Ground Layer Adaptive Optics Performance in Antarctica

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ABSTRACT

Ground layer Adaptive Optics (GLAO) is a new variant of adaptive optics that aims at correcting the seeing over a wide field of view by conjugating the deformable mirror to the boundary layer altitude. The South Pole, having the particularity to contain 96% of the seeing within a 220 m boundary layer and an absence of high altitude jets, is expected to be particularly well suited to this kind of AO. We present here the comparison of a GLAO system on a 2 m class infrared telescope at the South Pole and at Paranal. Our results, which show that the two sites obtain similar performance, are derived analytically using the simulation tool PAOLA.

Keywords: Adaptive optics, simulation, turbulence, Antarctica

1. INTRODUCTION

While most large telescopes are now equipped with adaptive optics systems (AO), their angle of correction is limited to a few arc seconds. The problem of anisoplanatism can be partly compensated by laser guide stars, however, for wide field correction the solution proposed is the conjugation of several deformable mirrors (DM) with the major turbulent layers. This technique, yet to be operational, will offer the resolution of the current AO systems over a few arc minutes.

The drawback of multi-conjugate adaptive optics (MCAO), beside the complexity, is the cost. For science cases, such as galaxy surveys, where diffraction limit is not required, an MCAO system is not justified. In 2001, Rigaut,[1] therefore proposed a subset of MCAO, borrowing its concept of height conjugation but using and conjugating only one DM to the surface layer of the atmosphere. Wide field adaptive optics (WFAO) or ground layer adaptive optics (GLAO) as it will be referred in this paper is capable of offering a significantly improved resolution over the very large field of view. This technique is motivated by the knowledge that the surface layer is usually the most intense turbulence layer of all, as shown in Table 1. Conjugating near the ground also greatly improves the isoplanatic angle, which makes the correction of this layer over a large field.

Table 1. Summary of the total boundary layer (BL) seeing statistics at several major site. This table is adapted from[2]

Site	Total seeing (″)	BL seeing (″)	% of seeing in BL	BL height	Ref.
Mauna Kea, Hawaii	0.74	0.52	70	-	[3]
Cerro Paranal, Chile	0.73	0.55	75	2000	[45]
La Silla, Chile	0.97	0.85	87	800 - 1000	[4]
La Palma, Canary Is	0.96	0.73	76	1 - 2000	[67]
South Pole	1.86	1.78	96	220	[2]

The requirements of this type of AO calls for a site with the largest proportion of turbulence in the atmospheric boundary layer which must be as low as possible. This characteristic is fulfilled at the South Pole. As shown in Table 1, 96% of the seeing is generated within a boundary layer 220 m high. The South Pole is located far

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from the latitudes where hot and cold air meet to create jets at the top of the troposphere. It is therefore free of high altitude turbulence. This particularity gives the South Pole a naturally high isoplanatic angle (Travouillon, 2003[8] & Marks, 1999[2]). The boundary layer, however, is very active. Katabatic winds originating from the top of the Antarctic plateau, create a convective layer with a large temperature gradient. This layer generates an average of $1.78''$ of seeing, making the site a poor candidate for high resolution observations. Despite this it offers the best sky background of any ground based site between infrared and millimeter wavelengths (e.g. Peterson, 2003[9] & Lawrence, 2002[10]). The atmospheric stability combined with the extremely cold temperature and water vapour absorption outweighs the average resolution for many types of observations. The design of an Antarctic GLAO system is therefore greatly justified. Extra-galactic surveys could, for example, be done faster at the South Pole than at any other ground based site.

2. THE GLAO SYSTEM

PAOLA[11] is an analytical, IDL based, simulation package that calculates the PSF of an aberrated wavefront after AO correction. In GLAO mode, PAOLA computes the residual phase power spectrum conjugating the deformable mirror at altitude h_c:

$$W_{GLAO}(f, h_c, \theta, \Omega) = k^2 \int_0^\infty W_N F_N^2(f, |z - h_c|, \theta, \Omega) dz. \tag{1}$$

This residual is a function of the Von Karman refractive index power spectrum, which depends on the intensity and distribution of the turbulence coefficient C_N^2 and outer-scale L_0:

$$W_N = (2\pi)^{-2/3} 0.033 C_N^2(z)(f^2 + 1/L_0^2)^{-11/6}. \tag{2}$$

In this paper we will use C_N^2 profiles measured at the two sites which details will be given in the next section. Since the outer-scale has not been physically measured we will base our results on a constant outer-scale of 30 m. The second important parameter of the residual phase power spectrum is the refractive index transfer function F_N^2:

$$F_N^2(f, |z - h_c|, \theta, \Omega) = 1 - 2cos(2\pi f \cdot \theta |z - h_c|) g(f, |z - h_c|, \Omega) + g^2(f, |z - h_c|, \Omega) \tag{3}$$

In this function appears the spacial filter $g(f, |z - h_c|, \Omega)$. This filter describes the correction given to a particular layer. In PAOLA this correction is done by averaging the optical transfer function over a cone of angular size Ω. In this case the filter takes the form of a Airy function:

$$g(f, |z - h_c|, \Omega) = 2 \frac{J_1(2\pi |z - h_c| tan(\Omega/2) f)}{2\pi |z - h_c| tan(\Omega/2) f} \tag{4}$$

It can be noted that other authors have proposed other kinds of filters. For example Tokovinin[12] proposed a Bessel function which is equivalent of averaging the transfer function over a ring while Rigaut[1] suggested a sinc filter. Regardless of the type of filter chosen, they will only apply to spatial frequencies that the deformable mirror can correct and depend on the actuator spacing d such that $f < 2/d$.

The GLAO system performance across a sky angle θ will be strongly dependent on the size of the cone used in the wavefront sensing. A large cone angle will produce a lower correction because of averaging but over a large part of the sky. Inversely a small cone angle will give a better estimate of the wavefront shape but only applicable to a small angle. PAOLA takes in account over parameters of the AO system to give realist performance results. It includes the fitting error, the wavefront sensor aliasing and noise, the control time lag and the anisoplanatism. The only assumption the software need to make is the wavefront is perfectly known over the cone surface. This means that the simulation results will be accurate is the system has a large amount of LGS or if enough natural guide stars are available within the cone angle. The last supposition is particularly true in Antarctica. Since the sky brightness on the Antarctic plateau is several orders of magnitude lower than at temperate sites, more stars will be available for a given signal to noise ratio.

In this paper will explore the performance of a GLAO system equipped on a 2 m telescope in the I, J, H and K bands. We use a wavefront sensor integration time of 1 ms and a control loop time lag of 0.7 ms.

3. THE SITES

In order to achieve realistic results of the performance of a GLAO system, we must use high spatial resolution profiles of turbulence and wind speed vectors. The high spatial resolution is important because, as shown by,[13] free atmospheric turbulence is formed in thin laminae often observed in pairs. A coarse sampling of the atmosphere, such as obtained with SCIDAR or MASS instruments are sufficient for seeing or isoplanatic angle measurements but only approximative for GLAO simulations. We have therefore chosen to use C_N^2 and wind speed profiles obtained from balloon borne microthermal sensors. With a resolution of roughly 5 m, this is currently the finest profiling technique available.

Also important for the analysis is the issue of averaging. Can we use an average profile to determine the performance of our GLAO instrument? There are two arguments against this. The first one is closely related to the issue of spatial resolution. Turbulence peaks are typically two or three orders of magnitude above the background and only a few tens of meters thick. The process of averaging a set of microthermal profiles would therefore smooth out the C_N^2 peaks and increase the background. The topology of the average profile would therefore not correspond to one of a realistic atmosphere and create misleading performance estimation of the AO system. The second argument comes from the importance of the isoplanatic angle. As we will show in the next section, the GLAO performance is strongly correlated to the seeing and isoplanatic angle. An average profile does not have an average isoplanatic angle. Fig.1 illustrates the average South Pole C_N^2 profile from 13 individual profiles. While its seeing angle corresponds to the average of all individually calculated seeing angles, the isoplanatic angle is overestimated in the average profile. Using it for our analysis would therefore bias our results towards better corrections.

In this paper we will therefore focus on the analysis of typical profiles chosen for having both seeing and isoplanatic angles close to their respective averages. Being recognized as one of the best sites in the world, the microthermal data from Paranal[14] will provide a comparative benchmark for the performance of a GLAO system at the South Pole. Paranal clearly has a better seeing than the South Pole. However, the isoplanatic angle of the South Pole is twice that of Paranal and can be explained by the lack of free atmosphere turbulence. This difference can be observed in Fig.2 which shows that the the South Pole boundary layer turbulence is more intense than at Paranal while the tropopause peaks of Paranal are non existent at the South Pole. The profiles of Fig.2 both have seeing and anisoplanatism values near the median of their respective sites. They will therefore be used in the analysis to represent the typical profiles of each site.

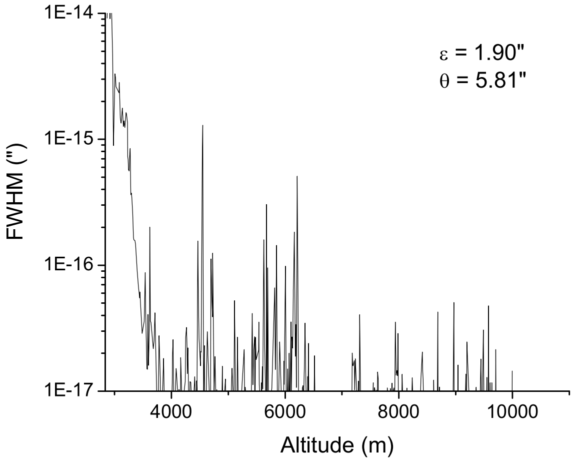

Figure 1. Average of the 13 South Pole C_N^2 profiles.ε is the seeing angle and θ the isoplanatic angle calculated from this profile. The ground level of the South Pole is at the altitude of 2835m.

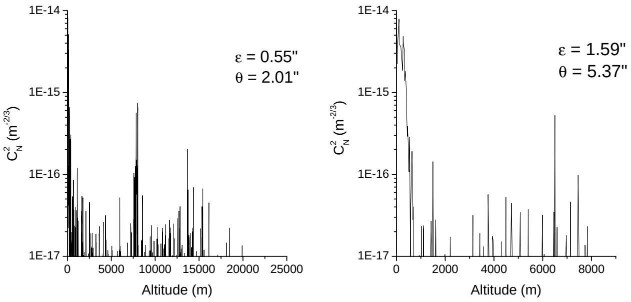

Figure 2. Typical C_N^2 profiles at the South Pole (right) and Cerro Paranal (left). The seeing ε and the isoplanatic angle θ are given in the diagram.

4. RESULTS AND DISCUSSION

In this paper we will present the performance of a specific GLAO system on a 2m telescope. This mirror size has been chosen as several IR telescopes of this size are currently being proposed for Antarctica. The AO rectified long exposure PSF will be expressed in term of residual full width half-maximum (FWHM) in arc seconds to make easy comparison with the uncorrected seeing conditions.

Table 2 summarizes the characteristics of the GLAO system. We will look at the performance of the system as a function of corrected field (ie. the distance between the science object and the guide star) in I (880 nm), J (1239 nm), H (1649 nm) and K (2192 nm) bands. The actuator pitch was chosen to be equal to the value of the Fried parameter in the I band and kept at this value for all the other bands in order to optimize the fitting error. While several turbulence and wind profiles will be used in this analysis, the outer scale of turbulence which is not experimentally measured will be assumed constant for all simulations and chosen to the commonly accepted value of 30 m.

Table 2. Summary of the parameters used in this paper

Primary mirror diameter	2 m	AO loop time-lag	0.7 ms
Secondary mirror diameter	0.56 m	Outer scale	30 m
Actuator pitch	r_0 @ I band	Field of correction	0' to 10'
WFS integration time	1 ms	WFS cone size	0' to 10'

Before estimating the performance of our system, we need to consider the altitude of conjugation. As shown in Jolissaint, 2003,[11] the optimal height of conjugation is not simply the ground. It is influenced by the overall distribution of the seeing in the atmosphere. This distribution is centered at a weighted altitude $\langle H\rangle = (\int h^{5/3} C_N^2(h)dh / \int C_N^2(h)dh)^{3/5}$. Sites with high altitude turbulence will therefore have an optimal conjugation shifted toward this height. At the South Pole the majority of turbulence is so close to the ground that this effect is non-existent. Fig.3. Shows the value of the residual FWHM calculated from the typical profile as a function of height conjugation. We have found that the performance of the system decreases with increasing height conjugation, while it remains acceptable up to 400m. It can be noted that $\langle H\rangle$ is low (lower than the top of the boundary layer) and indeed within the range of acceptable conjugation. In the rest of this paper our GLAO system will be conjugated to a height of 100 m at the South Pole and 120m at Paranal.

The key result of this paper is the amount of residual seeing as a function of field size. In standard AO systems, the field size is restricted to the isoplanatic angle that is an order of a few arc seconds. Beyond it, the correction quickly fades. In GLAO a much wider field of correction can be achieved, although the correction

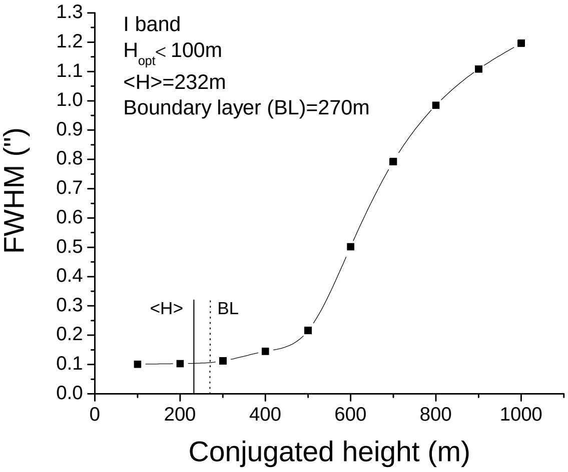

Figure 3. Comparison of the residual seeing as function of conjugation height using the typical South Pole profile.

may not be as strong. In Fig.4., we show the results of this correction at the South Pole for WFS cones ranging from 1' to 29' using the typical turbulence profile. The system performance can therefore be estimated by the lower envelope of these curves. It shows that about 80% of the natural seeing can be eliminated in a field of 4' depending on the wavelength used. In the J, H and K bands the improvement is more apparent. The best correction is obtained in the I band over a small field but it degrades more rapidly at wider field than it does for longer wavelengths.

The suitability of the site cannot be inferred from a single profile. We have therefore calculated the residual seeing using all the available microthermal profiles at the South Pole and Paranal. Due to their extra demand on computing power, the two worse profiles at the South Pole have been excluded from the calculation. The comparison was carried out in the I band for fields of 1' and 10' using their respective optimal WFS cone angle. The results are expressed in Table.3. along with the original seeing and isoplanatic angle of each flight at 500nm. While Paranal starts with a median natural seing much lower than the South Pole, we find that the corrected seeing of the two sites is comparable for both narrow and wide fields of view. This is an important result as the only weakness of the South Pole is its poor seeing angle. Equipped with a GLAO system a telescope at the South Pole can achieve the same resolution than it can at Paranal while taking advantage of the superior sensitivity. It is interesting to note that at both sites, the results of the smaller field are far less variable than at the larger field. At 1' the residual seing almost systematically reaches 0.15″ while at 10' it can either reach this same value or exceed 1″ in case of bad seeing and isoplanatic angle.

In order to further investigate the effect of the seeing and isoplanatic angle on the performance of our system, we show in Fig.5. and 6. the residual seeing of several representative profiles as a function of field size along with the average residual calculated using all profiles. As we expect, profiles with better isoplanatic angles produced better overall correction. However, it is the combination of both seeing and isoplanatic angle that drives the extent of this correction over larger fields. In nights of good seeing and isoplanatic angle, the GLAO system will therefore give excellent correction over a very wide field. In the case of the South Pole where the boundary layer turbulence dominates, it is the seeing angle that has large variations while the isoplanatic angle is always very good. The GLAO system will therefore give more consistent results for small angle corrections while the larger fields of view will see more variations. At Paranal, it is the opposite situation. The seeing is more stable while the isoplanatic angle changes more frequently. We have then more variation of the performance for small fields and less deterioration for wider fields.

To further explore the comparison of the South Pole with other sites, we have investigated the performance

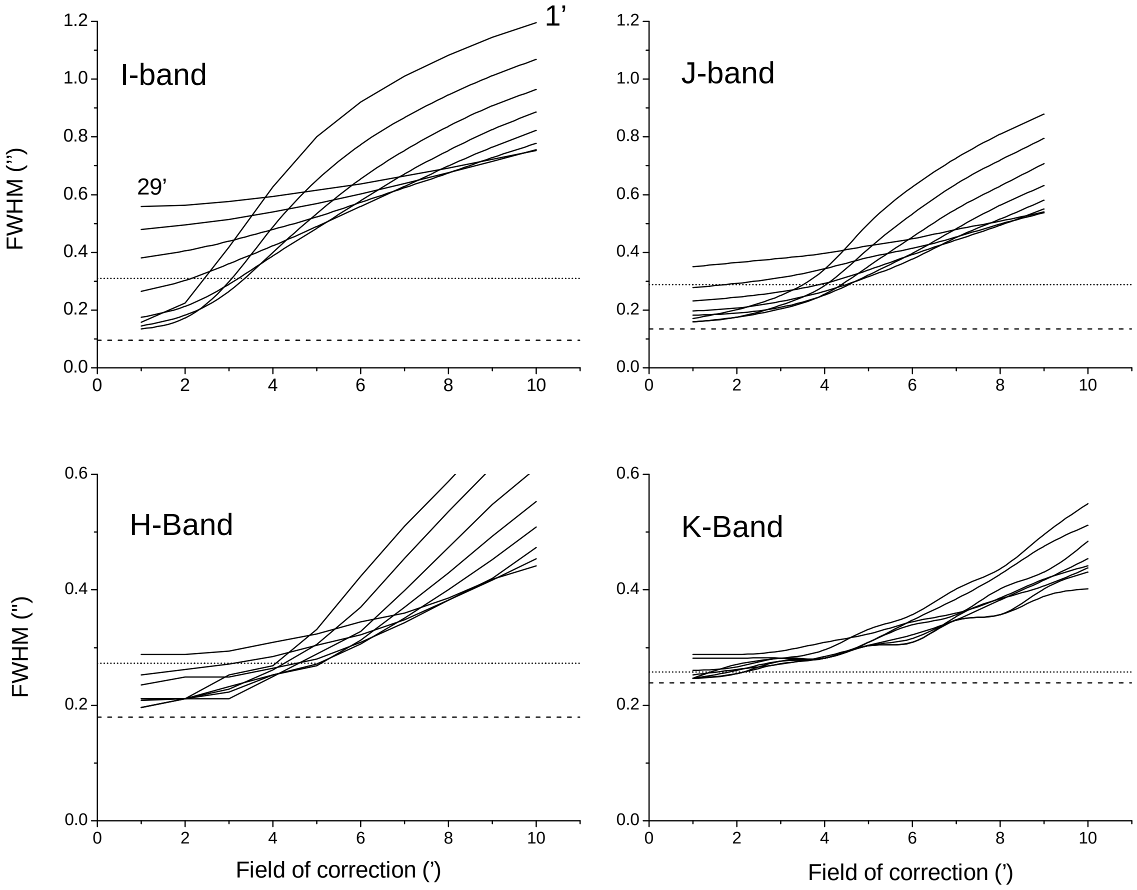

Figure 4. Residual FWHM as a function of corrected field for I, J, H and K bands for the South Pole typical profile. Each curve corresponds to a different cone angle from 1' to 29' with steps of 4'. The upper line corresponds to 20% of the natural seeing and the bottom line to the diffraction limit.

Table 3. Turbulence characteristics of all profiles used in the analysis and the residual FWHM after GLAO correction for a corrected field of 1' and 10' at I band. The seeing (ε) and the isoplanatic angle (θ) are expressed in arc seconds at a wavelength of 500 nm.

	South Pole				Cerro Paranal			
Flight ♯	ε	θ	res. ε for 1'	res. ε for 10'	ε	θ	res. ε for 1'	res. ε for 10'
1	1.86	5.63	0.14	0.40	0.82	4.03	0.13	0.3
2	0.59	4.81	0.13	0.16	0.58	3.53	0.14	0.27
3	2.12	1.46	1.05	1.28	1.49	0.41	0.73	0.92
4	1.26	4.04	0.17	0.35	0.54	2.04	0.18	0.28
5	2.06	3.92	0.13	0.73	0.46	1.71	0.16	0.19
6	1.47	5.51	0.13	0.43	2.7	2.45	1.12	1.76
7	5.44	4.33	-	-	0.82	1.74	0.13	0.32
8	1.02	3.81	0.14	0.37	0.55	2.01	0.11	0.14
9	1.01	3.57	0.14	0.25	0.62	2.30	0.11	0.15
10	0.99	5.84	0.12	0.23	0.62	2.79	0.12	0.28
11	4.07	5.33	-	-	0.91	1.63	0.18	0.36
12	1.59	5.37	0.13	0.74	-	-	-	-
13	1.31	6.14	0.11	0.23	-	-	-	-
Mean	1.90	4.59	0.22	0.47	0.91	2.24	0.28	0.45
Median	1.59	5.33	0.13	0.37	0.62	2.04	0.14	0.28

of the GLAO system on a 20 m telescope. Using the same GLAO properties, Jolissaint et al. shows their Figure 4, the performances of Mauna Kea, Cerro Tololo and Cerro Paranal using average profiles. In order to make a fair comparison, we have computed the I band performance of a 20m telescope using the South Pole average profile. The results are displayed in Fig.7. Unlike Mauna Kea and Cerro Tololo where the performance drop sharply over the first 2' of field, the South Pole achieves a corrected seeing below $0.2''$ within a field of 3.5' and an impressive $0.05''$ in the first 2'. If field size is the priority over the quality of the correction, Cerro Paranal is the best performer of the 4 sites with a residual seeing systematically below $0.3''$ over a large 10' field.

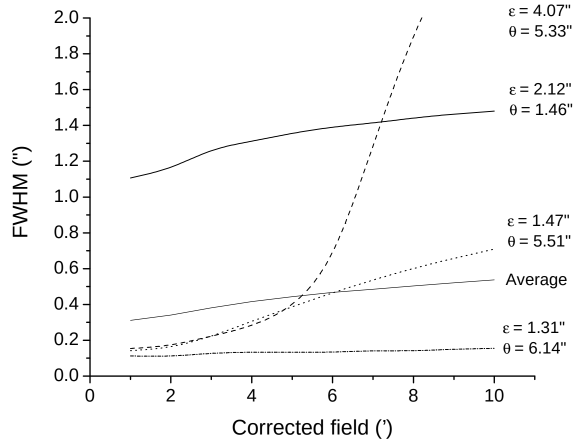

Figure 5. Residual FWHM of several C_N^2 profiles obtained at the South Pole with different combinations of seeing angle and isoplanatic angles. The average correction was calculated using all 13 profiles and a WFS cone angle of 5'.

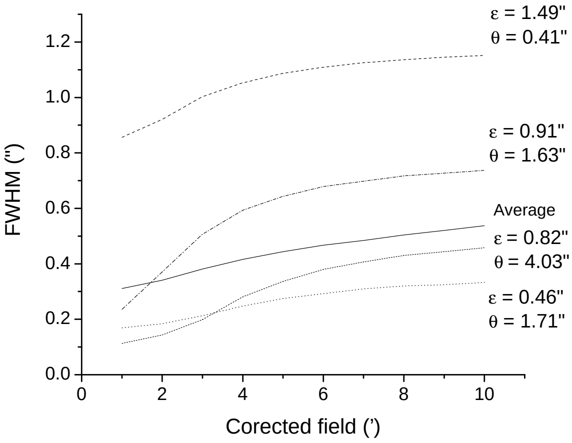

Figure 6. Residual FWHM of several C_N^2 profiles obtained at Paranal with different combinations of seeing angle and isoplanatic angles. The average correction was calculated using all 11 profiles and a WFS cone angle of 5'.

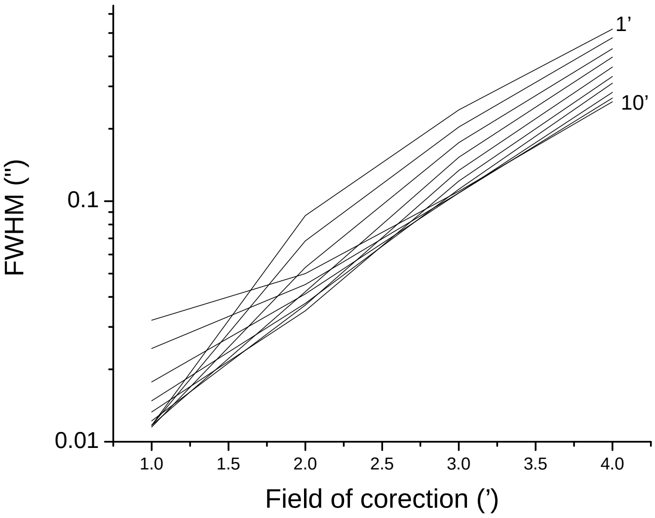

Figure 7. Performance estimates of a 20m class telescope at the South Pole in the I band.

5. CONCLUSION

We have demonstrated here that the South Pole is an ideal site for a GLAO system. It has relatively poor uncorrected seeing but the turbulence distribution in the atmosphere is so unique that its corrected seeing is better than the corrected seeing of other major sites. The excellent sky transparency of the site has already been well exploited by several experiments in the sub-mm where the effect of turbulence is negligible. GLAO gives us the opportunity to develop the site in the near infrared. The combination of the low sky background with the high resolution over a wide field will make the South Pole an ideal place to conduct fast wide field surveys.

It can be added that the low sky background as an additional advantage. The GLAO system presented in this paper relies on the wavefront measurement over several arc minutes using a constellation of stars spanning that surface. In practice it means that a site with a lower background will have more available stars above a certain signal to noise ratio within a certain field therefore making the WFS measurements more accurate.

As the site testing campaign continues in Antarctica, turbulence profiles of Dome C are expected to be available shorty. Dome C is located on a local maximum of the Antarctic plateau and 500m higher than the South Pole. We therefore expect even better GLAO performance at this site.

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