Modeling of RF signals passing through the near-ground trace with terrain relief reflections and troposphere scattering

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Abstract. In this paper we suggest the new approach to modeling RF signals being distorted by the ground propagation environment via impulse response of ground and troposphere channels using the energy delay profile. Representation of the impulse response correlation function using the energy delay profile and the correlation function of impulse response samples is the essense of the approach. While modeling the signal, this representation allows us to take into account the statistical dependence between the impulse response samples (that is a characteristic of short ground propagation traces). The results of output signals modeling are compatible with the experimental results.

1. Introduction

Algorithms of processing RF signals being distorted by random surface irregularities and terrain relief elements of near-ground traces are usually tested by digital modeling [1-5].

The fundamentals of RF signal modeling in a temporal domain lie in convolution of the impulse response from the linear system (that describes propagation environment properties) and the emitted signal [1, 5-9]. The use of the impulse response in modeling, realizations is formed using its statistical definition. For near-ground traces, where the RF wave is reflected mostly by terrain relief elements (like buildings, forest area etc.), the impulse response realizations are formed as a sum of delayed delta pulses $a(t\text{-}\tau_i)\delta(t\text{-}\tau_i)$ with random values of $a(t\text{-}\tau_i)$ and τ_i [10]. For closed near-ground traces with RF wave scattering by small-scale irregularities or a forest edge, the impulse response is described by energy delay profile $E(\tau)$, that results from averaging squared impulse responses for the specific near-ground propagation trace [10, 11]. As it demonstrated in many papers, the energy delay profile is defined by propagation environment properties, receiving equipment performance and a relative antenna orientation of an emitting source and areceiving unit.

For achieving the energy delay profile via experimental tests, large financial expenses are needed. That is why, the task of achieving realizations of the propagation traces impulse response using the energy delay profile taken from publications is a subject of interest. There are some papers where the energy delay profile is used for modeling signal depression in an ionosphere radio channel [11]. However, there are no approaches developed to form impulse response realizations for near-ground traces under the conditions of frequency-selective depressions.

In this paper, we consider digital modeling of realizations for the RF signal passing through the near-ground propagation trace in a temporal domain using the energy delay profile for near-ground traces under the conditions of frequency-selective depressions.

2. Modeling the RF signal passing through the near-ground trace

It is known that the impulse response of the propagation trace is a real random temporal function and it describes the linear system impulse response to a delta impulse impact [10]. Distortion of the emitted narrow-band signal is significantly influenced by the radio channel transfer function in a frequency band around the central frequency of f_0 [1, 6, 7]. For the truncated radio channel transfer function that is zero outside a frequency band of the emitted narrow-band signal let us consider the equivalent impulse response of the propagation trace [10]:

$$h_e(\tau)=\mathrm{Re}\left\{H(\tau)\exp\left[j\varphi(\tau)\right]\exp\left[j2\pi f_0\tau\right]\right\}=\mathrm{Re}\left\{\left[h_c(\tau)+jh_s(\tau)\right]\exp\left[j2\pi f_0\tau\right]\right\} \quad (1)$$

Equivalent impulse response $h_e(\tau)$ is related with energy delay profile $E(\tau)$ of the radio channel with independent scatters as the following [8, 17]:

$$R_h(\tau,\Delta\tau)=M\left[\dot{h}_{ý\hat{e}}(\tau)\dot{h}^{*}_{ý\hat{e}}(\tau+\Delta\tau)\right]=E(\tau)\delta(\tau+\Delta\tau) \quad (2)$$

As is shown by (2), the impulse response of the propagation trace presents a non-stationary random process on its existence interval of T_n. In [10, 11], quadrature components of equivalent impulse response characteristic $h_e(\tau)$ of the radio channel with independent scatters are described by a zero-mean white Gaussian noise with a dispersion that changes due to duration of impulse response. Let us consider a discrete representation. While modeling realizations of the near-ground propagation trace impulse response, quadrature components $h_e(\tau)$ are formed using the energy delay profile as follows:

$$\begin{aligned} h_c(u)&=E^{1/2}(u)\xi_1(u),\\ h_s(u)&=E^{1/2}(u)\xi_2(u), \end{aligned} \quad (3)$$

where u is aan index of the impulse response sample, $u = 1\ldots N$; $N = T_n/\Delta t$ is a total number of samples in impulse response; $\xi_1(u)$ and $\xi_2(u)$ are samples of the zero-mean white Gaussian noise with identity dispersion, while processes $\xi_1(u)$ and $\xi_2(u)$ are being uncorrelated; Δt is a discretization step which is chosen according to the sampling theorem.

Assuming the emitted radio signal to be a narrow-band one, $S_{in}(t)=\mathrm{Re}\left\{A(t)\exp\left[j\varphi_s(t)\right]\exp\left(j2\pi f_0 t\right)\right\}=X_{in}(t)+jY_{in}(t)$, for modeling the RF signal passing through the near-ground propagation trace, we will use the approach of [11] with respect of (1), (3):

$$\begin{aligned} S_{out}(k)&=\mathrm{Re}\left(\left\{\begin{aligned}&\Delta t\sum_{u=1}^{N}\left[E^{1/2}(u)\xi_1(u)X_{in}(k-u)-E^{1/2}(u)\xi_2(u)Y_{in}(k-u)\right]\\ &+j\Delta t\sum_{u=1}^{N}\left[E^{1/2}(u)\xi_1(u)Y_{in}(k-u)+E^{1/2}(u)\xi_2(u)X_{in}(k-u)\right]\end{aligned}\right\}\exp\left(j2\pi f_0 k\Delta t\right)\right)=\\ &=\mathrm{Re}\left\{\left[X_{out}(k)+jY_{out}(k)\right]\exp\left(j2\pi f_0 t\right)\right\}, \end{aligned} \quad (4)$$

where k is an index of the signal sample; $X_{out}(k)$ and $Y_{out}(k)$ are quadrate components of the RF signal passing through the near-ground propagation trace.

To take into account how the linear receiving flow influenced the RF signal, we should implement the further filtering to quadrature components $X_{out}(k)$ and $Y_{out}(k)$ as follows:

$$S_{outr}(k)=\mathrm{Re}\left\{\left[\Delta t\sum_{z=1}^{N}h_R(z)X_{out}(k-z)+j\Delta t\sum_{z=1}^{N}h_R(z)Y_{out}(k-z)\right]\exp\left(j2\pi f_0 k\Delta t\right)\right\}, \quad (5)$$

where $h_R(z)$ is a sample of the linear receiving flow impulse response.

Samples of the impulse response can be correlated [9]. To consider the case of correlation between impulse response samples, let us list the following autocorrelation function:

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$$R_h(\tau,\Delta\tau) = M\left[h(\tau)h(\tau+\Delta\tau)\right] = E(\tau)R_{Eh}(\Delta\tau) \quad (6)$$

where $E(\tau)$ is an energy delay profile; $R_{Eh}(\Delta\tau)$ is a correlation function for impulse response samples.

For obtaining correlated samples of the impulse response, we will use the well-known approach [11] that involves filtering of random process $\xi(u)$:

$$\xi^*(k) = \Delta t \sum_{v=1}^{N} h_{fR}(v)\xi(k-v) \quad (7)$$

where $h_{fR}(v)$ is a filter impulse response.

The formula of the impulse response depends on the formula of correlation function $R_{Eh}(v)$. Among other things, the exponential correlation function corresponds to the transfer function of the high pass RC-filter.

3. The results of modeling the RF signal passing through the near-ground propagation trace

Let us consider the results of modeling RF signal realizations. Let us assume that the emitted signal is a square signal with central frequency f_0 = 3 GHz, duration of 100 ns, amplitude A = 1 V and a random initial phase. For describing the near-ground propagation trace with the RF wave scattered mostly by small-scale troposphere irregularities, let us approximate the energy delay profile with the following relation: $E(\tau) = \tau \exp(-a\,\tau)$. A discretization step is Δt = 0.1 ns. The pass band of the receiving flow is 1 MHz.

Examples of RF signal realizations achieved via digital modeling using (4) and (5) are shown in Figures 1 and 2 for different energy delay profile durations $E(\tau)$. The notations of Figures 1 and 2 are: $|S_{in}(t)|$ is an emitted signal envelope, $|S_{out}(t)|$ is realization of a signal passing through the near-ground propagation trace, $|S_{outr}(t)|$ is an envelope realization of the signal passing through the near-ground propagation trace and the linear receiving flow.

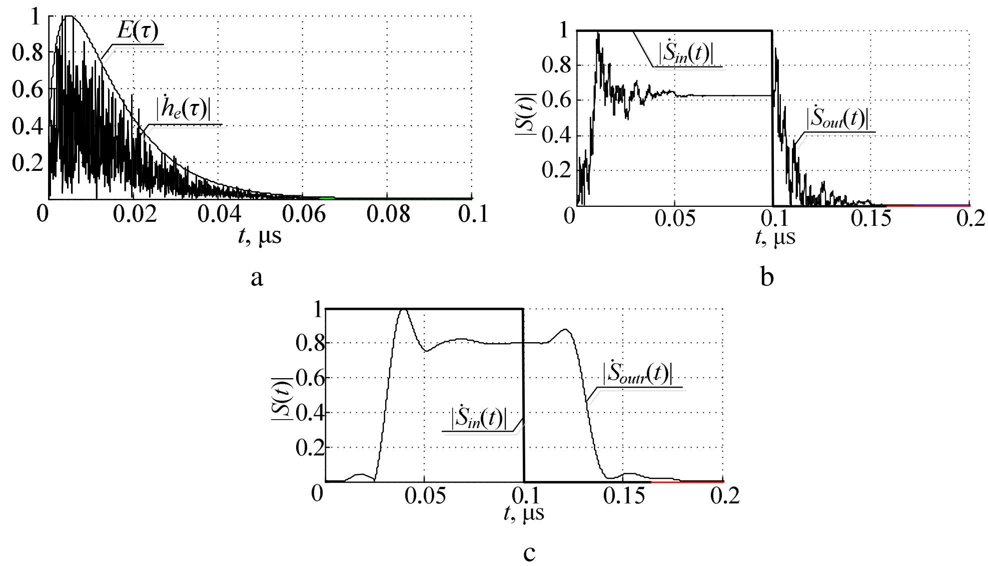

Figure 1. The results of modeling realizations of equivalent impulse response $h_e(\tau)$ and channel distorted RF signals, $a = 200 \cdot 10^6$ s^{-1}: a – normalized energy delay profile $E(\tau)$ and normalized realization of the impulse response; b – normalized envelope realization of the emitted pulse RF signal and a normalized envelope of the RF signal passing through the near-ground propagation trace; c – normalized envelopes of the emitted pulse RF signal and the RF signal passing through the near-ground propagation trace and the receiving flow.

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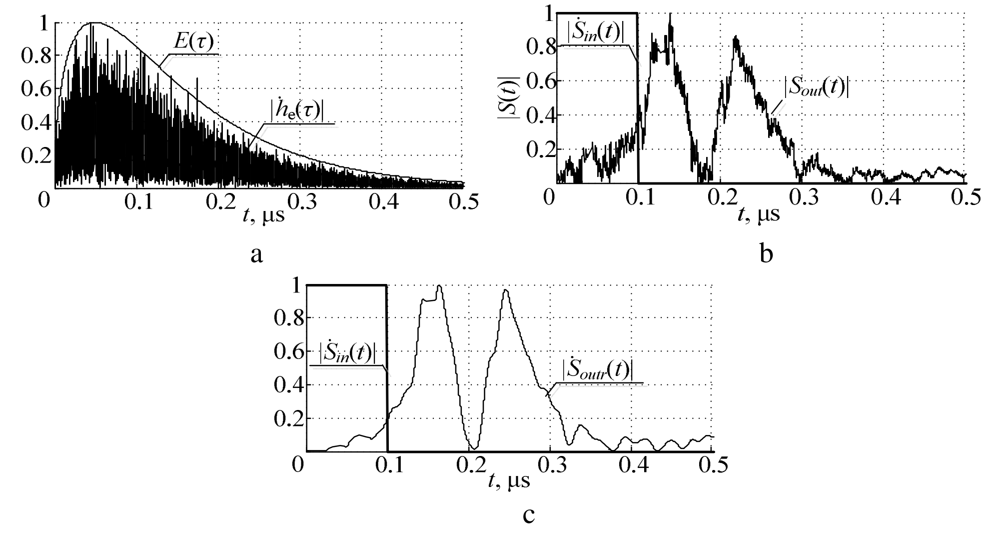


Figure 2. The results of modeling realizations of equivalent impulse response $h_e(\tau)$ and channel distorted RF signals, $a = 20{\cdot}10^6$ s^{-1}: a – normalized energy delay profile $E(\tau)$ and normalized realization of the impulse response; b – normalized envelope realization of the emitted pulse RF signal and a normalized envelope of the RF signal passing the through near-ground propagation trace; c – normalized envelopes of the emitted pulse RF signal and the RF signal passing through the near-ground propagation trace and the receiving flow.

Multiple results of modeling show that envelopes of distorted square pulses change drastically not only due to the shape or duration of the energy delay profile, but also due to realization of the random process.

It is necessary to note that from envelope realizations of the RF signal at the channel output (see figure 2), we can qualitatively determine two peaks, which are observed due to the energy delay profile duration, which is much greater than the duration of a single pulse. Interpreting these peaks as two separate beams is wrong.

Let us consider the results of modeling RF signals with respect to correlation between impulse response samples. The results are shown in figures 3 and 4.

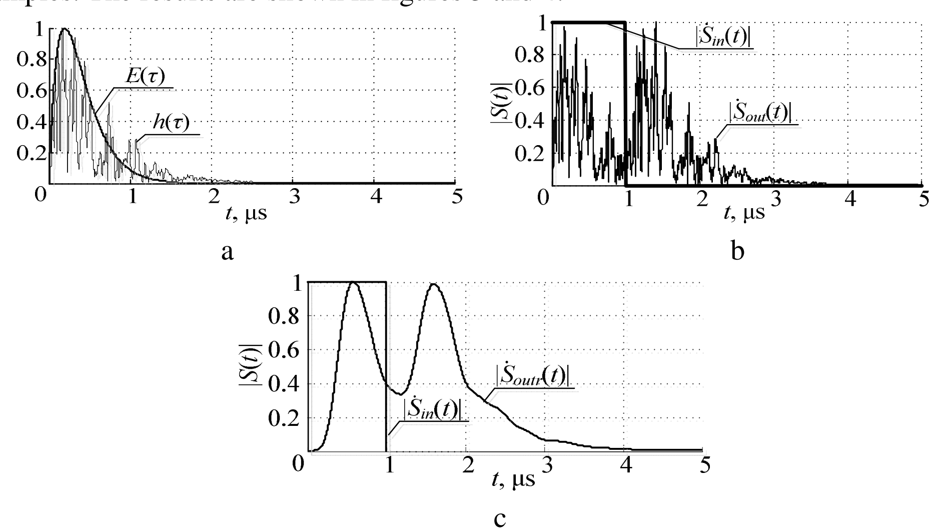


Figure 3. The results of modeling realizations of equivalent impulse response $h_e(\tau)$ and channel distorted RF signals, $a = 5{\cdot}10^6$ s^{-1}, $\tau_k = 50$ ns, the continuous scattering medium: a – normalized energy delay profile $E(\tau)$ and normalized realization of the impulse response; b – normalized envelope realization of emitted pulse RF signal and a normalized envelope of the RF signal

passing through the near-ground propagation trace; c – normalized envelopes of the emitted pulse RF signal and the RF signal passing through the near-ground propagation trace and the receiving flow.

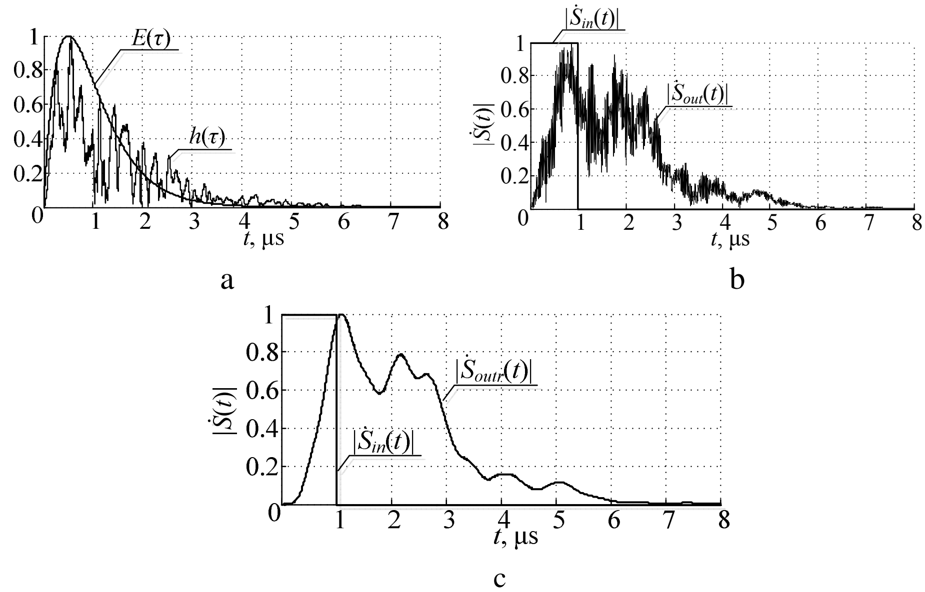
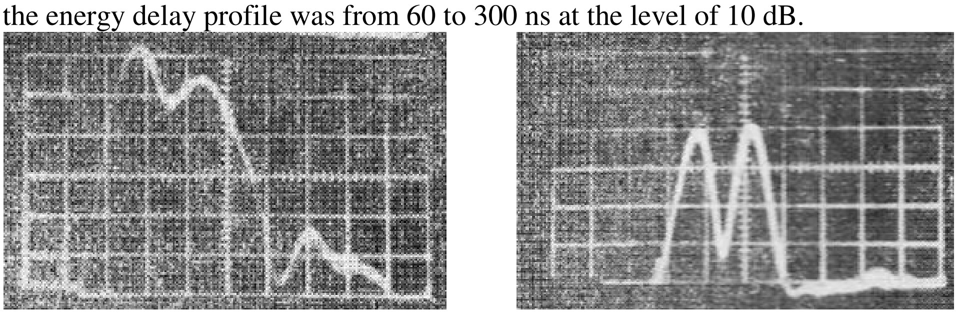


Figure 4. The results of modeling realizations of equivalent impulse response $h_e(\tau)$ and channel distorted RF signals, $a = 2 \cdot 10^6$ s^{-1}, $\tau_k = 80$ ns, the continuous scattering medium: a – normalized energy delay profile $E(\tau)$ and normalized realization of the impulse response; b – normalized envelope realization of the emitted pulse RF signal and a normalized envelope of the RF signal passing through the near-ground propagation trace; c – normalized envelopes of the emitted pulse RF signal and the RF signal passing through the near-ground propagation trace and the receiving flow.

Envelope realizations and the internal structure of the RF signal passing through the near-ground propagation trace or radio channel relate not only to the energy delay profile, but also to a correlation interval of impulse response samples. An increase of the correlation interval leads to smoothing realizations of the RF signal envelope, otherwise a decrease of the correlation interval leads to sharping realizations due to appearance of certain beams.

Realizations of RF signals in a 10 centimeter wave length range for the sea trace length of 220 km taken from [12] are shown in figure 5. The pilot signal duration in that experiment was 102 ns and the duration of the energy delay profile was from 60 to 300 ns at the level of 10 dB.



a b

Figure 5. Realizations of RF signal envelopes for the sea trace length of 220 km: a – pulse duration is 102 ns; b – pulse duration is 1000 ns.

4. Conclusion

In this paper, we proposed the approach to digital modeling of RF signals passing through the near-ground propagation trace using the given energy delay profile. This approach provides modeling of RF signals on near-ground traces with respect to correlation between impulse response samples. RF signal envelopes, obtained by modelling, resemble the experimental results. Results of the modelling of distorted RF signals drastically depend on the shape and duration of the energy delay profile.

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