

Cumulative Distribution of Rain Rate and Rain Attenuation in Ukraine

Odokienko Olexiy
Aerospace Radio-Electronic Systems
Department
National Aerospace University
"Kharkiv Aviation Institute"
Kharkiv, Ukraine
<https://orcid.org/0000-0002-5227-1000>

Ruzhentsev Nikolay
Aerospace Radio-Electronic Systems
Department
National Aerospace University
"Kharkiv Aviation Institute"
Kharkiv, Ukraine
<https://orcid.org/0000-0003-3023-4927>

Salnikov Dmitry
Radio-technologies of Inf. and
Communication Systems Dep.,
Kharkov National University of
Radio Electronics,
Kharkiv, Ukraine
<https://orcid.org/0000-0002-7202-1500>

Merzlikin Anatolii
Radio-technologies of Inf. and
Communication Systems Dep.,
Kharkov National University of
Radio Electronics,
Kharkiv, Ukraine
<https://orcid.org/0000-0003-1604-8837>

Anton Sobkolov
Aerospace Radio-Electronic Systems
Department
National Aerospace University
"Kharkiv Aviation Institute"
Kharkiv, Ukraine
<https://orcid.org/0000-0001-9356-4187>

Simeon Zhyla
Aerospace Radio-Electronic Systems
Department
National Aerospace University
"Kharkiv Aviation Institute"
Kharkiv, Ukraine
<https://orcid.org/0000-0003-2989-8988>

Vladimir Pavlikov
National Aerospace University
"Kharkiv Aviation Institute"
Kharkiv, Ukraine
v.pavlikov@khai.edu
<https://orcid.org/0000-0002-6370-1758>

Tsopa Oleksandr
Radio-technologies of Inf. and
Communication Systems Dep.,
Kharkov National University of
Radio Electronics,
Kharkiv, Ukraine
oleksandr.tsopa@nure.ua
<https://orcid.org/0000-0002-4881-5343>

Abstract—The grounded from a microclimatic point of view estimates of communication outages along slant Earth-Space links and near-surface links in the worst periods of the year were made for the first time on the territory of Ukraine. These calculations were based on the cycle of continuous meteorological observations of rain rate and experimental radiometric observations of atmospheric radio-heat radiation at a frequency of 39 GHz in Kharkov. Estimates of meteorological situations that are characteristic for communication outage have been determined for the frequencies 28 GHz, 38 GHz, 60 GHz and 94 GHz.

Keywords— rain rate, cumulative function, communication line, atmospheric attenuation, communication outage.

I. INTRODUCTION

The development of technologies in the field of mobile networks, the Internet and land-space communications has the increased demand for high speed data transmission. In view of this, it is supposed a wider usage the higher frequency microwave ranges up to 100 GHz in the field of data transmission technology. The use of this relatively new for the wide spread communication applications range allows to reach the acceptable levels of availability coefficient in communication networks with the growth of volumes and speed of transmitted information above 10 Gbit/s. The requirements to such network elements for summary availability factors reach 0.01-0.001%.

The problem of predicting the absorption and scattering of millimeter radio waves in the rain and in some types of clouds is important to meet these requirements [1]. The relevance of the study of the statistical parameters of the full vertical and specific near-surface attenuation of radio waves in the millimeter (MM) range has increased dramatically in the world in recent years, in particular, due

to the development of information-intensive and ultra-high-speed networks of Earth-Space and the tropospheric communication of the fifth (5G) and next generations.

The work presents for the first time the microclimatic-grounded estimates of the probabilities of communication outage on near-surface and slant paths for Ukraine (Kharkov) in the worst months of the year for the frequencies 28 GHz, 38 GHz, 60 GHz and 94 GHz.

I. STATUS OF THE PROBLEM

The Kharkov's climate is characterized, from the point of view of considered problem, by a dry period from July to August, during which a humidification occurs by thunderstorms mainly. The peak of precipitation falls on June and July thunderstorms (61 mm each). July precipitation occurs usually several times only, but these thunderstorms have heavy rainfall and are distinguished by tremendous strength. This circumstance may be the most destructive factor that disrupts the performance of the projected troposphere and ground-space communication lines.

The availability (unavailability) parameter of the communication line is a most important parameter which quantitatively characterizes the probability of communication outage [2]. The values of the link availability/unavailability parameter can be calculated using the recommendations of the International Telecommunications Union (ITU) [3-4].

The cumulative function of atmospheric attenuation distributions for each considered territory, besides for the hardware parameters of the communication line in the MM range (receiver sensitivity, transmitter power, antenna gain, etc.) is a critical parameter for predicting availability (unavailability) coefficient values [3-4]. Indeed, the signal

attenuation caused by rain and powerful cumulus clouds is the main cause of interruptions in the operation of systems of tropospheric and satellite communications of CM and MM wave bands (WB).

The cumulative distribution of specific attenuation in rain (dB / km) indicates the probability of exceeding one or another value of atmospheric attenuation. It is rather simple to determine it with the help of well-known radio-physical models if the statistical distribution of rain intensity p (R) is well known (probability p for which the rain intensity value is greater than R). It should be borne in mind that it is necessary to use meteorological data with a one-minute interval of averaging for these purposes. The ITU recommends to take into account the microclimatic features of the regions under consideration by experimentally accumulating seasonal and annual statistics of atmospheric attenuation with a one-minute interval of averaging, due to the importance of obtaining the most adequate estimates of communication reliability prediction. The long-term cycles of this kind of experimental research have already been carried out or are under way in a number of countries around the world.

Such experimental data on the cumulative functions of the total vertical and specific horizontal atmospheric attenuation in the MM WB are absent for the Ukrainian territory. Also, there is no such meteorological data as the temporal distribution of cloud water storage and one-minute rain rate which are necessary for the adequate calculation of the attenuation statistics of radio waves.

The initial data for constructing experimentally substantiated cumulative distribution functions for the total vertical attenuation of the CM and MM WB on slant paths can be obtained in three ways:

- 1) By determining the values of total atmospheric attenuation on slant paths using radiometry methods [5-8];
- 2) By the method of beacon-sounding of the atmosphere by transmission of signals with the help of transmitters of geostationary satellites;
- 3) By calculations that are based on measured cumulative functions of rain rate using regionally dependent models for rain cell sizes and spatial heterogeneity of cloudy moisture, effective path length and effective rain height which are recommended for these tasks by ITU-R.

The absence of a suitable geostationary satellite with irradiating the territory of Ukraine in the MM WB, as well as errors in the calculation method due to the total errors of the group of used models, makes the first method of obtaining the necessary data as more preferable.

The initial data for the construction of experimentally justified cumulative distribution functions of the near-surface specific attenuation of the CM and MM radio waves can be obtained in two ways:

- 1) Experimentally, by recruiting the long-term statistics of continuous changes in the horizontal specific atmospheric attenuation on terrestrial points-to-point routes [9-10]. The period of continuous accumulation of such suitable for practical usage data is 3–7 years [11];
- 2) By calculation, on the basis of experimental data on the temporal distribution of rain rate with using radio-physical models that adequately relate the intensity of rain to the value of the specific attenuation in a given wavelength range.

Despite the fact that the first method is considered more preferable from the point of view of the accuracy of assessments, its essential drawback is the relative difficulty of preparing and implementing such a long-term program of continuous point-to-point radio-physical observations.

The advantage of the second approach that is quite widely used in the world includes the presence of multi-year data-bases containing the intensity of precipitation in an extensive network of meteorological stations. Besides, takes place the presence of radio-physical models that quite accurately describe the values of specific attenuation for various rain rates in different ranges of radio waves (from 5% in the region of 10 GHz up to 30% at frequencies of about 1000 GHz). The disadvantages of this approach include the fact that the rain intensity values are presented with an averaging time (T) from 20 to 60 minutes in the overwhelming majority of the long-term data-bases. At the same time, one-minute periods of averaging the rain rates are considered as the most suitable for calculating the attenuation on the paths. This circumstance makes it necessary to recalculate T -minute data into 1-minute data by using additional models, which also have microclimatic peculiarities and which can lead to additional errors. Therefore, a more accurate solution in this approach is seen in the use of modern automated rain gauges with a 1-minute integration time for the long-term accumulation of statistical information about the rain intensity in the region under consideration.

II. HARDWARE-METHODOLOGICAL SUPPORT AND OBSERVATION CONDITIONS

A. Determination of Total Vertical Attenuation in the Atmosphere.

Knowledge of the statistical parameters of the signal attenuation on slant paths due to precipitation and cumulus types of clouds is necessary in determining the reliability and performance of satellite communication lines. We used an experimental approach for these data obtaining. This approach is based on the determination of the total vertical attenuation values according to the data of continuous radiometric monitoring of the intensity of the descending radio-heat radiation of the atmosphere in 8 MM WB.

The statistics of the total vertical attenuation in the atmosphere was obtained for the most unfavorable (in terms of signal propagation) summer month - June. The measurements were carried out in a fixed direction 40° from the zenith. The radiometer was calibrated by the method of two loads with controlled thermodynamic ambient temperature and boiling liquid nitrogen temperature. The fluctuation sensitivity of the radiometer of 39 GHz range [10] was 0.2K. The data sampling interval is 10 seconds. The 15 dB threshold values of the total attenuation on an inclined path as the sign of communication outage was used during analyzing the obtained data [1].

The calculation of the total vertical attenuation by the atmosphere in this work was carried out using the following expressions:

$$T_a = T_o - S \Delta U_a \quad (1)$$

where: T_a is the antenna temperature of the sky; S — radiometer calibration factor (K/V); ΔU_a is the difference between of output voltages of the radiometer which antenna is alternately directed to the matched load and to the sky.

$$T_a = T_{br}(1-\beta) + T_{ph}\beta - 2,73 e^{-\tau \text{Sec}\theta} \quad (2)$$

where: radio brightness temperature of the atmosphere $T_{br} = T_{eff}(1-e^{-\tau \text{Sec}\theta})$, T_{ph} - average value of background radiation (the values around 170K we used for our antenna in summer conditions), β - the parameter considering dispersion out of the main lobe of antenna pattern of the antenna system (measured value for our antenna is 4.5%), 2.73K is the space microwave background radiation, T_{eff} is the average value of the atmospheric effective temperature (the value around 288K we used for summer conditions of cloudy weather); θ – zenith angle of sight (40°).

The optical thickness of the atmosphere τ (neper) and atmospheric attenuation γ (dB) were defined as:

$$\gamma = 4.343\tau = \ln(T_{eff} - ((T_a - T_{ph}\beta)/(T_{eff} - 2,73)))/\text{Sec}\theta \quad (3)$$

B. Determination of the Near-Surface Specific Attenuation.

The main component of the signal attenuation which is critical for the near-surface communication is rain. The total contribution of gases, steam, fog and snow to atmospheric attenuation on horizontal routes in the presence of rain does not exceed as a rule 10-30%.

A computational approach which is based on experimental data on the temporal distribution of rain intensity was used in this work to build the cumulative function of the specific attenuation in the range of critical values for the probabilities of communication disturbances. The rain intensity measurements were carried out at KhAI continuously for 4 months in 2018 (June-September) using the automated wireless weather station TFA OPUS. The calculations of the specific attenuation values in rains were carried out with usage the MPM model [12].

The attenuation of 15 dB on a 1 km long path was used by us as a threshold criterion for communication outage for the considered frequencies 28 GHz, 38 GHz, 60 GHz and 94 GHz.

The form of annual probabilities of rainfall is usually used in most previous studies of rainfall attenuation for communication availability estimations. However, the annual statistics can be misleading, since in most places rain events with intensities higher than critical (when rain intensity can cause disruptions in the communication line) are concentrated only in certain months of the year. The low annual probabilities of communication outages due to rain may be unacceptably high in these months. Therefore, the monthly or the seasonal rain intensity statistics are preferred. The four-month term (June-September 2018) of continuous rain rate measurements was carried out in this work.

III. RESULTS

A. The Weakening of the Signal on Slant Paths.

The duration of communication outage on a slant path in general is a function of frequency, elevation, and the type of rain or cumulus clouds. The outage duration, for a given signal attenuation threshold and weather condition will increase with increasing a frequency and with decreasing an angle elevation.

Figure 1 shows the cumulative function of the total vertical attenuation in the atmosphere (in the direction of the zenith) obtained by the method of round-the-clock radiometric observations of radio-brightness temperature of atmosphere at 39 GHz for the worst month (June) in Kharkov.

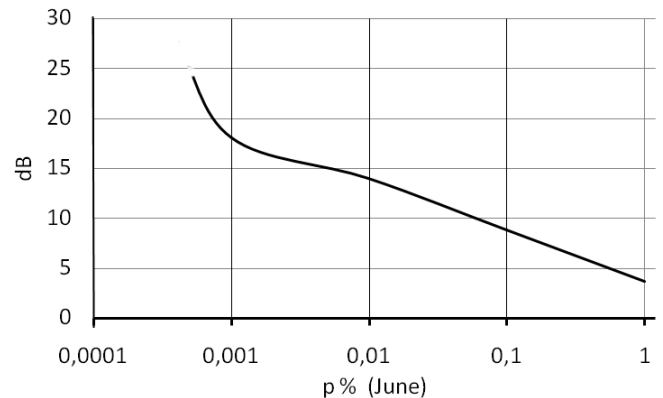


Fig. 1 The cumulative distribution of total vertical attenuation in the atmosphere for the frequency 39GHz (June, Kharkov)

Experimentally obtained and presented in Fig. 1 dependencies provide an opportunity to carry out a recalculation for other frequencies and viewing angles. When recalculating the experimental attenuation values from the frequency of 39 GHz to other frequencies, it should be borne in mind that in most cases there is a combined effect of various attenuation mechanisms (mainly due to rain and clouds) with a different frequency dependence for the droplets moisture of clouds and for rain. Therefore, it makes sense to make such frequency comparisons limited to only one of the attenuating effects.

The attenuation due to clouds at the frequencies of the MM WB can also be significant factor when using systems with a low margin for an outage. So, the water content of large cumulus clouds in middle latitudes during the year does not exceed 2 kg/m² with a probability of 99.9%, according to model estimates of ITU-R P.840-6. Our calculations show that such water storage causes a vertical attenuation of no more than 0.2 dB for frequencies about 12 GHz. However, it can be shown using the data from [14] that the attenuation values for frequencies of 19 GHz, 39 GHz and 94 GHz will increase by 2.5, 10 and 40 times respectively, for example, for cloud droplet temperatures of 10⁰ C. The attenuation values at each frequency also can increase up to 12 times as the angle of sight increases to 85° from the zenith (in accordance with the Sec θ value).

Alternatively, the models proposed by ITU-R P.837-7 can be used for similar estimates of the frequency and angular dependences of the signal attenuation in the rain for the considered territory. In accordance with them the

intensity of rain in the Kharkov region should not exceed 25 mm/h with a probability of 99.99%. The increase of signal attenuation (in dB) for 19 GHz, 39 GHz and 94 GHz compared to 12 GHz will be 2.6, 9.5 and 16 times respectively for the mentioned rain rate.

It is useful to note that the proximity of the values of frequency conversion coefficients for cloud drops and raindrops, makes it possible to rely on the adequacy of such estimates, at least in the frequency range up to 40 GHz. The accuracy of such frequency recalculations in the higher frequency ranges may decrease many times due to the difficulty of separating the contributions of rain and clouds to the overall attenuation because a significant difference in the conversion factors for these media. The estimated values of rain attenuation at each frequency as the angle of sight changes may increase as in the case of clouds, according to a value close to $\text{Sec } \theta$.

The above analysis of the dependencies obtained in 8 MM WB and a discussion of the results of estimation calculations show that the total vertical attenuation in the atmosphere should not exceed 15 dB for a zenith direction with probability more 0.01% at frequencies below 40 GHz in June weather conditions. However, the excess of this conventionally chosen threshold will quickly increase when the angle θ will increase after 60° on slant tracks and also when the operating frequencies increases. We should expect an approximately tenfold improvement in the situation for the probabilities of exceeding the chosen thresholds of the communication outage for the one-year estimating term, in contrast to the above considered June-July estimating term.

B. The Specific Attenuation of the Signal on the Terrestrial Paths

Fig. 2 shows the probabilities of exceeding the values of rain rate (that are plotted on the x-axis) which were obtained from meteorological observations (with a 5-minute integration interval) during the 4th warm months of 2018.

The 5 min averaging mode (that is a very close to 1 min mode) was used in this work for some reasons of a technical and organizational nature. The integral distribution function of rainfall intensity with an integration time of 1 minute can be obtained by converting the integral distribution functions from a longer integration time using the Recommendations ITU-R837-6. However, it is necessary to keep in mind that this and other similar models have microclimatic features, which can lead to additional errors.

The total precipitation time for the considered 4-months period of 2018 was 990 minutes: - 240 minutes in June, - 415 min. in July, - 35 min. in August and 300 min. in September.

The calculations of atmospheric attenuation were performed basing on these meteorological data with using the MPM model for the frequencies of 28 GHz, 38 GHz, 60 GHz and 94 GHz.

Fig. 3 shows the calculated dependences of the cumulative distribution of the atmospheric attenuation at the frequencies of 28 GHz, 38 GHz, 60 GHz and 94 GHz for the July and fig. 4 - for the June 2018.

The attenuation values for $p = 0.01\%$ are 1.4, 4.1, 7.7 and 8 dB/km for 28 GHz, 38 GHz, 60 GHz and 94 GHz respectively, for both August and September.

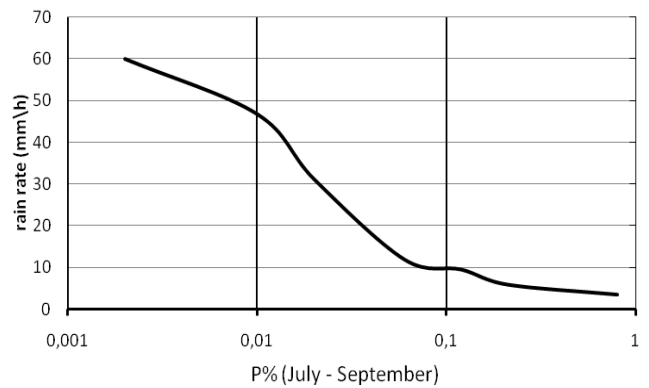


Fig.2 The cumulative distribution of rain rate over the 4-month period 2018 (June-September) in Kharkov (50N, 36E), Ukraine.

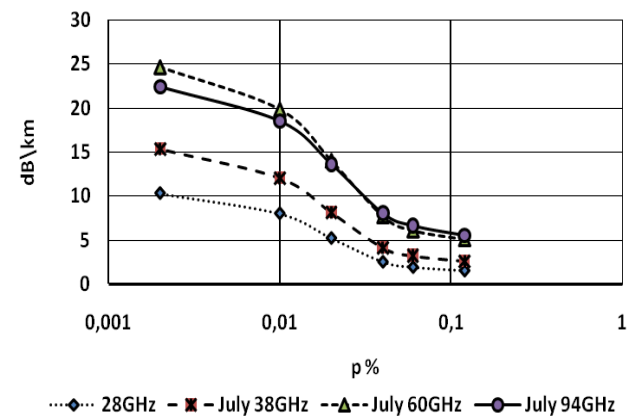


Fig. 3 The cumulative distribution of the atmospheric specific attenuation for the frequencies 28 GHz, 38 GHz, 60 GHz and 94 GHz (July)

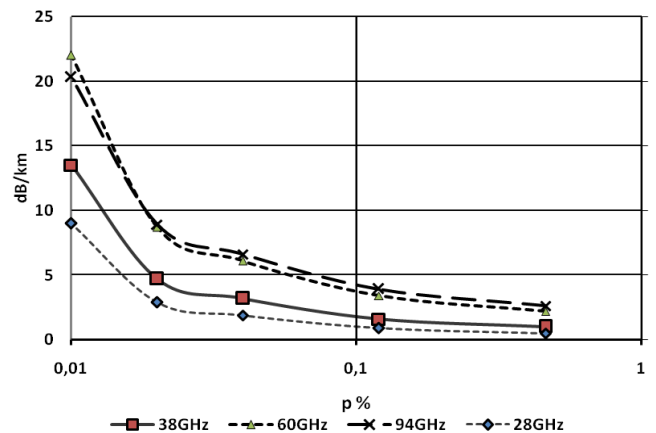


Fig. 4 Cumulative distribution of specific atmospheric attenuation for the frequencies of 28 GHz, 38 GHz, 60 GHz and 94 GHz (June)

The data obtained demonstrates that for $p = 0.01\%$ over a period of 4 warm months, the attenuation does not exceed 9 dB/km. So, the connection can be considered reliable in all considered wavelengths, at least for 2018. Accordingly, the even lower probabilities of extremely high specific attenuation values should be expected for the of one-year period. However, if the communication problems will be considered for the worst months (June-July), then the attenuation values for each of them separately with probabilities of 0.01% (Fig. 4) will exceed the threshold of communication outage noted above (15 dB/km) at frequencies of 60 GHz and 94 GHz.

The issues of precipitation events causing communication outage and their inter-year variability, as well as the ITU-R adequacy of the models for converting T-minute rain rate

data into 1-minute [rain rate data](#) in the considered region of Ukraine, deserve further study for development of high-frequency networks of troposphere and satellite communications.

IV. CONCLUSIONS

Data on rain intensity obtained from a 5-minute averaging interval for one of the most populated, industrially and infrastructural developed regions of Ukraine (Kharkov) are presented. The experimentally substantiated estimates of the probabilities of the troposphere communication outage due to manifestations of critical levels of rain can be made on their basis. Estimates of meteorological situations characteristic of communication outages were determined for the worst month and for 4 months of the warm period of the year using the radio-physical MPM model.

As a criterion for near-surface communication failure a attenuation threshold of 15 dB/km was used on a 1 km horizontal path for all considered wavebands — 28 GHz, 38 GHz, 60 GHz, and 94 GHz.

Data are presented on the cumulative distribution functions of the total vertical atmospheric attenuation in the worst month of the year in 8 MMWB. These data were obtained on the basis of the round-the-clock radiometric observations of the descending radio-heat radiation of the atmosphere. As a criterion for communication failure, a full vertical attenuation threshold of 15 dB was used.

The results indicate that it is possible to provide reliable communication in the range of average and zenith viewing angles in the considered frequency ranges with a probability of 99.99% for a one-year term of estimating. It is noted that the probability of communication outage will rapidly increases as the frequency and/or increases of the zenith viewing angles of the antennas. An approximate assessment of the impact of specific values of these parameters can be promptly carried out on the basis of the presented dependencies, using the conversion factors cited in the paper.

Attention is drawn to the fact that the annual statistics, which include the winter months with a very low probability of interruptions, hide the real effect of atmospheric attenuation on work during the warm period of the year. The design of EHF communications should also take into account the conditions during the months when the probability and duration of outages are [maximal](#).

The data presented in this study and the above findings may be useful in forming a general strategy for minimizing the effects of atmospheric attenuation. For example, switching to lower frequencies, changing data transmission routes and / or using higher power levels may be required to increase the availability of communication systems in the summer months, when rain attenuation is usually the largest.

New data on the intensity of rain which analyzed in the work allow for the first time to give for one of the regions of Ukraine a reasonable quantitative estimate of the likelihood and duration of interruptions in the EHF communication due to weather conditions for one of the regions of Ukraine.

Further study of the statistics of atmospheric attenuation of MM radio waves is planned to take place over several one-year cycles of continuous measurements with 1 minute interval for the integrated radio-physical and meteorological observations.

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