Site Considerations for the Next Generation of Optical Arrays: Mid-latitude Sites versus Antarctica

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Abstract: The experience from the first years of operation of the ESO VLT Interferometer at Paranal and the recent results of the site testing in Antarctica are used to review the expected performances of an optical array operating at mid-latitude sites or in Dome C, Antarctica.

1 Introduction

Most international observatories are located at mid-latitudes, on islands or on coastal mountains. Recent results of site testing at the new station of Dome C, Antarctica (75^o 06' S, 123^o 24' E, 3233 m) have encouraged the community to propose science projects which could make use of these exceptional observing conditions. Interferometry is particularly well represented in the competition and we address here an arbitrarily limited selection of the site parameters which should be among the main drivers for deciding how much improvement can be expected from operating an interferometric facility from Antarctica. We compare Dome C to the ESO Paranal Observatory (24^o 37' S, 70^o 24' E, 2636 m), the site of the VLT Interferometer (VLTI) with regards to available dark time first. Then, based only on meteorological model data, we consider the turbulence close to ground which decides on the height of the telescope structure. Finally we review the coherence timescale of the turbulence which determines the efficiency of adaptive optics correction as well as of fringe stabilization (Tubbs (2005)). As pointed out by Marrioti (1994) the outer scale of the turbulence is also a critical parameter for co-phasing an interferometer and should be taken into account in such a review. However it is not yet proven that this parameter is site dependent and only local measurements from Dome C can answer this question.

2 Dark Time

Civil twilight is the period from sunset when the solar disk has just left the horizon until the centre of the sun's disc is 6 degrees below the horizon. Nautical twilight occurs when the sun is between 6 and 12 degrees below the horizon. Astronomical twilight fills the time interval when the sun is between 12 and 18 degrees below the horizon. When the sun is below 18 degrees, the faintest stars which can be seen by the naked eye are visible. Such a definition is derived from visual observations and should maybe be revised for each type of observation mode and wavelength range. We show in what follows that the sun elevation limit chosen for the computation of usable time has severe consequences for ranking the sites close to the poles.

Using the traditional definition, the total number of dark hours available per year is shown on Fig. 1 as a function of the geographic latitude. The minimum occurs at a distance from the pole equal to the difference between the earth axial tilt (23.45^o) and the required minimum solar elevation. This computation takes atmospheric refraction effects into account, calculated for observation from sea level. On Fig. 2, the annual variation of the number of available dark hours is shown, again using the traditional definition. The disadvantage for polar sites is obvious, Dome C provides only half the observing time of what is available at mid-latitude. Moreover, as shown on Fig. 3 and Fig. 4, the so-called 7-month long polar night often advertised does not exist at Dome C where the sun never stays below 18 degree for 24 hour in a row. One has to relax the sun minimum position below horizon to about 10 degree to obtain observing nights longer than 24 hour. Counter arguments such as the higher transparency of the atmosphere and the lower content in airborne aerosol call in favour of revising the dark time constraints for Antarctic astronomy. For this purpose, on site measurements of sky background are planned in the current site testing activities at Dome C.

3 Ground Layer Turbulence

The ground layer turbulence is currently being studied at Dome C, in particular to determine the height above ground at which observing facilities should be built. This issue is particularly relevant for the implementation of large interferometric arrays with movable units where the project cost is heavily weighed by individual antenna parameters.

In a first approximation, the structure of the thermal turbulence in the surface layer follows the Kolmogorov law with a mean square temperature difference between two air parcels decreasing with their distance to the 2/3 rd power. In this model Coulman et al. (1986) have shown that the temperature structure coefficient C_t^2 can be expressed as a function of the rate of dissipation of half the temperature variance ϵ_θ, and the rate of dissipation of kinetic energy ϵ along:

$$C_t^2 = 1.6 \epsilon_\theta \epsilon^{-\frac{1}{3}} \ . \qquad (1)$$

For stable nocturnal conditions on a bare mountain summit, like Cerro Paranal before the construction of the VLT, de Baas & Sarazin (1991) have shown that this simple k-ϵ model was producing realistic results compared to microthermal measurements on a 30 m mast. Bougeault et al. (1995) have extended its application to the whole atmosphere with the assumption that there is a quasi equilibrium between the production and destruction of temperature variance in atmospheric turbulence:

$$C_t^2 = 1.4 \ l_k \ l_\epsilon^{\frac{1}{3}} \ (\frac{d\theta}{dz})^2 \ , \qquad (2)$$

where l_k and l_ϵ are respectively the mixing and dissipation lengths describing the up and downward motion of the air parcels. The immediate consequence is that the thickness of the turbulent surface layer is mainly determined by the vertical gradient of the temperature above the ground. It is thus tempting to obtain a preliminary information from analyzes produced routinely by meteorological forecasting institutes such as ECMWF in Europe and NCAR in the USA.

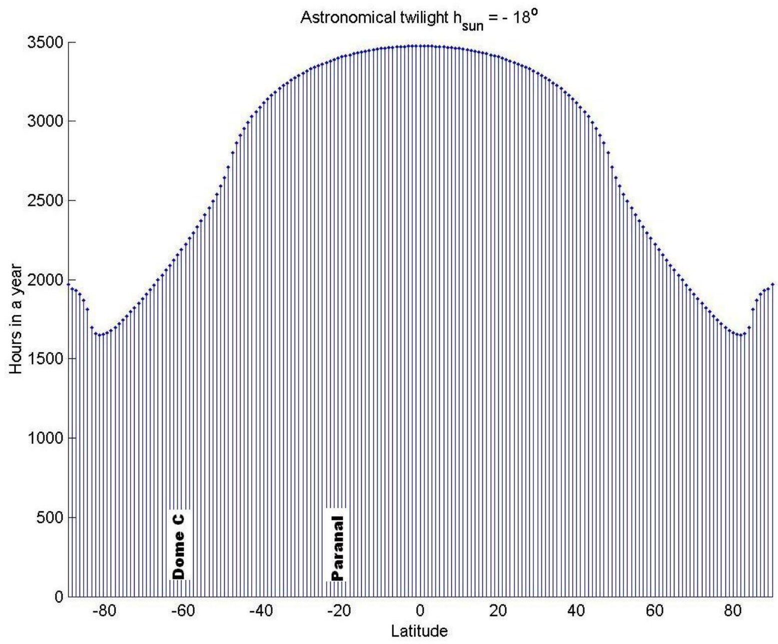

Figure 1: Total available number of dark hours per year as a function of latitude. Astronomical dark time is by convention defined when the sun is more than 18 degrees below horizon.

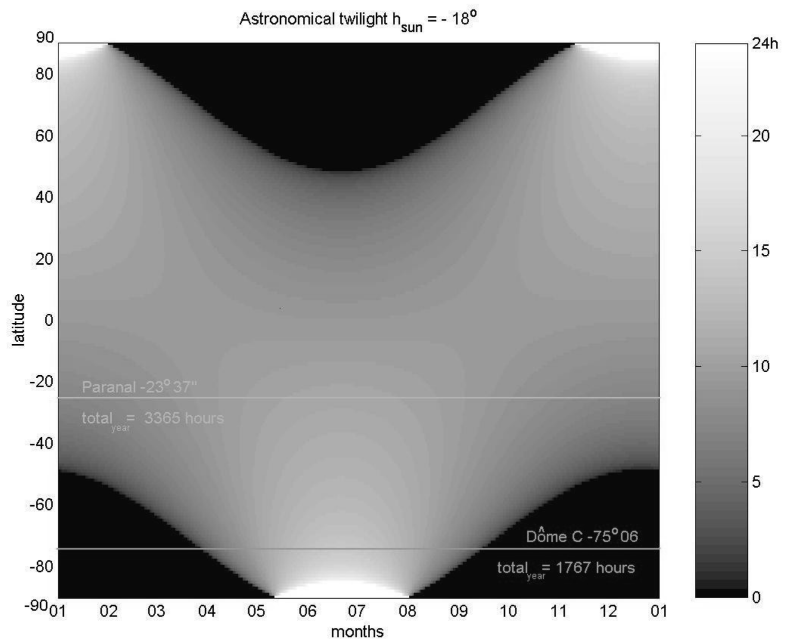

Figure 2: Total available number of dark hours as a function of latitude and time of the year (3365 hour at Paranal and 1767 hour at Dome C). Astronomical dark time is by convention defined when the sun is more than 18 degrees below horizon.

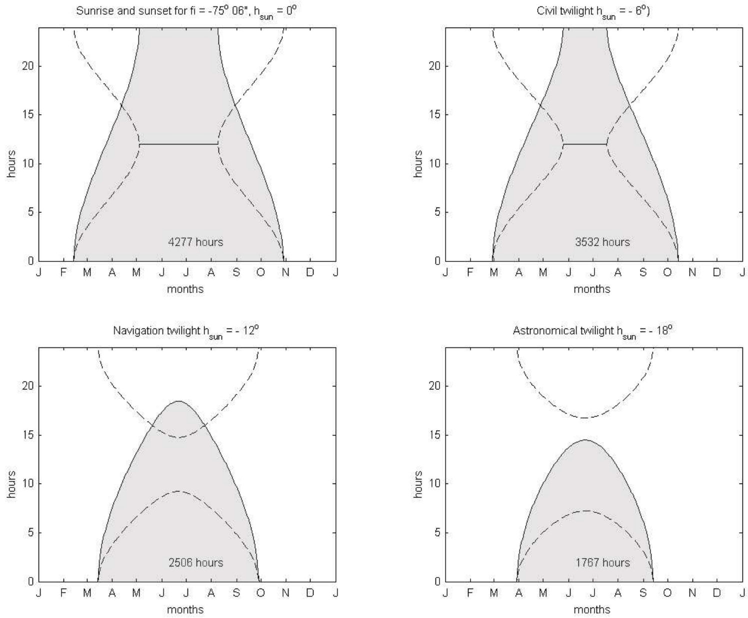

Figure 3: Total available dark time (grey) and local solar time twilight limits (dash) at Dome C along the year for various values of maximum sun elevation: relaxing the conventional limit from 18 degree to 6 degree below horizon doubles the available number of hours per year.

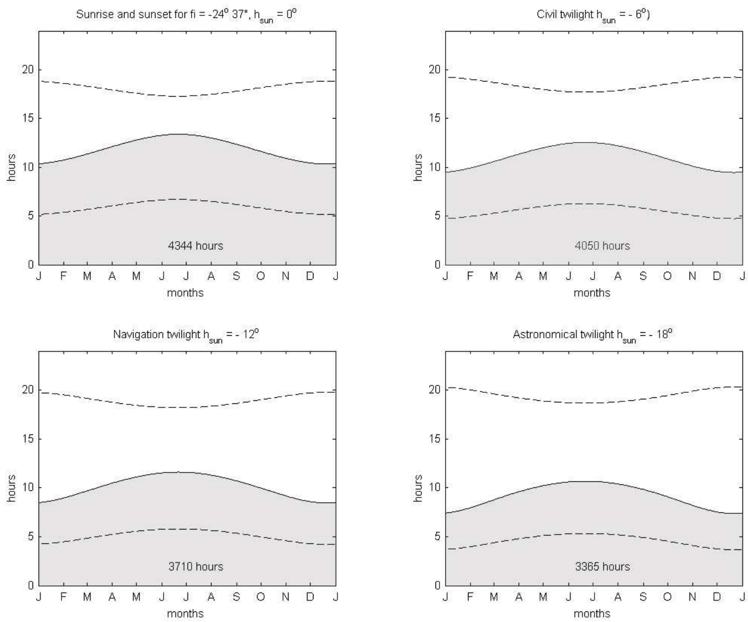

Figure 4: Total available dark time (grey) and local solar time twilight limits (dash) at Paranal along the year for various values of maximum sun elevation: relaxing the conventional limit from 18 degree to 6 degree below horizon only increases by 20% the available number of hours per year.

The ECMWF (European Center for Medium-range Weather Forecasts) produces 6-hourly operational meteorological analyses to initialize short - and medium-range weather forecast. The analyses are the results of the assimilation of real-time observations, where and when available, into a meteorological model. In Antarctica, most of the in-situ observations are made at weather stations scattered at the periphery of the ice sheet. Automatic weather stations, including one at Dome C (WMO 89625), also provide basic surface information for the interior of the ice sheet, but there is currently no radio-sounding done on the East Antarctic plateau and reported for analyses. However, polar-orbiting meteorological satellites provide all-season downward-looking sounder information. Further information on the ECMWF system can be found at http://www.ecmwf.int. The 6-hourly profiles have been interpolated to the Dome C coordinates (rounded to 75°S, 125°E) from the original spectral archives with a nominal spatial resolution is $\approx$ 75 km. There are 60 levels unevenly distributed along the vertical from the surface to 0.1 hPa, with typical resolution 2-3 hPa in the lowest levels.

None of the radiosoundings performed by the site survey team at Dome C by Aristidi et al. (2005) have been used in the analyzes, so the observations provide an independent evaluation of the model capabilities. Recently, the ECMWF model agreement with these local radiosoundings has been positively verified for Summer 2005 by Sadibekova et al. (2006). Fig. 5 presents the average temperature profiles for Summer and Winter months of the year 2003. Obviously, in confirmation of the local measurements conducted by Agabi et al. (2006), the temperature profile presents a stronger vertical gradient in the first in layer winter months than during the summer months. Thus the height of a telescope building at Dome C shall be determined by the strong winter time inversion. With a temperature gradient of several tens of degrees, the ground layer shall be noticeably larger at Dome C than what is experienced at most mid-latitude sites. Most mountain observatories usually present a shallow nocturnal inversion of a few degrees only which contributes to a small fraction of the total seeing (e.g. 8 % in the 6-21 m layer at the VLT Observatory measured by Martin et al. (2000)). Considering the difficulty of extensive local monitoring, modeling ground layer turbulence in Antarctica with the available input from global meteorological models should be encouraged.

4 Temporal Coherence Time τ_0

The coherence time of the wavefront is defined by Roddier (1981) for adaptive optics from the phase structure function as the time it takes for the wavefront phase difference to reach 1 radian rms.

$$\tau_0 = 0.31 \frac{r_0}{V_0}, \tag{3}$$

where V_0 is the average velocity of the turbulence.

$$V_0 = \left[\frac{\int_0^\infty C_n^2(h) V(h)^{\frac{5}{3}} \mathrm{d}h}{\int_0^\infty C_n^2(h) \mathrm{d}h} \right]^{\frac{3}{5}} \tag{4}$$

The direct calculation of V_0 is thus only possible when the vertical profiles of the turbulence $C_n^2(h)$ and of the wind velocity $V(h)$ are simultaneously available. However, based on the statistics of turbulence and wind vertical profiles recorded from balloons launched at Cerro Paranal and at Cerro Pachon in Chile, Sarazin & Tokovinin (2001) proposed an expression for V_0 which relates to meteorological variables only: $V_0 \approx Max(0.4 V_{200mb})$ (Figure 6).

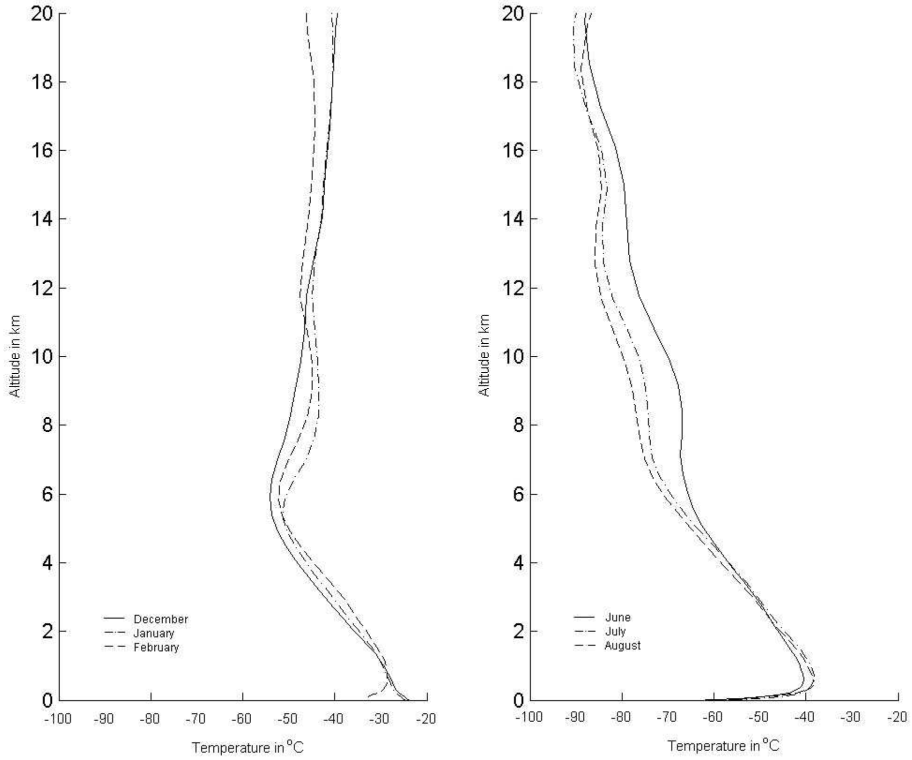

Figure 5: 2003 monthly average vertical temperature profiles above Dome C on 60 altitude levels starting from the ground, as produced by ECMWF.

Similarly, the coherence time for interferometry corresponding to 1 radian rms phase fluctuation about the mean, in the double aperture case, is given by Colavita 1999:

$$\tau_{0I} = 0.81\frac{r_0}{V_0}, \tag{5}$$

Di Folco et al. (2003) have extracted coherence time statistics from VLTI Vinci temporal spectra. They compared their data to the contemporaneous values generated using the seeing and wind recorded at ground level as well as the wind forecasted at 200 mB by ECMWF along the method described above, also taking the surface winds into account. The agreement shown on Figure 7 is very encouraging, showing a good correlation along the expected 0.81/0.31 slope. It is thus possible to produce long term statistics of coherence time at Chilean Observatories as shown on Table 1 for Paranal.

The question whether the empirical relation proposed for Chile by Sarazin & Tokovinin (2001) can be ported to other sites is still debated. The same relation was found for San Pedro Martir (Baja California, Mexico) by Carrasco et al (2005). However García-Lorenzo et al. (2005) have studied the wind profiles at several astronomical sites and concluded that, although the wind velocity at 200 mb was certainly a good tracer of the whole atmospheric motion, quantitative geographical differences were noticeable in the correlation coefficients of wind at various altitude. We thus limit ourselves to the comparison of tropopause wind velocity at Dome C and Paranal to obtain a qualitative estimate of the improvement expected for Antarctic observations. The tropopause altitude increases gradually from 7-8 km in the polar region to 17-18 km in the inter-tropical zone, with an average of 11-12 km in the subtropical regions. That is why we choose to compare the 200 mb wind velocity above Paranal to the 300 mb wind velocity above Dome C. From the data shown on Table 2 the atmosphere above Dome C should be slower by a factor of 2 on a yearly average compared to Paranal. Dome C however do present seasonal variations and some variability about the monthly means depending on the relative position of the polar jet. For instance Agabi et al (2006) monitored more than 30 m/s wind speed from balloons launched in June 2005.

Among the few in situ measurements of τ_0 available from Dome C, Kellerer et al. (2005) have extracted a range of 6 ms to 15 ms from piston variability measurements taken on January 31, 2005 at 3.5 m above ground with 0.7-0.8" seeing. The NCAR re-analysis site (http://www.cdc.noaa.gov/cdc/data.ncep.reanalysis.html) gives for this date about 12 m/s for the wind speed at 300 mB. Based on this limited experience, on the statistics of Table 1 and Table 2 and on the assumption that the turbulence in the ground layer is particularly slow, it can be expected that the coherence time τ_0 at Dome C should be at least twice larger than at Paranal and could extend well beyond 10 ms in the most favourable wind periods and in good seeing conditions.

5 Conclusions

A comparative analysis of the expected observing conditions at Dome C and at a mid-latitude site like Paranal was presented, using the experience accumulated at the VLTI. This analysis is based on an arbitrarily limited set of three parameters: the length of dark time, the height of the ground layer and the turbulence coherence time. It was demonstrated that the definition of dark time had severe consequences on the ranking of antarctic sites, and thus it is recommended that this limit should be addressed independently for each type of observations. Secondly, it was confirmed using meteorological model data that the height of the nocturnal inversion layer was expected to be larger in winter at dome C than at mid-latitude sites. Finally, it was demonstrated that the coherence time of the turbulence could be expected to be far longer than anywhere else during a sizeable fraction of the year.

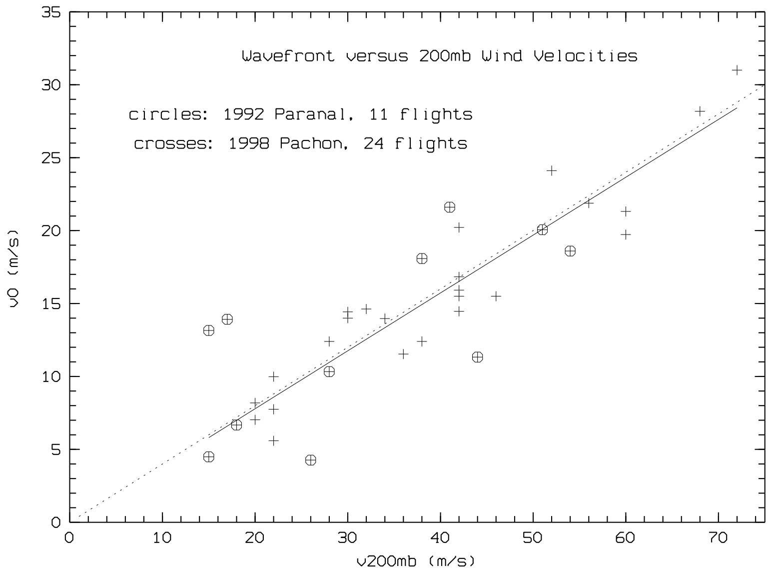

Figure 6: Proportionality between the wind velocity at 200 mb V_{200mb} and the wavefront velocity V_0 measured over 35 balloon flights at Paranal (crossed circles) and at Pachon (crosses). The full line corresponds to the best least squares fit, the dotted line corresponds to $V_0 = 0.4\ V_{200mb}$.

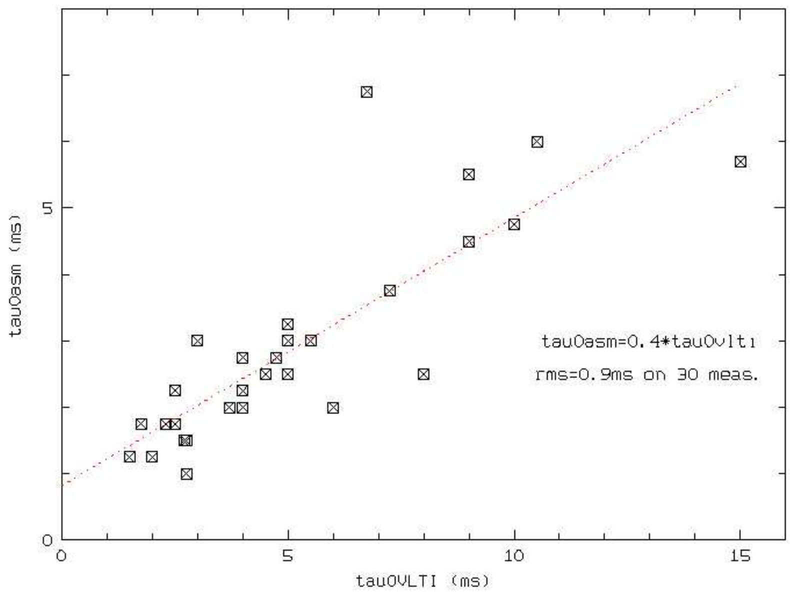

Figure 7: Temporal coherence extracted from VLTI-Vinci power spectra slope analysis (Aug01-Apr02, di Folco et al. (2003)) and as predicted using DIMM seeing and a wavefront velocity $V_0 = Max(V_{ground}, 0.4V_{200mb})$. The line corresponds to the ratio of the coefficients in the definitions (see text).

Table 1: Mean τ_0 and percentage of time with slow wavefront at Paranal for the period 1999-2003 (10 mn averages, 535000 samples)

Month	Median (ms)	$< 3\ ms$(% of time)
January	4.4	77
February	5.2	86
March	4.5	78
April	3.8	66
May	2.9	47
June	2.5	39
July	2.8	44
August	2.9	46
September	2.4	33
October	3.0	49
November	3.0	50
December	3.2	56
Year	3.3	56

Table 2: Comparison of the mean 300 mb wind velocity in m/s at Dome C (2003-2004, ECMWF analyzes, 4 per day, 0.5 degree horizontal resolution) with the 200 mb value at Paranal (1980-1995, NOAA GGUAS database, 2 records per day, interpolated from a 2.5 degree grid).

Month	Dome C	Paranal
January	10	20
February	16	19
March	12	22
April	12	30
May	14	36
June	14	36
July	14	37
August	17	36
September	14	37
October	11	36
November	15	31
December	11	25
Year	13	30

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