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Over-the-Air Methods for Determining the Radiated Power of Radio Station

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***Abstract*—The paper presents a detailed analysis and experimental results of the radiated power measurement in line with two over-the-air methods. The results indicated that the first method, which is based on the field strength measurement when changing the receiving antenna height, worked very well in DVB-T broadcast band. In FM broadcast band the use of this method becomes more difficult with the increase of the number of bays of the transmitting antenna array. In case of 6 and more bays, the application of this method is not possible. The second method, which is based on the field strength measurement along a route, worked very well in FM broadcast band. This method provides noticeably more accurate radiation power measurement results than the first over-the-air method. The application of this method in FM broadcast band basically is limited only by the possibility of finding a suitable route around the measured station. In DVB-T broadcast band the second over-the-air method has shown not very good results. Therefore, in order to determine the suitability of this method in DVB-T broadcast band, additional research is needed.**

Keywords—radiated power, field strength, radio station, measurement error, broadcasting, route, measurement, two-ray model, ground reflection

I. Introduction

The radiated power of a radio station is one of the most important parameters, which characterize stations' emission. It is 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. The limitation of the radiated power of a radio stations is essential for the limitation of co-channel re-use distances and for interference mitigation in adjacent channels. For these reasons the radiated power is specified in authorizations and the verification of its value for compliance with the authorisation conditions is an important task for the radio monitoring or inspection services.

Usually 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 cable losses and antenna gain. This RF power measurement can be done during the on-site inspections and generally only with the consent of the operator. Therefore, this method of measurements is sometimes impossible. Consequently, there is a need for remote measurement (over-the-air) methods for which consent of the operators is not needed.

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As we know, the over-the air measurement methods have been little studied. Paper [1] provides an over-the-air measurement method to determine the radiated power through field strength measurements at a fixed location. This method allows excluding the influence of a reflected wave from the ground because of information gained from a height scan of the field strength (further this method will be referred to as "height scan method"). Unfortunately, it is difficult to apply this method for determination of the radiated power of FM broadcast radio stations which usually use the frequencies from 87.5 to 108 MHz. At these frequencies, the height accessible by customary measuring antennas (9-10 m) will not be sufficient to capture both the maximum and the minimum of distribution of the main beams' field strength.

Paper [2] provides another over-the-air measurement method to determine the radiated power through field strength measurements along a route. This method is based on the comparison of field strength values measured along a route with the calculated field strength values (further this method will be referred to as "route scan method"). Paper [2] also presents the radiated power measurement results of FM broadcast radio stations. The results showed that the route scan method in FM broadcast band worked very well.

As it has already been mentioned above, the over-the-air methods are not well described. For us only the two above-mentioned papers are known. Therefore, the main purpose of this paper is to provide deeper analysis of applicability of over-the-air measurement methods. For this reason, the limitations of these methods imposed by the measured radio station's transmitting frequency and design of the antenna are defined.

II. Height Scan Method

While describing this method, we assume that terrain between radio station transmitting antenna and receiving (measuring) antenna is flat.

A. The principle of the method

Basic principle of the method was described in ECC Recommendation 12(03) [1]. The method is based on the fact that the measuring antenna receives two overlapping waves, one by direct path and one reflected wave from the ground. When changing the height of the measuring antenna, the field strength maximum E_{max} and minimum E_{min} caused by the

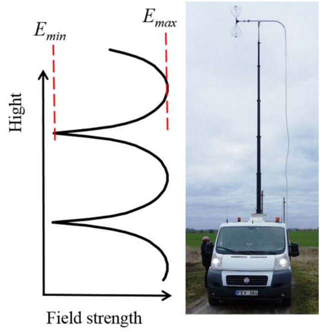

Fig. 1. The dependency of the field strength on height.

constructive and destructive combination of these two waves are observed (Fig. 1). These field strength maximum and minimum are given by:

$$E_{\max} = E_D + E_R \ , \tag{1}$$

$$E_{\min} = E_D - E_R \ , \tag{2}$$

where E_D and E_R, respectively, are field strength values of direct path and reflected waves (Fig. 2).

This equations system can be solved for E_D to obtain

$$E_D = (E_{\max} + E_{\min})/2 \ . \tag{3}$$

Finally, by using well known relation between the field strength (rms value) under the free space conditions and equivalent isotropically radiated power P, we obtain the expression:

$$P = \frac{1}{30}(E_D L_D)^2 \ . \tag{4}$$

This equation is more useful when expressed logarithmically:

$$P(dBW) = E_D(dB\mu V/m) + 20\log L_D(m) - 134{,}77(dB), \tag{5}$$

where L_D is the length of the direct propagation path.

B. Determination of the method applicability

The measuring antenna must be directed towards the maximum radiation from the transmitting antenna. Generally, it can be done easily because usually the broadcast antennas are characterized by low directivity in horizontal plane. As regards the choice of the separation distance between the transmitting and the measuring antenna positions, it should be noted, that this method can be applied only if two opposite conditions are fulfilled. On the one hand, the maximum necessary horizontal separation distance d_{max} between the transmitting and the measuring antenna positions must be determined in such a way that, by varying the receiving antenna height, at least one minimum and one maximum value of the field strength should be detected. On the other hand, the minimum necessary separation distance d_{min} between the transmitting and the measuring antenna positions must be determined, which corresponds to the largest elevation angle under which it is possible to evaluate the influence of the directivity of the transmitting antenna in vertical plane or ignore it. The method can be applied only if the elevation angle at the distance d_{max} is equal or less than the above mentioned largest elevation angle. As the elevation angle is the angle between the line connecting the measuring and transmitting antennas and the horizontal axis, it is clear that this elevation angle decreases with the increase of distance. And it is obvious that if the method can be applied, it is better to perform the field strength measurement at the maximum possible distance, i.e. at the distance d_{max}.

Let's assume that the measuring antenna height h was changed from the lowest value h_{min} to the highest value h_{max}. Following the notations in Fig. 2, when the height of measuring antenna above the ground was minimal, the length of the direct propagation path $L_{D,\min}$ can be expressed as follows:

$$L_{D,\min} = \sqrt{(H - h_{\min})^2 + d^2} = d\sqrt{1 + \left(\frac{H - h_{\min}}{d}\right)^2} \ , \tag{6}$$

and the length of the indirect propagation path due to the ground reflection will be:

$$L_{R,\min} = \sqrt{(H + h_{\min})^2 + d^2} = d\sqrt{1 + \left(\frac{H + h_{\min}}{d}\right)^2} \ . \tag{7}$$

In practice, the horizontal separation distance d between the transmitting and the measuring antenna positions is very large compared to $(H + h_{\min})$ and $(H - h_{\min})$. Therefore, the expressions (6) and (7) simplifies:

$$L_{D,\min} = d + \frac{1}{2d}(H - h_{\min})^2 \ , \tag{8}$$

$$L_{R,\min} = d + \frac{1}{2d}(H + h_{\min})^2 \ . \tag{9}$$

In such a case, the path difference is

$$\Delta L_{\min} = L_{R,\min} - L_{D,\min} = \frac{2Hh_{\min}}{d}. \tag{10}$$

Similarly, when the height of the measuring antenna above the ground is maximal, the path difference will be:

$$\Delta L_{\max} = L_{R,\max} - L_{D,\max} = \frac{2Hh_{\max}}{d} \ . \tag{11}$$

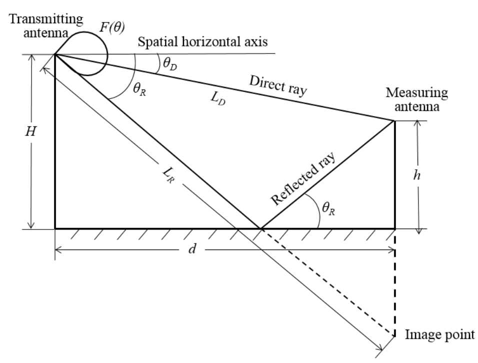

Fig. 2. Geometry of the two-ray ground reflected model.

So, if the height of the receiving antenna above the ground is changed from h_{min} to h_{max}, the displacement of path difference is

$$\Delta L_{\max} - \Delta L_{\min} = \frac{2H(h_{\max} - h_{\min})}{d}. \quad (12)$$

By varying the antenna height, at least one minimum and one maximum value of the measured field strength should be detected. This requirement is always met if the displacement of the paths differences is

$$\Delta L_{\max} - \Delta L_{\min} = \frac{2H(h_{\max} - h_{\min})}{d} \geq \lambda, \quad (13)$$

where λ – the wavelength of the transmitting signal.

It follows from inequality (13) that the maximum horizontal separation distance d_{max} between transmitting and measuring antenna positions is given by:

$$d_{\max} = \frac{2H(h_{\max} - h_{\min})}{\lambda} = \frac{2fH(h_{\max} - h_{\min})}{c}, \quad (14)$$

where f is the transmitting frequency and c is the velocity of light in free space.

This equation is more useful when expressed in such a form:

$$d_{\max}(m) = \frac{f(MHz)\,H(m)\,[h_{\max}(m) - h_{\min}(m)]}{150}. \quad (15)$$

Measurement must be carried out under the line-of-sight (LoS) condition, so the first Fresnel ellipsoid should be above the ground and in marginal case can only touch the Earth's surface. In that case the minimum value of height h_{min} is [1]

$$h^{m}_{\min} = \frac{75\,d(m)}{H(m)\,f(MHz)}. \quad (16)$$

As mentioned above, it is better to perform the field strength measurement at the distance d_{max}. In this case, when equation (16) is used for distance d_{max}, the system of equations (15) and (16) can be solved for d_{max} to obtain

$$d_{\max} = \frac{f(MHz)H(m)h_{\max}(m)}{225}. \quad (17)$$

It follows from this equation that the maximum distance is linearly dependent on the maximum achievable measuring antenna height. Comparing the expressions (16) and (17), the height $h^{m}_{\min}$ can be expressed in terms of h_{max}:

$$h^{m}_{\min} = \frac{1}{3} h_{\max}. \quad (18)$$

It is interesting to note that the ratio (18) is very close to practically achieved heights when using retractable masts. For example, Lithuanian Communications Regulatory Authority uses three types of the mobile monitoring stations with retractable masts. The maximum lifting heights of antennas for these stations are 10.78, 10.26 and 11.7 m. The minimum height of the antennas for them is respectively 0.353 h_{max}, 0.321 h_{max} and 0.342 h_{max}.

It follows from equation (17) that for broadcast frequencies following inequality may be applied:

$$d_{max} >> H >> h. \quad (19)$$

Therefore, elevation angles are very small and $\theta_D \approx \theta_R \approx \theta_{max}$. Considering this fact, it follows from inequality (19) and equation (17) that the elevation angle at the distance d_{max} is

$$\theta_{\max}(\deg) = \frac{180}{\pi} arctg \frac{H}{d_{\max}} \cong \frac{12900}{f(MHz)\,h_{\max}(m)}. \quad (20)$$

Note that angle θ_{max} is independent of transmitting antenna height above the ground H.

In most cases the terrain is not flat and the height of the measurement place does not coincide with the height of the place where the transmitting antenna is located. This might be dealt with the introduction of the adjusted height of the transmitting antenna H_{ad} instead of the height above the ground H. In the first approximation, it is enough to take into account that the adjusted height H_{ad} is equal $H+\Delta H$, where ΔH is the height difference between the locations of the measurement and the transmitting antennas.

For further discussion of the applicability of the height scan method, it is useful to consider the typical vertical radiation patterns for broadcast antennas, consisting of several bays. Tables I and II present elevation angles at which antenna gain is 1 dB and 10 dB less than the maximum gain (further they will be denoted as -1 dB and -10 dB elevation angles). These angle values are obtained from the radiation patterns, given in Kathrein catalogue “Professional Broadcast Antennas and Combiners”. Elevation angles θ_{max} were calculated using formula (20) when h_{max}=10.5 m.

The reason for use of these angles is the following. If -1 dB elevation angles are greater than the elevation angles θ_{max}, the directivity of the antenna in vertical plane can be neglected, otherwise it must be taken into account. Practice shows that the influence of the directivity of the antenna in vertical plane can be considered with sufficient accuracy if -10 dB elevation angles are greater than elevation angles θ_{max}.

It can be seen from Table I that in FM broadcast band (88-108 MHz) the directivity of an antenna in vertical plane can be neglected only for single bay antenna arrays. For 2 and 4-bays

TABLE I. TYPYCAL VERTICAL RADIATION PATTERN VARAMETERS FOR FM AND DAB SEVERAL BAYS BNTENNA ARRAYS WITH NULL FILL AND BEAMTILT

Quantity of bays in antenna arrays	**1**	**2**	**4**	**6**	**8**
Elevation angle at -1 dB level, deg	35	8	4.6	3.9	3
Elevation angle at -10 dB level, deg	60	24	12	8.8	7.2
Elevation angle θ_{max} in FM broadcast band, deg	12.7-17.1				
Elevation angle θ_{max} in DAB broadcast band, deg	5.7-7.9				

TABLE II. TYPICAL VERTICAL RADIATION PATTERNS PARAMETERS FOR DVB-T SEVERAL BAYS ANTENNA ARRAYS WITH NULL FILL AND BEAMTILT

Quantity of bays in antenna arrays	**1**	**4**	**8**	**12**	**16**
Elevation angle at -1 dB level, deg		2.5	1.2	1	0.8
Elevation angle at -10 dB level, deg		6	2.8	2.18	1.7
Elevation angle θ_{max} in DVB-T broadcast band, deg	1.6-2.9				

antenna arrays the directivity in vertical plane must be taken into account. In case of 6 and 8-bays the application of this method is not possible. At DAB broadcast band (174-240 MHz) the directivity of an antenna in vertical plane can be neglected for single and 2 bays antennas arrays. For antenna arrays with more bays the directivity in vertical plane must be taken into account.

It can be seen from Table II that in the lower part of the DVB-T broadcast band (470-862 MHz) the directivity of an antenna in vertical plane can be neglected only for four or less bays antenna arrays. For 8 bays antenna arrays the directivity in vertical plane must be taken into account in the whole band, and for 12 bays antenna arrays – only in the lower part of the band. In case of 16 bays antenna arrays or more the application of this method, generally, is not possible.

The accuracy of the method drops when in addition to one reflected wave from the ground more reflected waves exist. For determining the presence of the excess reflected waves, the comparison of experimental curves with theoretical can help a lot (Fig. 3).

III. ROUTE SCAN METHOD

A. *The principle of the method*

Basic principle of the method and its possible implementation was described by us in reference [2]. It was postulated that the difference between the measured and the calculated values occurs only because of the radiated power value used in the model. The radiated power value used in calculations is being adjusted in such a way that the minimum of the fitting error between theoretically calculated and experimentally measured data curves is achieved (Fig. 4). The best-fit radiated power value P_{bf} obtained by using this method

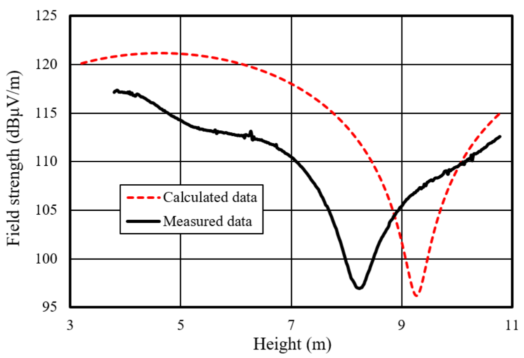

Fig. 3. The field strength level as a function of the height (f – 96.3 MHz, P = 29.7 dBW, H – 60 m, d – 346 m).

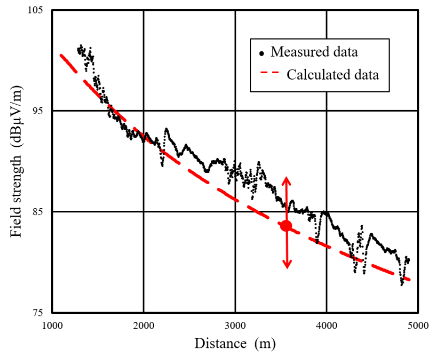

Fig. 4. The field strength level as a function of the distance from the transmitting antenna along a route which coincides with antenna's beam axis.

is the measured radiated power P_m.

For data fitting, we suggest using Root-Mean-Square Error (RMSE), which is a frequently used measure of the differences between the values calculated according to the model and the measured values. It was shown that if the best-fit radiated power P_{bf} was used in the model, then the arithmetic mean of all measured values along the route is equal to the arithmetic mean of all calculated values. This fact allows simplifying the procedure for determination of radiated power of a radio station and performing it in three stages:

1) for the selected route, an arithmetic mean $\overline{E}^c$ of the field strength is calculated for any selected value of radiated power P_s;

2) the field strength along the route is measured and its arithmetic mean $\overline{E}^m$ is calculated;

3) the radiated power P_m is calculated according to such expression:

$$P_m(dBW) = P_s(dBW) + (\overline{E}^m - \overline{E}^c)\,dB\,. \tag{21}$$

B. *Field strenght calculations along a route*

The accuracy of the method depends on the radio propagation model used for the field strength calculation. The most suitable model is the two-ray interference model. This model is well-known but only its simplified version for long distances is well-described and widely used. For the purpose of accuracy, a fully-featured two-ray model was used for verification of this method [2]. In case the field strength measurement route is far enough from the transmitting antenna, easily applicable Vvedenskij's formula can be used.

When the distance d is very long relatively to the height of the transmitting antenna H and receiving antenna h, the angles θ_D and θ_R are nearly equal and close to zero (Fig. 1) and the reflection coefficient of the ground is close to 1, then the exact expression for the calculation of field strength transforms into simplified expression [3]:

$$E = F(\theta)F(\varphi)\sqrt{30P}\,\frac{4\pi H h f}{d^2 c}\,, \tag{22}$$

where $F(\theta)$ and $F(\varphi)$, respectively, are the normalized directivity of an antenna in vertical and horizontal planes.

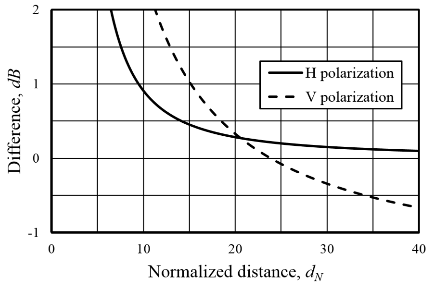

Fig. 5. Dependence of the field strength difference between calculated in line with Vvedenskij's formula and exact equations [2] on normalized distance (h=3 m, f=100 MHz).

The equation (22) is usually called the Vvedenskij's interferential formula. According to paper [3], this formula can be applied under the following condition:

$$\frac{2\pi H h f}{d c} \leq \frac{\pi}{9} . \quad (23)$$

It is more convenient to introduce the normalized distance $d_n=d/(Hhf/c)$ and (23) rewrite as:

$$d \geq 18 d_n . \quad (24)$$

This expression says nothing about the error that is made by using the Vvedenskij's expression (22). We have not found any information about this case in the literature. So, in order to determine the error of application of this expression, the field strength calculations according to the exact formulas [2], which include the dependence of the ground reflection coefficient on the grazing angle, and to Vvedenskij's formula were carried out. In calculations, it was assumed that the antenna's normalized directivity in vertical and horizontal planes is equal to 1. Calculated results as a function of normalized distance $d_n=d/(Hhf/c)$ are shown in Fig. 5. Calculations show that curves in this picture practically do not change when h=3 m and H varies within 50-200 m. It is seen that at the difference of 1 dB for horizontal polarization Vedenskij's formula can be applied starting from normalized distance equal to 10, and for vertical polarization – starting from 15.

C. Impact of non-ideal route evaluation

In most cases the surface of the measurement place is not completely flat, and its height does not coincide with the height of the place where the transmitting antenna is located. This might be dealt with the introduction of the effective height of the transmitting antenna H_{ef}, which is the height of the antenna above terrain height averaged along the route. In practice, this is performed as follows. Using digital map with terrain heights, the height of the antenna mast area above the sea level H_M is determined. Terrain heights of the selected route should be also checked, and the average route height above the sea level H_R should be determined. Then the effective antenna height H_{ef} is calculated as follows:

$$H_{ef} = H + (H_M - H_R). \quad (25)$$

In practice, the route direction usually does not match the

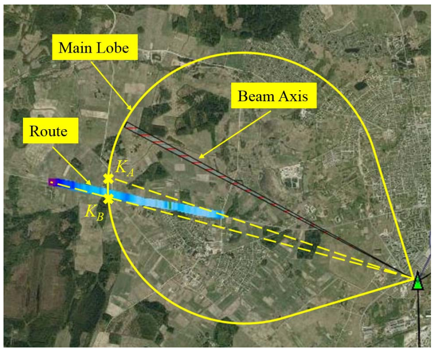

Fig. 6. Satellite map shows a route whose direction does not coincide with the exact direction of the antenna beam axis.

exact direction of the antenna beam axis. Such a situation is shown in Fig. 6. Usually the deviations from the beam axis were not significant, so the correction value was calculated simply by taking from transmitting antenna's H-plane pattern the value of field strength decrease from its maximum at the route's beginning K_A and at the end of the route K_B (see Fig. 6) and taking the average of them. So, this correction value is

$$\Delta P(dB) = K_{\max}(dB) + [K_A(dB) + K_B(dB)]/2 . \quad (26)$$

This correction value was added to the calculated value of P_m in line with equation (21).

IV. Experimental Validation of the Methods

It should be noted, that experimental verification of the over-the-air methods has been possible due to the two circumstances. First, Lithuanian Communications Regulatory Authority has reliable data on the station's antennas radiation patterns, the height above the ground, authorized radiated power and the transmitter's authorized power. Secondly, the actual values of the radiated power P_a were determined by on-site inspections.

A. Equipment used for field strenght measurement

Field strength measurements on-the-go with geographical coordinate registration were made using the mobile monitoring station of the Communications Regulatory Authority. This station is used for general purposes and is equipped with all the necessary monitoring equipment including monitoring antennas, GPS receiver, retractable mast, power generator and etc. With the mast down, this station can operate in motion.

Antennas R&S HK116, R&S HL223 and spectrum analyzer R&S ESPI-7 were used for field strength measurement. For control of the spectrum analyzer, download of raw data and for collection of GPS information, a portable computer was used. Measurement system records the data of time, field strength level, direction, latitude, longitude and line-of-sight distance away from transmitting antenna mast every 30 msec. Detailed procedure for measuring the field strength along the route is described in paper [2].

For measuring the field strength dependency on height at a fixed location, the same above mentioned equipment was used. During the measurement, the measuring antenna height was changing from minimum to maximum, at the same time spectrum analyser was recording curve of the field strength changes.

The field strength measurement error basically depends on the accuracy of the measuring instruments: antenna R&S HK116, HL223 and spectrum analyzer R&S ESPI-7. According to calibration certificates, HK116 and HL223 antenna factor calibration uncertainty is equal to ±1 dB and ESPI-7 level measurement uncertainty is equal to ±0.2 dB in FM broadcast band, and 0.5 dB in DVB-T broadcast bands. Thus, in the worst case, measurement error due to inaccuracy of the measuring instrument does not exceed 1.2or 1.5 dB.

B. *Measuring and analysing results for FM broadcast stations*

The FM broadcast radio stations were selected for measurements in the localities of Raseiniai, Rokiskis, Panevezys, Viesintos and Juragiai. Main characteristics of the measured stations are presented in Table III. All radio stations used broadband antenna systems, consisting of one, two and maximum four bays of vertically stacked antenna arrays. There are no radio stations which use antenna arrays with more than four bays in Lithuania. Note, that only in case of Raseiniai radio station was transmitting at a single frequency. In all other cases, several radio stations shared a single broadband antenna system, and it was transmitting at several frequencies. In most cases measurements were carried out at all of these frequencies and for each frequency along the route separately.

As mentioned above, suitable routes in the area of each radio station were selected. The selection was performed according to the recommendations given in paper [2]. Main characteristics of the routes are presented in Table IV (following abbreviations in this table are used: d_{st} , d_{end} – distance from the beginning and the end of the route to the transmitting antenna, respectively; L_r – length of the route; σ_h – standard deviation of the route's height).

Results of the measurement of radiated power of FM broadcast radio stations according to the height scan method are shown in TABLE V. It can be seen, that the directivity of the transmitting antenna in vertical plane $F(\theta)$ can be neglected only for single bay antenna arrays. It is desirable to evaluate its impact for 2 bays antenna arrays. In case of 4-bays antenna arrays, the directivity in vertical plane must be taken into account. It should also be noted that by varying the antenna height one minimum and one maximum of the measured field strength was detected very often at distances d which were up to 1.6 times longer than d_{max}, calculated according to expression (15).

It can be seen that the measurement error (it is nothing else but the difference between the measured radiated power and the actual radiated power) is small enough. In 9 cases the measurement error does not exceed 2 dB, and in four cases it is bigger than 2 dB. It is a good result for these over-the-air measurements.

Results of measurements of the radiated power of FM broadcast radio stations according to the route scan method are shown in TABLE VI (following abbreviations in this table are used: Δ, Δ_S – the radiated power measurement error in case

TABLE III. FM BROADCAST RADIO STATIONS LOCATIONS AND MAIN PARAMETERS

Location	Antenna type	Antenna height above the ground (m)	Frequency (MHz)
Raseiniai	Aerial Oy AV1542 1 bay, 2 sides	69.4	90.7
Rokiskis	ELTI DII/06-L 1 bay, 3 sides	59	92.6; 96.3
Panevezys	Kathrein K 523187 2 bays, 4 sides	97.7	93.7; 99.1 107.5
Viesintos	Kathrein K 523187 4 bays, 4 sides	139	101.9; 104.4 106.5
Juragiai	Aerial Oy AV1311-95 4 bays, 1 side	137	97.5; 103.5 106.6

TABLE IV. ROUTE PARAMETERS

Route	d_{st} (m)[a]	d_{end} (m)[a]	L_r (m)[b]	σ_h (m)[c]
Raseiniai				
Ras1	940	1320	380	2.09
Ras2	2800	4440	1640	1.53
Ras3	4150	5470	1320	1.25
Rokiskis				
Rok1	1050	2860	1810	1.47
Rok2	3330	4430	1100	1.33
Rok3	3160	5750	2590	2.53
Panevezys				
P1	1020	2270	1150	1.95
Viesintos				
V1	2000	4260	2260	3.66
V2	2000	5180	3180	2.37
Juragiai				
J1	8300	10400	2100	1.3

TABLE V. EXPERIMENTAL RESULTS OF THE HIGHT SCAN METHOD

Frequency (MHz)	d (m)	d_{max} (m)	$F(\theta)$ (dB)	Measurement error dB
Raseiniai, 1 bay antenna array, H-polarization				
90.7	250	268	-0.32	-0.72
Rokiskiai, 1 bay antenna array, H-polarization				
92.6	352	259	-0.09	-1,62
95.6	352	268	-0.09	-0,58
96.3	352	270	-0.09	-3,0
Panevezys, 2 bays antenna array, V-polarization				
93.7	547	458	-0.537	-0.74
99.1	547	547	-0.537	0.67
107.5	547	525	-0.537	0.99
Viesintos, 4 bays antenna array, H-polarization				
101.9	797	472	-6.94	0.72
104.4	797	484	-6.94	1.06
106.5	797	493	-6.94	2.1
Juragiai, 4 bays array, V-polarization				
97,5	852	624	-4.48	-0.25
103,5	852	662	-4.48	-3.9
106,6	852	682	-4.48	-2.2

when the field strength along the route was calculated using the two-ray model with considering the transmitting antenna directivity in vertical plane and without considering it, respectively; Δ_v, Δ_{vs} – the radiated power measurement error in case when the field strength along the route was calculated using the Vvedenskij's interferential formula with considering the transmitting antenna directivity in vertical plane and without considering it, respectively).

Looking at the TABLE VI, it can be seen that from all 23 measurements only in 3 cases the radiated power measurement error Δ is bigger than 2 dB and in 12 cases the measurement error does not exceed 1 dB. It is a very good result. By comparing errors Δ and Δ_s it can be concluded that the directivity in vertical plane must be taken into account only for radio stations in Viesintos and Panevezys. For the first station, the difference between the errors Δ_s and Δ is about 0.5 dB, and for the second station – (0.8-0.9) dB. This situation arose because the suitable routes could be found only in the vicinity of these stations. Therefore, in these routes the field strength was measured within large enough elevation angles, at which the transmitting antenna radiation is significantly below the maximum.

TABLE VI. EXPERIMENTAL RESULTS OF THE ROUTE SCAN METHOD

Route	Frequency,MHz	d_n	Measurement error (dB)			
			Δ	Δ_v	Δ_s	Δ_{vs}
Raseiniai, 1 bay antenna array, H-polarization						
Ras1	90,7	9-13	1.13	0.28	1.06	0.34
Ras2	90,7	28-37	1.26	0.89	1.25	1.13
Ras3	90,7	39-51	-2.1	-2.19	-2.12	-2.21
Rokiškis, 1 bay antenna array, H-polarization						
Rok1	92,6	14-38	0.62	0.41	0.59	0.38
Rok1	95.6	14-36	0.67	0.45	0.64	0.41
Rok2	92.6	61-81	1.01	0.97	1.0	0.97
Rok2	96.3	59-78	-0.04	-0.09	-0.04	-0.08
Rok2	95.6	59-78	0.93	0.88	0.93	0.88
Rok3	92.6	36-65	0.20	0.13	0.19	0.12
Rok3	96.3	35-64	-0.23	-0.31	-0.24	-0.32
Rok3	95.6	35-63	2.4	2.34	2.4	2.34
Panevėžys, 2 bays antenna array, V-polarization						
P1	93.7	9-18	0.06	-1.42	-0.83	-2.32
P1	99.1	9-19	-1.12	-2.56	-1.89	-3.33
P1	107.5	8-17	-0.32	-2.0	-1.14	-2.8
Viešintai, 4 bays antenna array, H-polarization						
V1	101.9	10-22	0.39	0.01	-0.17	-0.52
V1	104.4	10-21	-0.02	-0.4	0.55	-0.91
V1	106.5	10-20	0.52	0.1	-0.08	-0.47
V2	101.9	11-28	1.9	1.62	1.53	1.26
V2	104.4	10-21	1.75	1.39	1.24	0.9
V2	106.5	10-21	1.13	0.76	0.62	0.27
Juragiai, 4 bays array, V-polarization						
J1	97.6	42-54	1.02	1.53	1.04	0.45
J1	103.5	40-51	-1.47	-1.07	-1.46	-1.07
J1	106.6	39-50	-1.73	-1.39	-1.72	-1.38
Juragiai, 4 bays array, H-polarization						
J1	90.3	35-41	0.6	0.49	0.55	0.45
J1	96.2	33-41	2.26	2.15	2.22	2.11
J1	102.1	31-39	0.82	0.71	0.78	0.67
J1	104.1	30-38	0.7	0.58	0.66	0.54

If a suitable route can be found far away from the radio station (so that the normalized distance d_n would be greater than 20), even in case of 4 bays antenna array, the field strength along the route can be calculated by Vvedenskij's formula without considering the transmitting antenna's directivity in vertical plane. In such cases errors Δ and Δ_{vs} differ fractionally what can be seen in TABLE VI for Juragiai.

C. *Measuring and analysing results for DVB-T broadcast radio stations*

For the measurements, the DVB-T broadcast radio stations were selected in the localities of Raseiniai and Juragiai. Main characteristics of the measured stations are presented in Table VII. Such a small number or measured stations can be explained by the fact that most DVB-T stations in Lithuania use antenna arrays with 10-15 bays, and only in some regional stations 2 bays omnidirectional antennas K 770 811 are used. For the measurements of radiated power of DVB-T broadcast radio stations by the route scan method, the same routes for FM radio stations measurements were used.

The results of radiated power of DVB-T broadcast radio stations' measurements according to the height scan method are shown in TABLE VIII. It can be seen, that the directivity of the transmitting antenna in vertical plane $F(\theta)$ can be neglected only for 2 bays antenna. In case of 10 and more bays antenna arrays, the directivity in vertical plane must be taken into account. It should also be noted that when the radiated power is measured by the height scan method, the measurement errors in average in DVB-T broadcast band are noticeably lower than in FM broadcasting band.

The results of radiated power of DVB-T broadcast radio

TABLE VII. DVB-T BROADCAST RADIO STATIONS LOCATIONS AND MAIN PARAMETERS.

Location	Antenna type	Antenna height above the ground (m)	Channel
Raseiniai	Kathrein K 770811	100	22; 24; 26
Juragiai	Kathrein K 774 040 10 bays, 5 sides	234	21; 28 44; 45

TABLE VIII. EXPERIMENTAL RESULTS OF THE HEIGHT SCAN METHOD

Channel	d (m)	d_{max} (m)	$F(\theta)$ (dB)	Measurement error (dB)
Raseiniai, 2 bay antenna K 770 811, H-polarization				
22	1751	1607	-0.46	-1.04
24	1751	1660	-0.46	0.26
26	1751	1713	-0.46	-0.54
Juragiai, 10 bays array of panels K 774 040, H-polarization				
21	9516	5618	-1.41	1.75
28	9516	6282	-2	0.52
44	9516	7800	-3.74	1.04
45	9516	7894	-3.74	0.1

TABLE IX. EXPERIMENTAL RESULTS OF THE ROUTE SCAN METHOD

Route	**Channel**	d_n	**Measurement error (dB)**	
			Δ	Δ_{FS}
Raseiniai, 2 bay antenna K 770 811, H-polarization				
Ras1	22	1.3-2	-4.8	-5.1
Ras1	24	1.3-1.9	-6.93	-5.48
Ras1	26	1.3-1.9	-2.45	-0.95
Ras2	22	3.9-5.1	-5.3	0.36
Ras2	24	3.8-5.1	-5.39	0.32
Ras2	26	3.7-4.8	-5.24	0.555
Ras3	22	1.7-2.4	5.77	-1.5
Ras3	24	1.6-2.3	7.22	0.07
Ras3	26	1.6-2.3	9.05	1.49
Juragiai, 10 bays array of panels K 774 040, H-polarization				
J1	21	5.4-6.9	-5,17	-0.7
J1	28	4.9-6.1	-8.8	-3.76
J1	44	3.9-4.9	-7.32	-1.2
J1	45	3.9-4.9	-10.52	-4.77

stations' measurements according to the route scan method are shown in TABLE IX (following abbreviation in this table is used: Δ, Δ_{FS} – the radiated power measurement error in case when the field strength along the route was calculated using the two-ray and free-space model, respectively). The results are not as good as according to the height scan method. The measurement error Δ is unacceptably high.

The obtained result can be explained by the fact that the radio propagation model [2], used for field strength calculation, works well in FM broadcasting band, and it is not so suitable for DVB-T broadcast band. This is clearly seen from Fig. 7, showing the field strength variations of FM and DVB-T broadcast stations along the same route. In the areas where there are no additional reflections from trees and buildings near the route (e.g., at 9.5 km), the measured field strength in FM broadcast band is very close to the calculated one. It should be noted, that the fluctuations of the field strength, caused by additional reflections, are happening on either side of the theoretical (calculated) level. Therefore, the measured average field strength along the route is usually very close to a calculated average, as those above-mentioned outside fluctuations compensate each other. This explains the good accuracy of the route scan method in FM broadcast band. The measured DVB-T field strength in areas where there are no additional reflections, as seen in Fig. 7, is about 4-6 dB lower than the calculated one. Obviously, the two-ray field strength calculation model for DVB-T broadcast band needs to be improved. For the case, presented in Fig. 7, the measured DVB-T field strength is better described by the free-space model.

Application of the free-space model in DVB-T broadcast band gave better result than the two-ray model, but it was not always the case. As it is shown in TABLE IX, in 4 cases out of total 13 measurements, the measurement error was higher than 3 dB. Further studies are needed in order to find out the suitability of the free-space model application for radiated power measurements according to the route scan method.

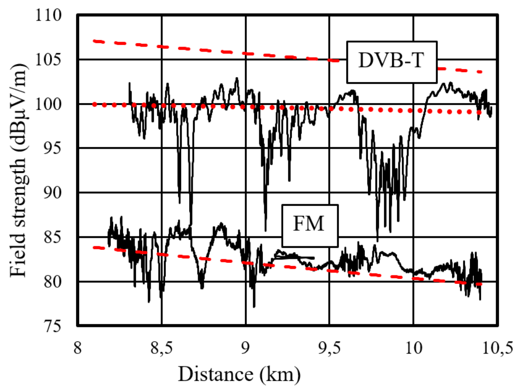

Fig. 7. The field strength level as a function of the distance from the transmitting antenna along the route J1. – measured data; - - -, ••• calculated data according two-ray and free-space models respectively.

V. CONCLUSION AND FUTURE WORK

The results, presented in this paper, show that in FM broadcast band the height scan method gives a reliable radiated power's measurement result without considering the transmitting antenna's directivity in vertical plane only if measured stations use 1 or 2 bays antenna arrays. This method can be applied for 4 bays antenna array, but directivity of the transmitting antenna should be taken into account. The route scan method provides noticeably more accurate radiated power's measurement results than the height scan method. The application of this method basically is limited to the possibility of finding a suitable route around the measured station.

In DVB-T broadcast band the height scan method has shown very good results. The radiated power's measurement error did not exceed 2 dB. For 10 bays and more antenna array the transmitting antenna directivity in vertical plane has to be taken into account. The route scan method has shown worse results in this frequency band. Therefore, in order to determine the suitability of this method in DVB-T broadcast band, additional research is needed.

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