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Joana S Torres, Andrew P Reeves, Caroline Kulcsár, Henri-François Raynaud, Ramon Mata Calvo, Helawae Friew Kelemu

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J. S. Torres [(1,2)], A. P. Reeves [(1)], C. Kulcsár [(2)], H.-F. Raynaud [(2)], R. Mata Calvo [(1)], H. Kelemu [(1)]

Institute of Communications and Navigation, German Aerospace Center (DLR), 82234 Weßling, Germany

{*joana.dosuldamotatorres, andrew.reeves, ramon.matacalvo, helawae.kelemu*}*@dlr.de*

Université Paris-Saclay, Institut d'Optique Graduate School, CNRS, Laboratoire Charles Fabry, 91127 Palaiseau, France

{*caroline.kulcsar, henri-françois.raynaud*}*@institutoptique.fr*

Abstract: Optimal control has been shown to improve astronomical adaptive optics, and is considered in free space optical communication, where signal stability is crucial. Disturbance behavior is characterized, turbulence models are defined and simulations are performed.

1. Introduction

Adaptive Optics (AO) systems, widely used for wavefront correction in astronomy, have recently been proposed for Free Space Optical Communication (FSOC) [2, 6]. However, the turbulence to which the beam is subjected in FSOC differs vastly from the conditions experienced in astronomical applications. Whilst astronomical observatories stand in geographical advantage points, usually above ground turbulence, FSOC requires more versatility in the chosen locations of optical ground stations (OGS) in order to achieve a worldwide broadband connection. This factor will frequently result in fast changing turbulence conditions and operation must be uninterrupted for twenty four hours in the day, so long as the sky is clear of clouds. It is therefore necessary to develop high performance AO controllers that are robust to these conditions, so as to ensure reliable high throughput links. Initial demonstrations of FSOC with AO have been carried out with the use of integral control [2, 3, 6]. The Linear Quadratic Gaussian (LQG) regulator has been considered in astronomical applications, leading to on-sky robust performance and stability [8]. More recently, simulations for satellite imaging have shown a potential dramatic improvement [7] in conditions that closely resemble those experienced in some FSOC links. Research regarding high performance control in FSOC is scarce. Thus, in this work, a disturbance characterization for FSOC scenarios using telemetry data from a horizontal FSOC test range is carried-out. In order to derive realistic simulation scenarios, appropriate turbulence parameters are chosen. These, together with covariances calculated from Von-Kármán statistics, are used to describe different parametric turbulence models for the Kalman filter. From here, different LQG regulators are synthesized and simulated in FSOC scenarios and, along with an integrator, compared for maximization of coupling into a single-mode fiber, minimization of the residual wavefront variance of the signal into the fibre, and reduction of the occurrence and duration of deep fades, in which it is not possible to transmit data at all.

2. Turbulence Characterisation in FSOC scenarios

When considering links with LEO satellites, the telescope tracking movement as it follows the satellite induces an apparent wind, which is expected to cause dominant frozen flow effects. Whilst communication with GEO satellites requires minimal tracking, it is nevertheless a low altitude observation (around 30° from Europe) when compared to most astronomical targets. The appropriate models are expected to consider both frozen flow and boiling turbulence. Lastly, horizontal links travel across mostly ground turbulence, that is potentially strong and fast changing. Boiling is expected to be the dominant effect. A 10.5 km testbed link between a valley and a mountain top in the Bavarian Alps has been selected to emulate the conditions between an OGS and a GEO satellite under worst-case turbulence conditions [2]. Open-loop Shack-Hartmann wavefront sensor (WFS) data analysis from this setup will lead to estimations of r_0 (Figure 1), τ_0 and other relevant parameters [5]. The estimated turbulence parameters will be used to generate covariance matrices from a spatial covariance structure function based on Von Kármán statistics [1, 7]. From the resulting covariance matrices, it is possible to build auto-regressive models where the parameters A_n can be obtained for instance by use of the Yule-Walker equations. For this work, auto-regressive models of order 1 and 2 will be considered, with parameters chosen as in [7] or [8] to account

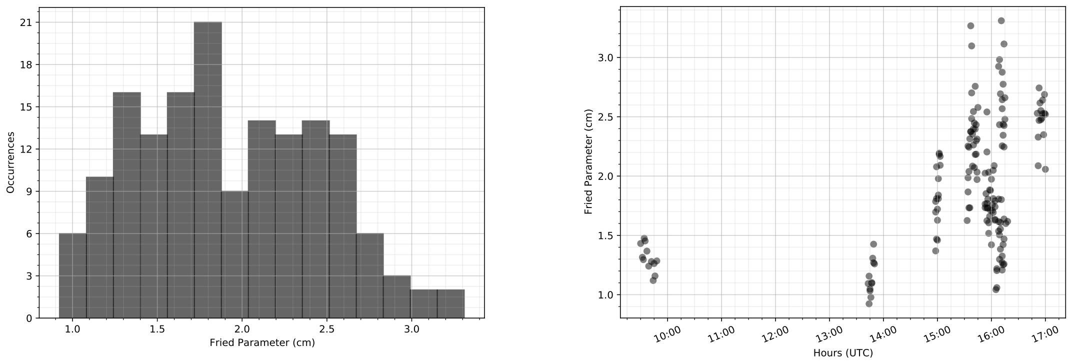

Fig. 1. Histogram of recorded r_0 measurements (left); plot demonstrating the variation of r_0 with time (right), recorded over the course of different days.The site features relatively strong turbulence, with a mean measured r_0 through the day of ≈ 1.9 cm. There is great variation depending on weather conditions, and a trend of stronger turbulence observed in early afternoon (right).

for different FSOC link conditions. In order to achieve good correction, the stochastic dynamical model of the wavefront fluctuations should match the spatial and short-term temporal statistics of the wavefront. The turbulence characterization performed in this work should then be used to derive an adequate model for LQG control.

3. High Performance Adaptive Optics Control Simulations

The LQG regulator has been successfully used in the context of astronomical AO [4, 7, 8]. It is a model-based controller that embeds a Kalman filter, the state-model of which can be built from priors, that can be identified by extracting parameters from AO telemetry data, similarly to the characterization performed in this work. The Kalman filter produces phase predictions that are projected on the actuator space to obtain the commands. To assess the resulting performance improvement, some initial simulations of LQG control for AO FSOC are proposed using the models described in section 2. The performance of the LQG regulators will be compared to that of the integrator in terms of the criteria mentioned in section 1. The simulations will emulate FSOC AO link characteristics, with telescope aperture diameters of the order of one meter, and will include the expected strong and fast turbulence conditions. The results will thus be an important first step into AO for FSOC under fast changing turbulence scenarios, and will serve as a starting point in the design of more complex models for LQG control that are then to be evaluated in simulation and ultimately implemented for on-sky testing.

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