Near-infrared sky brightness monitor for the South Pole

Michael C. B. Ashley

Michael G. Burton

James P. Lloyd

John W. V. Storey

Joint Australian Centre for Astrophysical Research in Antarctica (JACARA)
School of Physics, University of New South Wales
Sydney 2052, Australia

ABSTRACT

The antarctic plateau has the potential for being the best site on Earth for conducting astronomical observations from the near-infrared to the sub-millimeter. Particular gains are expected in the 1 to 5 micron region, where the high altitude, low water vapour content, and low thermal emission from the atmosphere combine to create observing conditions unequalled elsewhere on the surface of the earth. We describe an instrument, the Infrared Photometer-Spectrometer (IRPS), that we are using to quantify site conditions at the South Pole by measuring the near-infrared sky brightness. We also describe some of the unique problems associated with building instruments to work in Antarctica.

Keywords: near-infrared, Antarctica, astronomy, site-testing

1 THE ENVIRONMENT AT THE SOUTH POLE

The US Amundsen-Scott South Pole Station is located within a few hundred meters of the Geodetic South Pole, at an altitude of 2900 m. Centrifugal and temperature effects reduce the air-pressure to the equivalent of between 3200 and 3600 m depending on the weather. At these altitudes, there is noticeably less oxygen in the air, leading to sleeping difficulties, reduced mental capacity, loss-of-breath after moderate exercise, and sometimes more serious effects of altitude sickness. The wind velocities are low, averaging 5 knots. During winter, the winds increase and on many days the top layer of ice crystals on the ground becomes airborne, resulting in reduced horizontal visibility. The precipitable water vapour content of the atmosphere averages $300\,\mu$m in the winter, making this one of the driest places on Earth. A typical summertime temperature is $-30°$C, while in winter $-60°$C is typical, with lows down to $-75°$C. The sun is below the horizon for six months of the year.

This daunting physical environment provides the opportunity to carry out infrared astronomy with sensitivities rivalled only by space missions,[1] largely due to the increased transmission and decreased emission of the Earth's atmosphere, as well as the reduction in thermal emission from the telescope. Through the efforts of CARA (the Center for Astrophysical Research in Antarctica) astronomers now have a number of instruments working at the South Pole. In 1993 we began a collaboration with CARA to measure the brightness of the sky in the near-infrared, in order to confirm theoretical predictions of the low background levels. Results from the winter of 1994 from our group and from a University of Chicago group have been submitted for publication.[2,3] IRPS has shown that at 2.45 μm the sky background at the South Pole is some two orders of magnitude less than that at a typical observatory in a temperate location, such as Siding Spring Observatory in Australia.

South Pole Station has 100 to 150 people at any one time over the summer. During 1995, some 28 people were wintering-over, 4 of whom were astronomers (including one of us, JPL).

Travel to the Pole is via ski-equipped LC-130 (Hercules) aircraft from McMurdo station at $-78°$ latitude. Flights cease in early February when the Station is closed for winter, and do not resume until early November. An airdrop occurs in mid-winter, where a C-141 (Starlifter) aircraft drops several pallets of supplies, but does not land. This single airdrop is the only opportunity for delivery of replacement parts for the experiments during the nine-month winter isolation.

1.1 The astronomical observatories at the South Pole

The CARA observatories at the South Pole, AST/RO and the Martin A. Pomerantz Observatory (MAPO), are located 1 km from the Station. These observatories are well equipped with optical, mechanical and electrical supplies, computers, and vacuum equipment. During 1994, our IRPS experiment was on the roof of the AST/RO observatory; it was moved to the roof of the MAPO building in February 1995 and operated at that location for the remainder of the year. The computers, electronic systems, and vacuum pumps that are used with the experiments are generally housed in the heated laboratories.

Electrical generators running on JP-8 fuel provide electrical power for the South Pole Station at the US standard of 110 V/60 Hz. These generators are severely overloaded, and minimizing power consumption is an important issue with all experiments. The supply is reliable, although we have had problems with large spikes on one line circuit interfering with digital logic ICs. Achieving a good ground connection is difficult in the ice. Static electricity can be a problem due to the low humidity, and this problem is exacerbated by the many layers of synthetic fibre clothing and rubber boots worn by the experimenters. There are a number of experiments at the Pole involving the transmission of radio frequency signals and pulses, but these generally do not interfere with typical astronomical equipment. Overall, the radio environment is exceptionally quiet.

2 DESCRIPTION OF IRPS

IRPS is based on an instrument developed at the Anglo-Australian Observatory during the late 1970s for use on the 4-m Anglo-Australian Telescope.[4] When the observatory replaced the instrument with an array camera in 1992, John Bally of the University of Colorado discussed with us the possibility of it being re-engineered for use in Antarctica. Rather than using IRPS with a telescope, it was decided to have IRPS view the sky directly, thereby minimizing the contribution from the emissivity of additional optics.

A block diagram of IRPS appears in Figure 1. The dewar has two cans: the outer can is filled with liquid nitrogen (LN2), (74 K at the ambient pressure at the Pole), and cools the radiation shield; the inner can is also filled with LN2, which is then solidified by pumping down to pressures of a few torr. This reduces the temperature of the detector and optics to around 65K, greatly reducing the dark current of the single-element InSb detector.

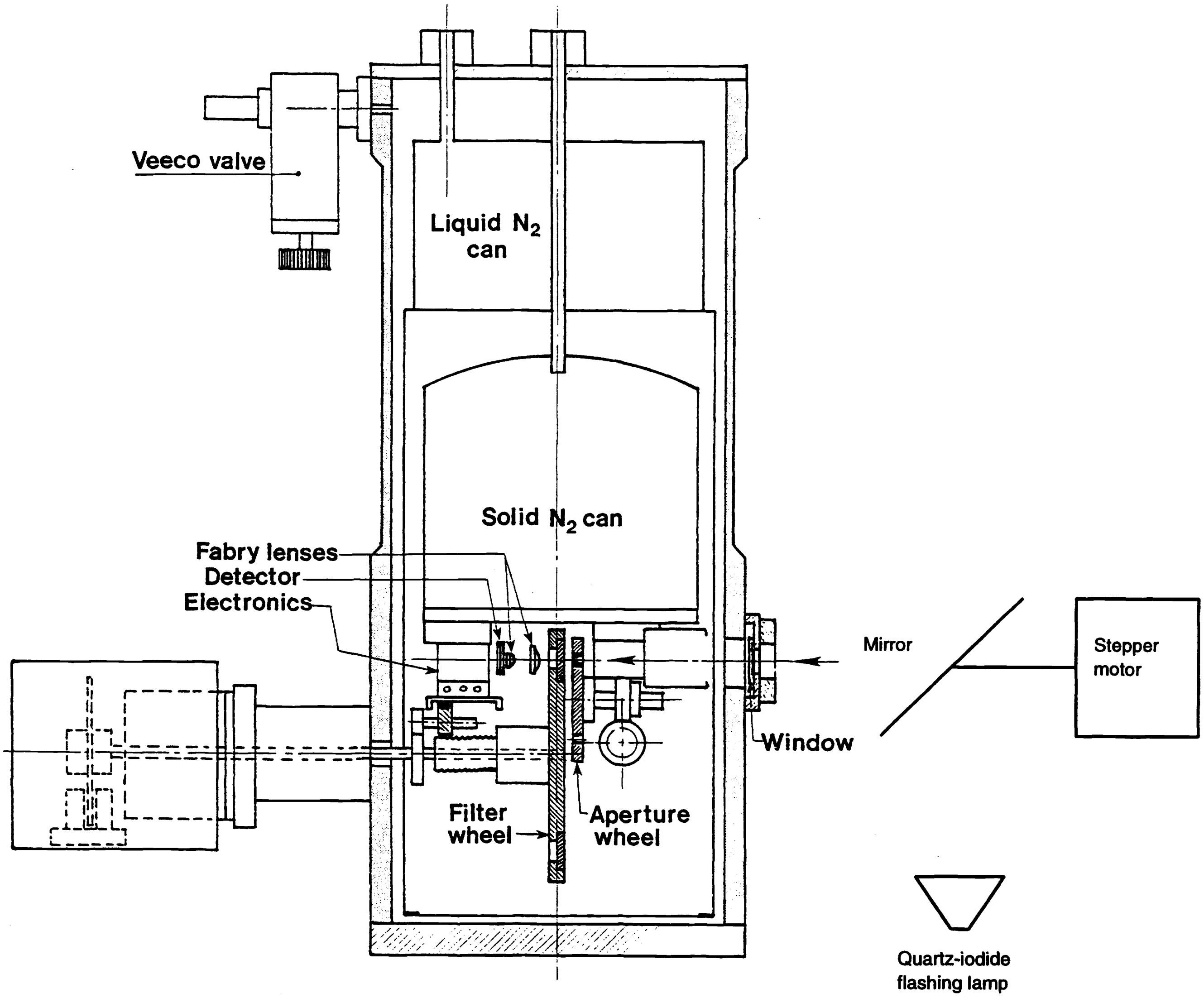

Figure 1. A simplified view of IRPS (adapted from Allen[4] by permission). The structure on the left is the stepper motor (with indexing wheel) used to drive the filter wheel. There is a similar motor at right angles to drive the aperture wheel. The 45° mirror (see Figure 3 for details) allows the sky to be scanned. By pointing the mirror down, the quartz-iodide lamp can be used to "flash" the detector (see text for details). This Figure does not show the thermal insulation for the motor, or the modifications made to the window.

Incoming light in an f/15 beam (~4° FWHM) is incident first on an aperture wheel, which offers 15 different apertures (circles with diameters of 0.2, 0.3, 0.4, 0.6, 1.0, 1.4, 2.0, 2.8, 4.0 and 5.5 mm, rectangles with dimensions 1.0×3.0, 1.0×4.0, 1.4×3.0 and 1.4×4.0, and a blank). In the present configuration of IRPS, this range of apertures serves only to increase the dynamic range of the instrument. The incoming light next passes through a filter wheel, with a selection of broad-band filters (astronomical bands J, H, K, L′ and M; the L′ filter was replaced with a 2.27–2.45 μm filter in February 1995), and two circular variable filters (CVFs), one covering the wavelength range from 1.4–2.5 μm, and the other covering 2.9–4.3 μm, both at a resolution of 1%. The resolution is degraded if apertures greater than 1.4 mm in width are used. During 1995, a 2.5 μm short-pass filter was inserted into the 1.4×3.0 mm rectangular aperture to act as an additional blocking filter when using the 1.4–2.5 μm CVF. An achromatic doublet lens focusses the light onto the detector, thereby defining the field of view of the instrument.

The filter and aperture wheels are rotated by stepper motors mounted on the outside of the dewar. The rotary vacuum feedthroughs are achieved with Wilson seals cut from fluorosilicone sheet (available in sample form from o-ring manufacturers; see §5 for more discussion of vacuum issues). Thin-walled stainless-steel shafts run from the vacuum feedthroughs to the aperture and filter wheels.

The entrance window to IRPS is a 2 mm-thick piece of sapphire. It is uncoated, and therefore introduces a reflection loss of approximately 8% from each surface. IRPS views the sky via a Cr-Au coated external flat mirror of 75 mm diameter. This mirror is rotated by a stepper motor, thus allowing IRPS to take data from any 4-degree region of the sky along a line from one horizon to the other passing through the zenith. Over a 12-hour period the rotation of the Earth is such as to let IRPS sample the entire celestial hemisphere.

The detector preamplifier is described in Barton and Allen.[5] The detector current is integrated on a small capacitor, which is periodically discharged by illuminating the input-stage field-effect transistor with a light-emitting diode. The resulting output signal is thus a "ramp", or sawtooth wave, with a period ranging from 1 ms to 100 s, depending on the infrared flux. In its original (1980) form, this output ramp was fed to a sample-and-hold circuit then digitized in a voltage-to-frequency converter. Both of these have now been dispensed with, and instead a modern 16-bit analog-to-digital converter (ADC) is used. Rather than simply sampling the voltage at the beginning and end of the ramp (as was done in 1980), we sample the voltage as often as every 100 μs and fit a straight line via a linear regression. This not only provides a better signal-to-noise ratio, but also allows accurate measurement of the signal strength even if the ramp becomes saturated during the integration period. (This technique is similar to to that in common use with infrared array detectors, where multiple non-destructive reads are employed.[6]) The software also allows points to be eliminated from the linear regression if they fall too far from the line, thus improving the fit in the presence of noise spikes. Extremely good fits can be obtained, sometimes exceeding the 16-bit quantization of the ADC.

The 1980-vintage InSb detector in IRPS only achieves minimum dark current after it has been "flashed". This is done by exposing the detector to a bright near-IR source (a quartz-halogen lamp) for several minutes. Once "flashed", the detector retains its high impedance as long as it remains cold. We have placed a flashing lamp where it can be seen at one particular orientation of the rotatable mirror, and can turn the lamp on and off under computer control. To reduce the thermal stress on the lamp (which may be at −75°C before being turned on) the computer controls the lamp current using pulse-width modulation, ramping up to full brightness in 60 s.

The computer is a Hewlett-Packard Vectra 486/25U PC running MS-DOS 6.2, and fitted with National Instruments cards (an AT-MIO-16X 16-bit ADC card, and a PC-DIO-96 96-bit digital I/O card). The computer can be operated in a stand-alone mode or remotely controlled via an ethernet connection to a UNIX workstation.

Before sending IRPS to the South Pole, it was tested at low temperatures in the laboratory. This was done in a polyurethane-insulated wooden box filled with a layer of solid CO_2 pellets. Cold-soak tests were conducted over a period of 2 days, while the temperature of the outer case of the dewar was monitored with an AD590 sensor. We are currently installing a refrigerator capable of reaching −86°C, for use with future experiments.

3 CALIBRATION

The wavelength coverages of the fixed filters used in IRPS were measured by their manufacturers, and can be assumed to be very stable with time. Similarly, the characteristics of the CVFs can be considered to be unchanging. The only calibration required in the field, therefore, is to determine the wavelength at *one* point on the CVF. At all other CVF positions the wavelength is determined as being a certain number of stepper-motor steps from this reference position. The reference wavelength used for this calibration is that of a mercury line at 1.530 μm; this line is strongly emitted by a normal domestic fluorescent lamp.

Intensity calibration is done by observing a black-body source placed directly in front of the entrance window of the dewar. The black body is a well-insulated aluminum can with a black-painted conical cavity let into one side. The can is filled with snow and water to give a primary calibration at 0° C, and with hot water to extend the calibration to shorter wavelengths.

4 ACTIVE HEATING

4.1 Temperature sensors

Integrated circuit temperature sensors are generally only rated down to −55° C, while the ambient temperature during wintertime at the South Pole can dip below −75°C. In practice, sensors such as the AD590 appear to work reliably down to at least −80° C, and survive repeated cycling to 77 K. The flat-pack version of the AD590 is particularly convenient.

4.2 The "generic heater block"

While the computer driving IRPS, and most of the electronic circuitry, could be placed inside the warm MAPO building and connected to IRPS through 10 m-long cables, some critical electrical and mechanical components had to be left outside. For proper operation, however, the preamplifier has to be kept warmer than −10° C, while the stepper motors are only rated down to −20° C. We therefore required a self-regulating heater that could be coupled to the various temperature-sensitive items to keep them within an acceptable temperature range. The resulting "generic heater block" is shown in Figure 2.

The heating element is a power MOSFET, with a temperature sensor (AD590, flat-pack) epoxied to its tab. We have used CMOS semiconductor components wherever possible since they are known to operate reliably at low temperatures. The only bipolar components used are the transistor that limits the MOSFET current, and the AD590. At low temperatures the transistor characteristics result in a higher threshold for the current limiting, which serves to heat the circuit more quickly. The printed-circuit board and all components were encapsulated to prevent moisture affecting the high-impedance parts of the circuit.

The generic heating block runs from any unregulated supply of between 15 and 50 volts, and can produce up to 24 watts of heat at 24 volts. When heated above its set-point, the heater block draws only 5 mA (@24 V), and thus generates minimal unwanted heat. Many such units can therefore be scattered about the equipment, with their set-points set just below the expected operating temperature of the unit at that location. During tests, the generic heating block was found to switch on reliably at all temperatures down to at least 77 K, and to reliably regulate to within 1° C.

4.3 Heating optical surfaces to prevent icing

Unheated optical surfaces, regardless of their orientation, tend to gather a layer of ice crystals. If pointing upwards, they collect snow in calm conditions. If pointing into the wind, they are blasted by wind-driven snow.

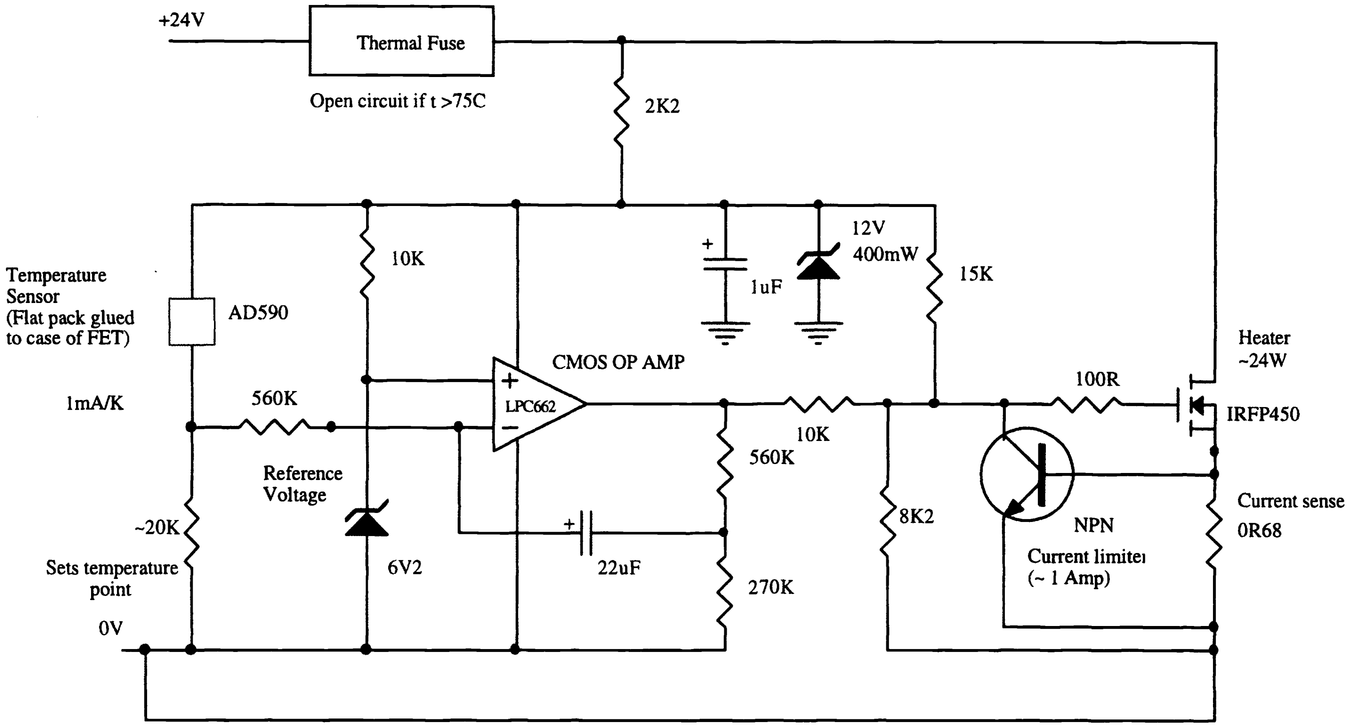

Figure 2. The "generic heater block", a two-terminal block powered by a 15–50 V unregulated supply, able to regulate to within 1 °C. The circuit can switch on reliably at temperatures down to 77 K.

If pointing down, or away from the wind, they have snow deposited on them from turbulent eddies in the wake of the wind. To counteract this, a constant heat input into the optical element (which results in a roughly constant temperature difference above ambient) will remove the ice through sublimation. We have found that a temperature difference of around 10°C is sufficient, except under extreme conditions of blowing snow. Under some weather conditions at the Pole ice crystals form and grow very rapidly, and additional heat input is required to prevent this. The external mirror in IRPS is heated with fixed resistors epoxied to its back (see Figure 3); the sapphire entrance window is heated with resistors epoxied around its edge. These precautions allowed IRPS to remain outside in all weather conditions with no protection from the elements.

4.4 Heating mechanical components

Stepper motors are usually only rated down to −20°C or so. Cryogenic motors are available (at a substantial cost premium), or conventional motors can be modified for use at low temperatures.[7] We chose a simpler and more economical alternative, which is to heat the existing motor to within its operating temperature range. To reduce the heat requirements we isolated the motor body from the ambient temperature with fibreglass standoffs, used a fibreglass coupler to isolate the shaft, and reduced convection losses by enclosing the motor in a double-walled cylindrical housing with fibreglass-batt insulation. The result is that the motor stays 70°C above the ambient temperatures down to at least −70°C, with only self-heating due to one of its two windings being energized (10 W heat input). If both windings are energized, the motor temperature differential rises to 90°C. To

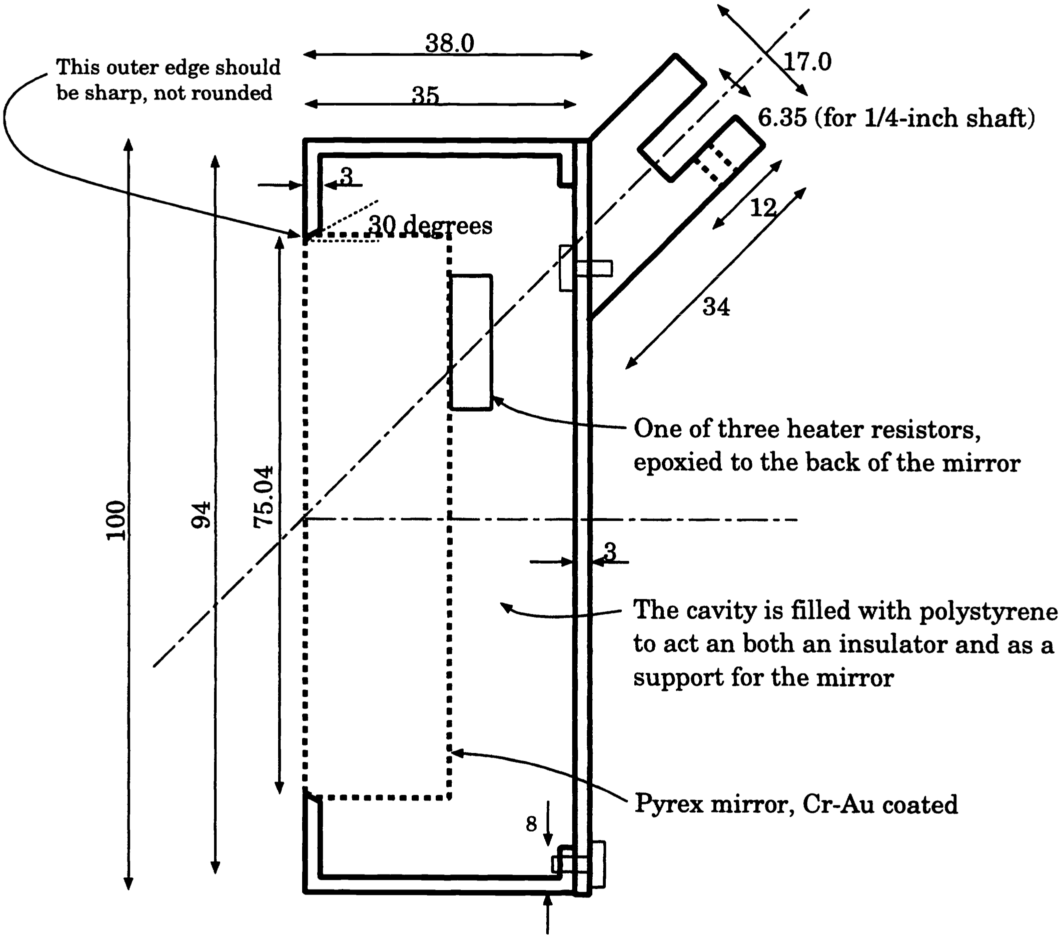

Figure 3. A cross-sectional view of the 45° mirror and its housing. The mirror is mounted in such a way as to minimize ice accumulation by avoiding lips and recesses, and to be thermally isolated so as to allow its temperature to be raised with minimum heat input. An AD590 temperature sensor (not shown) allows the mirror temperature to be monitored. All dimensions are in millimeters.

maintain the motor temperature in the case that neither winding is energized, a "generic heater block" is bolted to the motor case.

5 VACUUM CONSIDERATIONS

IRPS requires a vacuum better than 10^{-4} torr to provide sufficient thermal isolation to allow the detector to reach solid nitrogen temperatures and to achieve an adequate hold time for the liquid nitrogen. The dewar on which IRPS is based is a standard laboratory dewar, designed more for convenient and complete disassembly than for the ultimate vacuum performance. It thus contains a great many o-ring joints and feedthroughs that would be avoided were it to be designed specifically for the present purpose. The following sections describe our experiences with maintaining a good vacuum in this dewar under antarctic conditions.

5.1 Low-temperature vacuum seals

Elastomeric o-rings made from materials such as Viton become too hard at low temperatures to maintain a seal. Fluorosilicone o-rings do maintain flexibility down to −80°C, but they are up to 1000 times more permeable than Viton. This permeability makes leak-testing with helium very difficult, although with practice a difference can often be detected between a "genuine" leak and the slow rise and fall in pressure from permeability. Other properties of fluorosilicone o-rings include a low resistance to abrasion, a difference in size to Viton o-rings due to differing contraction from the moulding temperature to operating temperature, and an outgassing rate an order of magnitude higher than Viton. Fluorosilicone o-rings are not as readily available as Viton, and cost several times more. A useful discussion on o-ring selection is given by Peacock.[8]

The increased permeability of fluorosilicone is not a problem if the dewar is continuously pumped, or if enough molecular sieve (zeolite) is included to cope with the leak rate over the expected period of operation.

In the case of IRPS we used fluorosilicone o-rings, with continuous pumping with an ion pump, and a generous quantity (200 ml) of zeolite. When operated continuously at temperatures below −50°C IRPS was found to develop a vacuum leak that was traced to a rotary seal made with an o-ring. To close this leak we found it convenient to simply heat the dewar to −20°C.

With future instruments we plan to use ultra-high vacuum techniques to minimise the need for elastomer o-rings. Where o-rings are necessary, the leak-rate can be dramatically reduced by careful design and minimisation of the cross-sectional area exposed to ambient pressure.

5.2 Using an ion pump to maintain the vacuum

IRPS employs a small ion pump (a 2 liter/sec model 913-0032 made by Varian Vacuum Products) to maintain the vacuum despite the presence of minor leaks through the o-rings. This has worked very successfully, and has the added benefit of providing a measurement of the vacuum pressure by monitoring the ion current. We found typical pressures of 10^{-7} torr when the inner can was cooled to solid nitrogen temperatures, and 10^{-4} torr when the dewar was warmed to ambient. As of the time of writing (June 1995), the IRPS has maintained its vacuum without any need for human intervention for five months.

The only difficulty with installing the ion pump was in attaching the high voltage cable, which became rock-hard at low temperatures. Using a heat gun we were able to make the cable flexible enough to pass through a hole in the roof of the MAPO building to the controller below.

6 AN AUTOMATIC LIQUID NITROGEN FILLING SYSTEM

During 1994, IRPS was filled with LN2 by hand from a small transfer dewar using a funnel. Needless to say, this was a difficult task for the winter-over scientist in the extreme conditions at the South Pole. During the summer of 1995 we installed a computer-controlled LN2 filling system, employing a 50 liter pressurized storage dewar (with model 50LD liquid withdrawal device; made by Taylor-Wharton Cryogenics), thereby greatly reducing the maintenance requirements for IRPS.

The 50 liter dewar required modifications in order to survive the temperatures outside. We found that the dewar would not self-pressurize to the necessary 10 psi when the ambient temperature dropped below −40°C. This was probably due to the lower gas production rate combined with small leaks from sources such as the pressure-relief valves. We solved this problem by inserting a heater resistor into the LN2, and by warming the dewar using self-regulating heating tape to ~20°C. In addition we replaced all the o-ring seals in the liquid withdrawal device with fluorosilicone versions, and provided an additional seal over the dewar's evacuation port (previous experience has shown that the dewars go soft if left outside in Antarctica, due to failure of the evacuation port seal).

The auto-filling system uses standard cryogenic solenoid valves to control the flow of LN2, armoured 1/4″ teflon piping, and Swagelock connectors. Delivery into the IRPS cans is done with thin-walled stainless-steel tubes. The outer can level is sensed by a single silicon diode located at the end of the filling tube, about 20 mm above the bottom of the can. If sufficient current (~2 mA) is passed through the diode, its temperature will rise through self-heating when not immersed in LN2. The IRPS computer monitors the diode temperature (via its forward voltage drop), and initiates filling for a fixed length of time (determined by observation to be sufficient to almost fill, but not to overfill, the can). The inner can fill state is determined by monitoring the cold-surface temperature with a diode. When the temperature rises a few degrees above the nominal temperature for solid nitrogen, the inner can is filled for a fixed time.

The inner can filling system was more challenging to design since the inner can is normally pumped on by a rotary pump to solidify the nitrogen. We isolated the rotary pump with a vacuum solenoid during the filling operation, and provided a pressure relief valve so that the over-pressure resulting from the filling process would not damage the dewar. A diode placed alongside the relief valve is able to sense when the inner can is full, since a spray of LN2 emerges from the valve when this is the case. The vacuum solenoid was bypassed with an adjustable leak so that the pressure in the inner can could be slowly reduced before the solenoid was opened. If this is not done, the sudden drop in pressure upon opening the solenoid results in LN2 bubbling out of the inner can and flash-evaporating when striking the filling tube and vacuum fittings.

To reduce the likelihood of computer and/or software failure causing loss of valuable nitrogen (if, for example, the computer crashes immediately after opening a filling solenoid), the solenoid drivers are controlled by hardware that will reset itself to a safe state within 100 seconds if the correct sequence of logic pulses is not received from the computer.

7 "DIAMOND DUST"

At the Pole, snow can sometimes fall not as flakes but as micron-sized cylinders of ice called "diamond dust" (named from their visual appearance when observed by reflected sunlight). These ice cylinders are able to penetrate very small gaps in instruments, where they can accumulate. In the worst scenario they may be melted by the warmth of the instrument, and then re-freeze at a later time, causing severe damage. To guard against this problem, all vulnerable areas in IRPS (such as the motor housings and preamplifier box) were sealed with o-rings.

8 COMMUNICATION WITH THE SOUTH POLE

All electronic communication is via satellites. Unfortunately, geostationary satellites remain below the horizon when observed from the Pole. However, some of the older satellites have run low on fuel and have moved into orbits with significant inclinations, and so are visible for periods of up to 6 hours per day from the

Pole. When the satellite is up, full Internet access is available, and response is generally adequate for small amounts of interactive use. During 1995 the LES-9 satellite was used, at 38.4 kbaud. Transferring files up to a few hundred thousand bytes in length is readily possible.

Apart from the Internet satellite link, the South Pole is also regularly accessible to HF radio communication.

9 SOFTWARE FOR REMOTE OPERATION

The software to run IRPS is written in C. Care was taken to make the software reliable, and able to cope with as many non-fatal hardware problems as possible (for example, failure of a temperature sensor or a motor index wheel). The remote control aspects of the software are described elsewhere.[9] IRPS can be controlled from its PC, or from any Internet site, or by e-mail. When using a direct Internet connection, anything printed on the screen of the IRPS PC at the South Pole can also be displayed on a window on the workstation. The software source code can be patched remotely, and automatically recompiled and re-started. The data files produced by IRPS are automatically e-mailed in a compressed form to our workstations at the University of New South Wales.

The IRPS software has been written so that the parts of it that are independent of the instrument (e.g., the remote control capability, useful functions such as reading/writing files on the PC, timing functions, macros, conditional execution of commands) can be readily transferred to a new experiment. We have since used this software to control the Automated Patrol Telescope and CCD camera run by the University of New South Wales, the UNSWIRF Fabry-Perot etalon on the Anglo-Australian Telescope, and a 3.7 m radio telescope used in our 3rd year undergraduate laboratory. More details, and a copy of the software itself, can be found on the World Wide Web as http://www.phys.unsw.edu.au/~mcba/eric.html.

10 FUTURE PLANS

After completion of its measurements in 1995, IRPS will be retrieved from the South Pole and taken to Mauna Kea Observatory to make a direct comparison with that site. To explore other sites on the antarctic plateau, and to obtain site-survey data from the UV to the sub-millimeter, we are designing a suite of instruments to be deployed in an automated observatory.[10] The most up-to-date information on this project is available on the World Wide Web as http://www.phys.unsw.edu.au/~mcba/aasto.html.

11 ACKNOWLEDGEMENTS

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