

Duty cycle of Doppler ground-based asteroseismic observations

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ABSTRACT

We report the observations of the clear sky fraction at the Concordia station during winter 2006, and derive from it the duty cycle for astronomical observations. Performance in duty cycle and observation duration promotes Dome C for efficient asteroseismic observations. This performance is analyzed and compared to network observation. For network observations, simulations were run considering the helioseismic network GONG as a reference.

Observations with 1 site in Antarctica provide performance similar or better than with a 6-site network, since the duty cycle limited by meteorology is as high as 92%. On bright targets, a 100-day long time series with a duty cycle about 87% can be observed, what network observation cannot.

Subject headings: instrumentation: interferometers; instrumentation: spectrographs; site testing; techniques: radial velocities; stars: oscillations (including pulsations)

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1. Introduction

Stellar evolution theory, central to most areas of modern astrophysics, is not sufficiently tested by observations. The analysis of stellar oscillation modes, which propagate inside stars down to the core, constitutes a powerful tool to probe their internal structure, and provides the necessary observational basis for the theory. Already applied to the Sun with a remarkable success, after pioneering observations at the South Pole by Grec, Fossat & Pomerantz (1980), this technique is now opening up to stars showing solar-like oscillations, both from space and from the ground.

Successful monosite Doppler asteroseismic observations were performed recently with échelle spectrometers (CORALIE at the Swiss 1.2-m telescope in Chile, HARPS at the 3.6-m ESO telescope, UCLES at AAT in Australia). Mostly sub-giants were observed. Only global oscillations parameters, as the large splitting, were measured, eigenfrequencies being identified only for the brightest targets. The window effect due to daily interruptions leads to large uncertainties and ambiguities in the frequency determination, and the frequency resolution remains limited by short observations. Two-site observations were performed only on bright targets, with a time series with efficient duty cycle limited to about a few days: α Cen A and B were observed with UCLES/AAT and UVES/VLT, (Bedding et al. 2004); ν Indi was observed with UCLES/AAT and CORALIE/Euler telescope (Bedding et al. 2006).

The space project CoRoT, to be launched in December 2006, will provide high-precision photometric observations, with an unprecedentedly high duty cycle (Baglin et al. 2002). After CoRoT observations, we believe that the major contribution of ground-based observation will consist in monitoring the Doppler signature of stellar oscillations. In fact, even in an excellent site as Dome C, photometric measurements remain unable to provide the necessary precision.

In fact, spectrometric observations will be able to detect $\ell = 3$ oscillation modes that cannot be analyzed in photometry, and will be less affected by stellar activity noise, increasing the complementarity with space-borne photometric observations (Toutain et al. 1997). Such observations need long duration, in order to obtain a very precise determination of the eigenfrequency pattern. Precision in the frequency measurement $\delta\nu$ varies as the square root of the observation total duration T (Libbrecht 1992). Precise eigenfrequencies translate linearly into precise modelling, according to inversion technique.

In this paper, we address the question of optimized duty cycle of ground-based observations. Possible solutions are presented in Section 2, in the case of long-duration observations. Meteorological conditions and maximum duration of efficient observation are examined in

Section 3. We report the observations of clear sky fraction made during the winterover of Eric Aristidi at the Concordia station. In Section 4, we discuss the properties of spectroscopic asteroseismic observations at Dome C, and compare them to what could be obtained from network observation. The parameters for the comparison correspond to the observations of bright solar-like stars, as proposed by the observational projects SONG (Grundahl et al. 2006) or SIAMOIS (Mosser et al. 2006). The duty cycle of the time series and the energy in the first diurnal alias of its Fourier spectrum are calculated as a function of the total observation duration, for different observation conditions.

2. How to obtain ground-based continuous observations?

2.1. Network

The many results obtained by the helioseismology networks have shown their capability to provide long duration time series with a high duty cycle, better than 80% when averaged over long durations and about 90% for short runs, as reported by the GONG project (<http://gong.nso.edu>, Harvey et al. 1996). Such performance was prepared by intensive efforts in site survey (Hill et al. 1994). The duty cycle obtained by the WET campaigns dedicated to stellar variability photometric measurements has never reached such values, despite a greater number of sites involved in the network, but without a strict selection of the sites involved in the network. Dolez et al. (2006) report for example a 18-day campaign with a duty cycle of 66.5%. We note that the baselines of the SONG network project, dedicated to the Doppler monitoring of solar-like oscillations in bright stars, are clearly derived from the organization of the GONG project. The concept of SONG involves small size telescopes and iodine-cell échelle spectrographs (<http://astro.phys.au.dk/SONG/>, Grundahl et al. 2006), to be installed in selected sites similar to the ones of GONG. Accordingly, and taking into account the excellent duty cycle performance achieved by the network GONG, we consider in this paper its characteristics as a reference for a network dedicated to Doppler measurements.

2.2. Antarctica

In this paper, we do not consider possible observation at the South Pole, where strong catabatic winds yield recurrent cloudy periods, for a duty cycle limited to about 50% during winter. Attention is focussed on possible asteroseismic observation to be conducted at Concordia station, located on the Dome C summit on the Antarctic plateau (75°6' South,

121°21' East, altitude of 3250 m). Intensive site testing is currently made there (Aristidi et al. 2005 and references therein). The site presents very positive characteristic features for astronomical observation: very low temperature, humidity, very limited winds (Aristidi et al. 2005). The whole atmosphere nighttime seeing was first observed during the 2005 winter (Agabi et al. 2006). Kenyon et al. (2006) report a low scintillation level limited to about 50 μ mag. The amplitudes of solar-like oscillations, about a few ppm, remain too tiny for photometric asteroseismologic ground-based observations. In that case, spectrometric observations are definitely required.

Currently, observing conditions at Dome C are governed by the limited available infrastructures: in a near future, only light operations with small telescopes can be achieved. The SIAMOIS project (Mosser et al. 2006) has been designed accordingly. The SIAMOIS concept is based on Fourier Transform interferometry, which leads to a small instrument developed for the harsh conditions in Antarctica. Applied to the Sun in the 1980's, Fourier Tachometry was chosen for the GONG helioseismic network after a long study of competing measurement strategies, and it forms the basis of the Michelson Doppler Imager instrument on the SOHO spacecraft as well as the Velocity and Magnetic Imager on the forthcoming SDO spacecraft. Performance of a Fourier Tachometer for asteroseismology was estimated in Mosser et al. (2003).

3. Duty cycle and observation duration

Many factors may limit the duty cycle of ground-based observation. We focus here on two major points: meteorology and sky brightness due to twilight. Other factors, such as instrument down time, are not considered.

3.1. Clear sky fraction

The clear sky fraction at Dome C was observed during the 2006 winterover. It was estimated visually several times a day, using a scale from 0 (no visibility) to 1 (cloud-free sky). We consider here the data from March 21 to September 21 (Fig 1). Non-clear sky means the presence of thin cirrus or thicker clouds. During this period, the clear sky fraction was greater than 0.9 for 84% of the time. The average number of consecutive clear days (with a clear sky fraction > 0.9) was about 6.8.

From this global fraction \bar{f} , we have derived the condition of observation in a given direction. We simply assumed that, in that case, the observation is either possible ($f = 1$)

or not possible ($f = 0$). An observed cloud sky fraction \bar{f} of duration T translates into an obscure window of duration limited to $\bar{f}T$, with possible observation during the remaining period $(1 - \bar{f})T$. We have then directly obtained the window function for observations to be conducted at Dome C. The duty cycle limited by meteorology at Dome C is superimposed on the clear sky fraction in Fig. 1.

We have modelled the sky fraction of an asteroseismologic network according to the experience and data of the GONG site survey (Hill et al. 1994), under the assumption that the data collected for the Sun in diurnal conditions can be adapted to night condition. We adopted for the network configuration the one of the GONG network, with 6 sites (4 in the northern and 2 in the southern hemisphere) where the clear sky fraction was intensively measured (Hill et al. 1994), making use of the same model for cloud apparition (Hill & Newkirk 1985).

3.2. Time series

The determination of the observing time series in each site depends first on the star altitude h , as a function of its coordinates, of the latitude and longitude of each observing site, and of the local hour angle of the star. Possible observation in a given site requires the star to reach a certain altitude h_* , but also the Sun to be below enough the horizon (parameter h_\odot). Times series were produced in many configurations. We have limited the extent of these parameters to plausible values accounting for realistic observation condition.

The parameter h_\odot is of greatest importance for observation at Dome C, with the Sun never below -8° at noon, implying that neither astronomical nor nautical twilights occur in this site. Values within the range $[-12^\circ, 0^\circ]$ were explored, in order to consider different observation conditions, on faint or bright targets. However, future targets of ground-based asteroseismology will clearly be very bright targets, because they will be observed with small telescopes. Then, the contrast with the sky background will be high enough to permit observations during twilight, with values of h_\odot much smaller than the astronomical twilight definition. Observations realized by Eric Aristidi have shown that observation of bright ($mV < 5$) targets when the Sun is lower than -4° provides a sufficient contrast between the sky and the target. Therefore, simulations requiring the parameter h_\odot to be fixed were realized in the case $h_\odot = -4^\circ$.

The h_* value must be high enough, since the decrease of signal with airmass is always important; due to absorption, blue photons are strongly absorbed, and due to seeing, photons do not enter easily the fibre or the slit of the spectrometer. Simulations were realized for

airmass of 2.5, 3 or 4 ($h_{\star} = 23.5, 19.5$ or 14.5° respectively). For a network of 6 sites, we have checked that the parameter h_{\star} plays a limited role; its value is however important when extrapolating the analysis to the case of a network with less than 6 sites. We have measured that, for a network, a 1° decrease of h_{\star} improves the duty cycle by only 0.2%; this proves in fact the quality of the network, since 1° gain in one single site at latitude 30° represents for an equatorial target 9.2 min more observation, hence an increase of 0.6% duty cycle.

We included 2% overhead into the duty cycle at Dome C, for operations as calibration, or back rotation of the telescope. Therefore we automatically limit the maximum duty cycle at 98% for Antarctica observations.

3.3. Simulations

We have constructed time series with alternation of clear and cloudy weather, using a Monte Carlo model as described in Hill & Newkirk (1985), and with their meteorological parameters for the selected sites (probability of clear sky and mean interval between cloudy period). After having run many simulations, we have selected a median realization, normalized to the mean observed performance of the observing runs reported by the GONG network (duty factor equal to about 85%). Practically, this normalization was achieved when considering only the condition on h_{\star} (with the Sun as the target), and no other condition on h_{\odot} . We have checked that, in such conditions, the simulations gave significant and reproducible results.

We tried to limit the number of parameters of the simulation as low as possible. Simulations have shown that seasonal effects are limited, and therefore the right ascension influence is very limited too. Then, for sake of simplicity, we have run the simulations with a right ascension value $\alpha = 18\text{h}$, just in order to cophase network and Antarctica observations. Concerning the declination, we chose to focus on the most favorable case for the network simulation: $\delta = 0^{\circ}$. The variation of the duty cycle with the stellar declination is discussed hereafter.

Figures 2 and 3 present respectively the window functions observed at Dome C in 2006 or modelled for a 6-site network, represented for 140 days around the Southern summer solstice. The window function at Dome C is dominated by the sky brightness at noon local time in the days following (preceding) the beginning (end) of the night.

4. Discussion

4.1. Time series

In order to compare the simulations, we have calculated the filling factor, averaged over 10-day periods, for a network with 4 to 6 sites and for Antarctica.

We have sorted the results as a function of time (Fig. 4). Antarctica observations provide a better duty cycle for runs limited to about 2 months. For longer runs, the Sun skimming horizon appears as a limit. In that case, despite the shift between local and sidereal times, network observation gives a higher duty cycle, that nevertheless decreases sensitively with the total duration (respectively below 70% and 60% for 4 and 5-month long observations).

We have analyzed the importance of the Sun location by calculating the duty cycle obtained during the 100-day long night as a function on the condition on the altitude h_{\odot} . Table 1 shows the importance of observing targets bright enough in order to be observed with high SNR even with the Sun not far below horizon. Such targets are already identified (Table 2). However, the time series analysis is not sufficient for complete estimations or comparisons: the signature in the Fourier spectrum of the data interruption must be checked.

4.2. Frequency analysis

We focussed our attention on the first diurnal sidelobe in the power spectrum. The window function after 60 days of continuous observations is presented on Fig. 5. The energy around the day first alias at $11.57 \mu\text{Hz}$ is much reduced for Antarctica observation compared to network observation (Table 3).

The influence of the observation duration and Sun altitude below horizon can be discussed from Fig. 6, that represents the relative mean energy around $11.57 \mu\text{Hz}$, as a function of the observation duration and maximum Sun altitude. This contribution is about 5% for faint targets requiring the Sun -12° below horizon. It lays in the range $10^{-3} - 10^{-4}$ for bright targets observable as soon as the Sun is below -4° . Observations in Antarctica with a first side lobe limited to 1% of the signal may last as long as 4 months, providing therefore simultaneously excellent window and frequency resolution.

4.3. Targets

The observable sky fraction is limited to circumpolar targets at Dome C (Tab. 2). Right ascensions opposite to the Sun are favored. The preparative work of the SIAMOIS project (Mosser et al. 2006) has identified the different targets and proposed a scientific program for more than 6 winters. Conditions of network observations are quite different. The right ascension of the source plays no role, but the duty cycle varies as a function of declination in a complex way (Fig. 7). First, for increasing absolute value of the declination, the duty cycle decreases due to asymmetry in the network and less efficiency of sites with latitude opposite to the stellar declination. Then, around respectively $+50^\circ$ and -50° , the decrease is hampered by the increase of visibility duration of high declinations sources, that compensates the low altitude above horizon. With 4 sites in the Northern hemisphere, but 2 in the Southern hemisphere, the duty cycle is lower for austral targets. Nevertheless, the band with a duty cycle above 80% remains limited to declinations in the range $[-22^\circ, +35^\circ]$. This corresponds to 47% of the sky, when only 29% is observable at Dome C at airmass always less than 3.

4.4. Number of sites

As shown by the GONG site study, the number of sites is a crucial parameter for network observations. The performance of the network limited to 5 or 4 stations was therefore estimated. Simulations show that the star declination plays no important role, contrary to the identity of the absent observatories: the contribution of a Hawaiian site, without close neighbor, is of course highly valuable. The averaged duty cycle decrease is about 9% with 5 sites, and 20% with only 4 sites (Fig. 4). This decrease is slightly more pronounced with increasing observation duration. Note that a network with 3 sites in the same hemisphere may have performance comparable to a 4-site network, but with severe restrictions on the possible targets.

It is out of the scope of this paper to examine the question of maintenance, which is a crucial point for both network and Antarctica observations. At Dome C in Antarctica, the maintenance is limited to 1 site. Previous wintering (Agabi et al. 2006) has shown the potential of the site, with the logistic of the French and Italian polar institutes. Maintenance problems are also problematic for an efficient network, with an effort to be multiplied by the number of sites, in order to maintain all operational. We did not take into account the Moon influence. At Dome C, the Moon will not interfere with the observations of circumpolar targets. For network observation, with targets at declination in the range $\pm 30^\circ$, great care will have to be taken when selecting a target.

5. Conclusion

Observations conducted during the 2006 wintering at the Concordia station in Antarctica give an excellent clear sky fraction, that yields a meteorological duty cycle as high as 92%. Consequently, asteroseismic observations conducted at Dome C during the 100-day long polar night provide performance better or similar than realized with a 6-site network. The only case where a 6-site network may provide better performance, but limited to a duty cycle about 77%, is for a 5-month long observing run. On the other side, asteroseismic observations at Dome C may provide a 100-day long time series with a total duty cycle about 87%, what network observation cannot. With such a duty cycle, the relative residual energy in the first diurnal sidelobes will be limited to less than 10^{-3} for bright targets ($mV \leq 5$). Performance on faint stars is about 10^{-2} , limited by the sky brightness at noon local time.

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Sun limit h_{\odot}	0°	-2°	-4°	-6°	-8°	-10°	-12°
Duty cycle (%)	92.0	91.0	88.5	84.6	78.3	69.8	64.2

Table 1: Mean duty cycle at Dome C, over the 100-day long night, as a function of the Sun altitude limit. Bright stars, that can be observed without restrictive conditions on the Sun altitude, are clearly favored.

target	type	δ	V	$v \sin i$ (km/s)	A (cm/s)
β Hyi	G2IV	-77.25	2.79	5.0	59
χ Eri	G5IV	-51.61	3.71	1.1	165
p Vel	F4IV	-48.23	3.84	16.0	165
HD114613	G3V	-37.80	4.85	8.0	73
α CenA	G2V	-60.83	-0.01	2.7	34
α CenB	K1V	-60.84	1.33	1.1	18
δ Pav	G7IV	-66.18	3.56	3.2	111

Table 2: Possible targets list at Dome C, restricted to dwarfs and sub-dwarfs showing solar-like oscillations, with V magnitude brighter than 5, excluding giant or pulsators as δ -Scuti. The oscillation maximum amplitude A is estimated according to Samadi et al. (2005). All these targets can be observed with a 40-cm telescope.

Duration (day)	Duty cycle (%)				Energy at 11.6 μ Hz (1 @ Dome C)			
	Dome C	6 sites	5 sites	4 sites	Dome C	6 sites	5 sites	4 sites
40	<i>94</i>	84	76	68	<i>1</i>	5	15	40
60	<i>92</i>	84	76	67	<i>1</i>	5	15	40
80	<i>90</i>	83	75	66	<i>1</i>	1.3	5	20
90	89	83	75	66	1	0.8	2	9
100	87	82	74	65	1	0.5	1	4

Table 3: Best duty cycle and energy of the window function in the frequency range around the day alias at 11.6 μ Hz, for different network configurations (4 \rightarrow 6 sites) and different observation durations, normalized to the same energy obtained with the window function at Dome C. Best performance are highlighted in slanted text. With the energy criterion at 11.6 μ Hz, the performance at Dome C is better only for observation durations less than 90 days. However, the duty cycle at Dome C remains greater than the one with a 6-site network for observation duration up to 120 days, so that the total energy distributed in the spectrum of the window function at non-zero frequency remains lower.

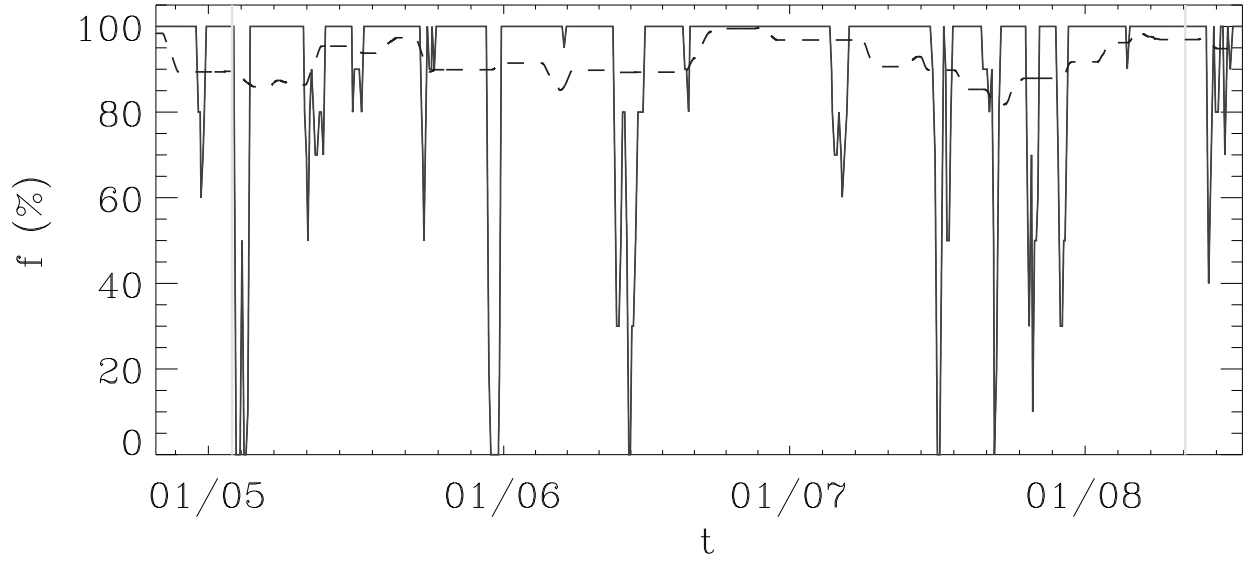


Fig. 1.— Full line: clear sky fraction f at Dome C, as observed during the 2006 wintering. Dashed line: duty cycle at Dome C, smoothed over a 10-day period. Lines at May 03 (embedded in a 2-day bad weather event) and August 11 represent respectively the beginning and the end of the polar night at Dome C. The meteorological duty cycle exceeds 92% during 3 months.

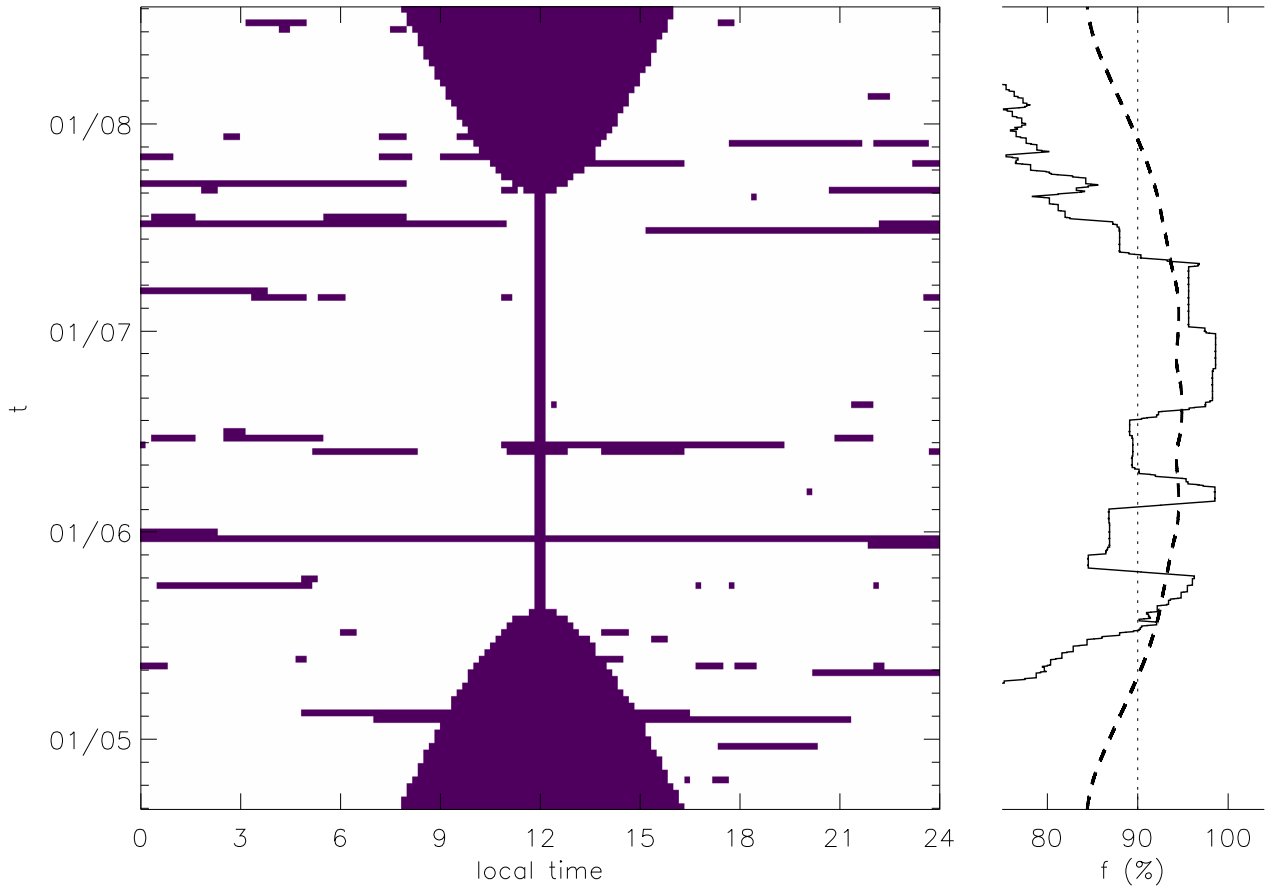


Fig. 2.— Left panel: observed window for Dome C, taking into account the meteorological conditions recorded in 2006 and the Sun altitude (at least 4° below horizon). The simulation also considers 20 minutes overhead per day, at 12:00 local time, for calibration and back rotation of the telescope. The right panel shows the variation with time of the duty cycle averaged over 10-day periods (full line) and the integrated duty cycle (dashed line).

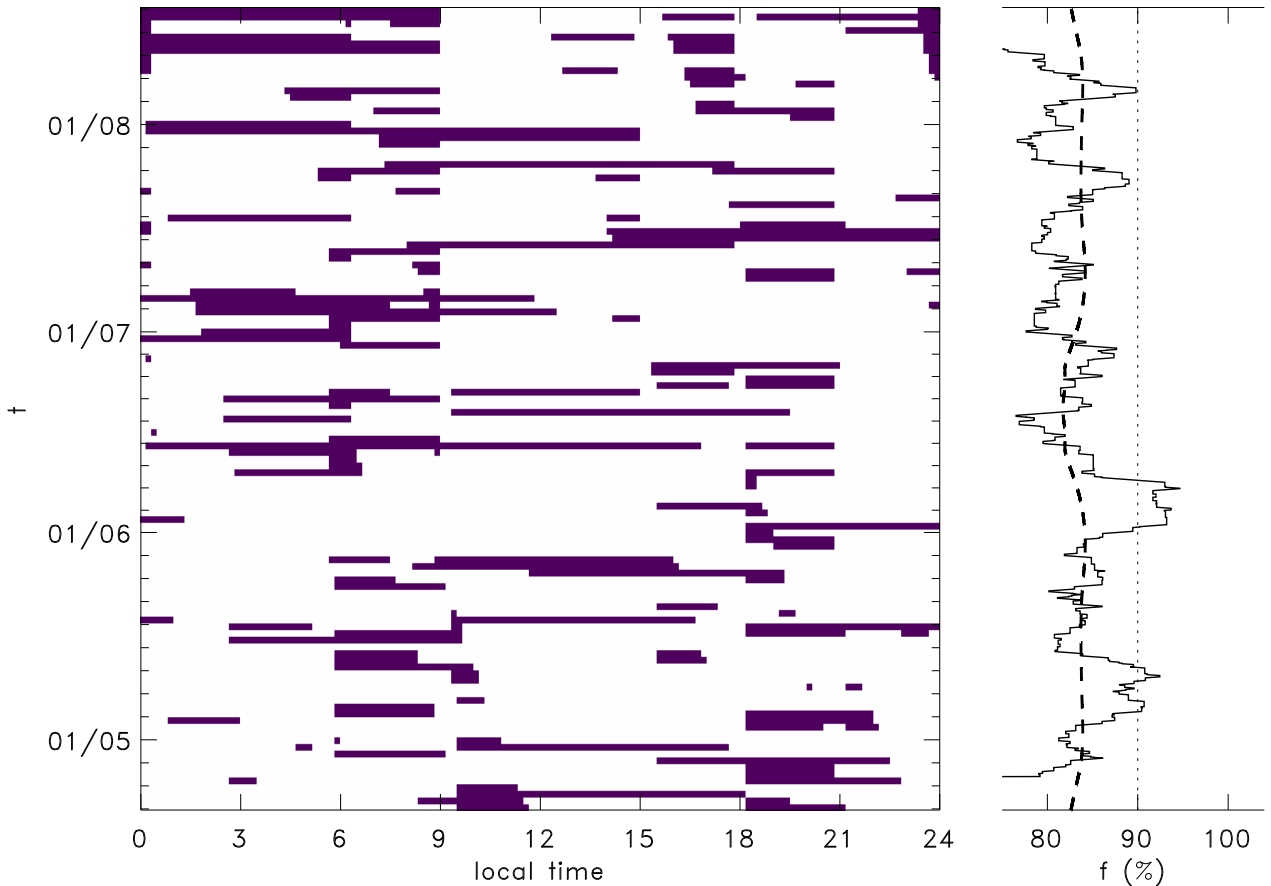


Fig. 3.— Same as Fig. 2 but for the simulated window for a 6-site network, taking into account the meteorological conditions derived from GONG (very short interruptions, practically related to local meteorological conditions, are not considered). Sidereal limitations, shifting by 4 min/day, and solar limitations, stationary with local time, can be easily distinguished. The maximum duty cycle is less than for Antarctica observations, but its decrease with increasing observation duration is much less sensitive. Stellar coordinates for this simulation: $\alpha = 18:00$, $\delta = 0^\circ$, $h_\star = 19.5^\circ$ (airmass = 3).

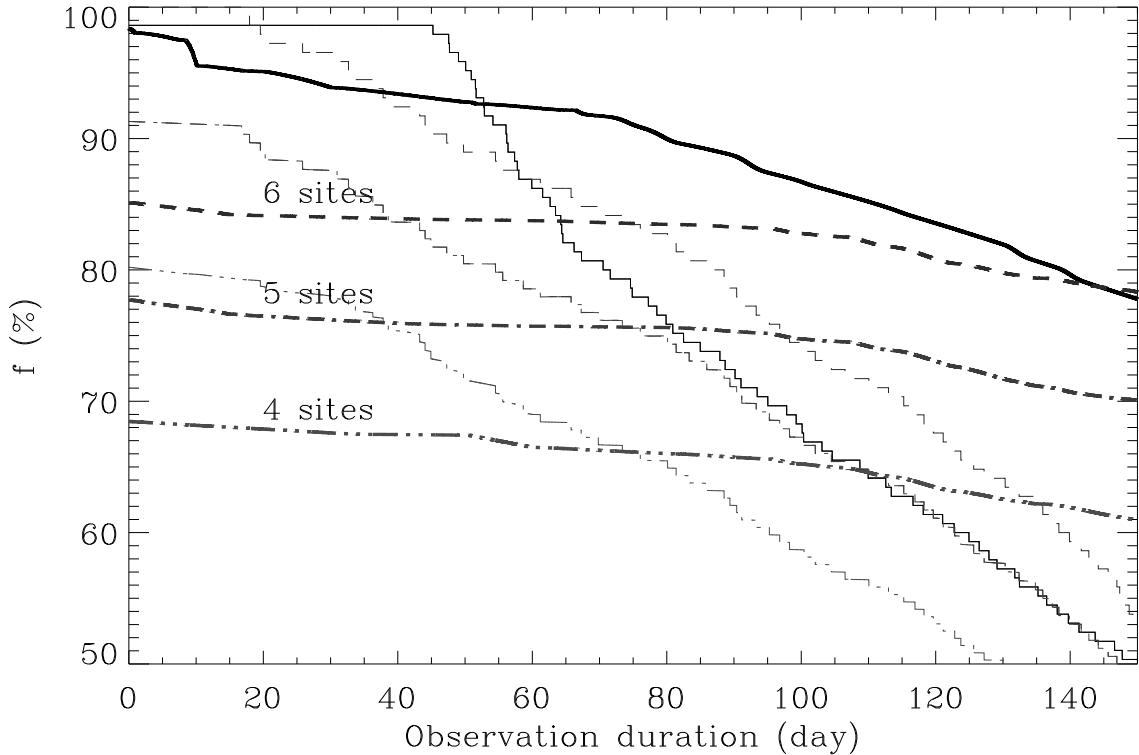


Fig. 4.— Comparison of the daily duty cycle distributions, at Dome C (full light line) or for a multi-site network (dashed light line: 6 sites; dot-dashed line: 5 sites; dot-dot-dashed line: 4 sites), and corresponding integrated duty cycle (heavy lines). Dome C provides long period with a duty cycle about 98% (not 100% in order to account for necessary diurnal operations, such as back rotation of the telescope). With 6 sites, network observations have a better daily duty cycle distribution only for periods longer than about 80 days. However, the integrated duty cycle remains better and Dome C for more than 4 months. Simulations for 5 or 4 sites depend on the absent site(s): results presented here have been averaged. Calculations for the network have been considered in the favorable case of an equatorial target, and for mean weather conditions. Simulations consider $h_{\odot} \leq -4^{\circ}$ and $h_{\star} \geq 19.5^{\circ}$ (airmass = 3).

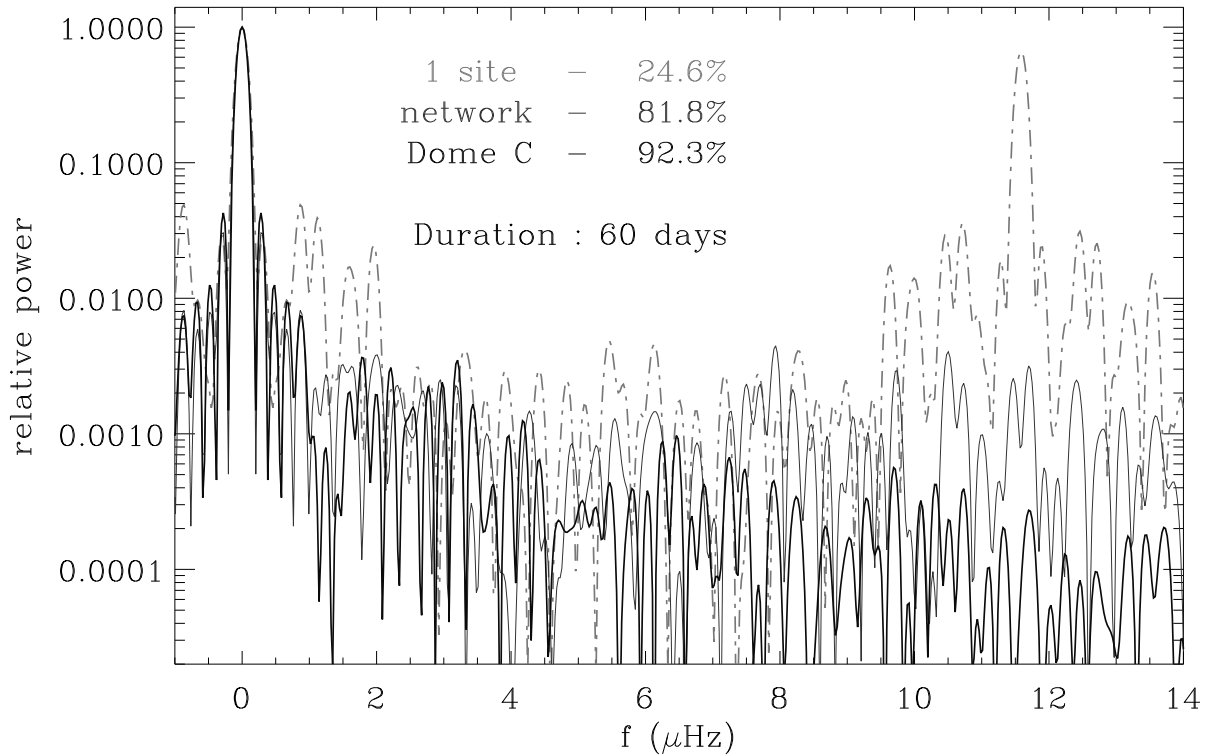


Fig. 5.— Window function obtained at Dome C during 60 days, compared to simulations for network and single-site observations (respectively grey and dotted lines). There is 10 times less energy emerging around the first day alias at $11.57 \mu\text{Hz}$ for Antarctica observations than for a network. The gain compared to the single site case is higher than 1000. Simulations consider $h_{\odot} \leq -4^{\circ}$ and $h_{\star} \geq 19.5^{\circ}$ (airmass = 3).

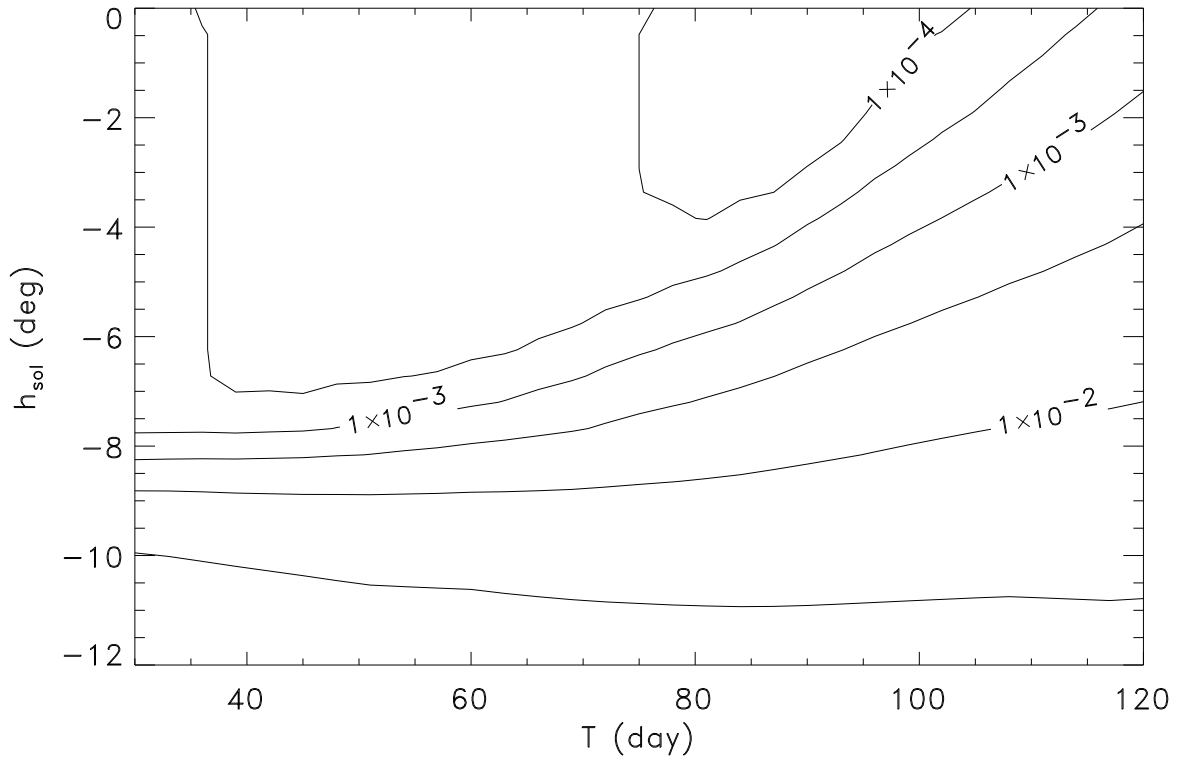


Fig. 6.— Contour plot of the mean energy around the first day alias $11.57 \mu\text{Hz}$ (Fig. 5), as a function of the observation duration and maximum Sun altitude, derived from the clear sky fraction observed in 2006. Performance is excellent for bright targets observable as soon as the Sun is below -4° . The energy in the daily alias increases with increasing observation duration and with increasing restrictive condition on the sky brightness.

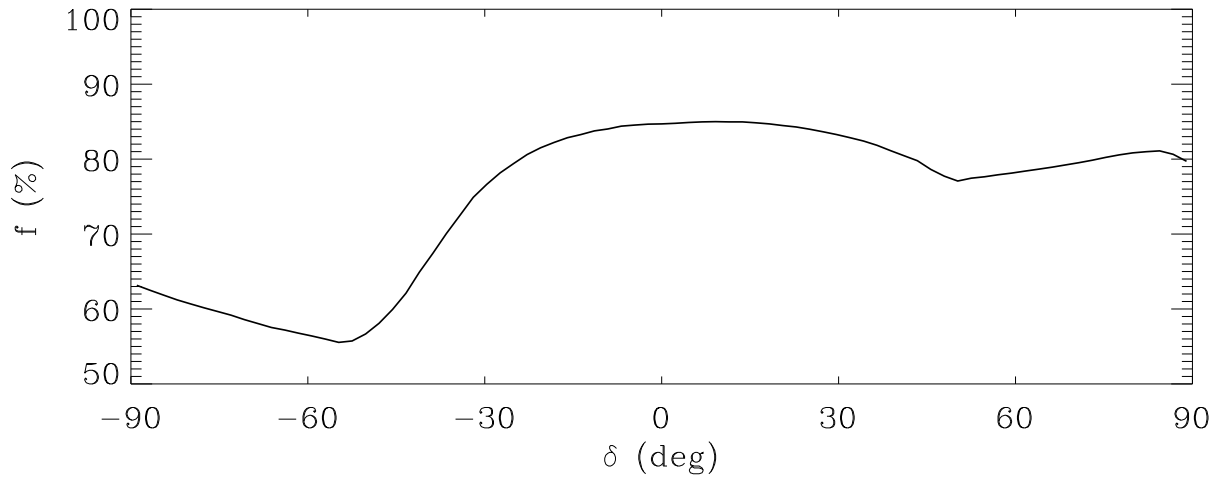


Fig. 7.— Mean duty cycle for a 6-site network, as a function of the declination δ of the target. The asymmetrical shape of the curve relates the fact that the network includes 4 sites in the Northern hemisphere, but only 2 in the Southern hemisphere. Circumpolar stars benefit from their longer visibility compared to lower declination targets, but are seen bad by a too limited number of observatories of the network.