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A roadmap for a new era turbulence studies program applied to the ground-based astronomy supported by AO.

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Abstract. Sites selection for ELTSs concluded and a new era opens for turbulence studies in application to the ground-based astronomy supported by the adaptive optics (AO). If in the last decade the main interest of astronomy has been focused on the characterization of sites, now priorities change. In the last years more and more AO systems have seen their first light. A few more complex AO techniques are still in a phase of verification/validation. The efficiency of the operating and forthcoming AO systems can strongly be affected by turbulence and observation strategies rely on our ability in knowing in advance the turbulence spatial distribution in a region around the telescope. Progresses in development of more sophisticated AO techniques (such as the LTAO, MCAO and MOAO) definitely depend on a more detailed knowledge of the main turbulence features such as the turbulence stratification at high vertical resolution. A European working group has been recently set-up aiming at defining the roadmap of a program of site testing campaigns for OT measurements having multiple goals mainly addressed to support requirements for 3D OT modeling with hydrodynamical approach and AO at wide field in application to the ground-based astronomy. The main first objective of this program will be the absolute instrument cross-calibration (in particular the vertical profilers for the whole troposphere and low stratosphere 20km) and validation of techniques for turbulence stratification on the same vertical range at high vertical resolution (with the optimal goal of 100-200m). In this contribution we will present the motivations of our work, the goals, the instrumentation we are taking into account, the different strategies and constraints we are considering for the conception of site testing campaigns.

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1 Introduction

Most of the efforts in the field of the atmospheric turbulence in application to the ground-based astronomy have been focused in the last decade on the site-testing for the selection of the sites for the Extremely Large Telescopes (ELTs). Among those the E-ELT, the TMT and the GMT. A huge amount of resources have been invested in this activity. For the turbulence characterization two instruments has been mainly used: the DIMM and the MASS. The DIMM is an instrument sensitive to the integrated turbulence on the whole atmosphere (typically 20 km); the MASS is a vertical profiler, with a vertical resolution $\Delta h \sim 0.5 \cdot h$ i.e. a very low resolution that corresponds, from a practical point of view, to six layers distributed on a logarithmic scale in the [0.5,16] km range above ground layer (a.g.l.) [1,2]. The main motivation for this choice has been the fact that both instruments are small size monitors i.e. instruments easily reproducible in copies to be placed in different sites and routinely run for long time scales. Sites for all the ELTs have been selected in the last years and this era can be considered concluded. The challenges of the ground-based astronomy, particularly that supported by the AO techniques, are now different and it is important to define as soon as possible a roadmap of actions to be undertaken. At the same time it is important to define a new philosophy of approach to the experiments in the field of the optical turbulence in application to the astronomy that aims at optimizing the outputs. The goal of this working group is double. From one side we aim to provide a contribution in the definition of the roadmap of the most critical turbulence studies fundamental for the ground-based astronomy supported by the AO to be carried out in the next years. On the other side, we intend to propose a concrete experiment that can optimize outputs i.e. answers to critical questions for the AO developers as well as for those scientists who study the optical turbulence (OT) prediction with non-hydrostatic atmospherical models. The intention should be to consider this experiment as a first action of a series that, we hope, will define a methodology of work. For what concerns the definition of the roadmap obviously the content of this contribution does not pretend to be exhaustive but the intention is that this can represent a starting point.

In the recent years the necessity of vertical profilers able to achieve high vertical resolution (order of 100-200 m) that might be used as automatic monitor to support the wide field AO, particularly for the ELT [3], appeared evident . At the same time, in both fields (AO and the OT prediction with atmospherical model), an absolute estimation of the OT stratification is fundamental. It has been put in evidence that, at present, measurements provided by the MASS, the unique vertical profiler commonly used so far in the astronomical context to collect continuous measurements over long time scales, present some not negligible uncertainties with respect to the reference which we consider to be the (Generalized-SCIDAR, hearafter GS) in terms of absolute estimates of the strength of the OT in individual layers distributed in the free atmosphere [4–6] and also on the free atmosphere itself [5,6]. This can represent a problem in all applications in which it is crucial to know the location and the OT strength of individual layers such as a few AO systems. A dedicated site testing campaign should be therefore suitable to clarify uncertainties still existent. Besides that, a set of new-generation vertical profilers has been developing in the last years such as the PBL [7] and the CO-SLIDAR [8]. These profilers are supposed to be used as automatic monitors and they in principle should achieve higher resolution than the classical profilers (GS, MASS and SLODAR) in the free atmosphere but it would be useful to validate them using the GS as a reference. Without entering in the details of each technique that can be found in the respective main references, we remind that the PBL principle is based on the observation of the moon limb through two apertures separated by a distance of ∼ 30 cm and on the calculation of the differential covariance of the angle of arrival fluctuations of the wavefront between a continuum set of couples of points selected on the two images that permits therefore a vertical resolution proportional to the separation between the couple of points. The CO-SLIDAR technique is based on the simultaneous calculation of the inter-correlations of the wavefront slopes and the scintillation indices, both recorded in Shack-Hartmann images of a binary star. Up to a height $H_0 = D/\theta$ where D is the pupil of the monitor and θ is binary separation, the C_N^2 profile is retrieved on the first km from the inter-correlation of slopes and then from those of scintillation indices. Above H_0 the auto-correlation of the scintillation produced by just one star permits to retrieve the complementary part of the C_N^2, provided the Fresnel length is sampled on several points at the sub-aperture scale. We precise that there are also other new-generation vertical profilers that could reach higher vertical resolution with respect to classical profilers and that have been studied in the recent years such as the Stereo-SCIDAR [9]. This instrument is however more useful, at our opinion, for dedicated experiments and not for automatic monitoring of the whole 20 km because of the size of the telescope it requires is $D \geq 1$ m. It has, in any case, the positive quality to be based on the solid principle of the GS technique and to achieve higher vertical resolution with respect to the GS on selected vertical slabs in the atmosphere. The main goal of the campaign we propose is to conceive a set of instruments running simultaneously in order to be able to cross-correlate measurements to validate new-generation instruments and to try to correct biases in classical vertical profilers where this is possible or to define/limit the fields of application suitable for these instruments where it is not.

The scheme of the contribution is the following. In Section 1.1 and Section 1.2 we describe the most important requirements in the fields of the AO and the OT prediction with non-hydrostatic atmospherical model. In Section 2 we review the physical conditions that permit us to achieve different vertical resolution using the technique of the Generalized SCIDAR, an instrument that can be considered a reference in our context. In Section 3 we describe the goals of the site testing campaign we propose and the strategy to carry out that. In Section 4 we summarize the most important conclusions.

1.1 AO main requirements

The typical specifications we are considering for the ELTs assume a pupil size D of the order of 30-40 m and a sub-aperture of the AO correctors *d* of the order of 50 cm.

We consider three different classes of AO systems classified depending on their constraints in terms of vertical resolution of the C_N^2 profiles we need to know for their optimization:

- **LTAO:** technical FOV 1-2arcmin - Δh=862m (Δh=670m @20km for Na LGS)
- **MCAO:** technical FOV 2-3arcmin - Δh=579m (Δh=450m @20km for Na LGS)
- **MOAO:** technical FOV 5-10arcmin - Δh=172m (Δh=134m @20km for Na LGS)

Where in all cases Δh is calculated for the largest FOV. These values are calculated following simple geometrical rules i.e. $\Delta h = d/\theta$ where θ is the field of view and *d* is the sub-aperture. For the LGS case the Δh values are slightly smaller at h = 20 km as indicated in the summary just reported. Obviously these Δh have to be considered as order of magnitude because the definitive Δh for each specific instrument depends also on other factors such as the required Strehl Ratio, Ensquared Energy, field of view uniformity, operating wavelength,... The strongest

constraints are obviously those related to the MOAO because associated to the widest field of view. In order to estimate with a higher order of accuracy the values of Δh for this specific AO system, dedicated simulations using an end-to-end code [10] are on-going in the context of the LESIA-Durham [1] collaboration on a multi-object spectrograph (MOS) for the E-ELT.
We highlight that in principle it should be useful to define constraints for Δh for the three different contexts:
(A) Δh required for numerical simulation to design and evaluate the performance of future AO systems.
(B) Δh required on site to run a given AO system with 'optimal' performance (this Δh may be provided by the system itself).
(C) Δh required on site to plan typology of AO system and typology of observation (flexible-scheduling). For this last item predictions with non-hydrostatic atmospherical models are crucial. Real-time measurements are not really useful.
The constraints might be not necessarily the same in the three contexts and, in some cases, they could be relaxed. We consider here the strongest constraints because we are interested in investigating the maximum vertical resolution required.
Additional requirements valid for all AO systems are the estimation of:
1a) Dome seeing (dome and telescope tube)
2a) Temporal variability of the relative intensity of each layer in the range [0,20km] a.g.l
- at short time scale: 16mHz (1min)
- at long time scale: 1mHz (15min)
3a) Temporal evolution of the wind speed vertical profiles on the [0,20km] range with a vertical resolution of Δh $\sim$ 1km. In perspective we can figure out a Δh achieving the same vertical resolution of the C_N^2 (h).
4a) Vertical profile of the outer scale $\mathcal{L}_0$(h) on [0,20km] range (Δh $\sim$ 1km)

1.2 OT predictions with atmospherical models main requirements

Measurements are an important element in the field of the OT prediction performed with non-hydrostatic atmospherical models (hereafter OTPAM). Measurements are indeed useful to calibrate and validate the model. Also they are useful to refine the model performances and quantify figures of merit of the efficiency of the models. Among the requirements in this field we remind:
1b) the estimation of the absolute value of OT stratification and of the integration of the OT along the whole atmosphere obtained by different instruments (vertical profilers and instruments based on integrated estimations).
2b) the availability of rich statistical samples of measurements of the different astroclimatic parameters performed by different instruments running simultaneously. At least one of these instrument need to be a vertical profiler covering the [0,20km] range a.g.l. This condition is mandatory otherwise it is not possible to disentangle between measurements discrepancies due to natural and intrinsic uncertainty of turbulence inhomogeneity and biases introduced by instruments.
3b) the access to OT measurements retrieved from AO systems i.e estimations of the optical turbulence affecting directly the focus of the telescope. These measurements are in general ancillary outputs of the AO system that can be, however, useful to be compared with the atmo-

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spherical models to better constraint them.
4b) the estimation of the finite size of the horizontal homogeneity of the OT as a function of the height a.g.l. Without this estimation it is strictly useless to use, for example, a DIMM located at a distance larger than the size of the horizontal homogeneity of the OT as representative measurement of the OT status at the focus of telescopes. This estimation is fundamental for the OTPAM to guarantee the reliability of whatever measurements taken as a reference in the context of a model against measurements comparison.
5b) the access to measurements of classical meteorological parameters near the surface (from Automatic Weather Station).
6b) the access to measurements of the vertical stratification in the boundary layer (1 km above ground) at high vertical resolution (from a few tens of meters up to 100 m) with preferably two different vertical profilers.
7b) Measurements of the solar radiation, ground heat flux and the sensitive heat flux performed above the site.
Many of these requirements are absolutely 'general requirements' fundamental not only for the OTPAM but also for many AO applications.

2 Vertical resolution

At present there does not exist a vertical profiler that can be used as an automatic monitor for the OT that is able to achieve a vertical resolution of the order of 100-200 m on the whole [0,20km] a.g.l range. A GS can achieve such a resolution ΔH [11]:

$$\Delta H = \frac{0.78\sqrt{\lambda |h - h_{gs}|}}{\theta} \tag{1}$$

where λ is the wavelength, h the height above the ground, h_{gs} is the conjugated plane underground and θ the binary separation, provided a suitable telescope pupil size (D) is used. Indeed, assuming a typical h_{gs} of the order of - 2km one has to select binary stars with different separations (θ) to be able to retrieve C_N^2 profiles all along the whole 20 km (H_{max}) depending on the pupil size D. If we fixed the pupil size D and we are interested in reconstructing the C_N^2 profiles along the whole H_{max}, the maximum binary separation θ_{max} is defined as:

$$\Theta_{max} = \frac{D}{H_{max}} \tag{2}$$

In other words, for each pupil size D, one has to associate a specific value of θ_{max}. Table 1 reports the values of θ_{max} for different pupil size D. Fig.1 shows the vertical resolution achievable by a GS for different telescopes pupil sizes assuming h_{gs}= - 2 km. Looking at Fig.1-right one can note that, to achieve a ΔH of the order of 100-200 m one has to consider pupil size D > 4 m and preferably of 8 m. It is obviously not conceivable to use a GS as an automatic monitor on a 8 m class telescope for systematic monitoring. However, the GS can provide fundamental measurements of reference to test other techniques that are under study in these last years.

Table 1. Maximum angular separations achievable so to maximize the vertical resolution and to be able to reconstruct a C_N^2 profiles extended on the whole 20 km.

Pupil Size (m)	Angular Separation (arcsec)
8	80
4	40
2.5	25
1.5	15

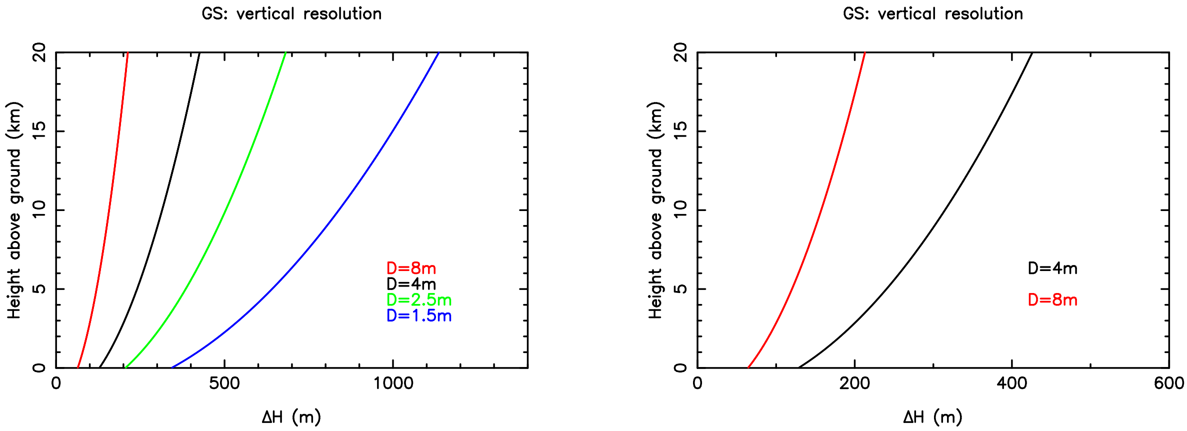

Fig. 1. Left: Vertical resolution at different heights for different telescope pupil size. Right: Zoom of Fig.1-left but with a different dynamic on the X-axis.

3 Site testing campaign strategy

The first main experience (site testing campaign) we propose is centered on two major issues:
(1) we intend to achieve the OT absolute estimation (with relative uncertainty σ) obtained with classical and new generation vertical profilers on the [0-20] km range. This means to calculate the cross-correlation of measurements provided by different instruments.
(2) we intend to validate instruments (vertical profilers) that can achieve C_N^2 profiles at high vertical resolution (~100-200 m) on the [0-20] km range.

The criteria used to conceive the first experiment and the instruments we intend to run are:
(a) all instruments have to be located at the same height above the ground (so to be able to monitor the same portion of atmosphere and to be able to compare measurements) and at short distance among them;
(b) the sequence of stars observed by the different instruments during each night should be done so that all instruments look at the same direction on sky during the night or at least inside a cone of width preferably of ± 10°. The line of sight should be preferably the zenith (or a cone of width ± 10° around zenith).
(c) minimum number of night for a statistical study: 15 nights in summer and 15 nights in winter;
(d) we intend to employ a couple of classical vertical profilers (GS [12] and SLODAR [13]) whose physical principle on which are based on has been already validated and they are widely used worldwide. The GS can be reasonably be used as a reference;

(e) the new generation vertical profilers to be validated are the CO-SLIDAR [8] and the PBL [7], ... ; [2]
(f) we envisage to use also a MASS-DIMM [14]. The DIMM is useful as a further reference value in terms of integrated turbulence on the whole 20 km. The MASS has been used so far in an extended way in the astronomical context particularly for site-testing being the unique automatic monitor for the OT stratification but some systematic uncertainties have been identified [5] with this instrument in terms of vertical distribution of the turbulent energy. It is important to include the MASS in the set of instruments to better investigate these problems and increase the statistic of simultaneous measurements with a GS;
(g) it should be suitable that, during the experiment, AO instruments able to provide vertical profiles of the C_N^2 run simultaneously to the other instruments conceived for the OT studies and monitoring.
Selected candidates:
Cerro Paranal (VLT, D = 8 m) and Roque de los Muchachos (WHT, D = 4 m):

- Cerro Paranal
Pros:
(1) a GS at the focus of a 8 m telescope would achieve the required vertical resolution of the order of 100-200 m.
(2) Measurements could be rapidly be used for testing the OT prediction in the context of MOSE project (it is already configured for the Cerro Paranal).
Cons:
(1) the allocation time on a 8 m class telescopes is more critical but not impossible. It should be extremely useful to have an independent channel in the active optics system of one UT to be able to run instruments for dedicated experiments addressed to the OT studies without affecting the normal scientific use of the UT for astrophysical observations.

- Roque de los Muchachos
Pros:
(1) the instrument CANARY [15] is available at the WHT. CANARY is the MOAO demonstrator that in principle can also provide information on the OT vertical distribution. A campaign at the WHT should permit to include in the goals also the cross-calibration of CANARY measurements.
(2) We already have a logistic plan for the disposition of the whole set of instruments.
Cons:
(1) we should achieve a lower vertical resolution of the order of 200-400 m.
(2) the measurements of the campaign should not be rapidly usable for OT modeling. Some more time is required to configure the model for this site.

4 Conclusions

In this contribution we present a first and preliminary structure for a roadmap for a new era turbulence studies program applied to the ground-based astronomy supported by AO. We also

[2] Other instruments, apart this baseline first list, might be taken into account provided they fit with the general framework and the logistic constraints.

present a concrete proposition for a first experiment to be carried on with several classical and new-generation instruments for OT characterization and aiming at obtaining answers to some specific requirements for the AO and the forecast of the OT with non-hydrostatic atmospherical model. The analysis has been developed in the context of a working group set-up around one year ago and constituted by several teams working in the field of the OT characterization and in the wide-field AO. We identified two sites (Cerro Paranal (Chile) and Roque de Los Muchachos (La Palma, Canary Islands)) to carry out such a campaign. The two possible solutions present some pro and contro aspects. The two solutions are however, independent, and, in principle, they can both be carried out. To finalize the plan it should be important to obtain results of simulations to be done with the end-to-end code [10] by the LESIA-Durham team to quantify more accurately the Δh for the MOAO case. These are planned in the context of a MOS for the E-ELT and they are important to better define the size of the vertical resolution in the case having the strongest constraint. We think that it should be particularly important to consider seriously the realization of an independent channel for OT experiments on one UT as described in Sec.3. The selection of the UT (one over fours) should be done, preferably, taking into account the possibility to equip the neighboring of the telescope with further temporary instrumentations for dedicated experience on the OT.

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