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Anomalous waves propagating at very high frequency in the atmosphere and their disturbances due to changes in refractivity profiles

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ABSTRACT

Anomalous waves propagation is severely affected due to almost always present variations in refractivity under various environmental conditions at different time, location and frequency. These conditions, representing different state of the atmosphere including e.g. foggy, rainy and cloudy etc., not only degrade the quality of the signal but sometimes completely eradicate the communication link. Such severe impact on propagation cannot be ignored by the designers of communication systems. The aim of this research is to present correlation between experimental and modelled link losses for variations in refractivity values recommended by International Telecommunication Union-Recommendations (ITU-R) as well as that of standard profiles. To do so, a communication setup of 50 km over the Sea operating experimentally over a period of a year at 240 MHz is analyzed for different refractivity profiles and their impact on propagation. A median value is taken for every set of 6000 values taken from the recorded data set of more than 48 million experimental link losses. This reduces the huge data set of the experimental link losses to 8000 values only. This reduced data set of experimental and modelled link losses were correlated and investigated for different evaporation duct heights throughout the year. For the considered link, the ITU-R refractivity profile was found to perform better than the standard refractivity profile. However, the new findings as observed in this research, which may be helpful for the recommendations authorities, is the existing of evaporation duct up to 10 m height.

Introduction

In wireless communication, the propagated radio waves are almost always affected by the space time variations existing in the refractivity profiles [1–3]. The impact of such inconsistencies occurs regularly when a signal at VHF (very high frequency) takes several ways to reach towards its receiver. A refractivity profile is used by the research community [4–7] as well as by the recommendation bodies [8,9] to mirror the atmospheric conditions or different states of the atmosphere at different times, locations and frequencies. These effects and the disturbances resulted in the propagated radio waves due to the variations in refractivity profiles is termed as anomalous propagation [10–12].

The designers of wireless communication systems are interested in knowing the variable atmospheric conditions. They seek the prediction of modified refractivity profiles that are replicating the state of the atmosphere following diurnal variations. Once the explored state of the atmosphere is known to the operators of telecom, they are in a better position to cope with anomalous propagation and deal with the causes of degradation in signal strength. This in turns help them to avoid frequent break downs of communication link and to provide better services to the consumers of communication systems.

The aim of this research is to present correlation between modelled link losses and experimental link losses for distribution/variations in refractivity values recommended by International Telecommunication Union-Recommendations (ITU-R) as well as that of standard profiles. To fulfil the aim, a communication setup over the Sea operating at 240 MHz frequency of the VHF band is analyzed for over a period of a year for different refractivity profiles. More than 48 million experimental link losses were reduced into 8 thousand values by taking the median of every set of 6000 values. These experimental link losses are correlated with corresponding 8000 modelled link losses. The impact of metrological parameters on propagation are investigated for different evaporation duct heights throughout the year from this data set of losses. Communication links especially when they are operating at very high frequencies are affected mostly by varying atmospheric conditions for which one of the popular technique is using weather

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parameters. These parameters can be very helpful in forecasting refractivity distributions that are responsible for assessing these continuously varying conditions. These weather parameters including air temperature, humidity, water vapor pressure and barometric pressure have impact on wireless communication links and are the main factors of the barometric radio index of refraction hence the modified refractivity [13–15].

In this research, we are presenting analysis made for the hourly experimental link losses between transmitter and receiver to discuss how to cope with the impact of anomalous propagation through an experimental setup. The location of receiving station of the experiment is Portland, United Kingdom where as that of the transmitting station is at Jersey, giving a short link of 50 km. This link is labelled as 'Short-VHF-Link'. The experimentally recorded values are correlated with the modelled link losses obtained by modelling parabolic equation technique on hourly basis at the same time, location and frequency. The investigation focuses on a comparison of measurements and simulations of a communication link losses occurred in a VHF radio link. The effect of the variations of the refractive index profiles is investigated as a source of path loss.

International Telecommunication Union [9] recommends the conditions for propagation in ducting layers and the frequency that is creating different phenomena of ducting. Mostly ducting happens in the lower atmospheric region called troposphere. When ducting occurs, it is basically a process in which a propagating wave is virtually trapped in a duct and due to this virtual trapping, it travels for more distance than the targeted destination. Over the Sea such conditions become more prominent and the behaviour of the propagating signal becomes more difficult to deal with [16,17]. We have investigated one of the four classified types of ducting over the surface of the English Channel named as evaporation duct which is characterized by a parameter named as evaporation duct height (EDH). EDH is a height over the surface of the Sea which in turn determines how refractivity is affecting communication links.

The experimental setup and the simulation technique for the modelled link results used in this research is provided in Section 2 where it is described in detailed how the model is implemented and why the method is chosen. The construction of modified refractivity profiles and the way it is used in this research is given in Section 3. The analysis is presented in Section 4 which is based on the discussion of results formulated for number of cases for different evaporation duct heights while considering several types of reactivity profiles. Finally, the conclusion of the work is presented in Section 5 based on the comparison of correlation coefficients for path losses obtained through the model and the experimental setup.

Experimental setup and simulation technique

Researchers have so far worked on numerous techniques for estimation of refractivity whether it is using refract-meter, Helicopter technique [18], Radar clutter return [19], Occultation from GPS [20], Radio-sonde or ground based [21] etc. The limitations of these various methods are also well known in many forms e.g. noise levels in the background or high extinction conditions limit the performance of LIDAR (Light Detection and Ranging) [16]. Recently, the research community is making use of new meteorological products and applying radar measurements based on dual polarization to provide an improved approach and more like a direct method for measuring refractivity [22].

For simulating the modelled link losses, parabolic equation method developed by [23,24] is fast and popular techniques amongst the methods used. Some alternate methods include physical optics [25], coupled mode analysis [26,27], geometrical optics [28], normal mode analysis etc. These rays based techniques are not reliable compared to parabolic equations technique as they are not incorporating real refractivity profiles. [29–33]. Parabolic equation technique provides a reliable solution for the prediction of electromagnetic field when refractivity profiles representing the environmental state are fed as an input to the model. A specialized numerical determination of this method along with its derivations and applications to numerous problems in electromagnetics is given in [34]. In addition, [35] provides a 3-dimensional description on parabolic equation by using various arrangement in detail. Some more implementation procedures and details about the chosen methodology can be found in [36,37].

In parabolic equation method, the basic concept of the energy propagation is in the form of a cone represented by time harmonic Helmholtz equations in altitude (z) and range (x), deduced from Maxwell's equations. The solution is obtained by using either split step Fourier transform (SSFT) [37,38] or finite difference method (FDM) [39]. These two approaches are compared in an artistic manner by the authors in [40] where the parabolic equation solution using the first approach has the advantage of utilizing lesser resources and implicit approach to specifying radiation boundary conditions. Converged solutions to the problem of interest is gained by marching in large steps in range (x) as named as Split Step Fourier Transform. Each phase screen of the marching steps is modulated with the real input modified refractivity profile. These modulated steps are orthogonal to the direction of field propagation in the form of a continuous series.

We have developed a propagation model using parabolic equation technique in MATLAB where the obtained refractivity profiles from the weather parameters are inserted. After extensive simulations, the model returns the link loss value corresponding to the experimental link loss at that specific location, time and frequency. In this way, the impact of refractivity on propagation at VHF is investigated on hourly basis for a specific period of a year. The model is well validated, and the results obtained from the model were compared with other software packages like AREPS (Advanced Refractive Effects Prediction System) [41,42].

The other experimental parameters of the communication link 'Short-VHF-Link' includes; the transmit-antenna having a height equal to 16.5 m above mean sea level and the receive-antennas at 12 m, 17° of half power beam width with vertical polarization. The experimental sample consist of more than 48 million values of the received signal strength for a year whose median value is taken on hourly basis for this analysis. More details of the experimental setup and equipment's calibration can be found in [4]. Median hourly data obtained in this manner is used to get data set of Experimental Link Losses (ELL) as given in Eq. (1) due to the limitations of the available weather data in an hourly format.

$$ELL = c + P_R \tag{1}$$

here: c is used as conversion parameter in dBm which is equal to 63.5 as obtained from Eq. (2), and P_R is received signal strength in dBm. In this research, the constant 'c' includes the total losses and gains at distinct parts like transmitters, amplifiers, feeders, receivers, etc. of the setup. It transforms the experimentally recorded received signal strength value into a more easily manipulate link loss value. The other parameters considered for getting the value of this constant 'c' is given in Eq. (2). [38] describes in detail the method of computation of all considered parameters used in Eq. (2) and tabulated in Table 1 along with its link budget.

$$c = P_{A(Tx)} + P_{s(Tx)} - L_{fd(Tx)} + G_{(Tx)} + P_{A(Rx)} - L_{fd(Rx)} + G_{(Rx)} \tag{2}$$

here $P_{A(Tx)}$ is the power gains of the transmitter's amplifiers, $P_{s(Tx)}$ is the power of transmitting source, $P_{A(Rx)}$ is the power gains of the receiver's amplifiers, $L_{fd(Tx)}$ is feeder loss at transmitting end and

Table 1
Measured values of different experimental parameters in the setup for 'Short-VHF-Link'[35].

$P_{A(Tx)}$ (dB)	$P_{s(Tx)}$ (dBm)	$L_{fd(Tx)}$ (dB)	$G_{(Tx)}$ (dB)	$P_{A(Rx)}$ (dB)	$L_{fd(Rx)}$ (dB)	$G_{(Rx)}$ (dB)
28.8	12.7	−1.15	12.15	0	−1.15	12.15

$L_{fd(Rx)}$ is the same at receiver end, $G_{(Rx)}$ and $G_{(Tx)}$ are receiver and transmitter gains, respectively.

Weather data of different parameters from four stations, having geographical coordinates as given in Table 2, were obtained; including air temperature, humidity, barometric pressure and water vapor pressure etc. This data set is utilized to compute the refractivity profile named as 'M-Profile' (see Section 3). The heights of these stations are also shown proving the vicinity of the experimental setup to these weather stations.

Modified refractivity profile

The aim of this research is to correlate experiment and modelled link losses for a specific region. Before doing so, different Modified refractivity profiles (M profiles) needs to be created for each model run corresponding to each experimental link loss. In this research four M profiles were created in total and everyone is representing a unique state of the atmosphere. Simulations were executed for more than hundreds of times with every M profile as input to the model to discuss the results presented.

The first of these four M profiles is named as 'M-Profile1' which represents state of the atmosphere up to a height of 102 m based on the weather data and above that height, it is based on the standard atmospheric behaviour, which is taken as 118 M-units per km. It is to mention here that the difference between the transmitter and receiver location and the nearby weather station can be ignored as the horizontal/range difference is reasonably insignificant [43]. The difference in this regard were linear interpolated to obtain refractivity values at heights located between the heights of these stations.

'M-Profile2' is created in the same fashion while keeping the ITU-R P.453-12 recommended values as described in [8], however, again the lower part (up to 102 m) of this M-Profile consists of weather data. In this regard, the value of surface refractivity and the monthly mean change in N-units per Kilometres were also taken from [8]. Again, to mention, the missing parts in the ITU recommendations were filled by linear interpolation. The surface refractivity used in this research is 315 NU/km which is taken from the recommendation of ITU for the region. In addition to surface value of refractivity, mean values of rate of change in refractivity on monthly basis used in this research were taken from the ITU-R recommendations, however, it was only available for four months of Feb, May, Aug and Nov. For the rest of the duration, linear interpolation is made to get the data of complete year. These values are 41.66, 40, 43.33, 46.66, 50, 50, 50, 50, 48.33, 46.66, 45, 43.33 N-units/Kilometers for January–December, respectively.

'M-Profile1' is reproduced to get 'M-Profile3' with the same arrangement except tidal variations included in this M-profile and hence making it different from first M-Profile. In the exact same manner, 'M-Profile2' is replicated to obtain 'M-Profile4' with the same arrangement except tidal variations is added to the M-Profile. In both the cases, the obtained tidal data from British Broadcasting Corporation (BBC) having four values per day is converted to hourly tidal format by taking linear interpolation. The values of datum for tidal data at the location of Jersey, Alderney and Portland is available as 6.12 m, 3.57 m and 1.09 m, respectively. This data has helped in the inclusion of the effects of high and low tidal occurrence at the location of experimental setup where the equipment in each model run were adjusted according to the variations in the tidal pattern.

Table 2
Geographical coordinates and heights of Weather stations near experimental setup.

Weather station	Latitude	Longitude	Height above mean sea level (m)
Jersey Airport	49.208	−2.196	84
Portland	50.517	−2.45	52
Guernsey Airport	49.433	−2.6	102
Channel Light Vessel (CLV)	49.9	−2.9	5

The four M-profiles constructed in this way were further modified to include the effect of evaporation duct at four different points in height (0, 10, 20 & 30) meters. The impact of these evaporation duct heights, is only up to height of 52 m. Eq. (3) describe the inclusion of exponential variations in refractivity between the surface of the earth and a height of 51 m. To explain the nomenclature of the used profiles with an example, 'M-profile2−10 m-EDH' means that an exponentially recorded data between 0 m and 10 m, meteorological data from 11 m to 102 m and ITU recommended values above 102 m are combined to obtain the refractivity M-Profile named as 'M-Profile-2−10 m-EDH'.

$$M = M_0 + 0.125 \times \left(z - E_{dh} \times \log_{10}\left(\frac{z + z_0}{z_0}\right)\right) \quad (3)$$

here z_0 is the Jeske's roughness length which is equal to 0.00015 m over the Sea, M_0 is modified refractivity at the Earth's surface and E_{dh} is height of the evaporation duct. 'M-profile1' and 'M-profile2', are shown in Figs. 1 and 2 as a sample hybrid plot where mean values of the whole data set of more than 48 million experimental link losses are used as the meteorological values are varying for each model run.

The simulations parameters can only be improved by using a very high resolutions data, as other parameters like antenna height, frequency of operation and length of communication link etc. are constant. The only factor left is the evaporation duct height

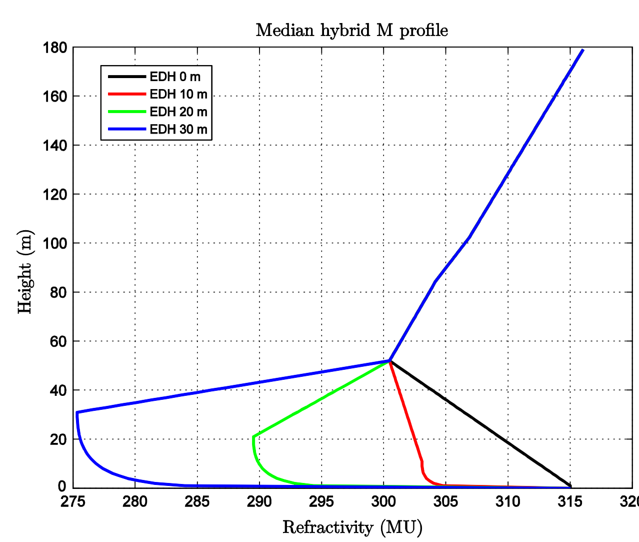

Fig. 1. Median of hybrid M profile with different evaporation duct heights (M-profile1).

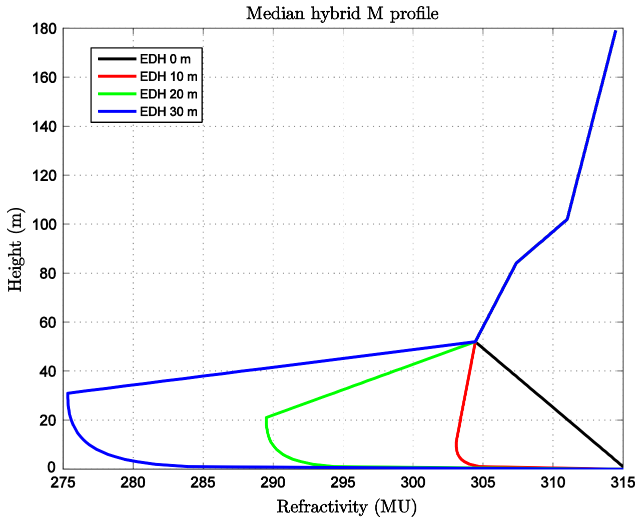

Fig. 2. Median of hybrid M profile with different evaporation duct heights (M-profile2).

as a variable quantity and the results presented are based on it in this work. Suitable change in EDH is made in this regard to have an accurate output from the model. Model outputs were also validated through other means including theoretical validation and model parameterization by analysing characteristic curves of all the used parameters. Those results are not shown as it was only to validate the implementations and simulations.

Results analysis and discussion

Depending on the available experimental link losses, the model simulation runs were executed which are different in different time of the year as given in Table 3. The simulation runs were correlated with the experimentally recorded link losses. It is to mention here that the amount of the available experimental data would affect the statistical analysis.

Table 3
Simulation runs throughout the year for Short-VHF-Link.

Month	Short-VHF-Link
January	694
February	619
March	708
April	714
May	677
June	664
July	673
August	672
September	682
October	716
November	712
December	571

Initially annual correlations for all selected evaporation duct heights were analyzed but as expected there were no meaningful output from huge amount of data for a year with varied conditions. The annual comparison for total set of 16 correlation coefficients is tabulated in Table 4. If the correlation coefficient lies in the range of 0.2–0.6, it is considered as significant while if it is between 0.6 and 1.0, it is highly correlated. In all other cases, the results are not significant and further investigation based on the actual link loss diagram is essential.

Figs. 3–6 shows monthly correlation coefficients in case of all modified refractivity profiles and evaporation ducts for Short-VHF-Link. These correlation coefficients are based on the 90% confidence level in the output which means that a correlation coefficient of less than 0.1 is not counted as effective in this analysis. In all the diagrams shown in Figs. 3–6, the correlation coefficients for M-Profile1, M-Profile2 and M-Profile3 are not inside the confidence level of 90% for all evaporation ducts. However, M-Profile4 gives mostly significant correlation coefficients. The very small values of annual correlation coefficients for these three profiles clearly indicates that the three profiles are affecting the behaviour of the signal strength in term of evaporation duct.

For 'M-profile3-10 m-EDH' as shown in Fig. 4 all the correlation coefficients (monthly) are insignificant except one which is for the month of November. The annual correlation coefficient for this profile is 0.13. Similarly, for 'M-profile3-20 m-EDH' and 'M-profile3–30 m-EDH' as shown in Fig. 5 and Fig. 6 respectively, all the monthly correlation coefficients are insignificant. The annual correlation coefficients for these profiles are 0.29 and 0.16 respectively.

Similarly, for 'M-profile2–0 m-EDH' as shown in Fig. 3 all the monthly correlations are insignificant except for December. The

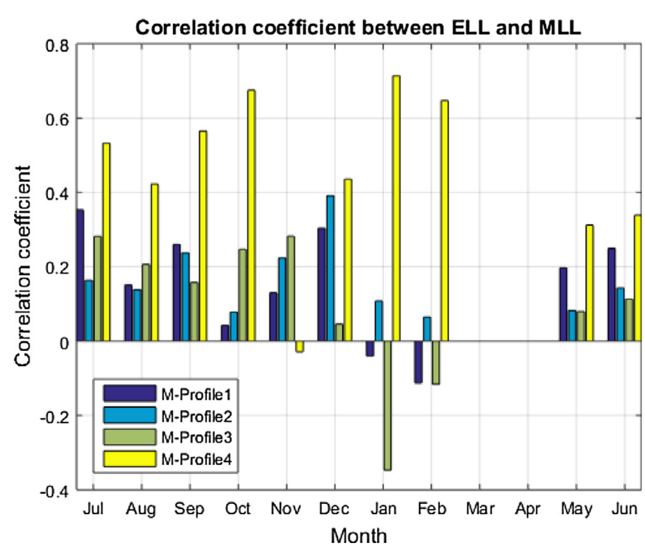

Fig. 3. Monthly correlation coefficients for different M profiles for 'Short-VHF-Link' in case of 0 m EDH. MLL and ELL are the modelled link loss and experimental link loss respectively.

Table 4
Annual correlation coefficients for 'Short-VHF-Link'. EDH is Evaporation Duct Height in meter and M-Profile is modified refractivity profile.

Profile	M-Profile1				M-Profile2				M-Profile3				M-Profile4			
EDH (m)	0 m	10 m	20 m	30 m	0 m	10 m	20 m	30 m	0 m	10 m	20 m	30 m	0 m	10 m	20 m	30 m
Values	0.22	0.25	0.19	0.17	0.09	0.07	−0.01	−0.12	0.13	−0.01	−0.15	−0.21	0.35	0.34	0.29	0.16

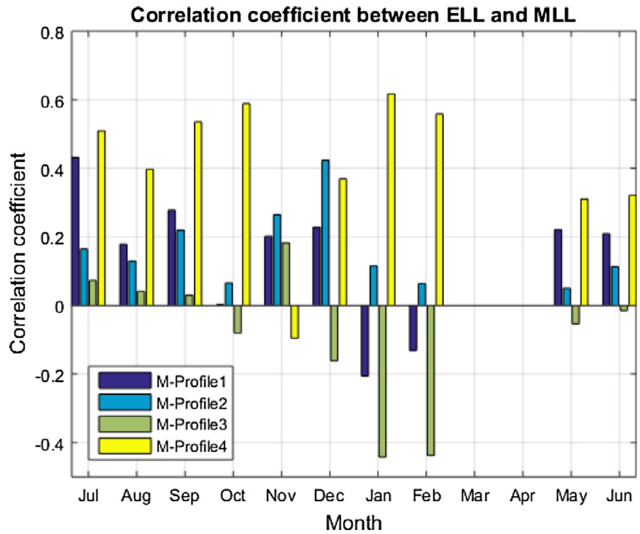

Fig. 4. Monthly correlation coefficients for different M profiles for 'Short-VHF-Link' in case of 10 m EDH. MLL and ELL are the modelled link loss and experimental link loss respectively.

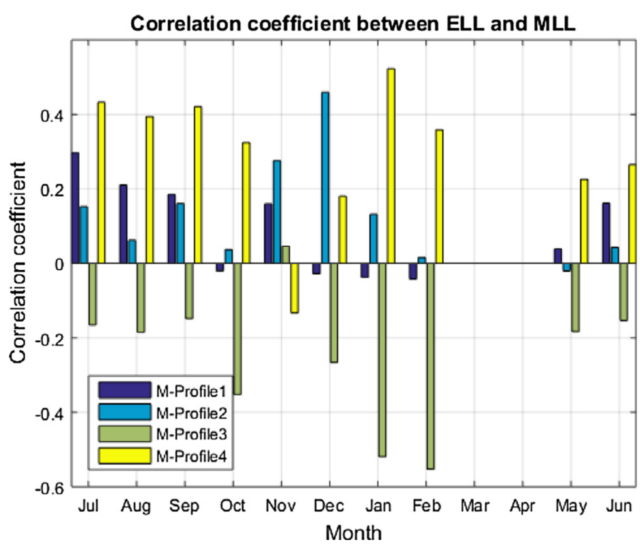

Fig. 5. Monthly correlation coefficients for different M profiles for 'Short-VHF-Link' in case of 20 m EDH. MLL and ELL are the modelled link loss and experimental link loss respectively.

annual correlation coefficient for this profile is 0.09. Similarly, for 'M-profile2−20 m-EDH' and 'M-profile2−30 m-EDH' as shown in Figs. 5 and 6 respectively, all the monthly correlation was found as insignificant except December. The annual correlation coefficients for these profiles are −0.01 and −0.12 respectively.

In the same way, 'M-profile1−0 m-EDH' as shown in Fig. 3 has all monthly correlation coefficients were found as insignificant except July and December. The annual correlation coefficient for this profile is 0.22. Similarly, for 'M-profile1−20 m-EDH' and 'M-profile2−30 m-EDH' as shown in Figs. 5 and 6 respectively, all the monthly correlations were found insignificant except July and August. The annual correlation coefficients for these profiles are 0.19 and 0.17 respectively.

'M-Profile4' is the best amongst all the profiles and 10 m of evaporation duct height is found to be more dominant amongst all the evaporation duct heights considered throughout the year of investigation as evident from the analysis presented in this research.

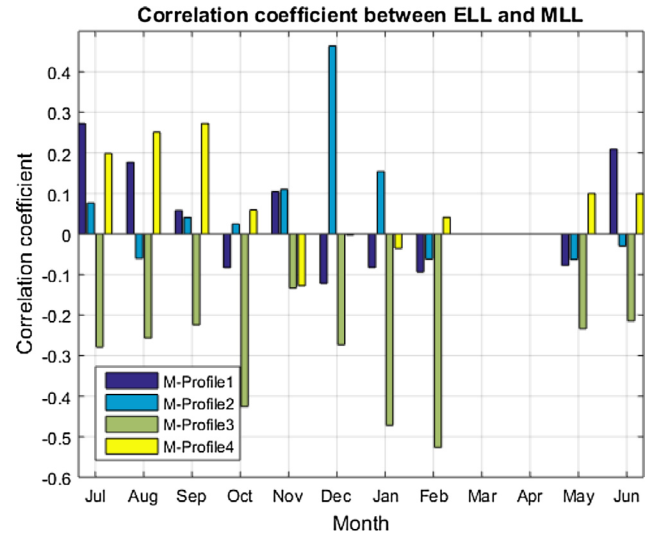

Fig. 6. Monthly correlation coefficients for different M profiles for 'Short-VHF-Link' in case of 30 m EDH. MLL and ELL are the modelled link loss and experimental link loss respectively.

Conclusion

The aim of this work was investigating the impact of modified refractivity on propagation at very high frequency by correlating experimental and modelled link losses for distribution/variations in refractivity values recommended by International Telecommunication Union – Recommendations as well as that of standard atmospheric profiles. A short-VHF-Link, consisting of 50 km length over the Sea, operating at a VHF of 240 MHz, was analyzed both experimentally and through computer simulations for the selected region. For the experimental propagation at different time, heights and distance between transmitter/receiver, a very high-resolution signal strength data (6000 values of per hour) was managed by taking the median of it. For the computer modelled propagation, a deterministic parametric model in MATLAB is used where different parameters e.g. length of the link, height of the antennas, resolution etc. were set in accordance to the parameters used in the installed experimental setup.

One important parameter amongst the characterized model parameters is refractivity profile, representing the atmospheric state at a specific time or location. The model gets this refractivity profile as input and gives the output in the form of path loss for selected communication link. Correlation analysis is performed for the modelled and experimental link losses for short-VHF-Link on monthly and annual basis. This investigation concluded that when electromagnetic waves are propagating at very high frequencies for a 50-km short link, the strongest correlation exists for the case of 10 m evaporation duct height. It is further concluded in this research that the ITU recommended refractivity profile was found to perform better than the other refractivity profiles for the VHF at the communication link of 50 km over the Sea.

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