

Algorithm for Parametric Accounting of the Underlying Surface Effect on Radio Wave Propagation Loss Based on Experimental Data

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Abstract. The accuracy of radio wave propagation loss estimation is limited by the fact that empirical models describe the environment through an averaged terrain category and do not distinguish open terrain, vegetation cover and water surface. The transition from heterogeneous field measurements to a set of parameters suitable for further modelling remains insufficiently formalized. The aim of this work is the development and experimental-statistical substantiation of an algorithm for parametric accounting of the underlying surface type effect on radio wave propagation loss based on field measurement data. Primary numerical series of signal level measurements in the 900 and 1800 MHz bands along seven paths were used (open terrain: 175 and 130 points; rural single-storey built-up area: 215, 108 and 78 points; fresh-water surface: 103 and 94 points), together with arrays of 893 and 359 measurements in vegetation cover. The algorithm comprises data pre-processing, classification of paths by the type of underlying surface, statistical processing of the samples with regression approximation and residual calculation, determination of quantitative propagation parameters, testing of their statistical significance with possible refinement, and formation of the output parameter set. It was established that the path loss exponent equals 2.32 and 2.33 for open terrain, 1.45–2.05 for single-storey built-up areas and 3.22 and 3.23 for the fresh-water surface, with a standard deviation of residuals of 3.25–9.50 dB. The result of the algorithm is a parameter set differentiated by surface type and suitable for the subsequent construction of a surface-conditioned loss correction.

Keywords: Radio wave propagation · Underlying surface · Propagation loss · Path loss exponent · Experimental data · Statistical processing · Residual deviations · Parametric accounting · Algorithm · Cellular communication

1 Introduction

The determination of radio wave propagation loss is the primary task in the design and optimization of mobile networks: the path loss value determines the signal level at the receiving point and hence the boundaries of the served area.

The accuracy of this determination directly affects the choice of base station sites, their power parameters and the cost of network deployment [11,14].

Propagation loss is formed by a combination of reflection, diffraction and scattering mechanisms whose characteristics depend on the properties of the underlying surface along the path. Vegetation cover introduces additional attenuation depending on frequency, density and penetration depth into the vegetation [5,8]; a water surface, in contrast, is characterized by a high reflection coefficient and virtually complete absence of shadowing, so that propagation above it is described by dependences different from those over land [2,7,15]. In recent studies the land cover type is used as an independent feature in loss prediction [10,16].

The widely used empirical models, Okumura–Hata [3], COST-231 [1] and their modifications, describe the environment by a terrain category (urban, suburban, open area). Such a representation is convenient for engineering calculations; however, open terrain, vegetation cover and a water body are thereby assigned to a single category, and the prediction accuracy outside the conditions for which the model was derived decreases considerably [9,13,14]. Review studies show that a priori models, irrespective of their complexity, provide limited accuracy, and that accuracy is improved by calibration against field measurements in the target area [6,11].

Calibration against measurements presupposes an ordered set of experimental parameters characterising the propagation conditions. At the same time, field series obtained along paths with different types of underlying surface are heterogeneous: they differ in measurement geometry, length, frequency and in the character of the level variation with distance. Processing such series within a single scheme requires prior classification of the paths and a consistent set of computed characteristics.

An analysis of published works shows that the statistical processing procedures for propagation measurements (regression on the logarithm of distance, estimation of the path loss exponent, residual analysis) are described in sufficient detail [11–13], whereas the transition from heterogeneous experimental series to a parameter set differentiated by the type of underlying surface and suitable for subsequent modelling is presented to a limited extent and requires further formalization.

The aim of the present study is the development and experimental-statistical substantiation of an algorithm for parametric accounting of the underlying surface type effect on radio wave propagation loss based on the processing of field data. The contribution of the work consists in formalizing a processing sequence that yields comparable quantitative parameters for four types of propagation conditions, and in the experimental determination of these parameters in the 900 and 1800 MHz bands. The construction of a loss model and coverage area calculation are beyond the scope of this paper; the formed parameter set is considered as the result of the algorithm.

2 Materials and Methods

2.1 Experimental Data and Measurement Conditions

The experimental arrays used in this study were formed during previously performed field measurements of the signal level of operating cellular base stations in the 900 and 1800 MHz bands and, in the present work, were subjected to statistical processing for the development of an algorithm for parametric accounting of the underlying surface type effect. The measurements were carried out at a uniform receiving antenna height of 1.5 m with coordinate referencing of the points; the recorded quantity was the received signal power P_2 , dBm, while for the paths over the water surface the field strength E , dB(μ V/m), obtained by conversion of the measured power in accordance with Recommendation ITU-R P.525 [4], was additionally used.

The composition of the experimental samples is given in Table 1. The samples of different paths were not combined, since they refer to different base stations and propagation conditions. The measurement array in vegetation cover was obtained while moving across the area with registration of the level from several serving sectors and has no uniform radial geometry; therefore, the level distribution and the level dependence on the distance along the measurement route are used for it.

Table 1: Experimental samples and measurement conditions

Type of underlying surface	Frequency, MHz	Sample size N	Distance range, km
Open terrain	900	175	0.14–11.55
Open terrain	1800	130	0.14–10.25
Rural single-storey built-up area, path I	900	215	0.66–12.91
Rural single-storey built-up area, path II	900	108	0.08–14.97
Rural single-storey built-up area, path II	1800	78	0.08–12.10
Fresh-water surface	938.6	103	0.32–6.22
Fresh-water surface	1873.4	94	0.39–6.17
Vegetation cover	900	893	route $\approx$ 5.3
Vegetation cover	1800	359	route $\approx$ 5.3

2.2 Characteristics of the Studied Types of Underlying Surface

Four types of propagation conditions differing in the character of the underlying surface are considered. Open terrain is a relatively flat area without dense devel-

opment; it is adopted as the reference condition, since the influence of additional mechanisms here is minimal. A rural single-storey built-up area is distinguished by regular shadowing from buildings while the terrain as a whole remains open. Vegetation cover forms a volumetrically distributed absorbing and scattering medium characterized by additional losses and increased level variability [5, 8]. A fresh-water surface is characterized by a high reflection coefficient and the absence of shadowing, which determines the interference character of the signal level variation along the path [2, 7].

The selection of exactly these four types is determined by the composition of the available experimental data and corresponds to the division of propagation conditions adopted in the classification of paths within the algorithm (Section 2.4). The numerical characteristics of each type are obtained as a result of the algorithm operation and are given in Section 3.

2.3 Methods of Statistical Processing of Experimental Data

The signal level measured at an individual point is considered as a realisation of a random variable formed by the superposition of waves with unaccounted phases; therefore, the set of measurements along a path is processed as an experimental sample. For each sample the size, distance range, minimum and maximum values, mean, median, variance, standard deviation and the half-width of the confidence interval of the mean at a confidence probability $\beta = 0.95$ are determined using the Student distribution with $N - 1$ degrees of freedom.

The average law of signal level decrease with distance is described by the normalised logarithmic dependence

$$P_2(r) = P_0 - 10n \lg\left(\frac{r}{R_0}\right), \quad (1)$$

where $P_2(r)$ is the measured received power, dBm; P_0 is the level referred to the reference distance $R_0 = 1$ km, dBm; n is the path loss exponent; r is the distance to the base station, km. The path loss exponent is estimated by the least squares method from the pairs $(x_i = \lg(r_i/R_0); p_i)$:

$$n = -\frac{N \sum x_i p_i - \sum x_i \sum p_i}{10 \left[N \sum x_i^2 - (\sum x_i)^2 \right]}, \quad (2)$$

where N is the sample size and p_i is the measured power at the i -th point, dBm. For the paths over the water surface a quadratic trend of the field strength is additionally extracted:

$$E_{\text{trend}}(r) = a_2 r^2 + a_1 r + a_0, \quad (3)$$

where E_{trend} is the smoothed field strength value, dB(μ V/m); r is the distance, m; a_2, a_1, a_0 are the coefficients determined by the least squares method. The quadratic approximation is used as a means of statistically extracting the average

spatial variation of the level and is not considered as a physical propagation model.

The approximation quality is evaluated by the coefficient of determination and the root-mean-square error:

$$R^2 = 1 - \frac{\sum (y_i - \hat{y}_i)^2}{\sum (y_i - \bar{y})^2}, \quad (4)$$

$$\text{RMSE} = \sqrt{\frac{1}{N} \sum (y_i - \hat{y}_i)^2}, \quad (5)$$

where y_i is the measured value (P_2 or E), $\hat{y}_i$ is the value obtained from the approximating dependence and $\bar{y}$ is the sample mean. The residual deviations with respect to the average trend are determined as

$$e_i = y_i - \hat{y}_i. \quad (6)$$

Their mean is zero by construction, and the standard deviation σ_e characterises the intensity of local level variations. The experimental loss at the reference distance is calculated from the radio link power budget:

$$K = P_b + G_b + G_m - L_f - P_0, \quad (7)$$

where K is the experimental loss at the reference distance, dB; P_b is the base station transmitter power, dBm; G_b is the transmitting antenna gain, dBi; G_m is the receiving antenna gain, dBi; L_f is the antenna-feeder loss, dB. The calculation was performed for the configuration $P_b = 43$ dBm, $G_b = 16$ –18 dBi, $G_m = 3$ dBi, $L_f = 0.5$ –1.5 dB; the exponent n does not depend on this configuration.

2.4 Algorithm for Parametric Accounting of the Underlying Surface Effect

The purpose of the algorithm is to obtain, from heterogeneous field data, an ordered set of quantitative parameters characterising propagation loss for different types of underlying surface in a form that ensures comparability of the parameters between surface types. The structure of the algorithm is shown in Fig. 1.

The input of the algorithm is the initial field measurement data containing the frequency f , the distance d , the measured signal level L_{meas} , the base and mobile station antenna heights h_{BS} and h_{MS} , as well as information on the surface type along the path under study; the data source is the measurement database of the 900 and 1800 MHz bands. Pre-processing prepares the initial data for the subsequent statistical analysis and includes a completeness check. In the initial source materials, the criteria of filtering and outlier removal are not specified; therefore, in the present work the corresponding stage is described to the extent corresponding to the original algorithm.

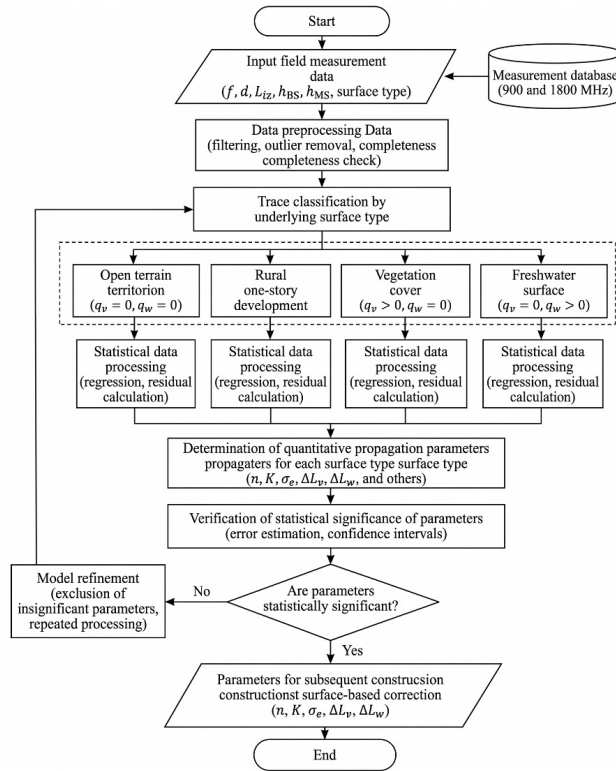


Fig. 1: Algorithm for parametric accounting of the underlying surface effect on radio wave propagation loss based on experimental data

The next stage is the classification of the measurement paths according to the character of the underlying surface with the identification of four groups: open terrain, rural single-storey built-up area, vegetation cover and fresh-water surface. The classification is performed prior to the statistical processing, which is essential: it ensures separate determination of the parameters for conditions differing in the field formation mechanisms and excludes averaging of the characteristics over heterogeneous paths.

For each identified group of paths, statistical processing of the experimental data is performed, including regression approximation and calculation of residual deviations. The regression approximation is carried out using dependence (1) with estimation of the path loss exponent by (2); for the paths over the water surface the quadratic trend (3) is additionally determined. The approximation quality is evaluated by (4) and (5), and the residual deviations by (6). The parallel organization of this stage for the four groups of paths ensures the application of a single processing scheme with different forms of describing the average level behavior.

The processing results for the groups are combined at the stage of determining the quantitative propagation parameters for each surface type. The determined parameters include the path loss exponent n , the coefficient K , the standard deviation of the residual variations σ_e , as well as the additional loss components caused by vegetation cover and water surface, ΔL_v and ΔL_w . The value of K is determined by (7) for the specified radio link configuration.

After the parameters have been determined, their statistical significance is assessed taking into account the errors and confidence intervals. If statistically non-significant parameters are identified, the algorithm provides for model refinement, i.e. the elimination of such parameters and repeated processing of the corresponding sample, for which a return to the path classification stage is provided. The iterative character of this stage makes it possible to form a consistent set of characteristics, each of which has statistical confirmation. If statistical significance is confirmed, the obtained parameters are accepted as the output ones.

The output of the algorithm is the set of parameters n , K , σ_e , ΔL_v and ΔL_w formed separately for the studied types of underlying surface. This set represents a parametric description of the propagation conditions obtained directly from field data; its use at subsequent modelling stages is beyond the scope of the present work.

3 Results

3.1 Statistical Characteristics of the Experimental Samples

The results of the statistical processing stage are given in Table 2. The mean signal levels are -69.48 and -69.99 dBm for open terrain, -80.86 , -76.71 and -79.29 dBm for the single-storey built-up area and -67.85 and -69.09 dBm for the fresh-water surface; for vegetation cover the mean levels are -73.5 and

−76.2 dBm with a standard deviation of 9.69 and 9.85 dB and a half-width of the confidence interval of the mean of ± 0.64 and ± 1.02 dB. Since the paths refer to different radio links, the differences in mean levels reflect both the propagation conditions and the power parameters; therefore, the subject of further comparison is the level decrease law and the variation characteristics.

The standard deviation of levels along the paths is 10.73–13.28 dB, and for the water samples it is practically identical in the two bands (10.75 and 10.73 dB), which in the subsequent analysis makes it possible to attribute the differences between the bands to variations with respect to the average trend rather than to the overall sample variability.

Table 2: Statistical characteristics of the experimental samples

Parameter	Open, 900	Open, 1800	Built- up I, 900	Built- up II, 900	Built- up II, 1800	Water, 938.6	Water, 1873.4
Mean $\bar{P}_2$, dBm	−69.48	−69.99	−80.86	−76.71	−79.29	−67.85	−69.09
Median, dBm	−71.20	−76.44	−83.52	−78.28	−80.52	−71.76	−71.16
Standard deviation s , dB	11.15	13.28	11.49	11.79	12.02	10.75	10.73
Range, dB	47.20	54.00	54.94	59.20	50.40	44.68	48.80
Half-width of the CI of the mean ($\beta = 0.95$), dB	1.66	2.30	1.54	2.25	2.71	2.10	2.20

3.2 Parameters of the Experimental Dependences

The approximation parameters obtained at the next stage of the algorithm are given in Table 3. The experimental dependences of the signal level on distance for open terrain are shown in Fig. 2, and for the fresh-water surface in Fig. 3.

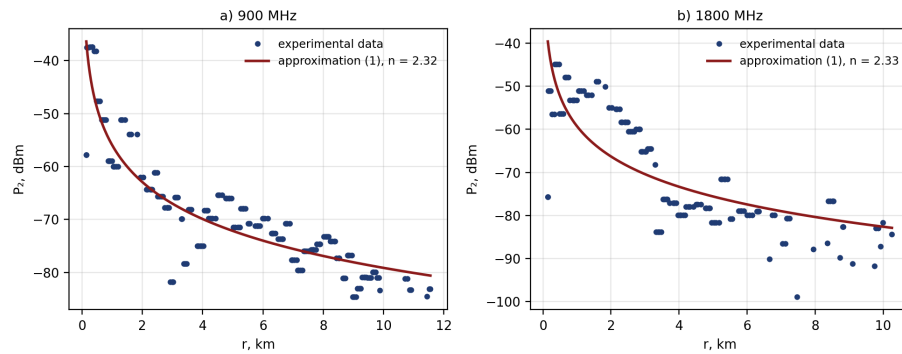


Fig. 2: Experimental dependences of the signal level on distance for open terrain and approximation (1): (a) 900 MHz; (b) 1800 MHz

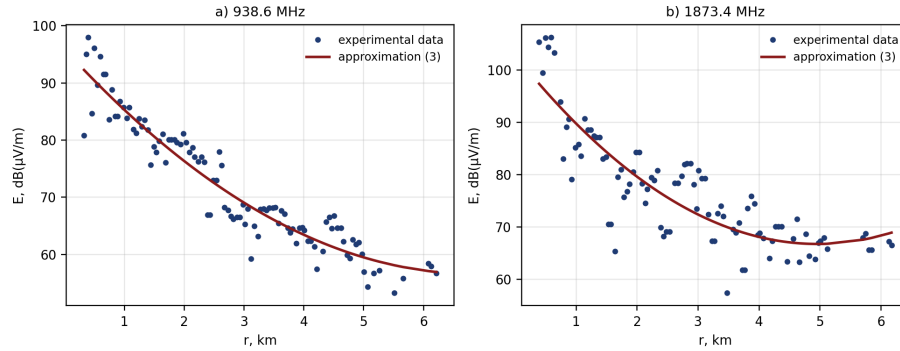


Fig. 3: Experimental dependences of the field strength on distance over the fresh-water surface and quadratic approximation (3): (a) 938.6 MHz; (b) 1873.4 MHz

For open terrain the path loss exponent is $n = 2.32$ (900 MHz; $R^2 = 0.816$; RMSE = 4.77 dB) and $n = 2.33$ (1800 MHz; $R^2 = 0.597$; RMSE = 8.40 dB). The practical coincidence of the exponents in the two bands along the same path indicates a common geometric mechanism of level decrease, whereas the difference in the coefficients of determination reflects the greater intensity of variations in the upper band. For the single-storey built-up area the exponents are lower: 2.05 on path I and 1.45 and 1.55 on path II with $R^2 = 0.363$ –0.461; such values show that the decrease with distance explains less than half of the sample variance, while the dominant factor is shadowing by buildings.

For the fresh-water surface $n = 3.22$ (938.6 MHz; $P_0 = -55.97$ dBm; $R^2 = 0.872$; RMSE = 3.82 dB) and $n = 3.23$ (1873.4 MHz; $P_0 = -56.87$ dBm; $R^2 = 0.765$; RMSE = 5.17 dB) were obtained. The exponents practically coincide, and the average decrease law turns out to be steeper than over open land. The quadratic field strength trend describes 90.9% of the variance at 938.6 MHz (RMSE = 3.23 dB) and 73.6% at 1873.4 MHz (RMSE = 5.49 dB) with the coefficients $a_2 = 8.3167 \cdot 10^{-7}$ and $1.4690 \cdot 10^{-6}$ dB/m², $a_1 = -1.1432 \cdot 10^{-2}$ and $-1.4567 \cdot 10^{-2}$ dB/m, $a_0 = 95.859$ and 102.876 dB(μV/m).

The experimental losses at the reference distance calculated by (7) for the central configuration values are $K = 117.9$ and 121.3 dB for open terrain, 132.1, 132.3 and 135.5 dB for the single-storey built-up area and 118.0 and 118.9 dB for the fresh-water surface. A variation of the antenna gain within 16–18 dBi and of the feeder loss within 0.5–1.5 dB shifts K by ± 1.5 dB, which is taken into account when interpreting the absolute values.

3.3 Analysis of Residual Deviations

The characteristics of the residual deviations obtained by (6) are given in Table 4, and the deviations themselves are shown in Fig. 4.

For the fresh-water surface the standard deviation of the residuals with respect to the quadratic trend is 3.25 dB (938.6 MHz) and 5.52 dB (1873.4 MHz),

Table 3: Parameters of the experimental dependences

Parameter	Open, 900	Open, 1800	Built- up I, 900	Built- up II, 900	Built- up II, 1800	Water, 938.6	Water, 1873.4
Path loss exponent n by (2)	2.32	2.33	2.05	1.45	1.55	3.22	3.23
P_0 ($R_0 = 1$ km), dBm	-55.94	-59.29	-70.11	-70.35	-73.49	-55.97	-56.87
R^2 by (4)	0.816	0.597	0.461	0.363	0.375	0.872	0.765
RMSE by (5), dB	4.77	8.40	8.42	9.36	9.44	3.82	5.17
a_2 by (3), dB/m ²	—	—	—	—	—	$8.3167 \cdot 10^{-7}$	$1.4690 \cdot 10^{-6}$
a_1 by (3), dB/m	—	—	—	—	—	$-1.1432 \cdot 10^{-2}$	$-1.4567 \cdot 10^{-2}$
a_0 by (3), dB(μ V/m)	—	—	—	—	—	95.859	102.876
R^2 / RMSE of the quadratic approximation	—	—	—	—	—	0.909 / 3.23 dB	0.736 / 5.49 dB

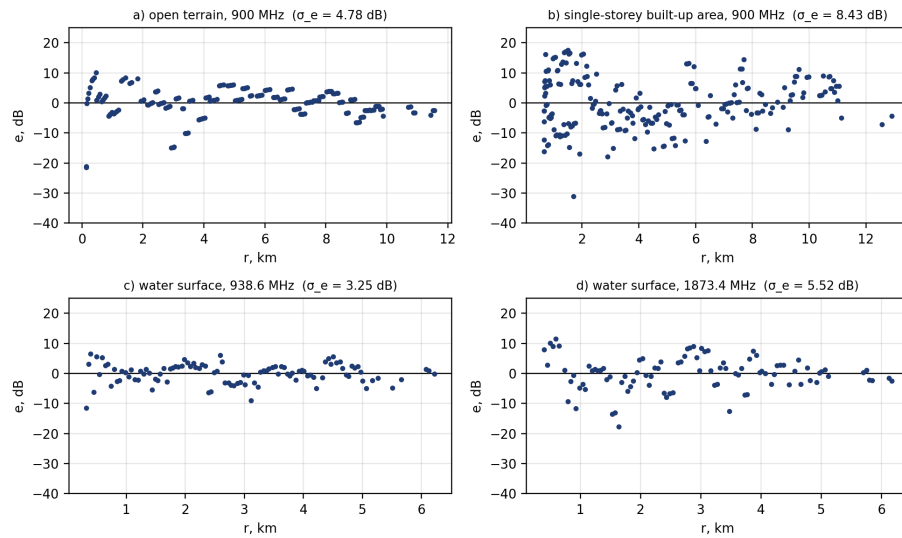


Fig. 4: Residual deviations of the experimental values from the approximating dependences: (a) open terrain, 900 MHz; (b) single-storey built-up area, 900 MHz; (c) water surface, 938.6 MHz; (d) water surface, 1873.4 MHz

with shares of points with $|e_i| > 5$ dB equal to 11.7 and 30.9 %. With a practically identical overall spread of the samples, the variations with respect to the trend in the upper band are 1.7 times more intense, which corresponds to the interference character of the level variation above a reflecting surface. The variations weaken with increasing distance from the base station: σ_e decreases from 3.58 to 2.85 dB and from 6.48 to 4.17 dB in the transition from the section up to 3 km to the section of 3–6 km.

For open terrain σ_e is 4.78 dB (900 MHz) and 8.43 dB (1800 MHz); the largest deviations are observed near the base station, and beyond 6 km the values decrease to 2.93 and 5.23 dB. The presence of extended sections of residuals with a constant sign indicates a deviation of the actual decrease law from a single logarithmic dependence. For the single-storey built-up area σ_e is 8.43–9.50 dB with a share of points with $|e_i| > 10$ dB from 25.1 to 27.8 %, which corresponds to the known log-normal description of shadowing with σ of the order of 8 dB [11, 13].

Table 4: Characteristics of the residual deviations

Parameter	Open, 900	Open, 1800	Built-up I, 900	Built-up II, 900	Built-up II, 1800	Water, 938.6	Water, 1873.4
Basis for residual calculation	(1)	(1)	(1)	(1)	(1)	(3)	(3)
σ_e , dB	4.78	8.43	8.43	9.41	9.50	3.25	5.52
$e_{\min} / e_{\max}$, dB	-21.4 / +10.0	-36.0 / +15.3	-31.1 / +17.5	-23.9 / +21.7	-22.5 / +20.1	-11.5 / +6.5	-17.6 / +11.4
Share of $ e_i > 5$ dB, %	20.6	52.3	57.2	58.3	60.3	11.7	30.9
Share of $ e_i > 10$ dB, %	4.6	16.2	25.1	27.8	26.9	1.0	7.4
σ_e at $r \leq 1$ km, dB	8.11	12.70	8.65	14.52	14.43	–	–
σ_e at 1–3 km, dB	5.47	2.52	11.22	10.24	6.78	3.58 (≤ 3 km)	6.48 (≤ 3 km)
σ_e at 3–6 km, dB	4.90	4.82	7.05	6.15	8.61	2.85	4.17
σ_e at $r > 6$ km, dB	2.93	5.23	5.48	5.37	5.97	–	–

3.4 The Formed Parameter Set of the Algorithm

The final parameter set obtained as a result of the algorithm operation is given in Table 5. For each type of underlying surface the path loss exponent n , the experimental loss at the reference distance K and the standard deviation of the residual variations σ_e are determined; for the fresh-water surface the coefficients of the quadratic field strength trend are additionally determined. For vegetation cover the exponent n and the coefficient K are not determined because of the absence of a uniform radial measurement geometry, and the characteristics of this surface type are the level distribution and the additional loss ΔL_v .

A comparison of the normalised experimental dependences for three surface types in the 900 MHz band is shown in Fig. 5. The three groups of conditions differ in their position relative to the free-space law ($n = 2$): open terrain (2.32) slightly exceeds it, the built-up area (2.05 and 1.45) formally lies below it owing to the dominance of shadowing with a weak relation between level and distance, and the fresh-water surface (3.22) is characterised by a substantially steeper decrease.

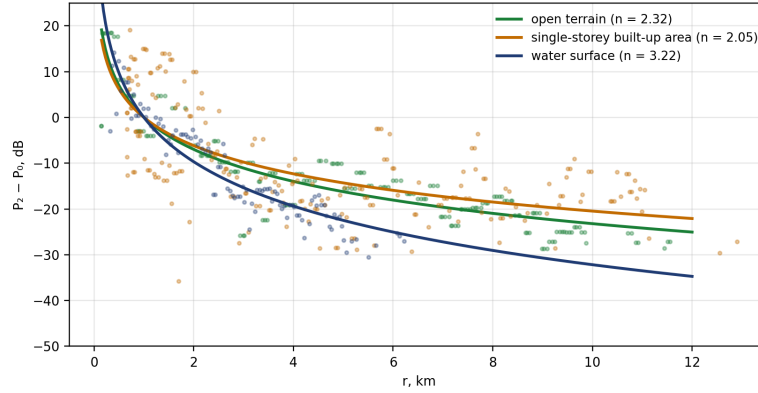


Fig. 5: Comparison of the normalised experimental dependences of the signal level on distance for different types of underlying surface, 900 MHz band

The additional loss in vegetation cover included in the output set is $\Delta L_v = 6.85$ dB (900 MHz) and 12.37 dB (1800 MHz); these values were obtained in preceding studies and are used in the present work as a characteristic of the corresponding surface type. The numerical value of ΔL_w for the fresh-water surface is absent in the initial experimental materials; in the output set of the algorithm this quantity is indicated as an element determined when the corresponding data are available.

4 Discussion

The obtained results show that processing field data within a single scheme with prior classification of the paths by the type of underlying surface leads to quantitatively different parameter sets. The difference in the path loss exponents, from 1.45–2.05 for the single-storey built-up area and 2.32–2.33 for open terrain to 3.22–3.23 for the fresh-water surface, exceeds the spread of values within each group, which confirms the necessity of separate parameter determination and, consequently, the expediency of classification as an independent stage of the algorithm.

The necessity of accounting for the type of underlying surface when processing experimental data also follows from the character of the residuals. With a similar overall spread of the samples over water in the two bands, the intensity of

Table 5: Formed parameter set of the algorithm by types of underlying surface

Type of underlying surface	Frequency, MHz	n	K , dB	σ_e , dB	Additional parameters
Open terrain	900 / 1800	2.32 / 2.33	117.9 / 121.3	4.78 / 8.43	–
Rural single-storey built-up area	900 (path I)	2.05	132.1	8.43	–
Rural single-storey built-up area	900 / 1800 (path II)	1.45 / 1.55	132.3 / 135.5	9.41 / 9.50	–
Vegetation cover	900 / 1800	not determined	not determined	9.69 / 9.85 (level spread)	$\Delta L_v = 6.85 / 12.37$ dB (obtained earlier)
Fresh-water surface	938.6 / 1873.4	3.22 / 3.23	118.0 / 118.9	3.25 / 5.52	a_2, a_1, a_0 by (3); ΔL_w when data are available

the variations with respect to the trend differs by a factor of 1.7, whereas for the built-up area shadowing with σ_e of about 8–9.5 dB prevails. If such series were combined into a single sample, the obtained estimates would lose their physical interpretation: the averaged path loss exponent would correspond to none of the actual types of conditions.

The most informative parameters of the output set are the path loss exponent n and the standard deviation of the residuals σ_e . The former is robust to changes in the power configuration of the radio link and characterises the shape of the level dependence on distance; the latter characterises the intensity of local variations and differs both between surface types and between bands. The coefficient K , in contrast, depends on the adopted configuration (± 1.5 dB for a variation of the gain and feeder loss), which must be taken into account in its use.

The coincidence of the path loss exponents in the two bands over water (3.22 and 3.23) together with a substantial difference in the intensity of the variations (3.25 and 5.52 dB) is consistent with the concepts of field formation above a reflecting surface, where the average decrease law is determined by the path geometry, while the frequency dependence manifests itself in the interference structure of the field [2, 7, 15]. The path loss exponent values for open terrain, lying between the free-space law and the typical values of empirical models, also correspond to published measurement results in rural conditions [9, 12].

The limitations of the algorithm are determined by the composition of the initial data. First, the parameters were obtained for two frequency bands and for specific paths, and therefore their transfer to other areas requires verification. Second, for vegetation cover the absence of a radial measurement geometry does not allow n and K to be determined, so the composition of the output set for this surface type differs from the others. Third, in the initial materials the criteria of filtering and outlier removal at the pre-processing stage are not specified, and the results of the statistical significance testing are represented by the confidence

intervals of the means, whereas cases of the actual elimination of non-significant parameters are not documented; the corresponding stages of the algorithm are presented to the extent supported by the initial data.

A distinction should be drawn between the results obtained directly in the course of the present processing and the characteristics relating to preceding studies. The former include the statistical characteristics of the samples, the path loss exponents n , the coefficients K , the trend parameters and the characteristics of the residual variations; the latter include the additional loss in vegetation cover ΔL_v and the calibration parameters of the empirical models, which were obtained earlier and are not claimed as an independent result of the present work.

5 Conclusions

An algorithm for parametric accounting of the underlying surface effect on radio wave propagation loss based on experimental data has been developed, comprising pre-processing of the initial field data, classification of the paths by the type of underlying surface, statistical processing of the identified groups with regression approximation and calculation of residual deviations, determination of quantitative propagation parameters, testing of their statistical significance with possible refinement, and formation of the output parameter set.

Based on the measurements in the 900 and 1800 MHz bands along seven paths and in the measurement array in vegetation cover, quantitative parameters characterising four types of propagation conditions were obtained: a path loss exponent of 2.32 and 2.33 for open terrain, 2.05, 1.45 and 1.55 for the rural single-storey built-up area, and 3.22 and 3.23 for the fresh-water surface; experimental losses at the reference distance of 117.9–135.5 dB; a standard deviation of the residual variations of 3.25–9.50 dB with a decrease at greater distances from the base station; and the coefficients of the quadratic field strength trend for the water path.

It has been established that the separate processing of paths by types of underlying surface leads to quantitatively different parameter sets, the differences between the types exceeding the spread within each group, while the most informative characteristics of the output set are the path loss exponent and the standard deviation of the residual variations.

The formed parameter set represents a parametric description of the propagation conditions obtained directly from field measurements and can be used at subsequent stages of propagation loss modelling for a heterogeneous composition of the underlying surface.

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