The PLATO Dome A site-testing observatory: Power generation and control systems

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The atmospheric conditions above Dome A, a currently unmanned location at the highest point on the Antarctic plateau, are uniquely suited to astronomy. For certain types of astronomy Dome A is likely to be the best location on the planet, and this has motivated the development of the Plateau Observatory (PLATO). PLATO was deployed to Dome A in early 2008. It houses a suite of purpose-built site-testing instruments designed to quantify the benefits of Dome A site for astronomy, and science instruments designed to take advantage of the observing conditions. The PLATO power generation and control system is designed to provide continuous power and heat, and a high-reliability command and communications platform for these instruments. PLATO has run and collected data throughout the winter 2008 season completely unattended. Here we present a detailed description of the power generation, power control, thermal management, instrument interface, and communications systems for PLATO, and an overview of the system performance for 2008. © *2009 American Institute of Physics.* [DOI: 10.1063/1.3137081]

I. INTRODUCTION

The Antarctic plateau is now widely regarded as offering the best atmospheric conditions for a ground-based astronomical observatory. The plateau is very high, cold, dry, and calm; factors which increase telescope sensitivity at infrared and submillimeter wavelengths, and enable high-resolution imaging at visible wavelengths. The desire to find the ideal location on the Antarctic plateau for astronomy has motivated a series of site-testing campaigns over the past decade by a number of international groups. The first site to be studied, the U.S. Amundsen-Scott South Pole station, was found to have many excellent characteristics;[1–6] there are now several world-class telescopes at this site, including the 10 m diameter South Pole Telescope.[7] Recent results from the French/Italian Concordia station at Dome C have demonstrated superior conditions for optical and infrared astronomy,[8–10] leading to the proposal for a 2.5 m class optical/infrared telescope at that site.[11,12] Several factors suggest that Dome A, a currently unmanned site lying at the highest point (~4100 m) on the Antarctic plateau (see Fig. 1), should have superior conditions to both South Pole and Dome C for certain types of astronomy.[13–17] The Plateau Observatory (PLATO) was therefore deployed to Dome A in January 2008, in order to measure the atmospheric conditions of relevance.[18]

PLATO offers a unique capability. It is the third-generation self-powered robotic Antarctic observatory developed at the University of New South Wales and dedicated to astronomical site testing. The first such robotic facility, the Automated Astrophysical Site Testing Observatory[19] (AASTO) was deployed to the permanently manned South Pole station in 1996. The AASTO was designed as a test bed for remote Antarctic power generation systems and as a control and communications platform for a number of site-testing instruments.[3,5,6] The AASTO was based closely on the U.S. Automated Geophysical Observatory,[20] and used a propane-fuelled thermoelectric generator that produced ~50 W of electrical power and ~2.5 kW of heat.

The second generation facility, the Automated Astrophysical Site Testing International Observatory (AASTINO),[21] operated at Dome C station from 2003 to 2005. Recognizing that astronomical site-testing instruments would eventually require an order of magnitude more power than the thermoelectric generators could produce and that higher efficiency was needed, the AASTINO utilized a hybrid Stirling engine/solar power generation system. This system produced ~200 W of electrical power and ~3.5 kW of heat. A further disadvantage of the thermoelectric generators was that they required liquid propane fuel. In contrast, the AASTINO (and subsequently PLATO) used Jet A-1, which is much easier to transport and store in Antarctica. AASTINO was operated fully remotely during the 2003 and 2004 winter seasons, and obtained valuable data from a series of site-testing instruments,[8,22] in the lead-up to Dome C station becoming permanently manned in 2005. The demand for yet more electrical power, and the need to operate PLATO at

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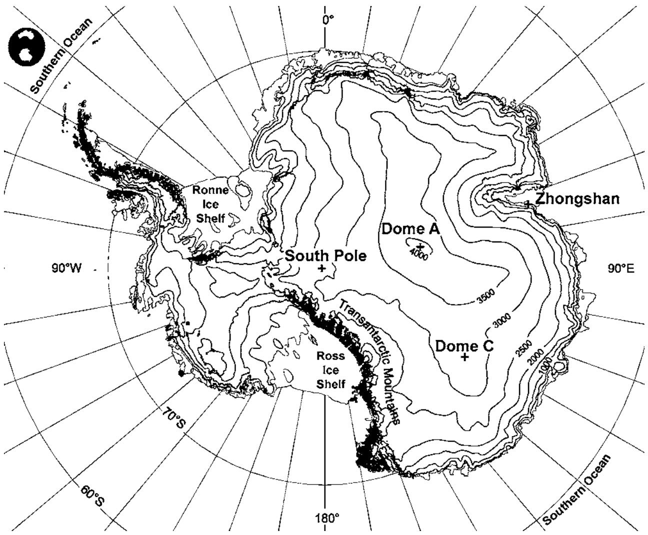

FIG. 1. Map of Antarctica showing the Chinese coastal station Zhongshan and the high plateau stations south pole, Dome C, and Dome A. Basic map courtesy of the Australian Antarctic Data Centre.

even higher altitude, led to the decision to replace the Stirling engines used in AASTINO with diesel engines.

PLATO was designed to provide continuous power and heat, and a high-reliability command, control, and communications system for a range of site-testing and science instruments. The PLATO observatory was designed and constructed during 2006–2007 at the University of New South Wales. Site-testing and science instruments[23–27] contributed by several international teams were integrated into the observatory in late 2007. PLATO was then delivered (via icebreaker and tractor traverse), installed, and commissioned at Dome A as part of the Polar Research Institute of China (PRIC) 2008 PANDA expedition. China, whose expeditioners were the first to visit the site in 2005, intends to establish a permanently manned base at Dome A within the next decade.[28] After the PRIC expedition left the site in late January 2008, the PLATO systems remained operational throughout the winter period, and ran unmanned for 204 days before it stopped communicating in August 2008. At the time of writing (December 2008), the next PRIC expedition is onroute to Dome A. As part of this expedition, maintenance will be performed and upgrades installed to the PLATO power generation, control, and instrument systems, to prepare it for the 2009 season.

Current plans are for a permanent, year-round station called Kunlun to be built at Dome A within 10 years. Once this is operational, a robotic facility such as PLATO is no longer needed at that site. However, it is likely that PLATO and its derivatives will continue to be used for many more years in the exploration of other Antarctic sites.

A detailed description of the PLATO instrument suite and the preliminary scientific results from the first season of operation is given by Yang *et al.*[29] Here we present the system design of the power generation, power control, thermal management, instrument interface, and communications systems for PLATO, and an overview of the system performance for 2008. A detailed analysis of the 2008 season performance is given by Luong-Van *et al.*[30]

II. PLATO DESIGN

As the Dome A site is currently unmanned during the winter months, the main design requirement for PLATO was that it be completely self-supporting, i.e., generating its own heat and electricity, and be able to operate robotically with only minimal external control via a low-bandwidth (2400 baud) satellite communication link. During the 2008 PRIC expedition only 2 weeks were spent at the Dome A site. It is likely that summer-time access to the site will be similarly restricted until the winter station is complete. PLATO is therefore designed with a series of partially assembled modular subsystems, which minimizes the on-site time required for installation, commissioning, and systems upgrading.

The extreme environmental conditions at Dome A impose a number of requirements on the system design for PLATO; see Refs. 31 and 32 for a review of the implications of Antarctic plateau conditions for telescope design. Dome A has a physical altitude of ~4100 m, but the atmospheric pressure is ~570 mbars; equivalent to a pressure altitude of ~4600 m; this difference is a result of the reduction in atmospheric scale height in polar regions. This very low pressure has implications for the performance of internal combustion engines and computer hard drives, and leads to difficult working conditions for personnel. The low atmospheric pressure at Dome A also requires that all electronic devices and modules that rely on air cooling be derated by a factor of 2. In PLATO this derating was often achieved by duplicating devices (such as power electronics) and running them in parallel. This also provides some redundancy (albeit at reduced power level). The ambient temperature at Dome A typically ranges from −25 to −40 °C during the summer months and from −55 to −75 °C in midwinter (see Fig. 2); electronic systems must be heated and/or heavily insulated and low-temperature materials must be used for all external components. As observed at other high Antarctic plateau sites such as Dome C,[33,34] the ground-level relative humidity at Dome A is typically 50% with respect to the dew point but supersaturated with respect to the frost point; any exposed surfaces will thus accumulate ice unless heated to a few degrees above ambient.

As shown in Fig. 2, Dome A experiences an ~130 day continuous period of darkness; solar power is thus only useful for a fraction of the year. Automated Weather Station data from Dome A have demonstrated that is one of the least windy sites on the planet,[35] making it difficult to derive significant power from wind generators. Similar to most sites on the Antarctic plateau, the main form of precipitation at Dome A is from diamond dust, a ground-level cloud composed of micron-sized ice crystals; this can lead to snow accumulation on exposed surfaces and snow drifts forming around ground-level structures.

PLATO consists of two separate modules: the engine module and the instrument module. Each module is based on a custom-modified 10 ft shipping container. They are designed to be coupled together and shipped as an ISO standard 20 ft container, allowing for convenient transport via road, rail, sea, and ice sled. Each module is heavily insulated with polyurethane-foam steel-clad panels fixed to all internal

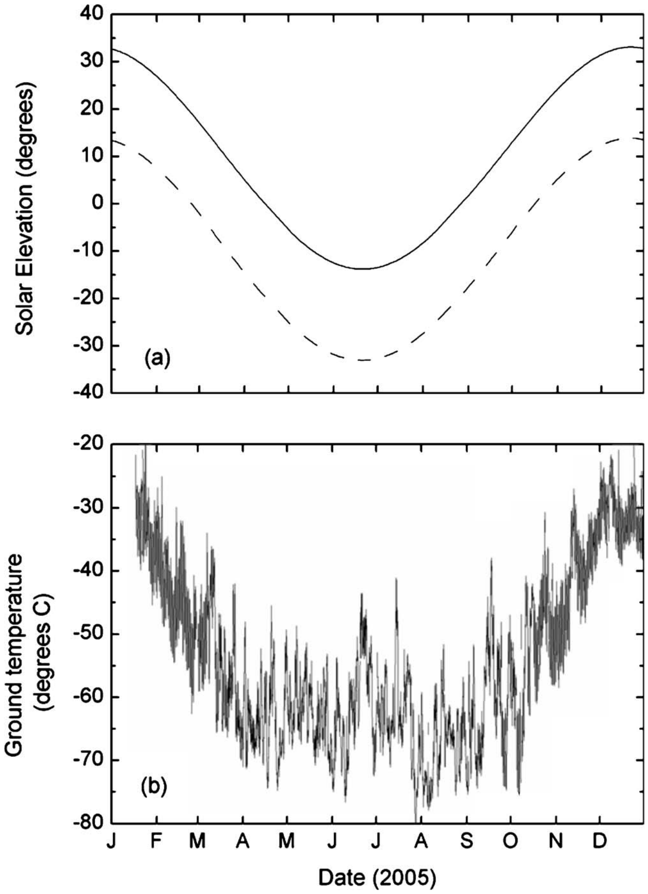

FIG. 2. (a) Maximum and minimum daily solar elevation throughout the year at Dome A. (b) Ground-level air temperature at Dome A during 2005 measured by a Chinese-Australian automatic weather station (data courtesy Australian Antarctic Division).

surfaces. The engine module houses the primary power source, consisting of a bank of diesel engines. This power is augmented, when sunlight is available during the summer months, by an array of solar panels mounted externally on small masts hammered into the snow. The PLATO instrument module, which is located ~40 m from the engine module, houses the power electronics, and control and communication systems. Site-testing and science instruments are mounted either on the roof of the instrument module or externally on the snow. The dual-module design of PLATO provides physical isolation of the control electronics and instrumentation from the noise, water vapor, and diesel fumes of the power plant; allows the system to be readily expanded in the future; and is motivated by logistics, manufacturing, and testing considerations. Figure 3 shows a picture of the PLATO installation at Dome A.

III. SYSTEM OVERVIEW

PLATO was designed to provide power and heating for a number of individual instruments. Initial estimates indicated a required average/peak power load of 800/1600 W during winter, dropping to 400/1200 W during the summer months when several instruments that require dark skies are not operational. This power is primarily provided by two banks of three diesel engines (located in the engine module) providing up to 1.8 kW per engine.[36] Additionally, two external solar panel arrays can provide a total of up to 1 kW when sunlight is available.

FIG. 3. (Color online) Picture of PLATO installation at Dome A. The (green) engine module is shown in the foreground. In the background the solar panel array and the (yellow) instrument module can be seen.

A schematic of the PLATO power and control system network is shown in Fig. 4. Electrical power from both the solar and diesel sources is converted to a 28 V dc (nominal) bus that is used to charge a 320 A h lead-acid battery bank, consisting of six 4 V gel cells located inside the instrument module. This battery bank provides uninterrupted power to the instruments and PLATO control systems in the event of an engine shutdown, and gives at least a day of leeway for recovery procedures to be implemented using the satellite communication system.

System control[37] is via a pair of "supervisor computers units," located in the instrument module. These computers communicate via a local controller area network (CAN) bus with the PLATO subsystem control units: the "engine control unit" (ECU), the "thermal control unit" (TCU), and the "power distribution unit" (PDU). The PLATO supervisor computers communicate with external (midlatitude site) computers via the Iridium satellite network, for more details see Ashley *et al.*[38]

The engine module is linked to the instrument module via an umbilical cable. This cable transfers high-voltage engine output power from the engine module to the instrument module, brings the 28 V bus back to the engine module to power the engine starting system and thermal management, and contains the bidirectional CAN bus link.

Details of the power generation and power control systems are given in Sec. IV. The thermal management systems, and the instrument interface and control systems are described in Secs. V and VI, respectively. The supervisor computer hardware and the system control software are detailed in Sec VII.

IV. POWER GENERATION AND POWER CONTROL

A. Diesel power

The primary power generation system for PLATO comprises two banks of three single-cylinder 350 cm^3 diesel en-

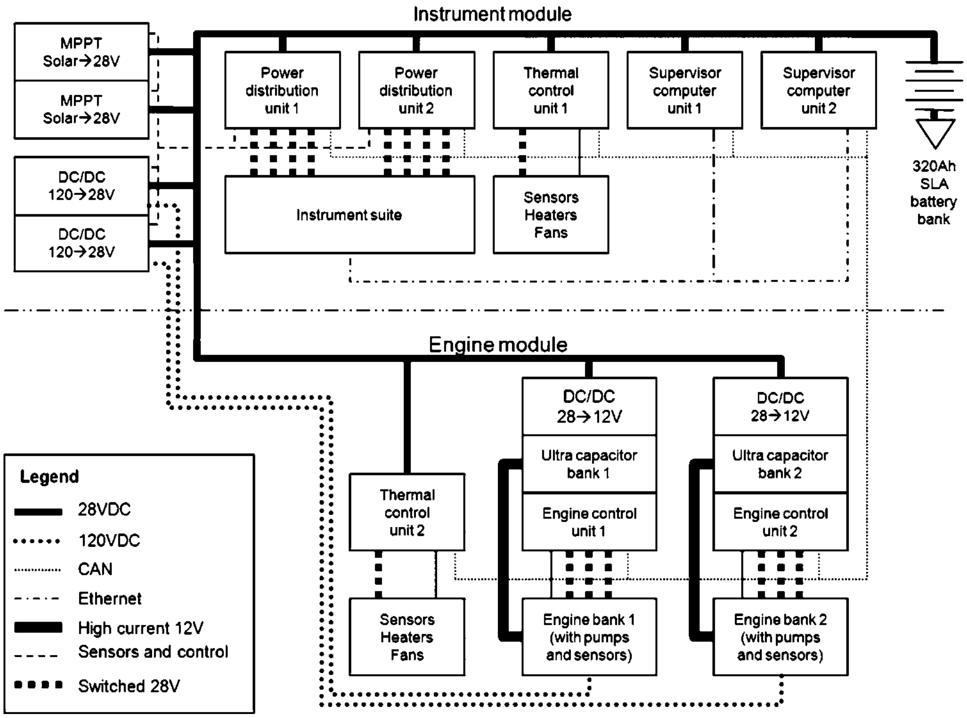

FIG. 4. Overview of the PLATO control system showing the interconnection of all major subsystems and power routing. From Luong-Van *et al.*, Proc. SPIE. Copyright © 2008 by SPIE. Reprinted by permission of SPIE—the International Society for Optical Engineering.

gines (Hatz 1B30). Four of the six engines are equipped with brushless (eCycle) alternators directly coupled to the crankshaft and producing three-phase ac output (120 V ac at 2200 rpm). The ac output from these alternators is diode rectified to produce a dc voltage that is fed into a common high-voltage bus for each engine bank. The remaining two engines are equipped with Mavilor dc high-efficiency motors connected via a flexible shaft coupling. These motors, used as generators, also produce a voltage of 120 V dc at 2200 rpm. This output is fed via a series diode (to prevent reverse current flow), into the common high-voltage bus. The high bus voltage is chosen to allow a large separation (~40 m) between the engine and instrument modules with relatively little power loss (<20 W) for a reasonably sized cable (16 mm^2). Diode rectification is performed in the engine module (rather than sending ac power between the modules) as this allows each engine rail to be wired onto a common bus, hence reducing cable requirements.

The engines are mounted via vibration isolators onto a large custom-built aluminum fuel tank that in turn is mounted onto the engine module floor. The fuel tank holds ~4000 l of Jet-A1 aviation fuel. This choice of fuel is motivated by its high energy density, clean burning, ready availability in Antarctica and low freezing point (−47 °C). For each engine, fuel is pumped from the bottom of the tank through a large-area fuel filter using a metering pump that is running much faster than the engine fuel-burn rate. Warm, unused fuel from the engine injector is fed back to the main tank via a return line in order to increase the fuel tank temperature in the vicinity of the pick-up point. Each engine is equipped with its own bulk oil filtration and recirculation system in order to extend the required servicing interval from the nominal 200 h of a stock engine to the required ~2000 h.

Each engine is equipped with a conventional starter motor that draws up to 300 A at 12 V. To provide this power, two banks of ultracapacitors are provided, giving 1000 and 500 F respectively at 12 V for the two engine banks. Each capacitor stack is charged from a dc/dc converter that takes its input from the 28 V PLATO bus. The ultracapacitor array is used in preference to lead-acid batteries, as it can operate to temperatures below −40 °C, provides ideal charging behavior (without the need for temperature compensation) and maintains an extremely high discharge current capacity even at very low temperatures; see Hengst *et al.*[39]

Engine control and monitoring is performed by the ECUs, one for each bank. These units are powered from the 12 V ultracapacitor bus. The ECUs contain a series of custom circuit boards that interface analog and digital inputs and power switching outputs (using a series of solid-state high-side switches) to the PLATO CAN bus network via a CAN I/O board. The ECU monitors and logs for each engine: cylinder head temperature, exhaust temperature, oil temperature, and oil pressure. Control is via three digital switches to each engine: start (starter motor solenoid), stop (fuel solenoid valve), and warm (air intake heater). Additionally, the ECU controls the fuel pump rate and the oil recirculation pump rate separately for each engine. These pulse-driven devices are software programed.

Inside the instrument module the high-voltage output from each engine bank is input into a parallel pair of Kepco RKW55 switched-mode power supplies. A feedback loop regulates the output voltage of these power supplies to correctly float charge the battery bank depending on the battery temperature. The voltage set point can also be trimmed by the supervisor computers over a range of ±5%. Thus, when the sun is up, the set point of the engines can be adjusted below the set point of the solar panels, giving priority to the panels.

Figure 5 shows an example of the logged parameters for

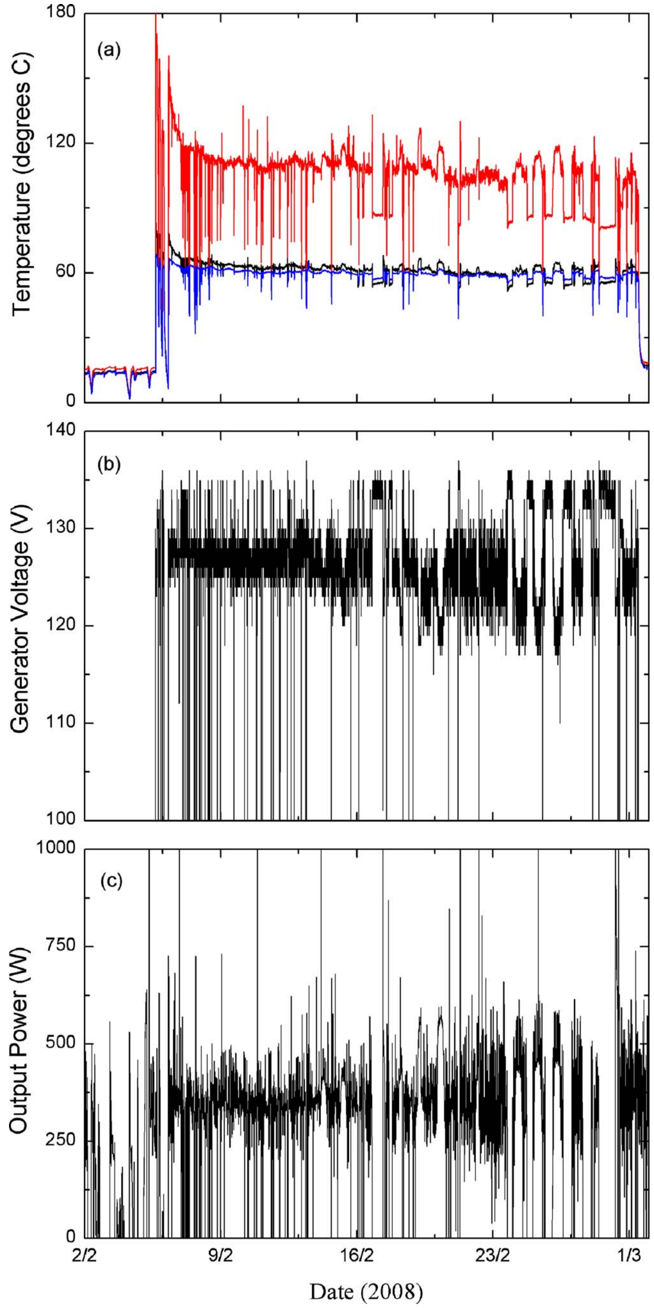

FIG. 5. (Color online) Example showing performance of one of the engines during February 2008. (a) Temperature of exhaust (red line), cylinder head (black line), and oil sump (blue line); (b) generator voltage; and (c) output power. Regular vertical lines correspond to engine stoppages. This data was transferred in close to real time via the PLATO Iridium communications link.

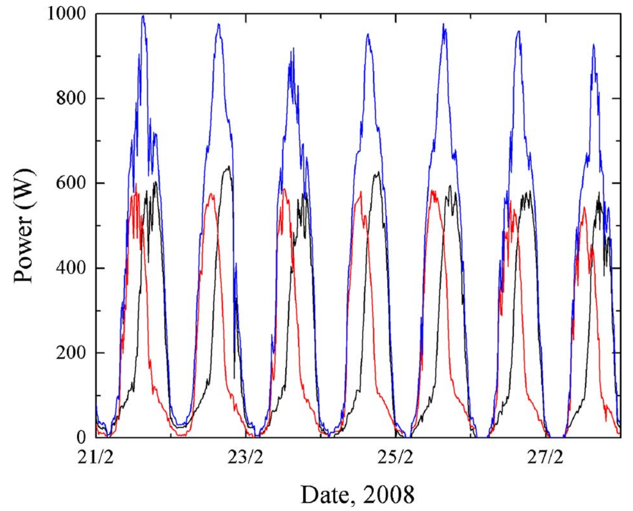

FIG. 6. (Color online) Solar power generated by the solar panel array during a one week period in February 2008. The plot shows the output from the north east array (red), the north west arrays (black) and the total combined power (blue).

one of the engines during a 1 month period in early 2008. Engine exhaust temperature is ~120 °C, with the engine block sitting at ~60 °C, which is ~45° above the internal engine module temperature. Total generated engine power is ~400 W during this period, with a slight increase in power with time as the solar panels begin to provide less output. During the winter months when no solar power is available and more instruments are operating, the engine output power is typically 800 W. The period toward the end of the month where an oscillation in engine parameters is observed in Fig. 5 corresponds to other engines being periodically started. The vertical lines in the data plots correspond to engine stoppages. The large number of these stoppages has been attributed to air trapped in the fuel lines, and will be corrected via a design change to be implemented in early 2009. Despite these stoppages, the automated engine control scripts (see Sec. VII B) were demonstrated to reliably restart the engines.

B. Solar power

The solar power system consists of two arrays of three vertically mounted polycrystalline silicon panels (Conergy C167P) that face north-east and north-west. This orientation is chosen as a compromise between maximizing the power when the sun last sets (in early April) and first rises (in late August), and minimizing the daily charge-discharge cycle of the batteries in the event of a complete loss of diesel power. The high reflectivity of the ice results in increased solar flux on the panels, and the low ambient temperatures lead to a significant increase in the panel conversion efficiency. As a result each panel produces up to 220 W—well above its nominal rating of 167 W.

The nominally 50 V dc output from the solar panels is regulated to the appropriate battery float voltage by a commercial solar panel controller (Apollo Solar T80), one for each array. This unit also performs maximum power-point tracking, for the most efficient use of the solar panels. The charge controllers automatically switch to bulk-charging mode when required. The solar charge controllers communicate via a RS485 bus; their performance is monitored by the PLATO supervisor computers via a CAN I/O board which rebroadcasts the RS485 messages as CAN packets on the local network.

Figure 6 shows a plot of output solar power as reported by the solar panel controller and logged by the supervisor computer for a one week period in February 2008. A peak power of ~1 kW is produced at local midday. With this panel configuration the average power generated in this period is ~2 kW h/day, and there are approximately 12 h of useable power produced each day. Figure 6 demonstrates the transition between the period in the early summer months

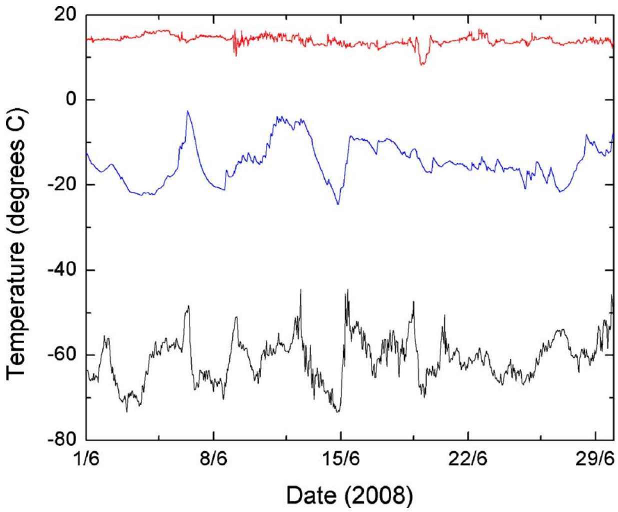

FIG. 7. (Color online) Engine module internal temperature (top red line), instrument module internal temperature (middle blue line), and external temperature (lower black line) during the month of June.

when power is produced even when the sun is directly behind the vertical panels (from solar radiation reflected off the snow surface) to the autumn period when the sun sets each day in the South.

V. THERMAL CONTROL

The Hatz 1B30 engine is ~33% efficient (to the engine shaft), losing ~30% of energy through exhaust gas, and ~37% through cooling air and radiation. The engine module is heavily insulated with 150 mm thick polyurethane-foam panels. It was designed for a heat loss of 15 W K^{-1}. Cooling air and radiant heat from a single engine generating more than 800 W of electrical power is therefore sufficient to maintain the engine module temperature well above 0 °C with an external temperature of −60 °C. In practice, a significant fraction of exhaust-gas heat is coupled into the engine module via radiation and conduction from the exhaust system. Additionally, as shown in Fig. 2, the external temperature at Dome A can be as high as −30 °C. Thus, there are times when more heat is generated than is required. To remove excess heat and to regulate the engine module temperature, a closed-loop proportional-integral-derivative (PID) temperature controller (Eurotherm 3200) is used. This controller drives a pair of 150 mm brushless axial fans that exhaust the warm room air via a 150 mm diameter polyvinyl chloride (PVC) duct, causing cold external air to be drawn in through a separate inlet duct. The engine module is regulated to a nominal temperature of 15 °C ensuring that the fuel is well above freezing point. The long thermal time constant of the fuel tank ensures that the module cools slowly from this nominal temperature in the event of engine failure. Data from Dome A during winter have confirmed that the thermal performance of the engine module meets expectations. Figure 7 shows the engine module and external temperatures throughout the month of June; the engine module is maintained to within ~2° of the set-point temperature independent of the external temperature, which drops as low as −75 °C in this midwinter period.

The instrument module is heated electrically. The instruments and electronic components within the module dissipate typically 100–200 W of heat. This is augmented with a set of resistive heater units located around the module that provide 0–360 W per heater unit when required. Several air circulation fans are also installed to prevent large temperature gradients due to stratification. The instrument module is more heavily insulated (with 200 mm thick polyurethane cladding) than the engine module, and was designed for a heat loss of ~8 W K^{-1}. The thermal performance during midwinter was found to meet this specification. As shown in Fig. 7, the internal temperature follows the external temperature with a differential of about 50°. During this period the internal input heat was in the range ~300–500 W. With this heating scheme the internal instrument module temperature is typically kept in the range of −20–0 °C. The critical electronic components in the instrument module have been tested for low-temperature operation and have been found to operate satisfactorily at temperatures well below the conservative lower limit set-point for this module. A similar regulation system to the engine module is installed (i.e., a PID controlled heat exchange system) that can provide a stable temperature if required and can exhaust excess heat during the summer months when solar radiant heating of the module exterior may be more significant.

In both modules temperature regulation is performed by a TCU. This unit consists of an analog interface board, a switching board, and a PID temperature controller. Similar to the ECU, a CAN I/O board in the TCU acts as an interface between these components and the PLATO supervisor computer, communicating over the local CAN network. The TCU analog interface board contains signal conditioning for a series of AD590 temperature sensors, which are located internally throughout each module, and externally at ground level. These sensors report the temperature structure inside each module. The TCU switching board distributes power to the internal module heaters (in the instrument module) and gives auxiliary power outputs (for the engine module), via a series of solid-state high-side switches controlled by digital outputs from the CAN I/O board. The power delivered to each heater unit is controlled by using a pulse width modulation (PWM) duty cycle (similar to the fuel and oil pump controllers in the ECU). The PID controller communicates via Modbus and is interfaced into the CAN I/O board which then translates to/from CAN messages. The PID digital output is then interfaced into the switching board to control one current-monitored channel. Each TCU is also equipped with a board-mounted absolute air pressure sensor.

VI. INSTRUMENT INTERFACE AND CONTROL

For each instrument, PLATO provides a mechanical, power source, and communications interface. These interfaces are designed to be generic enough to allow flexibility in instrument design, and to protect the PLATO power generation and control systems so that an instrument failure cannot bring down the complete observatory.

PLATO is designed mechanically to accept a variety of different types of instrument. A series of portholes of various size are mounted in the PLATO instrument module roof (and one of the side walls), each providing an external flange for instrument mounting. Instruments can be installed in a number of ways: externally on the ice surface (connected using a cable conduit through the module wall), externally on the module roof (with power and control cables connected through a roof porthole), completely internally (observing through a window attached to the external porthole flange), or internally/externally (using a module roof or wall porthole as a "optical" conduit). This allows for a variety of different heat exchange strategies and provides flexibility as to instrument size and configuration.

The power supplied to the instruments is delivered by a series of PDUs. Each PDU contains a CAN I/O board piggybacked to a large switching board. The PDU switching board uses a set of solid-state high-side switches controlled by digital outputs from the CAN I/O board (similar to the ECU and TCU). A shunt resistor and high-side differential amplifier for each high-side switch allows the CAN I/O board to monitor total power used by each instrument. Each instrument has a separate instrument-power and heater-power line paired into a shared connector. Similar to the other control units, all power lines can be programed with an asynchronous period and PWM duty cycle, allowing for control of instrument heater power. Software interlocks prevent devices such as instrument computers from being PWM driven.

PLATO provides each instrument with a budget of ~100 W average power. The supervisor computer continuously monitors current usage and can power-off any instrument that uses more than its allocation. Instantaneous current limiting is implemented electronically by the PDU. If the combined current of an instrument port goes above 12 A, the port is shut down for 1 s before retrying. The CAN I/O board performs the output reset and the supervisor computer decides whether to continue to power the port. The instruments are supplied with the unregulated battery bus voltage, which can typically vary from 22 to 30 V. All internal power regulation, conversion, and switching required for an instrument must be accomplished by that instrument's internal electronics and control system, although some degree of heat control can be assigned by the supervisor computer via the instrument heater lines.

Figure 8 shows an example of the current usage of two instruments monitored via the supervisor computer system. The Chinese small telescope array (CSTAR) instrument consists of an array of four optical telescopes.[27] The current usage (computer, charge coupled device, and heater power) from one of these telescope systems is shown over the ~7 month period from when it was first powered up in late February to when the PLATO system shuts down in August. Over this period the instrument was power cycled a total of five times (to fix software problems and to conserve battery power when all engines were off). The drop in current in the February and July periods is caused by the PLATO supervisor computer switching off the CSTAR telescope window heaters. The second example shown in Fig. 8 gives the preheat current usage over a 24 h period in midwinter. This instrument (a submillimeter tipping radiometer)[24] controls all

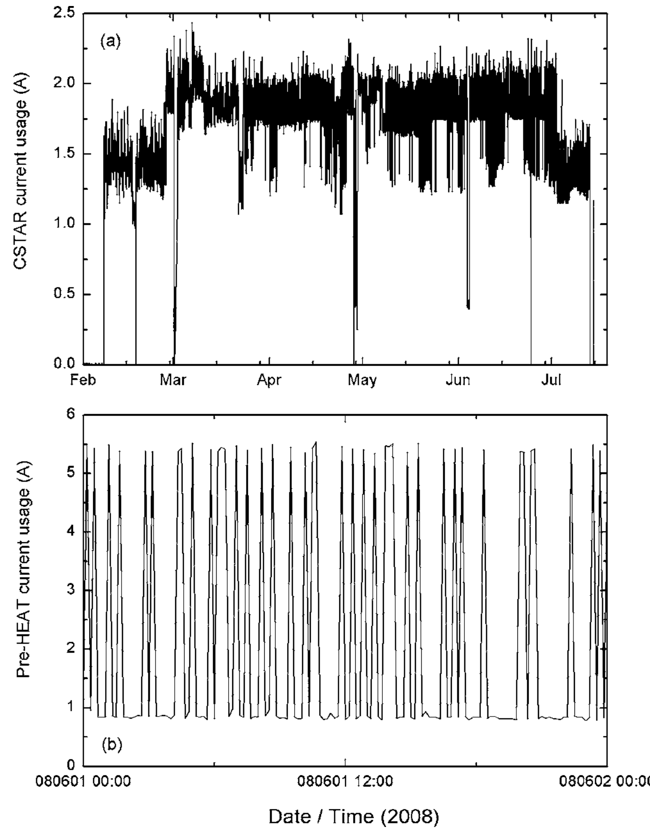

FIG. 8. Instrument current usage for (a) CSTAR over period 22 February to 9 August, and (b) preheat over a 24 h period on 8 June.

power switching between its own subsystems. PLATO monitors this current switching on a fine temporal scale, providing a useful diagnostic tool to determine the operational status of this instrument.

Instrument control systems are required to be autonomous; each instrument has its own computer and control programs, and enough storage capacity for the complete year. While any operating system is possible, a Linux-like environment (e.g., Cygwin) is required for WINDOWS machines to interface with the PLATO supervisor system. Each instrument has autonomous software such that the instrument begins taking data as soon as it is powered up. The PLATO supervisor can communicate with all instruments via the PLATO ethernet local area network (LAN), and can perform simple checks on the instrument status. Limited instrument data are downloaded via the supervisor computer Iridium link, and necessary changes to instrument operating parameters (based on an analysis of this data) are achieved by uploading configuration files.

VII. SYSTEM CONTROL AND COMMUNICATION

A. Hardware

The PLATO computer system is designed to run the complete observatory autonomously for long periods of time with little human intervention. To achieve such high levels of reliability we developed a system of two Linux-based supervisor computer units in a dual-redundant configuration, each with its own management electronics and Iridium satellite modem, which are installed inside the instrument module.

The supervisor computers monitor and control the PLATO power distribution, thermal, and engine management subsystems via the local CAN bus network. High-bandwidth communication between the instruments and the supervisor computers is provided via a wired LAN. External (i.e., mid-latitude site) communication with the module is via the Iridium satellite network at 2400 baud.

Each supervisor computer unit consists of a PC/104 stack, a CAN I/O board, and a low-temperature rated Iridium modem, installed inside a sealed rack mount case. The $\sim$10 W of heat produced by the PC/104 is distributed inside the case (via a computer-controlled fan) principally to keep the Iridium modem warm. In practice, the temperature at the PC/104 CPU heat sink is about 25 °C when the internal instrument module temperature is −10 °C and the outside ambient is −70 °C.

The PC/104 computer (Parvus CPU-1452) is a low-power passively cooled 400 MHz Celeron processor with 256 MB of directly soldered memory. The supervisor computer real-time clock and complementary metal oxide semiconductor (CMOS) power is maintained using two D-cell lithium thionyl chloride batteries, with a switched-mode voltage regulator that insures that the voltage remains within specification down to at least −60 °C. The BIOS settings are configured to boot the computer correctly even if power is lost to the CMOS. An internal four-port high-speed USB hub holds four 8 Gbytes (Sandisk) USB flash-memory keys; these keys have been cold tested and found to work reliably down to −55 °C. Solid state USB flash keys were chosen because although they have a lower capacity, they are much cheaper than low-temperature rated IDE solid-state flash drives, and are much more reliable than standard "spinning" hard drives, which tend to fail often in low-temperature and/or low-pressure environments. The computers were booted from Sandisk Ducati Extreme 4 Gbytes USB flash keys, which were found to be particularly reliable at low temperatures (down to −55 °C). The total supervisor computer storage capacity, 64 Gbytes, is enough for data logging of all PLATO engine parameters (from the ECUs), temperatures (from the TCUs), and subsystem current usage (from the PDUs), and provides a limited amount of data backup for the site-testing and science instruments.

The CAN I/O board powers the PC/104 and the Iridium modem, and runs a supervisor support program. The PC/104 uses the CAN I/O board as a gateway to the PLATO CAN network via an RS232 connection, with the CAN I/O board routing commands to and from the CAN bus. A watchdog-timer reset command must be sent by the PC/104 to the I/O board every 5 min otherwise the I/O board will power cycle the PC/104. The PC/104 sends commands to the I/O board to control power to the Iridium modem and the modem is only powered when communication is active.

Internal high-bandwidth communication between the supervisor computers, the instruments, and other network-based hardware is achieved with a LAN using unshielded twisted-pair 100 Mbytes/s Ethernet via TCP/IP. An industrial-grade dual-power supply Ethernet-switch that can be power-cycled via the CAN bus is used to interconnect the LAN devices. External communication with PLATO is achieved via the two (NAL 9522A) Iridium modems in the supervisor computer units. Each modem is capable of 300 bytes/s data rates and is fully independent. Two separate antennas (one omnidirectional and the other high gain) are installed externally on the instrument module roof. The Iridium L-band frame count is used to set the real-time clocks of the supervisor computers to an accuracy of 20 ms.

B. Software

The PLATO supervisor software is designed to autonomously make all high-level control decisions necessary to run the PLATO observatory. The software provides commands to all the CAN I/O boards in the engine control, thermal control, and PDUs, decides on the instrument power and heat scheduling, data logging and storage, engine bank power, battery charge voltage, and communications. A GNU/Linux operating system derived from Debian etch i386 is used as the platform for all supervisor control software.

Based on previous experience of running remote Antarctic observatories, a crucial implementation for the PLATO software system has been to use a completely read-only root file system that can be booted from a USB flash-memory drive. All volatile files are symbolically linked to a virtual-memory file system that is uncompressed during boot into random access memory. In this way nonpersistent changes can easily be made, and if they are unsuccessful, a power cycle is all that is needed to restore the system. The system can be powered down at any time without warning and still be guaranteed to boot up again cleanly. A script that allows updating of the read-only file system allows for permanent changes to be made if desired.

A power-management program, implemented in Perl, performs the majority of PLATO automation. This program monitors all solar, engine, battery, and instrument parameters (e.g., battery bus voltage, engine speed, and instrument current use), can power any of the PLATO components (e.g., engine starter motors, instrument module room heaters, instrument heaters, and instrument computers), and can adjust a number of system variables (e.g., battery float charging voltage, fuel, and oil pump rates). This script implements an algorithm that selects the engine running strategy, implements engine starts if faults develop, attempts to generate the most efficient use of fuel, ensures that the batteries are fully charged to the correct voltage, implements and monitors the adopted thermal management strategies for both modules, employs power and heat management schemes for all instruments, and logs all system parameters.

The Iridium modem communication software is also implemented in Perl. The majority of data are transferred via TCP/IP using a SSH tunneled connection. If this link is unreliable, a data transfer program can be used that constructs encrypted self-assembling messages and has the ability to execute arbitrary commands via "short data burst" messaging. As the data rate is extremely low (typically 300 bytes/s per modem), and connections are unreliable (a typical connection will last for 20 min) standard Linux file transfer programs such as "rsync" are not ideal as they are designed for large transmission buffers. A custom data-transmission protocol is thus implemented, which allows for retransmission and checksum verification of all data files and efficient continuation of data transfer in the case that communication has been severed midstream This protocol synchronizes (in both directions) a directory on the PLATO supervisor computer with a directory on a computer located at the University of New South Wales. Transferring data is as simple as creating a file in the appropriate directory, when the file is deleted by the communication software, the operator knows that it has been transferred without error.

During the 2008 season of operation over 3.5 Gbytes of "bzip2" compressed data have been transferred via the Iridium communications link. These data, which consist of all PLATO housekeeping data and a small subset of the total (about 1 Tbyte) of collected instrument data, are automatically uploaded to various websites for human inspection.[40] Additionally, scripts are implemented that automatically send SMS messages to mobile phones or email accounts if faults are detected that require human intervention. The Iridium data link has proven to be crucial as it allows the nominal operation of PLATO and its instrument systems to be verified, and operating parameters to be modified in close to real time when required. It also allowed for the efficient refining of the automation scripts that required modification during the year as PLATO "aged," e.g., certain engines were no longer serviceable.

VIII. CONCLUSION

PLATO is an entirely self-powered observatory with a multiply redundant, hybrid power generation system, designed to provide heat, power, control, and communications for a suite of automated astronomical site-testing and science instruments. In January 2008 PLATO was deployed to Dome A, which is the highest point on the Antarctic plateau and one of the coldest and most remote locations on the planet. The PLATO observatory ran successfully, throughout the Dome A winter period, for a total of 204 days before communication was lost in early August 2008. It is suspected that a blockage in an engine module air vent, possibly resulting from freezing water vapor from an exhaust leak, caused the module to overheat and the engine system to shutdown; this fault diagnosis cannot be verified, however, until the next traverse team return to the site.

The PLATO power generation system has been successful largely as a result of the conservative design and multiply redundant subsystems. This power system is an innovative solution with wide applicability to small-scale scientific facilities on the Antarctic plateau, creating minimum environmental impact and requiring minimal human intervention. The command and control systems for the observatory have proven to be robust against many potential failure points. The PLATO communications system has allowed the monitoring of close to real-time statistics, the remote tuning of operating parameters, and numerous updates to the control system software; these elements have proven to be crucial for long-term reliability. A variety of instruments have been easily integrated into the control structure, and there is enough capability for significant expansion in the future.

During a servicing mission planned for January 2009 all PLATO engines will be replaced with new units. Additionally, upgrades to a number of subsystem components, including the engine fuel and oil circulation system, the engine exhaust systems, and the solar power charging system, will be installed. These upgrades are intended to increase the system reliability, and provide greater control over system operating parameters. A new science instrument will also be installed during this mission, and many of the existing instruments will be upgraded.

The success of the PLATO power and control platform has allowed valuable data to be obtained on Dome A atmospheric and environmental conditions. Data have shown that Dome A atmosphere is exceptionally dry, opening up new windows for terahertz astronomy (Kulesa *et al.*[41]). The Dome A location has been demonstrated to be ideal for time-series astronomy, with over 100 000 images taken of the one region of sky over the winter period.[29] The summer-time turbulent boundary layer at Dome A has been shown to exhibit similar characteristics to other high Antarctic plateau sites, indicating that in midwinter the conditions may be ideal. Further results from these instruments await the collection of the complete season of data by the next expedition.

Plans now exist to extend the current instrument suite of PLATO over the next few seasons to more fully characterize the site. Additionally, a larger-scale observatory based on the modular concepts of PLATO is now being designed that will allow the deployment and control of several higher-power larger-scale astronomical facilities that are required to fully realize the potential of this site.

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