RESEARCH RESULTS

Analysis of the Radiation Pattern of a Collinear Array Over the Standard (4/3) Radio Horizon

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ABSTRACT

The radio horizon in the standard atmosphere at VHF is longer when compared to the optical line of sight (flat earth). This paper aims to present and discuss the radiation characteristics of a 4-bay broadcast collinear array (CA) over a radio horizon with an effective earth radius factor of 4/3. The analysis of the radiation characteristics over this radio horizon is more important and more realistic than the flat earth assumption. Using the computed gains of the array from 0^0 to 90^0 depression angles and tower height of 1000 feet, the normalized power density along the standard horizon is computed. Based on these computations, the main beam of the CA is missing the far-end of the radio horizon. It is above the horizon by 0.485^0, i.e. the angle of depression at the far-end of the horizon is a little lower than 0.5^0. Generally, the angle of depression increases as the tower height increases. Therefore, to optimize the coverage and to maximize utilization of the power from the transmitter, there is a need to tilt the main beam below the zero depression angle. Also, the signal levels on the earth's below the horizon do not pose any health issues for they are much lower than the set limit for day-to-day exposure. However, blanketing and maximum usable levels are easily exceeded.

KEYWORDS

Antenna Arrays, Beam Tilt, Coverage Optimization, Collinear array, Pattern nulls, Propagation, FM broadcasting

1. INTRODUCTION

Due to refraction by the atmosphere at VHF (Very High Frequency), it is a general knowledge that the radiowave propagation path is usually curved downward, thereby extending the radio horizon. One can look at the extension of the horizon as if the earth's radius is increased. This increase is usually indicated using the so-called effective earth radius factor, K. Generally, when the value of K is less than 1, the radiowave is arcing upward, travelling away from the earth and the radio horizon becomes shorter than the optical horizon. With K equal to 1, the radio horizon is equal to the optical horizon. When the value of K is greater than 1, the radio horizon is bending downward making the radio horizon longer than the optical horizon. In some books on radiowave propagation, the bending of the wave towards the earth when the value of K is greater than 1 is called superrefraction. It is also called ducting in some other sources. In the Philippines at VHF and higher frequencies, K is anywhere between 4/3 and 3/2 are the more common values. However, 4/3 (the lower limit) is the more common at standard atmosphere. Figure 1 illustrates the optical and radio horizon in which K is equal to a value that is greater than 1. In the figure, H_T is the transmiting antenna height and $\underline{a}$ is the mean radius of the earth which is assumed to be 3960 miles.

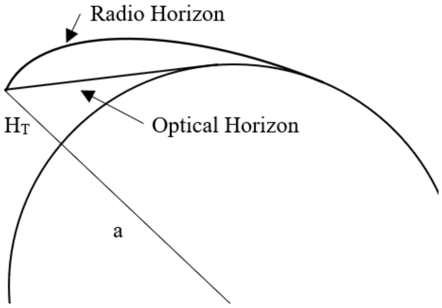


Figure 1. The difference between the radio and optical horizon when there exists a K>1.

Figure 2 illustrates the radio horizon with an effective earth radius factor of 4/3 making the effective earth radius (a') to be 5280 miles (a' = a (K)). For an antenna height of H_T in feet, the range of the radio horizon is about $\sqrt{(2H_{T(ft)})}$, miles. In this paper, the antenna height is assumed to be 1000 feet. This height has a range of about 44.72 miles. In the same illustration, one can compute for the distance traversed by the radiowave (D) and the corresponding distance between a point on the surface of the earth to the base of the tower (d). The 44.72 miles is therefore the maximum value of D with the given antenna height. The angle $\underline{\alpha}$ is the angle of depression. It is the angle formed by the line between the antenna and the far-end of the horizon, with the horizontal.

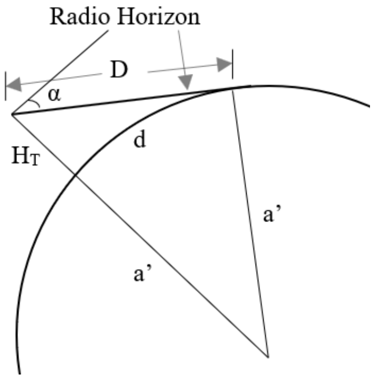


Figure 2. Standard radio horizon (K=4/3).

2. SYSTEM MODEL

Foremost, the generation of the gain pattern of the antenna array considered in this paper is through an advance antenna simulation software. Particularly, the advance multi-model Feko simulation software is used in this paper. Please note very well that most government regulatory bodies of the world, such as the Federal Communications Commission (FCC) of the USA, and the National Telecommunications Commission (NTC) of the Philippines accept simulated antenna characterization as proof-of-performance of antenna systems when applying for construction permits of broadcast stations.

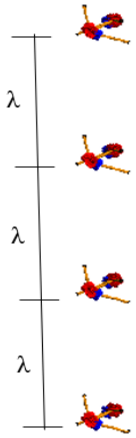
Figure 3(a) illustrates the set-up of the 4-element collinear array whose radiation characteristics are analyzed along the standard radio horizon. The basic elements composing the array are shunt-fed, slanted dipoles that are commonly used in FM broadcasting and spaced one wavelength (λ) apart. The elements are circularly polarized, having both horizontal and veritical components. The array is assumed to be in freespace, i.e. without a metallic tower to support the elements. Since this paper involves the analysis of the propagation along the standard radio horizon, it makes the said analysis more simple if the tower is not included. Each of the element dimensions are determined to operate at the center of the standard FM broadcast band (88-108 MHz) which is about 97.488 MHz. Figure 3(b) shows the gain pattern of the array on the vertical plane (with the azimuth angle $\varphi = 0^0$) in polar plot. The value of the elevation angle, θ, ranges from 0^0 to 360^0. Note that in broadcasting, the useful part of the gain pattern is that part that produces radiation below the horizon, i.e. $\theta = 90^0$ to 270^0. The other part of the pattern is responsible for the useless upward radiation of the signal. The equivalent cartesian plot is shown in Figure 3(c). Also, be aware that the gain pattern illustrated in this figure is just half of the one illustrated in Figre 3(b). As shown in the plots, there exist pattern nulls and sidelobe radiations along the horizon (for $\theta = 90^0$ to 180^0). Note very well that in the discussion of results, the values of the elevation angle, θ, from 90^0 to 180^0 corresponds to depression angle, α, values of 0^0 to 90^0, respectively.

As shown in Figure 3(b) and 3(c), pattern nulls are present at $\theta = 105^0$, 120^0, 139^0 and 180^0. Strictly speaking, the gain at these values of the elevation angle is relatively small, but not exactly equal to zero. Also, there exist components of the sidelobe that cause radiation along the radio horizon (below the main beam), particularly at $\theta = 111^0$, 128^0 and 155^0. These values of θ where the gains are relatively higher and producing downward radiation are more obvious in Figure 3(c). It is also worth noting where these nulls and sidelobe downward radiations will appear along the standard radio horizon. That will be presented and discussed in the results section.

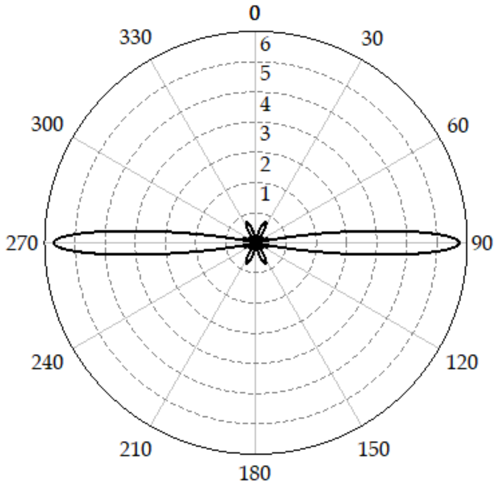
In the presentation of the radiation pattern along the standard horizon, the normalized power density (P_D) is used. The power density, generally is computed using Equation 1.

$$P_D = \frac{P_T G_T}{4\pi D^2} \quad (1)$$

where P_D is in W/m², P_T is the transmitted power in watts, G_T is the transmitting antenna gain. D is the distance traveled by the radiowave as illustrated in Figure 2. In this paper, the normalized values of the P_D in dB are used in the illustration and discussion of the radiation characteristics of the array along the horizon being considered. The array is composed of circularly polarized elements, thereby producing an array radiation pattern that is also circularly polarized, with horizontally and vertically polarized (H-pol and V-pol) components. In this paper, only the total radiation pattern is used in the presentation of results. Note that the total pattern is the vectorial sum of the H-pol and V-pol components.



(a)



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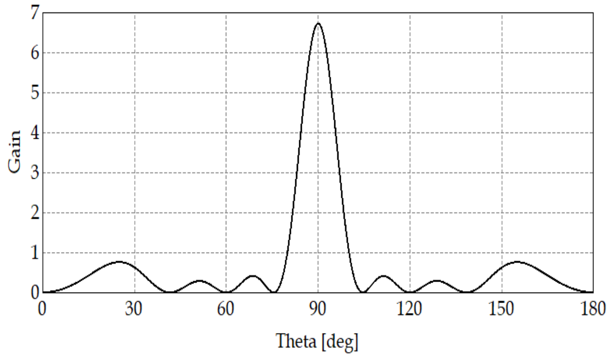


(c)

Figure 3. The 4-element Collinear Array model showing its (a) setup, (b) polar gain pattern with the elevation angle, θ, values ranging from 0^0 to 360^0 and (c) cartesian gain pattern with θ, values ranging from 0^0 to 180^0

PREVIOUS WORKS

The collinear array in this paper and the elements used as its basic building block are popularly employed in FM broadcasting. There are a number of published works by this author that are related to the characterization of collinear arrays used in FM broadcasting. Also, this author has published journl papers about the basic element in the construction of this array.

3.1 The Basic Element

The element used in the collinear array in this paper is the most published and described basic antenna by the author. Technically, it is known as shunt-fed, slanted dipole, and is shown in Figure 4. It is commonly used in FM broadcasting as a circularly polarized antenna exhibiting "a good circularity on the horizontal (azimuth) plane both for the horizontal and vertical components" [1]. It is basically composed of two 90^0-bent half-wave dipoles, each slanted by 22.5^0 from the horizontal [1]-[5]. The two bent dipoles are connected through a quarter-wavelength metallic boom. The dipoles are fed in-phase (shunt-connected) and the impedance is adjusted to match the transmission line impedance through gamma match at opposite arms of the dipoles. More elaborate descriptions of this basic element and its feeding system are contained in [5] [6].

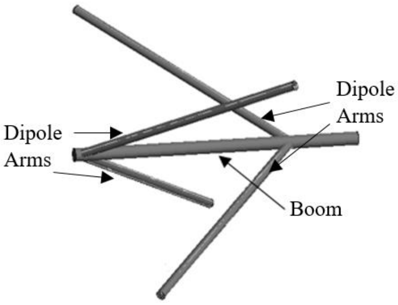


Figure 4. The shunt-fed, slanted dipole used as the basic element in the collinear array

3.2 The 4-Element Array

There are several published papers dealing with the collinear array shown in Figure 3 that describe its radiation characteristics and pattern optimization with and without a metallic tower. The array is generally a broadside array where maximum radiation occurs in directions perpendicular to the axis (plane) of the elements [5][7][9]. Generally, more identical elements are stacked to attain higher gains. The characteristics of a collinear array composed of shunt-fed, slanted dipoles in free-space (no metallic tower to mount the elements) is presented in a conference paper [2]. Though also included in this paper, characteristics such as array gains, beamwidth, minor and major lobe descriptions, etc. were discussed in that paper.

As it was shown in various papers about colliner arrays, inherent to the stacking of identical elements is the existence of sidelobes in the radiation pattern of the array. Together with the sidelobe gains, the actual locations where the corresponding downward radiation caused by these sidelobes are essential. For these can cause excessive amount of radiation resulting to blanketing in receivers and health hazards, especially when the limits on RF field Maximum Permissible Exposure (MPE) to humans are exceeded. Blanketing causes overloading in the front-end of radio receivers due to excessive signal level. The blanketing level where demodulation is almost impossible is about 115 dBu (dB referred to 1 uV/m) [1]. On the other hand, the signal level considered to be safe for day-to-day exposure is about 0.01 W/cm² [8].

Also, the actual locations of the pattern nulls is equally important for they present weak signals in those locations. These actual locations can only be realized using the more realistic standard 4/3 radio horizon rather than using the flat earth horizon where K = 1. Based on the NAB (National Association of Broadcasters) Engineering Handbook of the USA, though the sensitivity of radio receivers vary, 50 uV/m (34 dBu) of electric field intensity is considered to be the minimum useful signal level especially in the rural areas. Also based on the same NAB handbook, the maximum usable signal level is 82 dBu. In the Philippines, transmitter power for commercial FM broadcast stations ranges from 1kW to a maximum power of 25kW. Within this power range, the limitations described above must be observed.

3. PROPOSED METHODOLOGY

This paper attempts to present and discuss the radiation pattern along the standard (K=4/3) of a 4-element collinear array antenna system composed of shunt-fed slanted dipoles. In the presentation, it is assumed that the array center is at 1000 feet from the ground. As stated earlier, the normalized power density values are used to illustrate the radiation pattern along the horizon. Using equation 1, the power density in dB, $P_{D(dB)}$, is first determined using equation 2, then all values are normalized using the highest value. The normalization of the PD(dB) is achieved using the value of the highest power density.

$$P_{D(dB)} = 10log_{10}P_D \qquad (2)$$

In using equation 1, the value of the transmitter power is 1, so the P_TG_T product which is the effective isotropic radiated power is just simply the gain at a particular angle of depression. The resulting value of P_D where the assumed value of P_T is 1 watt is referred to as the normalized power density in this paper. In the simulation of the gain pattern of the array, the gain is referred to an istropic antenna. For clarification, a zero angle of depression is the same as having an elevation angle of 90^0 (θ = 90^0) referring to Figure 3(b).

4. RESULTS AND DISCUSSION

The figures in this section are presented to complement the discussion, particularly in providing the necessary understanding in analyzing the essentials of the radiation characteristic of a 4-bay collinear array along the standard radio horizon. Referring to Figure 2, and considering the height of the array center at 1000 feet, the range of the radio horizon is about 44.72 miles from the base of the antenna. Note that this is the maximum value of D in the figure, i.e. the maximum distance the radiowave can travel along the horizon with K = 4/3. At this value of D, the angle of depression, α, is calculated to be 0.485^0 and is shown in the graph of Figure 5. Between 1 and 10 miles from the base of the antenna, the corresponding angle of depression is 10^0 and 1^0, respectively. For less than 1 mile away (that is towards the base of the antenna), the depression angle is greater than 10^0. Being said that the angle of depression is about 0.5^0, the main beam then is above the horizon. Placing then the main beam of the array radiation pattern to be parallel to the surface of the earth does not maximize the utilization of the RF energy being transmitted. In fact, more than half of the total energy is wasted in the upward radiation of the antenna system. Also, the gain of the antenna that is directed towards the horizon is less than the maximum possible value. From this observation based on the results, there is a need for the main beam to be tilted below the horizontal. Initially, as much as 0.5^0 is recommended to point the maximum gain towards the horizon. The method of beamtilting is recommended to accomplish this requirement. However, tilting the main beam by an angle, which may not necessarily be 0.5^0, needs a more detailed study to attain optimum coverage.

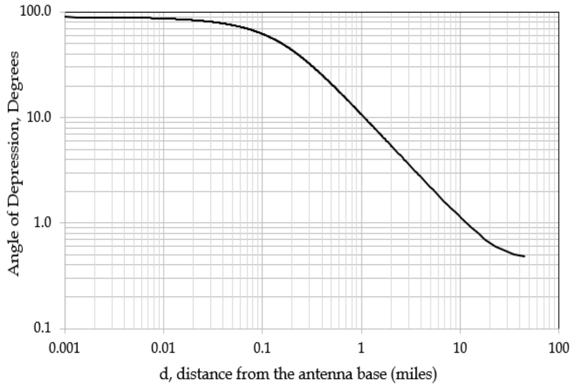


Figure 5. Variation of the angle of depression as the distance varies along the ground surface

Figure 6 shows the value of the array gain at distances away from the base of the antenna. The computed gain of the array is 6.733 (8.282 dBi). As shown in Figure 6, the maximum gain at the far-end of the horizon (d = 44.721 miles) is about 6.709 (8.267 dBi) which is a little lower than the maximum gain of the array. Pattern nulls and sidelobe downward radiations are located at distances less than one mile from the antenna base. For distances greater than 1 mile, higher gains are observed.

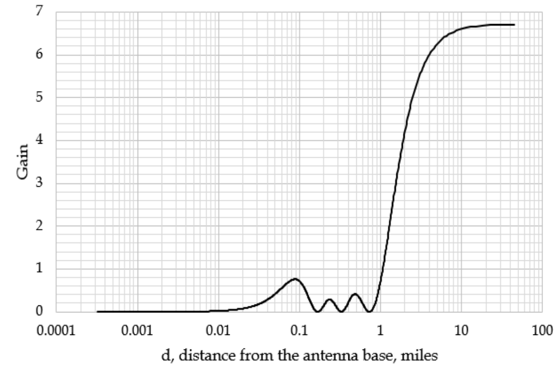
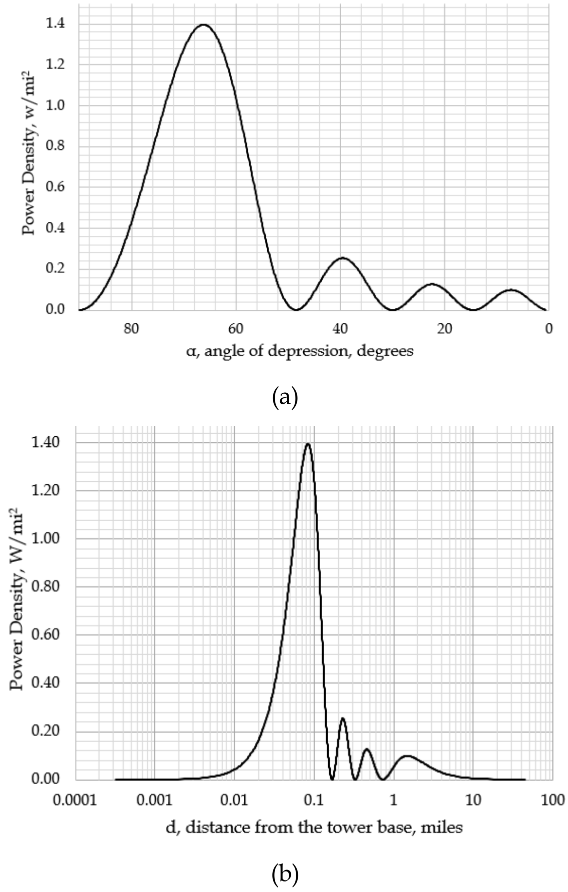


Figure 6. Array gain directed towards the surface of the earth below the horizon

As shown in Figure 7, the highest normalized power density (where P_T = 1 watt) is located at α = 66.2^0 or d = 0.084 mile with a value of 1.397 W/mi^2 while the lowest is 0.0000068 W/mi^2 at α = 30^0 or d = 0.328 mile.



(a)

(b)

Figure 7. Power density (P_T = 1 watt) at (a) different values of the angle of depression, and (b) distances from the base of the array on the surface of the earth. Note that the base of the antenna is located at d = 0, and α = 90^0

The signal level at any point on the surface of the earth within the horizon depends on the transmitted power, distance from the antenna array and the array gain at that point. Therefore, a high value of the gain at a point does not guarantee a high signal level. The highest power density just has a gain of 0.752 as compared to the gains at distances greater than 1 mile.

Similar to Figure 7, Figure 8 illustrates the normalized power density with varying distances on the surface of the earth below the horizon. The distance of about 0.084 mile is the location where the signal level is at maximum (with a value of 1.397 as discussed earlier). At this value and location, the power densities produced with transmitted powers of 1 kW, 10kW and 25kW are way below the limit of 0.01 W/cm^2 and is therefore safe for day-to-day exposure. However, there exists a high possibility of exceeding the level for blanketing. At 1kW, 10kW and 25kW transmitted power, the electric field levels are about 113 dBu, 123 dBu and 127 dBu, respectively.

The 0.328 mile distance from the antenna base is where the least amount of signal level occurs, and the field intensity is still above the required minimum signal level. Even with a transmitted power of 1kW, the signal level is about 60 dBu. At the far-end of the horizon, where the normalized P_D is 0.0002672, the electric field intensities with P_T = 25kW, 10kW and 1kW are 89.881 dBu, 85.901 dBu and 75.901 dBu, respectively.

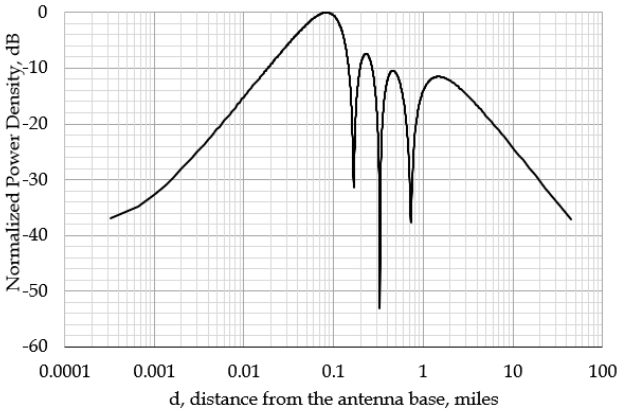


Figure 8. Normalized power density on the surface of the earth below the horizon

Summarizing the results and analyses, first, if the main beam of the transmitting antenna is oriented parallel to the surface of the earth, the maximum gain is not directly towards the far-end of the radio horizon. It is actually pointed above the horizon and more than half of the energy transmitted is wasted. Second, there exist nulls in between lobes, however, even with the lowest transmitted power and the lowest-valued null, the electric field intensity is still above the minimum usable signal level. Third, the highest signal level produced on the surface of the earth results to blanketing. However, it does not pose health hazards for it is way below the required limit. Lastly, at the far-end of the horizon, the signal level is in the vicinity of the maximum usable level of 82 dBu for a P_T = 1kW.

5. CONCLUSION

The analysis on the progation of radiowaves over the standard radio horizon from a 4-element collinear array 1000 feet high led to the understanding of the downward radiation of the antenna. Since the standard 4/3 radio horizon is more realistic than the straight line-of-sight horizon, the computed signal levels therefore are nearer than the actual levels. In the proposed radio horizon, generally, the signal levels produced along the surface of the earth do not pose any health hazard, though there are locations where the signals easily exceed the limit on blanketing and the maximum usable level. Within 1-10 miles away from the antenna base, which is considered as the key coverage area in metropolitan regions, enough signal levels exist. Also, it is shown that the signal level even at the far-end of the horizon is relatively much stronger than the minimum usable signal level, eventhough the main beam is not in the radio horizon. Based on these results and observations, it is recommended that a more detailed study in balancing the value of the transmitted power with that of the antenna height. Further, to maximize the utilization of the transmitted energy, tilting the main beam to a higher angle of depression is recommended. However, a more detailed analysis on the effects of beam tilting is likewise recommended. The method of null may also be considered to make the signal level more smooth along the surface of the earth below the horizon.

6. REFERENCES

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