Monthly and Seasonal CFLOS Statistics for Optical GEO Feeder Links Design

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Abstract. A methodology for the generation of seasonal and monthly cloud-free-line of sight (CFLOS) statistics for single optical satellite slant paths and joint CFLOS statistics for multiple spatially separated optical satellite links is proposed and evaluated with numerical results. It is assumed that the blockage of the satellite link is considered with the occurrence of clouds. The reported methodology is based on the stochastic dynamic modeling of Integrated Liquid Water Content (ILWC) and uses as inputs monthly statistical parameters of the logarithm of (ILWC) to produce CFLOS statistics. This methodology is an extension of an existing model that captures very well both the seasonal and monthly variability of clouds. The proposed model takes into account the temporal and spatial correlation of clouds, the elevation angle and the altitude of the ground station among others. The numerical results are concentrated on for hypothetical satellite links with optical gateways located in North and South hemisphere respectively are presented. The numerical results are compared with the corresponding annual results.

Keywords: Optical satellite communications
Cloud-Free-Line of Sight probability · CFLOS · Cloud coverage
Seasonal and monthly variability

1 Introduction

Nowadays, Earth-space optical communication links are gathering more and more of the attention of the communication society. The use of optical communications has additional advantages with respect to the radio frequencies (RF) communications such as: (a) absence of frequency regulation constraints due to the highly directive antennas, (b) smaller systems with potentially lower power consumption, (c) enhanced security due to directivity of the beams and (d) ability to completely reallocate RF frequency bands to the user link [1]. These advantages have motivated the investigations of optical satellite communication systems. Already, a bunch of studies have been conducted for

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the migration of feeder links from RF [2] to the optical band in the context of satellite communication systems [3–5].

Although optical links have a great variety of advantages, they are severely affected by several atmospheric phenomena like precipitation, atmospheric gases, liquid water particles and atmospheric turbulence [1]. Among these impairments clouds contain the dominant fading mechanism. Clouds induce tens of dBs attenuation in optical signal. Therefore, the blockage of the link can be considered with the occurrence of clouds [6]. For the mitigation of clouds site diversity technique is employed. Multiple ground stations shaping a ground station network are placed in large distances to cope with cloud coverage and to guarantee the desired availability of the system. Methodologies for the estimation of Cloud Free Line of Sight (CFLOS) probability for both single links and for a ground station network have been developed [6]. These methodologies have to take into account the temporal and spatial correlation of clouds, the elevation angle and the altitude of the stations among others. In addition, for the dimensioning of an optical ground station network, it is important to examine the monthly and the seasonal variability of the clouds occurrence. As it is expected the clouds are highly seasonal and monthly dependent. Even for regions which are favorable for optical communications (low cloud coverage among others) the percentage of cloud coverage greatly depending on the month and season. Moreover, significant differences can be identified between stations that are located in different hemispheres. For example, in Fig. 1 the cloud coverage per month (monthly variability) for year 2009 for one station in north hemisphere, Madrid Spain, and another in south hemisphere Santiago, Chile is presented.

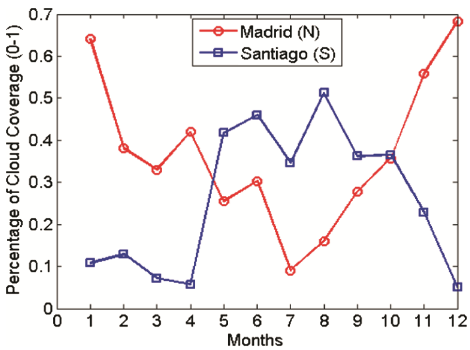

Fig. 1. Percentage of cloud coverage (0–1) for year 2009 for Madrid (North Hemisphere) and Santiago (South Hemisphere)

For the reliable and the accurate design of Cloud-Free Line-of-Site probability for the optical communication network, monthly and seasonal variability of clouds must be taken into account. The main objective of this contribution is to exhibit monthly and seasonal CFLOS statistics for single optical links and for optical satellite links separated in spatial domain. Moreover, the necessity of using such statistics for the dimensioning of an optical satellite communication system is revealed while, the seasonality differences and the benefits of using stations in different hemisphere are investigated.

The remainder of the paper is structured as follows: In Sect. 2 the methodology for the estimation of single and joint CFLOS statistics is presented. In Sect. 3 the exhibited methodology is evaluated for various single and spatial diversity scenarios. In addition, single and joint CFLOS statistics using both monthly and annual statistical parameters are synthesized and compared. Finally, in Sect. 4 the conclusions of this contribution are presented.

2 Methodology

In this Section, the methodology for the generation of seasonal and monthly CFLOS statistics will be exhibited. This methodology is based on the stochastic dynamic modeling of ILWC fields which is presented in [7]. The proposed methodology except from the spatial and temporal variability which is also included in [7] could be able to capture the seasonal and monthly variability of both single and joint CFLOS statistics. Moreover, this methodology takes into account the elevation angle and the altitude of the ground station for the evaluation of CFLOS statistics. To begin with, the main assumptions of the proposed methodology will be reported. Firstly ILWC can be sufficiently described by lognormal distribution [8] while Liquid Water Content (LWC) can be modeled taking into account the height and ILWC using the expression proposed in [9]. Moreover the statistical parameters of the logarithm of ILWC (mean value, standard deviation and probability of cloud coverage) can be derived from Numerical Weather Prediction databases on yearly, monthly, daily or hourly base and will be considered constant for the whole slant path.

For the generation of ILWC fields correlated both on temporal and spatial domain for either single or spatial diverse links, the methodology exhibited in [7] using stochastic differential equations is applied. However, for this contribution, as statistical parameters of the logarithm of ILWC, monthly parameters are used. For the calculation of these parameters the methodology presented in SMOC [9] will be followed. Firstly, from Numerical Weather Prediction databases, in our case ERA Interim database the monthly values of total cloud cover (probability of cloud coverage) and total column cloud liquid water for the places of interest are extracted. Then, according to SMOC the mean value and standard deviation of the log normal distribution of ILWC are derived. Thus, the monthly statistical parameters of logarithm of ILWC have been computed. It is assumed that these parameters are constant for the whole slant path. Now the main steps for the generation of CFLOS time series will be exhibited. The following steps are followed for each month:

1. ILWC time series are computed [7] using the monthly statistical parameters. More particularly, SDEs are employed and ILWC grids 1 km $\times$ 1 km correlated on temporal and on spatial domain as it is demonstrated in Fig. 1 of [7] are synthesized. It is assumed that ILWC is constant for each grid [6, 7, 9].
2. ILWC time series are converting into cloud vertical extent time series through the expression presented in [9] and also used in [7].
3. Time series of cloud coverage are estimated taking into account the elevation angle and the altitude of the ground station. Clouds block the link if there is a cloud

formation with such a vertical extent so as the link is impaired. The link is not impaired either when the top level of the cloud is under the slant path or the bottom of the cloud is above the slant path. The configuration of slant path taking into account the vertical extent of clouds is demonstrated in [6].

4. Time series of cloud coverage are converting into time series of CFLOS *CFLOS = 1–Cloud_Coverage.*

In Fig. 2 a 2-dimensional field of ILWC for a specific snapshot (step 1) is exhibited.

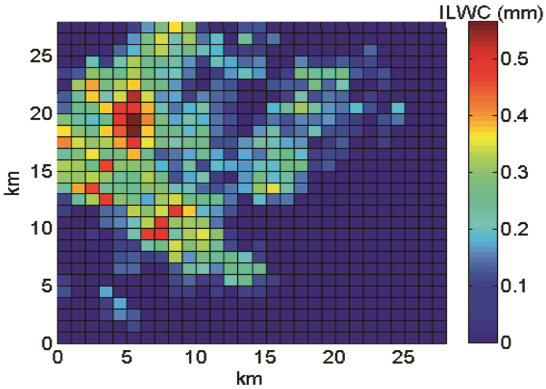

Fig. 2. ILWC 2-dimensional field for a specific time instance

3 Numerical Results and Discussion

In this Section, the methodology reported before will be evaluated for the generation of single and joint CFLOS statistics, in North and South America. The statistical parameters have been derived from the monthly database of Era-Interim for the period from 1/1/2009 to 31/12/2015 while the numerical calculation software has been developed in MATLAB. The hypothetical optical links which that are used for the numerical results are shown in Table 1. As space segment, the QuetzSat-1 GEO satellite at 77degW owned and operated by SES is considered along with a hypothetical optical payload on-board the satellite.

To begin with, following the reported methodology, the mean monthly CFLOS probability from 2009 to 2015 for the hypothetical stations at Santiago, Malargüe Steele Valley and Vernon are presented in Fig. 3. For the x label of Fig. 3, 1 means January, 12 December etc. From this Figure it can be easily observed both the monthly variability of each station and the variability between the two different hemispheres. For example, for the stations located in North the best months are from May to October while the opposite occurs for the ones located in South.

Table 1. Hypothetical optical satellite links

Station	Latitude (deg)	Longitude (deg)	Elevation Angle (deg)	Altitude (m)	Hemisphere
Santiago, Chile	–33.44	–76.68	50.51	600	South
Malargüe, Argentina	–35.483	–69.58	48.04	1400	South
Calama, Chile	–22.508	–68.95	62.1	2200	South
Steele Valley, California, USA	33.76	–117.32	32.0	612	North
Vernon, Texas, USA	34.218	–99.40	43.57	400	North
Kitt Peak, USA	31.96	–11.60	37.39	2000	North

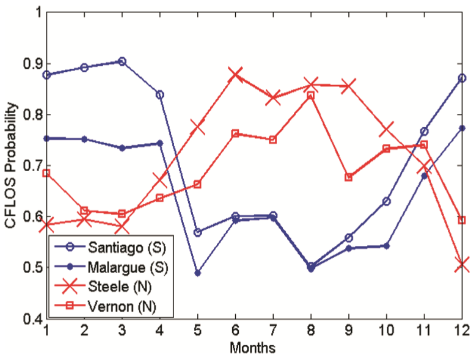

Fig. 3. Monthly CFLOS Probability

Now the same results are presented for the high altitude stations of Kit Peak and Calama. The reported methodology can capture the effect of the Altitude of the ground stations in the CFLOS statistics, among others (Fig. 4).

To continue, in Fig. 5 the mean Seasonal CFLOS statistics are reported. Again the seasonal variability in each station and between the stations of different hemisphere is made explicit.

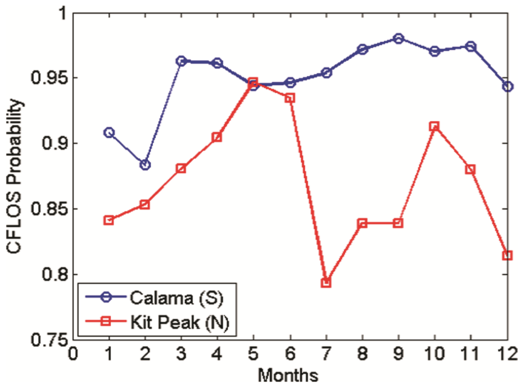

Fig. 4. Monthly CFLOS Probability, high altitude stations

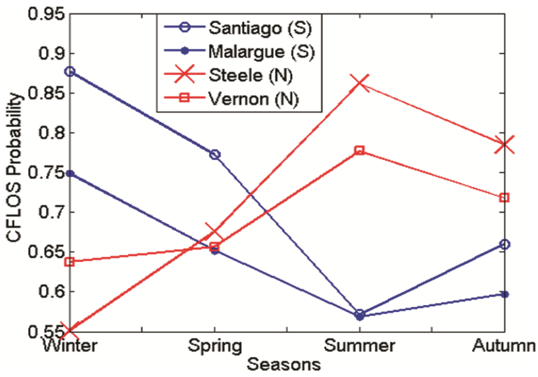

Fig. 5. Seasonal CFLOS Probability

At this point, with the following Figures the differences between using monthly and annual statistical parameters are demonstrated. Finally the following results are computed using the monthly statistics, and the annual statistics. The stations are the same as before and the period is 6 years (from 2009 to 2015).

In Figs. 6 and 7 the monthly and seasonal CFLOS statistics are depicted. For both figures the statistics are computed for two stations one in the north and another in the south hemisphere using monthly and annual statistical parameters. The results reveal that using annual statistical parameters, the monthly and seasonal variability of CFLOS probability and the variability between the two hemispheres cannot be captured. Thus, the use of annual statistical parameters cannot guarantee a robust optical ground station dimensioning.

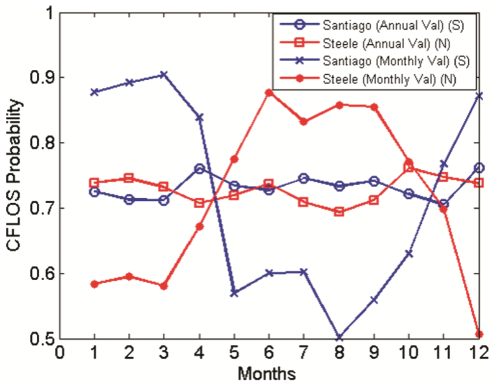

Fig. 6. Monthly CFLOS Probability using annual and monthly statistical parameters

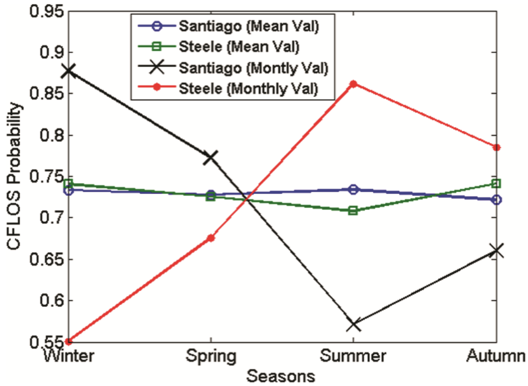

Fig. 7. Seasonal CFLOS Probability using annual and monthly statistical parameters

Except from the statistics for the single links, joint CFLOS statistics of a spatial diversity scenario are also presented. A double triple etc. diversity scenario means that at least one of the two three etc. stations respectively is not blocked. For the double site diversity scenario the stations of Santiago and Steele Valley are used, for the triple the station of Malargüe is added to the previous ones and finally for the quadruple scenario the station at Vernon is added. You can observe that for double scenario there is one station from the south hemisphere and another from the north etc.

In Figs. 8 and 9 the monthly joint CFLOS probability for the double, triple and quadruple spatial diversity scheme, is computed using annual and monthly statistical parameter.

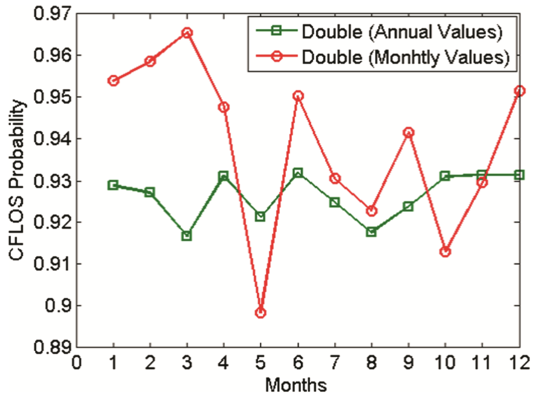

Fig. 8. Joint CFLOS Probability for double diversity scenario using annual and monthly statistics

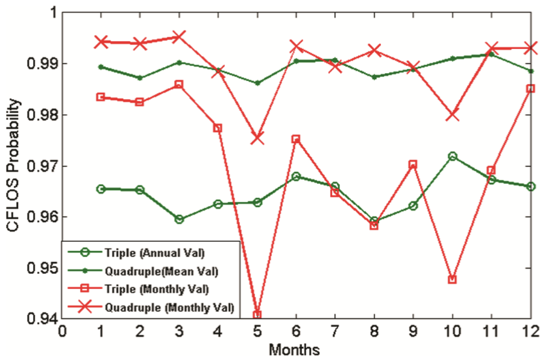

Fig. 9. Monthly joint CFLOS Probability for triple and quadruple spatial diversity scenario using annual and monthly statistics

In Fig. 10 the seasonal joint CFLOS probability for the double, triple and quadruple spatial diversity scheme, is computed using annual and monthly statistical parameter.

Finally in Figs. 11 and 12 the monthly statistics for the quintuple and sextuple spatial diversity scheme are exhibited. In Fig. 11 we have pinpointed the 99.9% CFLOS probability as reference. In addition, it can be easily observed that in case of using annual statistical parameters, the monthly CFLOS is always higher than the 99.9% reference level but in case of using monthly statistical parameters it is not true. Thus, depending on the system requirements, monthly CFLOS statistical parameters result on more reliable CFLOS results. For the quintuple scheme the station of Calama has been added to the before mentioned station while for the sextuple except from Calama the station in Kit Peak is also added.

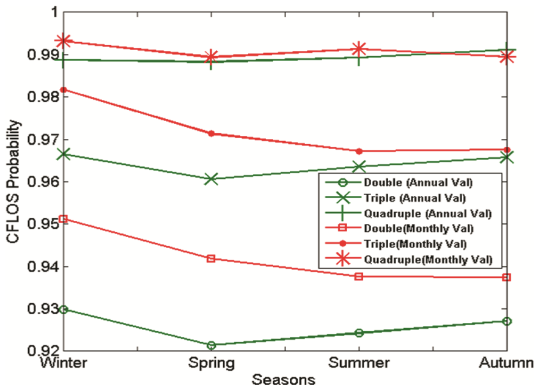

Fig. 10. Seasonal joint CFLOS Probability for triple and quadruple spatial diversity scenario using annual and monthly statistics

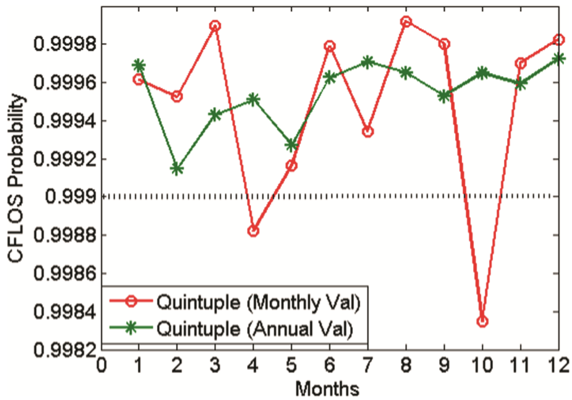

Fig. 11. Monthly joint CFLOS Probability for quintuple spatial diversity scenario using annual and monthly statistics

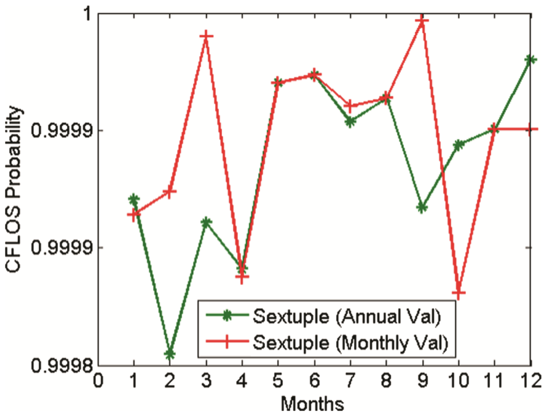

Fig. 12. Monthly joint CFLOS Probability for sextuple spatial diversity scenario using annual and monthly statistics

4 Conclusions

In this paper, a stochastic dynamic methodology for the generation of single and joint CFLOS statistics is presented taking into account the temporal, spatial, seasonal and monthly variability of clouds, the elevation angle and the altitude of the ground stations among others. This methodology is evaluated for hypothetical single optical GEO feeder links and for multiple spatially separated GEO feeder links in North and South America. In this contribution, the necessity taking into account the seasonal and monthly variability of clouds for the dimensioning of an optical ground station network is highlighted while the employment of optical ground stations located in different hemispheres is investigated.

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