Tools for VLF natural radio noise investigation in Yakutsk

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Abstract. A parallel VLF radio noise spectrometer has been used at a testing ground of the ShICRA SB RAS for recording ionospheric-magnetospheric radio emissions since 1972. The site located at a distance of 30 km from Yakutsk (62 N, 129.72 E). A one-point lightning discharge recorder was also installed at the site, which consists of a whip and two crossed loop antennas, an amplifier, an ADC, and a PC with a special program. The same direction finder with a change in gain and a special program can work as a narrow-sector direction finder for fluctuating radio noise. To investigate the function of propagation of VLF signals, narrowband radio noise, and their dependence on the space weather parameters, a VLF signal recorder that has been operating continuously in Yakutsk since 2009 is used. The World Wide Lightning Location Network (wwlln.net) data have been used for lightning discharge location since 2009. One of the WWLLN receivers was installed in Yakutsk. One-point lightning guides called "LD-250" and "Storm Tracker" for recording the coordinates of a lightning discharge and its type have been used for discharge registration within a territory of 400 km in radius around Yakutsk since 2006.

1. Introduction
The main natural source of very low frequency radiation (VLF: 3 - 30 kHz) is lightning discharges that generate radio pulses: atmospherics and bursts of VLF radiation from magnetosphere. Atmospherics propagate over long distances with low attenuation. One can distinguish the impulse (atmospherics) and fluctuation (overlapping radio pulses) radio noise components [1]. Parallel radio noise spectrometers are used for recording the fluctuation component of the VLF radio noise. One-point and multi-point lightning detectors are used to register the impulse VLF noise component [2].

Standard radio signals are used to study the diurnal, seasonal, and interannual variations of the parameters of the ionosphere lower regions that affect the VLF signal propagation. As reference signals it is proposed to use VLF signals of the radio navigation system "Alpha".

2. Equipment for the experiments
A parallel VLF radio noise spectrometer was installed at a testing ground of the Shafer Institute of Cosmophysical Research and Aeronomy SB RAS (ShICRA SB RAS) in 1972. The test site is located at a distance of about 30 km from Yakutsk (62 N, 129.72 E). It has high sensitivity and a wide dynamic range of 60 dB in amplitude on 9 overlapping frequency bands from 0.47 kHz to 8.7 kHz. The loop antenna diameter is 5.7 m, with 30 turns; thus, the effective area is 770 m², the resistance is about 20 Ohm, the inductance is 20 mH, and the capacitance is 1000 pF. The antenna is oriented to East-West, since the main source of industrial noise is located in the North (Yakutsk). The
spectrometer registers ionospheric-magnetospheric radio emissions coming from directions close to zenith. The magnetospheric origin bursts are most often recorded in channels of 2.2 – 5.6 kHz [3].

The signals of atmospherics exceeding the threshold come to separate counters. The detection threshold was chosen in such a way that the average density of the atmospheric flux in the diurnal daytime maximum at a threshold of 1B exceeded 1 sec\(^{-1}\). The total signal gain in the channels of the counters is 5000, and so the channel with a threshold of 1 V at the counter input corresponds to 192.5 \(\mu\)V at the antenna output. Taking into account the antenna effective altitude (\(h_d = 0.11\) m), the threshold level of the field received by the antenna is \(\sim 1.75\) mV/m, which makes it possible to record pulses at distances of up to \(\sim 6000\) km. The standard deviation of the noise component of atmospheric interference for the frequency band of 2 – 9 kHz measured in Canada in the 1950s is in the range of 0.03...2 mV/m [4]. Our measurements show that during summer close thunderstorms the magnitude of the fluctuation component reaches only 1 mV/m. Thus, the threshold set exceeds the upper estimate of the noise component. The atmospherics collection area with three thresholds is shown in Figure 1.

![Figure 1. Atmospheric collection area for three thresholds: 2 mV/m, 4 mV/m, and 6 mV/m.](image)

The amplitude distribution of atmospherics is expressed in the form of a power law. The index of the distribution increases from June to August. A one-point lightning-storm recorder is used to study the amplitude distributions of atmospherics. The recorder is located at the ShICRA test site. It consists of a whip (\(h = 10\) m) and two crossed loop antennas, a preamplifier, 400 m of a communication line with a transformer junction, a terminal amplifier, an ADC (E440), and a PC with a special program [5]. The total amplification of path 100 in the range of 0.3 – 100 kHz ensures the recording of atmospherics. A special program determines the direction and a range of atmospherics.

There are three characteristic periods in the diurnal variations: 8 – 12 UT is the maximum contribution of the local thunderstorm activity in summer and Northern India and China in winter; 15 – 19 UT is the nighttime maximum due to decrease in the attenuation during the VLF propagation; 3 – 7 UT is the minimum observed in all seasons due to the minimum Asian region thunderstorm activity and the maximum attenuation during the VLF propagation.

The diurnal variation of atmospherics except for the summer months has a half-wave form with a maximum from 15 to 19 hours (UT). For the summer months the variation has an additional maximum of 9 UT. The variation for the daily maximum of \(\sim 17\) UT between the summer and winter is 230%, and at 9 UT, 2600%, which is determined by the contribution of the local thunderstorm activity.

The mentioned thunderstorm centers for the mentioned time intervals are determined as a result by data of the narrow-sector thunderstorm seeker in the vicinity of Yakutsk [6]. The antenna system of the receiver consists of two multi-turn crossed loop antennas, each having an effective area of 360 m\(^2\) and a vertical electric antenna with an effective height of 3.5 m. The preamplifiers (the intrinsic noise was smaller than 1 \(\mu\)V in the 10 kHz band) with antennas were spaced at a distance of 400 m from the
Signals from three antennas come through the final amplifiers and delay lines to the ADC. We used an ADC sampling frequency of 250 kHz. Thus, signals from the three antennas are saved into the PC memory in the form of three data arrays. Then we obtained the signal received by the antenna system with a cardioid directional-response pattern (RP) (2.1) using the array of signals from the vertical electric antenna having a circular RP in the azimuthal plane and the array of signals from one pair of crossed-loop antennas having an eight-type RP:

\[ V_k = k \cdot V \cdot (1 + \cos \varphi), \]  

where \( k \) is the gain of the reception channels, \( \varphi \) is the arrival azimuth of the received signal, and \( V \) is the magnetic component:

\[ V = V_0 \cdot \sin(\omega \cdot t), \]  

\( \omega \) is the signal frequency.

From the values \( |V_k| \) (linear detection), we subtract the signal from the second loop amplified by a factor of \( m \) and also taken in absolute value. Thus, we obtain the dependence (2.3):

\[ V_{res} = k \cdot V \cdot (1 + \cos \varphi - m \cdot |\sin \varphi|), \]  

The dependence (2.3) describes the resulting directivity characteristics. The sum of the positive values of the obtained array (half-period detection) gives the values of the signal extracted using a narrow-sector RP of a finder with an azimuthal lobe width of 115'\( /m \). To obtain two rotated RPs unfolded to 90\( ^\circ \) with respect to each other, we used a mathematical method of axis rotation. Using the arrays of signals from the loop antennas in the East-West \( H_{E,W} \) and North-South \( H_{N,S} \) directions for each axis-rotation angle \( \alpha \), we calculated the values of the arrays:

\[ H_1 = H_{E-W} \cdot \cos \alpha - H_{E-W} \cdot \sin \alpha, \]  

\[ H_2 = H_{E-W} \cdot \sin \alpha - H_{E-W} \cdot \cos \alpha, \]  

Then we found the signal of the narrow-sector finder from the given direction \( \alpha \). Such is the method to construct a circular RP of the received signals.

Since calculations can be done with the required accuracy, for about the same accuracy in the measurement of signals from the three antennas, and for \( m \geq 10 \), the error is approximately equal to \( m \cdot \Delta H \), where \( \Delta H \) is the error of measurement of signals from the loop. Thus, on the one hand, an increase in \( m \) leads to lobe narrowing in the reception RP, and, on the other hand, this leads to an increase in the measurement error.

A narrow-band VLF signal recorder is used to investigate both variations of the function of VLF propagation and the radio noise intensity variations depending on the pace weather. The VLF recorder has been operating continuously in Yakutsk since 2009 [7]. Lattice Fast Fourier Transform functions are used to detect the VLF signals from the radio stations of the Russian Radio Technical Navigation System "Alfa". The duration of the "window" of the sample for FFT is selected. It has an integer number of periods for each VLF signal frequency. For the Fourier transform, a tabular array of values for trigonometric functions is preformed previously. It speeds up the calculation process significantly. The amplitude and phase for the three frequencies is calculated in the generated FFT "window" (sample). Then the values are averaged for each record separately for each frequency. A rectangular window is used. The size of the window is 40 periods for 14.880 kHz, 34 for 12.649 kHz, and 32 periods for 11.904 kHz. The specified number of periods corresponds to the frequency multiplicity of the studied signals of radio stations, which makes it possible to avoid overlapping of the signals of radio stations of different frequencies with each other using the FFT. Time synchronization of the recorder is carried out using a GPS-clock (Trimble Thunderbolt E). A similar methodology has been used in ShICRA since 2006 [8]. The recorder uses an electrical whip antenna. The height of the whip is 4 m. The effective height is 2 m. The antenna capacity is 220 pF. The calculation of the median
value at each of the averaging steps using the transform to dB taking into account the lognormal distribution of radio noise levels allows one to delete the impulse component. The first step: median averaging is performed on one package parcel (0.4 sec.) and the second step: median averaging is performed in an interval of 3 minutes. This corresponds to a "minimum detector" ideology [9].

The necessary correction for the transition to the field parameters is determined by the certified antenna P6-51 calibration [5]. Based on the study of the distribution of narrow-band radio noise (at a frequency of 14.88 kHz) obtained in Yakutsk in winter, it is found that the arithmetic mean, the median and modal intensity values practically coincide. The distribution of the radio noise is expressed by a power law, the index varies from daytime to nighttime from -2 to -2.5. The values of the exponent of the power law of the amplitude distribution correspond to the values obtained for broadband VLF radio noise. An analysis of the amplitude distribution parameters of narrowband VLF signals of navigation stations shows that the mean, median, and modal amplitude values practically coincide, reaching a maximum value in winter at night, changing about 5 times during twenty-four hours. The amplitude of the signal varies little during the day in summer and is 75% of the nighttime in winter. The distribution is much narrower than normal, which is expressed by large excesses with a small asymmetry toward higher values. The distribution of the amplitudes of the radio station signals for large values has a power law exponent of about 20, while for small values the exponent corresponds to the value for natural radio noise.

A one-point lightning direction – range finder has been used to study the thunderstorm activity in Yakutia since 1993 [10]. The finding of direction is carried out by three antennas, which measure the vertical electrical and two horizontal magnetic components of the atmospheres electromagnetic field. A three-meter electric antenna with a cone cap (for increasing the antenna capacity and broadband) is installed on the insulator on a seven-meter metal mast. Two twenty-twisted shielded square loop antennas (effective area: 360 m²) are placed on the same mast. The whip antenna output shunting is performed by a capacitor for required signal magnitude selection. For the same purpose, the outputs of the loop antennas are shunted by low-value resistors. The antenna system with preamplifiers is at a distance of 400 m from the registration point to exclude the local industrial noise influence. The signal from the preamplifiers is transmitted to the central collection point by symmetrical cable communication lines. The symmetrical lines are based on the separation transformers to eliminate line interference. The transmission ratio is 1. The electrical component channel has an antenna amplifier K = 1. The amplifier is used to shunt the large internal resistance of the electrical antenna and the subsequent amplifying stages. Low-noise preamplifiers (gain: 100) identical for all receiver channels amplify signals in the frequency band of 0.3-60 kHz to provide the necessary signal values for transmission over the cable communication lines. The power amplifiers provide alignment with the communication lines and the most efficient use of the dynamic range of the analog-to-digital converter (ADC). The ADC sampling frequency is 250 kHz. The entire path amplification is chosen so that the threshold for selecting atmospherics for registration, which is 50 mV at the input of the ADC corresponds to the signal at the input of an electrical antenna of 150 mV/m in the frequency band of 0.3-60 kHz. The implementation time of 1 ms is chosen to be at least three atmospheric durations.

The lightning discharges direction is determined by the ratio of the rms values of the atmospheric signals of \(U_{N,S}\) and \(U_{E,W,i}\) from orthogonal magnetic antennas oriented to North – South and East – West directions.

To eliminate the error introduced by the noise field component into the measured values, the background level is subtracted from the quadratic values of atmospheric signals (2.6):

\[
P_p = \sum_i (U_{p,i} - U_a)^2. \tag{2.6}
\]

The background level \(U_p\) is determined on the preceding atmospheric by a period of 1 ms. It is assumed that the mean values of the fluctuation component of the natural noise and the magnitude of the signals of low-frequency radio stations at neighboring intervals with a duration of one millisecond remain unchanged [1].

The equation for determining the azimuth signal arrival (2.7) is
\[ \alpha = \arctg \left[ \frac{\left( \sum_{i=1}^{n} (U_{N-S,i} - U_{\text{aver},N-S})^2 - U_{p,N-S}^2 \right)^{\frac{1}{2}} \left( \sum_{i=1}^{n} (U_{E-W,i} - U_{\text{aver},E-W})^2 - U_{p,E-W}^2 \right)^{\frac{1}{2}}}{} \right], \quad (2.7) \]

where \( U_{\text{aver},N-S} \) and \( U_{\text{aver},E-W} \) are the average (mean) values of signals within one millisecond from the atmospheric beginning received from the orthogonal magnetic loop antennas:

\[ U_{\text{aver},N-S} = \frac{\sum_{i=1}^{n} U_{N-S,i}}{n}, \quad (2.8) \]
\[ U_{\text{aver},E-W} = \frac{\sum_{i=1}^{n} U_{E-W,i}}{n}, \quad (2.9) \]

where \( n \) is the number of ADC samples per channel for one millisecond.

The ambiguity of the bearing is eliminated by comparing the signs of the mutual correlation between the electrical and magnetic components of the atmospheric signal. It is noted that the sign of the measured correlation coefficient of the mix of the useful signal and the instrumental noise is determined only by the sign of the signal correlation coefficient, since the instrument noise is uncorrelated. The antennas are connected in such a way that the signs of the correlation coefficients in the first quadrant (northeast) are positive.

The distance to a lightning discharge \( L \) is defined as the geometric mean magnitude of the ensemble of features. Based on the results of the analysis, we selected four characteristics: two amplitude and two spectral ones.

The amplitude signs are the rms values of the \( E \) and \( H \) components of the atmospheric signal (2.10) and (2.11):

\[ E_{\text{rms}} = \left( \frac{\left( \sum_{i=1}^{n} (E_i - E_{\text{aver}})^2 \right)/n}{0.5}, \quad (2.10) \right. \]
\[ H_{\text{rms}} = \left[ \frac{(\sum_{i=1}^{n} (U_{N-S,i} - U_{\text{aver},N-S})^2 - U_{p,N-S}) + (\sum_{i=1}^{n} (U_{E-W,i} - U_{\text{aver},E-W})^2 - U_{p,E-W})/n}{0.5}, \quad (2.11) \right. \]

The amplitude of the signals is inversely proportional to the distance.

The spectral characteristics are the numbers of positive \( N_+ \) and negative \( N_- \) half-cycles of the atmospheric \( E \)-component exceeding 0.1 of the maximum amplitude \( E_{\text{max}} \). The number of transitions is directly proportional to the distance.

Therefore, the distance to the lightning discharge \( L \) is given by equation (2.12):

\[ L = D \cdot \left[ \frac{N_+ N_-}{E_{\text{rms}} H_{\text{rms}}} \right]^{0.25}, \quad (2.12) \]

where \( D \) is a constant (normalizing) coefficient.

The rms values of the amplitude of the signals of atmospherics coming from a single source have an asymmetric distribution shifted toward smaller amplitudes interpreted as large distances. The distribution of the number of transitions is also asymmetric but shifted toward a smaller number of transitions interpreted as a shorter distance. Using four characteristics normalizes the distribution and reduces the measurement error. It should be noted that the distances from the point of observation to the lightning discharge determined by individual characteristics are correlated with each other. Thus, for the 315 atmospherics registered in July 2001 the value of the correlation coefficient between the distances determined by individual characteristics was 0.59-0.71.

The average density of lightning discharges in North Asia in the summer period of 2009 – 2016 [11] is determined according to World Wide Lightning Location Network data [12]. One of the WWLLN receivers is placed at the Institute of Physics and Technologies, North-Eastern Federal University in Yakutsk.

One-point thunderstorm direction finders "Storm Tracker" and "LD-250" have been used for the registration of lightning discharges around Yakutsk (within a radius of 400 km) since 2009. The direction finders are installed in Yakutsk, Neryungri, and for several years, in Mirny [13]. The "Storm
Tracker" provides the ability both to record the lightning discharge coordinates and to separate discharges by types [14].

Observations of thunderstorm clouds within a radius of 10 – 15 km from Yakutsk are conducted using an electrostatic fluxmeter [15].

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