Determination of the Radiated Power of Radio Station Through Field Strength Measurement Along a Route

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Abstract—The paper presents a method proposed to be used for determination of the radiated power of a radio station. The proposed method is based on the comparison of field strength values measured along a route with the calculated field strength values. This method is basically frequency-independent. For the purpose of verifying efficiency of the method, signal field strength of FM broadcast radio stations was measured along several routes. The field strength in these cases was calculated using the fully featured two-ray model. The results indicated that the proposed method worked very well. The radiated power determined according to this method in the worst case was only 2.72 dB different from the actual value of the operating radiated power.

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

I

INTRODUCTION

The radiated power of a FM broadcast radio station is one of the most important parameters, which characterize stations' emission. It is an essential parameter for the planning of FM transmission, especially for the determination of the coverage areas and the desired levels of signal field strength. For these reasons, the radiated power is specified in authorizations.

Usually the radiated power of radio stations is determined indirectly through the measurements of RF power at the output of a transmitter and further calculations by taking into account cable losses and antenna gain. It is sometimes impossible to use this method of measurements for inspection or radio monitoring services because there is no access to a transmitter site or no technical possibility to attach a power meter to the transmitter output. Reference [1] provides a measurement method to determine the radiated power from field strength measurements. This method allows excluding the influence of ground reflections because of information gained from a height scan of the field strength. Unfortunately, this measurement method loses accuracy for frequencies below 400 MHz because the height accessible by customary measurement antennas (10 m) will not be sufficient to capture both the maximum and the minimum of the field strength distribution at the angles close to the beam axis. Thus, it is difficult to apply this method for determination of the radiated power of FM broadcast radio stations because they usually use the frequencies from 87.5 to 108 MHz.

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The main purpose of this paper is to propose another offair method to determine the radiated power of a radio station. The method is based on the comparison of the field strength values measured along a route with the calculated field strength values. Obviously, the effectiveness of the proposed method mainly depends on the radio propagation model used for the field strength calculation. For testing the proposed method, the two-ray interference model was used. This model is well-known, but only its simplified version for long distances is well-described and widely used. For the purpose of the proposed method, a fully featured two-ray model should be used.

II. TWO-RAY FULLY FEATURED INTERFERENCE MODEL FOR FLAT SURFACE

The two-ray model is an improved version of the free space propagation model. It considers both line-of-sight (direct) and ground reflection paths and is based on geometric optics. This model is reasonably accurate for predicting the large-scale field strength at a distance of several kilometres.

A. Analytical modelling

Following the notations in Fig. 1, the length of direct propagation path can be geometrically derived to be

$$L_D = \sqrt{(H-h)^2 + d^2} , \qquad (1)$$

and the length of indirect due to ground reflection path derived to be



Fig. 1. Graphical representation of the two-ray model applied for a vertically polarized wave.

$$L_{R} = \sqrt{(H+h)^{2} + d^{2}} \quad . \tag{2}$$

The grazing angle θ_R and angle θ_D can be derived to be

$$\theta_{R} = \operatorname{arctg}\left(\frac{H+h}{d}\right) , \qquad (3)$$

$$\theta_D = \operatorname{arctg}\left(\frac{H-h}{d}\right) \ . \tag{4}$$

Based on the lengths L_D and L_R , on the equivalent isotropically radiated power P, on directivity of the transmitting antenna in vertical plane $F(\theta)$ and on the magnitude R and phase $\varphi(\theta)$ of the ground reflection coefficient, the direct wave can be expressed as

$$E_{D} = \frac{F(\theta_{D})\sqrt{60P}}{L_{D}}\sin[2\pi f(1-\frac{L_{D}}{c})] , \qquad (5)$$

and the reflected wave can be expressed as

$$E_{R} = \frac{R(\theta_{R})F(\theta_{R})\sqrt{60P}}{L_{R}}\sin[2\pi f(1-\frac{L_{R}}{c})+\varphi(\theta_{R})], \quad (6)$$

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

When doing field strength calculations, the type of wave polarization should be taken into account. In case of horizontal polarization, the electric vector of direct wave is horizontal to the reflecting surface. The electric vector of the reflected wave is also horizontal to the reflecting surface. Thus, these two vectors are parallel, and the total field strength can be calculated by adding the direct and the reflected waves accounting for the difference of phases. As follows from the equations (5) and (6), the phase difference is

$$\Delta \Phi = \frac{2\pi f}{c} (L_R - L_D) + \phi(\theta_R) . \tag{7}$$

Finally, for the total field strength (rms value) we obtain:

$$E_H = K_H \sqrt{30\pi P} , \qquad (8)$$

where

$$K_{H} = \left\{ \left[\frac{F(\theta_{D})}{L_{D}} \right]^{2} + \left[\frac{RF(\theta_{R})}{L_{R}} \right]^{2} + \frac{2R}{L_{D}L_{R}}F(\theta_{D})F(\theta_{R})\cos\left(\Delta\Phi\right) \right\}^{\frac{1}{2}}.$$
(9)

In case of vertical polarization, the electric vectors of direct and reflected waves lay in the plane of incidence. Fig. 1 shows the visualization of this situation. It is easy to obtain that the angle between the electric vectors of direct and reflected waves is $(\theta_D + \theta_R)$. Therefore, the total field strength can be calculated by adding the direct and the reflected waves accounting for difference of phases and difference of directions.

Finally, in the case of vertical polarization, for total field strength of the vertical component we obtain the expression similar to expression (8), but with different function K_V :

$$K_{V} = \begin{cases} \left[\frac{F(\theta_{D})\cos(\theta_{D})}{L_{D}}\right]^{2} + \left[\frac{RF(\theta_{R})\cos(\theta_{R})}{L_{R}}\right]^{2} + \left[\frac{2R}{L_{D}L_{R}}\cos(\Delta\Phi)\cos\theta_{D}\cos\theta_{R})\right]^{2} \end{cases}$$
(10)

When distance *d* is very long compared to the height of the transmitting antenna *H*, the angles θ_D and θ_R are close to zero, and expression (10) simplifies and transforms into expression (9).

The equations for total field strength are more useful when expressed logarithmically:

$$E_H(dB\mu V/m) = P(dBW) - 20\log K_H + 134,77$$
, (11)

$$E_V(dB\mu V/m) = P(dBW) - 20\log K_V + 134,77$$
. (12)

B. Computing of field strenght

Data processing and computation were carried out with *Microsoft Excel 2010*.

For the purpose of field strength calculations, separate *Excel* templates were created for several types of transmitting antennas. Directivity of the transmitting antenna in vertical plane $F(\theta)$ was described using two approximating polynomials. As the main beam is symmetrical, it is enough to describe only one side of it. Mostly the third order polynomial was used for its description. The first side lobe was described using the sixth degree polynomial. The coefficients of polynomials were determined using *MS Excel*.



Fig. 2. Magnitude and phase of the reflection coefficient of a plane surface and medium dry ground as a function of a grazing angle for vertical V and horizontal H polarizations [2] (the frequencies are given in GHz).

Dependencies of magnitude and phase of the reflection coefficient on grazing angle were taken from [2] and are presented in Fig. 2, which shows that, for horizontal polarization, the magnitude of a reflection coefficient changes smoothly with the change of a grazing angle. It was precisely described using one polynomial of the sixth degree. For vertical polarization, the magnitude of a reflection coefficient has a sharp deep minimum at a grazing angle of 15 degrees (Brewster's angle). For that reason, the reflection coefficient was described using two separate polynomials in the ranges from zero to 15 degrees and from 15 to 90 degrees of a grazing angle. As follows from [2], the phase of the reflection coefficient is equal to 180 degrees for horizontal polarization, and it decreases from 180 to zero degrees with the change of grazing angle from 10 to 20 degrees for vertical polarization. The magnitude of the reflection coefficient in a range from 10 to 20 degrees is less than 0.2. Therefore, we can presume, without significant influence on calculations of the total field strength, that the phase of reflection coefficient is equal to 180 degrees in the range of a grazing angle from zero degrees to 15 degrees, and it is equal to zero in the range of a grazing angle from 15 to 90 degrees.

Excel template was created where fixed ground distance *d* ranges from 100 m to 11,000 m with a step of 10 m. After entering the heights of transmitting and receiving antennas, transmitting frequency and power, the values of L_D and L_R , angles θ_D and θ_R and the corresponding antenna directivity, reflection coefficient magnitude and phase values were automatically calculated for every distance value. As the final result, the values of the total field strength were calculated by formulas (11) and (12) for each fixed distance value and represented graphically.

As an example, the results of field strength calculation for a FM broadcast radio station with typical narrow beam antenna are presented in Fig. 3. In this case, beam width in vertical plane equals to 14 degrees. For transmitting antenna with such a narrow beam width, it is possible to ignore the antenna directivity only for longer distance than 2 km. Fig. 3 demonstrates that there are significant variations between vertical and horizontal field strengths near the transmitting antenna.



Fig. 3. Calculation result of field strength at 3.8 m for FM broadcast radio station. Station parameters: equivalent isotropically radiated power – 30 dBW; frequency – 104.1 MHz; antenna height above the ground – 200 m; antenna model – four bays of vertically stacked antenna arrays (without null fill) desired of panel antenna K5231187.

III. EXPERIMENTAL VALIDATION OF THE METHOD

In order to verify the efficiency of the proposed method in practice, we used four routes. Selection of routes, field strength measurements along these routes and techniques of measured data processing are described below.

A. Equipment used for field strenght measurement

Field strength measurements on-the-go with registration of geographical of coordinates 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 and antenna, telescopic mast, generator and etc. Workplace for one operator is equipped with a computer and writing area. With the mast down, this station can operate in motion (Fig. 2).

Specifically in this case, antenna R&S HK116 and spectrum analyzer R&S ESPI-7 were used for field strength measurement. In order to control the spectrum analyzer, download raw data and collect GPS information, a portable computer was used.

The measurement system records, every 30 msec, the data of time, field strength level, direction, latitude, longitude and line-of-sight distance away from transmitting antenna mast. During the measurement, the vehicle moved at 32 km/h speed, so the distance between measurement points was about 0.3 m. According to [3], the distance between the measurement points must be less than 0.8 wavelengths. This requirement has been completely fulfilled because the wavelength of a radio wave with a frequency of 88 MHz is 3.4 m.

When performing the field strength measurements, it is essential to point the measurement antenna directly into the transmitting antenna. This requirement is usually fulfilled if the mobile station moves in radial routes from or to the transmitting antenna. During the measurement, the chosen height of the measuring antenna is 3.8 meters. Such antenna height is the maximum possible when vehicle is moving. Experimental measurements showed that at this antenna height the influence of a vehicle body on measurement results can be eliminated only when the transmitting antenna is located behind the vehicle. In case the vehicle faces the transmitting antenna, measured field strength values are about 2 dB higher.



Fig. 4. A picture of the mobile station with the measuring antenna in an operating position.

Therefore, measurements were performed when the car was moving away from the transmitting antenna mast.

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

B. Route selectiont

First of all, the route should be selected across the radial line from the transmitting antenna. There are two reasons for this. The first one is that in such case the vehicle body has no influence on measurement results. The second reason is that it is easy to evaluate the transmitting antenna directivity in a horizontal plane if needed.

Secondly, the route should be located in the rural area, which allows avoiding reflections from high buildings, big structures, etc. Moreover, this helps to ensure that ground electrical properties will not vary significantly along the route.

Route selection starts from the selection of a suitable country road in the area of the inspected FM broadcast radio station, and satellite maps help with this task a lot. Only a suitable section of the road may be used for measurements along the route. It is important that the section's length is not less than 300-400 m, and it is no closer than 1 km from the transmitting antenna mast. If possible, one should also check whether there are no local height variations above 5-10 meters along the route.

Physical location survey was the second stage of route selection. During visual inspection of the route, any obstacles such as tall trees, hills and structures capable of causing obstruction of radio waves along the line of sight were taken into account.

In this way, four routes were selected. As an example, the map and the view of route B are shown in the Fig. 5 and Fig. 6 respectively. Table I show route parameters and the measured FM broadcast radio stations as well as includes the parameters of transmitting antennas. All the inspected FM broadcast radio stations used broadband antenna systems, consisting of four bays of vertically stacked antenna arrays.



Fig. 5. Satellite map showing appropriate route in a rural area.



Fig.6. A picture of the dirt road leading directly to the transmitting antenna mast.

TABLE I.ROUTE PARAMETERS

Davamatar	Route				
rarameter	A	В	С	D	
The lenght of the route (km)	1	0.4	1.8	4	
Distance from transmitting antenna mast to the beginning of the route	1	1.1	8.2	1	
Height of transmitting antenna (m)	186	188	137	99	
Transmitting antenna model ^a	AV1541	K5231187	AV1311-95	BLR 2DBA	
Polarization	V	Н	V	V	
Height of measuring antenna (m)	3.8	3.8	3.8	3.8	

^{a.} Single antennas which are used in the construction of antennas' system

C. Results and analysis

In cases of routes A and D, radio stations were transmitting at single frequencies. As regards route B, four radio stations shared a single broadband antenna system which was transmitting at four frequencies. For the same reason, antenna system of route C was transmitting at three frequencies. Measurements were carried out at all of these frequencies and for each frequency along the route separately.

The theoretical calculations were performed using the actual values of the radiated power P_a , which was determined in the following way. The transmitter's operating power and the corresponding station's operating radiated power are specified in the stations' authorizations. Evidently, the station's authorized power in dBW is equal to the transmitter's authorized power in dBW plus a sum of cable losses and antenna gain in dB. During the on-site inspection, the difference between the transmitter's actual and authorized power was measured. It follows that the actual value of the radiated power is equal to the authorized radiated power shower bus this measured difference of transmitter's powers. The results showed that the actual values of radiated power at 0.1-0.9 dB differed from the authorized values.

The measured and calculated field strength values were well matched for all frequencies. The characteristic field strength data are presented in Fig. 7. This Figure shows severe



Fig. 7. The field strength level as a function of the distance between the transmitting antenna mast and the mobile station along the route D.

fluctuations in the field strength along a route, but these fluctuations do not prevent from reaching our objective.

For the purpose to determine the radiated power from the field strength measurement, we assume that the difference between the measured and the calculated values occurs only because the incorrect radiated power value in the model is used. This radiated power value should be adjusted in such a way that the best fit between theoretically calculated and experimentally measured data curves is achieved. Thus, the adjusted value P_m is the value of radiated power, determined from the field strength measurement along the route.

For data fitting, we used 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. In our case the expression for rmse is

$$rmse = \left[\frac{1}{N}\sum_{i=1}^{N} (E_i^m - E_i^c)^2\right]^{\frac{1}{2}} , \qquad (13)$$

where N – number of points along the route; E_i^m and E_i^c – measured and calculated field strength values at the point *i*.

As mentioned above, the field strength was calculated at a ground distance from the transmitting antenna from 100 m to 11,000 m with a step of 10 m. The measurements were performed without accurately fixed step size with length of about 0.3 m. Therefore, in order to calculate the rmse the route was divided into 10-meter sections and a mean of field strength in each section was calculated using *Microsoft Excel*. These mean values were used as the values E_i^m in equation



Fig. 8. Root-mean-square-error dependence on the radiated power used in calculations.

As an example, rmse dependence on the radiated power used in calculations for route A is shown in Fig. 8. The graph shows that the best-fit radiated power is equal to 41.55 dBW. It is interesting to note that the arithmetic mean of all measured data along the route \overline{E}^{m} is equal to arithmetic mean of all calculated data \overline{E}^{c} on the condition that the model used the best-fit radiated power P_{bf} . This fact allows simplifying the procedure for determining the best-fit radiated power.

Taking the measurements carried out, we set the arithmetic mean of field strength along the route \overline{E}^{m} . Then we calculated the arithmetic mean of field strength $\overline{E}^{c}(P_{s})$ at a freely set radiated power value P_{s} . Now we can calculate new value of radiated power:

$$P_m(dBW) = P_s(dBW) + (\overline{E}^m - \overline{E}^c) dB.$$
(14)

As the field strength is linearly dependent on the radiated power, it is obvious that the calculated mean $\overline{E}^{c}(P_{m})$ will coincide with the measured mean \overline{E}^{m} . This leads to the conclusion that P_{bf} and P_{m} values are equal which allows simplifying the procedure for determining the 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 strenght is calculated for a freely set radiated power P_s ;

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

3) transmitter's radiated power P_m is calculated according to the expression (14).

The results obtained by this method are listed below and considered as the measurement results.

The results of measurement of the radiated power of FM broadcast radio stations are shown in Table II. It demonstrates that the difference between the measured radiated power and the actual radiated power (it is nothing else but the measurement error) is small enough. In eight cases, the measurement error does not exceed 1.66 dB, and only in one case, it is equal to 2.72 dB. It is a very good result for these off-air measurements. In this regard, one can state that the proposed method has proved itself very well.

As mentioned above, theoretic values of field strength for

TABLE II. EXPERIMENTAL RESULTS

Route	Transmitting frequency (MHz)	Actual radiated power (dBW)	Measured radiated power (dBW)	Measurement error (dB)
Α	92.8	40	39.53	1.57
В	90.3	33.84	45.56	2.72
	96.2	39.1	40.76	1.66
	102.1	38.85	39.66	0.81
	104.1	42.21	41.33	0.11
С	97.6	35.72	37.25	1.53
	103.5	35.92	35.72	-0.2
	106.6	35.72	36.49	-0.77
D	92.5	25	26.59	1.55



Fig. 9. The dependence of the measurement error of the radiated power on the length of the route A.

all the routes were calculated with a step of 10 meters. The average values of field strength measured in the same points were calculated. In every section of a 10-meter length, about 33 field strength values were averaged. With those sets of values, it was easy to model the dependence of the difference of radiated powers on the distance of the route passed. Modelling results of route A are presented in Fig. 9. This Figure shows that in this case the length of a route does not have a significant influence on the value of the measured radiated power. When the length of a route changes from 20 m to 1,3 km, the measurement error varies only in the limits of 0,4 dB.

Fig. 10 presents modelling results of route B and shows that in this case the length of a route has more influence on the value of the measured radiated power. It is also obvious that the dependences of the measurement error on the length of the route in case of all four frequencies are very similar though four separate measurements were carried out. Such result is predictable as it is conditioned by roughness of horizontal surface of local roads and irregular reflections from the rough surfaces near the road. It is more difficult to understand why at lower frequencies the measurement error constantly increases. It is unlikely that such increase is conditioned by the changes in the parameters of measuring equipment because when the frequency changes from 90.3 MHz to 104.1 MHz, relative variation of frequency is small.

In order to determine the cause of such frequency-related dependence of results, the measurements of radiated power were



Fig. 10. The dependence of the measurement error of the radiated power on the length of the route B.



Fig. 11. The dependence of the measurement error on the frequency of the route B. ● – radiated power was measured by the proposed method; ■ – radiated power was measured by the method described in [1].

performed according to the method described in [1]. Measurement results are presented in Fig. 11. They show that the values of radiated power, measured by the method referred to [1], differ from the actual value of radiated power more than those obtained using the suggested method. However, even in this case it was observed that, when lowering a frequency, the measurement error constantly increases. Consequently, the conclusion can be made that the *de facto* radiated power slightly differs from the actual calculated radiated power. As the transmitters' output power was tested during the in-site inspections, we may conclude that the real gain of transmitting antennas differs from that which had been used for calculation of radiated power, and this difference depends on a frequency.

IV. CONCLUSION AND FUTURE WORK

The fully featured two-ray model was used to calculate the field strength along a route for 9 FM broadcast radio stations. The calculated results matched very well with the experimental ones. After comparison of these results, it was possible to determine, with sufficient accuracy, the radiated power of the tested FM broadcast stations. The differences between the power values determined in this way and the actual values differ from 0.11 to 2.72 dB.

It should be noted, that the presented method is basically frequency-independent. Therefore, it would be useful to verify it in the frequency range from 108 MHz to 400 MHz, where the method described in reference [1] is difficult to apply.

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