ANALYSIS TOOLS FOR THE CALIBRATION AND COMMISSIONING OF THE AOF

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Abstract. The Adaptive Optics Facility (AOF) is an AO-oriented upgrade to be implemented at the UT4 in Paranal in 2015, and which could serve as a test case for the E-ELT. Counting on the largest Deformable Secondary Mirror ever built (1170 actuators) and on four Na laser side-launch telescopes, the AOF will operate in distinct modes (GLAO, LTAO, SCAO), in accordance to the instruments attached to the 2 telescope Nasmyth ports (GALACSI+MUSE, GRAAL+HAWK-I) and to the Cassegrain port (ERIS). Such modes will be extensively tested on the dedicated bench ASSIST at ESO Headquarters.

Tools are under development to allow an efficient testing of important parameters for these systems when at commissioning and for posterior assessment of telemetry data. These concern the determination of turbulence parameters and $C_n^2$ profiling, measurement of Strehl and ensquared energies, misregistration calculation, bandwidth & overall performance, etc. Our tools are presented as Graphical User Interfaces developed in the Matlab environment, and will be able to grab through a dedicated server data saved in SPARTA standards. We present here the software tools developed up to present date and discuss details of what can be obtained from the AOF based on simulations.

1 Introduction

Telemetry data can provide a vast source of diagnostics for adaptive optics systems [7]. They allow a real-time and/or posterior evaluation of the system performance and a glimpse on the nature of the turbulence at the observing site. In the design phase of an instrument it provides constraints on the optomechanical demands of the system (such as actuator stroke, number of correcting elements, etc). In the functioning phase it allows to optimize the system in order to get the highest possible Strehls and ensquared energies (EE) by, for instance, loading optimized control matrices. This may be particularly true in the case of wide-field AO systems such as LTAO: knowing details of the turbulence distribution in altitude allows to improve the correction in pre-determined directions other than the ones probed by the sensors. Telemetry also allows to test in real-time the misregistrations of the system, as shown in [8].

Assessment of the resulting science image quality is another path to optimizing the system. Reliable tools to obtain parameters such as Strehl, EE and Full-Width at Half Maximum (FWHM) allow to fine-tune the calibration, to decrease the intrinsic aberrations and therefore to test new AO algorithms/control schemes.

Most AOF sub-systems are currently under tests in ESO-Garching. The tools mentioned above are envisaged to be used initially with simulations and the ASSIST bench, in order to corroborate their reliability. Details on the current project status can be found in [1].

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2 Calibration Tools for the AOF

In this section we describe the software tools that have been developed so far in the context of the AOF calibration and commissioning work. In section 2.1 the tool for assessing the image quality in the field-of-view of the AOF cameras is briefly described. Section 2.2 describes the tools for turbulence parameters estimation.

2.1 Strehl/EE/FWHM Parameters Estimation

The AOF sub-systems cameras require a dedicated tool to evaluate the performance of the system. These refer to the tip-tilt sensors, GALACSI commissioning camera and IRLOS, as well as the CAMCAO and HAWK-I for GRAAL laboratory tests and sky observations, respectively.

The so-called ”Strehl-O-Meter” was originally developed in the context of MAD for analyzing CAMCAO 2048x2048 pixel² images. It was coded by E. Marchetti in IDL. The GUI tool, translated into Matlab in order to facilitate its use during the AOF commissioning, includes currently the following features:

– Gradient level and background subtraction;
– Star finding routine - adapted from the IRAF task daofind - along with some rejection algorithms;
– Possibility to select/de-select objects from the image for the analysis;
– Centroid calculation;
– Theoretical profile fitting (Gaussian/Moffat);
– Strehl calculation;
– Ensquared energy calculation;
– Save results in a text file / export variables to Matlab workspace; Build contour maps of estimated parameters.

A snapshot of the first version of this GUI is shown in Figure 1. The tool is now undergoing modifications to accommodate specifications of the AOF cameras. These include the ability to estimate parameters such as Strehl and ensquared energies in coarsely sampled images.

2.2 Turbulence Parameters Estimation

Telemetry data consist basically of slopes and commands recorded simultaneously by the RTC during the system operation. Along with the - measured or modeled - zonal interaction matrix (M) recorded between the DSM and sensors, they allow us to analyze the nature of the turbulence. The standard formula for building the pseudo-open loop (POL) slopes from closed-loop (CL) telemetry data is:

\[ S_{POL,i} = S_i + MC_{i-k} \]  

where \( S_i \) and \( C_{i-k} \) refer to residual slopes measured by the sensors and commands in frame numbers \( i \) and \( i - k \), respectively. This delay of \( k \) frames accounts for the interval between the reading of the WFSs signal and application of the commands to the DSM. In open-loop (OL) regime the measured slopes reflect the total turbulence, if possible non-linearity effects can be neglected. OL and POL slopes can then be projected on a Zernike basis, allowing to identify more straightforwardly the contributions of different aberrations and discard those more susceptible to external uncertainties, such as telescope vibrations, tracking errors, etc. Atmospheric
models have a firm prediction of what to expect from the overall behaviour of the Zernike modes variances. As part of a collaboration with ESO, P. Andrade (Porto University) developed an algorithm that fits the Zernike variances expected in a von Kármán model for radial orders \( \geq 2 \), obtaining simultaneously the Fried parameter \( r_0 \) and the outer scale \( L_0 \). The code takes into account corrections for the measurement errors (subtracted through the auto-correlation method explained in [4]) and also for the aliasing effects that occur because of the SVD truncation of the modal interaction matrix. The algorithm has been initially tested with NAOS simulated and observed data and also on the MAD bench, providing estimates of the input simulated/bench \( r_0 \) typically within a 10% error. The outer scale estimation is subject to higher uncertainties and has to be addressed more carefully to decouple effects from the size limitation of phase screen simulations and dataset length, for example.

Tests in the context of the AOF have been conducted through simulations made with the Octopus parallelized code [5]. The maintenance and commissioning mode (MCM) case, a SCAO mode with NGS-like sources, is the first to be tested on ASSIST in the following months as a preparation for the forthcoming GLAO tests with GRAAL. In a first moment, this simplest AOF SCAO mode was also chosen to test in simulations the reliability of the Porto code of obtaining the basic atmospheric parameters in OL and POL.

Another important aspect of turbulence estimation concerns the determination of the atmospheric \( C_n^2 \) profile. The algorithm that was selected to be used on the AOF is similar to the one shortly described in [3] called Wind Profiler. It was originally developed by [9] for use with NGSs and later on adapted by the GeMS team to the LGS case with some additional ingredients. These include a calibration based on a theoretical flat profile and on measured slopes variances, under the assumption of a Kolmogorov model for the atmospheric turbulence. The
algorithm originally designed for the GeMS case was kindly provided by A. Guesalaga (PUC - Santiago) to ESO for adaptation to the AOF geometry (Figure 2).

The main idea behind deriving the relative turbulence profile through this method is to cross-correlate the OL or POL slopes for each pair of wavefront sensors that define a baseline. Assuming uncorrelated turbulence for different atmospheric layers altitudes, the cross-correlation of slopes is the sum of the cross-correlation in each layer, weighted by the local $C_n^2$. Due to the angular distance between the baseline stars, the cross-correlation between their WFS slopes peaks at different distances from the center of the correlation maps. This turbulence footprint on the correlation maps happens until the correspondent projection of the sub-pupils on the metapupil become totally uncorrelated (i.e. for cross-correlations 40 sub-apertures apart in the x/y directions, or 28 in the diagonal directions), defining a maximum altitude to be probed by the profiler. We concentrated here at using only zero time lag correlations, although the use of the delayed cross-correlations - leading to wind information - is also possible. We average the WFSs auto-correlations which give an estimate for the impulse response of the system to atmospheric turbulence. Both the cross-and auto-correlations individual bins are weighted by the inverse of the number of overlapping illuminated sub-apertures. The weighted cross-correlations along each baseline are then deconvolved by the average weighted auto-correlation of the WFSs. By performing a one-dimensional cut along the baseline stars direction for each pair of WFSs - starting at the center of the deconvolved cross-correlation maps and extending to its edges - we get a relative estimate of the turbulence.

We developed a method for calculating the unseen turbulence (i.e. the turbulence above the maximum altitude probed by the profiler) by using an approximate equation derived in [2] for the average angle-of-arrival variances and assuming a value for $L_0^1$. This way we can derive a $r_0$ that reflects the total turbulence seen by the WFSs and compare it to the $r_0$ provided by the profiler, which sees only the turbulence inside a limited range of altitudes. If the former can be trusted and does not suffer considerably from the cone effect, a scaling factor for the obtained $C_n^2$ profile can be derived. For systems such as GALACSI NFM and GALACSI WFM this unseen turbulence calibration should not be significant since the bulk of atmospheric turbulence is likely to be concentrated inside their probed range. GRAAL, on the other hand, suffers considerably

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1 The default value assumed for $L_0$ in Paranal is of 25 m.
from the small dynamical range probed by the profiler, allowing us access just to the very first few kilometers above the ground - however with unprecedented spatial resolution!

Table 1. Maximum altitudes probed by the method at a zenith angle of 30 degrees ($h_{\text{max,HR}}^{Z=30}$ and $h_{\text{max,LR}}^{Z=30}$).

For GALACSI NFM we opted to retain only the HR profile and limit it to a maximum altitude probed by $N_{HR}=20$ bins (higher altitudes should only contain noise, as the bulk of turbulence is contained in the first 20 km from the ground).

<table>
<thead>
<tr>
<th>Mode</th>
<th>$\theta_{LR}$</th>
<th>$N_{LR}$</th>
<th>$h_{\text{max,LR}}^{Z=30}$ [km]</th>
<th>$\theta_{HR}$</th>
<th>$N_{HR}$</th>
<th>$h_{\text{max,HR}}^{Z=30}$ [km]</th>
</tr>
</thead>
<tbody>
<tr>
<td>GALACSI NFM</td>
<td>14.1”</td>
<td>0</td>
<td>-</td>
<td>20.0”</td>
<td>20</td>
<td>24.5</td>
</tr>
<tr>
<td>GALACSI WFM</td>
<td>1.51’</td>
<td>27</td>
<td>12.4</td>
<td>2.13’</td>
<td>38</td>
<td>9.14</td>
</tr>
<tr>
<td>GRAAL</td>
<td>8.20’</td>
<td>27</td>
<td>2.49</td>
<td>11.6’</td>
<td>38</td>
<td>1.76</td>
</tr>
</tbody>
</table>

Table 1 shows the characteristics of each of the AOF wide-field systems and what can be retrieved from the $C_n^2$ profiler. Figure 3 exemplifies the result of applying the algorithm to OL data for these 3 AOF modes. The spatial resolution is mainly dependent on the angular separation of the baseline guide stars ($\theta_{HR}$ and $\theta_{LR}$) and decreases for higher altitudes due to the finite altitude of the Na layer. The output is filtered by $1\sigma$ of the profile noise - estimated from altitudes with small turbulence contribution - and renormalized; the original input layers are resampled to allow a more direct comparison with the results. The overall results are encouraging, and the deviations from the expected values are generally less than 2-3%.

Being GALACSI WFM the intermediate resolution case, we decided to use its OL data to test the overall sensitivity of the algorithm. One of the tests consisted in pushing the limits of the telemetry dataset length and sub-sampling. This study has an impact, for instance, on the computational power needed to run the algorithm in real time and on the storage size in disk for post-processing of telemetry data. Figure 4 shows the statistics of the residuals - defined as the absolute differences between the resampled input and the unfiltered output profiles - for different dataset lengths and keeping a sub-sampling of 1/10 frames (lower-left), and also for keeping the dataset length of 30 seconds - at 1kHz frame rate - with different sub-samplings (upper-left). The plots show that, for a fixed dataset length of 30 seconds, taking one out of every 100-200 frames in the cross-correlation analysis still produces reliable results. On the other hand, reducing the dataset length to less than 15 seconds starts to have an impact on the output profile accuracy.

Among other parameters tested in this mode are also the flux sensitivity on the WFSs and uncertainty in the knowledge of the input Na layer altitude (Figure 4 lower- and upper-right, respectively). Regarding the impact of different LGS photon fluxes on the profile reconstruction the plot shows that the uncertainty reaches an asymptotic limit from 30-60 photons/subaperture/frame onwards, consistent with the baseline of 40 photons/subaperture/frame assumed in the design of the AOF WFSs. The profiler is not highly sensitive to the assumption of the Na layer altitude in the analysis.

A last remark concerns the calculation of the POL slopes in the AOF wide-field corrections. In such cases the correction performed by the DSM is either the result of averaging the information received from the 4 WFSs (GLAO) or of manipulating it in order to optimize the on-axis correction (LTAO). We have verified some discrepancies between the $C_n^2$ profiles ob-
tained through OL and POL data using the same set of phase screens in the simulations. Studies of the linearity behaviour of slopes under these two regimes and DSM edge effects are ongoing.

3 Final Remarks

We presented here some of the tools being developed in the context of the AOF project. The Strehl-O-Meter tool is now under revision to include more specific capabilities and a more flexible use, allowing direct access to its functions and data from the workspace. Other possible sources of uncertainties in the analysis of the $C_n^2$ profiler have also been investigated and will be presented in detail in an upcoming paper. The turbulence profiler and parameter estimation are currently being implemented as functions in the SPARTA environment. We are also conducting an analysis on the possible non-linear behaviour of the WFSs as well as DSM edge effects under OL and CL regimes to assess their impact in the turbulence parameters estimation.

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References

Fig. 3. Results from the $C_n^2$ profiler applied to Octopus simulations of the AOF modes. The plots show a hypothetical case where the zenith angle is zero and the DSM is conjugated to the ground. A filtering of 1σ of the noise was applied to all the data. In NFM the $C_n^2$ normalization is done over the first 20 km, and for both GALACSI modes we applied no unseen-turbulence correction. In the cases shown here, the unseen turbulence contribution to the total turbulence is of 0, 4 and 26% for GALACSI NFM, GALACSI WFM and GRAAL, respectively. Note: in fact, M2 is conjugated to -89 m at the VLT.
Fig. 4. Sensitivity tests carried out with the $C_n^2$ profiler and Octopus simulations. Left: effect of sub-sampling the telemetry data (i.e. using 1/Delay in the computation of the $C_n^2$ profiler cross-correlations) for a fixed dataset length of 30 s acquired at 1kHz (top); effect of reducing the dataset length while keeping the sub-sampling as 1/10 (bottom). Right: effect of inputing an incorrect Na layer altitude in the analysis (top); effect of the photon flux on the detectors (bottom). No noise filtering done here.