Site testing at Dome C: summer and first winter results from the Concordiastro program

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ABSTRACT

We report site testing results obtained in summer and winter at Dome C. They consist in seeing and isoplanatic angle monitoring, as well as in-situ balloon measurements of the refractive index structure constant profiles $C_n^2(h)$. Summer results are based on data taken during two 3-month summer campaings in 2003-2004 and 2004-2005. Winter data were collected during the first Concordia winterover by A. Agabi. Optical turbulence appear to be very small in summer, with a median seeing of 0.54″ in the visible, and a median isoplanatic angle of 6.8″. In winter the amosphere presents a 37 m high turbulent surface layer. The median seeing measured with a DIMM placed on top of a 8.5 m high tower is 1.2±0.7 arcsec. Above this surface layer, at elevation $h = 30$ m the median seeing is very small: 0.36±0.18 arcsec.

Subject headings: Site testing

1. Introduction

The French and Italian polar station Concordia based at Dome C on the Antarctic plateau, has just completed its construction. This location (75S, 123E) 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., 2005b) as well as long time periods of clear sky and low sky brightness in the infrared range (Walden et al., 2005) makes it one of the best candidates for future installation of a large astronomical observatory.

These promising qualities encouraged our group to initiate a detailed analysis of the astronomical site properties. In 1995, a Franco-Italian group directed by J. Vernin made a pioneering prospective campaign at Dome C and launched a few meteorological balloons. A systematic site-testing programme was then initiated under the name of Concordiastro, first funded by IPEV in 2000. Proposed site-testing was based on two kinds of measurements. First, a monitoring of the turbulence parameters in the visible (seeing r_0, isoplanatic angle θ_0, outer scale $\mathcal{L}_0$, and coherence time τ_0) with a GSM experiment (Ziad et al. 2000) specially designed to work in polar winter conditions. In addition to this monitoring, it was proposed to launch balloons equipped with microthermal sensors to measure the vertical profile of the refractive index structure constant $C_n^2(h)$ (Azouit & Vernin, 2005).

So far, 6 summer campaigns have been performed between 2000 and 2005, totalling 80 man-weeks of presence on the site. During these campaings meteorological balloons were launched and corresponding results were published in Aristidi et al. (2005b). During the last two summer campaigns, we also monitored the seeing and the isoplanatic angle in daytime. Corresponding results were published previously (Aristidi et al. 2003, 2005a) and we will summarize them in section 3.

The first winterover has officially started on Feb. 15, 2005. Among the 13 winterers, Agabi, the project manager of Concordiastro is spending one year on the site to run the experiments. Dome C being at 15°of the South Pole, there is a transition period of $2\frac{1}{2}$ months from summer to winter where the Sun rises and sets. First sunset was observed on Feb. 16 and the Sun totally disappeared from the sky on May 4. During this period it was observed a dramatic drop of the ground temperature (roughly from -30°C in summer to -70°C in autumn) and the establishment of an almost permanent inversion layer with a very steep temperature gradient that led to strong optical turbulence near the ground. We present here the temperature and C_n^2 profiles obtained from 16 balloon-borne experiments from March 18 to July 18. Optical parameters (seeing ϵ, isoplanatic angle θ_0 and coherence time τ_0 are derived from these profiles. We show also the results of continuous ground seeing monitoring from March to June 2005, and isoplanatic angle monitoring in May and June 2005. These results have just been submitted for publication in PASP; the paper has been provisionnaly accepted (Agabi et al., 2005).

2. Experiments

Two experiments are currently operated 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 (DIMM type, Aristidi et al., 2005a), on the top of a platform $h = 8.5$ m above ground, provides a seeing value every 2 mn. Another telescope at height $h = 3.5$ m monitors either the seeing or the isoplanatic angle. Switching between the two modes is made manually by using different pupil masks. A detailled description is given in Aristidi et al., 2005a. Monitoring the seeing at two different heights allows to infer the influence of the 5 m thick ground layer (3.5 m$\leq h \leq$8.5 m). This influence is very faint on the isoplanatic angle, mostly sensitive to high altitude turbulence. All values (seeing and isoplanatic angle) are computed at wavelength $\lambda = 500$ nm and zenithal distance $z = 0°$

The second experiment consists in *in situ* measurements of thermal fluctuations using balloon-borne microthermal sensors. The principle of these microthermal measurements is detailed in Azouit and 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 seconds. This corresponds to a vertical resolution around 5 m, depending on the ascent speed. It gives access to the refractive index structure constant profile $C_n^2(h)$ (in fact we have two sensor pairs so two independent estimates of $C_n^2(h)$, which are averaged).

A third experiment was also set up in January 2005. It is a ground version of balloon radiosoundings. Four micro-thermal sensors pairs were set up onto the 32 m-high American tower, to estimate and monitor the ground layer turbulence, at elevations h =2m60, 8m10, 16m and 32m. First signals from this experiment were recorded between January 19th and January 28th, 2005. They showed the correct behaviour of the whole systems. Unfortunately this experiment did not work during the last winter.

3. Summer results

3.1. Seeing monitoring

A total amount of 31597 2-minute seeing values were been estimated during the 2003-2004 and 2004-2005 summer campaigns. Amazingly low seeing values were observed during the first days of the 2003-04 campaign. The first 2-day seeing time series are shown on Fig. 1. Exceptional seeing as low as 0.1″ was observed, and we had a continuous period of 10 hours of seeing below 0.6″.

Seeing statistics are summarised in Table 1. All measurements are computed at $\lambda = 500$ nm in daytime. Seeing values are in arcsec. Seeing his-

Summer statistics	Seeing	θ_0
# of measurements	31597	6328
Median (″)	0.55	6.8
Mean (″)	0.66	6.8
Standard deviation (″)	0.39	2.4
Min/max (″)	0.08 / 5.22	0.7 / 17.1

Table 1: Seeing and isoplanatic angle statistics in the summer. The seeing values stand for the DIMM at elevation $h = 8.5$ m.

tograms are displayed in Fig. 2. The 50% percentile (the median) is at $\epsilon = 0.55''$.

These values are exceptionally good for daytime seeing, when the Sun is present in the sky and heats the surface. It can compete with night-time seeing of the best observatories.

Another interesting result is the behaviour of the seeing with time. Figure 3 was calculated by binning all seeing values into 30-min intervals. Best seeing values, like $0.4''$or better, are generally obtained in mid local afternoon. It is extremely encouraging for solar imaging at high angular resolution. Indeed, the temperature profile in the first 200 m above the snow is flat in mid-afternoon (Fig. 4 and Aristidi et al., 2005b). At midnight and at noon, the low atmosphere presents a thermal gradient of the order of 0.1 °C/m. The seeing seems to be strongly dependent of this gradient.

3.2. Isoplanatic angle monitoring

Isoplanatic angle values were collected during the month of January, 2004. Statistics of θ_0 are summarised in Table 1 show a median value $\theta_0 = 6.8''$at wavelength $\lambda = 0.5\mu$m, which is far better than values obtained at any astronomical site. The histogram and cumulative histogram are shown in Fig. 5.

The high value of isoplanatic angle, roughly 3 times higher than at classical sites, is good news for adaptive optics. This corresponds to a gain of a factor 10 in the field used to find calibrator stars, which therefore increases the observable piece of sky.

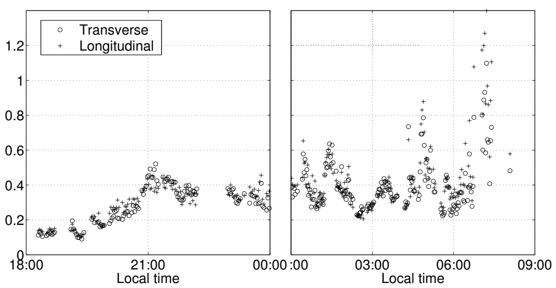

Fig. 1.— First seeing curves obtained in daytime during the 2003-2004 summer campaign on November 21 and 22, 2003.

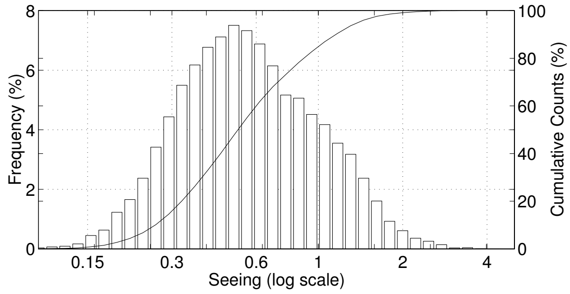

Fig. 2.— Histogram (stairs) and cumulative histogram (continuous line) of seeing values for the summer campaigns. Seeing axis is in logarithmic scale.

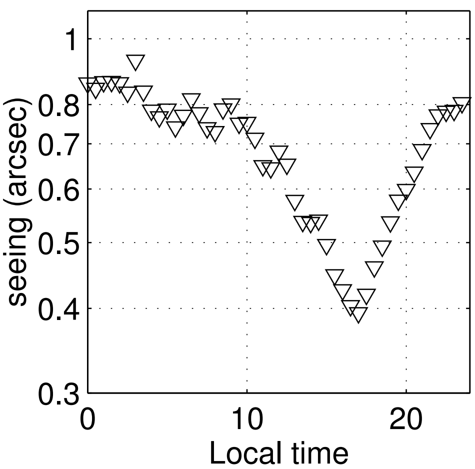

Fig. 3.— Seeing versus time, in the summer. Seeing values, obtained from the DIMM at elevation $h = 8.5$ m, were binned into 30-min intervals.

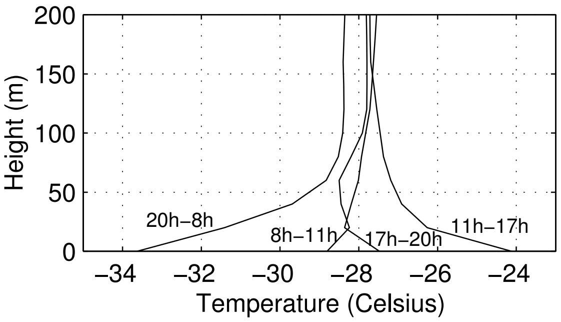

Fig. 4.— Mean temperature profiles above the ground in summer, based on in-situ radiosoundings. On the vertical axis, height is counted from the snow (altitude 3260m). The four curves correspond to measurements performed at four different times of the day

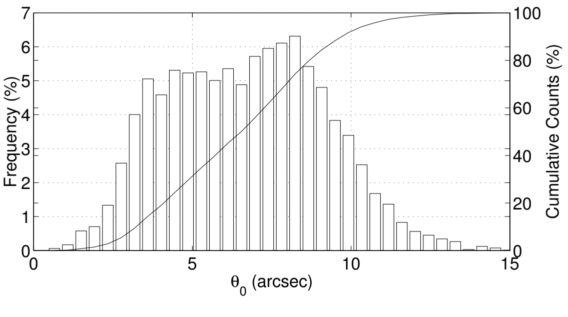

Fig. 5.— Histogram (stairs) and cumulative histogram (line) of isoplanatic angle values in summer.

4. Winter results

The first good news from the winter observations is the weather. Thanks to the presence of people, weather statistics have been made possible for the first time in winter. Indeed the sky was clear 96% of the time between February and June 2005. This number is computed from the DIMM data sequence. We observed very large periods of continuous clear sky; for example no cloud was observed between March, 17th and June, 1st.

4.1. Seeing and isoplanatic angle monitorings

The seeing data taken into account in this paper have been collected during the period March 1^{st} – June 30^{th} , 2005. The seeing statistics provided in Table 2 stand for the monitor located on the platform (elevation $h = 8.5$ m). The other seeing monitor at $h = 3.5$ m has also been running during the same period of time. Figure 6 shows, for the two monitors, the monthly averaged seeing evolution during the transition from summer to winter.

We were very disappointed to see such an evolution of the ground seeing. After the enthousiasm generated both by the summer measurements and the estimations given by the Australian group with the MASS (Lawrence et al., 2004) it was quite a surprise. Both seeings (at $h = 8.5$m and $h = 3.5$m) follow the same positive trend, and the values for $h = 8.5$ m are consistent with the seeing derived from the balloons (see table 2). Thus ground seeing at Dome C, measured at h =8.5 m, appears to be above 1 arcsec in autumn and early winter. However, as it can be seen in Fig. 7 it is still possible, in winter, to have a few days were the seeing average is comparable with the summer values (0.4 arcsec and below).

Isoplanatic angle θ_0 monitoring started later; data are available since May, 19^{th}. Time-series, displayed in Fig. 8, show a slight degradation of θ_0 between May and June. This degradation seems to have started earlier since the average value of θ_0 in summer is $6.8''$. Statistics are displayed on table 2. Here again, data from the monitor are consistent with data from the ballon C_n^2 profiles. θ_0 appears to be similar to South Pole value of 3.23 arcsec (Marks et al., 1999).

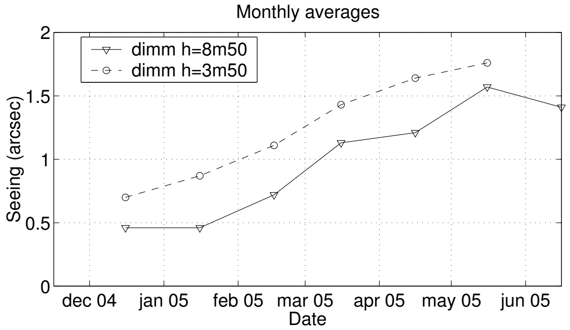

Fig. 6.— Monthly averaged ground seeing from the monitors located at elevations $h = 3.5$ m and $h = 8.5$ m.

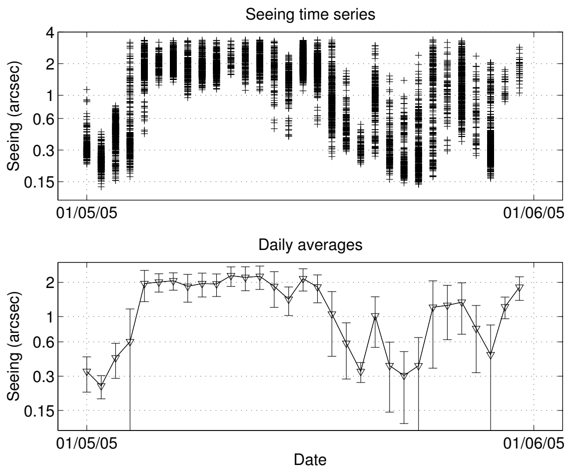

Fig. 7.— Seeing time-series (up) and daily averages (down) in May, 2005. Values collected with the DIMM at elevation $h = 8.5$ m.

4.2. Balloon measurements

We started to launch balloons on March, 15$^{\text{th}}$ 10:25pm when the Sun elevation was below -12°. All further launches were performed at night between 10 and 11pm local time. At the date of writing this paper, 16 balloons have been succesfully launched and provided exploitable vertical profiles of the temperature, wind speed and direction and two estimates of $C_n^2(h)$. The seeing at a given altitude is being computed from the mean $C_n^2(h)$ profiles (Marks et al., 1999). Fig. 9 shows a plot of these profiles for a typical balloon. We can see that there is a strong thermal gradient at the ground (3 times larger than in summer at midnight). We can also see strong wind speeds in altitude (they were expected, see Aristidi et al., 2005b). The turbulence profile exhibits a strong surface layer 30 to 40-m thick over which the atmosphere is calm. For this particular flight, seeing was 0.9 $''$at elevation $h = 8$ m and 0.4 $''$at elevation $h = 30$ m.

This behaviour has been observed systematically for all the flights. The thickness of the surface layer has been estimated for each flight, giving the median value of 37±11 m. Averaged profiles, in the first 200 m above ground, for the temperature and potential temperature (Marks et al., 1999), the $C_n^2(h)$ and the seeing are shown on Fig. 10.

We found a median ground seeing of 1.5±0.6 arcsec above $h = 8$ m and up to 15–20 km, . The surface layer accounts for 87% of the turbulent energy (the integral of C_n^2). The median seeing above $h = 30$ m is 0.36±0.18 arcsec. Other parameters deduced from individual profiles are summarized in table 2. Isoplanatic angle θ_0 and coherence time τ_0 correspond to the adaptive optics definition (eq. 7 and 9 of Marks et al., 1999). θ_0 appears to be smaller than the summer median value of 6.8 arcsec, though the surface layer is of little influence on it. High altitude strong winds (up to 30 m/s at h=16km) have indeed been observed in May, as shown in Fig. 9, and are likely to contribute to θ_0.

5. Discussion and conclusion

We presented the results of optical turbulence measurements during two summer campaigns at Dome C and one half winter campaign. The main result in daytime is the exceptional seeing quality,

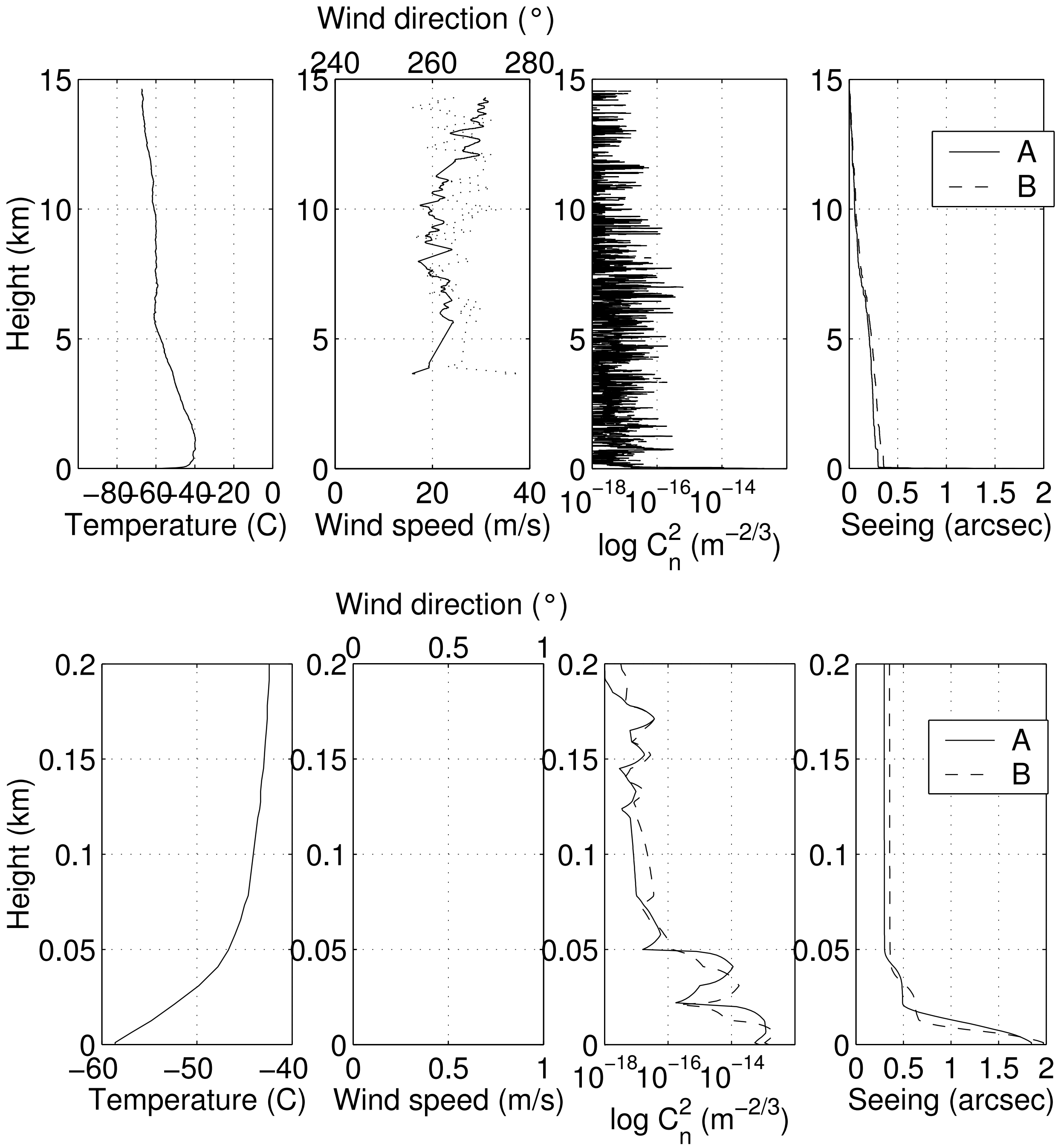

Fig. 9.— Vertical profiles of the temperature, the wind speed and direction, the $C_n^2(h)$ and the seeing for the flight 532, launched on May, 14, 2005. Up: the whole profile up to the maximum available altitude. Down: a zoom over the first 200 m above ground (no wind data available). The letters "A" and "B" in the legend box of the seeing graphs refer to the two C_n^2 estimates (see text)

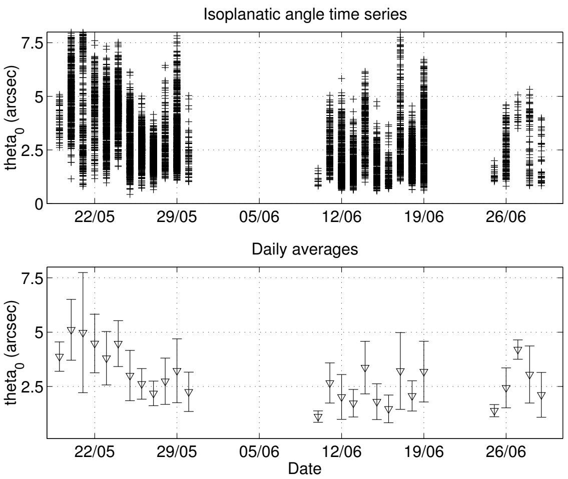

Fig. 8.— Isoplanatic angle time-series (up) and daily averages (down) in autum 2005.

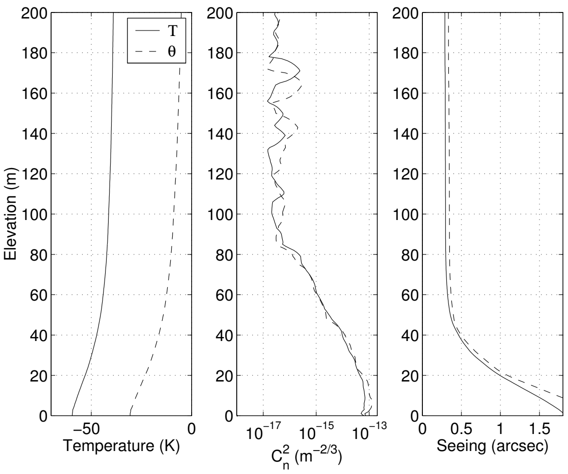

Fig. 10.— Averages vertical profiles over 16 flights in autum and early winter, in the first 200 m above ground. Left: Temperature (T) and potential temperature (θ). Middle: C_n^2 for the two sensor pairs. Right: Seeing derived from the C_n^2.

with a median value of 0.54 arcsec, and a deep seeing minimum around 0.3 arcsec, every day in mid-afternoon. Combined to a large isoplanatic angle of nearly 7 arcsec, Dome C is definitely an excellent site for solar and daytime astronomy.

These excellent conditions started to degradate in March. We observed the establishement of a a strongly turbulent boundary layer, 37 m high, contributing to 87% to the optical turbulence. The ground seeing (at elevation $h = 8.5$ m is 1.4 arsec) is poor, but becomes excellent at $h = 30$ m with a median value of 0.4 arsec. The isoplanatic angle around 3–4 arcsec remains good compared to other sites (see Table 3) though not as large as summer value; it suffers from high altitude winds that are absent in summer (Aristidi et al., 2005b). The coherence time is very sensitive to the surface layer: 3 ms at ground and 8 ms at $h = 30$ m. All values corresponding to $h = 30$ m are consistent with the Australian measures of Lawrence et al., 2004.

All these autumn/early winter observations are preliminary and incomplete since the winter is not finished yed. But they suggest several ideas and working orientations. First it is clear that the properties of the turbulence in the boundary layer need to be investigated carefully. We hope to have results to the mast experiment soon. It is intended to provide a monitoring of the C_n^2 in the first 30 m above ground. We also plan to put a DIMM onto the roof of the calm building of the Concordia station, to monitor the seeing at elevation $h = 20$ m.

For the future it is clear that the ground seeing is a severe limitation to HRA observations. It corresponds to diffraction-limited images with a 50 cm diameter telescope in K-band, and with a 85 cm diameter telescope in L-band. If one wants to be diffraction-limited in near-IR with larger telescopes, such as the PILOT project, a 2-meter class infrared telescope (Lawrence et al., 2005), solutions must be found. We could imagine, as it usual for solar astronomy, to build 30 m high structures and put telescope on top to benefit from the excellent free atmosphere seeing. We could also investigate the potential of a Ground-Layer Adaptive optics dedicated for Dome C conditions.

Balloon data

Elevation	ϵ (arcsec)	θ_0 (arcsec)	τ_0 (ms)
$h \geq 8$ m	1.5±0.6	4.6±2.7	2.8±6.8
$h \geq 30$ m	0.36±0.18	4.6±2.7	7.9±7.1

Monitors data

$h \geq 8.5$ m	ϵ (arcsec)	θ_0 (arcsec)
Median	1.2±0.7	2.7±1.6
Min/Max	0.12/3.37	0.43/10.91
Ndata	25915	9501

Table 2: Statistics for optical parameters in winter. The numbers are median values, computed at two elevations above ground. The balloon data are computed from 16 individual C_n^2 profiles. The uncertainties are standard deviations of the values.

Site	seeing (arcsec)	θ_0 (arcsec)	τ_0 (ms)
Paranal	0.87[1]	2.72[1]	3.66[1]
La Palma	0.96[2]	1.30[2]	6.64[2]
Cerro Pachon	0.67[3]	2.1[3]	4.9[3]
Maidanak	0.69[4]	2.47[5]	
South Pole	1.86[2]	3.23[2]	1.58[2]
Dome C (h =30 m)	0.4	4.6	7.9
Dome C (h =8 m)	1.5	4.6	2.8

[1]: www.eso.org
[2]: Marks et al., 1999
[3]: www.gemini.edu
[4]: Eghamberdiev et al., 2000
[5]: Ziad et al., 2000

Table 3: Optical parameters at Dome C versus other sites.

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