Research Result

Beam Tilt and Broadcast Coverage of Collinear Arrays

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ABSTRACT

Beamtilt is an antenna array concept that is used to improve the performance of the array by adjusting the radiation pattern to better serve the target area with higher signal level. The adjustment involves increasing the level of weak signals brought about by pattern nulls within the coverage area. In FM broadcasting, pattern nulls are present in the radiation patterns of collinear arrays composed of several identical bays that are usually stacked to achieve higer gains. With the use of a dependable antenna simulation software, this paper is presented to gain a better understanding on the advantages and limitations of beamtilt as far as coverage of collinear arrays in FM broadcasting is concerned. The capabilities of beamtilt in mitigating the effects of pattern nulls are presented, as well as its limitations. Simulated patterns of the electric field intensity from a four-bay collinear array with varied beamtilt angles along the standard 4/3 radio horizon are discussed and analyzed. Results show that the use of beamtilt is effective in lessening the effect of pattern nulls along the horizon by relocating the nulls and or increasing their signal level. However, the effectiveness of this method diminishes at the far-end of the radio horizon where the field intensity decreases as the tilt is increased. It is expected that this paper will benefit FM broadcast operators and engineers on the proper use of beamtilt in improving the signal of broadcast stations in their coverage areas.

KEYWORDS

Beamtilt, Null fill, Collinear Array, FM Antenna, VHF Broadcast, Pattern Null.

1. INTRODUCTION

Pattern nulls refer to parts of the radiation pattern of antenna arrays where the signal level is low or where the gain is relatively very low. These pattern nulls are usually present in between lobes (major and minor) in the radiation pattern. They particularly exist in collinear arrays that are usually used in FM broadcasting and other broadcast services in the VHF band where identical elements (or bays) are stacked to attain higher gains. Sources that discuss the concepts of pattern nulls are [1], [2], [3], [4], [5]. These sources indicate that as the number of bays is increased, the number of minor lobes (and so with the number of nulls in between) is also increased. Beamtilt is a method of mitigating the effects of pattern nulls. It is a method that was developed and experimented in past decades through *in situ* or antenna range measurements. However, due to the advent of more power computers and the development of antenna simulation software based on accurate mathematical antenna models, the concept of applying beamtilt to antenna arrays becomes more easy and less costly. Note very well that in the application of permits for the construction of new broadcast stations to national regulatory bodies in most countries, the results of mathematical modelling of antenna systems such as antenna simulation, are accepted as proof of performance.

Antenna beamtilt refers to the process of intentionally adjusting the direction of the beam of an antenna array in a vertical plane, usually by tilting it down below the radio horizon. The goal of beamtilting in VHF broadcasting is to improve the signal level where a pattern null is directed. Also, beamtilting is used to aim the antenna mainbeam towards the end of the radio horizon or to any specific target to avoid or minimize interference from other stations or to other broadcast services.

As dicussed in [6], [7], basically, there are two ways to achieve beamtilt: mechanical and electrical beamtilting. A combination of these two techniques can be considered as the third technique. Mechanical beamtilt involves physically tilting the antenna in the desired direction. However, this method has limited applications because mechanically tilting down the mainbeam on one side means tilting up the beam in the opposite side. On the other hand, electrical beamtilt uses phase shifters to adjust the phase of the signal across the antenna array, effectively tilting the beam. Practically, lengths of transmission lines are used in achieving the required phase shift. In this paper, only the electrical beamtilting is tackled; the upper bank of the array is phase-shifted making it leading in phase with the lower bank [8], [9], [10].

The need for beam tilt in collinear arrays is necessary, especially when the antenna height is great [11]. Figure 1 shows an illustration showing where the mainbeam of an antenna array is directed over the radio horizon. a' is the earth's radius which was increased by a factor of 4/3 (k = 4/3) due to superrefraction at VHF. In the figure, the radio horizon is perpendicular to the antenna tower and therefore misses the horizon. This is one particular application of beamtilt, where the mainbeam needs to be tilted at an angle of α. As the antenna height (H_T) increases, the amount of tilting needed also increases. The amount of tilting depends on the value of the antenna height and is expressed in Equation 1.

$$\alpha_H = \cos^{-1}\frac{a'}{a' + H_T} \quad (1)$$

With k = 4/3, a' is equal to 5280 miles, while H_T must be in miles. Assuming that the antenna height be 1000 feet, the mainbeam needs a 0.485^0 tilt. The approximate range of the horizon, D_H, is expressed in Equation 2, which is also dependent on H_T. It is equal to the square root of twice the antenna height, where D_H is expressed in miles and the antenna height is in feet. For an antenna height of 1000 feet, the radio horizon along the standard (4/3) radio horizon would be 44.72 miles (71.95 km).

$$D_H = \sqrt{2H_T} \quad (2)$$

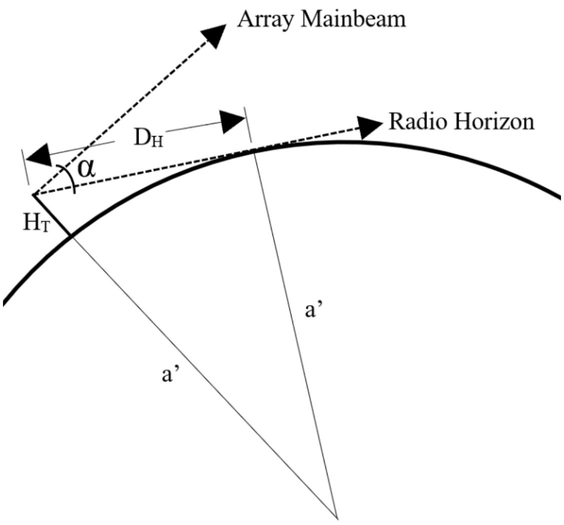

Figure 1. Array mainbeam direction without beamtilt on the standard radio horizon (K=4/3).

2. LITERATURE SURVEY

The basic element used in the construction of the collinear array is the so-called shunt-fed, slanted dipoles having circular polarization (C-pol) and thereby having both horizontal (H-pol) and vertical (V-pol) polarization components and is shown in Figure 2. The author has extensive publications about its characterization both in free-space and when mounted to a metallic tower. Also, the use of it in the construction of collinear arrays in FM broadcasting was also comprehensively investigated [].

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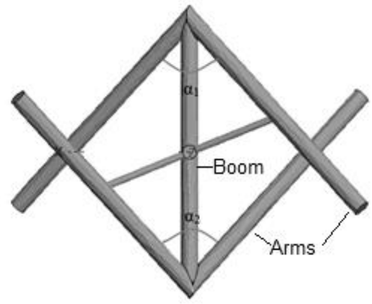

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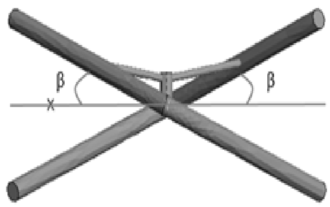


(c)

Figure 2. The shunt-fed, slanted dipole used as the basic element or bay in (a) isometric, (b) top, and (c) front views

The specifications of the dipole used as the basic element in the collinear array are shown in Table 1.

Table 1. Dimension and specifications of the basic element

Dimension/Physical Specification	*Value*
Boom Length	¼ λ
Boom and Arm Diameter	2 inches
Arm Length	¼ λ
a_1 (Arm Offset Angle 1)	90^0
a_2 (Arm Offset Angle 2)	90^0
β (Skew angle)	22.5^0

Antenna beam tilt is an essential parameter in the design of wireless networks to improve coverage and signal reception. It refers to the directional angle of an antenna's radiation pattern from the horizontal plane. The antenna is tilted downwards or upwards to enhance radio frequency (RF) coverage in the desired areas while reducing interference and signal absorption in other areas.

Several studies have been conducted on the impact of antenna beam tilt on wireless network performance. For instance, [6] investigated the effect of antenna beam tilt on the coverage area and signal quality of a long-term evolution (LTE) network. Their simulation results showed that tilting the antenna beams appropriately can increase the network coverage by up to 25%, enhancing signal quality and network performance.

Similarly, [7] studied the optimal tilt angle for directional antennas in wireless sensor networks (WSN). They found that antenna beam tilt could increase the area coverage of a wireless sensor network without increasing power consumption, thus improving network lifetime and reducing deployment costs.

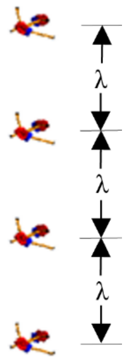
Moreover, [8] conducted a study on the effects of antenna beam tilt on the performance of 4G LTE networks. Their results indicated that the optimal antenna beam tilt angle depends on several factors, including the terrain, antenna height, and the number of antennas used.

In broadcasting, some literatures on beamtilting present some specific values of the phase difference between the upper and the lower banks of the antenna array. [12] presented an 8-bay antenna at 5000 feet AHAAT there exists a pattern null at 7.5 miles away from the tower base. The reference states that with a 60-degree phase lead of the upper bank will tilt the mainbeam to about 2.5^0 below the horizon. However, literatures lack other phase lead values that indicate corresponding mainbeam tilt values as maybe needed in specific situations by broadcast stations. Moreover, literatures lack discussions on the effect of beam tilt in the location and magnitude of pattern nulls and minor lobes.

3. METHODOLOGY

Primarily, all gain values used in all radiation patterns of the collinear array antenna in this paper are from the rendition of an advance antenna simulation software, specifically the MoM (method of moments)-based Feko simulation software. As mentioned earlier, and is reiterated here that regulatory bodies, especially from the Philippines and in the United States of America (USA) accept characterization results from simulation softwares as proof-of-performance of broadcast antenna systems.

This paper makes use of a 4-bay collinear array in demonstrating the use of beam tilt. It makes use of the shunt-fed, slanted dipole whose specifications are presented previously. Figure 3 shows the details of the 4-element collinear array and its radiation patterns. Figure 3(a) shows the 4 bays forming a collinear array and are spaced one wavelength apart. For all practical purposes and for the attainment of the necessary amount of gain, this is the usual set-up, specially in provincial FM broadcast stations. To better analize the effects of beam tilt to the radiation pattern of the array, the elements are assumed to be in free-space, therefore disregarding any source of pattern distortion from surrounding objects. All the elements in the array are tuned to operate at 97.488 MHz which is the center of the FM band (88-108 MHz) in the Philippines and in the USA. The gain pattern of the array in the vertical plane with the azimuth angle $\varphi = 0^0$ is plotted in Figure 3(b). The elevation angle, θ, ranges from 0^0 to 360^0. In broadcasting, only that part of the radiation pattern that corresponds to θ values of 90^0 to 270^0 is within the radio horizon and determine the broadcast coverage. The other values of θ correspond to the useless upward radiation of the pattern. Figure 3(c) illustrates the radiation pattern of the array in cartesian plot where θ ranges from 0^0 to 180^0. It is half of the polar plot in Figure 3(b). The gains described in this paper is only the H-pol gain, since in the Philippines and other contries, the standard polarization for FM and television broadcasting is horizontal polarization. Both the polar and catesian plots show the existence of pattern nulls and minor lobes with the mainbeam, along the horizontal plane. As shown in the plots, there exist pattern nulls and sidelobe radiations along the horizon (for $\theta = 90^0$ to 180^0).



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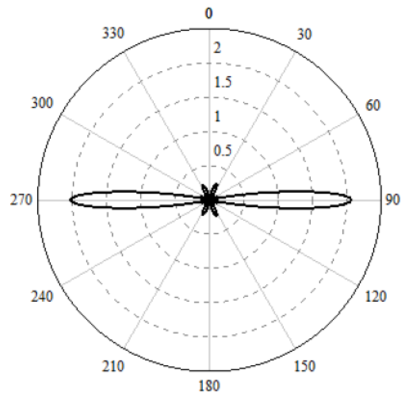

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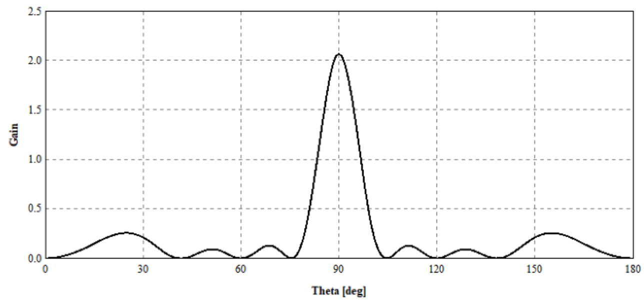


(c)

Figure 3. The collinear array for the application of beam tilt and null fill, (a) arrangement of the four bays, and the radiation gain pattern in (b) polar and (c) cartesian plots in the vertical plane

In the presentation and analysis of the effect of beam tilt on the broadcast coverage of the array, the electric field intensity, E, patterns are used and illustrated along the standard (4/3) radio horizon, against the values of the depression angle, α. The values of θ from 90^0 to 180^0 corresponds to the angle of depression values of 0^0 to 90^0, respectively. Also, E is plotted against the distance on the surface of the earth from the tower base up to the far-end of the horizon with antenna height equal to 100 feet.

Further, normalized values of E is used, which is expressed in V/m. Its equation is expressed in Equation 3, where the transmitted power, P_T, is equal to 1 watt, the transmiting antenna gain, G_T, is the array gain corresponding to each value of α. The array gain is referred to the gain of a half-wave dipole. The value of the propagation distance, D, is the distance from the antenna radiation center to the point on the surface of the earth corresponding to the value of α and must be expressed in meters.

$$E = \frac{\sqrt{30P_TG_T}}{D} \quad (3)$$

Figure 4 shows the general illustration of D as α is varied from 0^0 to 90^0. The value of D is expressed in equation 4 in terms of the antenna height and the value of α. A more exact equation for D_H is derived by setting the value of the radicand in Equation 4 to zero; another equation for α_H is also derived. Equation 5 is used to determine the distance, d, from the tower base on the surface of the earth, where y is in radians. All lenear measures are in miles. So, there is still a need to convert D to meters before using it in Equation 3.

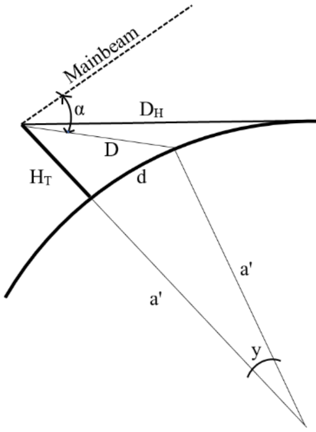


Figure 4. Propagation distance used in the determining the normalized power density

$$D = xsin\alpha \pm \sqrt{(xsin\alpha)^2 - [(x^2 - a'^2]} \quad (4)$$

$$d = y^r\, a' \quad (5)$$

where

$$y = \cos^{-1}[\frac{x^2 + a'^2 - D^2}{2a'x}]$$

and

$$x = a' + H_T$$

Summarizing, the following are the assumptions made in presenting and discussing the effects of beam tilt on the radiation pattern along the standard radio horizon: (1) Transmit power is 1 watt, (2) there are 4 bays, (3) antenna height is 1000 feet, (4) only the H-pol of the array gain is used in the G_T. Also, the minimum required signal levels in terms of the electric field intensity in different locations shown in Table 2 are used as the benchmark to determine whether or not a signal along the horizon is usable .

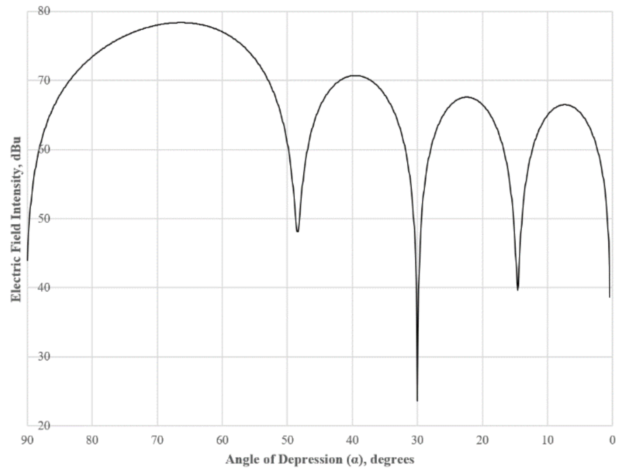
Table 2. Minimum Signal Strength for each Service Area

Service Area	*Minimum Signal Strength*	
	mV	*dBu*
Rural Areas	0.05	34
Suburban	1.00	60
Principal Cmmunity	3.16	70
Highest Usable level	12.64	82

Practically and theoretically, beam tilt is implemented by making the upper antenna bank (two uppermost bays) lead the lower bank (two lowest bays). The amount of tilting is varied by increasing the amount of lead of (or phase difference between) the upper bank over the lower bank. This paper considered the following leads: 15^0, 30^0, 45^0, 60^0, 75^0, 90^0, 105^0 and 120^0. When the upper bank and lower bank are in-phase, it is considered to be no beam tilt or a lead of 0^0.

4. RESULTS AND DISCUSSION

This section of the paper presents figures to illustrate the power densities along the standard (4/3) radio horizon as beam tilt is used in manipulating the radiation pattern of the collinear array. As stated earlier, and using equations 1 and 2, for an assumed antenna height of 1000 feet, the radio horizon can reach a distance of 44.72 miles and the mainbeam is above the horizon by 0.485^0 ($\alpha_H = 0.485^0$).



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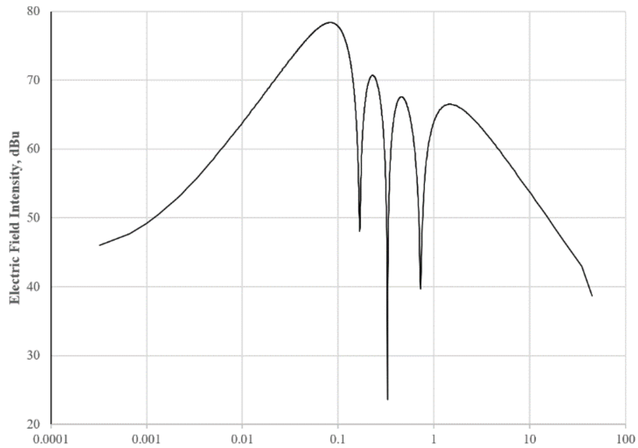
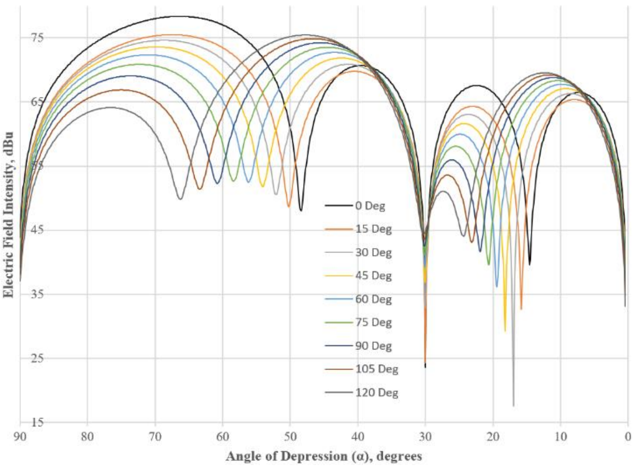


(b)

Figure 5. The electric field intensity of the array plotted against (a) the depression angle, and (b) distance from the tower base with and an antenna height of 1000 feet

The maximum gain of the collinear array is 1.262 (1.011 dB_D). With $\alpha_H = 0.485^0$, the array gain towards the horizon is slightly lower with a value of 1.258 (0.995 dB_D). Figure 5 shows the radiation pattern of the array in terms of the E (electric field intensity) in dBu (dB referred to 1uV/m) along the horizon. The E in Figure 5(a) is plotted along the horizon in terms of the value of the angle of depression. The 90^0 of depression angle corresponds to the location of the tower base, while the 0^0 value is the location of the far-end of the horizon. Figure 5(b) is the plot of the electric intensity along the horizon in terms of the distance, d, expressed in miles. Both plots of the field intensity show the locations of pattern nulls, with a lowest value of 23.623 dBu at 30^0. From the tower base to the horizon, the location of the pattern nulls are located between 15^0 and 50^0 of depression angle, the farthest being at 14.6^0, the nearest being at 48.4^0 and the deepest being at 30^0. With an antenna height of 1000 feet, these pattern nulls are located within the distance from 0.1 to 1 mile from the tower base. The E at the far-end of the horizon is 38.652 dBu.

To add context on this, if the FM broadcast station is a class B station, the minimum transmit power is 1000 watts and a maximum of 10 kW. Assuming that the power transmitted is 1000 watts, the field intensity at the location of the lowest null is about 53.623 dBu at 0.328 miles from the tower base. Based on Table 1, the value is below the required signal level for suburban areas, but still much higher than the requirement for rural areas.



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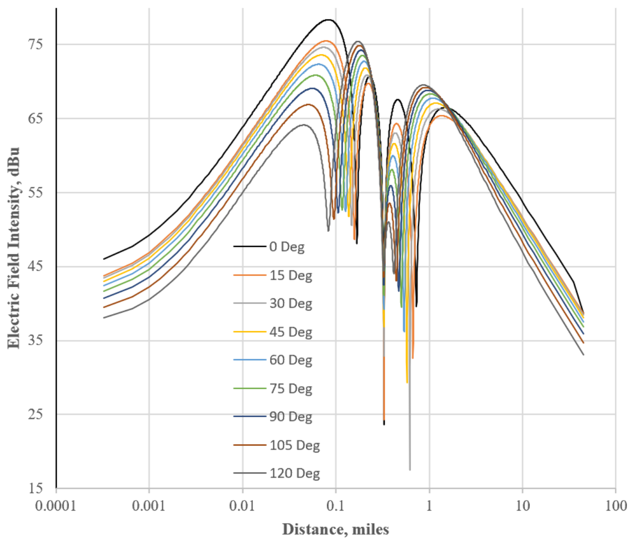

(b)

Figure 6. Plots of the array electric field intensity against (a) the angles of depression, and (b) distance from the tower base with different values of phase difference between the upper and the lower antenna banks

Therefore, if this pattern null is located in a highly populated area, i.e. suburban, urban or principal community, it must be relocated or the signal level should be increased. At the far-end of the horizon, with a power of 1000 watts, the signal level is 68.652 dBu.Figure 6 is the plot of the electric field intensity with varying values of the phase difference between the upper and the lower antenna bays to effect beam tilting. The intensity is plotted against the angle of depression as shown in Figure 6(a) and against the distance with an antenna height of 1000 feet as shown in Figure 6(b). Most of the pattern nulls move nearer to the tower base as the phase difference is increased. The farthest pattern null (located in the 15^0 to 25^0 range of the angle of depression) moves about 1.2^0 for every 15^0 (0.08^0 per degree) of phase difference between the antenna banks from its initial location (0^0 beamtilt located at 14.6^0). The details are shown in Table 3. Based on the the entries in table, the deepest null happens when the phase difference between the antenna banks is equal to 30^0 with a normalized intensity of 17.529 dBu. With a transmit power of 1000 watts, the resulting intensity at this location is 47.529 dBu. This is located at 0.620 mile from the tower base, considering an antenna height of 1000 feet. If the pattern null is located in a densely populated area and within a suburban area, this beam tilt implementation, i.e. with a phase difference of 30^0, must be avoided. However, the pattern null starts improving only when the phase difference is above 75^0 from the no beam tilt condition.

Table 3. Details of the farthest pattern null as the phase difference between antenna banks is varied

Bank Phase Difference	*Field Intensity, dBu*	*Location, a*	*Difference, degrees*
0^0	39.624	14.6^0	
15^0	32.638	15.8^0	1.2
30^0	17.529	17.0^0	1.2
45^0	29.289	18.2^0	1.2
60^0	36.160	19.4^0	1.2
75^0	39.542	20.7^0	1.3
90^0	41.657	21.9^0	1.2
105^0	43.111	23.1^0	1.2
120^0	44.070	24.4^0	1.3

Table 4. Details of the nearest pattern null as the phase difference between antenna banks is varied

Bank Phase Difference	*Field Intensity, dBu*	*Location, a*	*Difference, degrees*
0^0	48.062	48.4^0	
15^0	48.681	50.2^0	1.8
30^0	50.557	52.1^0	1.9
45^0	51.789	54.1^0	2.0
60^0	52.471	56.2^0	2.1
75^0	52.637	58.4^0	2.2
90^0	52.295	60.8^0	2.4
105^0	51.397	63.4^0	2.6
120^0	49.850	66.3^0	2.9

The pattern null nearest to the tower base are generally higher than the other two nulls. Its movement towards the base is shown in Table 4. As the phase difference is increased by 15^0 from 0^0, the corresponding increase in the movement increases approximately by 1.8+n, where n is 0, 0.1, 0.2, 0.3 and so on. The greatest pattern null level happens when the antenna bank phase difference is 75^0.

While the pattern nulls located farthest and nearest from the tower base are moving as the phase difference between banks is varied, the pattern null at the middle is not moving at all. Whether the phase difference is varied from 0^0 to 120^0, this pattern null remains at an angle of depression of 30^0 or at a distance of 0.328 miles from the tower base. Its lowest value is at no beam tilt condition with a normalized value of 23.623 dBu. As discussed earlier, a signal level of 53.623 dBu is produced at 0.328 mile from the tower base with a power of 1000 watts, lower than the required minimum signal level for suburban areas. Table 5 summarizes the details of this null.

Table 5. Details of the middle pattern null as the phase difference between antenna banks is varied

Bank Phase Difference	*Field Intensity, dBu*	*Location, a*	*Difference, degrees*
0^0	23.623	30.0^0	
15^0	24.317	30.0^0	0
30^0	32.870	30.0^0	0
45^0	36.986	30.0^0	0
60^0	39.634	30.0^0	0
75^0	41.540	30.0^0	0
90^0	42.929	30.0^0	0
105^0	43.999	30.0^0	0
120^0	44.812	30.0^0	0

One glaring disadvantage of beam tilt is the decrease in the value of the array gain as the tilt increases. Table 6 shows the maximum gain of the array as the phase difference between the antenna banks is varied. This has also a great effect on the value of the field intensity at the far-end of the horizon.

Table 6. Maximum gain of the collinear array as the phase difference between antenna banks is varied in the implementation of beam tilt

Bank Phase Difference	*Field Intensity, dBu*
0^0	38.652
15^0	38.628
30^0	38.442
45^0	38.089
60^0	37.560
75^0	36.835
90^0	35.886
105^0	34.665
120^0	33.088

Table 7 summarizes the signal levels at the far-end of the horizon, at an angle of depression of 0.485^0 or at a distance of 44.72 miles assuming an antenna height of 1000 feet. Based on the entries in the table, tilting the mainbeam decreases the field intensy by as much as 0.046 dB per degree of phase difference between antenna bank.

Table 7. Details of the electric field intensity at the far-end of the horizon as the phase difference between antenna banks is varied

Bank Phase Difference	*Field Intensity, dBu*
0^0	38.652
15^0	38.628
30^0	38.442
45^0	38.089
60^0	37.560
75^0	36.835
90^0	35.886
105^0	34.665
120^0	33.088

Generally, the more problematic pattern nulls are the ones in the middle and in the farthest. The middle pattern null assumes its lowest value when the antenna banks' phase difference is 0^0, or at no beam tilt. However, at no beam tilt, the lowest signal level along the horizon is in the far-end of the horizon. The greatest pattern null depth happens when the phase difference between banks is 30^0, with 17.529 dBu (47.529 dBu for P_T = 1000 watts).

5. CONCLUSION

The presentation of the radiation patterns of a 4-bay collinear array in terms of the electric field intensity along the standard (4/3) radio horizon led to a better understanding on the advantages and limitations of beam tilt in the task of improving the signal levels within the target area. Beam tilt offers a way of relocating and improving the signal levels of pattern nulls, especially for the ones located nearest and farthest to the base of the tower. It is capable of relocating the worst pattern null (farthest null) to within 9.8^0 (14.6^0-24.4^0) of depression angle. This is equivalent to a total distance on the earth's surface of 0.31 mile (about 500 m), ranging from a distance of 0.407 mile to 0.727 mile for an antenna height of 1000 feet. However, if the pattern null located at 30^0 depression angle becomes a problem, beamtilt is ineffective in relocating it, but it can increase the signal level to attain the minimum required level. A phase difference between the antenna banks of 75^0 and above is preferable. A phase difference of 30^0 should be avoided for it produces a deep pattern null.

Further, even if the mainbeam is directed towards the horizon, there is no assurance that the signal level at the far-end of the horizon will increase. This is due to the decrease in the mainbeam gain while the amount of tilt is increased. Anent to to this, beamtilt should not be used in increasing the signal level at the far-end of the horizon. The only way to do this is to increase the ERP. Since the collinear array considered in this paper has a low relative gain, the use of beam tilt in arrays with high gains (8-bay or more arrays) needs to be investigated in future endeavors.

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