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### ► To cite this version:

Baptiste Siquin, Caroline Kulcsár, Léonard Prengère, Henri-François Raynaud, Eric Gendron, et al.. Data-based modelling of low-order modes for AO control: what do on-sky experiments tell us?. COAT-2019 - workshop (Communications and Observations through Atmospheric Turbulence: characterization and mitigation), ONERA, Dec 2019, Châtillon, France. 10.34693/COAT2019-S3-002 . hal-03146244

**HAL Id: hal-03146244**

**<https://hal.science/hal-03146244>**

Submitted on 18 Feb 2021

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# Data-based modelling of low-order modes for AO control: what do on-sky experiments tell us?

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## ABSTRACT

It is well-known that data-driven models for the tip-tilt modes significantly improve the performance of Adaptive Optics (AO) systems as it allows to compensate for vibration-induced disturbances. Whether identifying from data the temporal dynamics of more modes makes an impact on the performance has been studied on-sky with the CANARY demonstrator at the William Herschel Telescope in July 2019. In this brief paper, we report on these experiments using both Strehl ratios computed from the science camera in H band or by replaying the AO telemetry data in numerical simulations. We show that Linear Quadratic Gaussian (LQG) controllers that embed a data-driven model for the low-orders (that are not limited to the tip-tilt) improve the performance of the AO for two different dynamical behaviours of the atmospheric turbulence.

**Keywords:** adaptive optics, Linear-Quadratic-Gaussian control, Kalman filtering, subspace identification, turbulence modeling, on-sky validation

## 1. INTRODUCTION

The disturbance that reaches an AO system for a ground-based telescope is not only induced by the atmospheric turbulence but also by dome turbulence and vibrations, that all contribute to poor Strehl ratios without a dedicated controller. The integrator has soon become a standard for its simplicity and for its good rejection of the lowest temporal frequencies. Linear Quadratic Controllers (LQG) produce rejection transfer functions that allow to better shape the inverse of the turbulence Power Spectral Density (PSD). This enables to compensate for a wide class of perturbations with the aim to reduce the temporal error and achieve better performance.<sup>1</sup> For example, vibrations are in general amplified by the standard integrator whereas LQG controllers that include a data-driven model on the tip-tilt efficiently correct these additional disturbances<sup>2,3</sup> The disturbance model that is used in such controllers should represent as accurately as possible the actual perturbation viewed by the sensor. Auto-regressive models of order two that depend on the wind speed and the seeing have been proposed and tested on-sky.<sup>4</sup> They represent a boiling behaviour of the turbulent atmosphere. There remains nonetheless unmodelled disturbances that are not captured by the model structure, for example dome turbulence (whose statistics are likely to be different) and frozen-flow. Whether using AO telemetry to model the temporal dynamics of more modes than only the tip and tilt would further improve the AO performance is investigated here.

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In this paper we propose to report on the on-sky experiments from July 2019 on the CANARY demonstrator<sup>5</sup> at the William Herschel Telescope (WHT) on La Palma, Canary Islands, Spain.

The paper is organized as follows. Section 2 details the LQG controller and Section 3 shows first on-sky results. Conclusions are then drawn.

## 2. THE LINEAR-QUADRATIC-GAUSSIAN CONTROLLER

The LQG controller minimizes the residual phase variance over an infinite time horizon,<sup>6</sup>

$$\min \lim_{K \rightarrow \infty} \frac{1}{K} \sum_{k=1}^K \|\phi_k^{\text{res}}\|_2^2. \quad (1)$$

The disturbance viewed by the sensor is the difference between the disturbance  $\phi$  and the one induced by the deformable mirror  $\phi^{\text{cor}}$ . The control commands are applied to the quasi-static mirror with a delay of one frame due to the zero-order hold, such that at time instant  $k$ , the correction wavefront is expressed as  $\phi^{\text{cor}} = Nu_{k-1}$ . The LQG cost function then reads

$$J(u) = \min_u \lim_{K \rightarrow \infty} \frac{1}{K} \sum_{k=1}^K \|\phi_{k+1} - Nu_k\|_2^2. \quad (2)$$

We have slightly modified this criterion as in<sup>4</sup> for our on-sky experiments using rather

$$J(u) = \min_u \lim_{K \rightarrow \infty} \frac{1}{K} \sum_{k=1}^K \|D\phi_{k+1} - M_{\text{int}}u_k\|_2^2, \quad (3)$$

where  $D$  is the sensor matrix and  $M_{\text{int}}$  is the interaction matrix. This allows to account for the transformations that occur between the sensor and actuator grids and to rely on the interaction matrix and not on the influence matrix. The control commands are then obtained as

$$u_k = M_{\text{com}}D\hat{\phi}_{k+1|k}, \quad (4)$$

where  $M_{\text{com}}$  is the command matrix and  $\hat{\phi}_{k+1|k}$  is the minimum variance estimate of the wavefront at time instant  $k+1$  using all the data up to time  $k$ , which is provided by the Kalman filter. The key in LQG controller design is the dynamical model used for describing the disturbance. Let the wavefront be expressed in a Zernike basis with 495 modes. We start from the auto-regressive model that successfully demonstrated its relevance on-sky:<sup>4</sup>

$$\phi_{k+1} = A_1\phi_k + A_2\phi_{k-1} + v_k \quad (5)$$

where  $v_k$  is a zero-mean white Gaussian noise with covariance matrix  $\Sigma_v$ . This model uses priors such as the wind speed and the Fried parameter. The temporal dynamics of the first  $n_{LO}$  Zernike modes  $\phi_k^{\text{LO}}$  are modelled with another state-space:

$$\begin{cases} x_{k+1}^{\text{LO}} = A^{\text{LO}}x_k^{\text{LO}} + v_k \\ \phi_k^{\text{LO}} = C^{\text{LO}}x_k^{\text{LO}} + \eta_k. \end{cases} \quad (6)$$

The matrices of this model are directly estimated using the system identification algorithm N4SID<sup>7</sup> on a temporal sequence of reconstructed wavefronts. This method uses Pseudo-Open-Loop (POL) slopes collected before closing the loop. The low-order modes therefore consist of the sum of the two models, one based on priors (5) and the other one that describes low orders (6). The remaining modes (not modelled by (6)) are only modelled through the priors, as illustrated in Figure 1.

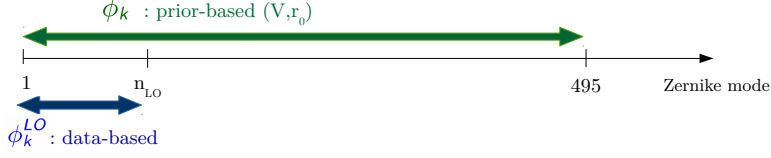


Figure 1. Schematic that illustrates how the temporal dynamics of the Zernike modes are represented, using both or either the prior-based and the data-based model.

The open-loop model of the wavefront sensor yields the slopes  $y_k$  as follows:

$$y_k = \underbrace{\begin{bmatrix} 0 & D & D^{\text{LO}} \end{bmatrix}}_C \begin{bmatrix} \phi_k \\ \phi_{k-1} \\ x_k^{\text{LO}} \end{bmatrix} + w_k \quad (7)$$

where  $w_k$  is a zero-mean white Gaussian noise with diagonal covariance matrix. The Kalman gain  $L_\infty$  is computed by solving the discrete algebraic Riccati equation so that the Kalman filter writes

$$\begin{cases} \hat{x}_{k+1|k} = (A - L_\infty C) \hat{x}_{k|k-1} + L_\infty y_k^{\text{POL}} \\ \hat{\phi}_{k+1|k} = C_\phi \hat{x}_{k+1|k} \end{cases} \quad (8)$$

where  $A = \begin{bmatrix} A_1 & A_2 & 0 \\ I & 0 & 0 \\ 0 & 0 & A^{\text{LO}} \end{bmatrix}$  and  $C_\phi = (I, 0, C^{\text{LO}})$ .

### 3. ON-SKY RESULTS

#### 3.1 Single Conjugate AO control on CANARY

The primary mirror of the WHT has a diameter of 4.2m. The Shack-Hartmann has a  $14 \times 14$  lenslet array leading to 288 x and y measurements. The control commands are applied to a tip-tilt mirror and to a deformable mirror (coupling of 0.45) that has 243 active actuators. The science camera collects photons in the H spectral band. The control frequency was set to 200 Hz.

During this observing run, we have experienced very different atmospheric conditions that could broaden our views on the impact that the data-driven model for the low-orders can have on performance. Note that no vibrations were observed on the data we report here.

We have also performed simulations using on-sky AO telemetry data. The replay mode allows to compare controllers whose performance was not evaluated on sky. In this case, the performance index is the residual phase variance evaluated as the sum of the first 197 modes, which corresponds to the number of mirror modes.

LqgZer-TT refers to the controller in<sup>4</sup> that uses the model based on priors (5) with a tip-tilt data-driven model computed from the mean slopes. LqgZer-LO $n_{\text{LO}}$  refers to the new controller that relies on the Kalman filter (8) and that includes temporal models identified from telemetry data for the first  $n_{\text{LO}}$  modes. LqgZer-LO2 thus differs from the LqgZer-TT from the use of tip and tilt that are reconstructed from data instead of using mean slopes.

#### 3.2 First case: large wind

We report on the experiments from the night of July 17-18th, 2019, between 3h08min and 4h21min (local time). The guide star has a magnitude of 5.2 in H band. Main layers at 0, 2 and 8 km were measured with a wind speed of respectively 12, 15 and 13 m/s using the stereo-SCIDAR.<sup>8</sup>

Figure 2-left shows the residual phase variance as a function of  $n_{\text{LO}}$ . At radial order 1, we indicate with a blue cross the performance on the integrator. As expected, all tip-tilt data-driven models improve performance with respect to the integrator. Also, increasing the number of modes  $n_{\text{LO}}$  in (8) significantly lowers the residual phase variance. The plot on the right-hand-side will be commented in next section.

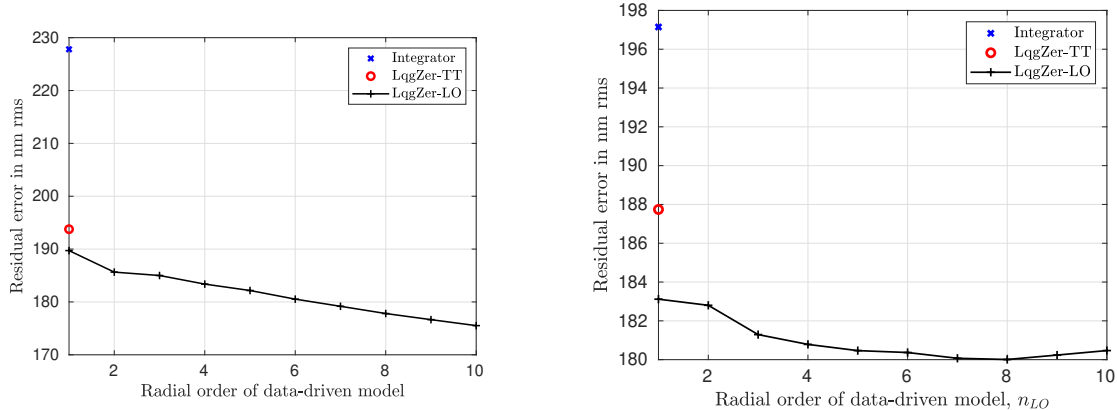


Figure 2. (Replay) Residual phase variance as a function of  $n_{LO}$  for a case with large wind speed (left) and low wind speed (right).

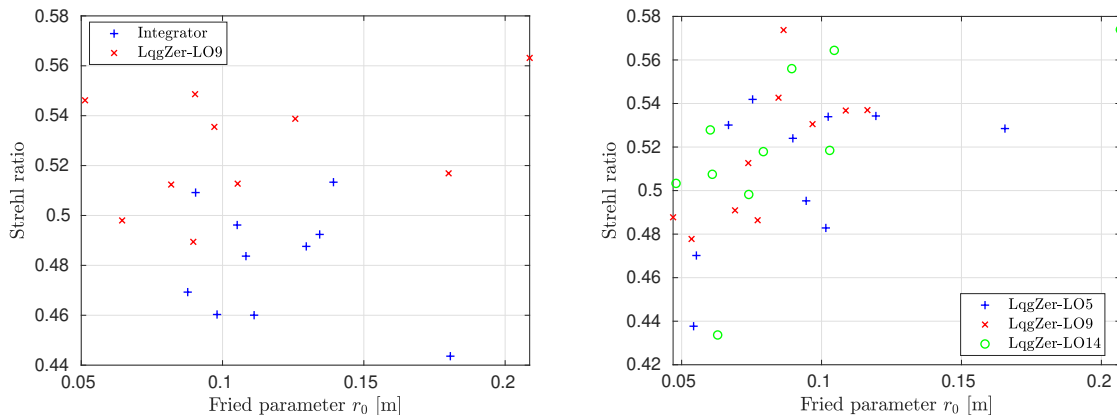


Figure 3. (On-sky) Strehl ratio as a function of the Fried parameter  $r_0$  for (left) the experiments from 4h31 with a comparison between integrator and LqgZer-LO9 and (right) the experiments from 4h51 the same night with a comparison between LqgZer-LO5, LqgZer-LO9 and LqgZer-LO14. One experimental point corresponds to 20 seconds of data recording.

### 3.3 Second case: low wind

This paragraph reports on the experiments from the night of July 20-21st, from 4h31min to 6h. The guide star has magnitude 5.8 in H band. The wind speed at ground level was no more than 3m/s.

An LQG controller featuring a model for the temporal dynamics of 9 modes identified from telemetry data outperforms the integrator, as shown in Figure 3-left. In Figure 3-right, we see that increasing  $n_{LO}$  from 5 to 9 improves the performance while it is less clear for  $n_{LO}$  from 9 to 14 due to the large variability of the atmospheric conditions even for two values having similar  $r_0$ .

Figure 2-right confirms what was observed on-sky: there is a significant improvement with a data-driven model on the 9 first modes rather than on the first 5 ones but increasing  $n_{LO}$  up to 14 has less impact. This trend is very different from the conclusion drawn when the wind speed was larger.

## 4. CONCLUSION

In this paper we have proposed to augment a prior-based disturbance model with a data-driven model to better represent the actual temporal dynamics of the perturbation. This controller was tested on-sky at the WHT using the CANARY demonstrator in order to assess the impact on performance of modelling from data more modes than only the tip and tilt. A gain of performance was evidenced even though no vibrations were detected on these modes. The number of modes  $n_{LO}$  that yields the lower residual phase variance depends very much on the atmospheric conditions, such as the wind speed of the different layers. If the wind speed is large, it was shown that increasing  $n_{LO}$  up to 65 increases significantly the performance whereas it is not necessary to consider so

many modes for a lower wind speed scenario, where 9 modes were enough. A more detailed analysis is to appear in a forthcoming publication.

### Acknowledgements

LQG tools for CANARY have been supported by the Agence Nationale de la Recherche (ANR) French program CHAPERSON ANR-09-BLAN-0162-01 and ANR-10-LABX-0039-PALM. CANARY was supported by Agence Nationale de la Recherche (ANR) program 06-BLAN-0191, CNRS/INSU, Observatoire de Paris, and Université Paris Diderot Paris 7 in France, Science and Technology Facilities Council (Grants PP/E007651/1, ST/I002871/1, ST/K003569/1, ST/M007669/1 and ST/N002660/1), and the University of Durham in the UK and European Commission Framework Programme 7 (E-ELT Preparation Infrastructure Grant 211257 and OPTICON Research Infrastructures Grant 226604). Horizon 2020: This project has received funding from the European Union's Horizon 2020 Research and Innovation Programme under grant agreement number 730890. The William Herschel and Isaac Newton Telescopes are operated on the island of La Palma by the Isaac Newton Group of Telescopes in the Spanish Observatorio del Roque de los Muchachos of the Instituto de Astrofísica de Canarias. This work of James Osborn was supported by the Science and Technology Funding Council (UK) (ST/P000541/1), UKRI Future Leaders Fellowship (UK) (MR/S035338/1) and Horizon 2020.

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