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Assessment of adaptive optics corrected optical links availability from integrated turbulence parameters by machine learning

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Abstract: We investigate the possibility to evaluate the fading statistics, and thus the availability of an adaptive optics corrected satellite to ground optical link using only four integrated turbulence parameters that are easily measured. © 2022 The Author(s)

1. Introduction

With the tremendous demand for accessing big amount of data in a very short time and the potential saturation of the radio-frequency spectrum, optical links shall become a credible alternative for ground-satellite data transmission. The development of these atmospheric optical links remains conditioned by their availability, which is highly dependent on atmospheric channel (absorption, scattering and turbulence).

High precision availability assessment of the impact of atmospheric turbulence on optical communications is necessary to adequately design the reliability mechanisms (adaptive optics, coding and interleaving) that will ensure an uninterrupted access to high data rate for the user. We investigate here the possibility to assess such high precision availability from atmospheric parameters measured locally with low cost instruments.

In this work, we show that the sole knowledge of integrated parameters of the turbulence profile (C_n^2) and associated wind profile, which can be easily measured with low cost instruments [1], provides us with enough information to entirely describe the statistics of the received optical power (ROP) after an adaptive optics correction. All the following study is done in the case of down-link GEO satellite with an elevation of 30°.

2. Evaluation of the fading statistics from atmospheric parameters

Let $f_{SMF}(t)$ be the coupling efficiency of an adaptive optics corrected optical link into a single mode optical fiber. Under the hypothesis of statistical independence between the phase fluctuation and the irradiance variations [2] we can write f_{SMF} as the product of two independent terms, $\rho_\phi(t)$, the coupling efficiency and $\rho_I(t)$, the term of scintillation. Analytical expressions of f_{SMF} and its distribution under the hypothesis of independence are given in [3]. Following the same logic of separation of effects as in [3], we can study independently the fluctuations of the injection efficiency and the variations of the power collected by the pupil.

Our problem focuses mostly on the low values of $\rho_\phi(t)$ for which the optical link is the most disturbed, and thus on the tail of its distribution. We therefore study $L_\phi(t) = 10 \log_{10}(\rho_\phi(t))$, the loss in power induced by the phase fluctuation in dB.

With a database of over 50,000 turbulence and wind profiles provided by Durham University¹, we can obtain time series of the instantaneous coupled flux in a single mode optical fiber using a pseudo-analytic AO modeling tool called SAOST [4] [5] [3] (Simplified Adaptive Optics Simulation Tool).

Assuming a standard AO system that corrects the first 10 radial orders with a frequency of 2kHz and a telescope with a 60 cm pupil, we have shown that the probability distribution of attenuation neglecting the scintillation ($L_\phi(t)$) follows a Gumbel distribution: $f_{L_\phi}(x) = \frac{1}{\beta} e^{-(z+e^{-z})}$ where $z = \frac{x-\mu}{\beta}$.

We also have shown that using machine learning and more specifically Gaussian process with a Matérn $\frac{5}{2}$ kernel, we are able to predict μ and β using as an input only the moments $\frac{1}{r_0}^{5/3}$, $\frac{1}{\tau_0}^{5/3}$, $\frac{1}{\theta_0}^{5/3}$ and σ_χ^2 . r_0 is the Fried parameter, τ_0 the turbulence coherence time, θ_0 the isoplanatic angle and σ_χ^2 the punctual log-amplitude

¹Profiles computed from ECMWF model over Tenerife for the year 2018.

variance. We obtained a R^2 regression score on the test data-set of 0.9995 on the prediction of μ and 0.999 on the prediction of β .

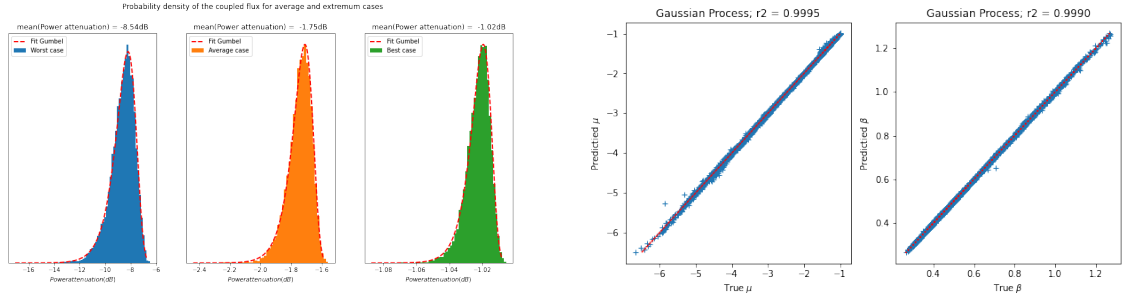


Fig. 1. **Left** : Experimental data of attenuation in 3 cases (worst case, best case and average case) and the associated Gumbel distribution. **Right** : Prediction by Gaussian process vs real values of μ and β using $\frac{1}{r_0}^{5/3}$, $\frac{1}{\theta_0}^{5/3}$, $\frac{1}{\theta_0}^{5/3}$ and σ_χ^2 as inputs.

The normalized aperture-averaged irradiance, under weak irradiance fluctuation hypothesis, can be written as $\exp(2\chi_{AP}(t))$ where $\chi_{AP}(t) \sim \mathcal{N}(-\sigma_{\chi_{AP}}^2, \sigma_{\chi_{AP}}^2)$ is the log-amplitude averaged on the pupil. We can then write the normalized irradiance distribution as the following log-normal distribution [6] :

$$f_{\rho_I}(x) = \frac{1}{2x\sigma_{\chi_{AP}}\sqrt{2\pi}} \exp\left[-\frac{[\ln(x) + 2\sigma_{\chi_{AP}}^2]^2}{2(2\sigma_{\chi_{AP}})^2}\right], \quad x > 0$$

This distribution is described only by one parameter: the variance of the averaged log-amplitude. In these circumstances, predicting the distribution is equivalent to predicting $\sigma_{\chi_{AP}}$, what we are able to do using machine learning with only the moments of the turbulence listed above. The prediction score on $\sigma_{\chi_{AP}}$ is 0.9992.

3. Conclusion and outlook

This preliminary work shows that with the use of easily measurable atmospheric parameters and simple machine learning, the distribution of f_{SMF} can be computed easily as the distribution of the product of two known random variables, $\rho_\phi(t)$ and $\rho_I(t)$ under independence hypothesis.

We looked also at the temporal correlation of the fading. A good approximation of the half-autocorrelation time was obtained using machine learning on the same integrated parameters as before (prediction score of 0.98). Further work is being conducted to fully describe the autocorrelation function and thus have a deep understanding of the fading statistics and duration.

Another improvement will be the modification of the moments calculation to simulate noise and a non-zero instrument pupil size. Tests on real world data will be conducted to measure the impact of the approximations made here and to set the limits of our model.

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