The Height Scan Method Accuracy in Rural and Suburban Areas

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***Abstract*—The paper presents the results of measuring the radiated power using the scanning of the field strength in height in rural and suburban areas, when the surface is flat and there are no interfering reflections from nearby surrounding objects. It also provides a detailed analysis of the influence of the ground surface and body of vehicle-mounted measurement station on the properties of the height dependence of the field strength at frequencies from 0.5 GHz to 6 GHz. When using the original technique, due to the influence of these factors, the measurement result randomly depends on the height at which the field strength due to the direct wave was determined. Good measurement results are obtained by using height-averaged value of this field strength or by determining this field strength by using a new method named as averaging of the log-scaled values method: the measurement error of the radiated power does not exceed 1.3 dB. The measurement results also showed that the measurement error of the radiation power is mainly influenced by the accuracy of the measuring equipment, and not by the surface or the car body.**

Keywords—radiated power, field strength, direct wave, reflected wave, ground reflection, antenna, measurement, measurement error

I. Introduction

The radiated power is an essential parameter in planning and managing the spectrum. The amount of radiated power of radio stations directly affects the electromagnetic compatibility in radio networks. For these reasons, the radiated power is specified in authorizations and the verification of its value for compliance with the authorization conditions is an important task of the spectrum monitoring or inspection services.

In this paper, the term ‘radiated power’ is understood as the effective isotropic radiated power P, that takes into consideration the power supplied to an antenna multiplied by the maximum antenna gain. Therefore, the effective radiated power (in logarithmic scale) is calculated by subtracting system losses (losses of antenna feeder, filters etc.) and adding isotropic antenna gain in a maximum radiation direction to the actual RF power at the output of a transmitter. Usually radiated power is determined in a similar way, the transmitter output power is measured, and the antenna gain is added to it and the system losses are subtracted. Of course, this commonly used method of determining the radiated power is indirect. Applying it, we must be sure that the system losses are accurately known, and they do not change over time. Therefore, it is more convenient to use one of the remote measurements (over-the-air) methods instead of the common indirect method because they have many advantages [1, 2].

At present there are two over-the-air measurement methods applied in practice: height scan and route scan methods. The first method allows determining the radiated power at a fixed place through the field strength scanning in height (understood as measuring field strength when a measuring antenna is scanned in height), the second one – along a route. The specifics and application possibilities of these two methods for broadcast radio stations are described in detail in paper [1].

Considering the application of over-the-air method in practice, the most suitable is the height scan method. The essence of the method is to scan the electric field in height. The obtained dependence of the field strength on the height makes it possible to exclude the contribution of the wave reflected from the surface and to calculate the field strength of only due to the direct wave. By determining the strength of the direct wave and knowing the distance between the radiating and measuring antennas, the radiated power is calculated. When using this method, preliminary calibration of the measuring site is unnecessary, and in this aspect it is fundamentally different from measuring electromagnetic emission in an open-areas test site.

As we know the height scan method was considered only in a few papers [1,2,3], which mainly deal with practical issues of application of the height scan method, such as the frequency range of the application, the maximum possible distance to the measured radiation source and so on. However, such a fundamental questions as the influence on the measurement results of the features of the reflecting surface or the vehicle body in which the telescopic mast and equipment for measuring the field strength are installed, are not completely covered in the existing publications and require more detailed studies. The results of such studies are presented in this work. The second purpose of this paper is to determine the maximum achievable accuracy of the height scan method when using standard measurement equipment for spectrum monitoring and with minimal environmental influence.

II. Basic Information about the Height Scan Method

The main features of the height scan method follow from the field strength dependence on height. Most simply and clearly, this dependence can be analyzed in the framework of a simple two-ray ground reflection model.

A. The Two-ray Ground Reflection Model for Plane Earth

This radio propagation model is based on ray optics and its geometry is shown on Fig. 1.

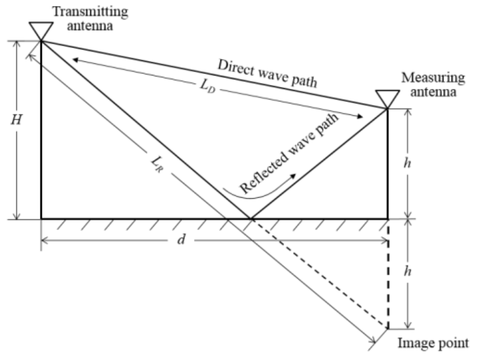

Fig. 1. Geometry for the two-ray ground reflection model.

When using the height scan method, the field strength must be measured far from the transmitting antenna in the region of the maximum in its radiation pattern. Therefore, in this case the horizontal distance between antennas d is much greater compared to the heights of the transmitting antenna H and the measuring antenna h. For the purposes of further analysis, it is enough to consider the simple case when the transmitting and measuring antennas are isotropic (if necessary, the directivity of the antennas can be considered when processing the measurement results). As shown in paper [3], under the above assumptions, the root mean square (rms) value of the magnitude of the resultant field strength is

$$E = \sqrt{(E_D)^2 + (E_R)^2 + 2E_D\, E_R \cos(\Delta\Phi)}, \quad (1)$$

where E_D is the rms value of the magnitude of the field strength due to the direct wave:

$$E_D = \frac{\sqrt{30P}}{L_D}, \quad (2)$$

E_R is the rms value of the magnitude of the field strength due to the reflected waves:

$$E_R = R \cdot E_D = \frac{R\sqrt{30P}}{L_R}, \quad (3)$$

$\Delta\Phi$ is the phase difference between direct and reflected waves:

$$\Delta\Phi = \frac{2\pi f}{c}(L_R - L_D) + \varphi, \quad (4)$$

where P (as has been mentioned above) is the effective isotropic radiated power, R and φ – the magnitude and the phase angle of the ground reflection coefficient, f – transmitting frequency and c – speed of an electromagnetic wave in vacuum.

Note, that field strength E_D is the field strength under the free space conditions and that (1) is applicable for both horizontal and vertical polarization.

B. The Field Strength Dependence on Height

Equation (1) allows to analyze the field strength dependency on the height h. This expression contains the interference term $2E_D\, E_R \cos(\Delta\Phi)$ whose magnitude and sign depend on the difference in the phase between direct and reflected waves $\Delta\Phi$. In [2] it is shown that under conditions $d \gg H$ and $d \gg h$, independently from the polarization type, the phase difference is given by:

$$\Delta\Phi = \frac{4\pi f H h}{c d} + \pi. \quad (5)$$

So, the phase difference linearly depends on height. Therefore, when changing it, the interference maxima E_{max} and minima E_{min} of the resultant field strength caused by the constructive (when $\cos(\Delta\Phi)=1$) and the destructive (when $\cos(\Delta\Phi)= -1$) combination of the direct and reflected waves are observed. From (1) it is readily seen that these field strength values are given by:

$$E_{max} = E_D + E_R \equiv E_D + R \cdot E_D, \quad (6)$$

$$E_{min} = E_D - E_R \equiv E_D - R \cdot E_D. \quad (7)$$

C. Determining the Field Strength Due to the Direct Wave and the Radiated Power

The field strength due to the direct wave E_D is determined from the dependence of the resultant field strength on the height, on which interference maximums E_{max} and minimums E_{min} are observed. It is straightforward to combine (6) and (7) to obtain the expression for calculation of the field strength E_D and reflection coefficient R:

$$E_D = (E_{max} + E_{min})/2. \quad (8)$$

$$R = (E_{max} - E_{min})/(E_{max} + E_{min}) \quad (9)$$

In paper [1], in which height scan method was first described, the field strength E_D is exactly calculated by (8). Further, as in [3], we will call this method for field strength due to the direct wave determination as max-min method.

We note that in deriving (8), it was assumed that the field strength of the direct and reflected waves, E_D and E_R, are independent on height. Let's look at this question in more detail. As it was mentioned above, the field strength E_D is measured under the free space conditions. Therefore, if these conditions are preserved when the height changes, then the field strength E_D remains constant. With the field strength E_R, the situation is different. In Fig. 2 the first Fresnel zone for the reflected path and efficient reflection zone (hereinafter referred to as the reflection zone) from which comes the major contribution to the

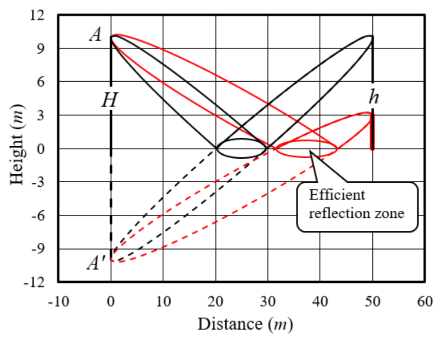

Fig. 2. The first Fresnel zone for the reflected path at the receiving point height of 3 m and 10 m (initial data for calculation: f=1.2 GHz, d=50 m, H=10 m).

reflected wave are plotted. From this figure it can be clearly seen that the position of the reflection zone depends on the height above the ground of the receiving point. In general, the ground surface is not perfectly smooth, and the reflection coefficient is non-uniform therefore its value may vary with position on the ground. So, it can be expected that the effective reflection coefficient (hereinafter referred to as the reflection coefficient) of the reflection zone will vary with its position. As a result, different reflection coefficients R_{max} and R_{min} can correspond to the field strengths E_{max} and E_{min} respectively. In this case, by combining (6), (7), (8) and (9) we can easily get, that measured by the max-min method the field strength E_D is

$$E_D(measured) = \frac{E_{max}+E_{min}}{2} = E_D\left(1+\frac{R_{max}-R_{min}}{2}\right), \quad (10)$$

and reflection coefficient is

$$R(measured) = \frac{E_{max}-E_{min}}{E_{max}+E_{min}} = \frac{R_{max}+R_{min}}{2+R_{max}-R_{min}}. \quad (11)$$

From (10) it follows that, due to the variability of the reflection coefficient, the error in determining the field strength E_D is

$$\delta_{max}(dB) = 20\log\left(1+\frac{R_{max}-R_{min}}{2}\right). \quad (12)$$

One can realistically assume that if the reflection zones, corresponding to these adjacent field strengths E_{max} and E_{min}, do not strongly overlap, the difference ($R_{max} - R_{min}$) can vary from 0.2 to +0.2. According to (13), this leads to a measurement error of the field strength E_D from 0.9 dB to +0.8 dB. In [3] it was shown that at microwaves frequencies, when the field strength scan contains many maximums and minimums, this error can be significantly reduced. To do this, when calculating the radiated power, it is necessary to use the average of the field strengths E_D calculated for all pairs of adjacent maximums and minimums.

Paper [3] proposed another method to determine the field strength E_D, which was named as averaging of the log-scaled values method. It is based on the following relation obtained in this paper:

$$\frac{1}{\pi}\int_0^{\pi} 20log\,(E)d\Phi = 20log(E_D), \quad (13)$$

where the resultant field strength E is described by the (1).

From (13) it is clear that if the field strength is measured by logarithmic units (for example in dBμV/m), then the field strength E_D is equal to the average value of the field strength E within the interval in which phase difference $\Delta\Phi$ changes from 0 to π. From (1) it may be seen that 0 corresponds to the field strength E maximum, and π – minimum. Therefore, from the periodicity of the function $cos(\Delta\Phi)$ it follows that the integration interval can be taken between any maximums or minimums of the field strength E. In practice it is convenient to use interval between minimums, because usually they are expressed more clearly than maximums.

To calculate the radiated power, the rearranged form of (2) is used, in which the radiated power is expressed as a function on the field strength:

$$P = \frac{1}{30}(E_D L_D)^2. \quad (14)$$

III. Technique to Study the Features of the Height Scan Method

To evaluate the influence of the reflecting surface and vehicle body on the method accuracy, measurements were carried out in two sites with a completely different surface. A vast field in the rural area with a crossing unpaved road was chosen as the first measurement site. Road surface is compacted mixture of gravel and sand. It can be assumed that the reflective properties of the road surface are the same as for the medium dry ground. Measurements were performed on road segment free from nearby trees. The segment size was about 1000 meters in length and 6 meter in width.

Car parking area with asphalt concrete pavement in the suburban area was chosen as the second measurement site. The size of the site was about 100×100 m. The surface of this site was noticeably smoother than in the first site. Of course, the measurements were carried out at the time when the car parking area was empty.

Two mobile spectrum monitoring stations were used for measurements. One station was used to transmit signal with known radiated power. The second measurement station was used for field strength scanning in height.

A. The Measurement Equipment

The equipment of the mobile spectrum monitoring stations is described in detail in [2]. Here we only note that the station which was used for field strength scanning is mounted in minibus Fiat Ducato and is equiped with a telescopic crank mast Geroh 9KVR6. This type of mast is distinguished by a uniform and smooth change in its height, both when the antenna is raised and when it is lowered. This feature of the mast is important when registering the dependence of the field strength on height. Widely used cheap pneumatic masts are not suitable for this purpose. Occasionally control measurements were made of the dependence of field strength on height using an adjustable height non-conductive 5 meter R&S HFU-Z antenna mast.

For field strength measurements we used standard equipment for radio monitoring: a measuring receiver ESPI7 with a spectrum analyzer function and antennas R&S HL223, R&S HL025. For each antenna, radiation patterns in E and H plane were measured at all frequencies used. A specialized software was used to control the receiver and automatically collect measurement data.

As we have said, one station was used to transmit signal with known level of the radiated power. The transmitting antenna R&S HL223 or R&S HL025 was placed on a retractable mast. The transmitter (microwave signal generator R&S SMR40) was emitting an unmodulated carrier (CW).

B. Measurement Procedure

In both measurement sites the field strength dependencies on height were measured at six frequencies. The main essential measurement parameters are given in Table I. A field strength measurement was performed by smoothly changing the measuring antenna height, at the same time recording the receiver's input level.

TABLE I. ESSENTIAL MEASUREMENT PARAMETERS

Parameter	Value
Transmitting frequency	0.5; 1; 1.2; 2.6; 4.5, 6 GHz
Polarization	H, V
Transmitting power	15 dBm
Transmitting antenna height	10.6 m
The range of scanning in height above the ground of the measuring antenna	3.12 – 10.01 m
Horizontal distance between antennas	50 m

C. Processing of Measurement Data

Data processing features were described in detail in [3]. We note only that after data processing there were obtained series of field strength values indexed in height order. These field strength data series were needed to calculate the field strength E_D using the new averaging of the log-scaled values method. Also, by using a special MS Excel-based application appropriate sequence of local maximums and minimums was extracted from this field strength data series. For all pairs that include the adjacent E_{max} and E_{min}, the field strength E_D by (8) and the reflection coefficient R by (9) were calculated. Note that further in the plots the values of field strength are displayed as a function of the average value of heights at which adjacent field strengths E_{max} and E_{min} were observed.

D. Measurement Uncertainty

The height scan measurement method accuracy evaluation depends on the level accuracy of the radiated power and the measuring accuracy of the field strength. Signal level calibration uncertainty of microwave signal generator R&S SMR40 is equal to ±1 dB and level measurement accuracy of spectrum analyzer ESPI-7 is equal to ±0.5 dB. Transmitting antenna's gain and measuring antennas' factor calibration uncertainty is equal to ±1 dB. As a result, the combined standard measurement uncertainty was equal to 1.66 dB.

IV. MEASUREMENTS RESULTS AND DISCUSSION

A. Reflection Coefficient

In Fig. 3 are shown the measurements results of the reflection coefficient for horizontal polarized wave in two different sites. As it has been mentioned above, in one case the ground was bare, in other it was covered with a layer of asphalt. For these two sites, we obtained different reflection coefficient dependences on the position of the reflection zone on the surface. These reflection coefficient dependences were also very well reproduced during repeated measurement. Thus, it must be logically concluded that the observed irregular and chaotic changes of the reflection coefficient can be explained only by such features of the reflection zone as the non-smoothness of the surface or the heterogeneity of its electrical parameters. This is also supported by the fact that for ground the value of the reflection coefficient fluctuates around the theoretical value.

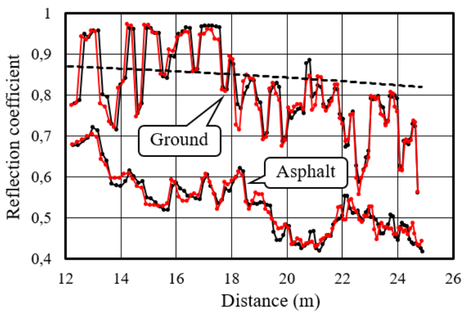

Fig. 3. Dependence of the reflection coefficient on the horizontal distance between measuring antenna and the geometrical reflection point measured at 6 GHz frequency for horizontal polarization. Results of the first measurement are marked in black and repeated in 10 min – in red. Dotted line represents calculated data for medium dry ground [4].

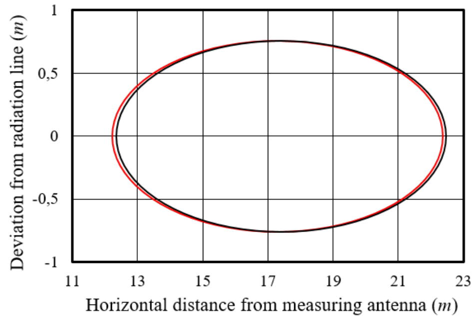

Fig. 4. The location of the reflection zone corresponding to the field strength maximum at the height h=5.6 m (red line) and the adjacent field strength minimum at the height h=5.662 m (black line) (initial data for calculation: f = 6 GHz, d =50 m, H = 10.6 m).

On the other hand, it can be seen from the Fig. 3, that big differences of the reflection coefficient values are observed (especially in the case of the ground) even for two adjacent points when the reflection zone moves from the position corresponding to the field strength maxima E_{max} to the position corresponding to the adjacent field strength minima E_{min}. The calculation results presented in Fig. 4 show that the reflection zones corresponding to these adjacent field strengths almost completely overlap. Approximately 98 percent of the area of these reflection zones is common to them and therefore it is unlikely that the reflection coefficients from these zones will differ greatly. But the measurement results shown in Fig. 3 confirm with this fact.

The results of measuring the reflection coefficient for vertical polarization are like those for horizontal polarization, with the only difference that the observed values of the reflection coefficient were noticeably less. For two different sites we also obtained different, but not completely, reflection coefficient dependences on the position of the reflection zone on the surface.

With a decrease in the frequency of measurements, the amplitude of chaotic changes in the reflection coefficient also decreased and, as at 6 GHz, to a greater degree was also determined by the properties of the reflecting surface. But in the case of horizontal polarization at 1.2 GHz, the influence of the vehicle body became obvious. From Fig. 5, although the reflection coefficient from the ground and asphalt differ in

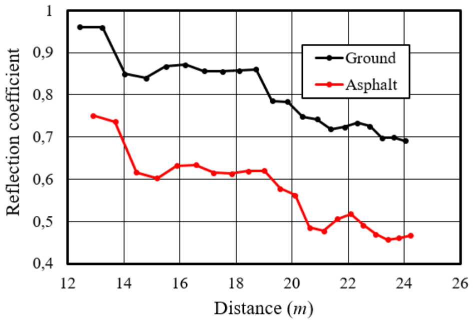

Fig. 5. Dependence of the reflection coefficient on the horizontal distance between measuring antenna and the geometrical reflection point at 1.2 GHz frequency for horizontal polarization.

magnitude, but its changes with the displacement of the reflecting zone along the surface occur in almost the same way. As already mentioned, the displacement of the reflection zone is caused by scanning the measuring antenna in height. And therefore, it is obvious that the changes in the value of the reflection coefficient observed in this case are largely due to the influence of the vehicle body, rather than variations in surface properties along the line of displacement of the reflection zone.

B. Influence of the vehicle body on the field strength scanning results

It turned out that the influence of the vehicle body is clearly fixed if measurements are carried out at frequencies below 1 GHz and at the appropriate distance from the radiation source, so that 1-2 peaks of the field strength are recorded. The results of such measurements are shown in Fig. 6. It shows that on the curves measured by the mobile station, frequent small fluctuations of the field strength are observed. When measured with a mast R&S HFU-Z, such oscillations were not observed. The period of these oscillations is equal to the wavelength (this was confirmed by measurements at a frequency of 300 MHz). This fact is explained if one assumes that among the waves reflected from the roof of the vehicle, some of them propagate in the vertical direction. When they interfere with the main wave, small oscillations with a period equal to the wavelength will occur.

Such a mechanism of the appearance of small additional oscillations makes it possible to explain why these oscillations

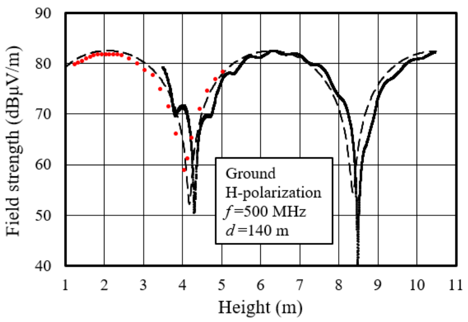

Fig. 6. The results of measuring the dependence of the field strength on the height obtained using a mobile station (black points) and a manual mast R&S HFU-Z (red points). Dotted line represents the calculated data.

are not noticeable in the case of vertical polarization. When measuring at a frequency of 500 MHz, an antenna R&S HL223 was used. In case of E-plane (it corresponds to vertical polarization) for directions perpendicular to the axis of the antenna, its gain drops sharply [5]. Therefore, the wave reflected from the roof, which propagates upward perpendicular to the axis of the antenna, does not influence the magnitude of the recorded signal.

C. Result of Determining the Field Strength due to the Direct Wave

As it can be seen from (8) and (9), the same measured values E_{max} and E_{min} of the resultant field strength are used to calculate the field strength due to the direct wave E_D, as well as the reflection coefficient. Therefore, everything that was said above about the influence of the reflecting surface and the body of the vehicle on the characteristics of the reflection coefficient remains valid for field strengths E_D.

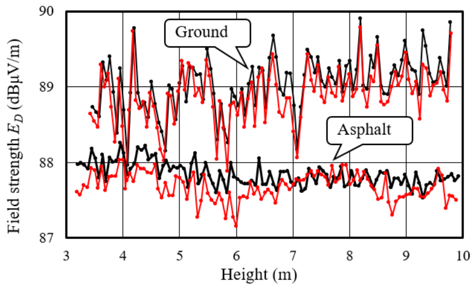

Fig. 7. The dependence of the field strength E_D values calculated by the max-min method on the height (f = 6 GHz, H-polarization). Results of the first measurement are marked in black and repeated in 10 min – in red.

Fig. 7 represents the results of the field strength for horizontally polarized wave in two sites, calculated by the max-min method. As with the reflection coefficient, irregular and chaotic changes in the field strength E_D are observed. As can be seen, these field strength dependencies were also very well reproduced during repeated measurements. When repeating the measurements, the scatter of the field strength E_D values averaged over the height scanning range did not exceed 0.15 dB.

The observed values of the range of scatter by height of the field strength E_D for several frequencies are shown in Fig. 8. It shows that in the case of asphalt pavement, the range does not

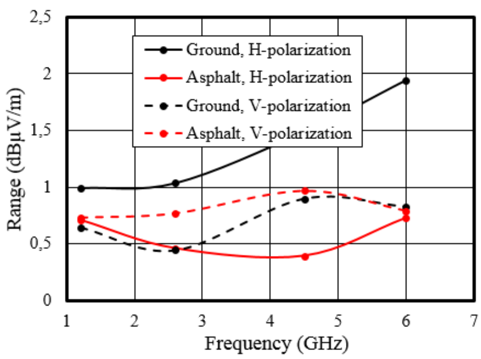

Fig. 8. The frequency dependence of the range of scatter by height of the field strength E_D. Values were calculated by the max-min method.

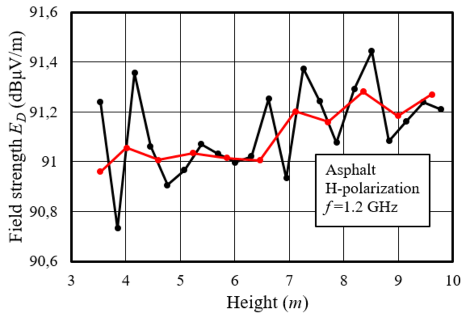

Fig. 9. The dependence of the field strength E_D values calculated by the max-min method (black line) and by averaging of the log-scaled values method (red line) on the height.

exceed 1 dB. In the case of ground for horizontal polarization, it is noticeably higher, reaching 1.9 dB at 6 GHz. To eliminate the error caused by the scatter in field strength E_D in height, for calculating the radiated power, it is necessary to use its average value in height.

The averaging of the log-scaled values method for calculation of the field strength has an important advantage. Thus, the value of the field strength here is the result of averaging the measured values of the total field in a certain range of height variation. If, when the height is changed, extraneous interfering reflections are observed (for example, from the vehicle body), which cause additional field fluctuations, then these fluctuations in averaging can be mutually compensated. This is clearly seen in Figure 9, where the results of the calculation of the field strength E_D using the two methods described at frequency 1.2 GHz are compared. At this frequency the scatter of field strength E_D values over height is mainly due to reflections from the vehicle body. We see, that in this case the scatter of field strength E_D is much smaller when using the averaging of the log-scaled values method.

D. Measurement Results of Radiated Power

The measured radiated power was calculated by (14) using the averaged over the height values of the field strength E_D. Note that regardless of the method of calculating the field strength E_D, their average values were very close: the difference was no more than 0.14 dB. Therefore, further presented results are only for log-scaled values averaging method.

In Fig. 10 the summary of the measurement error of the

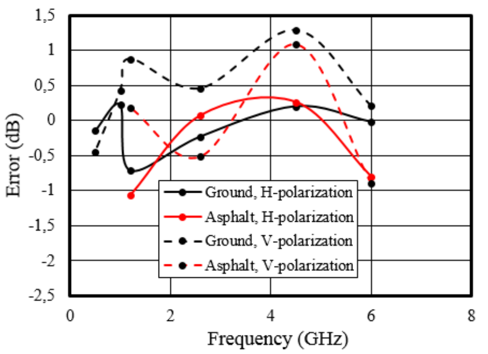

Fig. 10. Measurement error of radiation power.

radiation power is plotted (measurement error here is assumed as a difference between the measured radiated power values and the actual values). It shows that the measurement error is unlikely small for such a type of measurements and does not exceed 1.3 dB. This error is noticeably smaller than the combined measurement uncertainty, which, as has been mentioned above, in our case is equal to 1.66 dB. It should also be noted that the shape of the curves of the dependence of measurement error on frequency for the vertical and horizontal polarizations differ, but almost does not depend on the type of surface. The measurement error values for the two types of surface are also close, especially for horizontal polarization. Hence, we can conclude that the measurement error of the radiated power is determined mainly by the accuracy of the measuring equipment, and not by the properties of the surface. Also applies to the frequency range starting from 1.2 GHz and below. At a frequency of 1.2 GHz, an antenna R&S HL025 was used, and at a frequency of 1 GHz and below−R&S HL223. From the data in the Fig. 10, it follows that when changing the type of antennas, a sharp change in measurement error is observed. Moreover, for horizontal polarization, when at these frequencies the influence of the vehicle body is manifested, the magnitude of the change in error exceeds the error itself. From here it is indirectly possible to conclude that in this case the accuracy of the equipment also has a major influence on the measurement error of the radiated power.

V. Conclusion and Future Work

The results presented in this paper show that when calculating the radiated power, it is necessary to use the height-averaged value of the field strength due to the direct wave. In this case, when applying the height scan method in rural and suburban areas, when the surface is flat and there are no interfering reflections from nearby surrounding objects, the measurement error of the radiated power does not exceed 1.3 dB. The measurement error is mainly influenced by the accuracy of the measuring equipment, and not by the ground surface or the car body.

In order to determine the accuracy of the height scan methods in urban areas with additional disturbing reflections, additional research is needed.

Acknowledgments

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