Measuring scattering function of HF NVIS channel by sounding with the use of a noise-like BPSK signal

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Abstract. Measuring parameters of the scattering function of near vertical incidence skywave (NVIS) radio links employed for data transmission is topical and fosters better understanding signal propagation as well as developing state-of-the-art cognitive radio systems. In this regard, the paper presents the findings of the research into the application of a noise-like phase-shift keying (PSK) signal for vertical sounding of NVIS radio links. There are presented the developed algorithms for processing the PSK signal to measure the scattering function and its parameters (signal-to-noise ratio, delay spread and Doppler spread) for multiple communication channels in the high frequency (HF) band. To carry out experiments on measuring scattering function of radio channels with bandwidth of 24 kHz and different mid-band frequencies, we employed developed ionosonde based on the universal software radio peripherals (USRP) platform.

1. Introduction
NVIS radio links are used for tactical HF communications (communications over distances of up to 400 km). They are characterized by the high values of angles of incidence of the ray on the Earth's ionosphere. Therefore, that technology was termed to as NVIS. NVIS technology is especially suited for challenging relief communications (for instance, in mountain landscape (figure 1)).

Figure 1. NVIS radio channel for tactical HF communications.
It is seen that the signal is reflected almost from the zenith, so the roughness of the earth’s surface does not influence communication.

For HF communication, frequency division multiplexing of channels is typical, therefore, the usable frequency band manifests a multidimensional radio channel consisting of partial frequency channels [1].

Currently, there is an intensive research into the capacity of HF communication channels. In particular, the problem of spreading the channel bandwidth up to 24 kHz is being tackled. Wideband HF communication poses the challenges of creating a cognitive radio, including cognitive sounding, cognitive spectral analysis of the interference environment and estimation the channel availability and the propagation conditions of the communication signals according to gathered data. The need for cognitive sounding fosters the rapid development of state-of-the-art devices that are based on SDR technology and produce minimal out-of-band emissions by employing spread-spectrum noise-like signals with extremely low power. For this reason, an essential task is the development of methods and algorithms of processing sounding signals to obtain key channel characteristics. One of them is the channel scattering function (CSF). This work addresses studies into the usage of noise-like PSK signals for the purposes discussed above. Signals with intrapulse PSK belong to the class of spread spectrum signals, the time-bandwidth product of which is much greater than 1 [2]. Such signals are widely used in radar and wideband communication systems, and recently they started to be employed for ionosphere sounding [3, 4].

2. Channel scattering function.

The theory of ionospheric propagation of radio waves allows to reduce the problem of signal propagation in a medium to the equivalent problem of propagation in a linear system with a frequency response (FR) $H(j\omega,T)$. In this case, each partial frequency channel with mid-band angular frequency $\bar{\omega}$ is associated with an impulse response (IR) $h(\bar{\omega},\tau,T)$, where $\tau$ - fast time (delay in the channel), and $T$ - slow geophysical time.

The impulse response of the ionospheric channel is a stochastic function. Therefore, to get statistically stable estimates of the channel conditions, it is reasonable to use the channel scattering function:

$$G(\tau,F_d) = \frac{1}{T_a} \left| \int_0^{T_a} h(\tau,T) \exp(-j2\pi F_d T) dT \right|^2,$$

where $T_a$ - impulse response analysis time, $F_d$ - Doppler spread in the channel.

If multipath (from $K$ rays) reception occurs, the CSF will be the sum of terms (1) according to the number of rays. Gaussian CSF model can be represented as follows:

$$G(\bar{\omega},\tau,F_d) = \sum_{k=1}^K \left( \frac{S}{N} \right)_k \exp\left[ -\frac{(\tau-\bar{\tau}_k)^2}{2\sigma^{2}_\tau} - \frac{(F_d-\bar{F}_d)^2}{2\sigma^{2}_F} \right],$$

where $k$ - the number of ray, $\frac{S}{N}$ - signal-to-noise ratio in the channel, $\sigma^{2}_\tau$ - delay spread of the impulse response, $\sigma^{2}_F$ - Doppler spread of the impulse response.

If the channel spreading parameters do not exceed the limit values and the signal-to-noise ratio does not fade below a certain level, the channel will be suitable for communication. The limiting values of the CSF parameters are represented by the performance surface of the modem (MPS) [1]. So, MPS is in function of three variables: signal-to-noise ratio, delay spread and Doppler spread $(\frac{S}{N}, \sigma^{2}_F, \sigma^{2}_\tau)$.

Typically, the surface shows the limiting values of the parameters when the bit error rate does not exceed $10^{-3}$. In general, it is approximated by a rectangular parallelepiped (figure 2).
If the current channel state allows the point with coordinates equal to the CSF parameters get into a rectangular parallelepiped, the channel is available for the selected communication modem, and is considered unavailable in the opposite case. On figure 2 unavailable channels are indicated by the red color.

Sounding by a radio signal of appropriate form is employed to estimate the current channel conditions. The sounding signal must fit the technical capabilities of the equipment, have sufficient resolution and the necessary energy characteristics. State-of-the-art signal processing allows to employ for sounding and location spread-spectrum signals with intrapulse modulation, also termed to as noise-like signals. With regard to the sounding and location challenges, these signals ensure high noise immunity and resolution. These capabilities are exhibited by a binary phase-shift keying (BPSK) signal [3,4]

3. PSK signal for vertical-incidence sounding of the ionosphere

PSK signal consists of adjacent elements (chips) of harmonic oscillation, with a total duration \( T_s = L \cdot \delta T \) and amount \( L \). Switching from one chip to another, the initial phase of the oscillation can rapidly change by \( \pi \). The mathematical model of the chip of pulse PSK signal under the condition \( \omega \delta T = 2\pi \) is represented as follows:

\[
u_i(t) = \begin{cases} 
\sum_{k=1}^{N} \exp(j \vartheta_i \cdot \exp(j \omega t) & \forall t \in [0, L \cdot \delta T] \\
0 & \forall t \not\in [0, L \cdot \delta T]
\end{cases}
\]

(3)

where \( \delta T \) - chip duration, \( \vartheta_i \) - initial phase of the oscillation in the chip, taking values 0, \( \pi \) according to the spreading code, \( \omega \) - angular carrier (figure 1(a)).

Its spectrum is \( U_r(j \omega) \). It is known that the amplitude spectrum of the PSK signal with the Barker code is as follows:

\[
|U_r(j \omega)| = \delta T \cdot \sin(c(\omega \delta T / 2)) \cdot \left| N \pm \frac{\sin(L \omega \delta T)}{\sin(\omega \delta T)} \right|^\frac{1}{2}.
\]

(4)

Sign "+" corresponds to \( N = 5, 13 \) and sign "-" to \( N = 3, 7, 11 \).

In monostatic vertical sounding, the duration of a total PSK signal is limited by the first echo from the minimum reflection height, which is lower than 90 km (\( E \) layer (figure 1)). In that case, signal duration should be less than 0.6 ms. Signal transmission is repeated during sounding. The repetition rate

![Figure 2. MPS for different data rates and CSF parameters exhibiting the variations of the channel conditions.](image)
is defined by the required height range, which should cover at least 750 km. Therefore, the repetition period $T_r$ should be at least 5 ms (figure 3(b)). That range covers single-hop reflections from all ionospheric layers and two-hop reflections from the F layer. The repetition period of sounding on the selected carrier is defined by the channel coherence time, that is roughly 10 s.

![Figure 3](image)

**Figure 3.** (a) Block scheme of generating PSK signal, (b) PSK impulse.

Chip duration defines the duration of the main lobe of the autocorrelation function of the compressed PSK signal, which is equal to the delay resolution of the method. However, chip duration defines signal bandwidth which cannot be greater than the coherence bandwidth of the channel, which is roughly 30 kHz for vertical sounding [5]. Therefore, $\delta T < 33 \mu s$ and the amount of chips in the total signal should not exceed $L \leq 18$. Barker code with $L = 13$ meets that requirements. Its application with $\delta T = 40 \mu s$ ensures the total pulse duration of $T_S = 520 \mu s$.

The energy efficiency of the impulse sounding signal influences the signal-to-noise ratio at the receiver and is determined by signal energy $E = P \cdot T_r$. Measurement of the Doppler spread by channel sounding is equivalent to the coherent integration of the compressed PSK signal. Therefore, the signal energy rises because the total signal duration related to the chip duration increases and the signal analysis time related to its repetition period also increases.

4. **Algorithms of obtaining CSF and main channel parameters**

Matched filter processing of the sounding PSK signal involves calculating the autocorrelation function (ACF) from the sounding data. To theoretically justify the method of calculating CSF of a random channel by its sounding, let us employ the Rayleigh theorem and the shift theorem for the Fourier transform. Thus, one can get the following equation:

$$B_r(\tau, T) = \int_{-\infty}^{\infty} u_\text{r}(t) \cdot u_\text{r}^*(t - \tau) dt = \frac{1}{2\pi} \int_{-\infty}^{\infty} \hat{U}_\text{r}(j\omega, T) \cdot \hat{U}_\text{r}^*(j\omega) \exp j\omega\tau \cdot d\omega.$$  \hspace{1cm} (5)

Let us further consider the spectrum of the received signal, which defines a narrowband $B_{ch}$ (in the mathematical sense) radio channel with mid-band frequency $\tilde{\omega}$. Hence, the spectrum of the received signal can be written as follows:

$$U_\text{r}(j\omega, T) = U_T(j\omega) \cdot H(j\omega, T).$$  \hspace{1cm} (6)

The product of spectra can be written as follows:

$$U_\text{r}(j\omega, T) \cdot U_T^*(j\omega) = |U_T(j\omega)|^2 \cdot H(j\omega, T) \approx \text{const} \cdot H(j\omega, T).$$  \hspace{1cm} (7)

So, equation (5) is transformed to the following form:
Equation (8) specifies the algorithm for calculating the complex-valued channel impulse response from the sounding data. Using equation (2) and the data the impulse response, one can derive the CSF.

Figure 4 illustrates the simplified scheme of the CSF calculation algorithm. Several impulse responses obtained sequently are combined in a matrix by columns. Then, the discrete Fourier transform is applied to the matrix rows.

![Diagram](image)

**Figure 4.** Figure with short caption (caption centred).

The values of «widths» of the CSF measured along the fast time axis and Doppler spread axis are the channel spreading parameters \( \sigma_\tau \) and \( \sigma_d \).

We shall note that estimation of the parameters from the measured CSF requires application of the threshold methods to separate noise samples and signal+noise samples. To set the threshold, we used state-of-the-art methods: median equalization and CFAR [6, 7].

5. **Experimental findings**

Experimental data were collected by the original PSK ionosonde [8, 9]. It is implemented on the USRP N210 platform according to SDR technology. Therefore, its implementation was reduced to the development of the algorithms and relevant software. The device employs AH-710 antenna of T2FD type, located at the height of 17m above the ground. The power of the sounding PSK signal was 19 watts. Experiments were carried out in Yoshkar-Ola.

Figure 5 presents typical scattering functions corresponding to the channels with different mid-band frequencies.

The experiments showed that the scattering in the time and frequency domains rises with an increase in the channel mid-band frequency.

The data on scattering parameters were gathered at 100 sounding sessions and summarized in figure 6. Lines and color indicate the limiting values of the parameter for different channel conditions (according to the ITU classification [10]).

It is seen that the majority (70%) of the scattering parameters correspond to “moderately disturbed” channels, and the rest correspond to “moderate” ones.

6. **Conclusions**

Features of the application of the PSK signal in the problem of measuring parameters of the CSF of NVIS communication channels were considered. It was found that in 70% of cases channels with different mid-band frequencies exhibited "moderately disturbed" conditions. The remaining 30%
exhibited "moderate" conditions. Furthermore, it was experimentally found that the values of the scattering parameters rise with an increase in the channel mid-band frequency.

The proposed approaches seem rather promising for perspective systems of short-haul cognitive HF communication, especially in regions with challenging relief.

**Figure 5.** Experimental CSF measured at the day time at frequencies: (a) 3.6 MHz; (b) 4.8 MHz; (c) 5.1 MHz; (d) 5.5 MHz; (e) 5.8 MHz.
Figure 6. Results of measuring CSF by delay spread and Doppler spread.

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