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TIME-DOMAIN SIMULATION TECHNIQUE FOR ANTENNA TRANSIENT RADIATION, RECEPTION AND SCATTERING

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INTRODUCTION

This paper gives an insight on some features of transient electromagnetic events related to antenna and scattering problems involving the classical aspects of transient electrodynamics and engineering issues. Such properties like near-field range effects, peculiarities of transient antenna in radiation, reception and scattering modes and others, which are not considered enough in literature, will be treated here. Reaching this goal rigorous and asymptotic analytical bounds for linear and wire-grid modeled antennas will be introduced.

There are a variety of intuitively evident definitions here like pulse, ultra-wide band (UWB), transient, non-sinusoidal, non-stationary electrodynamics. Generally those phenomena can be treated from the point of view of energy beams (Zialkowski, 1992) as well as with its time history (Smith, 1997) or time-harmonic presentation. However inherent distortion of signal waveform is principal moment for electromagnetic pulse (EMP) simulators, high-resolution radars, spread-spectrum communications, electromagnetic compatibility (EMC) issue, VLSI and printed board design and so on. Generally each element of such system effects on signal waveform passing through it (Harmuth, 1990). Resulted signal is not rather simple replica of input waveform like in case of narrow-band or sinusoidal signal. Due to these reasons time-domain (TD) modeling of transient electromagnetic events is more preferable than frequency-domain (FD) techniques despite their mathematical equivalence due to the Fourier transform.

Traditionally numerical approaches to the transient electromagnetic problems are applied like FD method of moments with the next Fourier transformation or FDTD (Taflove, 1995). Also Baum (1965, 1971) developed analytical approaches with the Laplace transform for some asymptotic cases. Generally numeric studies, mostly applied, have principal drawback followed from sufficient programming and computing efforts. Finally the physical meaning of the most numerical solutions is not initially evident. Therefore we developed simple mathematical models, which enable numerical simulations with universal mathematical software like Maple, Mathcad, Matlab etc. The result of such simulations will illustrate the major points of our study.

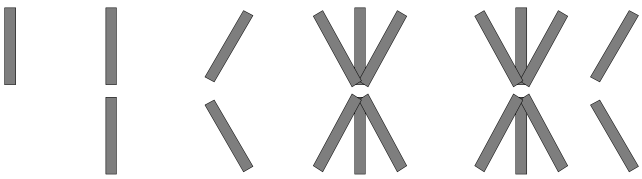
BASIC RESEARCH APPROACHES

All known analytical approaches and techniques (Smith, 1996; Martin *et al*, 1999; Shivinski et al, 1997) are based mostly on: i) far-filed asymptotic solutions; ii) using of first time derivative of exciting signal for radiated field characterization; iii) analysis of electrically short and geometrically simple antennas; iv) consideration of transient antennas in transmitting mode.

Sometimes far-field asymptotic solutions may be enough for such applications like wireless and radar systems, while other fields like EMC aspects of VLSI and high-speed printed circuit design, subsurface probing radar etc. demand more deep glance on near-field transient phenomena. Also it valuable involve in exploration, beside canonical structure like monopole and center-fed dipole, other antennas including biconical, V-shape, bow-tie, TEM-horn antennas. Those antennas are schematically shown with their wire-grid models in figure 1a. Analysis of such antenna structures in transmitting, receiving and scattering modes is practically important too.

Modes of antenna excitation resulted from its edge loading (Boryssenko and Tarasuk, 1999) should be carefully treated, figure 1b. Please note that number of pulse passing along antenna can be connected with number of time derivatives affected on initial exciting signal discussed by Ziolkowski (1992). This can be done explicitly for electrically short antennas and far-filed range operation while finite length antennas and not far-range operation is characterized by quite different, rather not simple, signal transformations.

Our primary goal in the presented study is straightforward expressions for characterization effects in mentioned above antennas and their operations modes. A relatively simple mathematical technique is developed here. Finally minimal programming efforts with Matlab, Maple, Mathcad are required for simulation to receive numerical results with productive physical meaning.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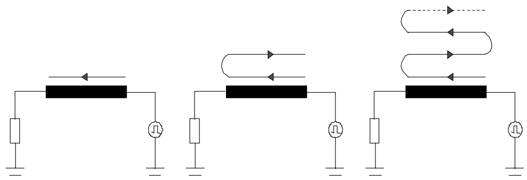
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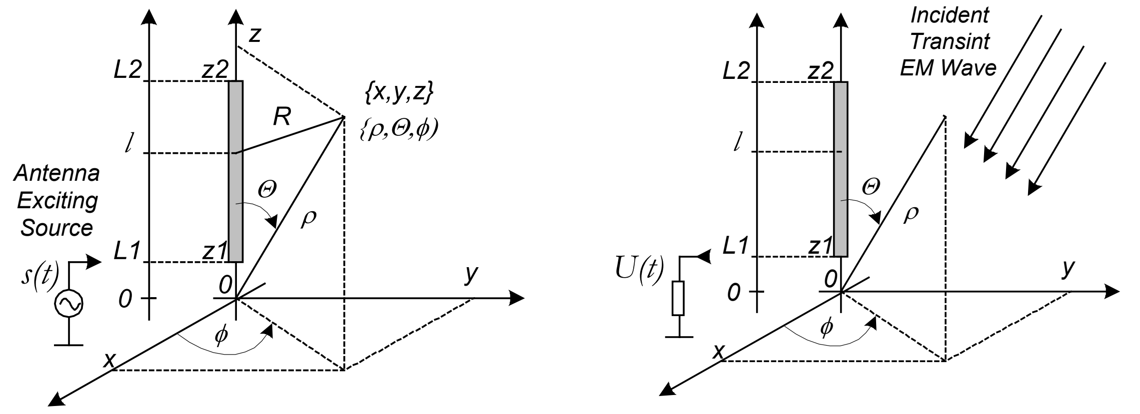
Figure 1. Transient antennas: (a) geometrical set of wire-grid antenna structures originated from monopole; (b) excitation modes depended on antenna edge matching (single-, double- and multiple current passing).

GENERAL VECTOR ANALYTICAL SOLUTIONS

We start our exploration from a simple case of radiated monopole by introducing, as usually (Baum,; Martin *et al*, 1999), the vector magnetic potential. That vector has for linear radiator, figure 2a, only tangential, z-axis, nonzero component (1) with respect to the observation point (2) in the given coordinates. The corresponding magnetic (3) and electric (4) vector fields are followed from Maxwell's equations (Franceschetti, 1997).

$$A_Z = \frac{\mu_0}{4\pi}\int_{z1}^{z2} \frac{S(t-(R+q)/c)}{R}\,dq \quad (1) \qquad R \equiv R(\vec{r},q) = \sqrt{x^2+y^2+(z-q-z_1)^2} \quad \vec{r} = \{x,y,z\} \quad (2)$$

$$\vec{H} = \frac{1}{\mu_0}\nabla\times\vec{A} \quad (3) \qquad \vec{E} = \frac{1}{\varepsilon_0}\cdot\int\left[\nabla\times\vec{H}\right]\cdot dt \quad (4)$$



a) b)

Figure 2. Radiating (a) and receiving (b) monopole in free space

Let note that we do not consider here the scalar potential function and the result of the Lorentz gauge application is included in (4). Also we do not study in detail antenna excitation that is specific boundary problem but assume that waveform of current in antenna is same as initial one (Martin *et al*, 1999). At this point the expressions (1)-(4) can directly transformed in numerically effective Maple code (Boryssenko, 2000) by using ramp-function approximation for antenna current proposed by Thomas *et al*, 1987. This approach is based on the Maple enhanced opportunities in symbolic computations. Results received in such mode are demonstrated later in this paper for illustration.

We developed also here for the problem in figure 2a other analysis technique based on analytical transformations of (1)-(4). Many researchers (Baum, 1971; Smith, 1997; Martin *et al*, 1999) have did same before. But we will study numerically the complete range of solutions, not only far-field asymptotic. Following this way one can receive after mathematical manipulations formulas for the magnetic (5) and electric fields (6) in the Cartesian coordinates. Related expressions like (7) and (8) give integro-differential operators applied to the original antenna exciting waveform. Such operators are more general than the slant transform (Shivinski *et al*, 1997) and define the waveform transformation more exactly than time differentiation (Ziolkowski, 1992).

$$\begin{bmatrix} Hx \\ Hy \\ Hz \end{bmatrix}(\vec{r},t) = \begin{bmatrix} -y & 0 & 0 \\ 0 & -x & 0 \\ 0 & 0 & 0 \end{bmatrix} \cdot \begin{bmatrix} F(\vec{r},t;z1,z2;s) \\ F(\vec{r},t;z1,z2;s) \\ 0 \end{bmatrix} \quad (5) \qquad \begin{bmatrix} Ex \\ Ey \\ Ez \end{bmatrix}(\vec{r},t) = \begin{bmatrix} -y & 0 & 0 \\ 0 & -x & 0 \\ 0 & 0 & 1 \end{bmatrix} \cdot \begin{bmatrix} G(\vec{r},t;z1,z2;s) \\ G(\vec{r},t;z1,z2;s) \\ H(\vec{r},t;z1,z2;s) \end{bmatrix} \quad (6)$$

$$F(\vec{r},t) = \frac{1}{4\pi\mu}\int_{z1}^{z2}\left(\frac{1}{v}\cdot\frac{S_\tau^{/}}{R^2}+\frac{S_\tau}{R^3}\right)dq \quad (7) \qquad H(\vec{r},t) = \frac{1}{4\pi\mu_0\varepsilon_0}\int_{z1}^{z2}\left(-\frac{\rho}{v^2}\cdot\frac{S_\tau^{/}}{R^2}+\frac{\gamma}{v}\frac{S_\tau}{R^2}+\frac{\gamma}{R^3}\int S_\tau d\tau\right)dq \quad (8)$$

We introduced also additional definitions (9) including slow-wave factor ξ to modify signal velocity in antenna and a retarded time τ with respect to observation point given by R quantity and antenna point, q, which is integration variable in (6)-(7):

$$v = \xi \cdot c \quad \gamma = 2 - 3\cdot\rho \quad \rho = (x^2+y^2)/R^2 \quad S_\tau = S(\tau) \quad S_\tau^{/} = dS_\tau \big/ d\tau \quad \tau = t-(R+q)/v) \quad (9)$$

Introducing now in (5)-(9) a slow-wave factor, ξ, and latter in (10) an attenuation factors, α, are important for studying special class of resistively loaded antennas to control antenna waveform by maintaining its single passing excitation, figure 1b. Next the current (10) in antenna, figure 2a, should be determined for its arbitrary excitation. One can do this by considering equivalent transmission line model with standing wave in straightforward mode or by incorporating the standard analysis technique with the Laplace transform.

$$S_\tau \equiv f(t,q,z1,z2,\Gamma1,\Gamma2,\xi,\alpha)=\sum_{i=0}^{N}\Gamma_1^{\left[\frac{i}{2}\right]}\cdot\Gamma_2^{\left[\frac{i+1}{2}\right]}\cdot U\left\{t-\frac{q-z1}{v}-2\cdot\left[\frac{i+1}{2}\right]\cdot\frac{z2-q}{v}-2\cdot\left[\frac{i}{2}\right]\cdot\frac{q-z1}{v}\right\}\cdot$$
$$\exp\left\{-\alpha\left((q-z1)+2\cdot\left[\frac{i+1}{2}\right]\cdot(z2-q)+2\cdot\left[\frac{i}{2}\right]\cdot(q-z1)\right\}\qquad(10)$$

The reflection coefficients $\Gamma_{1,2}$ characterize antenna edge loading and [...] is a common floor operator, which gives the number of pulse reelections from both antenna ends.

Receiving antenna, figure 2b, can be considered with simple boundary condition for conductive monopole illuminated by incident arbitrary, not only plane, electromagnetic wave where tangential component of electric field is taken into consideration. In contrast to dual radiating problem, figure 2a, we have distributed antenna excitation in this case and final integrating along antenna gives the induced current (11) with respect to the point, p $(z1 \le p \le z2)$, on antenna where this current is evaluated.

$$I(p,t)=\int_{z1}^{p} I1(q,p,t)dq-\int_{p}^{z2} I2(q,p,t)dp \qquad (11) \qquad I1,2\equiv f\{q,p,t;\Gamma1,\Gamma2,\alpha,\xi;E_{\tan g}(t,q)\} \qquad (11a)$$

The complete mathematical structure of (11a) is similar by main features to that (10) and not shown here due to limitations in paper space. One can use the expressions (5)-(11) for numerical simulation with Mathcad, Maple etc. It can be done with numerical integration and differentiation. Some obtained in that way results are shown and discussed later. Approximate, enough frequently for design practice, models for other antenna structures like those in figure 1a can be developed by using linear superposition of vector fields produced by each wire-grid monopole element, which composes entire antenna.

FAR-FIELD RANGE ASYMPTOTIC

One can obtain the far-field region asymptotic by limiting transition $R \to \infty$ (Baum, 1968) in (7)-(8). It has simple mathematical presentation in the spherical coordinates, figure 2. In this way the elevation electric component of the radiated monopole field with single passing excitation (figure 1b) is expressed with (6).

$$E_\Theta(\rho,\Theta,t,La)\cong\frac{\sin\Theta}{1-\cos\Theta}\cdot\left\{s(t-\frac{\rho}{c})-s(t-\frac{\rho}{c}-\frac{La}{c}(1-\cos\Theta))\right\} \qquad (12)$$

Similarly, a current (voltage) at a load of monopole receiving antenna, figure 2b, exited in single passing mode by incident plane electromagnetic wave with waveform $E(t)$, is determined with (13).

$$U(t,\Theta,La)\cong\frac{\sin\Theta}{1-\cos\Theta}\cdot\{e(t-La/c)-e(t-La/c\cdot\cos\Theta)\} \quad (13) \qquad e(t)=\int E(t)dt \quad (13a)$$

Please note that expressions (12) and (13) are similar by some general features but quite different concerning the transformation of primary waveform of exciting signal due to integration (13a). Some differences between transmitting and receiving antennas are summarized in Table 1 where two auxiliary functions (14) and (15) are used:

$$T(\Theta)=\sin\Theta/(1-\cos\Theta) \qquad (14) \qquad \dot{F}(j\omega,\Theta)=T(\Theta)[1-\exp\{-j\varpi La/c\cdot(1-\cos\Theta)\}] \qquad (15)$$

for the pattern factor (14) and the complex pattern function (15) of traveling-wave linear antenna with sinusoidal excitation. $\dot{S}s(j\varpi)$ and $\dot{S}_E(j\varpi)$ are complex spectra yielded from the Fourier transform of the exciting signals $s(t)$ and $E(t)$. Table 1 illustrates also connection of antenna representation in TD and FD, as well as behavior of electrically short antennas used ordinary as a simplest field probe.

Table 1. Comparison of features of transmitting and receiving monopole antenna in time-frequency domain.

	Transmitting Monopole Far-region Waveform	**Receiving Monopole** Antenna Load Voltage
Time Domain	$\sim T(\Theta)\cdot\left\{s(t)-s(t-\frac{La}{c}(1-\cos\Theta))\right\}$	$\sim T(\Theta)\cdot\left\{e(t)-e(t-\frac{La}{c}(1-\cos\Theta))\right\}$
Frequency Domain	$\sim \dot{F}(i\varpi,\Theta)\cdot\dot{S}\,s(j\varpi)$	$\sim \dfrac{\dot{F}(j\varpi,\Theta)\cdot\dot{S}_E(j\varpi)}{j\varpi}$
Short Probe	$\sim \sin(\Theta)\cdot s'(t)$	$\sim \sin(\Theta)\cdot E(t)$

SOME SIMULATION RESULTS AND THEIR DISCUSSION

Near-Field Range Effect

Without any loss of generality we consider simple case of monopole antenna with single passing excitation by the Gauss-shape pulse of 1-nanosecond (ns) duration. These enables receiving clear physical picture with principal features common for all antennas and not complicated due more complex geometry or excitation. Results of numerical simulations with Maple and Mathcad are shown in figure 3 and 4.

Figure 3 with data computed with Mathcad illustrates the near-field range effect when space observation point is chosen at different distances from antenna. One can observe asymmetric waveform of radiated field near antenna due to dc and low-frequency spectral component. Especially the presence or not of dc component can be used to characterize antenna operation range. The traditional Rayleigh criterion valid for sinusoidal signal can not be applied here due to broadband radiation (Zialkowski, 1992). We can introduce some criteria from the physical point of view that far-range field should demonstrate properties of an outward spherical waves. Such properties involve the amplitude change inversely proportional to the radial distance R. Also the ratio of the amplitude of principal electrical component to that of magnetic in free space must equal to 120π etc. (Boryssenko, 2000).

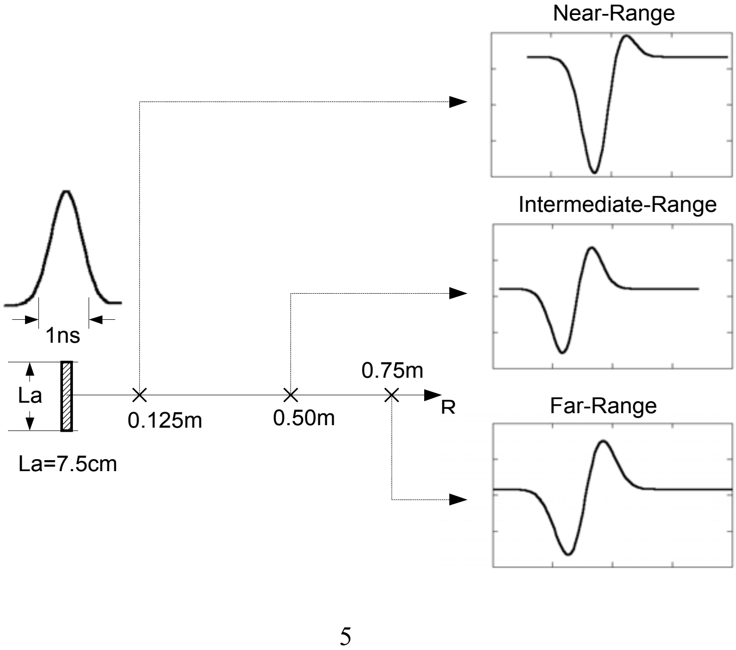
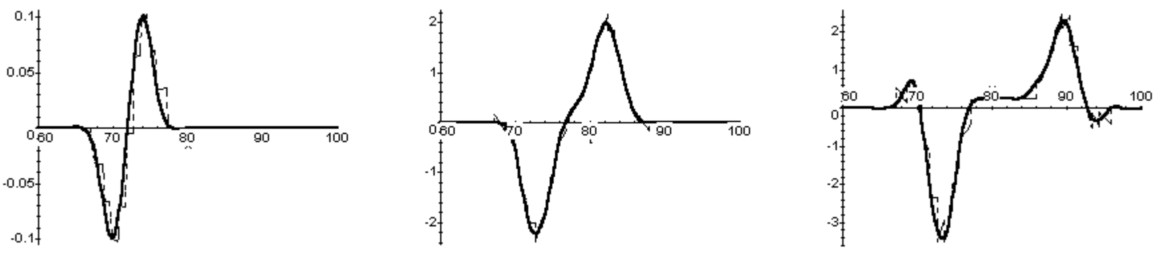


Figure 3. Matchad computed radiated field of transient monopole at different distance position.

The curves in Figure 4 has been obtained by computing with Maple



a) b) c)

Figure 4. Maple simulated waveform of monopole radiated field for antennas of different length: (a) 0.05m, (b) 3m, (c) 5m and same excitation with 1-ns Gauss pulse.

Other illustration of the near-range effect in transient antenna is given in figure 4 for the observation point with elevation angle equals 90^0, figure 2a. These data are computed with Maple (Boryssenko, 2000) for the case with same distance from antenna to the observation point but antenna length is different. Generally discrimination of antenna near/far field properties depends from ratio of antenna physical length and spatial length of exciting pulse. Notice in case of more complex antenna excitation, different from simple single passing or travelling wave of current (figure 1b) that exciting signal has a long time history. The last can results in more expansion in space of near field radiation as pointed out before by Ziolkowski (1992).

Filter Network Presentation

For far-field range system formed by pair of center-fed, pulse-driven, linear dipole elements (one terminated to transmitter and other to receiver) Zialkowski (1992) introduced the equivalent network presentation where main feature is a specific number of time derivatives applied to input waveform. So far we concentrated on the near-field range effects in antenna we present transient radio channel model with three same antennas operating in transmitting, scattering and receiving modes without any limitations concerning near or far range, antenna type and its excitation. Such generalized system is shown in figure 5 and can be simulated with presented above models. Each antenna in figure 5 is characterized by its own transformation operator A1,2,3.

For example, figure 6 demonstrates results of Mathcad simulation with respect to the notations in figure 5. We have in this case three center-fed dipole antennas with double passing excitation and the effect of near-field range is clear visible in this figure.

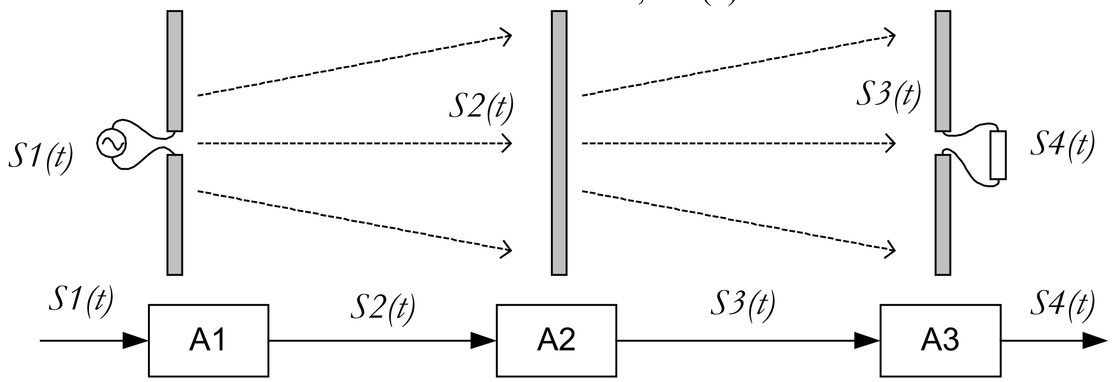


Figure 5. Network presentation of signal transformation between it is consequently passed between transmitting – scattering – receiving center-fed dipole antennas.

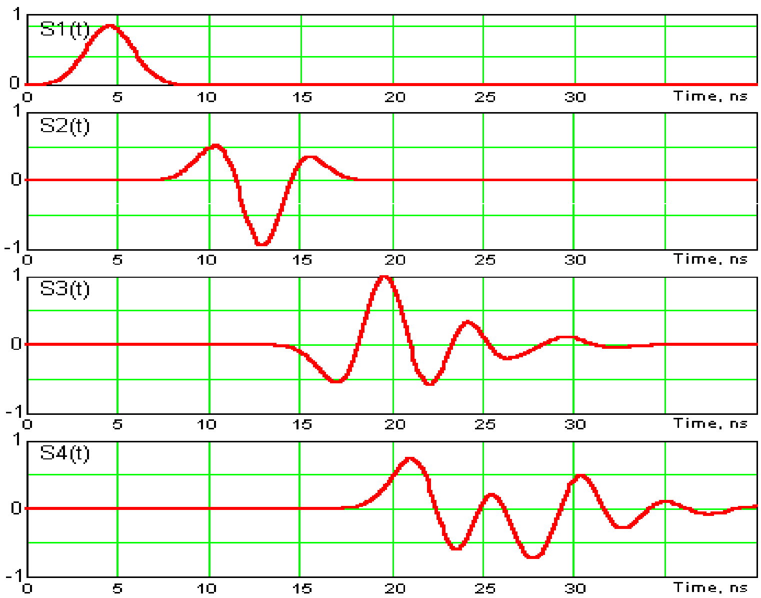
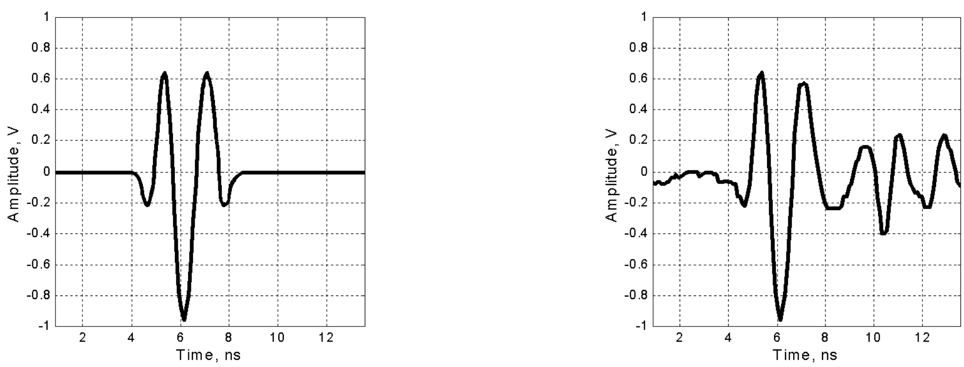


Figure 6. Mathcad simulated waveform transformation with near-field effects for the system in figure 5.

Figure 7 shows cross-link effect for a pair of closely spaced transmitting and receiving bow-tie antennas. Simulated waveform data, figure 7a, has been computed with Matlab wire-grid model while experimentally measured one is given in figure 7b. Both, computed and measured, curves have good agreement in early time behavior but different late time history due to effects in real system do not included in the presented models like non-ideal broadband antenna matching etc.



a) b)

Figure 7. Cross-link signal between two bow-tie antennas: (a) simulated with Matlab and (b) measured.

CONCLUSION

Time-domain interpretation of non-stationary electromagnetic events, including near-range effects, which is not enough shown in literature, is discussed here. Generally the results obtained with time domain simulations demonstrate more physical meaning and are more clearly dependent on the influence of problem parameters than those in frequency-domain.

All presented above regularities are important for UWB or transient antenna design. Inherent transformation of signal waveform passing through components of UWB system especially its antennas should be carefully treated. The last is ordinary achieved with complex numerical computing. In this sense the benefits of proposed physically meaningful straightforward technique with easy Matlab, Maple etc. simulation seems valuable for research and engineering practice as well for academic goals. Generally the presented above approach allows the next steps in research when time-domain antenna arrays can be considered that are in progress now.

REFERENCES

Baum, C., 1968, Some Limiting Low-Frequency Characteristics of a Pulse-Radiating Antenna, *Sensor and Simulation Notes*, 65.

Baum, C., 1971, Some Characteristics of Electric and Magnetic Dipole Antennas for Radiating Transient Pulses, *Sensor and Simulation Notes*, 125.

Boryssenko, A. A., Tarasuk, V. M., 1999, Ultra-Wide Band Antennas for Subsurface Radar Applications, in: *Proceedings of Antenna Application Symposium*, Monticello, IL, 478.

Boryssenko, A. A., 2000, Time-Domain Vector Representation of Monopole Transient Electromagnetic Radiation by Using Maple Software, *Submitted to IEEE Antenna and Propagation Magazine*.

Franceschetti, G., 1997, *Electromagnetics: Theory, Techniques, and Engineering Paradigms*, Plenum Press, New York.

Harmuth, H. F., 1990, *Radiation of Nonsinusoidal Electromagnetic Waves*, Academic Press, Boston.

Martin, G. R., Rubio, A. B., Gonzalez, S. G., 1999, Some Thought about Transient Radiation by Stright Thin Wires, *IEEE Antennas and Propagation Magazine*, 41: 24.

Shivinski, A., Heyman, E., Kastner R., 1997, Antenna Characterization in the Time Domain, *IEEE Trans. on Antenna and Propagation*, 45:1140.

Smith, G., 1997, *An Introduction to Classical Electromagnetic Radiation*, Cambridge University Press, Cambridge.

Taflove, A., 1995, *Computation Electrodynamics – The Finite Difference Time-Domain Method*, Artech House, Boston.

Thomas, D. E., Hutchins, R. L., Wiggins III, Nickei, F., S., 1987, Time-Domain Calculation of Radiated Fields, in: *AP-S International Symposium Digest: Antennas and Propagation*, Blacksburg, VA, 954.

Ziolkowski, R.W., 1992, Properties of Electromagnetic Beams Generated by Ultra-Wide Bandwidth Pulse-Driven Arrays, *IEEE Trans. on Antenna and Propagation*, 40:888.