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Dome C's Atmospheric Conditions: Implications for Astronomy[⋆]

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Abstract The expectation that exceptional conditions for astronomy would be found at Dome C on the high Antarctic plateau has motivated a coordinated effort by a number of international teams to comprehensively measure the atmospheric conditions at this site. This paper presents an overview of the current status of site testing at Dome C. We discuss the past, present, and planned instrumentation, the main results obtained to date, and the implications of these results.

Key words: site testing—Earth: Antarctic plateau: dome C

1. INTRODUCTION

It has long been recognised that sites on the Antarctic plateau should be ideal for astronomy. It was expected that low temperatures throughout the Antarctic plateau troposphere would result in a low sky thermal emission (Harper 1989) and low precipitable water vapour, and that the calm and stable atmosphere above the Antarctic plateau would result in weak turbulence and thus good seeing (Gillingham 1991).

These expectations have motivated over a decade of site testing at the US Amundsen-Scott South Pole station. The infrared sky emission was found to be 1–2 orders of magnitude lower than typically found at mid-latitude sites (Ashley et al. 1996; Nguyen et al. 1996; Phillips et al. 1999; Chamberlain et al. 2000), and the atmosphere was found to be very dry (Chamberlin 2001). The expectation of weak free-atmosphere turbulence was also confirmed. However, a very strong turbulent surface layer several hundred metres thick was found, which resulted in mediocre ground level seeing (Loewenstein et al. 1998; Marks et al. 1999).

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The new Italian/French Concordia station at Dome C, lying at a higher altitude than South Pole, should experience colder atmospheric temperatures, resulting in even lower thermal emission and lower water vapour content (Marks et al. 1999). The local topography of Dome C also indicated that the surface wind speeds should be lower and thus the turbulent boundary layer should be confined closer to the surface (Gillingham 1991).

2. SITE TESTING INSTRUMENTATION

Many site testing instruments have been operated, and are planned for operation, at Dome C. These instruments have operated as part of the Concordiastro project (led by the University of Nice), the AASTINO project (led by the University of New South Wales), and various independent projects. Among the other institutions who have contributed to these instruments are Arcetri Observatory, Caltech, Cerro-Tololo Inter-American Observatory, Jet Propulsion Laboratory, University of Idaho, Joseph Fourier University, University of Cardiff, University of Lethbridge, and University of Rome. Here we briefly list in three general classes (meteorology, sky emission and opacity, and turbulence) the various site testing instruments that have been, or are planned to be, deployed to Dome C.

2.1 Meteorology

- AWS: standard Automatic Weather Station measuring ground level pressure, temperature, humidity, and wind speed/direction (operating since 1980)
- met. balloons: standard probes measuring atmospheric profiles of temperature, pressure, humidity, and wind speed/direction (summer since 1995, winter 2005)
- COBBER: low power mid-infrared thermopile detector measured cloud cover statistics (operated winter 2003,4)
- ICECAM: autonomous self-powered visible CCD camera measured cloud cover statistics (operated winter 2002,3)
- Vaisala FD12: visibility sensor measuring rates of snow/diamond dust fall (operating since summer 2004)
- Gattino Allsky: wide field optical CCD camera designed to measure cloud cover and auroral distribution (planned for deployment in 2005/6 summer)

2.2 Sky Emission and Opacity

- solar photometer: measured precipitable water vapour (operated summer 1996/7)
- APACHE96: millimetre wave telescope measured atmospheric stability and sky noise (operated summer 1996/7)
- SUMMIT: Sub-millimetre tipper measuring opacity and sky emission at 350 μm and 200 μm (operating since summer 2003)

- PAERI: infrared Fourier transform spectrometer measured sky emission and opacity from 3-20 micron (operated summer 2002/3 and 2003/4)
- Nigel: Fibre-coupled spectrometer measuring sky spectral emission at optical wavelengths (deployed in 2004/5 summer)
- IRMA: infrared radiometer designed to measure sky emission and opacity at 20 μm (planned for deployment in 2005/6 summer)
- Gattino SBC: narrow field optical CCD camera designed to measure sky background in the visible (planned for deployment in 2005/6 summer)
- AIRBUS: infrared camera designed to measure sky emission in K band (planned for deployment in 2005/6 summer)
- McSHMISM: mid-infrared spectrometer with microbolometer array designed to measure sky emission spectrum in N band (currently under development)

2.3 Turbulence

- DIMM: Differential Image Motion Monitors measuring integrated seeing 3.5 and 8.5 m above the surface (operating summer since 2000, winter 2005)
- SODAR: acoustic radar measuring turbulence within the 30–900 m surface layer (operating since summer 2003)
- MASS: Multi-Aperture Scintillation Sensor measuring low spatial resolution turbulence profile of atmosphere from 0.5–22 km (operated winter 2004)
- Microthermal Balloon: balloon borne high accuracy temperature sensors measuring atmospheric turbulence profile with high spatial resolution (operating winter 2005)
- Microthermal Mast: tower mounted microthermal sensors measuring turbulence in the 0–30 surface layer (deployed winter 2005)
- SHABAR: lunar SHAdow Band ARray designed to measure surface layer turbulence distribution (planned for deployment in 2005/6 summer)
- EAGLE: Evolutive Antarctic Ground Layer Experiment using sonic anemometers designed to measure turbulence in the 0–30 m surface layer (planned for deployment in 2005/6 summer)
- SCIDAR: Scintillation detection and Ranging designed to measure turbulence profile (planned for deployment in 2005/6 summer)
- GSM: multiple DIMMs operated in Generalised Seeing Monitor mode designed to measure turbulence characteristics (planned for operation in 2006 winter)

3. RESULTS

3.1 Meteorology

Analysis of over 20 years of AWS operation at two sites close to the current Dome C station (Valenziano & Dall'Oglio 1999; Aristidi et al. 2005a) has shown extraordinarily low ground level wind speeds. Peak and average wind speeds (20.2 $\mathrm{m.s^{-1}}$ & $2.9\,\mathrm{m{\cdot}s^{-1}}$, respectively) are both less than half that recorded at the majority of other astronomical sites. Additionally, the wind speed is zero (or below the detection threshold of wind speed sensors used) for a significant fraction of the time.

Dome C summer-time solar photometer measurements of precipitable water vapour (pwv) column density reported by Valenziano & Dall'Oglio (1999) demonstrated a similar value (0.5–0.6 mm) to that found at South Pole during the summer-time. Extrapolations of high altitude balloon measurements from other Antarctic sites (Lawrence 2004) have predicted a mid-winter pwv column density at Dome C of 0.16 mm, significantly lower than the 0.25 mm mid-winter pwv measured at South Pole (Chamberlin 2001). Meteorological balloon data collected during the current winter season, and successive winters, should determine the validity of these predictions.

Atmospheric profiles obtained from meteorological balloons launched during the summertime (Aristidi et al. 2005a) have shown that Dome C has an extremely stable upper atmosphere and a very low inversion layer. The conditions for turbulence generation in the free atmosphere were found to be few and spatially thin, and the boundary layer thermal structure indicated an absence of mechanisms for turbulence generation at specific times of the day. Further balloon data from the next few winter seasons should give important information on the magnitude and frequency of occurrence of strong winds in the upper troposphere.

Statistics on cloud cover obtained to date demonstrate that Dome C is an extremely clear site. Instrumentation has given lower limits of 74–80% to the percentage of clear skies (Ashley et al. 2004 and references therein). Recent estimates by the winterover astronomer at Dome C put this number at a remarkable 96% over a 5 month period (Aristidi et al. 2005c). The Gattino All-Sky camera planned for deployment in the coming summer will provide complete quantification of the Dome C cloud cover statistics over the next winter seasons. More information on the snowfall and accumulation rate should also be achieved over the next winter season with continuous operation of the FD12 visibility monitor.

3.2 Sky Emission and Opacity

The sub-millimetre sky opacity at Dome C was measured during the 2000/1 summer season by the SUMMIT radiometer (Calisse et al. 2004). This instrument determined the median 350 μm zenith broadband opacity to be 1.61 at Dome C over a six week period. This was lower than the median 350 μm opacity measured at the South Pole (1.81) over the same 6 week period with a similar instrument. Additionally, the noise on this opacity value, which is determined by the strength of atmospheric turbulence, was qualitatively lower at the Dome C site. A 200 μm filter was installed in the SUMMIT instrument in summer 2004/5. Once operational it should give valuable information about the potential for astronomical observation in this atmospheric window.

The PAERI FTS was operated at Dome C during the 2002/3 and 2003/4 summer seasons, and measured the sky emission throughout the mid-infrared region (Walden et al.

2005). Median values of atmospheric emission in the M, N, and Q bands were found to be 0.9, 43, and 310 Jy·arcsec^{-2}, respectively. These emission values are similar to those observed at South Pole during the coldest winter months (Chamberlain et al. 2000). The Dome C sky emission was also found to be very stable, with only a 10% variation (43±4 Jy·arcsec^{-2}) observed in N band over a 5 day period. Atmospheric models of infrared sky emission based on this data combined with winter-time meteorological balloon data predict that the winter time infrared atmospheric emission should be 20% lower than these summer-time values (Lawrence 2004).

Important data on Dome C atmospheric emission and opacity will be obtained by the set of new instruments planned for deployment to Dome C in the 2005/6 summer. IRMA will measure the 20 μm sky emission and opacity (Phillips et al. 2004), allowing a further refinement of atmospheric models to better predict emission throughout the infrared, and a better estimation of the atmospheric precipitable water vapour concentration. The AIRBUS instrument (Epchtein 2005) will perform the first measurements of near infrared sky emission at Dome C, and determine whether near infrared airglow emission is lower at Dome C than typically observed at mid-latitude sites, as suggested by South Pole results (Phillips et al. 1999). In the visible, the sky background will be measured with the Gattino SBC camera. This is crucial for the understanding of visible sensitivity comparisons between Dome C and mid-latitude observatories. Although the high latitude of the Dome C site results in a lower number of total hours per year of astronomical twilight (sun elevation below −18°), simulations by Kenyon & Storey (2005) suggest the amount of usable dark-time is comparable to that at other sites. Operation of the Nigel spectrometer will determine the intensity of optical auroral emission at Dome C. South Pole data show auroral intensity in the optical can significantly contribute to the visible sky background (Dempsey et al. 2005). It is thus important to know to what extent this also occurs at Dome C.

3.3 Turbulence

Measurements of atmospheric turbulence at Dome C station obtained from DIMM instruments operated over two summer-time seasons (2003/4 and 2004/5) give a median seeing of 0.54 arcsec (Aristidi et al. 2005b) when the sun is up. A strong diurnal trend was observed over these two summers, with seeing dropping to a median of 0.4 arcsec in the late afternoon, coincident with a flat thermal inversion layer observed with meteorological balloons. DIMM measurements of the isoplanatic angle performed in January 2004 give an average of 6.8 arcsec (Aristidi et al. 2005b).

Winter-time turbulence measurements at Dome C were first obtained in 2004 (Lawrence et al. 2004). For a six week period after sunset the mean seeing above 30 m, as measured by the combination of SODAR and MASS instrument data, was 0.27 arcsec, and the 25% quartile was 0.15 arcsec. The atmospheric coherence time and isoplanatic angle were also determined by SODAR/MASS over this period to be 7.9 ms and 5.7 arcsec, respectively.

During the current 2005 winter, measurements of seeing have been obtained with two separate DIMMs (at heights of 3.5 m and 8.5 m above ground level) and from a series of microthermal balloon launches (Aristidi et al. 2005 c; Agabi et al. 2005). The 8.5 m DIMM has shown a median seeing of 1.2±0.7 arcsec. Balloon measurements are consistent with the DIMM measurements (integrated from 8.5 m) and are consistent with the 2004 MASS/SODAR measurements when integrated from 30 m, giving a seeing of 0.36±0.18 arcsec. Balloon measurements above 30 m of isoplanatic angle (4.6±2.7 arcsec) and coherence time (7.9±7.1 ms) are also consistent with SODAR/MASS measurements.

New instruments planned for operation in winter 2006 are crucial for increasing our understanding of atmospheric turbulence at Dome C. EAGLE, SHABAR, and tower-mounted microthermals will characterise the strength and distribution of the boundary layer turbulence. Combining the data from these instruments with MASS, SODAR, DIMM, balloon microthermals, SCIDAR, and GSM, all measuring different aspects of turbulence through different mechanisms, will lead to an exceptionally robust quantification of atmospheric turbulence at this site.

4. IMPLICATIONS

Many aspects of the meteorological conditions at Dome C are advantageous for astronomy. Low winds speeds will increase the efficiency of any telescope operating there, and should reduce mechanical requirements on the telescope and enclosure structural design. The high percentage of cloud free nights provides a significant increase in observing efficiency relative to any existing site. Some meteorological conditions, however, such as the extremely low ground level temperatures, the large thermal gradient in the surface layer, and the existence of diamond dust, are unfavourable and will require unique technological solutions.

Data indicate that the Dome C infrared sky emission in winter will be the lowest of any existing observatory. It is also expected that the water vapour will be the driest of any existing site. These factors lead to a significant increase in sensitivity in the near to far infrared, and the opportunity of observing through sub-millimetre atmospheric windows that are not accessible elsewhere from the ground.

The ground level seeing at Dome C is relatively poor compared to most mid-latitude sites. The majority of the turbulence, however, is confined within a layer 20–40 m above the surface. This unique turbulence structure will require unique solutions. A telescope located at ground level with a ground layer adaptive optics system should be capable of achieving close to the free atmosphere resolution. A telescope located above the turbulent surface layer will experience exceptional natural seeing, and if operated with an adaptive optics system should achieve higher resolution than a similar sized telescope at any other ground based site. Although mounting a telescope above the turbulent layer, i.e. on a 20—40 m tower or hill, may seem a difficult technological challenge, many existing telescopes at other sites are located at similar heights above ground level (e.g. the AAT at 26 m, the CFHT at 28 m, the ESO 3.6 m at 30 m, and the 4 m Mayall at 57 m).

5. CONCLUSIONS

Many instruments over the last five years have contributed to our current knowledge of the atmospheric conditions at Dome C station on the Antarctic plateau. Data show that this is an exceptional site, with most relevant parameters superior to those found at any existing mid-latitude site. This evidence justifies the next step towards the development of Dome C as an astronomical observatory, which should include the deployment of a 2—3 m class optical/infrared telescope, such as PILOT (Lawrence et al. 2005). Such a facility will not only do unique science, but can also help to complete the characterisation of this site to the level required for much larger telescopes in the 8–30 m range. A few winter seasons of data obtained from the current suite of Dome C site testing instruments with the addition of new instruments to be deployed in the coming summer season, should fulfil this requirement.

Dome C may not, however, be the best astronomical site on the Antarctic plateau for all purposes. Dome A, which has recently been visited for the first time by the Polar Research Institute of China, lies on the highest point of the Antarctic plateau, some 800 m higher than Dome C. It should thus experience colder atmospheric temperatures, lower wind speeds, and a turbulent boundary layer confined closer to the ground. This provides strong motivation to develop a program dedicated to astronomical site testing at this location.

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