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Turbulence characterization and mitigation with Adaptive Optics systems for laser applications

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Abstract: Imaging and laser delivery system performance is degraded by atmospheric turbulence. The presentation will give an overview of the different tools developed at Onera to assess the complete acquisition imaging chain through turbulence including mitigation techniques.

1. Introduction

Imaging and laser beam delivery system performance is degraded when used over long distances or very close to the ground through the atmosphere. The atmospheric turbulence present along the path disturbs the optical wave propagation inducing in a focal plane of a receiver a degradation of the point spread function (PSF). The shape and the position of this latter temporally evolve leading to intensity fluctuations in the context of laser beam delivery or to the movement, distortion and blur of the observed scene. The degradation of the optical system performance depends on the strength and the distribution of the turbulence (turbulence and wind profiles) along the line of sight.

It is possible to reduce this drop in performance with techniques like adaptive optics (AO) or image processing but their effectiveness is linked to the turbulence conditions encountered. A complete master of the environmental conditions and their impact on system performance including or not turbulence mitigation techniques is the main key to design and experiment optical systems facing to atmospheric turbulence. The performance criterion and the turbulence-induced perturbation depend on the application and the geometry of the line of sight. For example, in case of astronomical observation, the parameter of interest is the optimization of the Strehl ratio and its evolution with the field of view in small scintillation regime; for uplink it is the reduction of the fade statistics in presence of small as well strong scintillation.

Theoretical studies implies simulation tools at different levels, analytical approach whom validity domain is limited to Rytov conditions, simplified models which are more application specific and relevant for sensitivities studies or instrument sizing and physical models which enables to perform a real propagation of the optical waves in all turbulence conditions (strong scintillation in particular) and to asses performance analysis obtained with simplified approaches.

The paper will present some simulation tools and examples of turbulence characterization on experimental data.

2. Simulation tools

2.1. End-to-end reference model

For more than two decades, ONERA has been developing a wave optics model based on split-step method [1]. The turbulence is sampled by a finite number of phase screens. Spherical and plane waves as well Gaussian beams can be considered. The output of this model is directly the complex field of the wave after propagation through turbulence. It is possible to consider small to very strong perturbations as well as coupled effect of pointing jitter and turbulence. They are able to simulate temporal evolution of the field (amplitude and phase) and spatial evolution of the PSF in case of imaging extended objects. The main issue is the sampling (both spatial and temporal) of the physical phenomena. A version with an automatization of the simulation parameters has been realized to perform temporal sequences of intensity fluctuations in the context of optical links between satellite and ground. This model includes adaptive optics correction and correlation between down and uplink to take into account point-ahead angle effect on the pre-compensated uplink. It has been validated on experimental data using as sources both bright stars seen at different elevation angles [2] and optical links provided by an on-board terminal [3]. It allowed also characterizing the turbulence conditions encountered during the collection of the data.

This model serves as reference for the development and the validation of simplified models. A few of them are described in the following sections.

2.2. SAOST

This model provides coupled intensity statistics in a single mode fiber for an optical downlink link with or without adaptive optics compensation [4]. It is based on error budget used for performance assessment of AO system and it

takes into account scintillation effect appearing in the receiver pupil due to strong turbulence effects induced by a low elevation angle (long distance propagation in the atmosphere). It also considers the coupling efficiency in a single mode fiber. It uses analytical models coupled with Monte Carlo simulation, which is less time consuming than wave optics simulation and very convenient for sensitivity studies and during the sizing phase of a ground station. Taking into account reciprocity of the channel [6], it is possible to provide fluctuation intensity statistics in the satellite plane including Point-Ahead angle influence. For example, this tool was intensively used to define the FEDELIO experiment [5], the objective of which was to evaluate the capabilities of a pre-compensated GEO-ground upright link taking into account forward pointing.

2.3. WPLOTT

This tool models the temporal evolution of the beam footprint in the satellite plane by considering the effect of the first orders (tip/tilt, defocus and astigmatism). Contrary to models proposed in literature which focus on fade statistics, it delivers long time series of irradiance fluctuations. Indeed, it allows to generate time series of received flux taking into account point-ahead angle and pointing correction with very short simulation times. It is limited to D/r_0 of the order of 2, D being the size of the emitter and r_0 the Fried parameter. The long time series generated are useful to work on the contributions on interleaving and on error correction codes.

3. Turbulence characterization with experimental data

By using slope and intensity measurement given by the Shack-Hartmann wavefront sensor and their relative correlation between each sub-aperture, it is possible to evaluate the turbulence profile encountered during the collection of the data. An example is presented in the case of a link between a LEO satellite and the ground [3] and for adaptive optics corrected imaging [8]. The comparison with a profile obtained by similitude laws shows a very good match between them. This possibility to evaluate the turbulence conditions along the path during the data acquisition is very valuable to estimate the performance and limitations of the system and to optimize its use according to the real operational conditions.

4. System performance validation

By combining turbulence characterization and performance assessment with model like SAOST, it is possible to understand the behavior of the system in use, the performance degradation induced by strong scintillation or misalignment, or other error source induced by the system environment. An example is presented in [3].

5. Conclusion

The control of the propagation channel including the source and the receiver up to the post-processing, both at the modelling and experimental implementation level, makes it possible to evaluate the impact of turbulence on instrumental performance and to design and develop new reduction techniques that are effective and robust to a great variability of turbulence conditions, in particular in strong scintillation regime, or rapid temporal evolution of the degradations induced by a target or a platform moving at high speed...

This control is based on the development of fine models and dedicated simplified models, validated in real experimental conditions and in the laboratory under controlled conditions.

3. References

- [1] J. Martin and S. Flatté, "Intensity images and statistics from numerical simulation of wave propagation in 3-D random media," *Appl. Opt.* 27(11), pp-2111-2126, (1988)
- [2] N. Védrenne, J.-M. Conan, M.-T. Velluet, M. Sechaud, M., Toyoshima, H. Takenaka, A. Guérin & F. Lacoste, "Turbulence effects on bi-directional ground-to-satellite laser communication systems," in *Proc. Int. Conf. Sp. Opt. Syst. Appl* (Vol. 12) (2012).
- [3] C. Petit, N. Védrenne, M.-T. Velluet, V. Michau, G. Artaud, E. Samain & M. Toyoshima, "Investigation on adaptive optics performance from propagation channel characterization with the small optical transponder," *Opt. Eng.*, 55(11), 111611. (2016)
- [4] N. Védrenne, J.-M. Conan, C. Petit & V. Michau, "Adaptive optics for high data rate satellite to ground laser link," in *Free-Space Laser Communication and Atmospheric Propagation XXVIII* (Vol. 9739, p. 97390E). (2016).
- [5] N. Védrenne, J.-M. Conan, A. Bonnefois, C. Petit, M.-T. Velluet, & V. Michau, "Adaptive optics pre-compensation for GEO feeder links: Towards an experimental demonstration," in *2017 IEEE International Conference on Space Optical Systems and Applications (ICSOS)*, (pp. 77-81), (2017)
- [6] J.H. Shapiro & A. L. Puryear, "Reciprocity-enhanced optical communication through atmospheric turbulence—Part I: Reciprocity proofs and far-field power transfer optimization," *Journal of Optical Communications and Networking*, 4(12), 947-954. (2012).
- [7] A.-R. Camboulives, M.-T. Velluet, S. Poulénard, L. Saint-Antonin, L., & V. Michau, "Statistical and temporal irradiance fluctuations modeling for a ground-to-geostationary satellite optical link," *Applied Optics*, 57(4), 709-721 (2018)
- [8] N. Védrenne, A.B. Montmerle, C. Robert, V. Michau, J. Montri, & B. Fleury, "C2n profile measurement from Shack-Hartmann data: experimental validation and exploitation," in *Optics in Atmospheric Propagation and Adaptive Systems XIII* (Vol. 7828, p. 78280B). (2010)