First Whole Atmosphere Nighttime Seeing Measurements at Dome C, Antarctica

A. Agabi, E. Aristidi, M. Azouit, E. Fossat, F. Martin, T. Sadibekova, J. Vernin, and A. Ziad
Laboratoire Universitaire d’Astrophysique de Nice, Université de Nice Sophia Antipolis, Parc Valrose, F-06108 Nice Cedex 2, France

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ABSTRACT. We report site-testing results obtained in the nighttime during the polar autumn and winter at Dome C. These results were collected during the first Concordia winterover by A. Agabi. They are based on seeing and isoplanatic angle monitoring, as well as in situ balloon measurements of the refractive index structure constant profiles $C_n^2(h)$. Atmosphere is divided into two regions: (1) a 36 m high surface layer responsible for 87% of the turbulence, and (2) a very stable free atmosphere above, with a median seeing of $0.036 \pm 0.019$ at an elevation of $h = 30$ m. The median seeing measured with a differential image motion monitor placed on top of an 8.5 m high tower is $1.73 \pm 0.08$.

1. INTRODUCTION

The French and Italian Concordia polar station, based at Dome C on the Antarctic Plateau, has just completed construction. This location (75° south, 123° east) has remarkable properties due to its position on the top of a local maximum of the plateau, at an elevation of 3250 m. Low wind speeds (Aristidi et al. 2005a) as well as long time periods of clear sky and low sky brightness in the infrared range (Walden et al. 2005) make it one of the best candidates for future installation of a large astronomical observatory. Several site-testing programs were undertaken at the end of the 1990s to qualify the site. Concordia Astro is a program conducted by our group, and its goal is to characterize this site for high angular resolution astronomy in the visible. Recent results in the summer (Aristidi et al. 2005b, 2005a) have shown the potential of this site for turbulence near the ground. We present here the temperature and $C_n^2$ profiles obtained from 16 balloon-borne experiments from March 15 to August 1. Optical parameters (seeing $\epsilon$, isoplanatic angle $\theta_{iso}$, and coherence time $\tau_c$) are derived from these profiles. We also show the results of continuous ground seeing monitoring from 2005 March to June, and isoplanatic angle monitoring in 2005 May. At the time of this writing, the winterover had not yet finished; this paper can be considered as a first look at the data. A more detailed study will be published later when the full-season data set is collected.

2. EXPERIMENTS

Two experiments are currently being conducted at Dome C to measure the turbulence. The first one aims at monitoring the seeing and the isoplanatic angle. It is based on two small telescopes located at two different heights above the ice. A seeing monitor (the differential image motion monitor [DIMM] type; Aristidi et al. 2005b) on the top of a platform at $h = 8.5$ m above the ground provides a seeing value every 2 minutes. Another telescope at height $h = 3.5$ m monitors either the seeing or the isoplanatic angle. Switching between the two modes is performed manually by using different pupil masks. A detailed description is given in Aristidi et al. (2005b). Monitoring the seeing at two different heights allows us to infer the influence of the 5 m thick ground layer ($3.5 \leq h \leq 8.5$ m). There is a very faint influence on the isoplanatic angle, which is mostly sensitive to high-altitude turbulence. In mid-July, a third seeing monitor was placed on the roof of the calm Concordia building, at elevation $h = 20$ m. All values (seeing and isoplanatic angle) are computed at wavelength $\lambda = 500$ nm and zenith distance $z = 0^\circ$.

The second experiment consists of in situ measurements of thermal fluctuations using balloon-borne microthermal sensors. The principle and performance of these microthermal measure-
ments are detailed in Azouit & Vernin (2005; see also Marks et al. 1999). The balloon scans the atmosphere between the ground and an altitude of 15–20 km, sending data every 1–2 s. This corresponds to a vertical resolution around 5–10 m, depending on the ascent speed. Each $C_n^2$ value provided by the sensors has an accuracy of around 20%–25%. The lower limit of detectable $C_n^2$ is around $10^{-20}$ m$^{-2/3}$. Detailed information about the microthermal experiment (including balloon wake effects) can be found in Azouit & Vernin (2005).

3. RESULTS

3.1. Turbulence Profiles from Balloon Measurements

We started to launch balloons on March 15 at 10:25 PM, when the Sun elevation was below $-12^\circ$. All further launches were performed at night between 10:00 and 11:00 PM local time. As of the date of writing this paper, 16 balloons had been successfully launched and provided usable vertical $C_n^2(h)$ profiles. Averaged profiles are shown in Figure 1b. The seeing at a given altitude has been computed from $C_n^2(h)$ profiles (Fig. 1c). Individual plots of four typical profiles are shown in Figure 2. The largest values of around $10^{-15}$ m$^{-2/3}$ are found just above the ground, the remaining turbulent energy being well distributed with altitude, with values of around $10^{-18}$ m$^{-2/3}$ at the highest elevations ($h = 15$ km). The average $C_n^2$ profile in the first 200 m is plotted together with the potential temperature gradient $d\theta/dz$ in Figure 3. This gradient appears in the definition of the Richardson number (eq. [5] of Marks et al. 1999), which describes the apparition of turbulence. The similarity between the two curves is remarkable. Wind speed gradient, also appearing in the Richardson number, could not be estimated because of a lack of data near the ground.

We found a ground-level seeing, above the ground and up to 15–20 km, of $1''9 \pm 0.5$, and a 36 ± 10 m thick surface layer accounting for 87% of the turbulent energy (the integral of $C_n^2$). The seeing above this surface layer is $0''36 \pm 0''19$. The upper limit of the surface layer is defined as in Marks et al. (1999): it is the altitude at which successive seeing calculations differ by less than $0''001$. Other parameters deduced
Fig. 2.—Individual characteristic profiles of $C_n^2$ and of the potential temperature gradient $\frac{d\theta}{dz}$ for four balloons.

Fig. 3.—Average vertical profiles of $C_n^2$ and of the potential temperature gradient $\frac{d\theta}{dz}$ in the first 200 m above ground.

from individual profiles are summarized in Table 1. Isoplanatic angle $\theta_0$ and coherence time $\tau_c$ correspond to the adaptive optics definition (eqs. [7] and [9] of Marks et al. 1999). All values computed above the surface layer are in remarkable agreement with measurements reported by Lawrence et al. (2004). Isoplanatic angle $\theta_0$ appears to be smaller than the summer median value of 6.8, although the surface layer has little influence on it. Strong high-altitude winds (up to 30 m s$^{-1}$ at $h = 16$ km) have indeed been observed in May and June, as illustrated by Figure 4. The correlation between these high wind speeds and the optical turbulence parameters will be addressed in a forthcoming paper when more data are available.

### 3.2. Seeing and Isoplanatic Angle Monitoring

The seeing data taken into account in this paper were collected during the period 2005 March 1–August 23. The seeing statistics provided in Table 1 represent the monitor located on the platform (elevation $h = 8.5$ m). The “ground” seeing monitor at $h = 3.5$ m was also run during the same period of time, while the “roof” monitor at $h = 20$ m has provided data since July 23. Figure 5 shows, for the two monitors, the monthly averaged seeing evolution during the transition from summer to winter. Both seeings follow the same positive trend. Figure 6 shows a plot of the seeing integrated from $C_n^2$ profiles as a function of the DIMM seeing at $h = 8.5$ m, taken at the same time and averaged over the duration of the flight (typically 2 hr). The two data sets are consistent, with a correlation of 0.73. The dashed line in the graph is the first bisector.
Fig. 4.—Wind speed profiles measured by three radiosondes in May and June.

Isoplanatic angle monitoring started later; data are available since May 19, and the statistics are displayed in Table 1. Here again, data from the monitor are compatible with data from the balloon $C_n^2$ profiles. Isoplanatic angle $\theta_0$ appears to be similar to the South Pole value of 3".23 (Marks et al. 1999).

4. CONCLUSION

The situation at Dome C appears to be similar to that of the South Pole (Marks et al. 1999): poor ground seeing mainly due to a strongly turbulent boundary layer. In both sites, the free-atmosphere seeing is around 0".35 and the isoplanatic angle is around 3", the main difference being the height of the boundary layer: 220 m at the South Pole and 36 m at Dome C. This boundary layer seems to be mainly due to the strong thermal gradient near the ground (around 20°/100 m). This gradient is likely to exist on the whole Antarctic Plateau; we might find a similar boundary layer everywhere. The question is the thickness of this layer. For Dome C we could imagine building a 30 m high structure and putting a telescope on top to benefit from the excellent free-atmosphere seeing. This is not an insurmountable problem: existing telescopes are often elevated (ESO 3.6 m at La Silla is at 30 m, CFHT at Mauna Kea is at 28 m).

As Lawrence et al. (2004) note in their paper, the MASS + SODAR profiling technique does not account for the first 30 m of the atmosphere. Our measurements now show that unfortunately, this layer is very turbulent and contributes 87% of the total seeing for a telescope mounted at ice level. Thus, although the free-atmosphere seeing at Dome C is excellent, it is important to appreciate that the surface layer (which we conclude is typically 36 m thick) results in very poor seeing for a telescope at ice level.

The properties of the turbulence in the boundary layer need to be investigated carefully. For this purpose, four microthermal sensors pairs were set up on the 32 m high American tower to estimate and monitor the ground-layer turbulence at elevations $h = 2.6, 8.1, 16, \text{ and } 32 \text{ m}$. Results from this experi-

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**TABLE 1**

**MEdian Optical Parameters at Two Elevations Above Ground**

| Elevation | $e$ (arcsec) | $\theta_0$ (arcsec) | $\tau_0$ (ms) |
|-----------|--------------|---------------------|---------------|
| $h \geq 8.5 \text{ m}$ | 1.4 ± 0.6 | 4.7 ± 2.6 | 2.9 ± 7.0 |
| $h \geq 30 \text{ m}$ | 0.36 ± 0.19 | 4.7 ± 2.6 | 8.6 ± 7.1 |

**NOTE.** Values are computed from 16 individual $C_n^2$ profiles. The uncertainties are standard deviations of the values.

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Fig. 5.—Monthly averaged ground seeing from the monitors located at elevations $h = 3.5, 8.5, \text{ and } 20 \text{ m}$. Individual points are balloon-based estimations at $h = 8.5$ and 30 m.

Fig. 6.—Plot of the seeing estimated by the DIMM at $h = 8.50 \text{ m}$ vs. seeing computed from the balloons profiles at the same height and around the same time, when available.
iment are expected soon, as are other measurements during the rest of the winter.

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