Amplification of the Radiation from Two Collocated Cellular System Antennas by the Ground Wave of an AM Broadcast Station*

Dr. Bill P. Curry

EMSciTek Consulting Co.,
22W101 McCarron Road Glen Ellyn, IL 60137, USA, BPCurry@MCS.com

It has been known since the early days of the twentieth century that transmissions from powerful low frequency radio stations travel for distances of hundreds of kilometers by a ground wave that follows the contours of the earth's surface and is predominantly polarized vertically, if the broadcasting antenna was vertically oriented. Broadcasting through larger distances of thousands of kilometers is primarily the result of the reflection of radio waves from the ionosphere. The worldwide proliferation of microwave radiation sources has taken place in the background of an extensive and ubiquitous set of low frequency broadcast transmitters. For the most part, the interaction of the much higher frequency telecommunications sources with the existing low frequency radio background has largely been ignored when siting these microwave towers. In this author's opinion, ignoring existing powerful low frequency radio sources within a few kilometers of a proposed microwave installation, can lead to potential health problems for the inhabitants of the region near the tower. In all cases, tower siting considerations should include a thorough analysis of the existing electromagnetic environment.

This paper examines the magnification of the microwave radiation density that results from mixing the low frequency radio fields and the microwave fields. Usually, fields from sufficiently separated sources do not mix, because the waves from the two sources interact in the far field of each other, and the result is an addition of radiation intensities (power densities), rather than an addition of fields. In the case to be presented in this paper, however, the wavelength of the low frequency source is several hundred meters. Thus, the ground wave of the low frequency source completely envelops the antennas of the microwave sources. Mixing of the low frequency ground wave fields with the radiated fields from the microwave antennas occurs in the near field of the microwave antennas. In such conditions, the fields from the various sources must be added vectorially. Both the low frequency field and the microwave fields are predominantly polarized vertically and, thus, can be added to get the total electric field of the multiple sources. The stored power density in the vertical component of the electrical field will be evaluated in this paper. This quantity is proportional to the square of the absolute value of the composite field. The power density arising from the mixing of the low frequency and microwave fields thus contains cross products of the microwave fields and the fields of the low frequency ground wave. Because of the large disparity in frequencies between the microwave fields and the low frequency fields, the sum and difference frequencies of the two different types of sources will differ negligibly from the original microwave frequencies. Thus, the cross product terms will act to intensify the microwave components. The formulation is developed in such a way as to identify magnification terms that multiply the radiation density that would normally be radiated by the microwave sources without the ground wave being present. These magnification terms are both spatially and temporally varying terms. The temporal variations are assumed, for simplicity to be sinusoidal, though in actual telecommunications transmissions, the wave form will be more complex on account of pulsed data transmission and sophisticated modulation techniques. Conventionally, these sinusoidal terms would be averaged to zero, and physical quantities such as the radiation density or the Poynting vector would be regarded as representing mean values. In this paper the full time de-

*) Original paper

pendence of these terms has been retained, and these physical quantities are regarded as having instantaneous values.

The situation which motivated this author to analyze the interaction of RF sources has persisted since 1997. A number of families live on a ridge in a community near Schenectady, New York. They are less than 4 miles from 50,000 watt, low frequency AM broadcast station WGY, which has been broadcasting since 1922. For years these people have coexisted with WGY without any significant difficulty. In late December of 1996, a telecommunications tower was erected at the edge of the aforementioned ridge. The antennas for an analog cellular phone provider are mounted at the top of the tower, and the antennas of a provider of pulsed digital phone and data transmissions are mounted 15 meters lower down the tower. The top of the tower is less than 80 meters above the valley floor and less than 22 meters above the ridge. Among the inhabitants of the ridge there are 40 documented sufferers of possible RF radiation sickness, the severity of whose symptoms ranges from severe headaches, nausea, and eye pain to complications involving far more serious conditions such as diabetes, liver problems, and Alzheimer's disease. The physical maladies began to noticed about a month and a half after the microwave sources began operation. One of the significant aspects of this peculiar situation is the fact that the people suffer more, usually, during the night than during the day. The people on the ridge think this to be the consequence of a higher volume of data transmission at night than in the daytime, because companies sending faxes send them at night to get cheaper telephone rates. Another possibility is related to the diurnal variation of the position of the ionosphere and the change in ground reflection characteristics. Another significant aspect of this situation is the fact that the physical maladies of these people are far worse when there is rain than in good weather. This strongly suggests the role of reflective properties of the ground, as the conductivity of the soil increases several orders of magnitude from dry to wet surface conditions

This paper presents a mathematical model of the interaction of low frequency and microwave sources based on Sommerfeld's description of the propagation of radio waves from a vertically oriented dipole over a partially reflective ground plane. This work by Sommerfeld and several other authors was developed between 1909 and 1925 and is thoroughly described in two standard, but out of print, textbooks.[3,4] Modern electromagnetic field computer codes, such as the U.S. Navy's code NEC, use methods derived from Sommerfeld's to compute the induced fields and currents arising from having RF sources placed near boundary surfaces. Further, in the high frequency limit, Sommerfeld's formalism reduces to the description of fields arising from a simple dipole source.

The Sommerfeld formulation can be expressed in more modern terms by transforming variables and using Fresnel integrals which are accessible to evaluation on personal computers. The electric field in the complex plane is given by

$$E_{(3,3)} = \left(\frac{\pi}{2} \sqrt{\frac{k r}{\pi \eta^2}} \left[\left\{ 2 \left(C\left[\sqrt{\frac{k r}{\pi \eta^2}} \right] + i\, S\left[\sqrt{\frac{k r}{\pi \eta^2}} \right] \right) - 1 - i \right\} e^{-\frac{1}{2} \frac{i k r}{\eta^2}} \right] + i \right) \frac{e^{i(k r - \omega t)} I Z_0 k l}{2 \pi r} \quad (1)$$

In this equation, k = 2p/?, where ? is the free space wavelength of the low frequency source, l is the physical length of the transmitting dipole, Z_0 is the impedance of free space, I is the RMS average of the current flowing in the dipole, ? is 2p times the frequency of the radiated wave, r is the distance from the transmitter to the observation point, ? is the average value of the complex refractive index of the ground, and The functions C and S are Fresnel integrals whose value depends on their common ar-

[3] A. Sommerfeld, *Partial Differential Equations in Physics,* Academic Press, Inc. New York (1949)

[4] J. A. Stratton, *Electromagnetic Theory,* McGraw-Hill Publishing Co., New York (1941)

gument. The double subscripts mean that this is the z component of the field from the third source (the low frequency source).

The form of this equation shows clearly that there is an interplay between field terms that fall off as the inverse of the distance from the source and those that fall off as the inverse square root of that distance. This is the hall mark of a mixture of sky waves and ground waves - i.e. waves that travel along the interface between the earth's surface and the atmosphere. In the high frequency limit, the Fresnel integrals each asymptotically approach 1/2, and the complex field equation reduces to

$$E\left(_{3,3}\right) = \frac{1}{2\pi r} i\, I Z_0 k l\, e^{j\left(kr - \omega t\right)} \qquad (2)$$

This is the equation for the complex field of a simple dipole, whose electrical size is kl, in the presence of a perfectly conducting boundary surface.

Although the most mathematically expedient way to carry out electromagnetic field calculations is in the complex plane, the physically significant part of the field is the real part of the expressions stated above. The current appearing in these expressions is proportional to the output power of the source divided by the radiation resistance of its antenna. An equation relating the radiation resistance to the electrical size of a dipole antenna is given in Balanis' book[5] on p. 157. The broadcast source is actually a monopole source over a lossy ground plane. The radiation resistance for a monopole over a surface is 1/2 the radiation resistance of a dipole that is twice as long as the monopole.

Using the parameters stated on the Federal Communications Commission (FCC) web site, I have computed the electric field of radio station WGY as a function of distance from the antenna. At 1 km, the field is calculated to be about 20 V/m, in fairly good agreement with the FCC's stated value of 19.15 V/m. This calculation assumed a value of the soil refractive index that is consistent with results from both Balanis P. 173 and Kraus[6] P. 851 for dry earth. The refractive index is a function of the wave frequency, the relative permittivity of the soil, and the electrical conductivity. WGY's frequency is 0.81 Mhz. For Balanis' set of dry soil parameters: permittivity = 10 and conductivity = 0.01 S/m, the absolute value of the complex refractive index of the soil is 14.905, and this is in good agreement with the value 14.916 for Kraus' parameters for dry midwestern U.S. soil of permittivity = 16 and conductivity = 0.01 S/m. Therefore, the refractive index of 14.9 was used in these calculations for dry earth.

The figure on the next page shows the real part of the electric field resulting from the low frequency source at various distances from the source. This field is time dependent, being a sum of two different functions of position multiplied by a sine term in the time and a cosine term, respectively. The results on the next page correspond to time = zero or an integer multiple of the oscillation period. Some of the people on the ridge live between 6 and 6.5 km from the source. Thus, they are subjected to a fluctuating ground wave field whose maximum amplitude is about 2 V/m. More importantly, the microwave sources on the tower are enveloped in this field.

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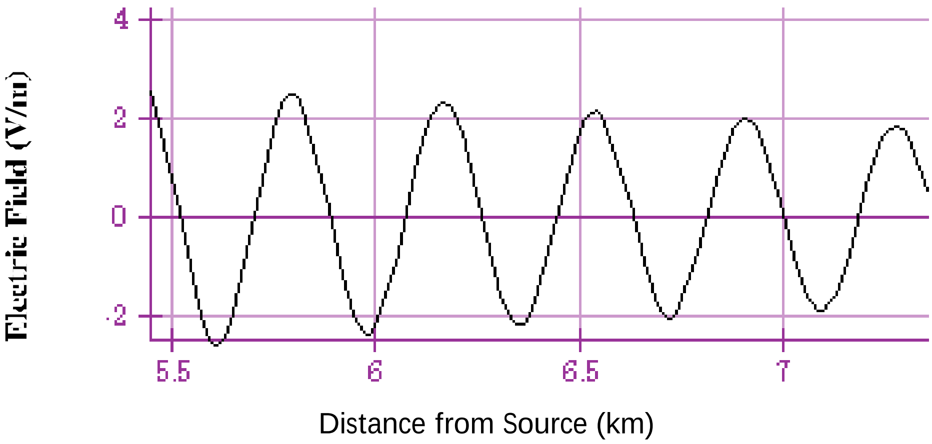
[5] C.A. Balanis, *Antenna Theory: Analysis and Design,* second edition, John Wiley and Sons, New York (1997)

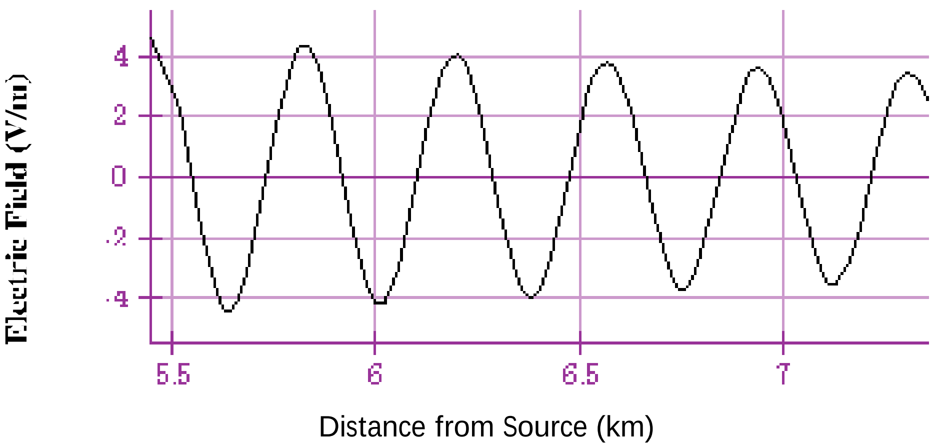
[6] J.D. Kraus, *Antennas,* second edition, McGraw-Hill, Inc., Boston (1988)

Fig. 1 Field from Low Frequency Broadcast Transmitter in Dry Conditions



For wet conditions, the conductivity can be orders of magnitude higher than used in Fig. 1. Balanis uses conductivity = 10 S/m for the wettest conditions. This gives for very wet ground. Fig. 2 shows that, on account of the increased ground reflectivity, the field from the broadcast source is doubled at the locations of interest.

Fig. 2 Field from Low Frequency Broadcast Transmitter in Wet Conditions



In order to determine the extent to which the radiation density from the microwave sources is affected by the presence of the strong low frequency ground wave shown in Figures 1 and 2, one must compute the absolute value of the square of the electric field arising from the two microwave sources and the low frequency broadcast station. This requires evaluating both real and imaginary parts of the total field strength. Note that there is a horizontal component of the ground wave field, but it is much smaller than the vertical component, and it is neglected in this paper. Also, the broadcast station produces a local magnetic field that is azimuthal around the transmitting antenna. Although there will be a local azimuthal field about each of the microwave sources, also, the only significant magnetic fields are associated with the radiated electric fields.

To demonstrate magnification of the microwave radiation by interaction with the low frequency radiation, it is sufficient to add the vertical electric field components of all the sources and take the square of the absolute value of the result. This squared field is then divided by two times the impedance of free space to get the power density stored in the composite electric field. Although there are sum and difference frequencies for the components corresponding to the interaction between the microwave radiation and the low frequency radiation, there are no sum and difference frequencies representing interaction of the two microwave beams, because the wavelengths of these sources are only about 0.35 m, and they are spaced 10 m apart. Thus, they interact only in each other's far field.

In the approximation that the frequency of the broadcast source is much smaller than either microwave frequency, one can write the power density of the composite field from all three sources as

$$s = \left(N_2 \cos\left[-k_2 r_2 + \omega_2 t \right] + M_2 \sin\left[-k_2 r_2 + \omega_2 t \right] + 1 \right) \rho_2 + \left(N_1 \cos\left[-k_1 r_1 + \omega_1 t \right] + M_1 \sin\left[-k_1 r_1 + \omega_1 t \right] + 1 \right) \rho_1 + \frac{1}{2} \frac{A_4^2 + A_3^2 + 2 A_4 A_3 \sin\left(2\left[-k_3 r_3 + \omega_3 t \right] \right)}{Z_0} \quad (3)$$

In this equation, ? and ? are power densities in the absence of the low frequency source for each of the microwave fields, the M's and N's are magnification terms for each of the microwave sources, and the last term in the equation represents the power density stored in the fields of the low frequency source. The magnification terms can be written in terms of ratios of field amplitudes, where the amplitude is defined as the coefficient of the sinusoidal time dependent terms that appear in the electric fields. Thus, the magnification terms are

$$M_1 = 2 \frac{A_4 \cos(k_3 r_3) - A_3 \sin(k_3 r_3)}{A_1}, \quad N_1 = 2 \frac{A_3 \cos(k_3 r_3) - A_4 \sin(k_3 r_3)}{A_1} \quad (4)$$

and an analogous pair of terms applies to the second microwave source. The amplitudes of the microwave fields can be written in either of two equivalent forms.

$$A_1 = -\frac{1}{2} \frac{\sqrt{2 \frac{Pw_1}{R_{rad\ 1}}} Z_0 k_1 l_1}{\pi r_1}, \qquad A_2 = -\sqrt{\frac{1}{2} \frac{Pw_2 Z_0}{\pi r_2^2}} \quad (5)$$

with analogous equations for the amplitude of the fields from the second microwave source.

To use the first form of the amplitude, one must know not only the effective isotropic radiated power (EIRP), accounting for the gain characteristics of the antenna, but one must also know the radiation resistance of the antenna. High gain microwave antennas are more complicated structures than simple dipoles - e.g., the antennas for the second microwave source are log periodic antennas, and the formula quoted here for radiation resistance does not apply. Thus, second equation has to be used here.

For the first source, the maximum power put into any one horizontal sector is 3800 watts. The distances of these antennas from the most medically stressed people on the ridge varies from 150 m to 500 m. Thus, the maximum power density and field strength (in the absence of the low frequency source) of the first microwave source vary from 1.34 µw / cm^2 and 3.18 V/m, respectively to 0.12 µw / cm^2 and 0.95 V/m at the locations of the most affected people. The second microwave source has total maximum EIRP of 12000 watts, but, to be conservative, only a third of that amount will be assumed to radiate into any one sector. The power density and field strength for the second microwave source at the same distances range from 1.4 µW / cm^2 and 3.27 V/m to 0.127 µW / cm^2 and 0.98 V/m.

The amplitudes A_3 and A_4 are computed from the equations which follow:

$$A_3 = \left(\left[\left\{ -2\,S\left(\sqrt{\frac{k\,r}{\pi\eta^2}}\right) + 1 \right\} \cos\left\{\frac{1}{2}\,\frac{k\,r}{\eta^2}\right\} + \left\{ 2\,C\left(\sqrt{\frac{k\,r}{\pi\eta^2}}\right) - 1 \right\} \sin\left\{\frac{1}{2}\,\frac{k\,r}{\eta^2}\right\} \right] \left[\frac{\pi}{2} \sqrt{\frac{k\,r}{\pi\eta^2}} \right] - 1 \right) \frac{I\,Z_0\,k\,l}{2\,\pi\,r} \quad (6)$$

and

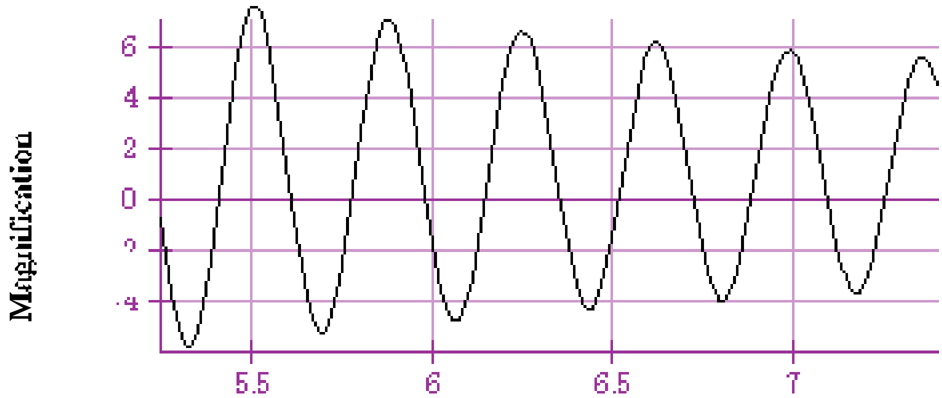
$$A_4 = \left(\left[2\,C\left\{\sqrt{\frac{k\,r}{\pi\eta^2}}\right\} - 1 \right] \cos\left[\frac{1}{2}\,\frac{k\,r}{\eta^2}\right] + \left[2\,S\left\{\sqrt{\frac{k\,r}{\pi\eta^2}}\right\} - 1 \right] \sin\left[\frac{1}{2}\,\frac{k\,r}{\eta^2}\right] \right) \sqrt{\frac{k\,r}{\pi\eta^2}}\;\frac{I\,Z_0\,k\,l}{4\,r} \quad (7)$$

The total time dependent magnification factor for microwave source 2 is

$$N_2 \cos\left(-k_2 r_2 + \omega_2 t\right) + M_2 \sin\left(-k_2 r_2 + \omega_2 t\right) + 1$$

Conventionally, the magnification effect would be ignored on the basis that the average value of this term is 1.0. However, laboratory experiments have demonstrated that sinusoidal RF waves can affect biochemical processes in cells. Thus, it seems likely that these terms should not be averaged out, but the maximum magnification effect should be determined, so that any likely hazard to health can be noted. Fig. 3 shows the total magnification factor for source 2 at a location 500 m from the tower for dry earth conditions and time = 1/8 oscillation period of source 2.

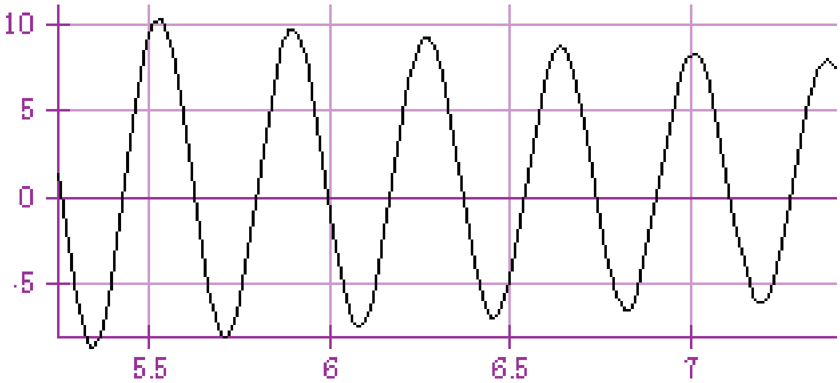
Fig. 3 Total Magnification of Microwave Source 2 versus Distance from Low Frequency Source for Location 500 m from Microwave Tower (time = 1/8 period of source 2, Dry Soil)



Distance from Low Frequency Broadcast Source (km)

Figure 4 shows the same kind of results, except that the calculation considers the effect of wet soil.

Fig. 4 Total Magnification of Microwave Source 2 versus Distance from Low Frequency Source for Location 500 m from Microwave Tower (time = 1/8 period of source 2, Wet Soil)



Distance from Low Frequency Broadcast Source (km)

Very similar results are also obtained for the other microwave source (but not shown here). Having two microwave sources, whose electric field strengths are nearly the same, doubles the overall level of the microwave radiation field on the ridge where the radiation sufferers live. Also variation in the local surface terrain and in soil conditions can likely create hot spots in the radiation density, and these occurrences cannot be predicted, but can be measured. These calculations suggest that the microwave tower could have been located in a minimum ground wave region, had some effort been made to survey the radiation field of all RF sources in the area.