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Dome C—the best astronomical site in the world?

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Abstract. A decade of site testing at the South Pole has shown that the Antarctic Plateau can offer enormous opportunities for astronomers. The combination of extreme cold and dryness, high altitude and very low wind speeds throughout the troposphere confers powerful advantages—especially for infrared and sub-millimetre astronomy. However, Dome C is higher, drier and colder than South Pole, and has significantly lower wind speed. Could it be an even better site? In this paper we review the South Pole results and derive predictions for Dome C. We also discuss new and existing Dome C data, and present plans to further characterise the Dome C site with experiments such as the AASTINO.

Key words. Site testing – atmosphere – optical – infrared – sub-millimetre – millimetre

1. Introduction

Astronomers have always sought the best possible locations for their observatories. In the beginning, a small hill close to the astronomer's own city was considered adequate. Then, as cities grew and light pollution became a serious issue, astronomers moved to remote mountain-tops. More sophisticated site-testing methodologies followed, taking into account cloud cover, seeing, wind and sky brightness. These surveys resulted in the identification, and subsequent development, of the current "best" astronomical sites in the Canary Islands, Hawaii and Chile.

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However, there are a number of reason why the high plateau of Antarctica should offer a substantial improvement over existing sites. The most obvious of these are the extreme cold and dryness, which lead to quite remarkable reductions in the infrared sky brightness and very significant improvements in the infrared and sub-millimetre atmospheric transmission. In addition, the very low wind speeds at all altitudes and the unique distribution of turbulence that results have a profound effect on the performance of astronomical instruments. Finally, despite the apparent difficulty of constructing a telescope in Antarctica, there are a number of reasons why it is not so difficult as might at first be expected.

For the past decade astronomers have been carrying out detailed site-testing studies at the Amundsen-Scott station at the South Pole. The result is that the South Pole is now one of the best characterised sites on earth. In addition, telescope such AST/RO (Stark et al. 1997) and SPIREX (Fowler et al. 1998) have, by making important astronomical discoveries, demonstrated that not only is the South Pole an exceptionally good site in theory, but that no real obstacles exist in practice to the deployment of experiments that can successfully exploit these conditions. More recently, the DASI experiment (Leitch et al. 2002) has demonstrated beyond doubt the outstanding results that can be achieved by taking advantage of what the site has to offer.

Dome C, where the Concordia station is currently under construction (Candidi & Lori 2003), is some 400 metres higher than South Pole and is further from the coast than the Pole. Being a "dome" (a local maximum in the elevation of the terrain), it experiences much lower wind speeds—both average and peak. On the face of it, Dome C should be a substantially better site than even the South Pole. Although winter-time site testing at Dome C has only been underway for the past two years, there is already a significant amount of information available on summer-time conditions. Taken together, all the data available so far suggest that Dome C is a truly remarkable site.

2. Millimetre wave

Millimetre-wave atmospheric stability measurements were amongst the first astronomical experiments to be conducted at Dome C (Valenziano et al. 1998). These data, combined with data on the precipitable water vapour (Valenziano and Dall Oglio 1999), lead to the conclusion that Dome C should be an outstanding site at these wavelengths. This result is of particular importance to cosmologists, who need to be able to make long, deep integrations of the cosmic microwave background.

3. Sub-millimetre

The South Pole is already known to be the best existing sub-millimetre site in the world (Chamberlin et al. 1997; Lane 1998). In the summer of 2001–02 the University of New South Wales deployed a 350 micron tipper to Dome C for a period of 6 weeks (Calisse et al. 2003). Throughout the same period, an almost identical tipper was in operation at the South Pole. Although this experiment offers only a limited comparison to be made, the data clearly show a substantial advantage to Dome C. Specifically, it is seen that during those six weeks, the average 350 micron opacity (tau) at Dome C was less than that at South Pole by about 0.2. For 50% of the time at South Pole, tau was below 1.8, while at Dome C it was below this value for 75% of the time. If a tau of 1.8 is considered to be about the maximum acceptable for useful science, then Dome C is seen to offer 50% more usable observing time than South Pole. Just as importantly, the atmospheric opacity at Dome C was much more stable than at Pole.

Paradoxically, a colder site is not necessarily a better sub-millimetre site. This is because the lower temperatures lead to a greater population of water molecules in the lower energy states, and it is these states that are responsible for the sub-millimetre opacity (Pardo et al. 2000). Nevertheless, it is clear that the dramatically lower water vapour content over Antarctica compared to even the best temperate sites is more than sufficient to compensate for this effect.

4. Infrared

Near infrared measurements at the South Pole (Nguyen et al. 1996; Ashley et al. 1996; Phillips et al. 1999; Lawrence et al. 2002) have shown that, between 2 and 5 microns, the sky is between one and two orders of magnitude darker than at temperate sites. Since the majority of near-infrared instruments currently operate under background-limited conditions, this translates directly into a sensitivity increase of up to a factor of 10.

The first determination of the South Pole mid-infrared sky brightness during the summer (Smith and Harper 1998) showed that it was even darker than would be expected from considerations of the temperature alone. This was confirmed for the winter-time as well (Chamberlain et al. 2000), with results showing that the sky was as much as 20 times darker than Mauna Kea in some portions of the 10 micron window.

These results imply a direct and substantial gain in sensitivity for a telescope. Put another way, a small telescope in Antarctic can achieve similar sensitivity to a much larger one placed at a temperate site. For example, when imaging at the same spatial resolution, a 2-metre telescope in the Antarctic can achieve similar (and at some wavelengths better) sensitivity to an 8-metre telescope on Mauna Kea or in Chile.

There are of course many advantages to performing the same science with a smaller telescope. One such advantage is in the instrumentation. Because the $A\Omega$ product of the telescope is conserved throughout the entire optical train, the linear size of the instruments scales directly with telescope aperture.

Although a systematic year-round study of the infrared sky brightness at Dome C has yet to be undertaken, there is no reason to suspect that it will not be at least as dark as South Pole—based on purely geographical considerations. Preliminary summer-time measurements (Walden & Storey 2003) demonstrate beyond doubt that exceptionally good conditions can occur.

5. Visible and atmosphere

As far back as 1980 astronomers have been exploring the potential of the South pole for research at visible wavelengths (Grec et al. 1980). Unfortunately, the seeing at ground level has been found to be quite poor (Loewenstein et al. 1998; Travouillon et al. 2003). However, this is not the end of the story. A systematic study of the turbulence throughout the atmosphere has been carried out with microthermal sensors attached to a tower (Marks et al. 1996) and flown from balloons (Marks et al. 1999). These results show that almost all of the seeing degradation occurs in the lowest couple of hundred metres of the atmosphere. Above that, the atmosphere is remarkably stable, and completely unlike any temperate site.

It is this absence of high altitude turbulence that leads to some of the most exciting predictions (Marks 2002; Lloyd et al. 2002) about the potential performance gains of certain astronomical experiments.

Summer-time measuremens of the seeing at Dome C (Aristidi et al. 2003) show that, as at South Pole, it is on average quite poor. However, a very strong diurnal variation is seen, with periods of exceptionally good seeing when the temperature gradient through the atmosphere is favourable. This suggests that th winter-time seeing may in fact be rather good.

Acoustic radar measurements at the South Pole (Travouillon et al. 2003a) have confirmed that the turbulent boundary layer extends only two to three hundred metres above the ice, and have established a very strict linear relationship between ground level wind-speed and the thickness of the turbulent layer. This result implies that the seeing at Dome C should be substantially better, as the average wind speed there is less than half that at South Pole.

Two experiments have been deployed to Dome C to determine the amount of cloud cover throughout the year. The first, Icecam (Ashley et al. 2003), uses a CCD camera and frame grabber to take images of the sky every two hours. Icecam is fully self-contained and is powered by a battery pack of lithium thionyl chloride cells. Data are stored locally on flash memory for retrieval at the end of each year, while a synopsis is sent out in real time via the ARGOS satellite system.

A second instrument, COBBER (Demspey et al. 2003), uses a mid-infrared detector to observe a 30-degree patch of sky. Because clouds are warmer than the interstellar space they obscure, the presence of clouds is readily detected by an increase in mid-infrared flux. COBBER uses the same power supply, data acquisition computer and ARGOS transmitter as Icecam.

Data from these instruments is still being analysed, but preliminary results suggest that Dome C is at least 80% cloud-free, placing it amongst the best sites in the world on the basis of this criterion alone.

6. The AASTINO

In order to obtain detailed site-testing information from Dome C as soon as possible, the University of New South Wales have recently deployed a self-contained autonomous observatory called the AASTINO (Automated Astrophysical Site Testing International Observatory), see (Lawrence et al. 2003). The design of this facility is a development of a similar facility, the AASTO, that has operated at the South Pole for several years (Storey et al. 1996; Storey 1998; Storey et al. 2000). The AASTINO is powered by two Stirling engines, augmented during the daylight hours by solar panels. Two-way communication with the outside world is via the Iridium satellite network but, in the event of a communications failure, the AASTINO can operate completely autonomously and store data on local flash memory.

The AASTINO was deployed to Dome C in January 2003, and put into operation. It currently carries two instruments—an acoustic radar (SODAR) and a submillimetre tipper (SUMMIT). The first results from these experiments have been presented at this meeting (Travouillon et al. 2003b) and are extremely encouraging. In future years additional instruments will be installed in the AASTINO, including infrared sky-brightness monitors. The AASTINO also hosts a web camera, which allows remote monitoring of the site.

7. Future plans

As soon as the Concordia Station is open for year-round operation, it will be possible to deploy a powerful arsenal of site-testing instruments, including the Generalised Seeing Monitor (Martin et al. 1994). However, enough is already known about the site to justify the construction of medium to large scale telescopes. At the present time, proposals have already been made by Australia (Lawrence et al. 2002, 2003a), Italy (Busso et al. 2002) and the US (Jackson 2003) to construct infrared telescopes at Concordia. An ambitious project to construct a multi-telescope infrared interferometer is planned (Swain et al. 2003) while at millimetre wavelengths plans are well advanced for experiments to study the Cosmic Microwave Background radiation (Ali et al. 2002).

8. Conclusion

The next few years will see Dome C take its place alongside the most important astronomical observatories in the world. There is no doubt that for many kinds of observations, the challenges of building telescopes at Dome C will be more than outweighed by the greatly improved capability conferred upon them by the remarkable site conditions.

In addition, since Dome C has the closest conditions on earth to those experienced in space, the site should become an important "test-bed" for technology and for concepts that will later be flown as space missions (Storey et al. 2002, 2003). Indeed, for some projects Dome C may offer a sufficiently attractive alternative to space that it allows a "ground based" experiment to be conducted instead, resulting in a faster turn-around time and significant cost savings.

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