Height Scan Methods for Determining the Radiated Power at Microwaves Frequencies

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***Abstract*—The paper presents a detailed analysis and experimental results of the radiated power measurements at microwaves frequencies in rural area. The measurements were carried out using the original height scan method and the new height scan method was developed by us. The results indicated that both methods worked very well in case when signal-to-noise ratio was higher than 20 dB and the average value of direct wave field strength was used for the radiated power calculation. At low signal-to-noise ratios the new method provides more accurate radiation power measurement results than the original method. In order to determine the accuracy of both height scan methods in urban area, additional research is needed.**

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

I. Introduction

Electromagnetic compatibility in radio networks is determined not only by receiver parameters, but also by radio transmitter radiation parameters. The most important radiation parameter that influences electromagnetic compatibility is the radiation power. Therefore, it is an essential parameter in planning and managing the spectrum. For example, it is required to calculate the coverage areas and the signal field strength levels desired. In mobile networks, the radiated power makes impact on co-channel re-use distances and its increase over the planned value may cause co-channel interference. 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 radio monitoring or inspection services.

It is more convenient to use one of the remote measurement (over-the-air) methods instead of the common indirect method, when the radiated power of radio stations is determined through the RF power measurements at the output of a transmitter and further calculation by taking into account antenna gain and losses of antenna feeder. Over-the-air measurement methods have many advantages. First of all, these methods are direct measurement methods because the radiated power is measured by measuring its created field strength. Usually it is enough to know only the height of a transmitting antenna and the azimuth of the main beam when applying these methods. Moreover, the application of the common indirect method requires the consen of operator because on-site RF power measurements at the output of a transmitter must be carried out. Over-the-air measurement methods do not require operator's consent.

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 measurements of the field strength at different heights, the second one – along a route. The specifics and application possibilities of these two methods for broadcast radio stations were discussed in detail in paper [1].

Considering the application of over-the-air method in microwave frequencies, the most suitable is the height scan method. It is considerably simpler in realization than the route scan method. The height scan method and peculiarities of its application are described in ECC Recommendation (12)03 [2]. This document recommends applying this method for the frequencies up to 6 GHz, however it is mentioned that this method was approved by measurements of GSM base stations only (that means for frequencies up to 1 GHz). Recently, the German Communications Administration conducted a detailed research on the accuracy of the high-scan method in urban conditions [3]. The radiated power of three transmitters emitting CW and wide band OFDM signals on 5,85 GHz was measured. Measurement error varied within interval from 0.8 dB to practically unacceptable 6 dB. In most cases high measurement error was observed in case of CW signal. Authors of the paper suppose that the measurement error may be unreasonably high mainly due to multiple reflections from surrounding buildings. In paper [4] it was proposed to increase the measurement accuracy by averaging multiple height scan results, but practical realization of this method was unsuccessful because of technical difficulties that authors could not deal with existing equipment.

From above it follows that there is no clarity about the application of the height scan method at microwave frequencies. Therefore, the main purpose of this paper is to provide deeper analysis of applicability of height scan measurement method in frequency range of 1,2 GHz-6 GHz, which is important for mobile communications, with the aim to improve the measurement accuracy.

II. Basic Information about the Height Scan Method

The principle of the method was first described in ECC Recommendation 12(03) [2], mainly focusing on measurement techniques and peculiarities of the application. This section provides a more detailed analysis of the physical side of the method and on this basis proposes a new version of the method.

A. The Principle of the Method

The method is based on a well-known relation between the rms (root mean square) value of the magnitude of the *E*-field strength under the free space conditions and equivalent isotropically radiated power P:

$$E = \frac{\sqrt{30P}}{L}\ , \qquad (1)$$

where *L* is the distance between transmitting and measuring antennas.

The equation (1) can be used for the calculation of radiated power if the *E*-field strength is only due the direct path wave. However, ground reflections will always be present, and the measuring antenna necessarily receives two overlapping waves, one by direct path and one reflected wave from the ground (Fig. 1). To separate these two waves, the measurement results of *E*-field strength dependency on a height are used. Let's analyse this separation technique in more detail.

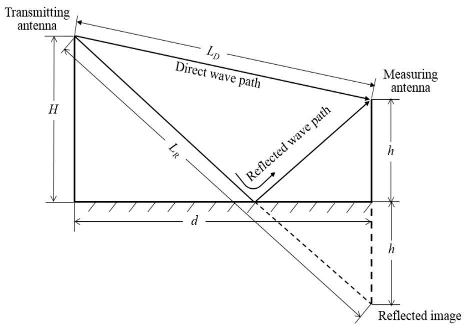


Fig. 1. Geometry of direct path and ground-reflected multipath.

For the beginning, let's calculate *E*-field strength dependency on a height in the simplest case, when transmitting and receiving antennas are isotropic and wave polarization is horizontal. These assumptions are not essential, but they make calculations simpler. It this case, based on the lengths L_D and L_R (see Fig. 1), on the equivalent isotropically radiated power *P* and on the magnitude *R* and phase φ of the ground reflection coefficient, the *E*-field of the direct wave can be expressed as

$$\mathcal{E}_D = \frac{\sqrt{60P}}{L_D}\sin\left[2\pi f t\left(1-\frac{L_D}{c}\right)\right], \qquad (2)$$

and the *E*-field of the reflected wave can be expressed as

$$\mathcal{E}_R = \frac{R\sqrt{60P}}{L_R}\sin\left[2\pi f t\left(1-\frac{L_R}{c}\right)+\varphi\right], \qquad (3)$$

where *f* – the transmitting frequency; *c* – the velocity of light in free space.

In case of horizontal polarization, the electric vectors of direct and reflected waves are horizontal to the reflecting surface. So, these two vectors are parallel, and the resultant field strength can be calculated by adding direct and reflected waves accounting for the difference in phases. As it follows from the equations (2) and (3), the phase difference is

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

Therefore, for the resultant *E*-field strength we obtain:

$$\mathcal{E} = \sqrt{\left(\frac{\sqrt{60\pi}}{L_D}\right)^2 + \left(\frac{R\sqrt{60\pi}}{L_R}\right)^2 + \frac{2R\sqrt{60\pi}}{L_R L_D}\cos(\Delta\Phi)} * \sin(2\pi f t). \qquad (5)$$

In this equation, the initial phase is considered to be zero because it has no influence on further calculations. From this expression follows that the rms value of the magnitude of the resultant *E*-field strength is

$$E = \sqrt{(E_D)^2 + (E_R)^2 + 2E_D\,E_R\cos(\Delta\Phi)}\ , \qquad (6)$$

where E_D and E_R, respectively, are the rms values of the magnitude of the field strength due to direct wave and field strength due to reflected waves. Further the rms values of the magnitude of the *E*-field strength will be denoted as the field strength *E*.

As it can be seen from equation (6), the resultant field strength dependency on height is defined by phase ΔΦ because it is proportional to the difference between the lengths of the direct and the reflected propagation path (see eq. (4)), and this difference is proportional to height [2]:

$$(L_R - L_D) = \frac{2Hh}{d}. \qquad (7)$$

Therefore, when changing the height of the measuring antenna, the field strength maximum E_{max} and minimum E_{min} caused by the constructive (when cos(ΔΦ)=1) and destructive (when cos(ΔΦ)= -1) combination of these two waves are observed. As follows from equation (6), these field strength values are given by:

$$E_{max} = E_D + E_R \qquad (8)$$

$$E_{min} = E_D - E_R. \qquad (9)$$

In paper [1], the field strength of direct wave E_D is exactly calculated from these measured maximum and minimum values:

$$E_D = (E_{max} + E_{min})/2. \qquad (10)$$

Further we will call this field strength E_D determination method the original max-min method. This method for determination field strength of direct wave E_D assumes that field strength of reflected wave E_R is independent of height. But, as Fig. 1 shows, the position of geometrical reflection point on the ground depends on height at which the field strength is measured. This reflection point is in centrum of the surface of Fresnel zones from which comes the major contribution to the reflected wave. In general, the reflection coefficient is non-uniform and its value varies with position on the ground. As a result, the field strength E_R can slowly vary with height. Therefore, in paper [2] it is recommended to determine the field strength E_D from the difference between the maximum field strength and the adjacent minimum field strength.

Finally, it follows from the expression (1) that radiated power P is given by

$$P = \frac{1}{30}(E_D L_D)^2. \quad (11)$$

In practice the field strength is measured in $dB\mu V/m$, therefore, this equation more often is used in a logarithmic form:

$$P(dBW) = E_D(dB\mu V/m) + 20logL_D(m) - 134.77(dB). \quad (12)$$

B. Measurement Techniques of the Original Height Scan Method

As it follows from above, the necessary condition for application of the height scan method is that, when varying the receiving antenna height, at least one minimum and one maximum of the field strength should be detected. This requirement is always met if the minimal displacement of the phase differences ΔΦ (see eq. 4) is equal to 2π. Combining equations (4) and (7) it is possible to show that the phase difference of 2π corresponds to the height difference

$$\Delta h = \frac{cd}{2Hf}. \quad (13)$$

It is understandable that Δh in this equation is equal to the difference of heights between the adjacent field strength minimums (or maximums). The maximum value of the heights difference Δh_{max} (it is defined by the construction of retractable mast) corresponds to the maximum separation distance d_{max} between the transmitting and the measuring antenna positions at with one minimum and one maximum of the field strength can be detected. As follows from equation (13), this distance is

$$d_{max} = \frac{2fH\Delta h}{c}. \quad (14)$$

On the other hand, depending on the transmitting antenna directivity [1] there exists the minimum necessary separation distance d_{min} between the transmitting and the measuring antenna. It is obvious that the height scan method can be applied if the distance d_{max} is more or equal to the distance d_{min}.

Field strength is usually measured using spectrum analyzer in zero span mode. Usually the analyzer measurement is started manually at the same time when the antenna mast starts to rise. As a measurement result we obtain one trace, representing the field strength variation along the height. Using markers, we get the values of one maximum and adjacent minimum, and their average value (see eq. 10) is equal to the field strength E_D.

The maximum and minimum values are easy to capture and determine when trace contains only several of them. At microwave frequencies the trace may contain hundreds of maximums and minimums. Another problem occurs when there are many pairs of maximums and adjacent minimums. The average field strength for different pairs may vary up to 2-3 dB ant then it is not clear what criteria for selection of the "right" pairs is. These questions will be discussed later.

C. A New Approach to Determination of the Field Strength of Direct Wave

We will show another way to determine the direct wave field strength E_D. For that reason, let's take the common logarithm of both sides of equation (6)

$$20logE = 10log[(E_D)^2 + (E_R)^2 + 2E_D E_R \cos(\Delta\Phi)]. \quad (15)$$

By introducing new symbols

$$a = (E_D)^2 + (E_R)^2, \quad (16)$$

$$b = 2E_D E_R \quad (17)$$

equation (15) can be written as follows

$$20logE = 10\log[a + b \cdot \cos(\Delta\Phi)]. \quad (18)$$

By integrating this equation from 0 to π we will obtain

$$\int_0^\pi 20\log E d(\Delta\Phi) = 10\int_0^\pi \log[a + b \cdot cos(\Delta\Phi)]\, d(\Delta\Phi). \quad (19)$$

By changing logarithms from common to natural, the right side of the equation acquires a shape:

$$\frac{20}{\ln(10)}\int_0^\pi ln[a + b \cdot cos(\Delta\Phi)]d(\Delta\Phi). \quad (20)$$

If $a \geq |b| > 1$ (this is valid for our case), then this integral is computed [6]:

$$\int_0^\pi \ln[a + b \cdot cos(\Delta\Phi)]\, d(\Delta\Phi) = \pi \cdot ln\frac{a+\sqrt{a^2-b^2}}{2}. \quad (21)$$

Taking into account (16) and (17), we obtain

$$\pi \cdot ln\frac{a+\sqrt{a^2-b^2}}{2} = \pi \cdot ln(E_D)^2. \quad (22)$$

Using this equation and going back to common logarithms, equation (19) acquires a shape:

$$\int_0^\pi 20log\,(E)d(\Delta\Phi) = \pi \cdot 20\log(E_D). \quad (23)$$

By dividing both sides by π we finally obtain

$$\frac{1}{\pi}\int_0^\pi 20log\,(E)d\Phi = 20log(E_D). \quad (24)$$

From this equation it follows that in case the field strength is measured by logarithmic units (the sweep spectrum analyzers present signal level measurement data on a logarithmic scale, usually in dBμV/m), then the field strength of direct wave is equal to the average value of the resultant field strength values within the interval in which phase difference ΔΦ changes from 0 to π. Note, that 0 corresponds to the resultant field strength 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 resulting field strength. In practice it is convenient to use interval between minimums, because usually they are expressed more clearly than maximums. From here follows the new field strength E_D calculation method (further it will be called the averaging of the log-scaled values method), when it's value is calculated by averaging all resultant field strength E values between two minimums. It is clear that in order to make the averaging correctly, the field strength values must be arranged evenly by phase (at the same time arranged evenly by height, see eq. 4 and eq. 7). It can be considered that the field strength E_D value, calculated by averaging many experimental values, will be more reliable than that determined from only two values calculated by the original max-min method. This method allows to take into account the influence of internal noise of measuring equipment, which at these frequencies usually exceed radio noise. Therefore, it is applicable to the measurement of weaker emissions than the original max-min method.

III. The Measurement Setup and Procedure

A. The Measutement Equipment

Measurements were carried out in urban area far away from buildings, forests or separate trees (see Fig. 2). Such measurement location was chosen with the aim to verify the maximum achievable accuracy of the height scan method when it is limited only by parameters of the measurement equipment and ground reflections. In addition, such conditions allow more objective comparison of the original and new measurement methods.

Fig. 2. View of the measurements place.

Two mobile monitoring stations of the Communications Regulatory Authority were used for measurements. These stations were equipped with all the necessary monitoring equipment including antennas, GPS receiver, retractable mast, generator and etc. One station was used to transmit signal with known radiated power. The transmitting antenna R&S HL025 was placed on a retractable mast. The transmitter (microwave signal generator R&S SMR40) was emitting an unmodulated carrier (CW). The second measurement station was used for field strength height scan. Antenna R&S HL025 and spectrum analyzer R&S ESPI-7 were used for this measurement. In order to control the spectrum analyzer and download raw data, a portable computer was used.

B. Measurement Steps

Measurements were carried out at four frequencies and three horizontal distances between transmitting and measuring antennas. Essential measurement parameters are given in Table I. In order to assess noise immunity, at frequency of 6 GHz additional measurements with 40 dB lower (comparing to the table below) radiated power were carried out.

During the measurements it was necessary to take into account transmitting and measuring antenna's E-plane pattern.

TABLE I. Essential Measurement Parameters

Parameter	Value
Transmitting frequency	1.2; 2.6; 4.5, 6 GHz
Polarization	H, V
Transmitting power	-12 dBm (6 GHz), - 16 dBm
Transmitting antenna height	10.6 m
Minimum height of measuring	3.12 m
Maximum lifting height of measuring	10.01 m
Horizontal distance between antennas	50, 75, 110 m

For that reason, E-plane patterns were measured separately for each frequency because antenna HL025 manufacturer presented only a typical radiation pattern. Patterns were measured at the same place and using the same equipment that was used for the height scan measurements. To minimize ground reflections, radiation patterns were measured at 10 m distance between the transmitting and receiving antennas and 10 m above the ground. The patterns were measured by changing azimuth of receiving antenna, so the measurements of E-plane vertical polarization were carried out with both antennas in horizontal position and vice versa: E-plane horizontal patterns were measured with both antennas in vertical position. E-plane patterns were measured with a step of 1 degree, and finally the measurement data was processed using MS-Excel to determine approximating polynomials of the patterns.

A height scan was performed by smoothly changing the measurement antenna height from minimum to the maximum (or vice versa), at the same time recording the spectrum analyzers' input level changes. The settings for a spectrum analyzer are shown in Table II. Spectrum analyzer was set to a zero-span mode. To capture the height change interval exactly, the sweep time was chosen to be about 10 % longer than the antenna mast raising or retraction times.

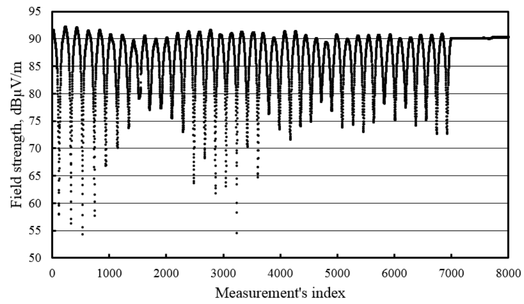
TABLE II. Used Settings for a Spectrum Analyzer

Parameter	Value
Resolution bandwidth (RBW)	30 kHz
Video bandwidth (VBW)	300 kHz
Span	0 Hz (Zero Span)
Sweep time	150s
Sweep mode	Single Sweep
Trace detector	RMS (root mean square)
Trace mode	Clear Write
Number of trace points	8001

C. Evaluation of Measurement Data

During each height scan, the measurement data (trace) was captured and saved in MS Excel worksheet format by analyzer controlling software. Each worksheet row contains field strength value, measurement index and measurement time. Example of indexed field strength data, when antenna was swept from minimum height up to the maximum, is presented in Fig. 3. Such graphs were automatically generated by the above-mentioned software.

Data processing starts from determination of the index, where antenna reaches its maximum height. As it follows from Fig. 3, this index corresponds to the position where field strength stops changing. It is clear that the minimum antenna height corresponds to index 0. Antenna raising was pretty smooth, so the height change is proportional to the change of the index. Therefore, if we know the above-mentioned indexes and their corresponding heights, it is possible to calculate relevant heights for each index (at the same time – for each field strength value). A completely analogous procedure was applied when antenna was scanned from up to down.



.Fig. 3. A set of field strength values obtained by raising the antenna (f=6 GHz, d=75 m, H-polarization).

Next step was the calculation of elevation angles between transmitting and measuring antennas for each field strength value by using simple geometry formulas. Using antennas' pattern approximating polynomials and these elevation angles, all field strength values were recalculated to conform to elevation angle value of 0. These field strength data series were used for calculation of field strength of direct wave.

Calculating the field strength E_D by the original (max-min) method, at the beginning a special MS Excel-based application from the field strength data series extracted appropriate sequence of local maximums and minimums. Thereafter, using formula (10) the field strength E_D was calculated. A special MS Excel-based application identified rows, corresponding to the field strength minimums, further they were used for calculation of the field strength E_D by the averaging of the log-scaled values method.

D. Measurement Uncertainty

The height scan method accuracy evaluation depends on accuracy of the level of the radiated power and the accuracy of the field strength measurement, which basically depend on the accuracy of the measuring instruments. According to calibration certificates, signal level calibration uncertainty of microwave signal generator R&S SMR40 is equal to ±1 dB and measurement uncertainty of spectrum analyzer ESPI-7 level is equal to ±0.5 dB. According to calibration certificates, transmitting and measuring antennas' factor calibration uncertainty is equal to ±1 dB. Thus, in the worst-case measurement uncertainty, due to inaccuracy of the measuring instrument, does not exceed 3.5 dB. The combined standard measurement uncertainty is equal to 1.66 dB and expanded standard uncertainty (95 % confidence level) is equal to 2.77 dB.

IV. Measurement Results and Discussion

A. Verification of reproducibility of height scan

To verify the reproducibility of measurement results, repeated measurements were carried out for vertical and horizontal polarizations at frequencies 4.5 GHz and 6 GHz for distances of 110 m and 50 m. The results showed that in all cases field strength dependency on height matched very well. Characteristic example of repeated measurements is presented in Fig. 4, which also shows that in all cases irregular and chaotic changes of the field strength maximum and minimum values were observed with the change of receiving antenna height. As it was already explained above, these changes occur because the reflection

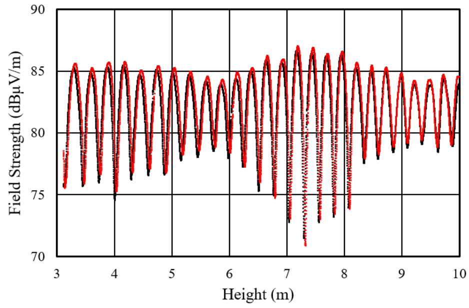


Fig. 4. Data of the first measurement (in red) and repeated in 20 min measurement (in black) (f = 6 GHz, d = 110 m, V-polarization).

coefficient is non-uniform, i.e. its value varies with the position on the surface.

B. Result of Determining the Field Strength of Direct Wave

First of all, it should be noted that extraneous noises (i.e. internal noise of spectrum analyzer, radio noise) are significantly lower than the measured signals, and both calculation methods give practically the same results (see Fig. 5) (to present more details, only narrow ranges of the height and the field strength are displayed).

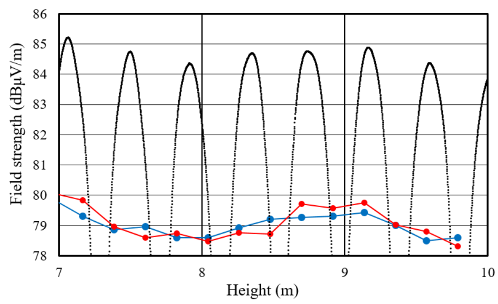


Fig. 5. The resultant field strength (black points) and the field strength of direct wave calculated by the original max-min method (red points) and by the averaging of the log-scaled values method (blue points) (f = 2.6 GHz, d = 75 m, H-polarization).

As it is seen from Fig. 5, the field strength E_D value, calculated by the averaging of the log-scaled values method, with the change of height varies more evenly than the value, calculated by the original max-min method. Usually, when the height varies within the whole interval from 3.12 m to 10.01 m, the field strength varies within 2 dB, less often – within 3 dB. It should be noted the repeatability of the field strength E_D dependency on height is very good. It could not be otherwise because, as it was already mentioned above, the resultant field strength E dependency on height repeated very well.

C. Result of Determining the Radiated Power

It should be noted that the compared radiated power measurement methods differ only in the field strength E_D calculation methodology. Thus, to make this comparison objective, the same trace data was used for calculations.

It can be assumed that the field strength E_D dependency on height is caused by random variations of the reflection coefficient with position on the ground. In this case the influence of these variations could be diminished by using the average

TABLE III. EXPERIMENTAL RESULTS OF THE HEIGHT SCAN METHODS

Frequency (GHz)	Polarization	Distance (m)	Measurement error (dB)	
			Δ(original)[a]	Δ(new)[b]
6	Horizontal	110	1.31	1.16
		75	0.32	0.15
		50	-0.02	-0.02
	Vertical	110	-0.29	-0.29
		75	0.45	0.44
		50	0.21	0.21
4.5	Horizontal	110	1.11	1.06
		75	0.37	0.42
		50	0.28	0.2
	Vertical	110	0.94	0.95
		75	1.32	1.33
		50	1.24	1.29
2.6	Horizontal	110	0.68	0.63
		75	0.36	0.45
		50	-0.17	-0.23
	Vertical	110	0.33	0.32
		75	0.19	0.24
		50	0.46	0.46
1.2	Horizontal	110	-0.66	-0.63
		75	-0.30	-0.35
		50	-0.72	-0.71
	Vertical	110	0.57	0.57
		75	0.65	0.62
		50	0.88	0.88

[a] radiated power was calculated according to the original method
[b] radiated power was calculated according to the new method

field strength E_D values for radiated power calculation in line with formula (12). This assumption was well proven in practice.

Table III presents the summary of the measurement results. Measurement error here is assumed as a difference between the measured radiated power values and the actual values.

As it is seen from Table III, the measurement error is unlikely small for such a type of measurements. Besides, the measurement errors for both methods were very close: the difference was no more than 0.15 dB for the rest 19 measurements.

D. Result of Determining the Radiated Power at Low Signal Level

It can be seen from Fig. 6 that at low levels of measured signal the new measurement method was much more accurate. It is hard to believe but using this method the acceptable measurement error was obtained even at signal-to-noise ratio of about 3 dB. Such example of field strength dependency on a height is presented in Fig. 7. We can see that, for such a low signal-to-noise ratio, the field strength peaks are barely noticeable.

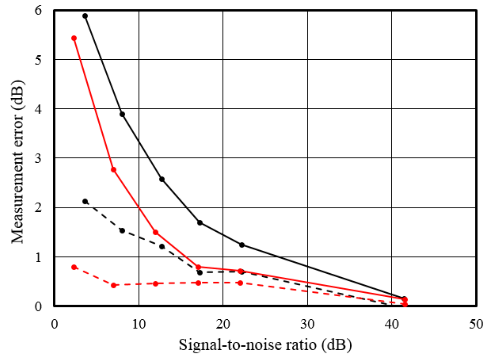


Fig. 6. The radiated power measurement error at various signal-to-noise ratios. Solid line marks the results of the original height scan method, dotted – of the new method (f=6 GHz, d=110 m, black color – H-polarization, red - V-polarization).

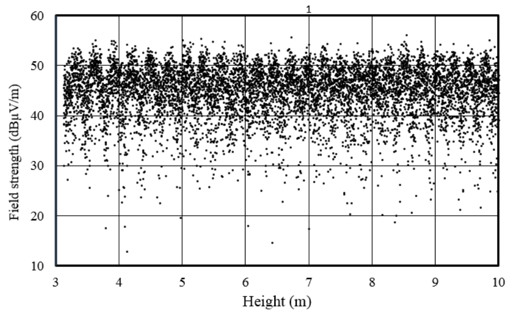


Fig. 7. The field strength at low signal level as function on height (f=6 GHz, d=110 m, V-polarization).

V. CONCLUSION AND FUTURE WORK

The results which are presented in this paper show that original and new height scan methods for determining the radiated power at microwaves frequencies in rural areas worked very well. But in case of low levels of the measured signal, the use of the new method yielded noticeably better results than in case of the original method.

In order to determine the accuracy of the height scan methods in urban area, additional research is needed.

ACKNOWLEDGMENTS

G. Leontjev thanks to those who have contributed to this work, particularly to Saulius Gelžinis and Regimantas Gruslys.

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