve opened when the temperature in the enclosure was higher and closed when it was lower than the set point. When the temperature inside the enclosure was lower than the set point then all the heat stayed in the enclosure and was radiated through the fins of the TEG to maintain its temperature (Fig. 4). When the enclosure inside temperature rose above the set point, the working fluid was driven into the condenser where it liquefied and the liquid returned to the fluid reservoir in the TEG. The electrical power requirements and heat production of the AGO are listed in Table III. We have derived the theoretical minimum fuel requirements also in Table III. There were additional inefficiencies that were not considered and in practice the stations needed about twice as much fuel as given in Table III. This system, shown in Fig. 5, worked exceptionally well and kept the enclosure inside temperature constant while the exterior temperature went through its Antarctic extremes.

Another feature of the system was the heated exhaust stack. During the prototype development a frequent failure mode of the system was the icing up and eventual plugging of the exhaust stack. A large fraction of the effluent output of the propane combustion is water vapor. In the Antarctic winter temperatures this vapor rapidly turns into solid ice crystals especially if there was a cold surface nearby. In the early models the stacks were not heated and ice started forming near the output aperture. The ice became a substrate for further water vapor collection until an ice vault was formed around the stack. In some cases the ice would completely close off the stack vent and the AGO thermoelectric generator would go out due to lack of air flow required for burning the propane.

To overcome the stack icing problem special heated stacks were developed. One of these is shown on Fig. 6. Some of the thermal system working fluid vapor was si-

TABLE III. Propane fuelled AGO summary table. Based on a 5% efficient thermoelectric generator. The required insulation is calculated in British Thermal Units for easy comparison to building insulation codes.

Electric power requirement	50	W
Produced heat	1 000	W
	3 418	BTU/h
AGO building surface area	640	ft^2
Temperature differential	100	°F
Minimum insulation requirement	19	*R* value
Propane heat production (BTU)	71,000	BTU/gallon
Propane heat production (metric)	19.8	MJ/l
Annual propane requirement	1 596	L
Specific gravity of propane	0.585	at −40°
Annual propane requirement	934	kg

FIG. 5. (Color online) Propane heated AGO during field testing at Williams airfield near McMurdo Station, Antarctica in the early 1990s. The propane fuel tanks are on the right.

FIG. 6. (Color online) Vapor heated hollow exhaust stack. Photo was taken when station was opened showing that ice formation was minimized on this exhaust stack and the ice did not plug up the exhaust orifice on the top of the stack.

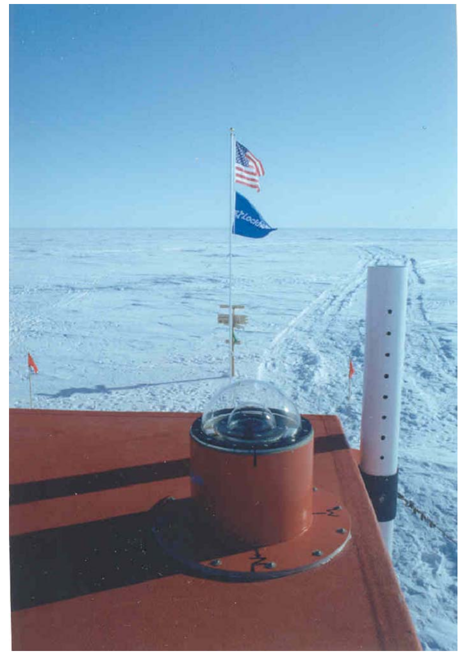

FIG. 7. (Color online) Closeup of the all-sky camera double dome. The upright pole on the right is part of the four-legged AGO elevation system.

phoned off near the fluid reservoir at the output of the TEG and (see Fig. 4) was connected by a tube to the inside of a hollow double walled metal exhaust stack. The object of this feature was to keep all the outside surfaces of the stack above freezing to prevent ice formation on them by heating with hot coolant vapors from the TEG. This arrangement worked at most stations, but as we can see on Fig. 6 that it was only partially successful at the station where the photograph was taken.

The exhaust stack icing was only partially solved with the propane fuelled AGOs and some stations at the coldest location did ice up some years. The addition of the above described exhaust stack heating was a retrofit and did not use an active control as was used to control the enclosure temperature. The narrow tubing used to bring up the coolant fluid vapors from the TEG boiler was not sized adequately to prevent icing during the coldest winter conditions at some stations. Station failures due to icing of the exhaust remained a recurrent problem. It seemed that since the system worked reliably at some stations and not at others a minor reengineering of the stack heating arrangement would have made all AGOs 100% reliable. However, before this final redesign could be incorporated the propane fuelled systems were abandoned for reasons discussed later.

One other important lesson which was learned with the propane fuelled models was the type and placement of the air intake. The AGO enclosures were well sealed and insulated and special provision had to be made for air intake for the TEG catalytic burners. First it was thought that a large area intake with snow filters mounted on the side of the enclosure was the best solution. Unfortunately the wind direction affected the TEG operations because under certain conditions the wind suction could reverse the airflow and adversely affect the TEG operation. After some period of experimenting it was recognized that the best air intake location was on the roof at the same height as the exhaust stack. This mounting ensured that the wind pressure was the same at the air intake as at the exhaust stack. Using this arrangement regardless of the direction and strength of the wind, the cold air at the intake would sink down into the AGO and the warm exhaust would lift.

Lastly one of the most difficult problems in Antarctica is dealing with snow drifts. Although some of the AGO locations had only a few inches of annual snow precipitation the wind would build up large, many feet tall snow mounds behind any obstacle in the path of the wind drift. Such snow build up threatens to bury anything which is left above ground level. To minimize the snow drift build up the AGO enclosures were elevated on poles to permit the wind to blow underneath them. There are four poles attached to the station enclosures and they each have a block and tackle mechanism to elevate the station by pulling it up along each pole. Using the block and tackle system the AGO enclosures were lifted a few feet above the snow level each year at the time of the annual visit.

The instrument sense heads and antennas were located outside the enclosure. The imaging riometers had antenna fields in the vicinity of the AGO enclosure. On the Antarctic plateau there is a several kilometer thick ice layer between the snow level and solid ground and the conductivity of the ice layer is not high enough to act as a good ground plane. Therefore an artificial ground plane had to be provided for the riometer which was a horizontal layer of chicken wire. One of the most demanding instruments was the dual wavelength all-sky camera[22] requiring a port in the AGO enclosure. The all-sky lens is located about 12 in. above roof level inside a fiberglass cylinder with a dual dome placed on top of the assembly shown in Fig. 7. We recognize that the dual dome assembly represented a considerable heat leak, however, this ensured that the dome was a little warmer than the ambient temperature. This and the physical shape of the camera protrusion ensured that the sublimation and wind scouring kept the dome free of ice or snow.

A summary of the system performance until the Austral summer of 1997 is shown in Fig. 8. The dark brown horizontal bars show when the stations were operating. The background color shows the number of stations that were simultaneously operational. After a reasonably successful year in 1994 when three stations were commissioned, two of

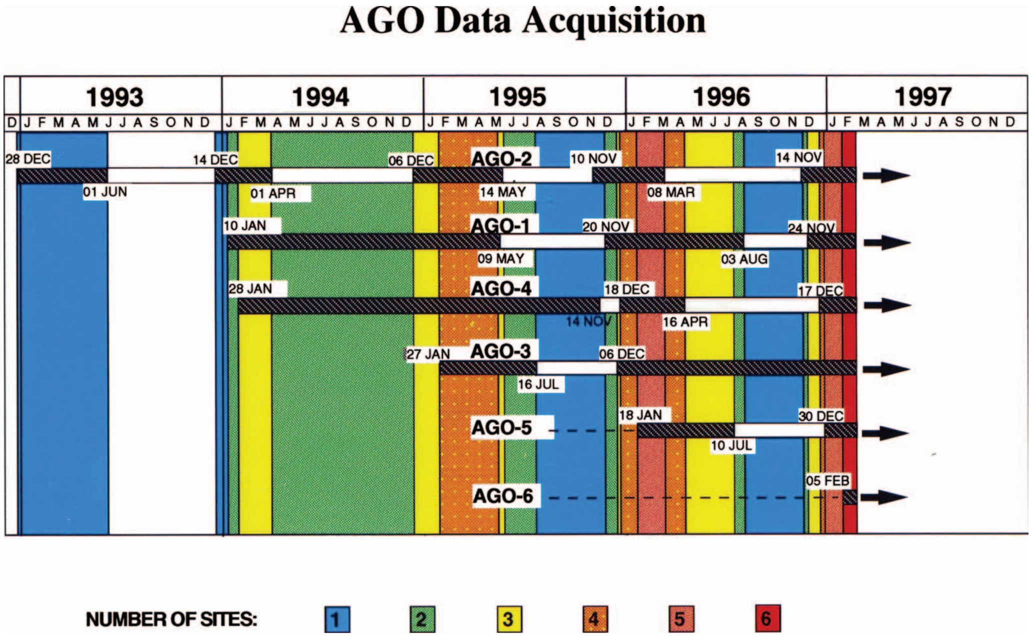

FIG. 8. (Color) Data acquisition from the AGO stations between 1993 and 1997.

the three (AGO-1 and AGO-4) functioned through the entire Austral winter. The following years were less successful because as more stations came on line, only one station a year would stay operational through the entire Austral winter. At this point there were sufficient data to determine what caused the AGO mortality. It was most often the stack icing or a gas leak at some tubing joint in the tank farm. One main advantage of these ground-based autonomous satellitelike observatories over real space based ones is our ability to examine the failed components and take action to mitigate future failures.

Up to 1996 Dr. J. Doolittle of the Lockheed Palo Alto Research Laboratories managed the AGO system development. In 1996 the Lockheed group split and Dr. S. B. Mende, who was responsible for the optical observations, moved to UC Berkeley. The station power engineering and management was taken over by the NSF service contractor. The NSF contractor personnel are generally highly competent and dedicated. However, the field engineers were usually hired on each year fresh and there was insufficient cross training to have them acquire the detailed intimate knowledge required for servicing these propane fuelled AGOs which were really finely tuned instruments needing adjustment to the ambient conditions.

The increasing cost of fuel deliveries prompted the AGO team to look for other energy sources. The propane fuelled AGOs required the annual visit of each site by the C-130 aircraft to deliver several thousand pounds of payload consisting mainly of propane tanks. In addition to the dollar cost of these fuel flights there was the consideration of the aircraft safety associated with open field landings of the large C-130 aircraft on the ungroomed Antarctic ice. A mitigation scheme was to send in first a small aircraft with a field party to groom the runways. However, this meant that servicing each of the six stations now required three dedicated aircraft flights. Initially it was suggested to replace the existing propane fuelled system with a summer only system using solar panels. However, the science especially the optical instruments required winter operation and it was then proposed that AGOs should operate through the winter by using wind power and the work of adapting wind generators for the AGOs was initiated.

VI. PHASE 2: WIND/SOLAR POWER GENERATION

We will spend little time reviewing prior efforts using wind power in Antarctica except to say that most negative experiences come from manned stations near the coastal regions where the forceful katabatic winds make conditions unfavorable for wind turbines. Basically, the turbines were damaged or destroyed by severe winds and blowing debris. However, the AGOs are located on the polar plateau, and annual wind data measured with collocated weather instruments show a much more benign environment. In fact, as can be seen in Fig. 9 (produced by Dan Detrick) the wind speed distributions exhibit a prominent peak at winds ideally suited for wind turbine power generation, at around 5–10 m/s (10–20 kn). It is also evident from the distributions that excessively large or small winds are quite rare. The Antarctic plateau appears to provide ideal conditions for operating wind turbines, which has now been demonstrated by continuous wind power generation at the AGOs during several years of operation.

Reviewing the wind data from Fig. 9 we can see that the winds at the AGOs are quite normal and benign. We rarely see wind speeds of over 30 kn. The other good thing is that ultralow wind speeds are also very rare. That makes the Antarctic plateau ideal for operating wind turbines.

In order to provide a workable wind power system it was necessary to identify an appropriate wind turbine model. Several types of turbines were field tested in Antarctica, some originally designed for marine use delivering a few hundred watts. A common failure mode was observed which

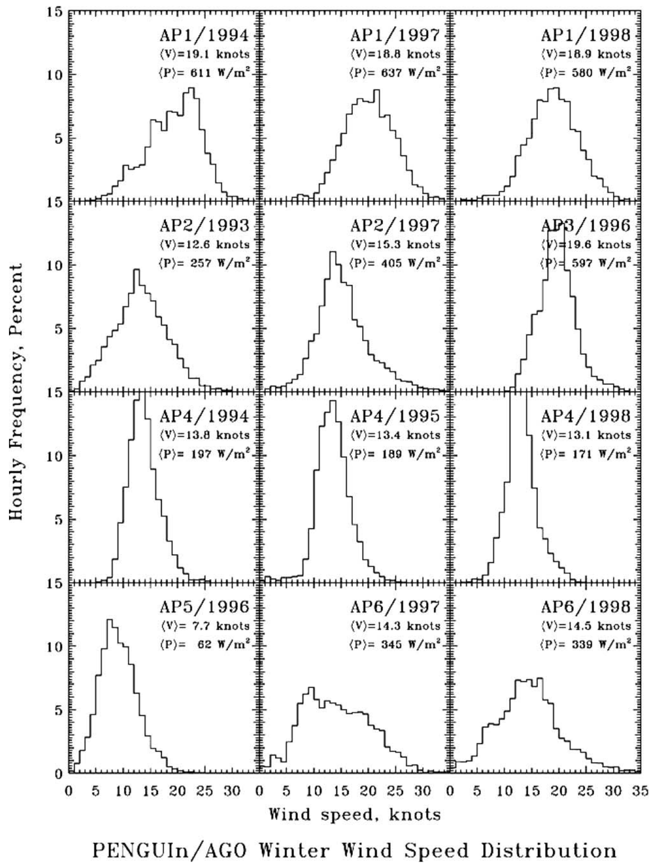

FIG. 9. Wind velocity distribution and average data for AGO-1, 2, 4, and 5 during the years indicated in each panel. The power number is the calculated power available in the air mass passing through a square meter of surface area.

was associated with the slip rings or brushes; for reasons not quite clear the lifetime of these components was very short in the Antarctic cold and dry environment. Eventually, the African Wind Power (AWP) 3.6 turbine was selected by R. Sterling of UC Berkeley, principally because of its simplicity, ruggedness, high power generating capacity in low wind conditions, and because the expected power available from the demonstrated winds at the sites would be sufficient for operating during the winter environment, when solar power is not available. This generator, shown disassembled in Fig. 10, has a set of ceramic permanent magnets glued to the

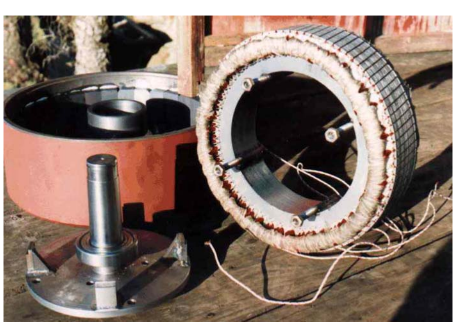

FIG. 10. (Color online) African Wind Power type 3.6 wind turbine. Blades (not shown) bolted to the rotating red magnet assembly at top left. This alternator uses a stationary coil assembly (right) which is mounted on the shaft and back plate (bottom left). There are no moving wires, slip rings, or brushes.

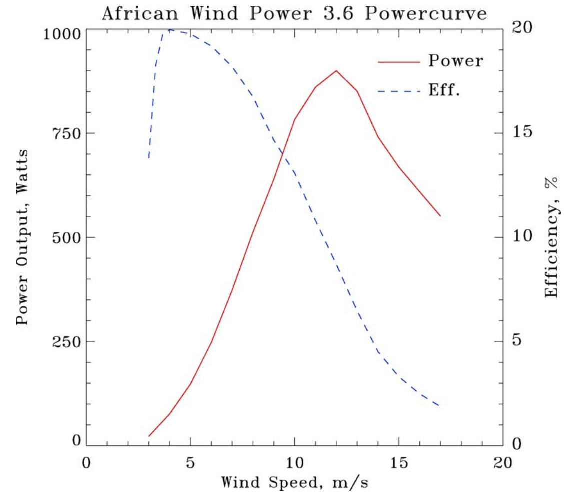

FIG. 11. (Color online) AWP power output and efficiency. This generator puts out significant power even at low wind speeds. (For quick approximation, 1 m/s=2 mph.)

inside of the rotor, so that the coils are nonrotating, all the current carrying elements are hard wired. Instead of the coils rotating within or over magnets, the magnets rotate around the fixed coils. There are only three moving parts in the system and no slip ring. The turbine rotates on its tower to point into the wind, and twisting is accommodated by a flexible wire instead of a slip ring; since the wind direction does not vary significantly, rotation of the turbine around the vertical axis has not been a problem. Even this generator required modifications for the Antarctic supercold applications, and the bearings were replaced with new ones providing a looser fit and a low temperature lubricant “Royco 27” (also known as LG-68) was applied to accommodate operation in the cold temperatures.

The power output and efficiency are shown in Fig. 11. It should be noted that even at fairly modest wind speeds substantial power is produced. The generator is highly efficient at lower wind speeds, and although the efficiency drops with increasing winds there is still a significant increase in the power output, so that adequate power is available at the AGOs year round.

It is important to extract the power from the generator and thereby provide a load on the unit preventing it from spinning too fast and generating too high a voltage for the wire insulation. The electronics therefore have to be able to handle the large output power range.

Conventional control electronics for this generator, as recommended by the manufacturer, use a “pulse width modulation” technique to control the output voltage of the generator and extract the power. In this method, the generator is primarily used to charge the batteries, which are the direct power source for the station payload. The batteries play an integral role in providing the regulated output voltage. In this arrangement a charge controller circuit switches the rectified turbine output rapidly between the batteries and a resistive dump load (typically an air or water heater). The controller regulates the voltage and the pulse width determines the time of the battery being in or out of the charging circuit depending on the battery state of charge. The system

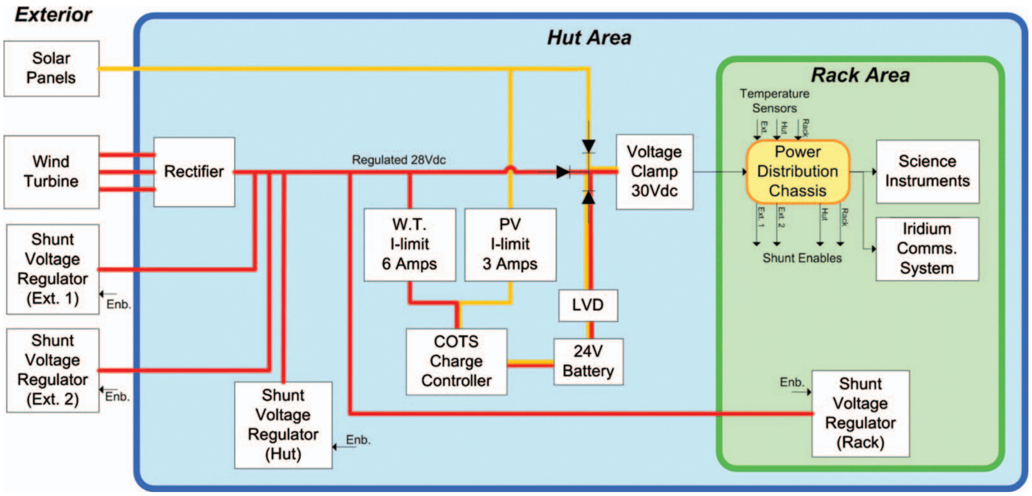

FIG. 12. (Color) Block diagram showing the primary power system components: wind and solar inputs, current-limited battery charging system, and shunt voltage regulators. The wind power path is shown in red while the solar path is shown in yellow.

will not function if either the batteries or dump load are not present or are damaged. This design was tested in the laboratory at UC Berkeley and installed in two AGOs in the initial power system redesign. Unfortunately at both stations the systems stopped working after a few weeks of unattended operations. It was later learned that in one case the manufacturer supplied dump load resistor had burnt out because it was not able to handle the power generated by the WT on a continuous basis. In all cases the batteries were charred and destroyed by overheating when the stations were inspected during the subsequent visit. It is suspected that the batteries got overcharged because there was no other way to dissipate the excess energy produced by the WT.

William Rachelson of UC Berkeley adopted a new design when he assumed the management responsibility for the AGO power system and with S. McBride of UC Berkeley designed a new power system based on large shunt regulators. This system was then adopted and installed into most AGO stations.

The system is schematically illustrated in Fig. 12 and an actual installation photo is provided in Fig. 13. This new system uses a variable shunt regulator to load the AWP wind turbine and produce both heat and a regulated output voltage. In this design, the batteries are not a critical element and a relaxed charging scheme is employed.

One of the largest design challenges is to maintain the temperature inside the enclosure to operate the instrument control and data recording electronics.

The first step in improving the thermal control was to put an additional insulated enclosure for the critical electronics inside the original AGO enclosure. This additional insulation houses only the critical instrumentation and reduces the volume which needs to be kept warm. This more than doubles the original insulation between the critical components inside and outside. Based on the original AGO design requiring about 1000 W to keep the AGOs at operating temperature the added insulation (R value) means that the system could maintain operating temperature at a third or a quarter of the original power. Therefore 2–300 W would be sufficient to maintain the operating temperature. This is well within the range of the AWP generator. The reader should also note that in this design it is immaterial whether the power is burned in heaters or in the operating circuits.

The overall radio frequency interference generated by the power system is relatively benign and it is concentrated at relatively low frequencies associated with the turbine rotation rate. The control system uses active analog current control instead of a switching scheme thereby minimizing the higher frequency emissions.

The new AGO power system is illustrated in Fig. 12. The wind turbine and solar panels are shown on the left hand side along with two voltage regulators. The large original AGO enclosure is shown in blue and the added thermal enclosure for the equipment rack is shown in green. The wind

FIG. 13. (Color online) Since the operating temperature of the AGO can be photograph of the interior of the AGO enclosure. Payload equipment rack is shown on the left with electronic control units, batteries in the middle, and a rack containing bottles of water on the right. The photo shows the added insulation, which keeps the electronics at operating temperature. Note that the insulation was removed from the front for the photograph.

generator is controlled by four shunt voltage regulators. Within each Vreg are 15 field effect transistors (FETs) mounted on five large heat sinks. Each shunt regulator alone can dissipate up to 1500 W, 25% more than the maximum rated output of the AWP wind generator. In practice, however, the load is shared between multiple regulators. The resistance of the each unit is variable and is controlled by a feedback circuit inside each regulator. Two Vreg units are mounted outside of the hut and two are mounted inside, one within the insulated electronics rack and one in the general hut area. Each Shunt Voltage Regulator (Vreg) can be independently switched on or off by means of an enable line (shown as "Enb." in Fig. 12) asserted by the power distribution chassis (PDC). Two Vregs are enabled by the PDC at any given time and are selected based on two temperature sensors, one in the electronics rack and another in the hut. When either of the rack or hut areas reach the maximum allowable temperature, an external Vreg is enabled and the appropriate internal Vreg is disabled (Fig. 12). This arrangement ensures that regulated power and controlled thermal conditions are made available to payload electronics, while also presenting the appropriate load to the wind generator at all times.

Within the PDC (Fig. 14), a Campbell Scientific CR10X data logger performs the primary control functions for the power system. The CR10X is a commercially available, reliable, low-power control module designed for unattended operation. It is software programmable and can take analog or digital inputs from temperature and other sensors and produce appropriate analog and digital control signals. It uses very little power and has its own backup battery illustrated in Fig. 14 as PS100. The CR10X has a wide operating temperature range (−80 to 50 °C) and can operate for several weeks on its own battery.

Both the wind and solar inputs are connected through a current-limiting circuit to the battery charge controller, which charges the station batteries. The current-limiting circuits allow the instrument load to continue operating even when a dead short is presented to the charge controller. Although the station batteries are sufficiently large to ensure operation through short breaks in the wind, they cannot handle the

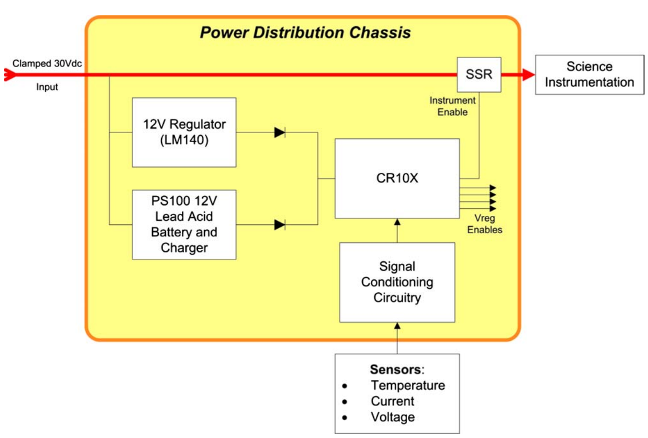

FIG. 14. (Color online) Block diagram of the PDC. Within the PDC, the CR10X can derive its power from a regulator (if there is bus power) or from a dedicated backup battery.

heating requirement for any length of time. For prolonged windless periods the station stops operation and can fall below its operating temperature range. The most important feature of the AGO power system is that it can recover from such "cold soaks." The CR10X orchestrates the recovery by bringing the unit up to operating temperature prior to restoring instrument power.

The photovoltaic portion of the power system consists of four 12 V 120 W Kyocera panels, mounted in series pairs on opposing sides of the AGO shelter, forming two 24 V circuits. Only one circuit is illuminated at a time and there are periods of the day when the sun does not directly illuminate either set of panels. During these times the station operates on wind or battery power. After sunset, which occurs during April, the system runs entirely on wind power. The solar panels, via the isolation diodes described below, may charge the station batteries up to the current-limited rate and supply current to the payload.

The three main power system inputs, wind, solar, and batteries, are connected together at a common point with isolation diodes. This common point is the input to a voltage clamp circuit, which serves to regulate the solar panel output voltage as well as protect the payload electronics from possible overvoltage conditions. Such conditions could occur should the Vreg circuits fail entirely for some reason, leaving the wind turbine free running with an unregulated output. The voltage clamp circuit can withstand input voltages up to 200 V while still supplying the full 50 W instrument load (at 25 °C) and protects itself from excess power dissipation by means of a bimetallic thermal cutoff switch. The cutoff switch, which engages when the voltage clamp components reach 100 °C, open circuits the output until the temperature decreases. This allows for continued, although limited, operation of the instrument and data system payload given the unlikely failure of the Vreg components.

Figures 15–17 are schematics of the specially engineered components for the AGOs, namely, the voltage regulator dynamic shunt, the voltage clamp, and the current limiter for charging the batteries. Figure 15 is the shunt regulator circuit shown schematically. It uses series resistance of the generator (0.4 Ω) plus the external series resistance in combination with a shunting transistor array to provide a reduced and regulated voltage output. The circuit has five arrays of transistor-resistor combinations, each of which can sink 10 A. Resistors limit maximum current and provide heat dissipation, while source resistors ensure that the current through the circuit is properly divided among the transistors. A simple feedback mechanism using the differential transistor pair controls the circuit. A diode provides the reference voltage for comparison.

The voltage clamp (Fig. 16) is a simple feedback regulator using P-channel metal oxide semiconductor field effect transistor (MOSFET). When the input voltage is lower than the desired output voltage, the MOSFETs are fully on, and the output voltage approximately equals the input voltage. When the input voltage is greater then the set voltage, Q1 and Q2 form a simple feedback amplifier to control the out-

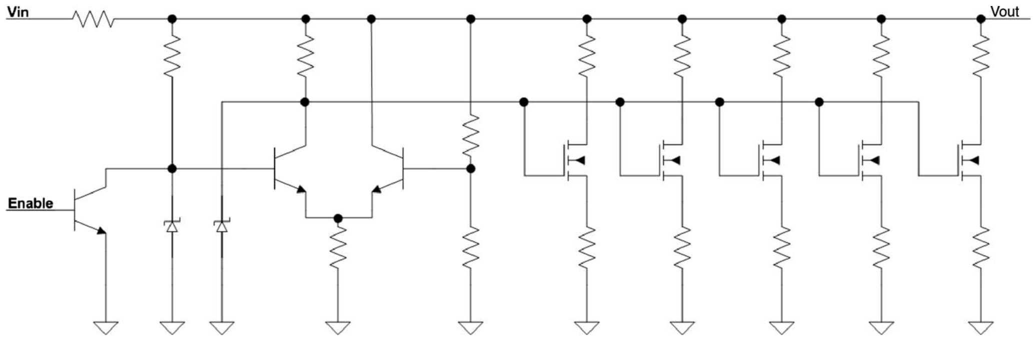

FIG. 15. Schematic of shunt-type voltage regulator dynamic shunt.

put MOSFETs. The voltage setpoint is determined by D1 and the feedback resistors R2 and R3. Extra protection is provided by a thermal cutout switch.

The current limiter (Fig. 17) uses P-channel MOSFETs as controlling devices. The circuit is a simple means of controlling current. A current sense resistor forward biases the base-emitter junction of a transistor, which turns on the MOSFET. The transistor is mounted on the MOSFET to reduce current when it gets hot. In addition, a thermal switch provides an extra element of safety in case of overheating. The heatsink/transistor combination can dissipate approximately 150 W and was tested with a dead short across the output. The circuit allows 50% more current at −65 °C.

It was suggested that it is possible to increase the heat capacity of the AGO and store the heat in the form of water within the rack enclosure for low wind periods (shown in Fig. 13). Since the operating temperature of the AGO can be around 0 °C, water is an ideal heat storage medium because its heat capacity is enhanced by its latent heat of fusion providing temperature stability close to 0 °C. Although water bottles were stored in the AGO this system of heat storage was relatively inefficient because there was limited heat exchange between the atmosphere in the enclosure and the water contained in the plastic bottles. The scenario is quite likely to occur that the air temperature in the enclosure drops way below freezing and the water is still in liquid state inside

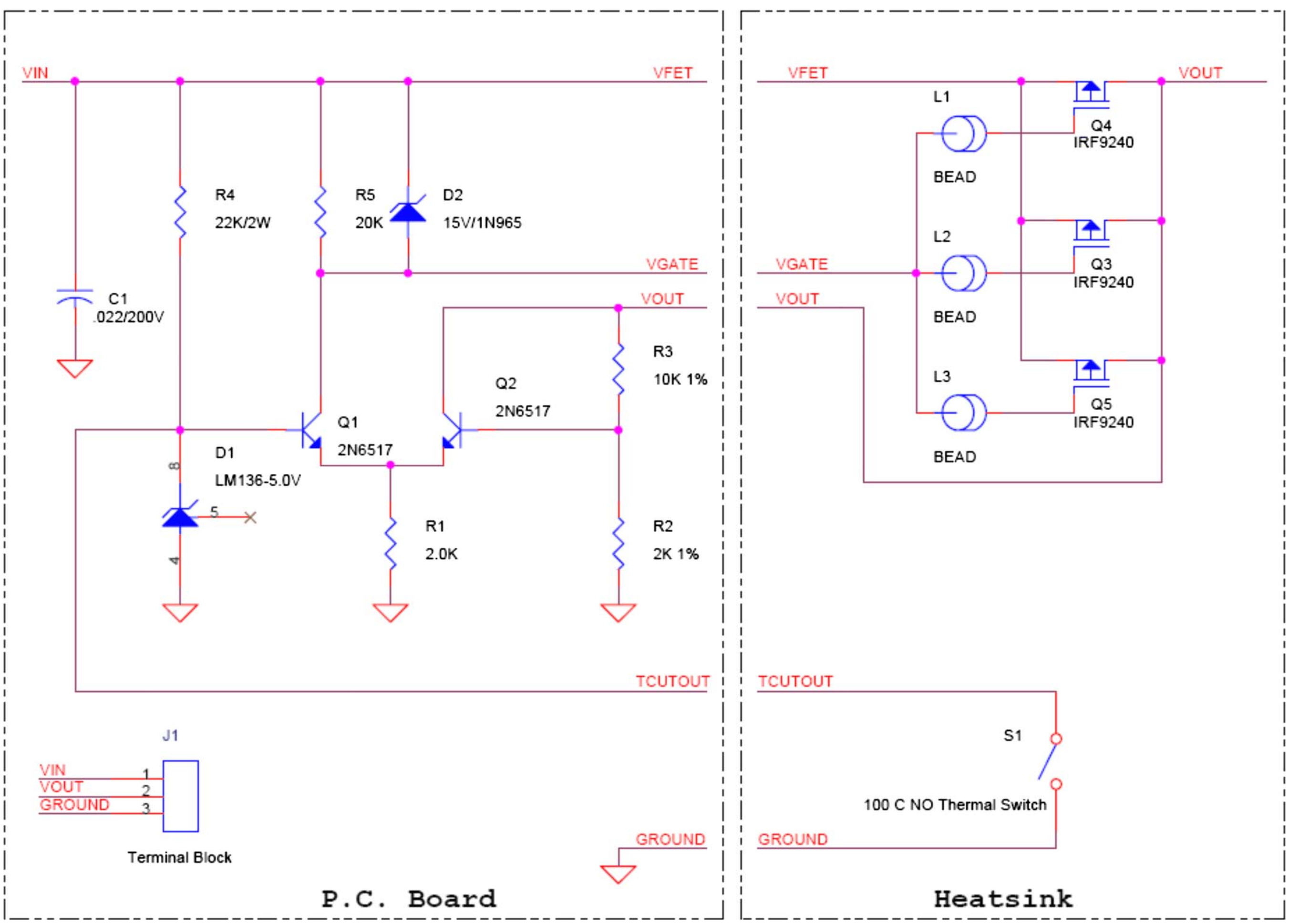

FIG. 16. (Color online) Schematic of the voltage clamp.

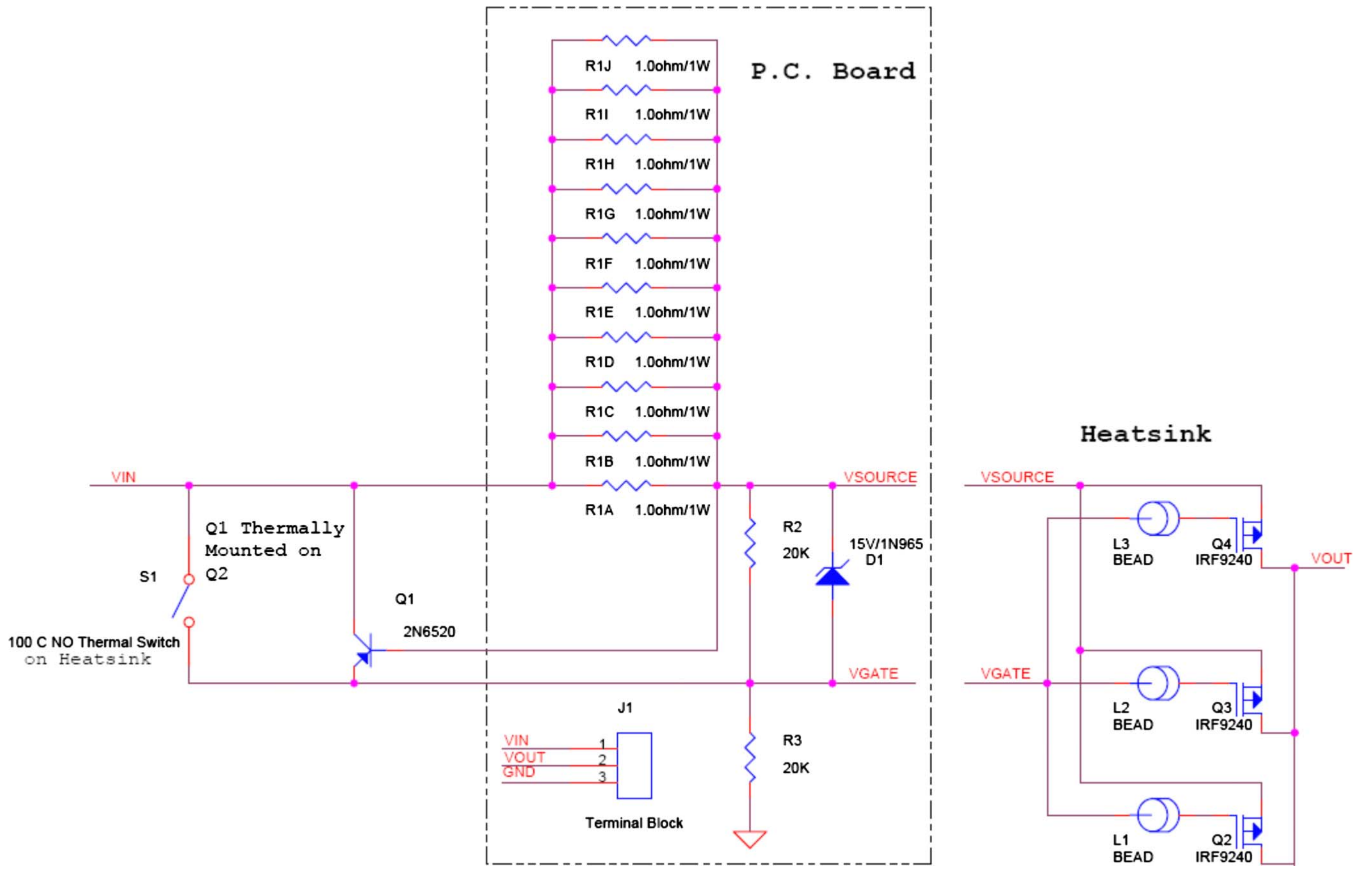

FIG. 17. (Color online) Schematic of the AGO current limiter.

the plastic bottles. This scheme, if properly engineered for exchanging the heat between the air and water with appropriate highly conductive water containers and large convection fins, could be a promising technique to prolong the operation through windless periods.

Wind generators typically operate much better when they are elevated high above ground where there is less turbulence and more wind. Because of the completely flat terrain and steady winds on the Antarctic plateau, it is not necessary to install a very tall mast. We opted for a 20 ft pole mount for our AGO installation. The erection of the pole with a 250 lb generator on top is still quite a challenge at a remote field site (Fig. 18). It is accomplished with a hinged mast and an appropriate arm ("gin pole") attached at the foot of the mast. Figure 18 shows a picture taken of such a hoist operation. Each of the guy wires and the hoist line terminate under the snow surface with a "deadman" anchor. These anchors are constructed from 2 ft $\times$ 2 ft $\times$ 3/4 in. plywood and buried about 4 ft below the snow surface.

Figures 19 shows one of the AGO installations. The AWP is the large turbine with the white blades. The other generators are not in service, they are just left over from prior field tests. Figure 19 shows the small "twin otter" plane which is now used for servicing the sites. There is no need for several annual visits by the large C-130 planes, which were used to deliver the fuel tanks.

The new design proved itself to be much more reliable than the old one. In the Austral summer of 2005–2006 the new power system was installed into AGOs 1, 2, and 5 with AGO-3 following in the next season of 2006–2007. From the

FIG. 18. (Color online) AWP turbine installation at a field site. The WT is attached to the 20 ft pole and then winched into place.

FIG. 19. (Color online) AGO installation with the small Twin Otter plane used to drop and pick up the service crew.

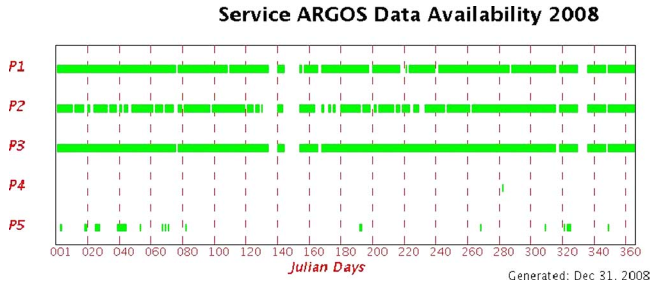

FIG. 20. (Color online) Service ARGOS data for the AGO system in 2008. There are some gaps in the data primarily because of extended windless periods. However, the stations recover from those periods and continue operating through the rest of the year. P5 had a problem with the housekeeping transmissions but the power system and on site-data recording was operational. P4 and P6 were non-operational because they had not had the wind generation system installed.

standpoint of accessibility AGO-6 is the toughest and currently there are no plans to visit it. We are planning to make the necessary changes at AGO-4 in the future. To illustrate the station reliability we show the ARGOS housekeeping data for the AGOs as Fig. 20 for 2008 the second year when all four AGO-s were operating. P5 had some problem with its satellite transmission and the recurrent marks bear witness that the power system was alive throughout the year. Thus the reliable powering of four stations during a whole Antarctic winter season was demonstrated in 2008. At the time of writing the manuscript the 2009 data were not available.

VII. OPTICAL DATA FROM AGOs

In the early season in 1995 we had AGOs 1–4 deployed and operational (Fig. 8) and it was possible to make auroral mosaics. An example of such a mosaic is shown in Fig. 21. The fifth station is South Pole. To make such mosaic the auroral imagers had to be projected into geographic coordinates. Such a transformation is not unique and requires several assumptions, for example, the mean altitude of emission. Nevertheless they provide a larger area of coverage of the Aurora Australis.

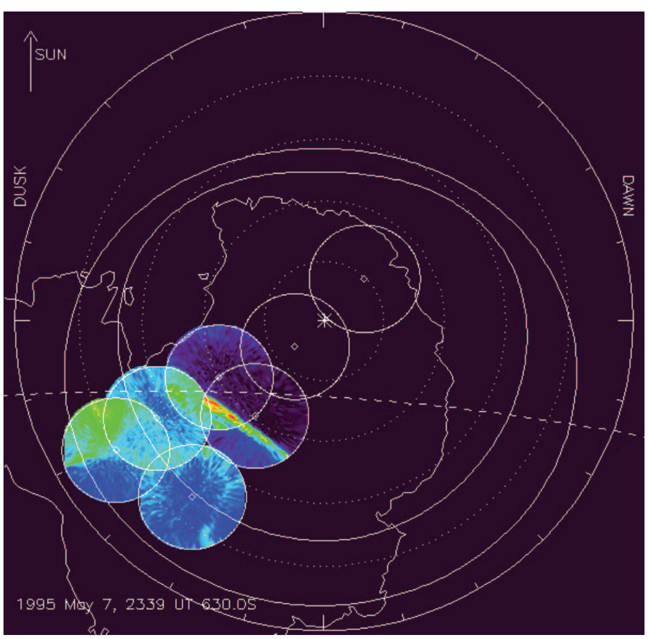

FIG. 21. (Color) AGO auroral mosaic. During the 1995 observing season AGO1 to AGO4 were operational but 5 and 6 were not yet deployed. The all-sky images were projected on a "plane and a mosaic" display was constructed.

A more recent application of the AGO imager network is the observation of auroras under the THEMIS 5 satellite cluster. The main objective of the THEMIS mission was to investigate nightside auroral substorms during northern winter. Thus the satellite orbits were optimized for this task by making sure that the apogees were lined up so that the satellites reach their greatest altitude around midnight in the northern hemisphere in winter (February–March). However the same orbit configuration equally applied to the dayside during northern summer (July–August). This is exactly the time when the Antarctic optical observations from South Pole and the AGOs are optimum.

In Fig. 22 we are providing a collage of all-sky imagers taken at AGO-1 on 12 August 2007. This was taken at a time when the THEMIS satellites were entering the magnetosphere on the dayside in a region magnetically conjugate to South Pole and AGO-1. In the image collage we are observing the poleward boundary of the aurora (magnetic poleward is up). This is a representative sample showing an image once every 5–10 min. Intrinsically the time resolution is about 1 min for P1 and 20 s for the instrument at South Pole Station. In Fig. 23 we reproduced the Keogram which was produced from the full time resolution image sequence both for P1 (top) and South Pole (bottom). The thick yellow horizontal bar shows the period of the Fig. 22 collage. The Keogram for P1 illustrates the auroral latitude dynamics at the poleward edge of the aurora showing what one might recognize as poleward moving auroral forms. We have superimposed the THEMIS-A satellite Bz magnetic field data. THEMIS A is near the subsolar point approximately conjugate to the stations. At the beginning of the period prior to 14:30 the satellite Bz component is low because the satellite is just outside of the magnetosphere in the magnetosheath. After about 16:45 the satellite is firmly inside the magnetosphere. In between the two times the magnetopause boundary was moving in and out crossing over the spacecraft several times. This is an example of a data set which may be key in trying to investigate whether or how the aurora responds to motions of the magnetopause. These motions could be a response to either erosion of the closed field line magnetosphere through the process of reconnection or it could be caused by solar wind pressure pulses compressing the magnetosphere as a whole.

In summary having the unattended Automatic Geophysical Observatories enables us access locations in Antarctica where key measurements related to Earth space can be made.

VIII. SUMMARY

The Automatic Geophysical Observatories provide a suitable unattended platform to operate auroral imagers. It has taken many years to develop them to their current state of reliability. Some success was accomplished by using a propane fuelled power system. However, this approach was

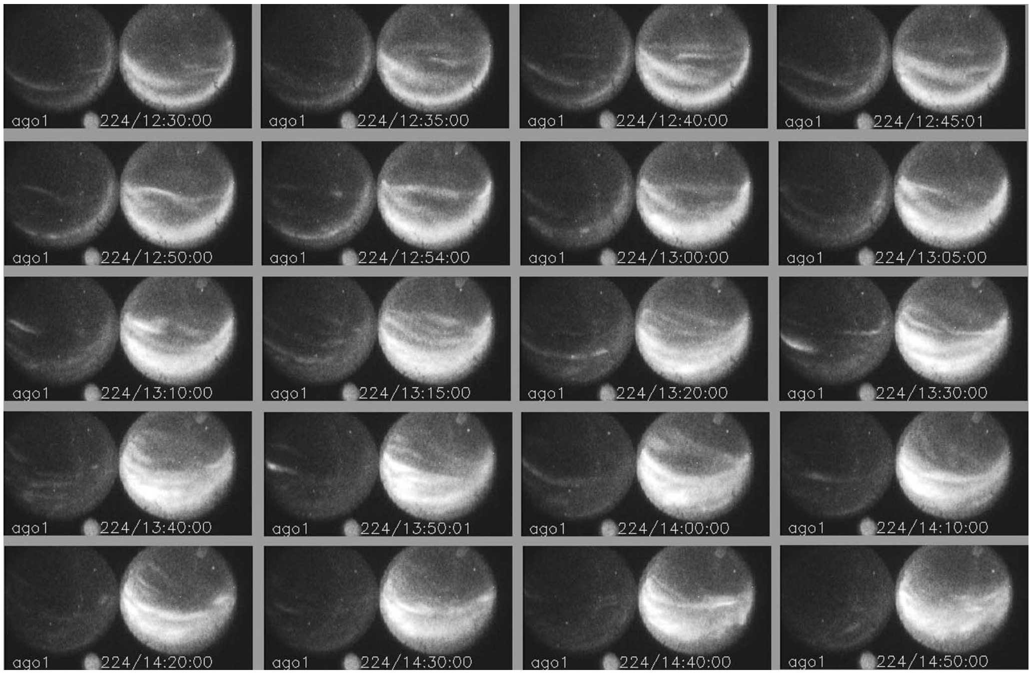

FIG. 22. Time sequential images taken from AGO1 during the period when the magnetic foot points of the THEMIS satellites were crossing the field of view.

discontinued primarily due to the high cost of fuel delivery to these far away Antarctic sites and to continue the program the stations were retrofitted with wind turbines and solar cells. Although during the winter the stations rely on the highly variable local wind, the only available local energy source, the new power systems were operational over 90% of the time. These new reliable power systems use wind generators which have stationary coils and rotating magnets thus avoiding current conduction through moving components. For reliable performance these types of generators require active controlling of their output load and a new type of power management system was developed that performs this function and at the same time delivers temperature control of the station electronic enclosure.

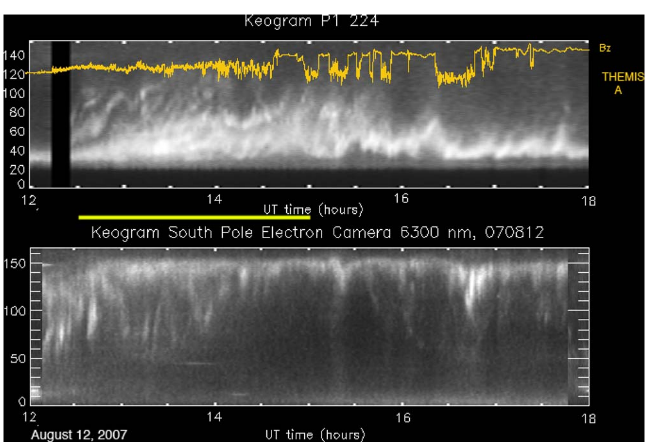

FIG. 23. (Color online) Simultaneous Kegram from South Pole and AGO1. These stations are on the same meridian. The yellow bar between the Keograms represents the time interval of the time of the collage of Fig. 22. The THEMIS-A satellite was located near the subsolar point and the magnetometer Bz data were superimposed on the upper Keogram in yellow showing when the satellite was in the magnetosphere and when in the solar wind. Higher Bz signifies that the satellite is in the magnetosphere.

The imaging of the dayside aurora under the THEMIS constellation is an example of a measurement at a key location which would not be possible without the technology developed for the AGO platform. All instrument data for the first few years of quasicontinuous data from the AGOs are currently being analyzed. We expect to have several significant papers to appear in the near term using these data. The THEMIS constellation provides a significant correlative data set and the Antarctic data are the "ground truth" through observables of the dynamics of Geospace. The apogee of the satellites of the THEMIS constellation drifts across the various local time zones optimizing the joint observations at different local times each year. The drift rate of the apogee of the three innermost satellites, those which remained in Earth orbit, is approximately 1 month per year. To cover all local time ranges takes 12 years. Depending on the longevity of the satellites significant data collection can continue for another 10 years.

ACKNOWLEDGMENTS

The authors recognize that this article only covers part of the entire U.S. AGO PENGUIN program and many others have made great scientific and technical contributions to the program, including Professor H. Fukunishi of Tohoku University and Professor Roger Arnoldy of the University of New Hampshire. The entire program also involves a complex data retrieval system and credits are due to Professor N. Petit of Augsburg College for providing the data processing and archival system. The authors gratefully acknowledge the many outstanding engineering contributions of the staff of the Lockheed Palo Alto Research Laboratories and the UC Berkeley Space Science Laboratories. Special mention should be made of Mr. Steve Geller who wrote the AGO imager software and Mr. Francis Pang who built the AGO all-sky imager electronics. The writing of the paper was supported by the Antarctic program of NSF under Grant Nos. 0636899 and 0340845. The THEMIS data analysis program was supported by NASA under Contract No. NAS5-02099.

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