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Ground Wave Propagation of a Video Pulse Source Part II

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Ground Wave Propagation of a Video Pulse Source Part II*

Abstract

In a previous paper we developed a simple model describing the far-field from a video-pulse source near the ground and for grazing incidence. We report here on a recent field test in which we attempted to verify the model. Our results show quantitative agreement with the model for most of the tested parameter space. We have also extended our model to include all elevation angles, including up to vertical. The computed engagement envelope shows three distinct regions: At grazing angles the field is small and diminishes to near zero at the earth's surface; at low-to-moderate angles strong lobing occurs; at high angles the video-pulse field approaches its free-space form.

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Introduction

In a recent technical note¹ we analyzed the propagation of an impulsive source of electromagnetic radiation with frequencies in the video band (video-pulse) over a flat and planar earth. Our basic finding of the analysis, which was limited to shallow reflection angles, is that the pulse is greatly altered from what it would be in free space. Our model, though quite simple, predicted that the field strength would vary linearly with the height of the receiver and transmitter, inversely as the square of the distance between the two, and its time history would follow the derivative of the source field. In particular we derived,

$$\vec{E} = \frac{2h_t h_r}{d^2} \frac{\partial \vec{E}_0}{c \partial t} \quad (1)$$

where $\vec{E}$ is the electric field strength at some point in the far field, $\vec{E}_0$ is the free-space field, reduced to one meter (m) distance (volts = V/m times one m distance), d is the horizontal distance between the transmitter and the receiver, and h_r and h_t are the receiver and transmitter heights, respectively.

We have recently performed a series of field experiments attempting to verify the approximate model given above.² We examined the experimental behavior as a function of time, distance and elevation to compare with the scaling laws implied by equation (1). Our results generally show quantitative agreement with the model for most of the tested parameter space. The only exception is that the experiment failed to verify linear scaling of the field strength with receiver height.

We have also extended the region of calculation to include all elevation angles, including up to 90°. No simple analytic form describing the field appears possible, so we continue the use of Norton's method.^{3,4} The engagement envelope show three distinct regions: At shallow angles, the direct and reflected pulses overlap almost completely, resulting in a small field strength that diminishes to nearly zero at the earth's surface; a second region at higher reflection angles in which the direct and reflected pulses continue to overlap, with resultant strong lobing; and a third region that extends up to 90° in which there is no overlap at all between the direct and reflected pulses.

Summary of Experimental Results

During Project Evergreen, we made measurements of the electromagnetic fields propagated over ground at various distances from several "video pulse" sources. Our purpose was to gather signatures and see how they matched against predictions based upon the simple model of equation (1). We varied time, distance, and elevation of the receiving antenna and compared with the predicted behavior.

Our measurement and recording system used to collect the VHF data is shown in the block diagram of Fig. 1. The system is based upon a HP 54111D digitizing oscilloscope with a sampling rate of 10^9 samples/s, providing an effective bandwidth of 250 MHz. Signals are collected with two $\vec{B}$ sensors and are split with the other

half of the signal power going to a Tektronix 7104-based system (1GHz effective bandwidth).

In our first example we compare the signal measured close-in, $\vec{E}_0$, to that measured remotely, $\vec{E}$. We compare the two by plotting $2h_t h_r / d^2 \partial \vec{E}_0 / c \partial t$ and $\vec{E}$ in Fig. 2. Shape of the measured pulse is close to the shape of the derivative of the launch pulse, and, although the DC peak field predicted from the launch pulse is less than that measured (600 V/m vs 800 V/m), the peak-to-peak AC field is again close (1,300 V/m vs 1,400 V/m). Agreement, although not exact, is good.

The $1/r^2$ scaling of the distant fields is also verified. In Fig. 3 we compare the mean values of peak-to-peak electric fields from several shots at

distances of 50, 100, 200, and 400 m. Deviation from $1/r^2$ scaling is small, and is most pronounced at the 50 m position. At further distances the scaling is nearly exact.

Another important prediction is that the time behavior, embodied in the $\partial \vec{E}_0 / \partial t$ term, contains no functional dependence upon receiver distance. Thus, we expect to observe no change in the shape of the time history as a function of distance. Figure 4 shows the measured time history at four different distances. Time

independence is clearly demonstrated in the measurements.

The last prediction we examine is that the electric field strength varies linearly with height of the receiver. We measured the peak-to-peak ratios for two heights, 6.55 and 9.6 m, and took the mean from a series of six shots. The mean ratio turned out to be 2.36; the value predicted by the formula is 1.47. According to the measurement, the field increases faster than linearly. Results are shown in Fig. 5.

Figure 1. Block diagram of VHF measuring system.

Figure 2. Comparison between field predicted from launch pulse to actual field.

Figure 3. Variation of peak fields with distance.

Figure 4. Constancy of pulse shape with distance.

From a series of 6 shots, the mean ratio of upper to lower probe peak to peak fields is 2.36; from the previous formulas one would expect it to be $9.6/6.55 = 1.47$

Sample data, probe heights of 9.6 and 6.55 m resp

Figure 5. Variation of field amplitude with receiver height.

Engagement Envelope

In our previous note we restricted our region of interest to shallow (grazing) reflection angles. This allowed us to make several simplifying approximations to the propagation equations, resulting in the simple form for the field given in equation (1): reflection coefficients are nearly unity for shallow angles; the time delay between the direct and reflected pulses are very small, allowing a differential approximation to be used in place of a true difference; and the angle between the propagation vectors for the direct and reflected fields is small, so a simple scalar superposition of fields is possible.

To extend our development to larger elevation angles we must generalize to remove the approximations of our previous model. In the far-field, the total field is the sum of three parts; a direct pulse, a reflected pulse, and a pulse from the surface wave. A full vector formulation for proper superposition of direct and reflected fields must be employed; complex (real and imaginary parts) earth reflection coefficients must be substituted for pure reflection; and, because the off-axis angles can be large, the radiation pattern of the antenna must be taken into account. We also note from our previous report that the surface

wave for video pulse frequencies is negligible beyond a few meters from the transmitter, so we do not retain the pulse from the surface wave. Geometry of the direct and reflected pulse is shown in Fig. 6.

Because the Fresnel reflection coefficients,⁵

$$R_h = \frac{\sin \psi - \sqrt{\epsilon - \cos^2 \psi}}{\sin \psi + \sqrt{\epsilon - \cos^2 \psi}}, \quad (2)$$

$$R_v = \frac{\epsilon \sin \psi - \sqrt{\epsilon - \cos^2 \psi}}{\epsilon \sin \psi + \sqrt{\epsilon - \cos^2 \psi}}, \quad (3)$$

are functions of frequency, as well as polarization, reflection angle and material conductivity and

permittivity, expressions for the field components are derived for the Fourier transform,

$$F\{\vec{E}(t)\} = \int_{-\infty}^{+\infty} \vec{E}(t) e^{-i\omega t} dt = \vec{E}(\omega). \quad (4)$$

In the above expressions R_h and R_v are the horizontal and vertical reflection coefficients, respectively, ψ is the reflection angle, ϵ is the complex permittivity,

$$\epsilon = \epsilon_r - \frac{j\sigma}{\omega\epsilon_0}, \quad (5)$$

$$h_r = d \tan \beta$$

$$\alpha = \tan^{-1} \left\{ \frac{h_r - h_t}{d} \right\}$$

$$\psi = \tan^{-1} \left\{ \frac{h_r - h_t}{d} \right\}$$

$$d_d = \sqrt{d^2 + (h_r - h_t)^2}$$

$$d_r = \sqrt{d^2 + (h_r + h_t)^2}$$

$$\delta d = d_r - d_d \approx 2 \frac{h_r h_t}{d}$$

Figure 6. Geometry of direct and ground reflection paths.

ϵ_r and ϵ_0 are the relative and vacuum permittivity, respectively, σ is the conductivity (s/m), ω is the angular frequency, and $\vec{E}$ is the electric field strength. The tilde symbol, " $\sim$ ", indicates that the variable is expressed in the frequency domain.

To derive expressions for the component fields we use the standard spherical-polar coordinate system, shown in Fig. 7. The x-axis is pointed in the vertical, the y-z plane is horizontal, and the z axis is in the direction of the horizontal projection of the pulse propagation vector. In that coordinate system the propagation vectors of the direct and reflected pulses are,

$$\hat{k}_d = \hat{x} \sin \alpha + \hat{z} \cos \alpha, \quad (6)$$

$$\hat{k}_r = -\hat{x} \sin \psi + \hat{z} \cos \psi. \quad (7)$$

Likewise, the polarization vectors are,

$$\hat{p}_d = \hat{x} \cos \eta \cos \alpha + \hat{y} \sin \eta - \hat{z} \cos \eta \sin \alpha, \quad (8)$$

$$\hat{p}_r = \hat{k}_r \times (\hat{p}_d \times \hat{k}_r) = \hat{p}_d - \hat{k}_r (\hat{p}_d \cdot \hat{k}_r), \quad (9)$$

We must also specify the radiation pattern of an antenna. For simplicity we choose a square aperture antenna. Its diffraction-limited radiation pattern is,⁶

$$f = \frac{E_0 \pi w^2}{d_r 2\lambda^2} \left[\frac{1 + \cos(\alpha + \psi)}{2} \right] \frac{\sin u}{u}, \quad (10)$$

where $u = kw \sin(\alpha + \psi)$, k is the wave number, w is the square width of the aperture, and λ is the wavelength.

With these definitions the total field in the frequency domain is,

$$\vec{E}(\omega) = \frac{\tilde{E}_0(\omega) \pi w^2}{d_d 2\lambda^2} e^{-i\omega t_d} \left(\hat{p}_d + \hat{p}_r R_{h,v} \frac{e^{-i\omega \delta d/c}}{1 + \frac{\delta d}{d_d}} \left[\frac{1 + \cos(\alpha + \psi)}{2} \right] \left[\frac{\sin u}{u} \right] \right), \quad (11)$$

and in the time domain is,

$$\vec{E}(t) = \frac{E_0(t - d_d/c)}{d_d} \left[\hat{p}_d \mathcal{F}^{-1} \left\{ \frac{\pi w^2}{2\lambda^2} \right\} + \hat{p}_r \mathcal{F}^{-1} \left\{ R_{h,v} \frac{\pi w^2}{2\lambda^2} \frac{1 + \cos(\alpha + \psi)}{2} \frac{\sin u}{u} \frac{e^{-i\omega \delta d/c}}{1 + \delta d/d_d} \right\} \right], \quad (12)$$

where $\mathcal{F}^{-1}$ is the inverse Fourier transform,

$$\mathcal{F}^{-1} \left\{ \vec{E}(\omega) \right\} = \frac{1}{2\pi} \int_{-\infty}^{\infty} \vec{E}(\omega) e^{i\omega t} d\omega = \vec{E}(t). \quad (13)$$

For purposes of illustration, consider the following time waveform,

$$y = e^{-(t/t_w)^2} \frac{\sin \omega_0 t \sin \Delta \omega t}{\pi t}, \quad (14)$$

where t_w is the Gaussian width of the envelope, $\omega_0 = 2\pi f_0$, f_0 is the carrier frequency, $\Delta \omega = 2\pi \Delta f$ and Δf is one-half the pulse bandwidth. A plot of the waveform is shown in Fig. 8 and the magnitude of its FFT is shown in Fig. 9. We choose this waveform because its frequency distribution has sharp limits and can be completely controlled by the three parameters, t_w , f_0 and Δf . It also represents the kind of video pulse waveform typically used. Figure 10 shows the radiation pattern of the square aperture antenna driven by the time history given in equation (14). Differences between the radiation pattern of the wide bandwidth source and a narrow bandwidth source centered on f_0 are small, except that the pronounced notch of the pattern from the narrow bandwidth source is smoothed in the pattern of the wide bandwidth source. Antenna gain is about 2.7 (8 dB).

A sample calculation of the engagement envelope is shown in Fig. 11 using the parameters $t_w = 1 \times 10^{-8}$ seconds, $f_0 = 300$ MHz, and $\Delta f = 125$ MHz. A contour of the electric field strength is plotted as a function of altitude of the target. We assume that the antenna points directly at the target; the field is then the vector sum of the direct and ground reflected pulses. The source field strength we use is 100 kV/m @ 1 m, and the contour field strength is 1 kV/m.

$\hat{k}_d$ is the propagation vector of the direct pulse

$\hat{k}_r$ is the propagation vector of the reflected pulse

$\hat{p}_d$ is the polarization vector of the direct plane

$\hat{p}_r$ is the polarization vector of the reflected pulse

Figure 7. Coordinate system, polarization, and propagation vectors.

Figure 8. Time history of pulse waveform.

Figure 9. FFT magnitude of pulse waveform.

Three distinct regions, labeled I, II, and III on the plot, of the engagement envelope are apparent. Region I is very near the ground, and is characterized by small electric fields. In this region the time delay between the direct and ground reflected pulses, $t_d \approx 2 h_r h_t / cd$, is small and the interference is mostly destructive. Although somewhat arbitrary, we can define a boundary to the region from,

$$t_d \approx 2 \frac{h_r h_t}{cd} \sim \frac{1}{5f}. \quad (15)$$

Thus, the altitude and elevation angle of the boundary is,

$$h_r \sim \frac{cd}{10h_t f}, \quad \beta \sim \tan^{-1} \left(\frac{c}{10h_t f} \right) \quad (16)$$

For the transmitter height, $h_t = 2$ m, $d = 100$ m and $f = 300$ MHz, then $h_r \sim 5$ m and $\beta \sim 3^\circ$.

Region II is characterized by strong lobing. In this example we have a large lobe formed by constructive interference of the direct and ground reflected pulses. For constructive interference to occur we must have the path length difference equal to one-half of the carrier wavelength, or the time delay equal to one-half of the inverse of the carrier frequency,

$$t_d = 1/(2f) \quad (17)$$

The altitude and elevation angle of the strong lobe is,

$$h_r \sim \frac{cd}{4h_t f}, \quad \beta \sim \tan^{-1} \left(\frac{c}{4h_t f} \right). \quad (18)$$

The upper boundary of region II is found by setting the time difference of arrival of the pulses equal to the pulse width,

$$t_d \approx t_w, \quad h_r \sim \frac{ct_w d}{2h_t}, \quad \beta \sim \tan^{-1} \left(\frac{ct_w}{2h_t} \right). \quad (19)$$

From our example again, the altitude and elevation of the strong lobe is $h_r \sim 12.5$ m and $\beta \sim 7^\circ$. Similarly, altitude and elevation of the upper boundary of the region is $h_r \sim 75$ m and $\beta \sim 37^\circ$.

In region III, the time difference of arrival between the pulses is longer than the pulse width, so effectively there is no overlap between the direct and reflected pulses. Consequently, the peak field attained is identical to the peak field free space.

Of course, details of the engagement envelope depend upon the exact parameters chosen. In Fig. 11 we demonstrated the differences in the envelope between horizontal and vertical polarization. This is caused by the difference in their respective ground reflection coefficients. Obviously, we expect differences when we change the antenna radiation pattern. If, for example, we had used an omni-directional antenna instead of a directional antenna then the lobing in region II would be more pronounced, as we demonstrate in Fig. 12.

The engagement envelope is also sensitive to the transmitter height as the expressions imply in equations (15) through (19). In Fig. 13 we plot the envelope at three different heights; 3, 5 and 10 m. It is clear from the figure that the range of the regions I and II is lowered as the transmitter height is increased. Results are sensitive, too, to the time waveform chosen, but less so because restricting frequencies to the video pulse regime (100 MHz to 400 MHz) limits the shape of impulsive sources to those similar to the time history given in equation (14). In Fig. 14 we compare the engagement envelope between the analytic pulse give in equation (14) and the empirical pulse of Ref. 1. The empirical waveform and its FFT magnitude are shown in Figs. 15 and 16. Note that although the engagement envelope of the empirical pulse does not exactly follow the envelope of our analytic pulse, but major features of the shape are the same.

Finally, we expect some change in the envelope as a function of ground electrical parameters, conductivity and permittivity. We found virtually no difference at all in the shape of the envelope for horizontally polarized pulses when we varied over reasonable values expected of the ground. Larger, but still very small differences are apparent for vertically polarized pulses. Differences are too small to be clearly seen on a plot.

Figure 10. Antenna gain of wide bandwidth pulse waveform and narrow bandwidth signal.

Figure 11. Engagement envelope.

Figure 12. Comparison of engagement envelopes between directional and omni-directional antennas.

Figure 13. Comparison of engagement envelope for three different transmitter heights.

Figure 14. Comparison of engagement envelope for the analytic pulse and the empirical pulse.

Figure 15. Time waveform of empirical pulse from Ref. 1.

Figure 16. FFT amplitude of empirical pulse from Ref. 1.

Thus, exact details of the engagement envelope depend upon the shape of the time waveform, transmitter height, antenna radiation pattern, polarization of the pulse and the local values of ground electrical parameters. Of these variables we find greatest sensitivity of the

envelope shape to transmitter height, antenna radiation pattern and pulse polarization. Only small changes are apparent when varying the video pulse waveform and local ground electrical parameters.

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