COST
EUROPEAN COOPERATION IN SCIENCE & TECHNOLOGY

SHORT TERM SCIENTIFIC MISSION (STSM) SCIENTIFIC REPORT

This report is submitted for approval by the STSM applicant to the STSM coordinator

Action number: COST CA15127 Action, STSM reference number: 42399
STSM title: Analytical channel modeling and reliability of a FSO communication system operating in different coastal weather conditions
STSM start and end date: 09/01/2019 to 19/01/2019
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PURPOSE OF THE STSM:

The main purpose of the current STSM was investigation of a Free Space Optical (FSO) communication link in the presence of coastal weather based disruptions. In particular, during my STSM, I joined the Atmospheric Optics Group at Department of Communication Engineering, University of Malaga, Spain and worked together with Prof. Antonio Jurado-Navas over evaluation of a FSO system performance in the presence of coastal atmospheric conditions. The maritime (coastal) fog was already well considered in the literature and during various measurement campaigns. Therefore, the main focus of the current work was on turbulence effect which is caused by random changes of the atmospheric refractive index. This leads to deformation of the transmitted optical beam and significant signal attenuation respectively. Having in mind this issue, the undertaken research considered terrestrial and ground-to-space FSO channel characterization, which involved two different cases of the chosen atmospheric turbulence statistical model. A special focus was put on the newly developed Malaga and Gamma-Gamma turbulence models. In particular, based on Gamma-Gamma model of the received intensity and Meijer G-functions, the outage probability in the presence of different turbulence conditions was derived. The statistical design approach was supported with real maritime atmospheric data. In other words, this analysis directly addresses the availability parameter of a FSO system in the presence of coastal weather conditions typical for Mediterranean climate. Consequently, the current analysis is fully related to Working Group 2 (WG2), which main goals are to investigate the reliability and availability of FSO communication systems in the presence of various weather based disruptions. *In addition, the carried out research can be considered as an important contribution to our book chapter "Free Space Optics system reliability in presence of weather-based disruptions". The provided detailed analysis of the outage probability of FSO communication link operating in atmospheric turbulence environment will be considered in the book chapter. Moreover, until this point the draft version of the book chapter, takes into account only the terrestrial FSO link operating in specific continental weather conditions without including the coastal one.*
In conclusion, the current completed STSM in frame of the COST action RECODIS is very narrow related to Working Group 2 and our book chapter "Free Space Optics system reliability in presence of weather-based disruption", which main objectives are to investigate and increase the reliability of end to end communication links in the presence of different atmospheric distortion problems.

DESCRIPTION OF WORK CARRIED OUT DURING THE STSMS

My research stay in the Atmospheric Optics Group of University of Malaga includes intensive work regarding the impairments of FSO communication link due to atmospheric turbulence. This also includes daily discussions with Prof. Antonio Jurado-Navas *and his colleagues. I also gave a talk regarding my current and* previous research in terms of weather based disruptions influencing the FSO communications. In particular, the main accomplished work is described with the following block diagram.

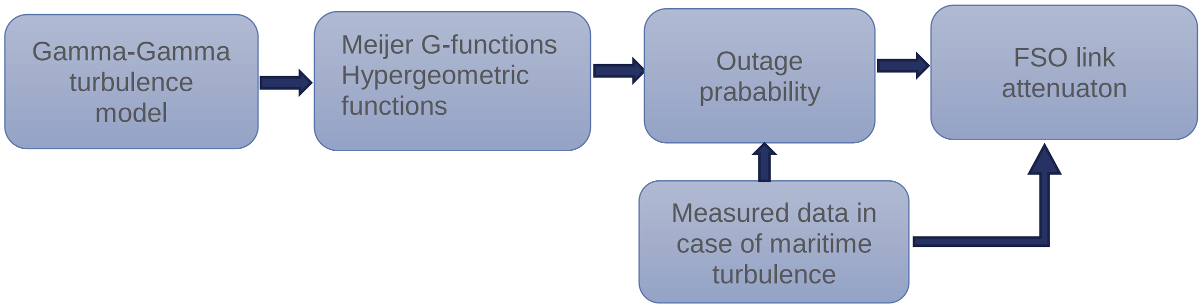

Fig. 1

The shown diagram considered the following important tasks which were accomplished:
1) Good overview over the most prominent fade statistical models used to investigate the performance of a FSO system in terms of atmospheric turbulence conditions. Together with the well-established atmospheric Gamma-Gamma and log-normal turbulence models, also the newly developed Malaga distribution was considered [1].
2) Based on Gamma - Gamma turbulence model, the outage probability of a FSO system operating in coastal atmospheric turbulence weather conditions was investigated. The outage probability was derived based on Meijer G-functions and Hypergeometric mathematical functions.
3) All simulations are accomplished based on MATLAB Development Environment
4) A theoretical comparison between costal and terrestrial atmospheric turbulence conditions was accomplished. The several available sources shows the difference in turbulence spectrum between terrestrial and maritime climate. The spectral models of refractive-index fluctuations regarding terrestrial and maritime turbulence are shown in Fig. 2 which is provided in paper [2].

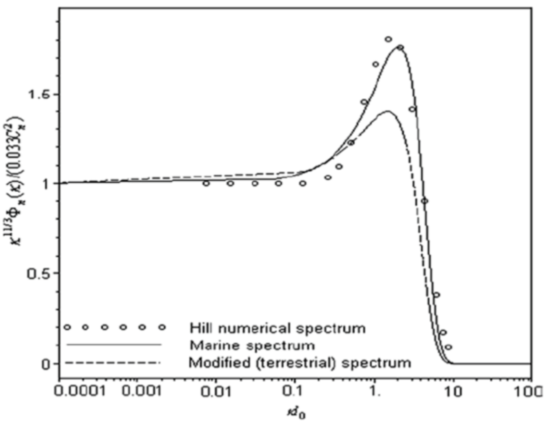

Fig. 2

According to Fig. 2, the spectrum of maritime turbulence differs from terrestrial one with characteristic bump. This shows the necessity of separate maritime turbulence investigation.
5) Taking into account different values of α and β parameters, characterizing Gamma – Gamma turbulence model, the three most important turbulence regimes were theoretically investigated. In particular, this includes weak, moderate and strong turbulence.
6) In addition, the dependence of FSO communications on real coastal atmospheric turbulence conditions was considered. Atmospheric data for Sardinia Island including atmospheric pressure, temperature, humidity, wind orientation, wind velocity are taken into account. Based on the aforementioned analytical approaches and real data, the atmospheric turbulence conditions were investigated.
7) More specifically, the meteorological data obtained by real observations were processed. The theoretical method for calculation of irradiance variance based on refractive index structure parameter was presented.
8)Once the irradiance variance regarding the turbulence-induced fading was calculated and the fractional fade time parameter (outage probability) is derived, the turbulence-induced fading can be calculated. Moreover, based on the considered theory, the number of turbulence-induced fades per unit time for several different threshold values of optical receiver can be estimated. This would allow accomplishing of more accurate link budget analysis.
9)Finally the above carried out analysis and simulations allow comparison of availability and reliability of a FSO link operating in coastal climate with FSO link operating in continental weather conditions. This is

important for both WG2 as well as the book chapter "Free Space Optics system reliability in presence of weather-based disruption".
Regarding the techniques used in the accomplished work, they are as follows: Statistical design approaches; Simulations in MATLAB Development Environment; Weather data based on measurements of coastal atmospheric turbulence.
Having in mind the description of the accomplished work, the current STSM is clearly assigned to WG2, namely Weather-based disruptions. Respectively, my STSM was focused on coastal atmospheric turbulence perturbation effect and more specifically their influence over the availability and reliability of a FSO communication link. In particular, the carried out research will highly contribute to our book chapter "Free Space Optics system reliability in presence of weather-based disruption". Until this point the draft version of the book chapter does not consider the outage probability analysis. Moreover, until now only terrestrial FSO link operating in specific continental weather conditions is investigated. In other words, the current STSM, which is related to WG2 provides enough knowledge which can be used for comparison between FSO system availability in the presence of weather based disruptions in terms of two different atmospheric environments namely coastal and continental one.

DESCRIPTION OF THE MAIN RESULTS OBTAINED

The current section contains, part of the important results in terms of the carried out STSM research. The developed theoretical approach allows evaluation of FSO link availability in terms of all kinds of atmospheric turbulence including also coastal turbulence effect. In particular, the derived outage probability in the current work allows evaluation of the influence of atmospheric turbulence over FSO link, which is very important for WG2 as well as our book chapter in COST action RECODIS's book. At first two diiferent atmospheric turbulence models including Gamma – Gamma and newly delevoped Malaga model are considered [1], [3]. Their PDFs are provided in (1) and (2). Where I is the received noramized irradiance.

$$f(I) = \frac{2(\alpha\beta)^{\frac{\alpha+\beta}{2}-1}}{\Gamma(\alpha)\Gamma(\beta)} I^{\frac{\alpha+\beta}{2}-1} K_{\alpha-\beta}(2\sqrt{\alpha\beta I}) \quad (1)$$

$$f_I(I) = A \sum_{k=1}^{\beta} a_k I^{\frac{a+k}{2}-1} K_{a-k}\left(2\sqrt{\frac{\alpha\beta I}{\xi_g\beta+\Omega'}}\right) \quad (2)$$

Where: $A \triangleq \frac{2\alpha^{\frac{\alpha}{2}}}{\xi_g^{1+\frac{\alpha}{2}}\Gamma(\alpha)}\left(\frac{\xi_g\beta}{\xi_g\beta+\Omega'}\right)^{\beta+\frac{\alpha}{2}}$ $\quad a_k \triangleq \binom{\beta-1}{k-1}\frac{(\xi_g\beta+\Omega')^{1-\frac{k}{2}}}{\Gamma(k)}\left(\frac{\Omega'}{\xi_g}\right)^{k-1}\left(\frac{\alpha}{\beta}\right)^{\frac{k}{2}}$

Although Malaga turbulence model also can be applied, the following calculations are based on Gamma-Gamma turbulence model (1) which provides enough accurate results in the current case. The outage probability $P_{out}(I)$ is the CDF of the noramilzed irradainace which can be calculated based on the Gamma – Gamma PDF in equation (1). The I_T is the threshold intensity which is connected to the sensitivity S_r of the appleied FSO receiver.

$$F(I) = P_b(I_T) = \int_0^{I_T} \frac{2(\alpha\beta)^{\frac{\alpha+\beta}{2}-1}}{\Gamma(\alpha)\Gamma(\beta)} I^{\frac{\alpha+\beta}{2}-1} K_{\alpha-\beta}(2\sqrt{\alpha\beta I})\,dI \quad (3)$$

Althought there are different ,methodology for solving the equation (3), the solution in our work is based on Meijer G and Hypergeometric functions. In case of Maejer G- function, we derived the following equation:

$$P_{out}(I_T) = \int_0^{I_T} \frac{2(\alpha\beta)^{\frac{\alpha+\beta}{2}-1}}{\Gamma(\alpha)\Gamma(\beta)} I^{\frac{\alpha+\beta}{2}} \frac{1}{2} G_{0,2}^{2,0}\left(\alpha\beta I \,\middle|\, \frac{\alpha-\beta}{2}, \frac{\beta-\alpha}{2}\right) dI \quad (4)$$

Involving intregration by substitution (z= $\alpha\beta I$) and Meijer G-function transformations, we derived the following equation for P_{out}

$$P_{out}(z) = \frac{1}{\Gamma(\alpha)\Gamma(\beta)} G_{1,3}^{2,1}\left(z \,\middle|\, \begin{matrix} 1 \\ \alpha\ \beta\ 0 \end{matrix}\right) \quad (5)$$

Equation (5) also can be written based on Hypergeometrical functions which are more robust against numerical inconsistencies. The derived equation based on Hypergeometrical functions is provided in (6):

$$P_{out}(z) = \pi \csc(\pi(\beta - \alpha))\, \Gamma(\alpha) z^{\Gamma(\alpha)} F_2(\alpha, \alpha - \beta + 1\, \alpha + 1, z) - \Gamma(\beta) z^{z^{\Gamma(\beta)}} F_2(\beta, \beta - \alpha + 1\, \beta + 1, z) \quad (6)$$

Once the outage probability of $z = \alpha\beta I$ *given in equation (5) and (6) is derived the weather based disruptions in terms of different atmospheric turbulence conditions can be investigated. In the case of the current work, the availability of a FSO system is investigated in terms of maritime (coastal) weather conditions. The considered atmospheric turbulence data are for Sardinia island which has typical coastal climate. After the data from Sardinia island are processed, the changes of the refractive index structure parameter* C_n^2 *versus height are provided in Fig. 3.*

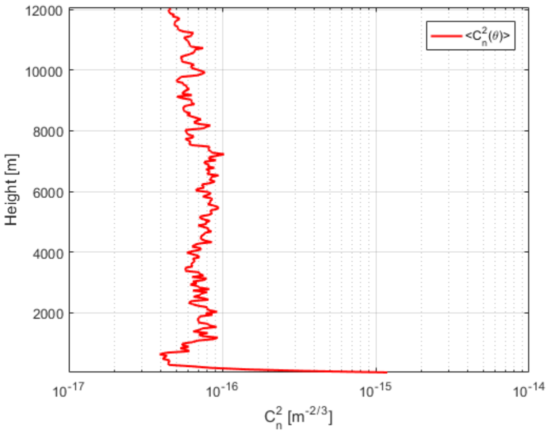

Fig. 3

Once the refractive index structure parameter is available, the log-amplitude variance σ_l^2 *parameter can be calculated for the two cases of terrestrial and deep space FSO link.*

$$\sigma_l^2 = 1{,}23 k^{7/6} L^{11/6} C(0)_n^2 \quad (7)$$

$$\sigma_l^2 = 2{,}25 k^{\frac{7}{6}} L^{\frac{11}{6}} \int_{z_0}^{H} C(0)_n^2 \,(H - z)^{5/6} dz \quad (8)$$

The parameters α and β in the outage probability equation (5) and (6) are calculated in terms of the processed real maritime turbulence data and log-amplitude variance (7) and (8) . In addition to the possibility of α and β calculations based on real data, also their theoretical values in terms of weak, moderate and strong turbulence were taken into account. The values are provided inTable 1.

Turbulence type	*Weak*	*Moderate*	*Strong*
α	11.1	*4*	4.2
β	10.1	1.9	1.4

Table 1

FUTURE COLLABORATIONS (if applicable)
The current STSM, which is part of COST action RECODIS, provided me with important knowledge regarding the influence of atmospheric turbulence over a FSO link. In comparison with previous works, the current work considers maritime atmospheric turbulence, which has different impact over FSO link in comparison with the terristrial one. Similar to terrestrial turbulence, the characterization of FSO link in terms of maritime atmospheric turbulence is based on Gamma-Gamma turbulence model. To address its influence over deep space as well as terrestrial scenarios the outage probability of a FSO link is derived. This is accomplished based on Meiger-G and *Hypergeometrical* functions, which are very well suited to describe the outage probability. Once the outage probability is available, the attenuation of the FSO signal can be calculated. In addition, atmospheric data for Sardinia Island including atmospheric pressure, temperature, humidity, wind orientation, wind velocity are considered during calculation of *refractive index structure parameter and the irradiance variance.* The results of the current STSM can be considered as an important contribution for our book chapter in COST RECODIS book "Free Space Optics system reliability in presence of weather-based disruption" and WG2. In addition, the results of the current collaboration will be published in an appropriate conference or journal. The scientific paper will be related to the topic clearly presented above. In addition, based on the already presented results, I will continue the narrow collaboration with Prof. Antonio Jurado-Navas and his Atmospheric Optics Group at Department of Communication Engineering, University of Malaga, Spain

References

[1] J. M. Garrido-Balsells, A. Jurado-Navas, J. F. Paris, M. Castillo-Vázquez, and A. Puerta-Notario, "On the capacity of $\mathcal{M}$ distributed atmospheric optical channels," Optics Letters Vol. 39, Issue 3, pp. 653-653 (2014)
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[3] A. Jurado-Navas, J. M. Garrido-Balsells, M. Castillo-Vázquez, A. Puerta-Notario, I. T. Monroy and J. J. Vegas Olmos, "Fade statistics of M-turbulent optical links," Eurasip Journal on Wireless Communications and Networking, Vol. 2017, Issue 1, (2017)