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Elevation and Pseudo-Brewster Angle Formation of Ground-Mounted Vertical Antennas

The formation of the elevation pattern of ground mounted vertical antennas is the result of two basic mechanisms. The first is a very slow lowering of the main pattern lobe over hundreds of wavelengths, and the second is ground attenuation due to dielectric losses that result from the very low center of radiation of the vertical antenna.

The purpose of this article is to investigate the mechanisms for the formation of the radiated elevation angle in ground-mounted vertical antennas. The commonly published explanation is that ground reflections reverse the phase, and thus wave cancellation occurs in the far field, and produce the pseudo-Brewster angle. The reflected cancellation wave is often made easier to visualize by referring to it as the antenna "image".

However, this explanation is not possible with ground-mounted vertical antennas ¼ wave or shorter in height. Simple geometry instructs us that this is not the case. The center of radiation from a ¼ wave or shorter ground mounted vertical antenna is at or very close to the ground. Therefore the point of ground reflection must be very close to the antenna, indeed within the radius of the radial system! Thus for the common theory to hold, the vertical antenna must have a reflection point on the antenna proper, and within the near field. Even if the near field could be considered the same as the far field for reflections, then a perfectly conducting radial system would not produce reflected waves that would cancel.

[1]Notes appear on page 20.

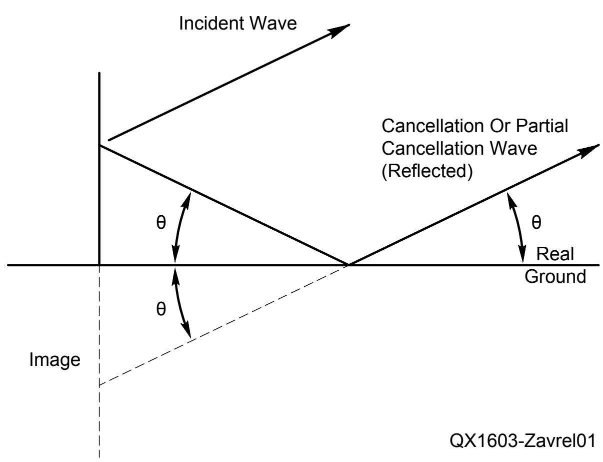

Figure 1 — The geometry for phase cancellation (or partial attenuation) from a ground-reflected interfering wave.

Vertical Antenna Over Ideal and Real Grounds

Figure 1 shows the basic principle of phase cancellation — or partial attenuation — from a reflected interfering wave. From electromagnetic theory and simple geometry the incident angle and the reflected angle θ ar*e always equal a*bove the reflector's surface. Figure 2 shows the sinusoidal current distribution along a ground-mounted quarter-wave vertical antenna. If we include the return ground current, the center of radiation is at the center of the antenna at ground level.

To complicate the matter farther, very close-in ground reflections, if they

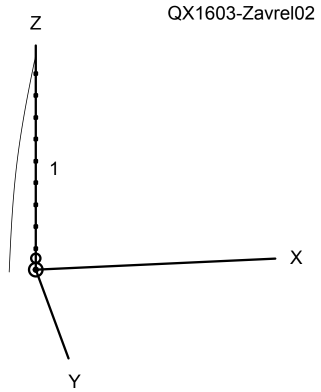

Figure 2 — The sinusoidal current distribution along a ground-mounted quarter-wave vertical antenna.

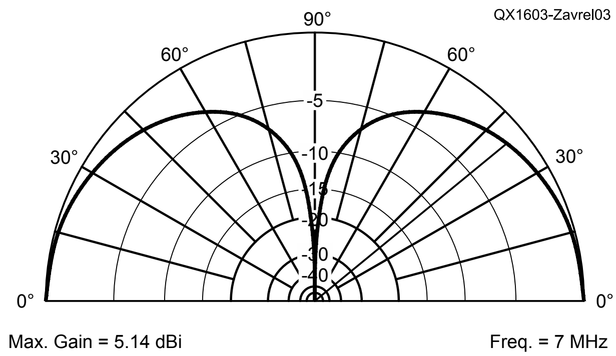

Figure 3 — Elevation pattern of a quarter-wave vertical antenna mounted over a perfectly conducting infinite ground plane.

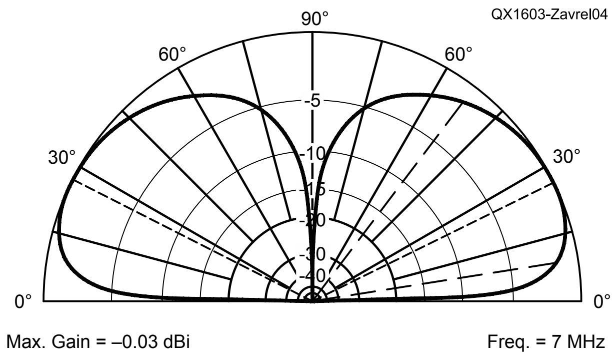

Figure 4 — Elevation pattern of a quarter-wave vertical antenna mounted over "average" ground. The pattern peak gain is at 26 degrees elevation.

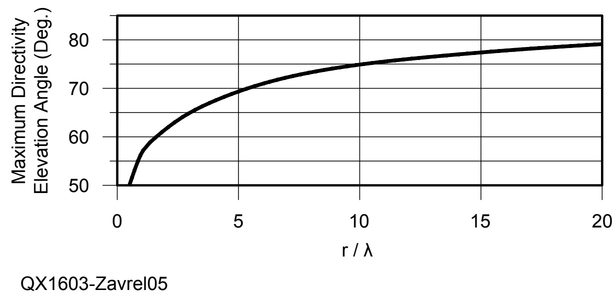

Figure 5 — The variation of the maximum directivity elevation angle (measured from the vertical) with respect to disc radius in wavelengths.

existed, would have to be determined by a rather complex integration, using antenna segmented amplitudes and phases. This is in contrast to a much simpler calculation of far-field reflections and cancellations that assume the antenna to be a point source.

If the conventional theory were true, we could lay out a more extensive radial system, say one-wavelength radials, and dramatically lower the angle of radiation and increase the overall gain, particularly at elevation angles whose associated reflection points fall on the new radial system no matter what the ground characteristics. This simply does not happen. There is very little effect upon the antenna directivity with even substantial increases in radial length. The increase in over-all gain occurs because of reduction of ground losses in the antenna *per se*.

The case for raised vertically polarized arrays — short wave broadcast curtains — is somewhat different. The elevation angle is affected by extensive ground screens and is used effectively to maximize patterns at lower elevation angles at many such facilities. This is achieved because the patterns of raised vertical antennas are affected by ground reflections as discussed later in relation to Figure 8.

Now, let us compare the elevation angle of a quarter-wave vertical antenna over a perfect ground with the same antenna over average ground. Figure 3 shows the well-known elevation pattern of a quarter-wave vertical antenna mounted over a perfectly conducting infinite ground plane. In this case we model a 7 MHz antenna. The scale is linear in decibels rather than the ARRL scale. Figure 4 shows the pattern of the same vertical antenna as in Figure 3, but over average ground. This is also quite familiar to many radio amateurs. Table 1 shows the gains of the two cases, in dBi, for elevation angles from 0 to 45 degrees.

The differences are quite striking. The gain at the "grazing angle", is maximum in Figure 3, but very heavily attenuated in Figure 4, indeed, indicating a complete null at this low angle. The grazing angle could be explained by phase cancellation since even a very low center of radiation could result in a reflection point well into the far field.

Of more interest to this discussion, the maximum gain response in Figure 4 (at 26 degrees elevation) is about 3 dB lower than at the same elevation angle in Figure 3. If this 3 dB attenuation were due to reflection cancellation (worst case ignoring the image), the reflection point would range between 0 and about 25 feet from the vertical antenna, on top of the radial field! Even at the relatively high angle of 45 degrees, we see almost 3 dB of attenuation. Furthermore, the feed-point impedances are identical, and since the feed-point is at a current maximum on a single conductor radiator, the radiation resistances are also identical. Also, there is no ground loss in either configuration indicating that both antennas are nearly 100% efficient. What can be the cause of this very significant difference?

A Closer Look at the Grazing Angle

As Figure 3 shows, the maximum radiation over a perfect infinite ground plane is at 0 degrees for the quarter-wave vertical antenna. Again, conventional wisdom suggestes that the low-angle null in Figure 4 is due to refelction cancellation. The infinite ground plane is useful only as a theoretical model, since the ground is really the spherical Earth. The EM simulation of Figure 5 shows a ¼ wave antenna over a perfectly conducting ground of varying radius. For very small ground radius there is nearly identical radiation below the ground plane, closely approximating the pattern of an antenna using ¼ wave radials. There is considerable radiation at the horizon (including below the ground plane) for all radii, however the maximum can appear only at the horizon for an infinite radius.[1-5]

The convergence to a maximum at the horizon, occurs at several hundred wavelengths away. In principle it represents a log function and thus never reaches the maximum. In practice, even 100 wavelengths at 160 meters is 16 km. The curvature of the Earth begins to influence and distort the theoretical pattern shown in Figure 3. In effect, there are two factors at work. First, the very gradual convergence to the 0 degree elevation angle maximum, and second, the significant influence of the Earth's curvature on the planar assumption. A low band vertical antenna can be thought of as an elevated vertical antenna since it is mounted on top of a sphere (Earth), not a plane. The gain maximum of a low-band ground-mounted vertical antenna will never be realized at the 0 degree elevation angle, even over sea water.

Even with a perfect ground there is a null at very low elevation angles. This has a very important effect on the over-all elevation pattern, but does not explain the additional pattern attenuation over real ground.

Another View

By using an advanced electromagnetics modeling tool we can begin to see the mechanisms of pattern creation. I have been using *EMPro*, by Agilent for designing GPS and other antennas for some time. As an aside, I modeled a quarter-wave vertical antenna — in this case at a 7.5 GHz operating frequency. The absolute numbers in the

Table 1.
Gain of a vertical antenna above perfect and average grounds.

Elevation angle, deg	*Perfect ground gain, dBi*	*Average ground gain dBi*	*Δ dB gain*
0	+5.14	-∞	∞
5	+5.09	-6.32	11.41
10	+4.95	-2.55	7.54
15	+4.71	-0.99	5.70
20	+4.37	-0.28	4.65
25	+3.93	-0.04	3.97
30	+3.40	-0.10	3.50
35	+2.76	-0.40	3.16
40	+2.01	-0.89	2.91
45	+1.14	-1.56	2.70

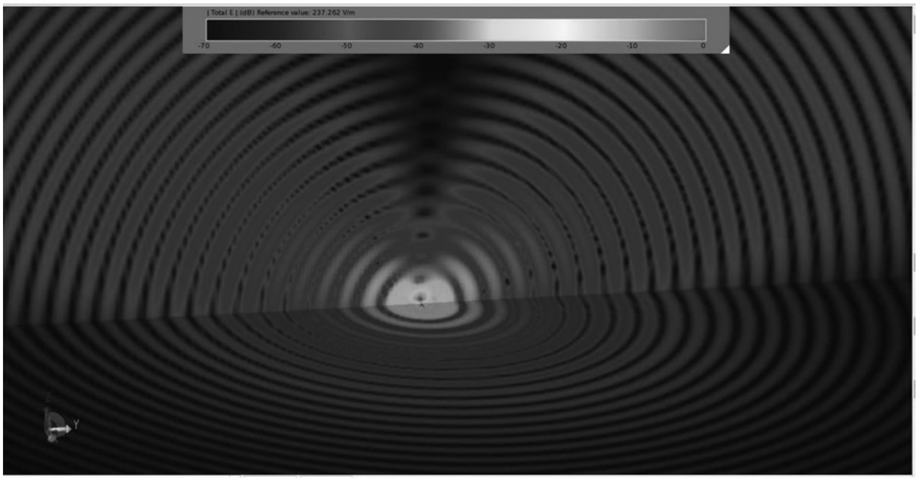

Figure 6 — *EMPro* image of both the surface and elevation angle radiated E-fields of a quarter-wave vertical antenna on average soil.

patterns at different frequencies are products of multiple variables, but the general results show pattern similarities between Figures 4 and 6. Care must be taken to ensure that the soil characteristics are nearly identical at 7.5 GHz for simulation, and at MF and low HF in practice.

Figure 6 shows the 7.5 GHz *EMPro* simulation of both the surface and elevation angle radiated E-fields of a quarter-wave vertical antenna on average soil. As expected, Figure 6 shows no evidence of field cancellation due to reflected interfering waves. Rather, the grazing angle field intensity is equal to the field intensity along the surface of the ground. The ground intensity decreases faster than for free space due to its lossy characteristics, and the field intensity maintains a continuous function at the point of intersection with the free space just above the ground and along the surface of the ground.

FCC graphs used for plotting AM broadcast ground wave intensity for predicting coverage areas can be found at **www.fcc.gov/encyclopedia/am-broadcast-groundwave-field-strength-graphs-sections-73183-and-73184**. However, ground wave attenuation is somewhat different from the *EZNEC* and *EMPro* plots. Ground waves at MF tend to hug the ground due to a tilting of the electric fields as they propagate over lossy ground. However, for the first several wavelengths away from the antenna, lower angle radiation, in effect, is also a ground wave and is subject to the same increased attenuation as true ground waves. Thus the lower the radiation angle, the greater the ground attenuation as shown in Table 1.

Modeling the same antenna over a perfect ground yields results with much higher E-fields at the ground level, and thus in free space just above the perfect ground. With a bit of practice you can see the similarity in patterns between Figure 7 and Figure 4. In the Figure 6 far field, the blue colored — slightly left of center on the grey scale at the top of the image — field lines are more intense than the purple — extreme left on the grey scale [For color Figures see **www.arrl.org/QEXfiles** — *Ed.*]. This diagram implies a very different mechanism for pattern formation than interfering reflected waves:

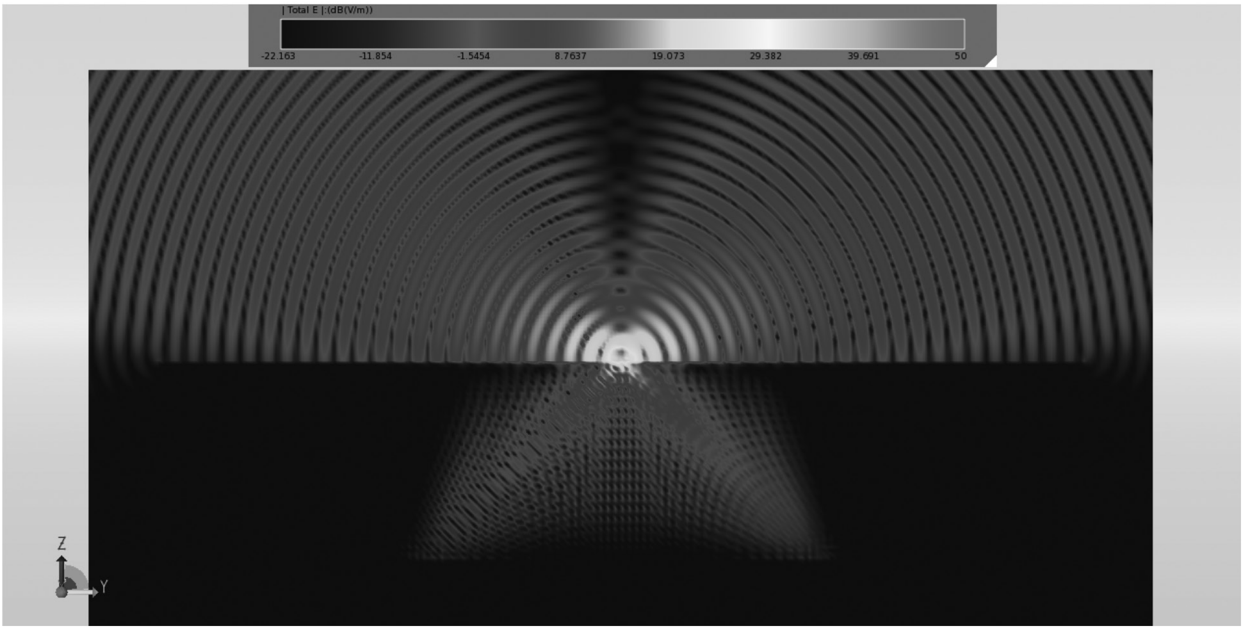

Figure 7 — Elevation plot of a base-fed ¼ λ monopole, on 24 λ diameter real ground (0.005 S/m, ε=14). Soil thickness is 5 λ. The antenna ground system is a solid ½ λ in diameter disc of a perfect conductor, to simulate a perfect antenna ground or an infinite number of ¼ λ radials.

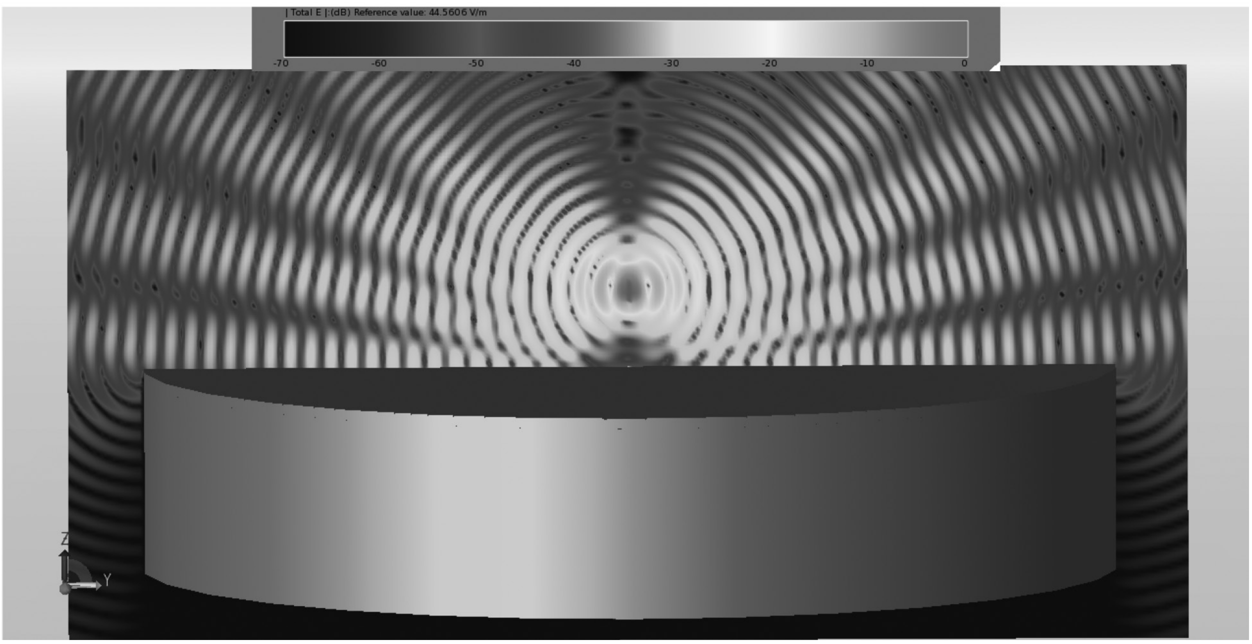

Figure 8 — The electric fields of an elevated half-wave vertical dipole, with feed point 2 wavelengths above a large slab of average ground.

ground wave attenuation as a function of ground loss. Notice that the E-field amplitude at low angles is simply attenuated faster than in free space, unlike the nearly discontinuous function the NEC models imply. Of course in the very far field, the NEC pattern becomes a good approximation, but the assumption of phase cancellation appears incorrect. The more advanced versions of *EZNEC* do permit modeling of the ground wave, but only at designated distances.

The Figure 7 simulation is the same as in Figure 6, except the ground surface field plot is removed to reveal the E-field underground. It appears from this simulation that the pseudo-Brewster angle — actually its counterpart — is formed by the attenuation of the ground-surface wave. As the radiation angle increases, its distance to the ground increases faster for a given distance from the antenna. In other words as an E-field propagates tangentially to a lossy dielectric, it is attenuated greater than in free space.

The elevation pattern is formed by the antenna's inherent pattern, and then further shaped by the lossy Earth. Also, the pattern or directivity of a ground mounted vertical antenna is independent of the antenna ground, or "image". The gain (directivity multiplied by the efficiency) *is* increased by lowering the ground losses of the antenna proper. Ground losses forming the directivity in the far field are the result of propagation

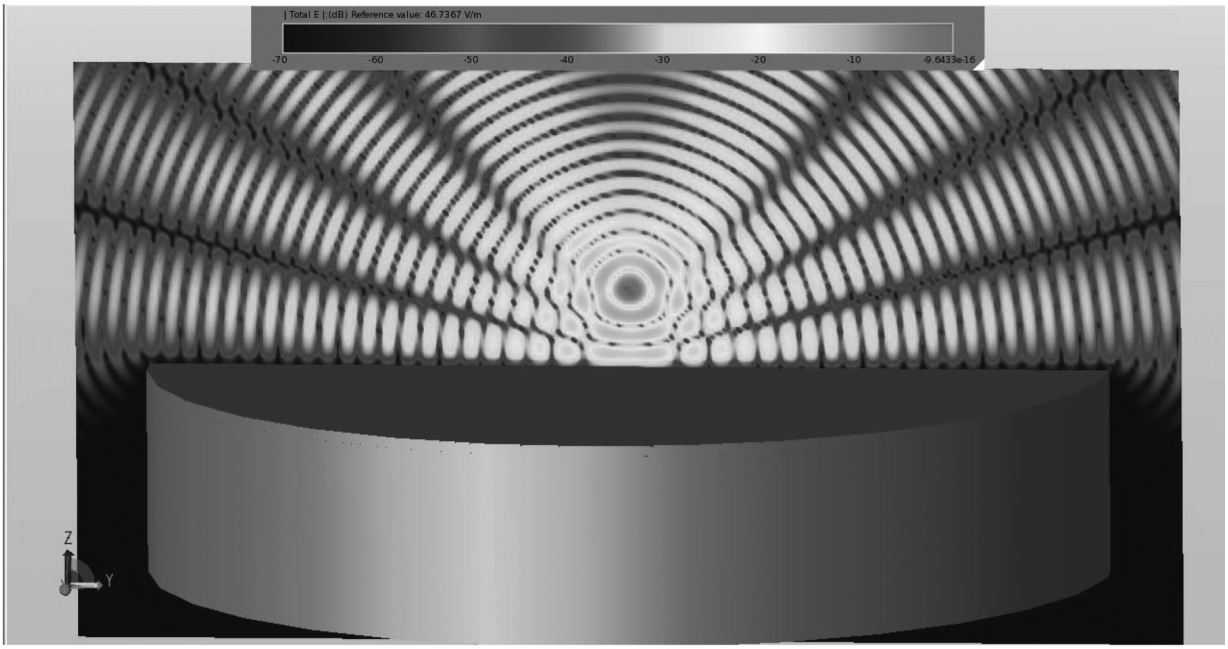

Figure 9 — The electric fields of half-wave horizontal dipole 2 wavelengths above the same average ground as in Figure 8.

losses, not antenna losses. The power that would normally be in the elevation angle close to the ground (with a perfect ground) is not cancelled because there is no cancelling wave present.

Figure 8 shows a plot of an elevated half-wave vertical dipole, with its feed point 2 wavelengths above a large slab of average ground. In this case we can clearly see the effects of reflected waves, with interfering and opposing fields creating the final pattern. If you look closely you can also see a phase difference in the various lobes that are not present in Figure 7. Here, plane waves are present and conventional wisdom of the pseudo-Brewster angle from ground reflections is valid. The cancellation and re-enforcement of far-field waves also have the effect of distorting the apparent point source of the wave. Notice that the grazing angle — lowest angle of radiation — appears to be coming from a source on the surface of the ground.

The plot of Figure 8 brings up another interesting point regarding raised vertical dipoles. The radiation resistance of a free-space vertical dipole is about 73 Ω, the same as a free-space horizontal dipole. However, as the vertical antenna is lowered closer to the ground, the radiation resistance — and in this case, also the feed-point impedance — rises to a maximum value of about 100 Ω when the end of the dipole is just above the ground surface. At lower elevations the ground actually becomes part of the antenna and thus increasing the effective height of the radiating antenna. This happens no matter what the ground characteristics are, perfect or real, and are not due to losses.

For comparison I also include a plot a half-wave horizontal dipole (Figure 9) to see the same reflected-wave cancellation mechanism at work. The view is down the axis of the dipole thus highlighting the broadside E-field pattern of the dipole. This view also shows the disc representing the real ground. Formation of nulls and peaks of gain at various elevation angels is clearly shown to be the result of reflections adding and subtracting from the field strength.

Conclusions

Antenna pattern formation by re-enforcing and cancelling reflected waves are clearly the mechanism for raised antenna systems — creating the pseudo-Brewster angle. However, for ground-mounted vertical antennas quarter-wavelength or shorter, the formation of the elevation pattern is the result of two basic mechanisms. First, there is a very slow lowering of the main pattern lobe over hundreds of wavelengths distance, and second, there is ground attenuation due to dielectric losses that result from the very low center of radiation of the vertical antenna.

There is insignificant influence of reflected waves on the antenna pattern of ground-mounted vertical antennas that are a quarter-wave or shorter height.

Bob Zavrel, W7SX, is an ARRL Life Member, Technical Advisor and Amateur Extra class licensee. He has been licensed since 1966. His primary interest in Amateur Radio is low band DXing and designing and building antennas, tuners, and amplifiers. Bob holds 5BDXCC, 5BWAZ (200), has 334 mixed, and 324 CW entities confirmed. Bob is on the DXCC Honor Roll and the CW DXCC Honor Roll, all using only tree-supported wire antennas. He also holds 9-Band DXCC on 160 through 10 meters. Previous call signs include WN9RAT, WA9RAT, WA9RAT/HR2 and SV1/W7SX.

Bob has a BS in Physics from the University of Oregon and has worked in RF engineering for over 30 years. He has five patents, and has published over 50 papers in professional and Amateur Radio publications, including the first block diagram of an SDR receiver in 1987. He was involved with the first generation of RF integrated circuits for cellular phones, and worked extensively with DDS, WLAN and passive mixer development. Bob is currently an RF Research and Development Engineer for Trimble Navigation with a primary focus on high precision GPS, down to millimeter accuracy.

Notes

[1]Z. Živković, D. Senić, C. Bodendorf, J. Skrzypczynski, and A. Šarolić, "Radiation pattern and impedance of a quarter wavelength monopole antenna above a finite ground plane", in *2012 20th International Conference on Software, Telecommunications and Computer Networks (SoftCOM),* pp. 1-5, IEEE, 11-13 Sep 2012.

[2]E. C. Jordan and K. G. Balmain, *Electromagnetic Waves and Radiating Systems*, 10th printing, 1967, Prentice-Hall Inc.

[3]R. K. Wangsness, *Electromagnetic Fields*, Wiley & Sons, 1979.

[4]J. Kraus, *Antennas*, McGraw Hill, 1988.

[5]R. C. Johnson and H. Jasik, *Antenna Engineering Handbook*, Second Edition, 1984, McGraw-Hill.