The magnetic field of a vertical monopole antenna cannot induce ground currents

Mike Hasselbeck, WB2FKO

mph@sportscliche.com

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Abstract

An analysis is made of the magnetic field vector generated by a vertical monopole antenna in the near-field. The field amplitude drops off dramatically below the base, but retains a circularly symmetric pattern as suggested by Ampere's Law. It is shown that the rotating magnetic field from the vertical element cannot induce currents in the ground below it or in a counterpoise of segmented radials.

Keywords: antenna, vertical, monopole, magnetic field, induction

Introduction

Vertical antennas are attractive because they can achieve a low takeoff angle, have an omnidirectional radiation pattern, small area footprint, and may offer a less demanding installation compared to horizontally polarized alternatives. Crucial to the performance of a vertical antenna is an effective radial system or counterpoise. This serves as a replacement for the "missing" lower element of a vertical dipole.

An understanding of the physics that occurs in the near-field aids in the interpretation of antenna modeling software and should lead to better engineered antennas. Complicated calculations performed by the software, however, may mask the underlying, fundamental physics. This physics can be revealed by an approximate but direct analysis using Maxwell's equations. This note characterizes the magnetic field generated by the vertical radiator and its implications for radially directed currents beneath it.

B-field from vertical radiator

The currents and resulting B-fields are visualized in Fig. 1 [1]. In the analysis that follows, we are only interested in the field produced by the vertical element and whether it can induce any currents. Contributions from any radial elements that may be present are ignored. Ampere's Law and the right-hand rule demonstrate that current in the vertical element produces symmetric, rotating field lines. The rotation direction depends on the direction of current flow, which alternates sinusoidally at the frequency of the driving potential. Neglecting edge effects (i.e. assuming an infinite length radiator), the magnetic field decreases as the inverse of radial distance from the antenna.

One polarity of the dual-conductor feedline is connected to the vertical element and the other terminal to the radials or counterpoise. Due to conservation of charge, current in the vertical radiator must flow in the radials [1]. This is the foundational principle of Kirchoff's Current Law, which requires that the sum of the radial currents must equal the current in the vertical.

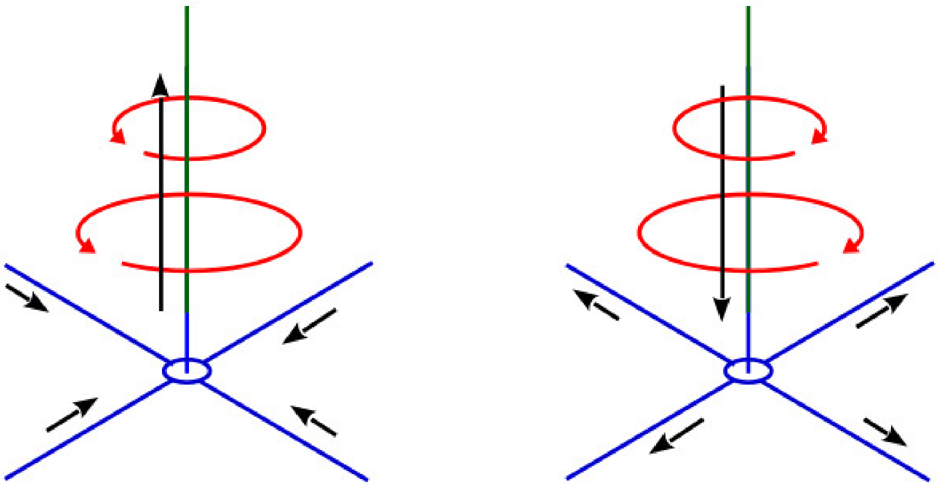

Figure 1: Sketch of currents (black arrows) and magnetic field lines (red circles) for a vertical antenna. The current and rotation directions alternate at the radio frequency. The fields generated by the radial segments are not shown.

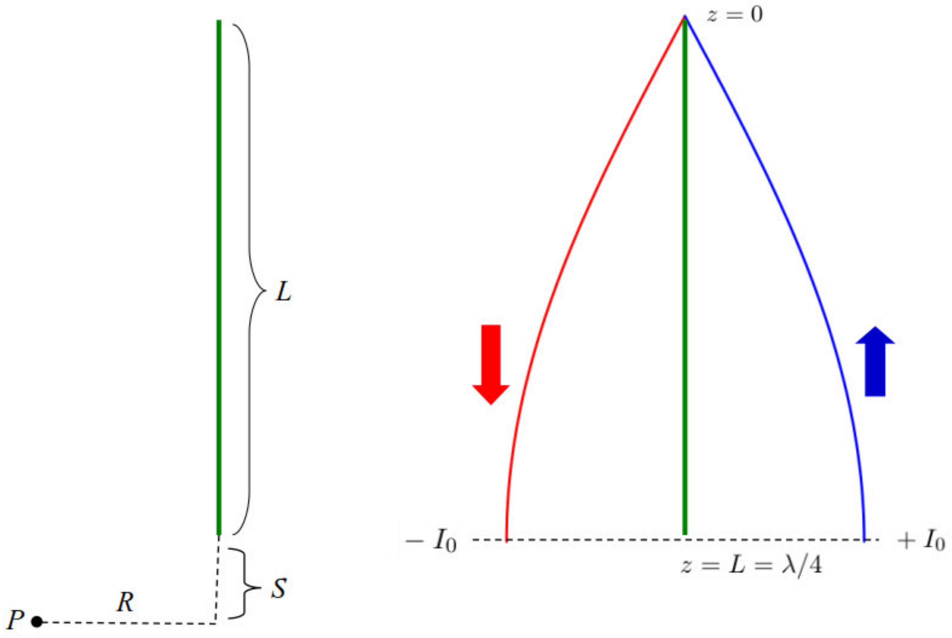

Figure 2: Left: Geometry for calculating B-fields at and below a vertical radiator of length L. Right: Magnitude of the current flowing along the length of a quarter-wavelength vertical radiator. The peak current I_0 occurs at the feedpoint. The sign depends on the direction of current flow that oscillates at the radio frequency.

The Biot-Savart Law facilitates calculation of the amplitude and direction of the magnetic field that is generated by current-carrying elements of finite length. This is the general-case formulation of Ampere's Law. We use it to find the magnetic field of the vertical radiator at and below its base. This is where a counterpoise or an arrangement of spoked radials on or above the earth are located.

Figure 2 (left) shows the geometry for determining the B-field vector at a position P, located at a radial distance R and vertical displacement S below the base of a vertical radiator of length L. For simplicity, we ignore contributions from: i) propagating electromagnetic radiation and ii) displacement currents arising from distributed capacitance between the vertical element and ground. The current along the length of a driven half-wave dipole antenna is a half-sinusoid, with amplitude and direction alternating at the radio frequency. This non-uniform current profile results from the spatially-varying distribution of moving charge. Since a quarter-wave vertical is one element of a dipole, the current takes the form of a truncated sinusoid in the radial angle range $0 - \pi/2$ as sketched in Fig. 2 (right). It is maximum at the feedpoint and vanishes at the top, where we define $z = 0$; the feedpoint is at the base where $z = L$ so that the positive direction of the z-axis is downward. The time-dependent current profile can be written:

$$I(z,t) = I_0 \sin\left(\frac{2\pi c\ t}{\lambda}\right) \sin\left(\frac{2\pi z}{\lambda}\right) \tag{1}$$

where λ is the wavelength and c is the speed of light. Every half-cycle the current collapses when it changes direction. The time-dependence is irrelevant here because the present analysis is comparing the *relative* magnetic field strength produced by the same instantaneous current at different positions near the base of the antenna. The Biot-Savart Law is formulated with the following integral equation:

$$|\overrightarrow{B}| = \frac{\mu_o I_0}{4\pi} \int_0^L \sin\left(\frac{2\pi z}{\lambda}\right) \frac{dz}{(L - z + S)^2 + R^2} \tag{2}$$

where μ_o is the magnetic permeability. We set $L = \lambda/4$ for a quarter-wavelength vertical, hold I_0 constant, and calculate the magnitude of $\overrightarrow{B}$ at four different displacements S starting at the base of the vertical: $S = 0$, 0.05, 0.1, and 0.2 λ. This equation can be evaluated using straightforward numerical integration with just a few lines of code. Results are shown in Fig. 3. The horizontal-axis is the radial distance R from the vertical element in units of λ. The vertical-axis is in arbitrary units, normalized at $S = 0$ and $R \approx 0$ [2]. The curves clearly show that the B-field drops off rapidly outside of the near-field. There is no wavelength dependence, consistent with plots in the ARRL Antenna Handbook [3].

The complete form of the Biot-Savart Law is a vector cross-product that also gives the direction of $\overrightarrow{B}$. It is normal to the plane of the page in Fig. 2. Although amplitude decreases dramatically with increasing distance from the antenna, pure circular rotation as shown in Fig. 1 is maintained. Unless the soil below the antenna has some ferromagnetism, the B-fields of an antenna mounted near the ground will be the same as calculated for free-space.

Misconceptions in the ARRL Antenna Handbook

The effect of ground on antenna performance is the subject of an entire chapter in the Antenna Handbook [3]. At several places in this chapter it is asserted that the circular magnetic field emanating from the vertical element induces radial currents directly in the ground and/or the antenna counterpoise. This claim is incorrect as can be understood by considering the following:

1) Faraday's Law of Induction explains how a magnetic field gives rise to current in a conductor. This requires a time-varying flux passing through the area of a closed current loop. Magnetic

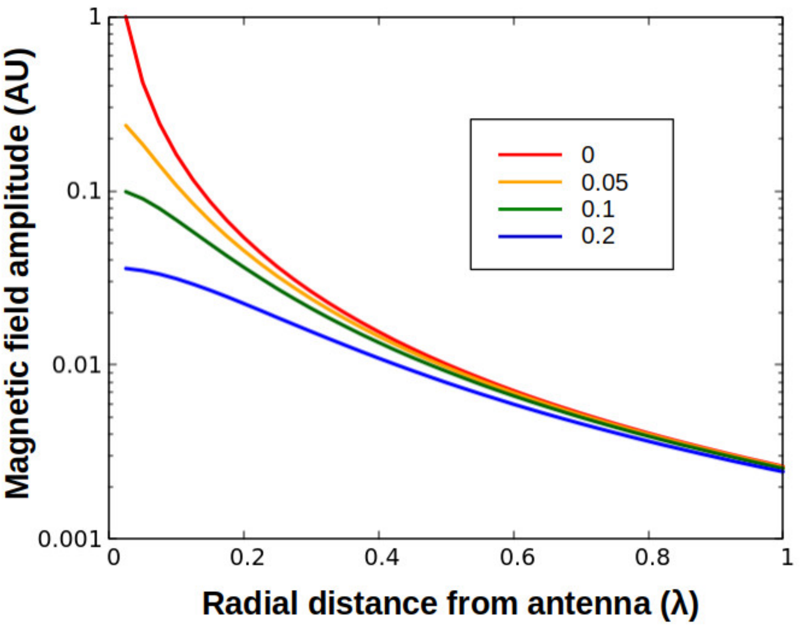

Figure 3: Normalized magnetic field amplitude as a function of radial distance R from a quarter-wave vertical element. The curves are for displacements $S = 0$, 0.05, 0.1, 0.2λ below the bottom of vertical.

induction is fundamental to the operation of transformers, electric motors, and power-generating turbines. Examination of the vertical antenna geometry in Fig. 1, however, shows no current loop to define an area for the magnetic flux. A magnetic field interacting with a straight radial wire segment at any angle (including right angles) cannot induce a current in it [4].

2) Assume for the sake of discussion that the circular magnetic field is indeed responsible for inducing current in the radials. If that is true, we could disconnect the radials from the second conductor of the feedline, re-connect this terminal to ground, or ignore it altogether and let it float. We know from experience that this will be a very poor antenna. It is also worth looking at this from the perspective of a vertical dipole where the upper and lower elements are being driven by a time-varying potential. No magnetic field is required to produce currents in either element. Now bend the lower element upwards, putting it closer to horizontal. When does the oscillating feedline potential stop being relevant and the magnetic field take over? This is a logical discontinuity.

The source of this error appears to be a technical article published in the July 2000 issue of QST that was subsequently incorporated into the Antenna Handbook [5]. The radials and counterpoise are best understood as the missing lower half of a vertical dipole as the Handbook discusses elsewhere.

Magneto-resistance in the radials

Magneto-resistance is a phenomenon relevant to this discussion that we consider briefly. When current is flowing in a conductor oriented orthogonal to a magnetic field as we have here, there will be a Lorentz force on the moving electrons. The force is perpendicular to the electron direction of travel – pushing them upward into the wall of the conductor. This effectively increases the resistance of the radial and would tend to favor positioning them at an angle below horizontal to reduce the effect. In practice, the additional resistance has been shown to be negligible for antennas built from conventional materials and operating at nominal temperatures. The skin effect already confines current to the surface of the radial element, suggesting that any magneto-resistance will be a weak, secondary effect.

References

[1] G.H. Brown, "The phase and magnitude of earth currents near radio transmitting antennas", Proc. IRE **23** 168 (1935).

[2] The singularity at $R = 0$ arises from using a zero radius conductor. It can be resolved with a more complicated model but offers no additional insight.

[3] *The ARRL Antenna Handbook*, 25th ed., Ch. 3, ARRL Inc. (2025).

[4] Time-varying magnetic fields can induce compact, circulating eddy currents on conductive surfaces. These currents are assumed to be negligibly small on thin radials and do not contribute to the antenna excitation current.

[5] R. Severns, "Verticals, Ground Systems and Some History", QST, July (2000); also R. Severns, "Radiation and Ground Loss Resistances in LF, MF, and HF Verticals; Part 2 Appendix B", QEX, Sep/Oct (2015).

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