Robotic telescopes on the Antarctic plateau

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Abstract. The high plateau that covers half of the continent of Antarctica contains the best astronomical observing sites on Earth. The infrared sky background is low, the precipitable water vapour is low, the sub-millimetre sky opacity is low, the winds are low, the atmosphere is exceedingly clear and stable, it never rains, there is no dust, it is geological stable, and the seeing at some sites, notably Dome C, is superb. The turbulence profile in the atmosphere is beneficial for adaptive optics, with fewer actuators and fewer deformable mirrors being required, and with significant correction being possible at visible wavelengths. For projects that require continuous monitoring, e.g., planet detection through micro-lensing, a single robotic telescope in Antarctica can replace a network of 4–6 telescopes placed around the world at mid-latitude sites. For many projects requiring large apertures, a given size telescope in Antarctica will outperform a telescope of 2–3 times the aperture at a mid-latitude site. We review what is known about the site conditions, and outline some of the issues involved with designing robotic telescopes to work in Antarctica.

Key words: Telescopes — Site testing — Atmospheric effects — Instrumentation: adaptive optics — Instrumentation: high angular resolution

1. Introduction

The possible advantages of the Antarctic plateau for astronomical observations have been speculated about for over 30 years (e.g., Townes and Melnick 1990, Gillingham 1991, and see Indermuehle et al 2004 for earlier references), but it is only recently that sufficient site-testing information has been obtained to make definitive comparisons with mid-latitude observatories.

First, we need to be clear that we are discussing the high plateau regions in the center of Antarctica, not the coastal regions. On the plateau there are no high mountain peaks, just gentle (1:1000) slopes rising to a ridge where there are a few local high points, such as Dome C (3260m), Dome Argus (4084m), and Dome Fuji (3810m). Katabatic winds originate from the domes and flow radially outward, accelerating as they go. The domes, therefore, are natural places for observatories, not only because they are local high-points, but more importantly since the low surface winds cause less atmospheric turbulence in the ground layer.

The US Amundsen Scott South Pole Station is somewhat away from the ridge of domes, and so does experience stronger winds, averaging 6m/s. These winds stir ground-layer turbulence which results in disappointing levels of optical seeing: a median of 1.7 arcseconds at 500nm (Loewenstein et al 1998, Travouillon et al 2003b). A telescope placed on a 200–300m tower would be above the boundary layer, and would experience median seeing of 0.3 arcseconds (Marks et al 1999, Marks 2002, Travouillon et al 2003a). Such a tower should not be dismissed out of hand, given the considerable infrastructure already invested at the South Pole.

In what follows, however, we will concentrate on Dome C, the only dome site for which site-testing has currently been performed.

2. Antarctic advantages

2.1. Superb seeing

The first summertime seeing measurements from Dome C were obtained by Aristidi et al 2003. The early measurements were to some extent affected by local turbulence in the telescope, and data taken during 2003–04 showed periods of seeing below 0.2 arcseconds during summertime (E. Aristidi and E. Fossat, personal communication).

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The first wintertime measurements were obtained by Lawrence et al 2004a during March–May 2004, and show a median seeing of 0.27 arcseconds, and below 0.15 arcseconds for 25% of the time.

It is worth noting that the full-width at half-maximum of a star image measured with a large telescope (where the aperture is much greater than the Fried parameter), can be less than predicted from, e.g., Differential Image Motion Monitor (DIMM) measurements, since the predictions assume an infinite outer-scale of turbulence. Tokovinin 2002 discusses this point in detail.

2.2. Wide isoplanatic angle, long coherence time

The isoplantic angle at Dome C is 2–3 times larger than at good mid-latitude sites (Lawrence et al 2004a). The coherence time is also longer.

Lloyd et al 2002 estimated that for narrow-angle differential astrometry, as might be applied to detect extra-solar planets, a mid-IR interferometer at Dome C would be 300 times faster than one at Mauna Kea. Lawrence 2004b and Lawrence et al 2004d showed that adaptive optics at Dome C would require fewer deformable mirrors, fewer actuators, few if any laser guide stars, and would achieve useful levels of correction in the visible. Travouillon et al 2004 discuss the potential for ground layer adaptive optics (GLAO) in Antarctica.

2.3. Greatly reduced telescope costs

Naively one would think that a telescope designed for Antarctic conditions would be more expensive than a mid-latitude design. While this is true for small apertures, when one considers telescopes of 2m or greater in aperture the performance improvements available in Antarctica equate to a larger telescope at a mid-latitude site. Given that the cost of a telescope goes as roughly $d^{2.6}$, the Antarctic option rapidly becomes cost effective. The cost differential is even greater when instruments are factored in: an instrument for a 30m telescope is an exceedingly costly project; if a 10m telescope in Antarctica had equivalent performance, the overall savings would be immense.

Another aspect to consider for large telescopes is that the average and maximum wind speeds are low on the plateau, which greatly simplifies the telescope design, particularly since the force on a structure is proportional to the square of the wind speed. The lack of seismic activity is another factor that reduces the cost of structures. Telescope enclosures can be relatively inexpensive, lightweight designs due to the low winds, lack of rain, and low snow precipitation. So, even for the same aperture, an Antarctic telescope could well be cheaper. And for extremely large telescopes (ELTs), the wind issue alone may make Antarctica the only viable option.

Angel et al 2003 describes a proposal for a 21m ELT in Antarctica.

2.4. Longer mirror coating lifetimes

Mirror coatings tend to be destroyed by the accumulation of airborne dust particles, coupled with humidity from the air, which chemically attack the coating. In Antarctica, the complete lack of dust, and the low water vapour content of the air, are expected to lead to dramatically increased coating lifetimes. The cost savings for telescopes of ELT proportions could outweigh the additional cost of building and operating a coating plant in Antarctica. More work needs to be done on the issue of coating performance in Antarctica.

2.5. Increased sky coverage, for some projects

While sites in Antarctica see less overall sky than mid-latitude sites, for observations such as interferometry and adaptive optics imaging that require bright reference stars, the larger isoplanatic patch available from, e.g., Dome C, leads to a many-fold increase in the total usable sky coverage.

2.6. Low precipitable water vapour

The Atacama desert has less annual precipitation than the Antarctic plateau, but the figure of merit that is important for astronomers is not the precipitation, but the column of precipitable water vapour (PWV). All the plateau sites are superior to Atacama, both in absolute PWV and, perhaps more importantly, in the stability of the PWV on timescales of minutes to hours.

The low PWV has two effects: it opens up new windows, e.g., 200μm, and it makes existing windows from the UV to the sub-mm and beyond wider and more stable (Lawrence 2004c).

2.7. Low infrared background

The sky at the South Pole is at least a factor of 10 lower in emission than Mauna Kea throughout the near and mid-infrared (Smith and Harper 1998, Chamberlain et al 2000, Hidas et al 2000). At 2.35μm there is a natural gap between the airglow emission and the steeply rising thermal emission that leads to a factor of 100 improvement (Ashley et al 1996, Nguyen et al 1996, Phillips et al 1999, Lawrence et al 2002).

2.8. Low telescope temperatures

Longwards of about 2μm, the lower telescope temperature (see Figure 1) significantly reduces the background. This is particularly important for applications such as interferometry or adaptive optics that involve many reflections, each one of which adds a small background signal.

2.9. Lower scintillation

Atmospheric scintillation results in a temporal variation in stellar flux and is an important parameter for many astronomical applications requiring high photometric accuracy, such as astroseismology, micro-lensing, and planetary transit observations. The degree of intensity scintillation for a large aperture telescope ($>$15 cm) at any site scales as the integral of the turbulence strength (given by the refractive index structure constant) multiplied by the square of the altitude. It is thus strongly dependent on turbulence in high altitude layers.

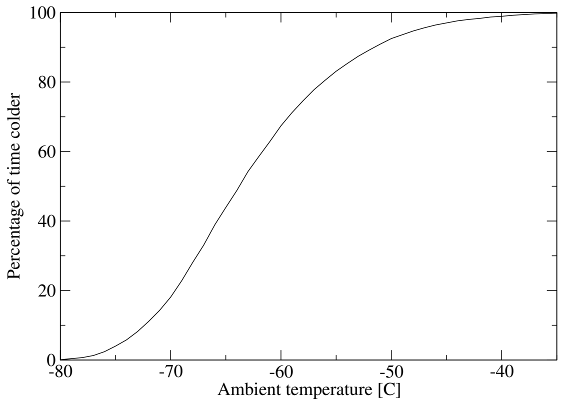

Fig. 1. The distribution of ambient temperatures during the coldest months (May through August) at Dome C. This plot was generated from data from the Automatic Weather Station at Dome C II, using 10 minute data samples from December 1995 to July 2004.

Sites, such as Dome C, where there is little high altitude turbulence will thus have low scintillation. Data taken from the Dome C MASS (Lawrence et al 2004a, 2004e) suggests that for a given telescope size the scintillation index (the ratio of the RMS intensity variation to the average stellar intensity) will be a factor 4–5 lower than found at typical mid-latitude sites (such as Mauna Kea and Cerro Paranal). This will result in a significant increase in photometric precision for a given integration time.

2.10. Reduced airmass variations

From Antarctica, objects experience less variation in airmass as their hour angle changes, which reduces this contribution to the error budget for high-precision photometry.

Field rotation and distortion due to differential refraction is also less of a problem for wide-field imaging.

2.11. No aerosols or dust particles

The almost complete lack of aerosols and dust particles leads to a highly transparent and stable atmosphere. At South Pole or Dome C obscuring the sun with a small object held at arm's length reveals no clue from the sky brightness gradient that the sun is hidden. The reduced scattering is beneficial for solar work and observations requiring extreme contrast ratios.

2.12. Good fraction of cloud-free days

Determining the fraction of cloud-free days at Dome C is surprisingly difficult, since satellites can not reliably distinguish between cloud and the ice below. Ashley et al 2003 ran a camera for a year at Dome C in 2001, and found 74% clear skies. As yet unpublished statistics from the AASTINO (Lawrence et al 2003) webcamera for 2003/4 show in excess of 90% clear skies. More work needs to be done to quantify the distribution of cloud-free days.

2.13. Long periods of continuous observations

The lack of diurnal aliasing can be a major advantage for some projects, e.g., surveys for transiting hot-Jupiter planets with periods measured in days. From the known cloud statistics, objects can often be monitored continuously for a week at a time, possibly extending to months. The mid-latitude alternative is to have a network of 4–6 telescopes at different longitudes, which is an expensive proposition, and produces data of lower quality due to the variation in instruments/telescope/sites.

2.14. Low windspeeds, and stable wind directions

The average wind speed at Dome C is 3 m/s, compared with 4.4 m/s at Mauna Loa and 6.6 m/s at La Palma and Paranal (see Aristidi et al 2004 for a detailed discussion). Figure 2 shows the distribution of wind speeds at Dome C, and Figure 3 shows the distribution of wind directions. The highest wind speed ever recorded in 23 years of monitoring at Dome C is 20 m/s, a mere breeze compared to the violent storms that are known to occasionally lash all other observatory sites.

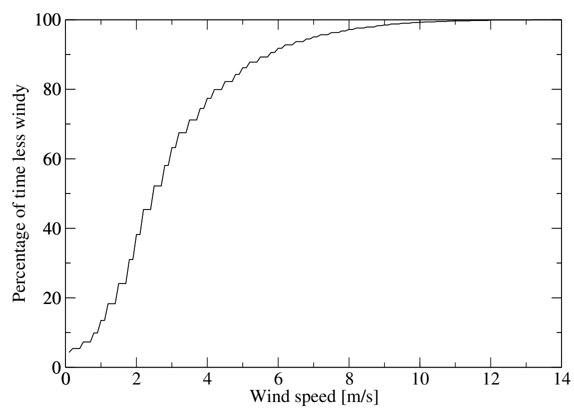

Fig. 2. The distribution of wind velocities during the coldest months (May through August) at Dome C. The data were obtained from AWS measurements as per Figure 1.

2.15. No earthquakes

There is no seismic activity on the plateau that would be relevant to the design of a telescope.

2.16. No lightning

Lightning is a major concern at mid-latitude observatories. It is absent on the Antarctic plateau.

2.17. No land usage issues

There are no endangered species or land usage sensitivities that could influence the construction of a telescope. Of

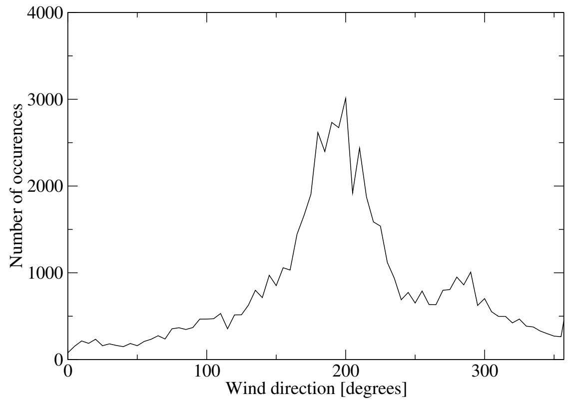

Fig. 3. The distribution of wind directions during the coldest months (May through August) at Dome C, for winds that exceed the median of 2.7 m/s. The data were obtained from AWS measurements as per Figure 1.

course, strict environmental protocols must be observed, as at any site.

3. Antarctic disadvantages

3.1. Practical difficulties

Winterizing a telescope requires engineering skills and experience that is not commonly available. It is difficult to repair telescopes during mid-winter. Transporting large structures to Dome C incurs a year's delay at Dumont d'Urville station. There can be large temperature excursions ($> 20°$C) even after sunset. The low relative humidity increases the risk of static damage to electronic components.

3.2. Astronomical difficulties

The net amount of dark time is less than at mid-latitude sites. There is less overall sky coverage (although important regions such as the Galactic Center, the Magellanic Clouds, and the South Galactic Pole, are all visible). Aurorae are yet to be fully quantified as a problem for visible operations at Dome C (Dempsey et al 2004b), although Dome C is in the center of the auroral oval, which is the optimum location on the plateau.

3.3. Remaining unknowns

More work needs to be done on some aspects of site-testing, most notably cloud statistics, aurorae, and the sub-mm transparency at 200μm. A long time-series of atmospheric turbulence measurements needs to be made—there should be occasional periods of high altitude turbulence as the winds in the polar vortex circulate over Dome C.

4. Designing a robotic Antarctic telescope

We now address some of the practical issues associated with building a telescope to operate in Antarctica. The telescope should be robotic, and designed to reduce to a minimum the complement of staff required to service it. The increased initial cost of a robotic telescope is repaid handsomely by increased observing time and greater reliability.

4.1. Environmental issues

4.1.1. High altitude

The equivalent pressure altitude on the Antarctic plateau is typically between 3000 and 4500m, and is somewhat higher than the physical altitude due to the thinner atmosphere above Antarctica. In common with mid-latitude observatories at such altitudes, care must be taken with instrument cooling (since heat removal through convection and fan-forcing is less effective) and with hard disk drives (these suffer an increased failure rate due to the decreased distance between the read heads and the disk platters; heat removal is also a problem).

The altitude also, of course, affects the reasoning ability of humans who are working on the equipment. So it is wise to plan on complicated tasks taking longer than at sea level.

4.1.2. Low temperature

Somewhat paradoxically, a significant source of instrument failure in Antarctica is *overheating*, since designers tend to pay great attention to thermally insulating the equipment to protect against $-80°$C ambient temperatures, leaving the possibility of overheating when the temperature soars to $-30°$C at the height of summer.

Batteries lose capacity at low temperatures, and may crack and leak acid if subjected to temperatures below about $-50°$C. Connecting bars between cells need to be able to flex. It is wise to test batteries in a fridge. A fully-charged lead-acid cell will freeze at a lower temperature than a partially-charged one. Lithium thionyl chloride batteries perform well, and retain a usable capacity even when buried below the surface at Dome C where the average temperature is $-57°$C, although their terminal voltage declines with temperature, leading to potential failure in, e.g., computer real-time-clock backup circuits, which have a small safety margin even at room temperature. For such applications it is worth using a regulated battery supply, rather than relying on the open-circuit battery voltage.

Vacuum systems need careful consideration, particularly if o-rings are used. Nitrile o-rings should probably be replaced with fluorosilicone o-rings, which maintain their flexibility at much lower temperatures, although they have worse abrasion resistance, which will be an issue for moving seals. Pumps and closed-cycle coolers are likely to be damaged if started at low temperatures (perhaps $< -20°$C), so appropriate safeguards need to be in place to heat these components, and not to start them from cold following a power-failure.

Electronic components often work at much lower temperatures than for which they are specified. For example, we have used a Watec 902-HS video camera at $-80°$C, and a DSP Design PC/104 computer for several years at $-57°$C. On the other hand, a solid-state disk that was rated down to $-40°$C consistently failed if taken below about $-10°$C. It is best to test all components in a low-temperature fridge.

Many plastics become unusably brittle at low temperatures. Teflon is an exception, and all wiring exposed to ambient conditions should be teflon insulated. Teflon flows if pressed against a sharp edge, leading to insulation breakdown.

Differential thermal expansion, while an obvious problem when cooling an instrument from a laboratory at $20°$C to an ambient temperature as low as $-80°$C, needs to be thoroughly considered. Invar can be a useful choice. Nuts should be retained with spring washers.

Some steels become brittle and hard to work at low temperatures. Drilling holes at $-60°$C can be difficult.

Grubb screws can be a major cause of problems. Even for room temperature applications, grubb screws often come loose over time after repeated vibration. At low temperatures, and with frequent thermal cycling, the differential thermal expansion of the screw, shaft, and collar lead to almost certain failure.

4.1.3. Relative humidity, desiccants

The ambient air on the Antarctic plateau is almost always close to 100% relative humidity, although the absolute water vapour content is exceedingly low. The ability of air to hold water decreases rapidly with temperature, so much so that even commercial dry nitrogen has a relative humidity of 100% at temperatures below about $-60°$C. Room temperature desiccants such as silica gel, are entirely useless, and will be a source of moisture rather than a sink. Aggressive desiccants such as calcium hydride do continue to work at Antarctic temperatures, but require care in handling and packaging.

4.1.4. Electrostatic damage

Although the ambient air may be close to 100% humidity, once it is warmed up inside a building it drops to a few percent or less. A consequence of this is that electrostatic damage to electronic components is very common, and rigorous precautions, such as anti-static workbenches and wrist straps, need to be taken.

4.1.5. Icing of optics

There are two distinct problems affecting optical surfaces: icing of a surface exposed to ambient conditions, and icing of a surface within an instrument. The former is best tackled by heating the surface by $5°$C or so above ambient (this can be conveniently done to a reasonable approximation by using a fixed heat input), and also ensuring that there are no sharp edges or strongly concave areas that can exacerbate ice accumulation. If the surface can not be heated, then a mechanical method might be needed to periodically clean the surface.

Interior surfaces can ice-up if the optical element is at a temperature below the dew-point, which can easily happen if the temperature of the instrument drops and even trace amounts of water are present. Warming the optics helps here, as does sealing the instrument and using a powerful desiccant (not silica gel). Of course, a sealed instrument may be destroyed by differential pressure caused by ambient pressure/temperature fluctuations. One solution to this is to use a bi-directional blow-off valve than opens if a pressure difference is exceeded.

4.1.6. Engine exhaust

Exhaust from engines will contain a large percentage of water vapour, and the moisture will almost instantaneously freeze when it reaches the ambient air. If the exhaust velocity is insufficient, the moisture can start forming an ice structure at the point where the temperature is $0°$C. In extreme cases, the ice can grow in extent until it threatens to block the exhaust, or chunks of ice may fall into the exhaust, melt, and cause problems. One solution to the problem is to keep the exhaust as hot as practical and to maintain a high exhaust velocity, by restricting the outlet pipe diameter. A simple uninsulated copper tube has worked well for the AASTINO at Dome C (Lawrence et al 2003, 2004f).

4.1.7. "Diamond dust"

"Diamond dust" is the name for micron-size crystals of ice that are the most common form of precipitation on the plateau. The particles can penetrate any tiny cracks in an instrument with surprising ease, and then fill-up internal spaces. In the worst case, if the space is heated, the ice can melt and/or refreeze. The solution is to stop the particles from entering, and to avoid concave surfaces and sharp edges where the particles can accumulate.

4.1.8. Burial by wind-blown snow

Although the annual precipitation in the form of snow (almost always as "diamond dust", not as flakes) may be 10cm or less, wind-blown ice particles can rapidly bury experiments, particularly at locations away from the Domes, such as South Pole, where higher winds are more common. The mechanism for burial is that ice particles entrained in the wind drop to the ground in the turbulent wake downstream of structures. One technique for reducing the problem is to put the experiment on stilts, preferably with a method for raising the platform every year or so.

4.1.9. Telescope foundations

With solid rock being 3km below the surface, it is necessary to mount the telescope on the ice. There is experience with this issue in the US Antarctic Program. The 7.5m tower shown in Figure 4 tilted by about 20 arcseconds per month (Dempsey et al 2004a).

Fig. 4. The 7.5m high G-Tower supporting a 500kg low-power telescope mount at South Pole Station.

4.1.10. Ease of maintenance

Equipment will almost certainly require repair on occasion during wintertime when the external temperatures are often below −60°C. At these temperatures, the ability of humans to manipulate small fasteners such as nuts and bolts is severely limited. It is therefore crucial to design experiments so that major components can be easily removed and taken to a warm environment for further disassembly. It is good practice to standardize on as few different nut sizes as possible, and to use over-sized fasteners that be easily manipulated with heavy gloves, with the minimum number of different tools.

4.1.11. Testing in a fridge

As much as possible, it is invaluable to test components of an instrument in a low-temperature fridge. Commercial fridges that reach −80° are available, and are an essential part of preparing an instrument for Antarctica. Not all aspects of the site can be duplicated, e.g. diamond dust.

4.1.12. No need for weather protection

A major issue with mid-latitude observatories is protecting telescopes from rain, wind, and dust. On the Antarctic plateau, with no rain, light winds, and no dust, it is entirely practical to leave a telescope exposed to the weather at all times. The only reason for having an enclosure is to provide a wind break to make it more comfortable for people to carry out repairs.

Fig. 5. Telescopes should be designed for maintenance at low temperatures.

4.2. Human issues

For the forseeable future humans will be an essential component in building, operating and maintaining telescopes in Antarctica. There is a great deal of experience within the various national Antarctic programs of the issues involved with human interactions and performance in the extreme conditions in Antarctica. For an interesting summary, see Burton 2004.

4.3. Robotic telescope design—general comments

4.3.1. Computer control

At UNSW our philosophy has been to minimize the number of computers used to control an experiment, even to the extent of using a single computer to control the telescope, CCD camera, data reduction, thermal management, etc. This simplifies issues of interprocess communication, and greatly increases reliability.

4.3.2. Software

At UNSW we have followed the "UNIX philosophy" of providing modular tools to perform simple functions. These tools can then be embedded in any scripting language that the astronomer is familiar with. This has given us a great deal of flexibility with telescope control. For example, the Automated Patrol Telescope at Siding Spring Observatory can be operated from within IRAF scripts, making it possible to adaptively alter the observing program on the basis of real-time analysis of the data.

For telescope control systems, we have had great success with the Portable Telescope Control System (PTCS) described by Bailey and Prestage 1997.

4.3.3. Watchdogs

A robotic telescope needs to have a well thought-out strategy for coping with system failures. Hardware and software watchdogs need to be carefully constructed. One of the major issues is restarting a system that has been allowed to cool down to ambient, perhaps through a power failure.

5. Conclusion

While there are some challenges to working in Antarctica, the advantages for astronomy are overwhelmingly compelling.

There will be people who argue that Antarctica is too difficult, and then there will be people who go ahead and build a telescope there.

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