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Abstract. We present in this paper the very first on-sky results of full Multi-Object Adaptive Optics (MOAO) LQG control (i.e. all modes, with coupling, controlled with an LQG regulator), obtained in Spring 2013 on the CANARY demonstrator at the William Herschel Telescope (La Palma, Spain). The MOAO on-sky pathfinder CANARY features two AO configurations that have both been tested: single-conjugated AO and multi-object AO with NGS and NGS+LGS, together with vibration mitigation on tip and tilt modes. The successful MOAO results are presented and shortly analyzed in terms of performance and tuning.

1 Introduction

Many concepts of Wide Field AO (WFAO) systems are under development, especially for Extremely Large Telescopes (ELTs) instruments. Multi-Object Adaptive Optics (MOAO) is one of these WFAO concepts, well suited to high redshifts galaxies observations in very wide Field of View (FoV). CANARY is the on-sky pathfinder for MOAO operating at the William Herschel Telescope (WHT, La Palma, Spain) since 2010. We have demonstrated that Linear Quadratic Gaussian (LQG) control was an appealing strategy in this context [Sivo *et al.*(2012)], which moreover provides optimal performance (in the sense of minimum residual phase variance) with respect to the chosen models. It is based on a unified formalism that allows accounting for multi WaveFront Sensors (WFSs) channels, both on Laser Guide Stars (LGSs) and NGSs, and for various disturbance sources (turbulence, vibrations). We present the very first on-sky IR images recorded with full LQG AO. These world premieres have been obtained in Summer 2012 and Spring 2013 at the WHT on the CANARY demonstrator. Two AO configurations have been tested: single-conjugated AO (see [Sivo *et al.*(2013)]) and multi-object AO with NGS and NGS+LGS. These results demonstrate the feasibility of implementing an LQG control for single-conjugated and tomographic AO, as well as the efficiency of our strategy for vibration identification and filtering on tip-tilt. The MOAO results presented in this paper are shortly analyzed in terms of performance, and influence of turbulence conditions and control tuning parameters is evidenced. Note that this very first demonstration has been made possible thanks to a close collaboration between the CANARY teams (Durham University, Observatoire de Paris LESIA-GEPI, IOGS/UP13, ONERA, UK ATC, ING).

The first section presents the structure of the dynamical models used for LQG design. Section 3 presents the chosen perturbation models and their identification. We also illustrate our LQG tab within the graphical user interface (GUI) STYC (the GUI developed at Observatoire de Paris-LESIA). Section 4 presents the MOAO on-sky results. Some perspectives for ELTs and conclusion elements are proposed in Section 5. Also note that references given throughout the paper are limited to contributions directly related to the LQG approach as implemented on CANARY. See, e.g., [Sivo *et al.*(2013)] for a more comprehensive state-of-the-art on LQG control developements in AO.

2 Minimum variance control and dynamical models for LQG control

The control performance criterion to be minimized is the residual phase variance

$$\mathrm{Var}(\phi - \phi^{\mathrm{cor}}) \tag{1}$$

where the correction phase ϕ^{cor} is defined using the influence matrix N as

$$\phi_k^{\mathrm{cor}} = N u_{k-1}, \tag{2}$$

u_{k-1} beeing the Deformable Mirror (DM) command applied during interval $[(k-1)T, kT]$ where T is the frame length. Details on such a formulation for adaptive optics and on the developements below can be found in [Kulcsár *et al.*(2012)]. The optimal control is obtained thanks to the separation principle, which consists in splitting the optimization procedure into two steps: minimum variance estimation of the phase through

$$\hat{\phi}_{k+1|k} = \mathrm{E}(\phi_{k+1} | y_k, \ldots, y_0), \tag{3}$$

and control computation through an orthogonal projection of the phase onto the DM:

$$u_k = P_{\mathrm{proj}} \hat{\phi}_{k+1|k} \tag{4}$$

where the projector P_{proj} corresponding to equation (1) is simply the pseudo-inverse of N. When the stochastic process ϕ_k is obtained as the output of a linear state-space system with Gaussian white noises, the conditional expectation in equation (3) can be computed as the output of a Kalman filter. The state-space system takes the following form

$$\begin{cases} x_{k+1} &= A x_k + v_k \\ y_k &= C x_k + w_k \\ \phi_k &= C_\phi x_k \end{cases}, \; x_k = \begin{pmatrix} x_k^{\mathrm{tur}} \\ x_k^{\mathrm{vib}} \end{pmatrix}, \begin{cases} x_k^{\mathrm{tur}} = \begin{pmatrix} \phi_k^{\mathrm{tur}} \\ \phi_{k-1}^{\mathrm{tur}} \end{pmatrix} \\ x_k^{\mathrm{vib}} = \begin{pmatrix} \phi_k^{\mathrm{vib}} \\ \phi_{k-1}^{\mathrm{vib}} \end{pmatrix} \end{cases} \tag{5}$$

where ϕ^{tur} and ϕ^{vib} are the turbulence and vibration parts of the global perturbation ϕ defined as

$$\phi = \phi^{\mathrm{tur}} + \phi^{\mathrm{vib}}. \tag{6}$$

The state matrix A defines the dynamical behaviour of the perturbation, y_k is the measurement vector, C_ϕ is a matrix that extracts the global perturbation ϕ, w is a white Gaussian measurement noise, and v is a white Gaussian state noise independant from w.

3 CANARY implementation: model building and identification

Both turbulent and vibration models are chosen as auto-regressive models of order 2, as proposed for example in [Sivo *et al.*(2012)]. The turbulence model is described for all modes in each layer as

$$\phi_{k+1}^{\text{tur}} = A_1^{\text{tur}} \phi_k^{\text{tur}} + A_2^{\text{tur}} \phi_{k-1}^{\text{tur}} + v_k^{\text{tur}} \tag{7}$$

where parameters A_1^{tur} and A_2^{tur} are defined such that the temporal Power Spectral Density (PSD) cut-off frequency of each mode corresponds to the theoretical cut-off frequency of a process satisfying the dynamical Taylor hypothesis and the spatial Kolmogorov statistics. The resulting damping factors are then fixed at 0.9, meaning that there is no resonance (see [Sivo *et al.*(2013)] for details). The covariance matrix of v^{tur} is chosen so that ϕ^{tur} satisfies Kolmogorov statistics.

The vibration model for tip and tilt modes has the same structure:

$$\phi_{k+1}^{\text{vib}} = A_1^{\text{vib}} \phi_k^{\text{vib}} + A_2^{\text{vib}} \phi_{k-1}^{\text{vib}} + v_k^{\text{vib}} \tag{8}$$

albeit with damping factors around 0.3, so that the models are resonant, see figure 1. Parameters A_1^{vib} and A_2^{vib} also determine the location of the resonant frequencies, whereas the variance of v^{vib} determines the energy level.

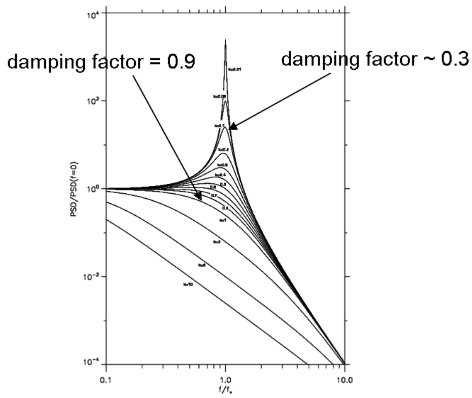

Fig. 1. Spectra of AR2 models with different damping factors. For damping factors greater than $1/\sqrt{(2)}$, there is no resonance.

3.1 Identification for tip and tilt modes

Tip and tilt models for turbulence and vibrations have been identified using the method in [Meimon *et al.*(2010)] based PSDs fits. The method estimates the dynamical parameters needed to build A_1^{vib}, A_2^{vib}, and the tip and tilt parts in A_1^{tur} and A_2^{tur}, together with the power of the corresponding generating noises v^{vib} and v^{tur}. The PSDs are estimated using x- and y-averaged pseudo-open loop slopes from on-sky measurements.

3.2 Identification for higher orders modes

The models for higher modes are build from priors which are the C_n^2 profile, the wind norm in each layer and the geometry of the asterism. All priors have been estimated from on-sky data thanks to the Learn algorithm [Vidal *et al.*(2010)], save the wind norm in each leayer. However, the Learn gave us a global wind value.

3.3 The LQG tab on STYC

The GUI which provides the necessary interface between the bench and the user was developed at LESIA. Thanks to their help, we have developed an LQG tab that gathers all necessary parameters to compute the matrices used in LQG control and to tune the controller according to a given strategy (number of Zernike modes in each layer, tuning of the model measurement noise for the computation of the Kalman gain, choice of any substet of guide stars to evaluate their impact on performance, possible activation of vibration filtering).

The tab is illustrated in figure 2. The blue rectangle gathers the parameters needed to compute model matrices. The green rectangle concerns the vibration filtering method, and the red rectangle contains the push buttons that activate the Kalman gain computation and the transfer to the RTC DARC [Basden *et al.*(2010)] developed by University of Durham. Estimated spectra of tip and tilt are plotted on the side for quick checking (red and black curves correspond to estimations using truth or averaged off-axis NGS WFSs). The console on the far right informs on the progression of the algorithms.

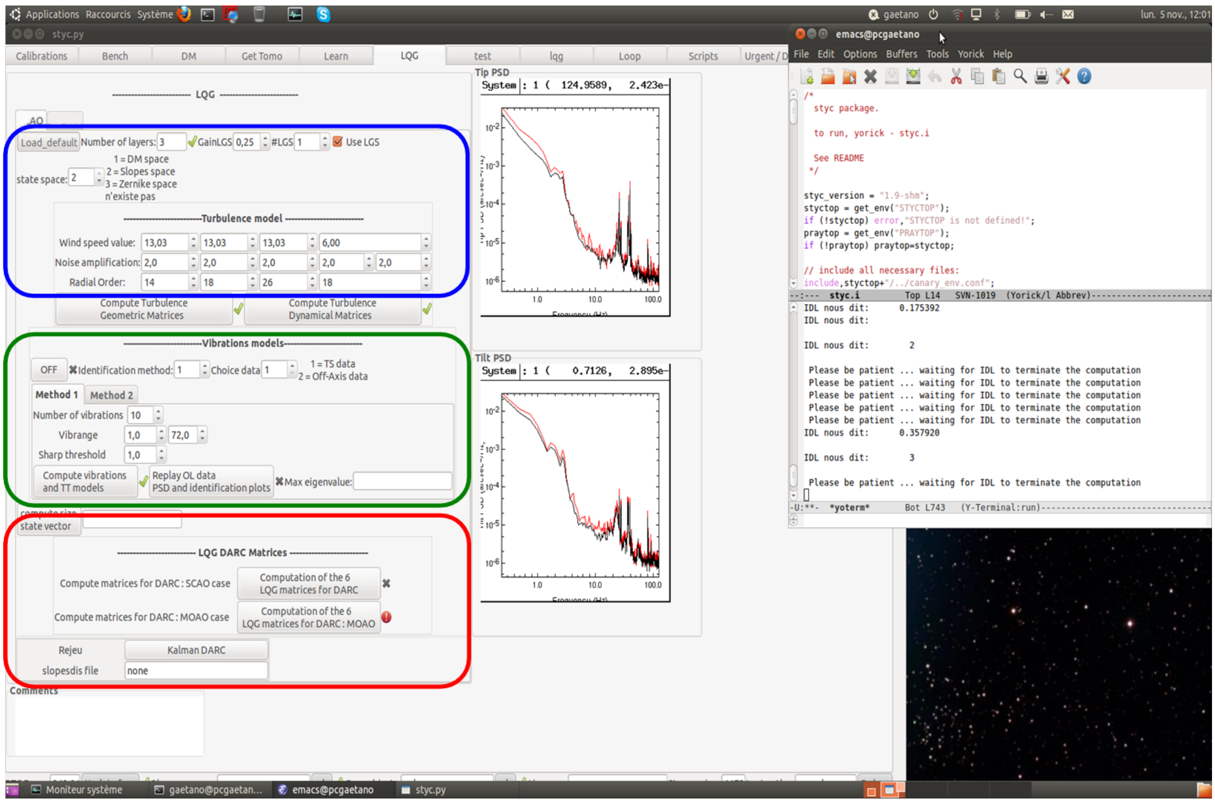

Fig. 2. The LQG STYC tab which allows to load as default values priors identified from the Learn tab, and to define all options of the controller.

4 MOAO on-sky preliminary (and last minute) results

The results presented here have been obtained on 25th May 2013, in a configuration with 4 LGSs plus 3 NGSs WFSs, see figure 3 left, where LGSs are in green and NGSs are circled in red. The maximum separation is here about 2 arcmin, and LGSs are at 20 arcsec from the central star. The loop sampling frequency is $F_s = 150$ Hz. Point Spread Functions (PSFs) correspond to H band (1.55 μm).

The turbulence profile given by Learn corresponds to 3 layers at altitudes 0, 6 and 13 km (see figure 3 middle). The r_0 values versus time given by STYC are plotted in figure 3 (right), where blue circles correspond to Apply tests and red ones to LQG tests. The Apply [Vidal *et al.*(2010),Gendron *et al.*(2011)] reconstruction corresponds to a slopes-based MMSE derived from the turbulence profile priors indentified with the Learn algorithm. It does not use priors on the temporal behaviour of the perturbation, but spatial priors are exactly the same than the ones used for LQG control.

The LQG state vector in this configuration had 1258 components corresponding to two temporal occurences of the total perturbation and two delayed commands (56 actuators each). The computational time for the Kalman gain was less than 3 minutes.

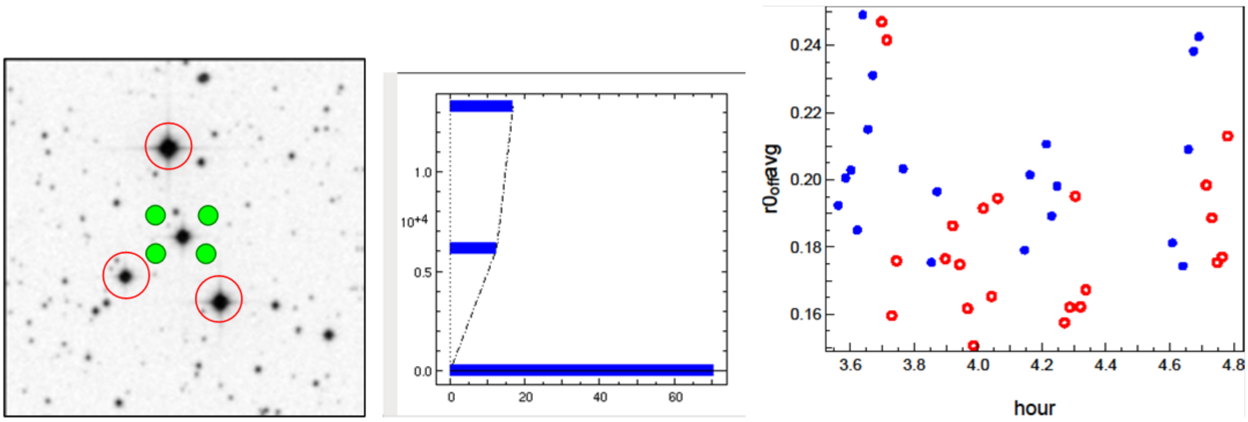

Fig. 3. Left: the asterism with 3 NGS, and the 4 LGSs plotted as green disks. Middle: C_n^2 given by Learn, with layers at altitudes 0, 6 and 13 km and a 70% strength at ground layer. Right: values of r_0 versus time during the run as given by STYC.

Figure 4 presents Strehl Ratios (SRs) obtained with different star configurations, all with vibration filtering. A first comment concerns comparisons between LQG 4LGS+3NGS and LQG 3NGS, which show that the LGS+NGS fusion is efficient, and that the presence of LGS WFS measurements clearly improves performance. The performance gap between LQG and Apply is slightly in favor of LQG control, but the influence of the r_0 value in these results may be not negligible. Another point that worths to be mentioned is the influence of the wind. During this night, we could have access to wind velocities in all layers thanks to the StereoSCIDAR driven by J. Osborn from University of Durham [Osborn *et al.*(2013)]. These values were rather high (30 m/s in high altitude layers), meaning that phase prediction may bring more in terms of performance than in situations were the wind velocity is very low. Further data reduction and behaviour analysis are still in progress, but these preliminary results show that LQG control is efficient and are extremely promising in terms of overall performance.

5 Some conclusions

Myth busting (inspired from Olivier Guyon's talk) may be required in order to revisit some comments or appreciations encountered about LQG control:

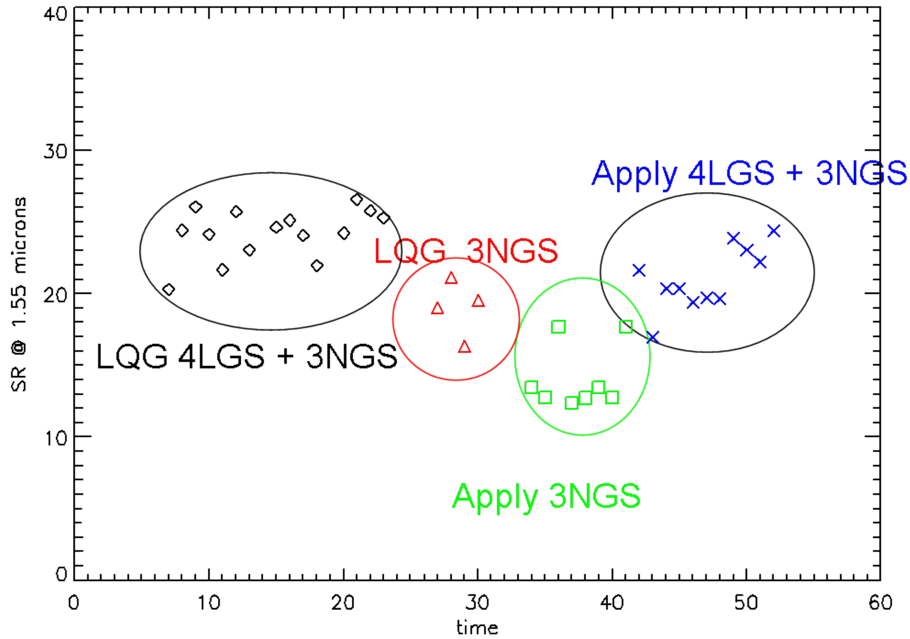

Fig. 4. MOAO Strehl Ratios (SRs) for the 25th May 2013 run. Results are obtained with various configurations that are indicated by different colors. LQG control includes vibration filtering. The $r0$ variation corresponding to these records is plotted in figure 3 right.

- "It will never work (too many priors and heavy computations)": sensitivity to priors appeared to be reasonnable. For example, while the wind norm was set by rule of thumb, this has not led to any disaster. The fact that models are build on priors and that it works rather well also means that the Learn algorithm did a good job! As for the off-line computations, the heaviest calculations were obtained with 2000 components in the state vector, leading to 6 mn of computing time for the Kalman gain on a standard computer with a non optimized code.
- "It will never work (LQG control is not robust)": we never encountered any robustness issue. In fact, as the control is obtained with a simple orthogonal projection, stability margins are similar to those of the Kalman filter, see [Sivo *et al.*(2013)] for a detailed analysis in the context of SCAO.
- "It will never work (too complex for real-time computation)": the RTC DARC developed by University of Durham is designed to offer a good compromise between speed and flexibility. In this regard, we have tested up to 2000 components in the state vector without any real-time computation problem.

A nice feature of these model-based controllers is their high flexibility to various single conjugated or wide-field AO configurations. The ability to account for specific disturbances like vibrations [Petit *et al.*(2009),Correia *et al.*(2012)] or very slow low-order turbulence and windshake is also very interesting [Conan *et al.*(2011)].

The extension of such control laws for ELTs is however not straightforward. However, large number of degrees of freedom have been tackled in an AO LQG context, see for example [Correia *et al.*(2010),Massioni *et al.*(2011),Gilles *et al.*(2013)]. The tricky part is obviously to keep flexibility and performance, together with a highly parallelizable algorithm.

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