Exceptional astronomical seeing conditions above Dome C in Antarctica

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One of the most important considerations when planning the next generation of ground-based optical astronomical telescopes is to choose a site that has excellent 'seeing'—the jitter in the apparent position of a star that is caused by light bending as it passes through regions of differing refractive index in the Earth's atmosphere. The best mid-latitude sites have a median seeing ranging from 0.5 to 1.0 arcsec (refs 1–5). Sites on the Antarctic plateau have unique atmospheric properties that make them worth investigating as potential observatory locations. Previous testing at the US Amundsen-Scott South Pole Station has, however, demonstrated poor seeing, averaging 1.8 arcsec (refs 6, 7). Here we report observations of the wintertime seeing from Dome C (ref. 8), a high point on the Antarctic plateau at a latitude of 75° S. The results are remarkable: the median seeing is 0.27 arcsec, and below 0.15 arcsec 25 per cent of the time. A telescope placed at Dome C would compete with one 2 to 3 times larger at the best mid-latitude observatories, and an interferometer based at this site could work on projects that would otherwise require a space mission.

In searching for sites for a major observatory, many factors need to be considered, including the atmospheric turbulence, cloud cover, precipitable water vapour, thermal emission from the atmosphere, auroral activity, aerosol/dust pollution, average and maximum wind speeds, seismic activity, rates of snow/rain fall, light pollution, accessibility, infrastructure and cost of operation. It has long been recognized that sites on the Antarctic plateau excel in many of these characteristics[9–11]. However, the poor seeing at the South Pole itself, caused by a highly turbulent layer of air within 200–300 m of the ground[12], is a major limitation. It has been postulated that such a turbulent layer may be absent at Dome C, owing to the local topography, lower wind speeds and higher altitude (3,250 m, compared to 2,840 m)[13,14]. Seeing measurements from Dome C during the 2003–04 summertime (daytime in Antarctica) have eliminated sources of local turbulence that had affected earlier measurements[15] and have now demonstrated periods of superb seeing below 0.2 arcsec (E. Aristidi and E. Fossat, personal communication). Summertime balloon-borne experiments have shown low levels of high-altitude winds[16]. However, the crucial information that astronomers need, and that we provide here, are measurements of the seeing in the wintertime, after sunset. Obtaining this data presented a formidable technical challenge,

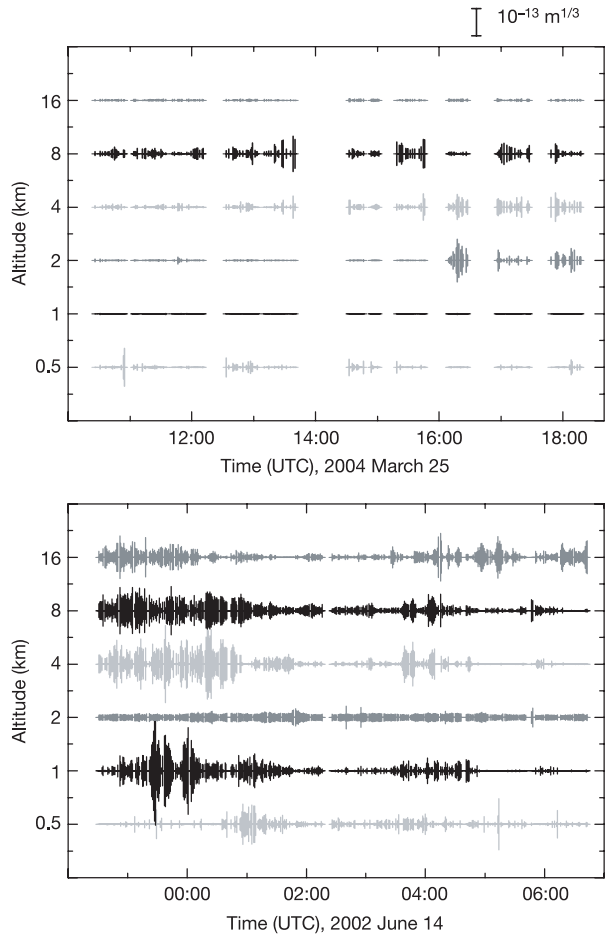

Figure 1 Comparison of turbulence profiles obtained from similar instruments at Dome C and Cerro Tololo. A typical night (representing ~50th percentile conditions) of the refractive index structure constant profile for Cerro Tololo[28] (bottom panel) and Dome C (top panel). Data are from similar MASS instruments. The length of the vertical bars at each altitude represents the magnitude of the refractive index structure constant integrated over that layer.

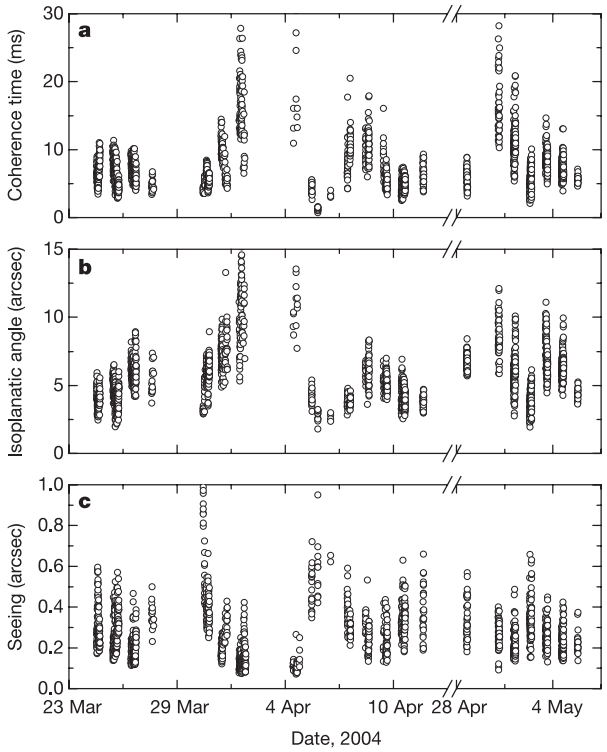

Figure 2 Dome C atmospheric coherence time, isoplanatic angle and seeing data as a function of time. Coherence time (**a**) and isoplanatic angle (**b**) are derived from the MASS instrument. Atmospheric seeing above 30 m (**c**) is computed from a combination of the refractive index structure constants from MASS and SODAR. Data covers the period 23 March to 5 May 2004. All data refer to observations at 1–1.5 airmass scaled to the zenith, and at a wavelength of 500 nm.

given that the French/Italian station at Dome C is currently uninhabited during winter[8], and that infrastructure such as electrical power and communications is not available.

To obtain data over the winter months, we developed a remote autonomous laboratory, the AASTINO (Automated Astrophysical Site Testing International Observatory)[17]. This observatory was constructed at Dome C in January 2003, and it provides heat, electrical power, Iridium satellite communications, and computer control for a series of site testing instruments. In January 2004, we installed a Multi-Aperture Scintillation Sensor (MASS)[18] to measure the wintertime seeing. MASS uses the spatial/temporal structure of single star scintillation (that is, intensity fluctuations) to evaluate vertical refractive index fluctuation profiles[19,20]. The advantage of MASS over other techniques for measuring the seeing is that MASS uses a small telescope (making it less costly, and easier to automate) and it is able to measure the contributions to the seeing from six layers within the atmosphere, at fixed altitudes of 0.5, 1, 2, 4, 8 and 16 km. A limitation of MASS is that it is insensitive to seeing below about 500 m. We have therefore simultaneously used a SODAR (Sonic Detection And Ranging) instrument to determine the contribution from the layer between 30 and 500 m. From the MASS profiles, the 'free-atmosphere' seeing (above 500 m) and the isoplanatic angle (the angle over which atmospheric phase fluctuations are coherent) can be determined, and have been well-verified against other techniques (J. Vernin, A. Ziad and A.T., manuscript in preparation). The atmospheric coherence time (defined as the time over which the phase fluctuations are coherent) can also be derived from MASS, although the validity of this derivation for a complete range of atmospheric conditions is yet to be fully confirmed[21]. A MASS is currently in operation at Cerro Tololo[19] and several more are being deployed to other sites as part of a global site-testing effort.

The Dome C SODAR has been calibrated against microthermal sensors[22]. Robust performance of this instrument under Antarctic winter conditions, and good agreement with DIMM (Differential Image Motion Monitor) measurements, have previously been demonstrated through operation at the South Pole[12]. The calibration of the SODAR instrument is also significantly simplified in the low absolute humidity environment on the Antarctic plateau.

Figure 1 compares a typical night's profile of the refractive index structure constant (which describes the refractive index variations) from the Dome C MASS and a similar MASS instrument at the Cerro Tololo Inter American Observatory in Chile. The Tololo atmosphere, typical of mid-latitude sites, exhibits strong turbulence within the lower troposphere, extending up to 1 km above the surface. Additionally, strong turbulence is observed throughout the upper troposphere bounded by the jet stream at 10–14 km above the surface. The Dome C turbulence profile is quite different, and is unlike any observed at mid-latitude sites. The strongest turbulent layer occurs at a lower altitude owing to the lower tropopause height (5–8 km above the surface), and is of lower intensity owing to the lack of strong winds at this altitude. The only mechanism for turbulence generation in the Antarctic stratosphere above 10 km is from the Antarctic polar vortex, a system of strong high-altitude winds circling the continent[23]. Prior to our MASS data, it was a matter for speculation to what extent the vortex winds would affect the turbulence at Dome C. Our data show no evidence thus far of such turbulence.

The low values of high-altitude turbulence at Dome C lead to refractive index variations that are coherent over a large angle (that is, large isoplanatic angle) and over a long time (that is, large coherence time), see Fig. 2. The average values, 5.7 arcsec and 7.9 ms respectively, are higher than average values recorded at any other site, as shown in Table 1.

Combining the refractive index structure constant values for the free atmosphere determined by the MASS, with the surface boundary layer turbulence determined by the SODAR, gives the atmospheric seeing above 30 m (Fig. 2, Table 1). Whereas the surface boundary layer (within a few hundred metres of ground level) is usually a significant contribution to the total atmospheric seeing at mid-latitude sites, the 30–900 m turbulence observed at Dome C by the SODAR is exceptionally low, and is typically below the SODAR detection threshold (0.05 arcsec). This is expected from the very low-velocity ground level winds at this site. An additional contribution to the total atmospheric seeing is expected from the first 30 m above ground level (a region in which the SODAR is not sensitive).

A histogram of the atmospheric seeing above 30 m is shown in

Table 1 **Comparison of observatory site conditions**

Site	ϵ_0	θ_0	τ_0
Dome C	0.27	5.7	7.9
South Pole	1.8	3.2	1.6
Mauna Kea	0.5–0.7	1.9	2.7
San Pedro Martir	0.59	1.6	6.5
Cerro Paranal	0.80	2.6	3.3
La Palma	0.76	1.3	6.6

ϵ_0 is the seeing in arcseconds, θ_0 is the isoplanatic angle in arcseconds and τ_0 is the coherence time in milliseconds. All values are corrected to the zenith and at a wavelength of 500 nm. Seeing, isoplanatic angle and coherence time at South Pole are mean total atmosphere values (above ground-level) from 16 microthermal balloon launches in winter 1995 combined with microthermal tower measurements of the 0–30 m ground layer[7]. Seeing and isoplanatic angle values at Mauna Kea, Hawaii are based on 20 nights of SCIDAR observations in 1995 (seeing above ground level)[1], and FWHM measurements from the Auto Guider of the Subaru telescope during focus checks over a 12 month period from 2000 to 2001 (seeing above ~15 m)[4]. Seeing from San Pedro Martir, Mexico, is the median from 2 yr of DIMM measurements (seeing above 8 m)[3]. Isoplanatic angle and coherence time from San Pedro Martir are obtained with generalized SCIDAR (located 15 m above ground level) over 27 nights in 1997 and 2000[29]. Seeing and isoplanatic angle from Cerro Paranal, Chile, are average values from DIMM measurements (above 5 m) over 10 yr (1989–95 and 1998–2002)[2]. The coherence time at Cerro Paranal is derived (to an accuracy of 20%) from DIMM measurements combined with balloon-borne wind speed measurements[2]. Seeing from La Palma, Canary Islands, is from 9 months of DIMM measurements (seeing above 5 m)[5]. Isoplanatic angle and coherence time from La Palma are from six microthermal balloon launches[30] in 1990.

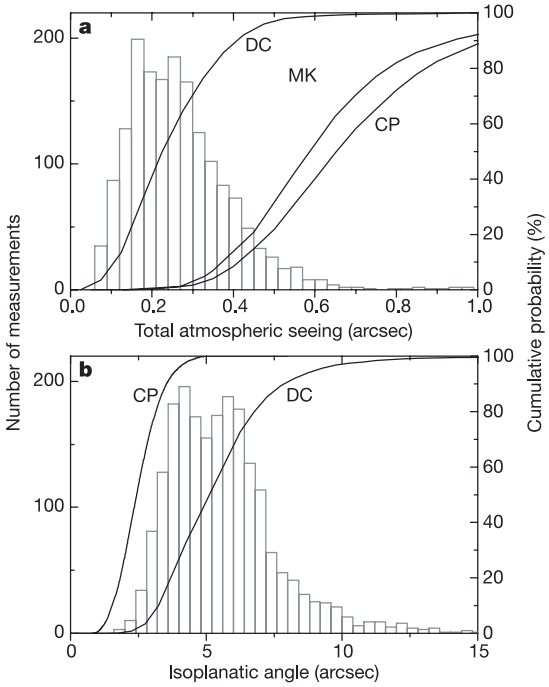

Figure 3 Histograms and cumulative distributions of the atmospheric seeing and the isoplanatic angle. **a**, Histogram of Dome C seeing above 30 m from MASS combined with SODAR, and cumulative distributions of seeing at Dome C (DC), Mauna Kea (MK) (derived from ref. 4), and Cerro Paranal (CP)[2]. **b**, Histogram of Dome C isoplanatic angle derived from the MASS instrument, and the cumulative distribution of isoplanatic angle from Dome C and Cerro Paranal.

Fig. 3, and is compared to the probability distribution for seeing at Mauna Kea and Cerro Paranal. The mean Dome C seeing of 0.27 arcsec is only observed at mid-latitude sites under exceptionally calm conditions ($\ll$ 1% of the time). The best seeing we observed at Dome C was 0.07 arcsec, which, to our knowledge, represents the lowest value reported anywhere.

The atmospheric characteristics of a site strongly influence the degree of correction and field of view achievable by using adaptive optics (AO)[24,25]. A factor of 4–10 fewer actuators would be required on a Dome C AO system to achieve the same residual wavefront error as a mid-latitude system. The larger isoplanatic angle of the Dome C atmosphere leads to a factor of ~3 increase in the field of view correctable by AO. The longer atmospheric time constant allows increased integration times for the AO wavefront sensor, which means that fainter guide stars can be used. The combination of a long coherence time with a large isoplanatic angle results in a greatly increased sky coverage for an AO system, both with natural and laser guide stars[24]. An AO system at Dome C would thus provide a higher level of correction for a larger fraction of the sky, compared to any other site. Additionally, for multi-conjugate AO, the complexity (number of deformable mirrors and actuators per mirror) is significantly reduced.

A world-wide search is currently being conducted to determine the most appropriate sites for the next generation of large optical and infrared telescopes. Advantages of the Dome C atmosphere for astronomy include the very low infrared sky emission, 10–100 times lower than observed from any mid-latitude site; the high percentage (>75%) of cloud-free time[26], which is comparable with the best mid-latitude sites; the low atmospheric precipitable water vapour content, which in winter should be lower than at any other site so far investigated, resulting in significant increases in atmospheric transmission[27]; and the low aerosol and dust content of the atmosphere. Advantageous site conditions include the very low ground level wind speeds[16] and lack of seismic activity (which reduces structural requirements on telescope mounts and domes), and low levels of light pollution. These advantages of the Dome C site must be weighed against its accessibility, any associated increase in system cost resulting from this, and any engineering issues resulting from the extremely low site temperatures. Many of the benefits of Dome C are also characteristics of the other Antarctic plateau stations. The poor ground-level seeing found at the South Pole station, however, severely limits its applicability for optical astronomy. Although it is expected that the turbulence conditions at Dome A, the highest point on the Antarctic plateau at an altitude of 4,200 m, will be superior even to Dome C, the complete lack of infrastructure at this site (it has never been visited) means that Dome C may be a preferable location.

The extremely favourable seeing, the large isoplanatic angle, and the long atmospheric coherence time reported here are compelling advantages that lead us to conclude that Dome C is the best ground-based site to develop a new astronomical observatory. □

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