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SCUOLA DI INGEGNERIA INDUSTRIALE
E DELL'INFORMAZIONE

Executive Summary of the Thesis

Investigating Visibility for the Development of Fog Attenuation Models Affecting FSO Links

Laurea Magistrale in Telecommunication Engineering - Ingegneria delle Telecomunicazioni

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1. Introduction

Free Space Optic (FSO) technology is increasingly important in terrestrial communications due to its many advantages, and its utilization of a wide unlicensed spectrum. However, FSO propagation is subject to atmospheric attenuation that can impair the quality of service. As a consequence many propagation models based on visibility phenomenon have been developed in order to predict the impact of atmospheric attenuation, various path loss models, depending on visibility, offer an analytical approach. This study aims to investigate the use of a worldwide visibility database, ECMWF, to deduct a new Path Reduction Factor based on visibility, in order to accurately predict the attenuation of an optical link.

2. Free Space Optic Technology

FSO technology is a superior solution to other mm-Wave devices due to its optical technology, bandwidth scalability, deployment speed, and cost-effectiveness. The transmission of optical signals through a medium with no physical connection is carried out with the transmission of photons via LEDs or lasers. FSO technology is used in inter-satellite links, lasercom links, and terrestrial links - the focus of this study. Despite its advantages, FSO is challenged by propagation impairments, particularly meteorological events, according to experiments and theory.

2.1. Visibility General Definition

From a physical point of view fog is a thick cloud of tiny water droplets that forms near ground level and can cause horizontal visibility to fall below 1 km. The term "fog" can also be used to describe clouds made up of mixtures of smoke particles or ice particles. If visibility is greater than 1 km, the phenomenon is usually referred to as either mist or haze, depending on whether the obscurity is caused by water droplets or solid particles. Adhering to the WMO recommendations, visibility is equal to the Meteorological Optical Range (MOR)[3], which is defined as the distance the light from a 2700 K incandescent lamp has to travel through the atmosphere before the intensity drops to 0.05 of its original value. The irradiance propagation through a uniform layer of particles follows an exponential decay behaviour, as predicted by the Bourguer-

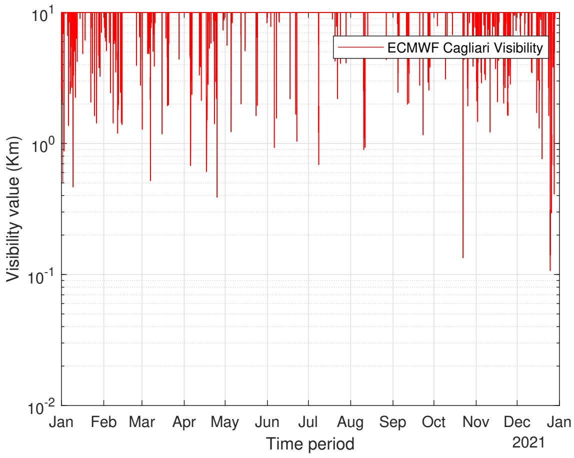

Figure 1: Cagliari ECMWF Time Series

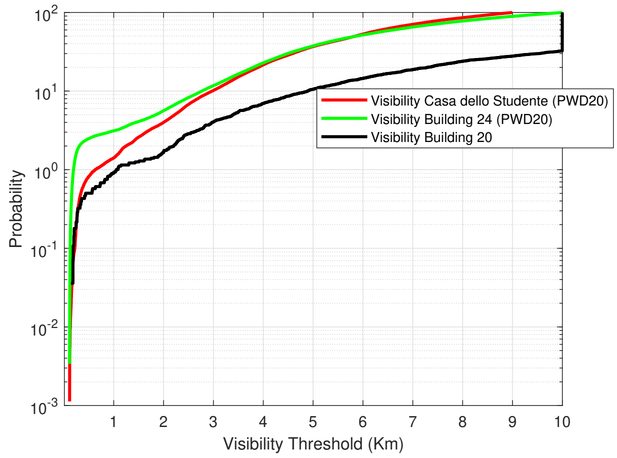

Figure 2: CDF comparison between B24,B20 and Casa dello Studente

Lambert law. We are able to derive the relationship between γ (dB/km) and V (km).

$$\gamma = \frac{13}{V} \quad (1)$$

When we introduce visibility concept we must take into account the scattering phenomenon, as well. Mie scattering is the main cause of attenuation for beam propagation trough fog. A simple empirical formula, found in literature (ITU-R P.1814) and that is broadly used in the FSO society to calculate the attenuation coefficient due to Mie scattering, is given by the following formula, where q depends on visibility value and K on visibility observation method:

$$\gamma = \frac{K}{V}(\frac{0.550}{\lambda})^q \quad (2)$$

3. Analysis of Visibility Meteorological Data

Surface meteorological data have been taken from various locations. The reference database is the European Center for Medium-Range Weather Forecasts (ECMWF). In order to be more accurate we are going to refer to the Meteorological Archival and Retrieval System (MARS) catalogue which is a set of data from ECMWF operational archive. The location considered are: Milano, Cagliari (Fig.1) and Palermo. In ECMWF database visibility is expressed as function of the total extinction coefficient, β_{tot} , considering optical wavelength in the atmosphere, and the parameter ϵ which represents the fixed liminal contrast for the visual range [1]. The visibility, V (in meter), is defined as follow:

$$V = -(\ln \epsilon)/\beta_{tot} \quad (3)$$

According to ECMWF dataset we have downloaded visibility data of Milano from January 2021 up to December 2022 to be compared with visibilimeter data set of Politecnico di Milano, while for Cagliari and Palermo only for 2021.The pixel analysed, which dimension is 0.1° x 0.1°, are spaced of about 10 km each other, and the grid is composed by 6x6 pixels. Data sampling time is 1 hour.

3.1. Visibilimeter database

The visibilimeter measures atmospheric turbidity and aerosols concentration that affect visibility and air quality. It emits a narrow beam of light and measures the amount scattered back, providing an indication of visibility. The database is built using the data collected by Politecnico di Milano in the framework of a propagation experiment within Huawei's "JointLab".

3.2. Politecnico di Milano - Buildings

In Milano campus there are different available visibilimeters installed on different buildings. Building 24 (B24) and Casa dello Studente (CdS) have the Vaisala PWD20 visibilimeter installed. Building 20 (B20) has a different visibilimeter manufactured by Campbell. The plot in Fig.2 shows the trend of the visibility values. It is clear the similarity between the red (CdS) and the green (B24) curves which come from the

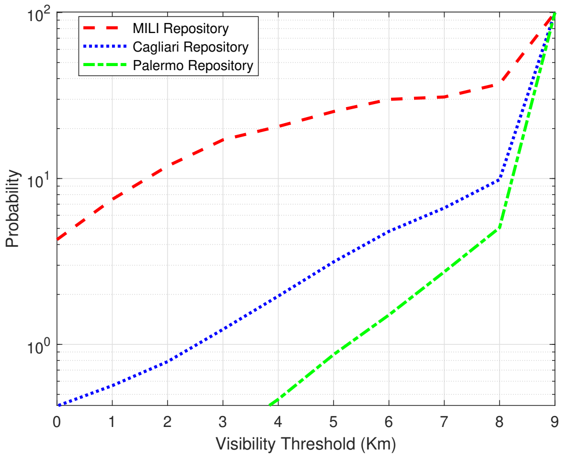

Figure 3: CDF of MILI, Cagliari and Palermo from repository data

same kind of instrument. Data collected goes from August 2022 up to January 2023. The main role of this data is to make possible a reliable comparison between the estimated data (ECMWF) and the measured one. These data will also be used for the prediction of our correlation coefficient.

3.3. Milano Linate, Cagliari and Palermo Airport

In this section we exploit the analysis of the three locations obtained through the NOAA (National Oceanic and Atmospheric Administration) database available at University of Wyoming repository. In the following sections we are going to call this set of data as "repository". Surface data are collected in airports worldwide. The data collected are near by airport due to the presence of visibility phenomena which are object of study in such kind of locations. The data sampling time is 30 or 60 minutes and they are available from 1997 until 2021. For our purpose we considered only the data set belonging to 2021 year. The repository not only has visibility information but also temperature, pressure, dew point and so on [3]. The same procedure made on ECWMF data has been iterated on this data. The values go from 0 up to 10 km. Our data are shown in the CDF (Cumulative Distribution Function) in Fig.3.

Table 1: RMSE Value Based on Visibility

Locations	RMSE
MILI w.r.t. B24 Visibilimeter	1.33 km
MILI w.r.t. repository	0.7538 km
Palermo w.r.t. repository	2.948 km
Cagliari w.r.t. repository	2.23 km

3.4. Accuracy of ECMWF Data with respect to the Visibilimeter and Wyoming Repository

Data obtained from ECMWF need to be validated by means of a comparison with the measured one. We are assuming that our data from the visibilimeter and other repositories are reliable enough.
We are going to use a mathematical approach which regards the so called Root Mean Square Error (RMSE). RMSE will be used in comparison between visibility and attenuation of the three main locations of repository with respect to ECMWF.
In order to calculate RMSE, work out the residual (difference between prediction and reality) for each data point, calculate the norm of residual for each data point, take the average of residuals and take the square root of that average. This is commonly expressed as follow:

$$RMSE = \sqrt{\sum_{i=1}^{N} \frac{(\hat{y}_i - y_i)^2}{n}} \tag{4}$$

where:

- $\hat{y}_i$ is the actual observation time series
- y_i is the estimated time series
- n is the number of non-missing data points

In Tables 1 and 2 are shown the numerical results of our analysis regarding RMSE based on visibility and attenuation (KIM model), respectively. According to visibility results the best result obtained regards Milano Linate compared with the repository. Cagliari and Palermo can be considered really far from the expected result. Thus, in terms of visibility we can conclude that ECMWF does not guarantee always a reliable data set. It is influenced by the considered location. According to the obtained results in terms of Attenuation we found a similarity in the two data set considered.

Table 2: RMSE Value Based on Attenuation

Locations	RMSE
MILI w.r.t. B24 Visibilimeter	32.3854 Np
MILI w.r.t. repository	11.3481 Np
Cagliari w.r.t. repository	2.9095 Np

4. Model for the Attenuation due to visibility

Originally, visibility was conceptualized for meteorological purposes, with the intention of having it determined by a human observer. Nowadays, this method of observation is still widely practiced, though the evaluation of visibility is subject to numerous subjective and physical factors. However, the Meteorological Optical Range (MOR), which represents the critical amount of atmospheric transparency, can be measured in an objective manner. In order to calculate visibility, meteorological visibility (during daytime) and meteorological visibility at night, the farthest distance at which a black object of appropriate size (positioned on the ground) can be recognized against the horizon during the day, or detected and identified at night under typical daylight lighting conditions, is considered.

4.1. Spatial Correlation

Visibility observations taken in different places may not be independent. For instance, readings made in close proximity could be nearer in value than those taken in more distant locations. This is known as spatial correlation indicated in the following paragraph as ρ. Spatial correlation assesses the correlation of a parameter with itself across space. Spatial correlation can be either positive or negative. Positive spatial correlation close to 1 indicates that the two locations considered may have same trend over time. Negative spatial correlation close to -1 implies that there is a low correspondence between the two analysed data set.
In order to perform this calculation we are going to refer to the following formula [2]:

$$\rho_s(j_1,j_2)=\frac{\mathbb{E}[R_s(j_1,t)\cdot R_s(j_2,t)]-\mathbb{E}[R_s(j_1,t)]\cdot\mathbb{E}[R_s(j_2,t)]}{\sigma[R_s(j_1,t)]\sigma[R_s(j_2,t)]} \quad (5)$$

In Fig.4, the initial graph provides us with an assessment of the degree to which correlation values are spread among pixels and how much

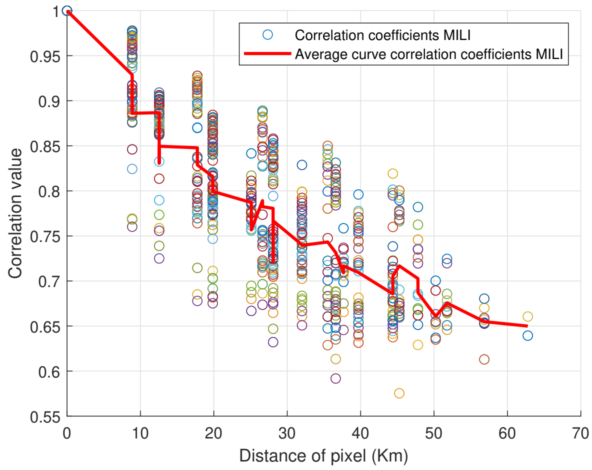

Figure 4: Correlation Values for each pixel MILI

they change in relation to distance. The correlation value is represented by colored circles, which are combinations of each pair of pixels in the ECMWF grid. Meanwhile, the red line denotes the average value for each distance. The ECMWF pixels are separated by 10 km, necessitating the use of an intermediate point for curve approximation over short distances. Regarding Milano, two additional points are included in the calculation of spatial correlation to achieve greater accuracy.
Best way to work on this correlation coefficients is to build a robust and effective statistic model. Data sets are fitted with an exponential curve:

$$f(x) = ae^{bx} + ce^{dx} + k \quad (6)$$

The results of this fitting are shown in Fig.5. Milano Linate data set covers two years (2021 and 2022) and have been subdivided in two databases. Results are available for the other locations such as Cagliari and Palermo as well (Fig.6).

5. Path Reduction Factor computation

The path reduction factor (PRF) is the main parameter in the prediction model for predicting total attenuation from specific rain attenuation. In literature regarding attenuation due to rain we have many models which explain and evaluate it whereas this study investigates path reduction factor models for the prediction of fog attenuation. The PRF takes into account in an

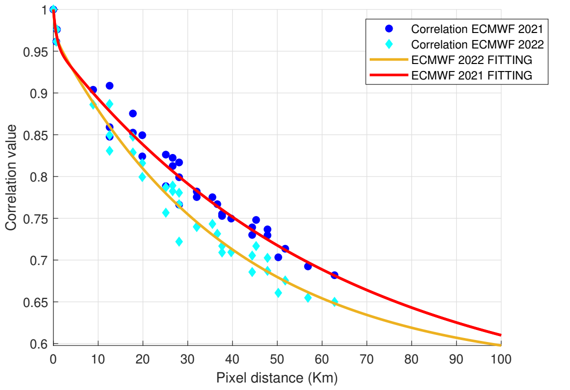

Figure 5: MILI 2021 vs MILI 2022 fitting model

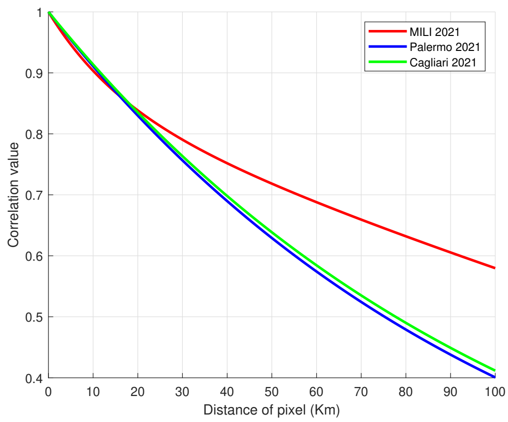

Figure 6: MILI, Cagliari and Palermo 2021 fitting models, range 1-100 km

equivalent way the change of the visibility along the path with respect to the value measured at the transmitter or receiver site. It can happen that for a long (i.e. 2 km) link the meteorological phenomenon of fog is not homogeneous. This in-homogeneity can be translated in an effective path through the PRF, which take into account the effect of fog variations along the propagation path [3].

5.1. Bulding 24 and Casa dello studente analysis

In our case we are going to analyse a PRF for ECMWF data set and the visibilimeters database: Building 24 (B24) and Casa dello Studente (CdS) which are distant 800m apart. PRF has been obtained by means of this calculation:

$$PRF = \frac{A_{tot}}{\alpha \cdot L} \tag{7}$$

where:

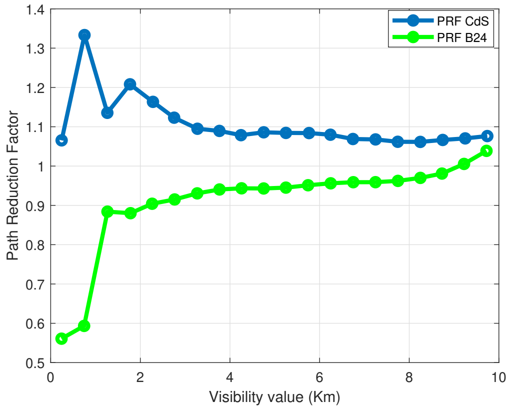

Figure 7: B24 vs CdS PRF

- A_{tot} is the total link attenuation
- α is the specific attenuation calculated from the initial or final link value
- L is the path length

The fundamental purpose of this calculation is shown in the PRF comparison between the B24 and CdS in Fig.7. In this figure a sharp change of the PRF in the first 2 km of visibility with two opposite trends is shown. If we consider the Building 24 as far away from the city centre we can observe the high values that PRF assumes. This behaviour is not strange since it is well known that fog is much concentrated in open areas and far away from city centers. According to the blue curve we can estimate an high Path Reduction Factor if we assume out of city visibility values. In fact the green line which represents the Building 24 has the opposite behaviour in the first 2 km of visibility with respect to Casa dello Studente. For values of visibility higher than 2 km the PRF seems to normalize around 1 which means that low visibility values affect the link in a more incisive way. An effective way to analyse our PRF and understand how much it improves the attenuation estimation on the link is to compare the link's attenuation with the total attenuation. In Fig.8 is clear the role of the Path Reduction Factor. Starting from the black dash-dot line which represents the attenuation curve of B24 with a PRF which is equal to 1. In order to obtain this result we have manipulated the following formula imposing PRF = 1:

$$A_{tot} = \alpha \cdot L \tag{8}$$

The grey dash-dot line is the attenuation regarding CdS with PRF = 1. Thus, grey and black

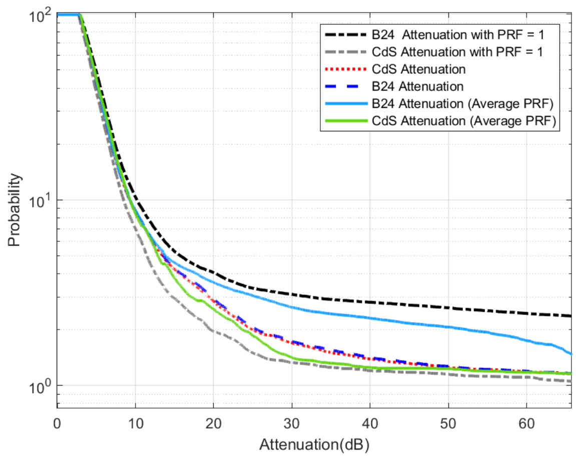

Figure 8: Comparison between different PRF values

curves simulate the worst case for the link attenuation because they do not consider the PRF introducing a considerable error. This error can be seen comparing the curves with PRF = 1 to the red and blue curves which represents the total attenuation on the link. Let us turn instead to the curves where PRF is considered. Still focusing on Fig.8 the B24 curve (azure) was calculated taking into account the PRF values calculated in the plot 7. The same was done for the CdS curve (green). What tell us that PRF improved the attenuation approximation (at least in the first 30 dB of margin) is the proximity of the blue and green curve to the original attenuation curves (red and blue).

5.2. Milano, Cagliari and Palermo analysis

Same steps were made on ECMWF data set. In this case the comparison is between pixels which are spaced, 10 km apart, between hinterland and city for MILI and coastal and hinterland for Cagliari and Palermo. Proceeding on MILI, the results are shown in Fig.9. We can appreciate the similarity of ECMWF results with respect to the visibilimeters PRF in Building 24 and Casa dello studente.

6. Conclusions

Free Space Optics (FSO) technology enables communication without giving up on all the benefits of fiber, but atmospheric impairments must be considered. Visibility is a seasonal

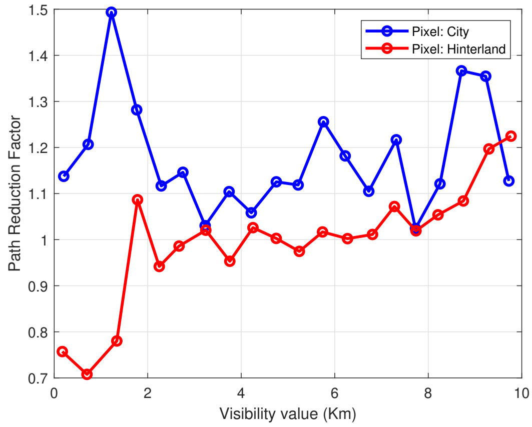

Figure 9: MILI ECMWF Average PRF calculation

phenomenon influenced by climate and locality morphology. ECMWF is one of three analyzed databases and shows varying reliability depending on location. The correlation coefficient is used to interpret visibility evolution along different paths and decreases with distance. A new model using Path Reduction Factor (PRF) estimates attenuation due to visibility and is helpful in dimensioning link budgets. The main future development could be the testing of the model for estimating fog attenuation that includes the PRF against the data we are collecting with the experiment in Politecnico di Milano.

References

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