Characterization and Simulation of HF Propagation in a realistic disturbed and horizontally inhomogeneous Ionosphere

Vadim E. Gherm and Nikolay N .Zernov,

Department of Radiophysics

University of St.Petersburg, St.Petersburg, Russia

Hal J. Strangeways,

School of Electronic and Electrical Engineering

University of Leeds, Leeds, U.K.

Wideband HF simulator

Current developments in HF (3 – 30 MHz) broadcasting and communications e.g DRM and the need for higher speed data links require the characterisation of the HF channel for digital signals and at wider bandwidths (10 kHz – 1 MHz) than previously employed.

Deficiencies of existing narrow band simulators

Narrow band HF simulators, e.g. the Watterson model are available, but are not adequate to characterise the wideband HF channel. The Watterson model is limited by:-
a fixed (i.e. no dispersion) delay for each ionospheric mode (e.g. 1 hop E, 1 hop F2, 2hop F2),

only a Gaussian distribution for the Doppler spread

only the low angle (and not the high angle) ray path

channels having time and frequency stationarity

Deficiencies of existing wide band simulators

- Although most of the these restrictions are overcome in the more recent Mastrangelo et al. wideband simulator model (based on the work of Vogler and Hoffmeyer), this model also has various disadvantages.

- It is empirically based and consequently requires a large number of input parameters for each propagation mode. These cannot be directly determined from the parameters of the transmission path and model ionosphere.

- The empirical models are based on a limited amount of data for an undisturbed ionosphere and it is rather questionable whether extrapolation to disturbed ionosphere conditions is valid.

Deficiencies of existing wide band simulators continued

- It is not clear what is the basis for the delay profile modelling which is the main difference from the Watterson model.

- The model assumes that the fading observed at intervals (“taps”) along the delay profile of a propagational mode is independent of fading at other taps but there is no supporting evidence for this.

- There is also implicitly the assumption that fading of amplitude and phase are independent.

- Doppler shift and Doppler spread should not be independently chosen variables for different propagational modes e.g. IF1, 1F2, 2F2.

New wideband HF simulator

- Thus a new wideband HF simulator has been constructed for communication/data links involving multipath ionospheric reflected paths e.g. 1E, 2F etc, for both o- and e- modes.

- It is based on a detailed physical (rather than empirical) model including both background and stochastic ionospheric components.

- It also includes the effect of the Earth's magnetic field both on propagation and the shape of the time-varying irregularities.

- A noise model which includes Gaussian and impulsive noise and interferers is included.

Methodology

In our simulator, the channel simulation for the multipath HF ionospheric sky wave random channel is based on the most general theory of HF wave propagation in the real fluctuating ionosphere.

The complex phase method (or modified Rytov's approximation) is employed. This accounts for the main effects of HF propagation in the disturbed ionosphere:-

- Ray bending due to the inhomogeneous background ionosphere
- Scattering by random ionospheric irregularities including diffraction by localised inhomogeneities
- The Earth's magnetic field is taken into account through the anisotropic spatial spectrum of the ionospheric turbulence
- The propagation paths are determined using a Nelder-Mead homing-in algorithm together with a 3D ray-tracing model which takes into account the effect of the geomagnetic field on the refractive index and also permits horizontal gradients of electron density to be included.

Simulation of random time series and statistical moments of the HF field

A random realisation of a pulsed signal propagated through the fluctuating ionosphere can be represented as the following Fourier integral in the frequency domain

$$E(\mathbf{r},t,\tau) = \sum_n \int_{-\infty}^{+\infty} P(\omega)\, T_n(\mathbf{r},\omega,t)\, R_n(\mathbf{r},\omega,t)\, e^{-i\omega\tau}\, d\omega \qquad (1)$$

E is the field at the point of observation **r**, represented by the sum **n** of propagating ionospheric modes;

P is the spectrum of the transmitted pulse;

$\mathbf{T_n}$ is the transfer function of the **n-**th mode in the background ionosphere;

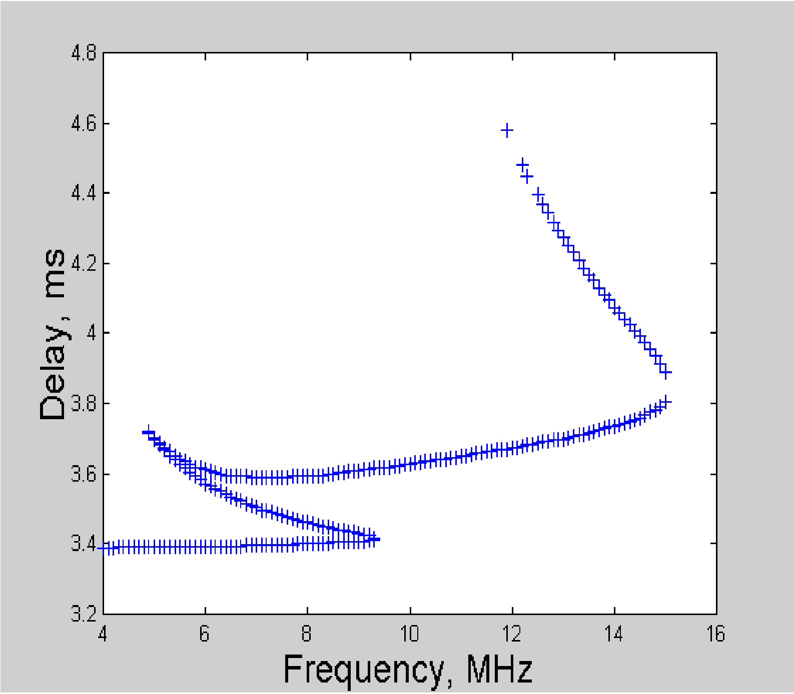
$\mathbf{R_n}$ are the random functions (also called phasors), which account for the effects of the ionospheric electron density fluctuations on each mode.

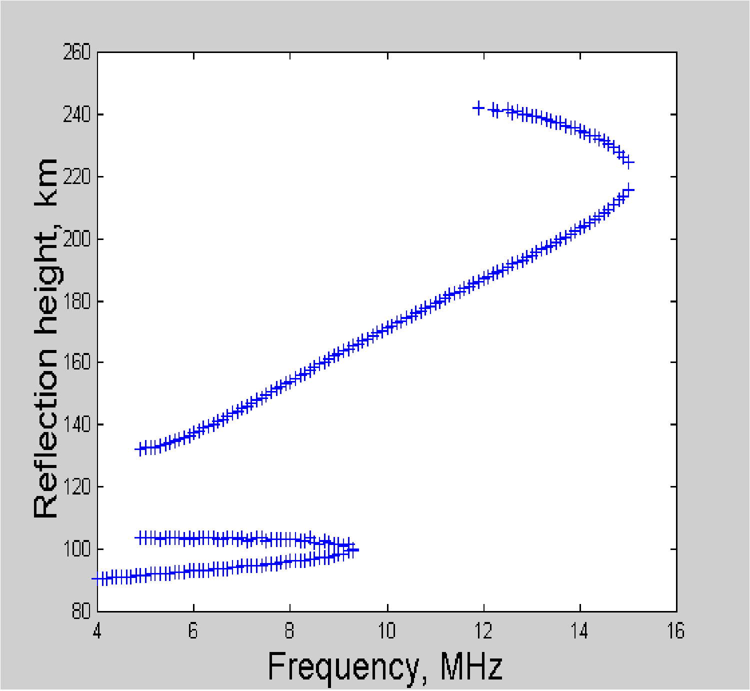
Employing (1), the statistical moments (e.g. scattering function) of the received signal **E** can be obtained and its random time series representation generated. To this end:

i) transfer functions $\mathbf{T_n}$ of each mode propagating in the background ionosphere should be constructed;

ii) statistical properties of random functions $\mathbf{R_n}$ (phasors) should be described.

To determine transfer functions $\mathbf{T}_n$, the Jones 3D ray-tracing code was further extended to enable solution of the homing-in problem and amplitude calculations. This enables determination of $\mathbf{T}_n$ for any given model of the 3D background ionosphere.



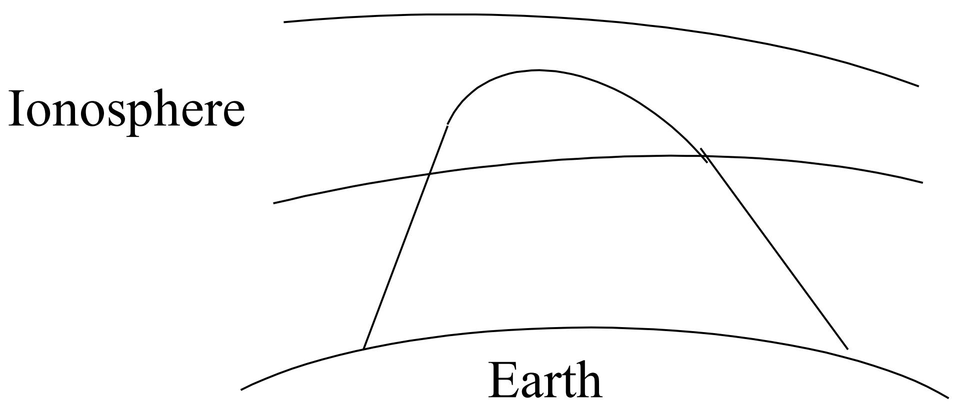


Solving the statistical problem for phasors $\mathbf{R_n}$ is the core point of the problem. It is considered in the approximation of the complex phase method.

The method is the extension of the classic Rytov's approximation to the case of the 3D inhomogeneous anisotropic background medium and the point source field. It works in terms of complex phases ψ_n

$$R_n = e^{\psi_n}, \qquad \psi_n = \chi_n + iS_n \tag{2}$$

Complex phases are represented by the appropriate integrals, written in ray-centred co-ordinates where the reference rays are constructed for an arbitrary 3D background ionosphere. For each ray-centred co-ordinate system, defined by a given reference ray, the appropriate complex phase is written in the Fresnel approximation for forward scattering.



$$\psi_1(s_0,0,0,) = \frac{k^2}{4\pi}\iiint ds\,dq_1\,dq_2\,\frac{\varepsilon(s,q_1,q_2)}{n_0(s)}h_s(s,q_1,q_2)\left[\det \hat{B}^+(s)\right]^{1/2}$$

$$\cdot\exp\left\{\frac{ik}{2}\left[\left(b_{11}+b_{11}^g\right)q_1^2+\left(b_{22}+b_{22}^g\right)q_2^2+2\left(b_{12}+b_{12}^g\right)q_1q_2\right]\right\}. \qquad (3)$$

$$\hat{B}^+ = \hat{B} + \hat{B}^g$$

The elements of matrices $\hat{B}, \hat{B}^g$ are defined from equations

$$n_0\frac{\partial\hat{B}}{\partial s}+\hat{B}\cdot\hat{B}=\hat{C} \qquad -n_0\frac{\partial\hat{B}^g}{\partial s}+\hat{B}^g\cdot\hat{B}^g=\hat{C} \qquad (4)$$

$$c_{ik} = \frac{1}{2}\frac{\partial^2 n^2(s,0,0)}{\partial q_i\partial q_k} - 3n_0^2(s)\frac{\partial \ln n(s,0,0)}{\partial q_i}\frac{\partial \ln n(s,0,0)}{\partial q_k}$$

The scattering effects are described in the Fresnel approximation for forward scattering. As a result, the full-wave type solution of the problem of HF propagation in the 3D fluctuating ionosphere is determined accounting for ray bending and scattering on local random inhomogeneities including the contribution of diffraction in the scattering.

The product of the complex phase method is the spaced time and frequency auto- and cross-correlation functions of χ_n and S_n, and their frequency and time spectra, and, finally, statistical properties of phasor R_n

This is all further utilised to produce the statistical moments of the full field as well as random time series for χ_n , S_n and the full field.

In the numerical simulation, the anisotropic inverse power law spatial spectrum of fluctuations of the ionospheric electron density is employed

$$B_{\varepsilon}\left(\vec{\kappa}, s\right) = C_N^2\left[1 - \varepsilon_0\left(s\right)\right]^2 \sigma_N^2 \left(1 + \frac{\kappa_{tg}^2}{K_{tg}^2} + \frac{\vec{\kappa}_{tr}^2}{K_{tr}^2}\right)^{-p/2} \qquad (5)$$

C_N^2 - normalisation coefficient

$\varepsilon_0\left(s\right)$ -distribution of the dielectric permittivity of the background ionosphere along the reference ray

σ_N^2 -variance of the fractional electron density fluctuations

$K_{tg}=2\pi/l_{tg}$; $K_{tr}=2\pi/l_{tr}$ where l_{tg} and l_{tr} are the outer scales of the turbulence tangential and transverse to the geomagnetic field direction respectively

$$E(\mathbf{r},t,\tau) = \sum_n \int_{-\infty}^{+\infty} P(\omega)\, T_n(\mathbf{r},\omega,t)\, R_n(\mathbf{r},\omega,t)\, e^{-i\omega\tau}\, d\omega \qquad (1)$$

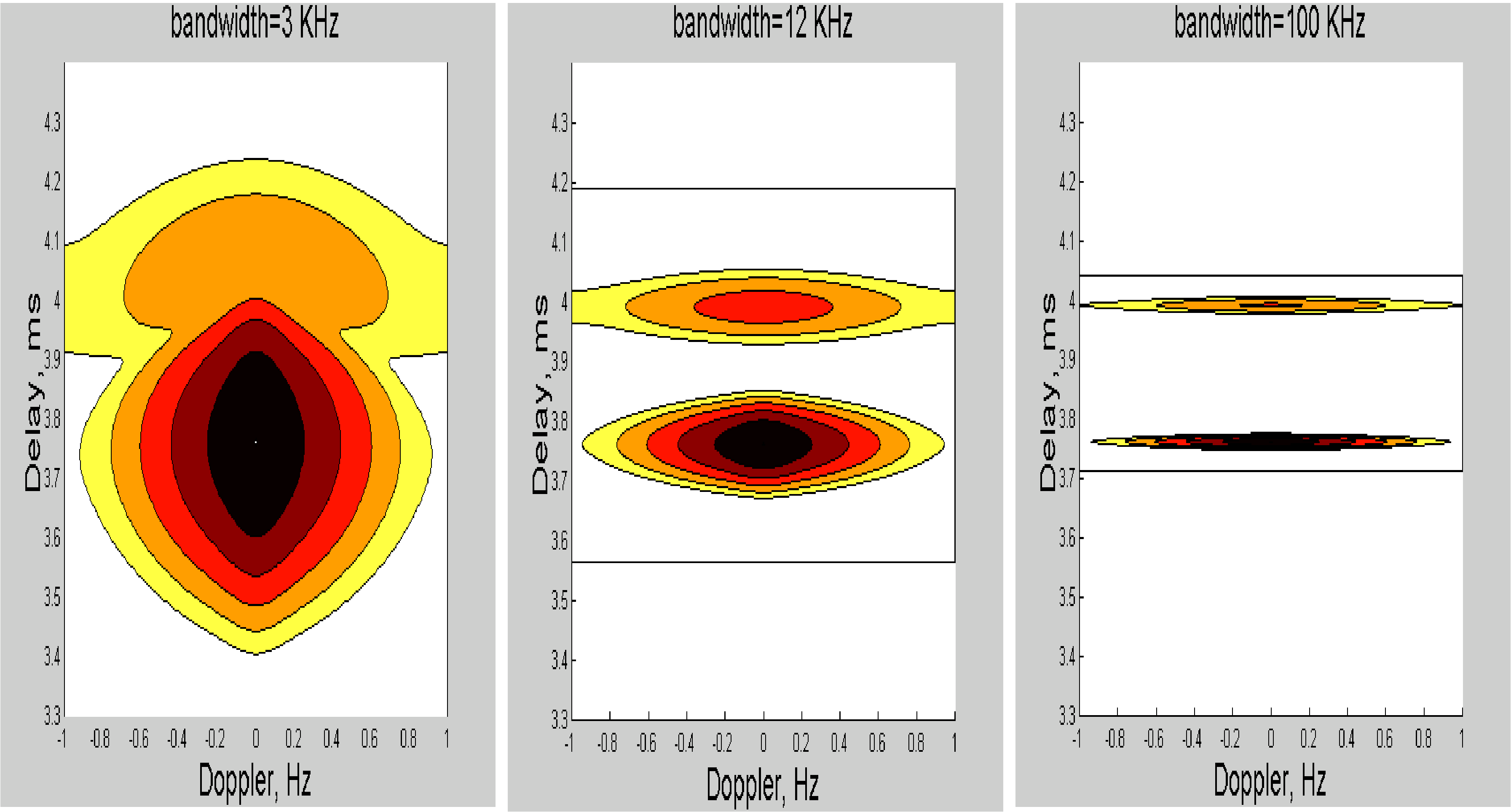
Scattering function for the field E from (1)

$$F_s(\tau,\omega_d,t) = \frac{1}{2\pi}\iiint P\left(\Omega+\frac{\delta}{2}\right)P^*\left(\Omega-\frac{\delta}{2}\right)\sum_n T_n\left(\Omega+\frac{\delta}{2},t\right)T_n^*\left(\Omega-\frac{\delta}{2},t\right)$$

$$\cdot\,\Psi_n(\Omega,\delta,t,\Delta t)\exp\left\{-i\left[\tau-\tau_{gn}(\Omega)\right]\delta + i\omega_d\Delta t\right\}d\Omega\, d\delta\, d\Delta t \qquad (6)$$

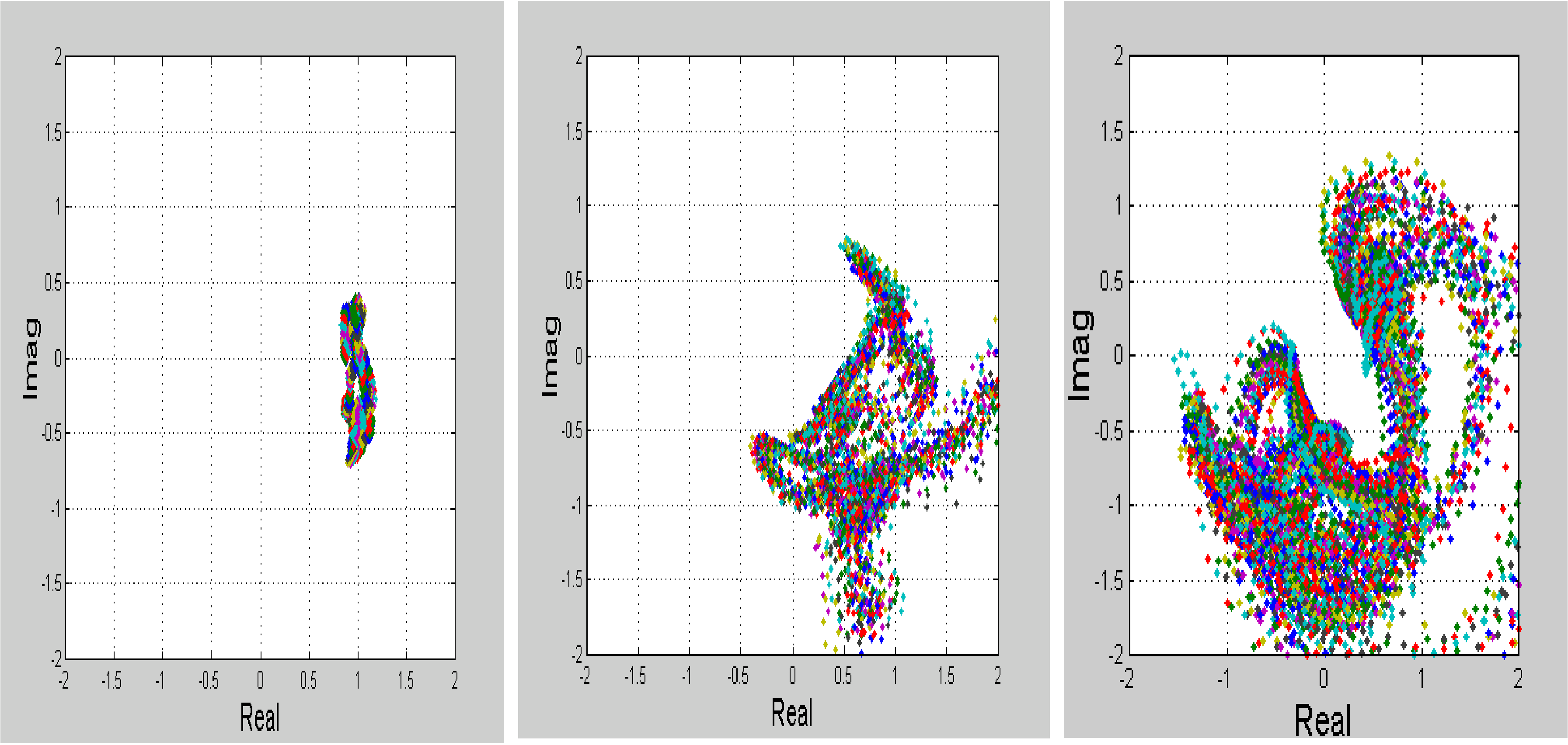
$\Psi_n(\Omega,\delta,\Delta t)$ is the correlation function for R_n, expressed in terms of correlation functions of χ_n and S_n .

Two-mode scattering function



$$E_n(\mathbf{r},t,\tau) = \int_{-\infty}^{+\infty} P(\omega)\ T_n(\mathbf{r},\omega,t)\, R_n(\mathbf{r},\omega,t)\, e^{-i\omega\tau}\, d\omega$$

Time and frequency random walk of phasor R_n

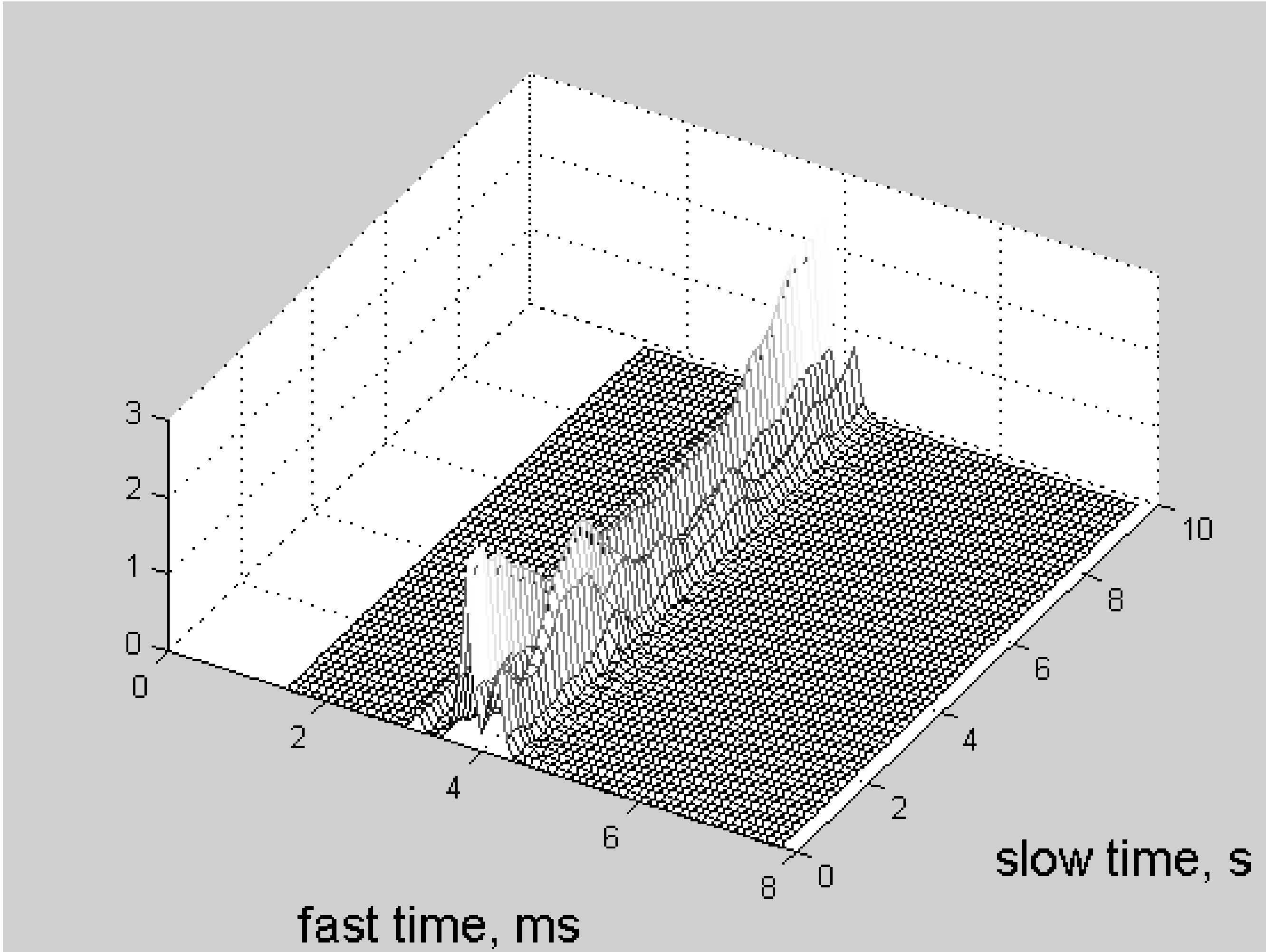


Simulations

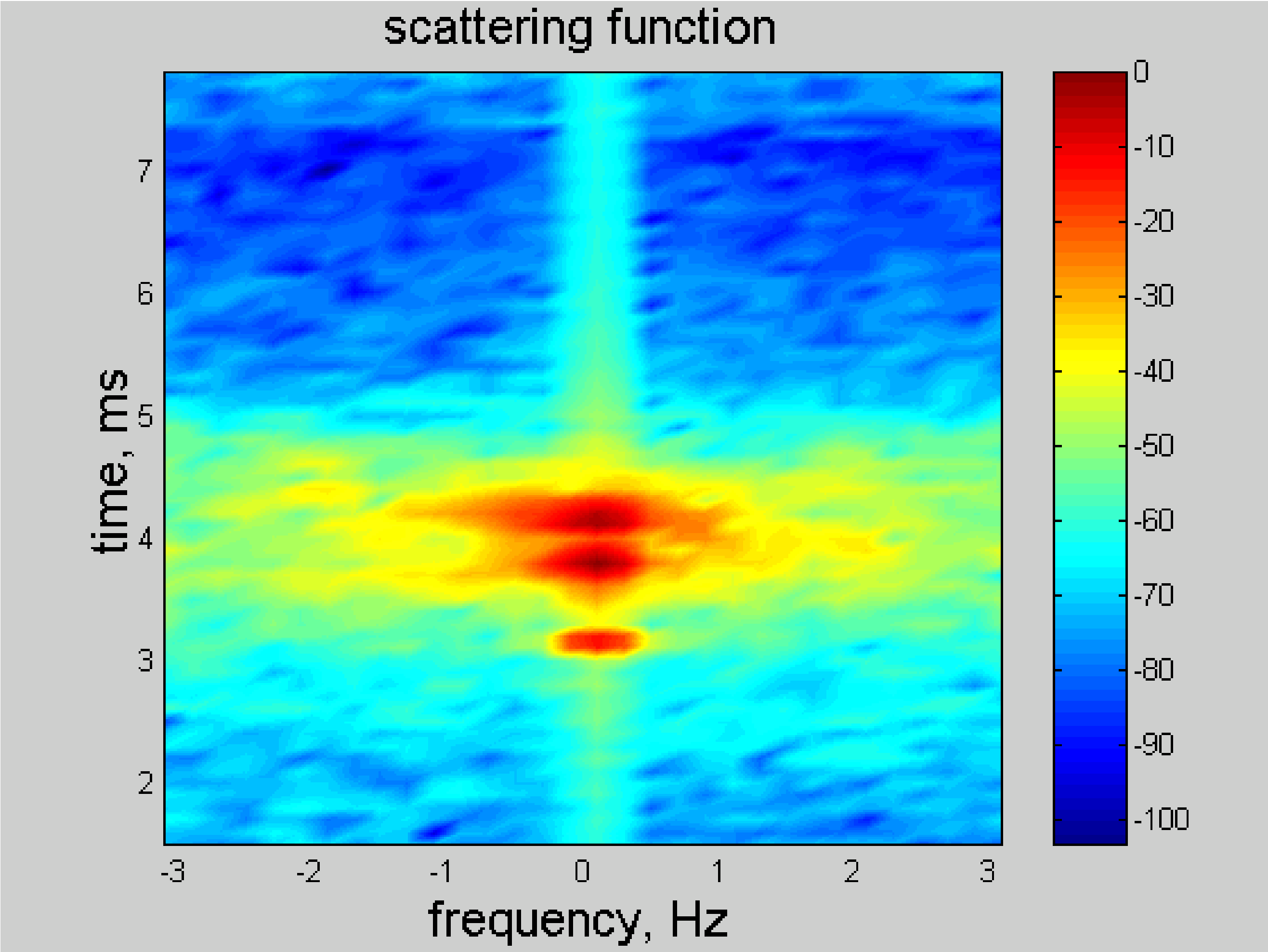
IRI (International Reference Ionosphere) input parameters
St.Petersburg, July, local time 14:00, R12 = 70
Oblique path East-West, distance 900 km.
Carrier frequency 8.3 MHz.

Parameters of electron density fluctuations:
Anisotropic inverse power law spatial spectrum with the spectral index p=3.7
Outer scales: 5 km - across and 15 km along the magnetic field
R.m.s. of the relative electron density fluctuations 1%
frozen drift velocity across the path of propagation V = 0.5 km/sec

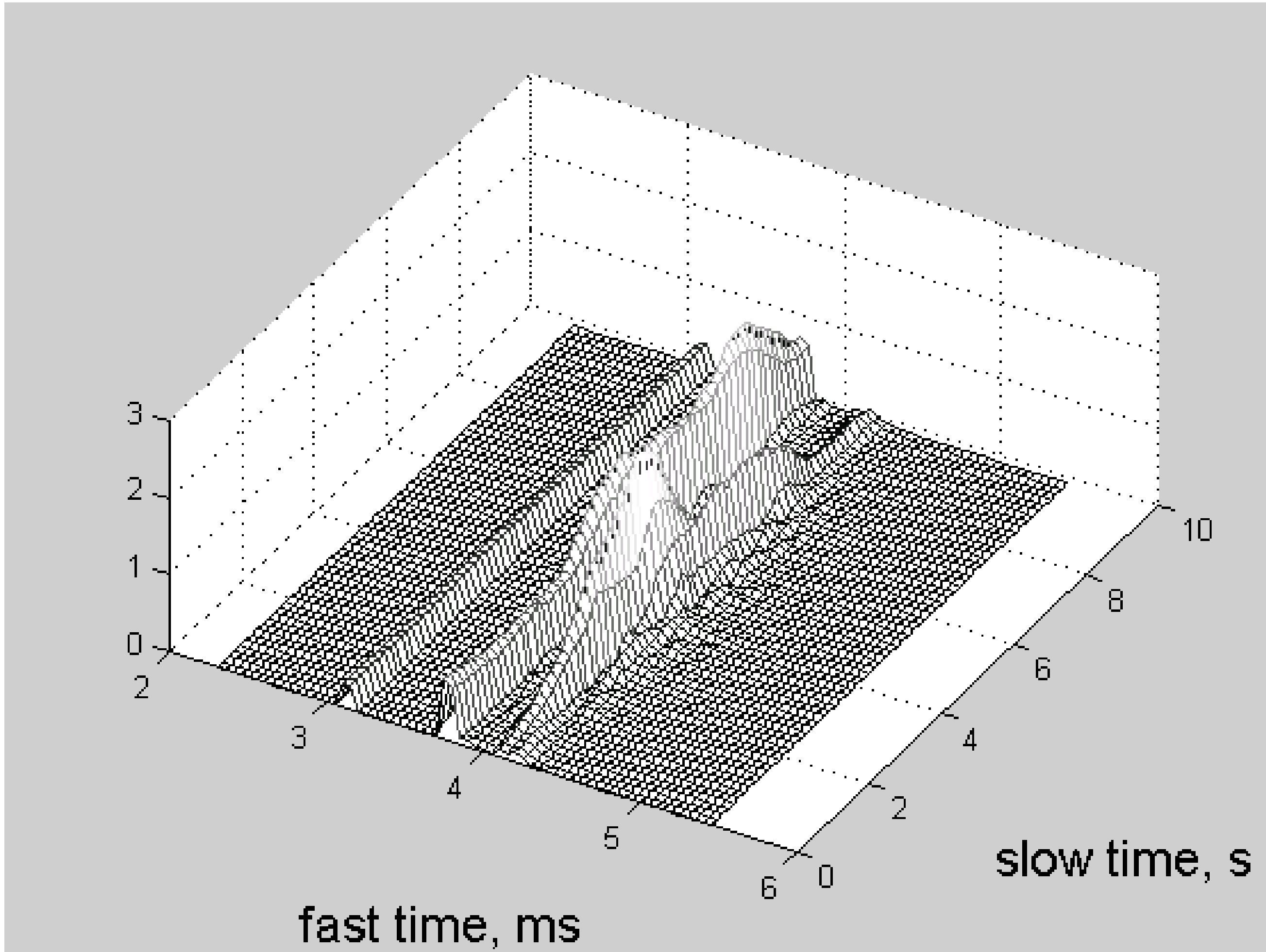
Transmitted signal:
Rectangular impulses, pulse repetition cycle 0.157 s
length of a pulse: 0.2 msec for the bandwidth of 10 kHz
0.1 msec for the bandwidth of 20 kHz,
0.05 msec for the bandwidth of 40 kHz



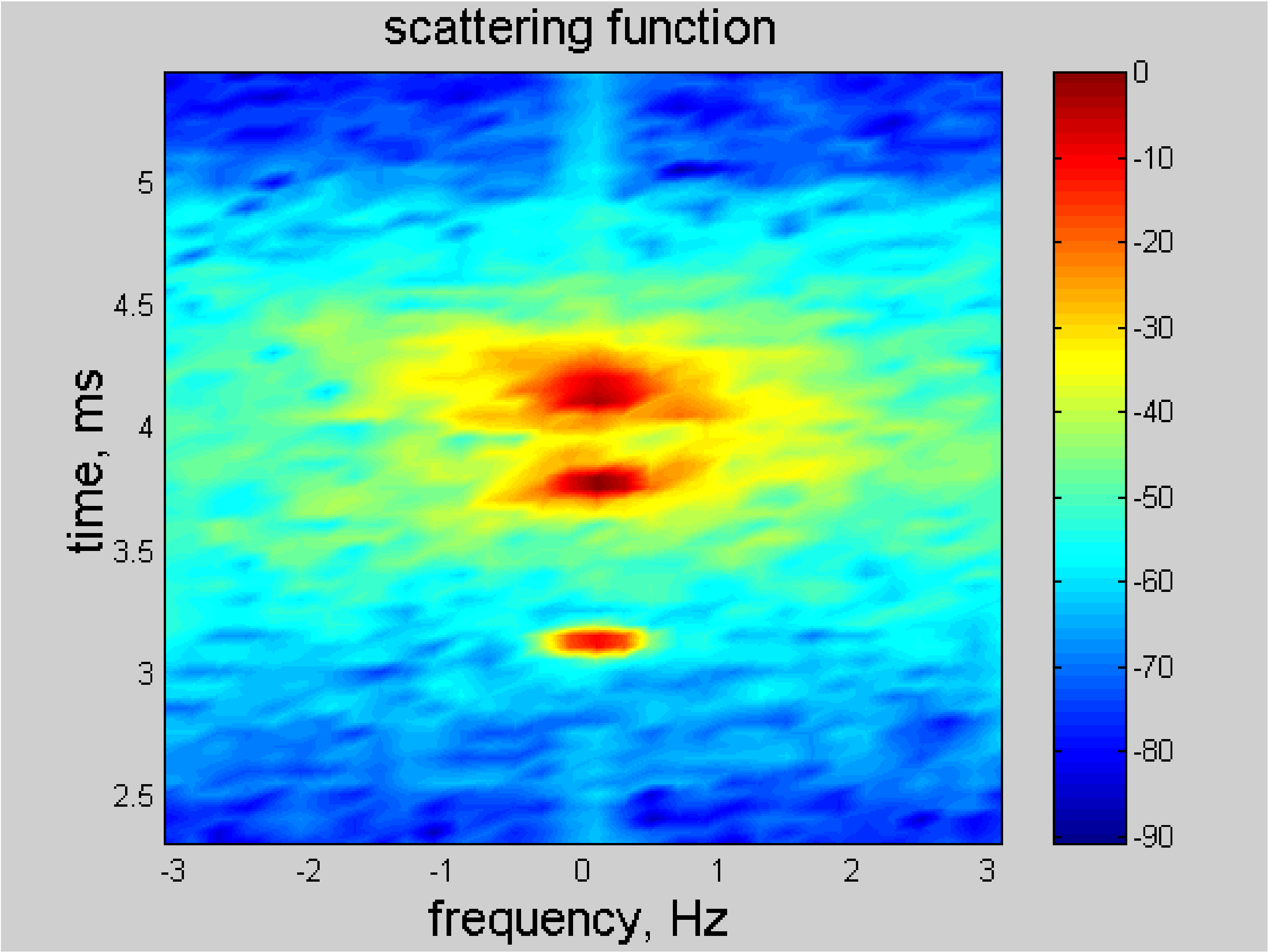
Bandwidth 10 kHz



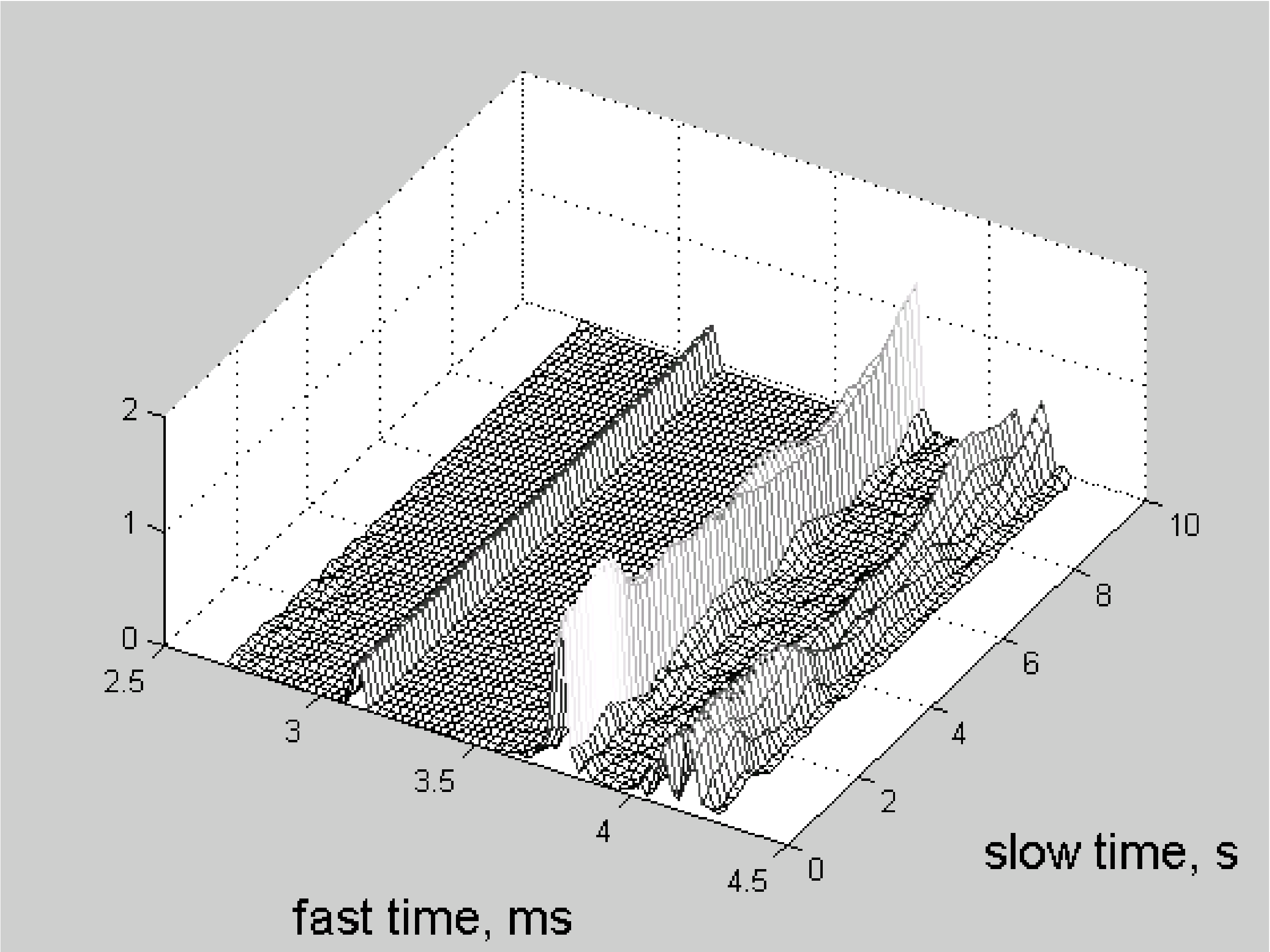
Bandwidth 10 kHz



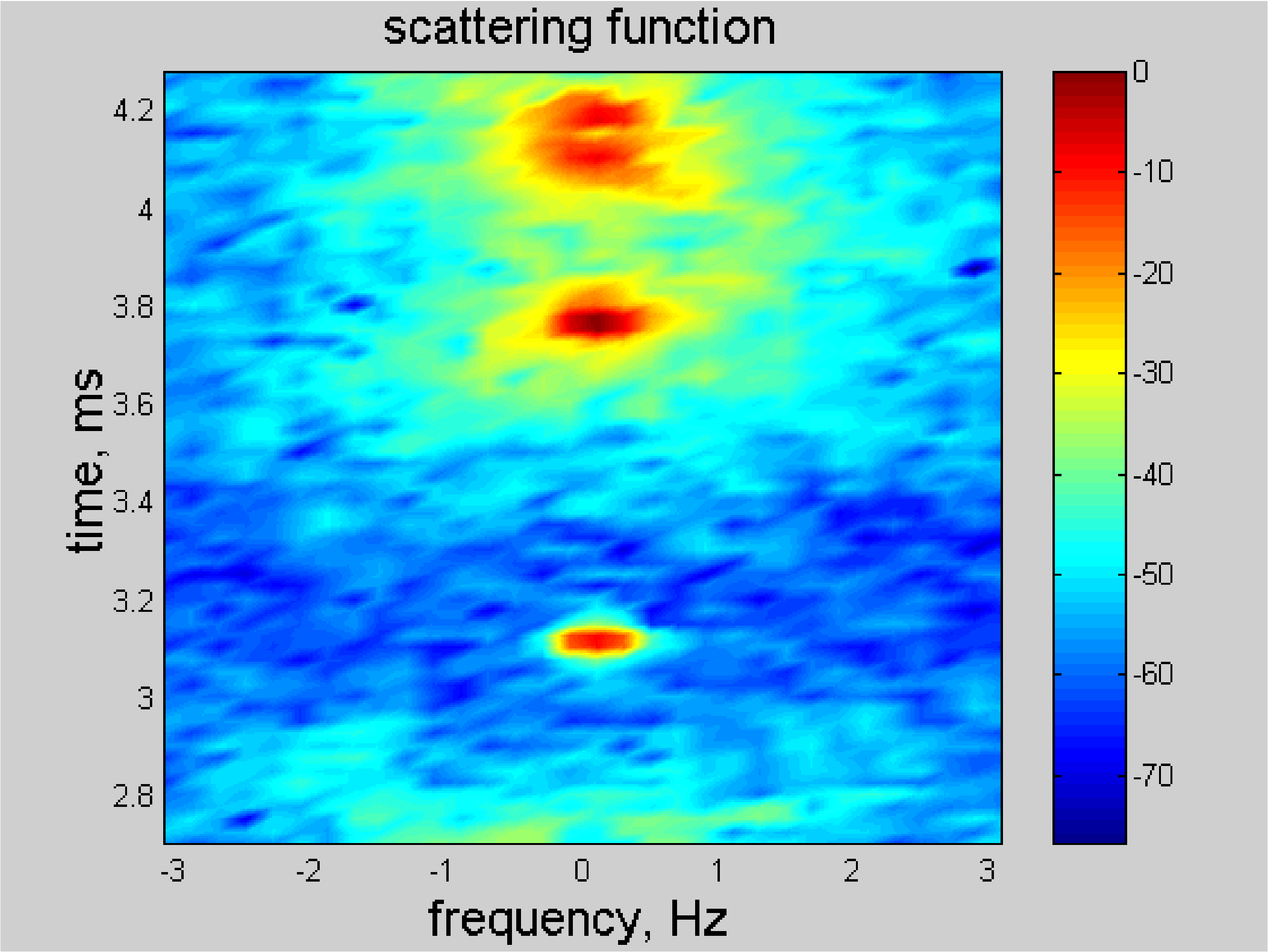
Bandwidth 20 kHz



Bandwidth 20 kHz

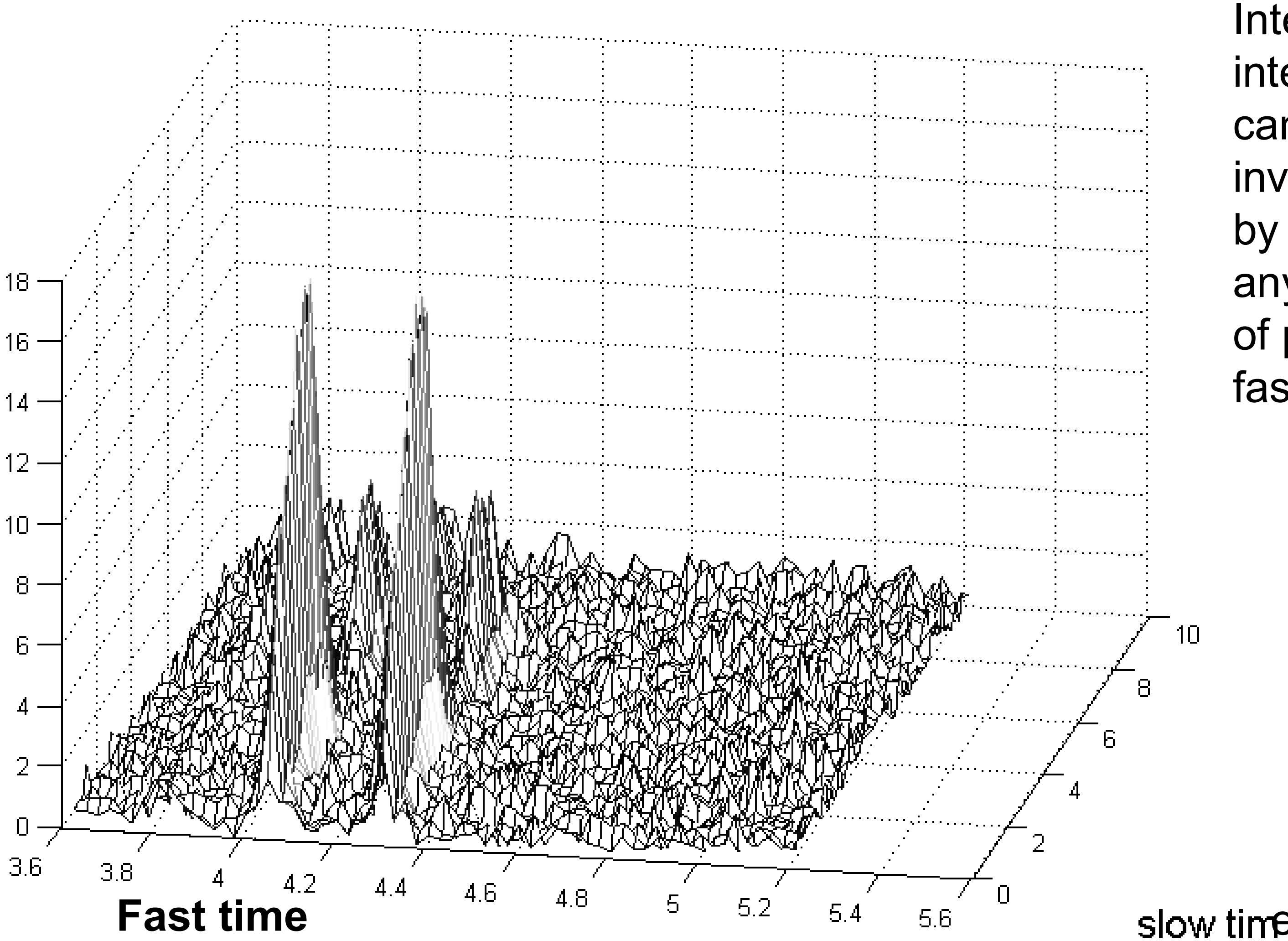


Bandwidth 40 kHz



Bandwidth 40 kHz

Inter-symbol Interference

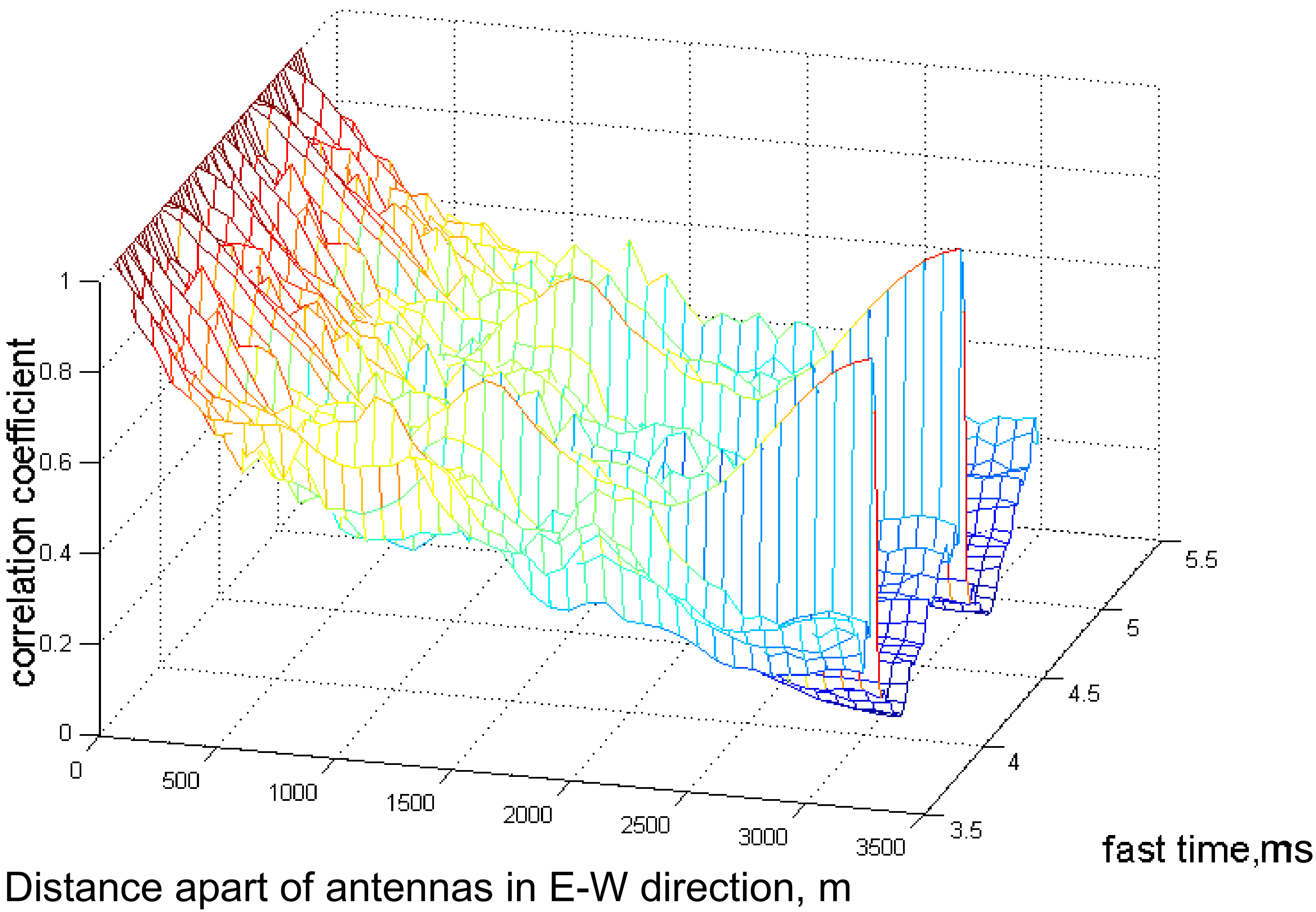


Inter-symbol interference can be investigated by adding any number of pulses in fast time

Spatial Diversity

- In spatial diversity systems, two or more spaced antennas are employed
- It is important that the antennas are sufficiently far apart that the fading is independent at each
- The most important contribution to the fading is generally that of the time-varying irregularities
- The correlation distance for mulipath HF communications has been determined using the HF simulator assuming frozen in drift of the irregularities.
- As an example, consider a North South path from 40° to 50° latitude with an East-West drift of the irregularities of 0.5 km/s
- E and F layer reflected paths exist for both magneto-ionic modes but the correlation of the F-mode falls off more rapidly with distance.

Correlation at spaced antennas with fast time vs. distance apart of antennas



Conclusions

The analytic-numerical technique demonstrated allows simulation of the effects on the wideband ionospheric HF channels for a wide range of the following parameters:

(1) the transmission bandwidth
(2) the transmission frequency
(3) the variance of fractional electron density fluctuations
(4) the speed and direction of the drift of the turbulence
(5) the anisotropy and outer scale of the irregularities
(6) the background ionosphere model
(7) the orientation of the propagation path to the geomagnetic meridian
(8) the multi-mode effects.
(9) the noise models.

Conclusions continued

The simulator can be used to test out new modems for spread spectrum systems; both direct sequence and frequency hopping.

The simulator can be used for the planning of new DRM broadcasts

It can also be used to investigate spatial diversity systems and increased channel capacity for fixed HF links using SIMO/MIMO by determining the correlation between spaced antennas taking into account the time-varying irregularities and multipath interference.

The simulator can also be used to identify the correspondence between physical parameters (e.g. the variance and anisotropy of the electron density fluctuations, orientation of the propagation path to the magnetic meridian, bulk ionosphere motions) with observed channel parameters (e.g. Doppler spread and shift, time delay spread). This permits continued refinement of the simulator.

A hardware version of the simulator could be constructed.