Radio interferometric location finding of VLF signal transmitters

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Abstract. The article presents some experimental results of using a very low frequency (VLF) interferometer designed in INRTU for radio direction finding of VLF transmitters. It is evaluated that amplitude angular-position measurements provides azimuth accuracy of several degrees. Distant VLF stations (3000 – 5500 km) can be located in a 2-6 km area if the signal azimuth is known with 0.001° accuracy. In order to minimize errors associated with antenna’s angular offset the authors developed a correcting algorithm. Using both radio direction finding methods and additional geophysical data (year and daily variations of solar terminator moving, signal disturbances during solar flares) the authors ascertained that 24.1 kHz and 25.0 kHz signals are emitted from the transmitter in Mokpo (South Korea). The phase measurements give about two times lower error of 1.5–2° for the NWC station (19.8 kHz, Australia) which is located more than 8200 km away from the VLF interferometer.

1. Introduction

Very low frequency (VLF, 3-30 kHz) radio waves are commonly used for radio navigation and communications with ships and immersed submarines, for transmitting standard time and frequency signals. These signals propagate over long distances via reflecting from the lower ionosphere and the Earth surface which makes the use VLF sounding as an effective metod for remote geophysical diagnostics of processes in D and E layers in the ionosphere [1]. VLF radio interferometry method can be also used for electrical exploration of different geological structures [2]. Many geophysical researches require polarization separation of radio wave components and estimation of signal reception azimuth.

2. Interferometric measurements

For long term monitoring of the ionosphere we designed in INRTU a VLF receiver [3, 4] with special algorithm for amplitude and phase measurements of MSK, GMSK and CPFSK signals [5]. Currently a three element VLF interferometer is deployed near Lake Baikal as it is shown in the Figure 1. The bases of the interferometer form a rectangular triangle with 16.891 km, 30.946 km, and 35.818 km sides. The red lines indicate expected VLF signals propagation paths along the great circle. The transmitters are located 3000 – 8600 km away from the receivers, a list of operational VLF stations is available for instance in [6]. If the signal reception azimuth is known we can apply the triangulation method [7] to find the transmitter location.
Figure 1. Configuration of location of the VLF interferometer and expected VLF signals arrival paths.

In the Table 1 the calculated sides of spherical triangles are shown for JJI and VTX transmitters. As it can be seen long distances 3000 – 5500 km require azimuth accuracy of 0.001° to get 1-3 km errors. There are two common techniques for receiving signal azimuth estimation: amplitude and phase radio location finding methods.

3. Amplitude method of VLF transmitter location finding
This method is based on using signal amplitude measurements with directional antennas. Each of our VLF receivers have two orthogonal magnetic 80 cm round loops with 36 turns of copper 0.5 mm² wire. One of loop antennas is oriented in the north-south (NS) direction, the other one is for west-east (WE). The azimuth can be found as $\tan A = B_{WE}/B_{NS}$. There is a indeterminacy of the angle quarter as loop antenna directional diagram has two maxima and amplitudes are always positive. However it can be evaluated if an approximate direction is known.

The Figure 2 shows some detection results for a 24.1 kHz signal. At night and especially in the evening (dashed lines) the signal amplitude has deep interferometric minima which lead to significant azimuth errors. In the daytime this polarization effect is less prominent as the radio signal propagates

| Station | Teploenergetic (T) | Lesnaya polana (L) | Karluk (K) |
|---------|--------------------|--------------------|------------|
|         | map                | calculated L₁ (km) | map        | calculated L₂ (km) | map        | calculated L₃ (km) |
| JJI     | 126.572°           | 3074.376 (L)       | 126.198°   | 3071.537 (T)       | 126.186°   | 3134.457 (T)     |
|         | 3077.289 km        | 3103.782           | 3074.451 km| 3069.691 (K)       | 3108.964 km| 3103.205 (K)     |
| VTX     | 216.373°           | 5469.392 (L)       | 216.307°   | 5452.739 (T)       | 215.817°   | 5459.248 (T)     |
|         | 5455.164 km        | 5463.184 (K)       | 5438.511 km| 5439.467 (K)       | 5451.228 km| 5452.183 (K)     |
primarily in the one-mode conditions [8]. The round circles in the Figure 4 show azimuths measured with day amplitudes for several VLF transmitters and their evaluation errors. One of reasons why the absolute errors reach 10° is antennas angular offset. The actual position of loops’ planes is not strictly orthogonal and their orientation is slightly different from NS-WE directions.

4. Correction of antennas’ angular offset

Let ε be the angle between the ideal and real NS antenna positions and ξ represents angular offset of the WE antenna. These variables are positive for counter clockwise shifts and negative when it is clockwise. The Poynting vector and the OX axis (see the Figure 3) form signal reception angle \( \phi = \phi' - \xi \). The amplitudes ratio is given then as

\[
K' = B'_{NS}/B'_{WE} = \sin(\phi - \epsilon)/\cos(\phi - \xi).
\]  

From the (1) let’s express \( \epsilon \) and write the equation for two signals with \( \phi_1 \) and \( \phi_2 \) arrival angles

\[
\phi_2 - \phi_1 = \arcsin[K'_1 \cos(\phi_1 - \xi)] - \arcsin[K'_2 \cos(\phi_2 - \xi)].
\]  

The equation (2) can be solved graphically or using numerical methods. When \( \xi \) is known then

\[
\epsilon = \phi + (-1)^n \arcsin[K'\cos(\phi - \xi)] + \pi n, \quad n \in \mathbb{Z}
\]  

forms a number of solutions for \( \epsilon \). The angles \( \epsilon \) and \( \xi \) can be found more precisely for different pairs of signals \( \phi_1 \) and \( \phi_2 \). Finally the signal reception angle with correction is expressed as

\[
tg \phi = \frac{\sin \epsilon + (\pm K')\cos \xi}{\cos \epsilon - (\pm K')\sin \xi},
\]  

where (+K’) is used for the signals in the I and III coordinate plane quarters, and (−K’) is for the II and IV quarters. The antennas in Teploenergetic have proved to have \( \xi_T = -12.1^\circ \) and \( \epsilon_T = -6.3^\circ \) angular offsets. The corrected azimuths in the figure 4 have residual errors of 2–3°. The location finding has shown that 18.3 kHz and 21.75 kHz signals are belong to the same transmitter (HWU). The 24.1 kHz signal source is not known, some studies \([9, 10]\) refer to the east seaboard of China. But its azimuth is close to the direction at the 25.0 kHz transmitter in Mokpo, South Korea (128.235° and 128.883° respectively in Teploenergetic, 127.830° and 128.817° in Lesnaya polana). The amplitude variations of these signals during 2017 year are compared in the Figure 5.
Figure 3. Estimation of angular offset of reception antennas for signals in the I coordinate quarter.

Figure 4. Residual errors of location finding in Teploenergetic before (circles) and after (asterisks) correction of antennas angular offsets $\gamma_T = -12.1^\circ$ and $\varepsilon_T = -6.3^\circ$.

Figure 5. Amplitude variations of 24.1 kHz (a) and 25.0 kHz (b) signals in 2017. The panel (c) shows sum of (a) and (b) spectrograms. The panels (d, e) demonstrate time moments of the signals’ switching.
As it can be seen from the figure 5 the 24.1 kHz and 25.0 kHz signals have the same power of radiation, their annual amplitude variations are described with identical cycles of solar terminator moving. The analysis of amplitude disturbances during solar flares confirm that the transmitter is located in the east from the VLF interferometer.

5. Phase angular-position measurements
The phase method of location finding requires identical heliogeophysical conditions of VLF signal paths. By this reason interferometer should have short baselines [11]. The angle between an interferometer baseline $\ell$ and normal to the signal path are found as

$$\alpha = \arcsin \left( \frac{\lambda \cdot \Delta \varphi}{2 \pi \ell} \right) = \arcsin \left( \frac{k \cdot \Delta \varphi}{2 \pi f \ell} \right),$$

where $\Delta \varphi$ is phase difference for two receivers (rad), $f$ is signal frequency (Hz); $\lambda = \nu / f$ is wavelength (m); $\nu = kc$ – mean phase velocity (m/s); $c$ – speed of light (m/c); $k$ – wavelength shorting coefficient, experimental reviews in [12] adduce for VLF range $k \approx 0.9978... 0.9985$ in the daytime and $k \approx 0.9951... 0.9974$ at night.

This technique was applied to find the direction of wave surface propagating for NWC signal (Australia, 19.8 kHz). The scheme is presented in the Figure 6 while the results of phase measurements are shown in the Figure 7. The phase method has demonstrated errors less then 2° which is a good result for such a distant transmitter location (8260 km).

6. Conclusion
The location finding of VLF signal sources is useful for geophysical researches and in some practical applications. The triangulation method requires 10^{-3} degree accuracy for short baseline interferometry and distant VLF stations (3-5 thousand km). The amplitude technique of azimuth evaluation has shown residual errors of 2–3° when the correction algorithm is applied. The phase angular-position measurements are more accurate, the errors are less than 2°. Using both radio location finding method and geophysical data about signal propagation conditions have helped to identify that 25.0 kHz and 24.1 kHz signals are radiated by the same transmitter located in Mokpo, South Korea.

Figure 6. A scheme of wave front arrival for NWC signal (Australia, 19.8 kHz). The side of triangles are $l_{TK} = 19.145$ km, $l_{LK} = 32.849$ km, $l_{LT} = 13.704$ km, $l_{TK} = 24.347$ km, $l_{LK} = 14.398$ km, $l_{LT} = 9.949$ km. The angles are $\alpha_{TK} = 38.179°$, $\alpha_{LK} = 66.332°$, $\alpha_{LT} = 54.021°$. The expected signal azimuths are $A_T = 170.879°$, $A_L = 170.766°$, $A_K = 170.502°$. The measured values are $A_T = 169.167°$, $A_L = 166.201°$, $A_K = 171.323°$ which mean errors $\varepsilon_T = -1.71°$, $\varepsilon_L = -4.57°$, $\varepsilon_K = 0.82°$ respectively. Measured wave front delays between receivers are $\tau_{TK} = 64.0$ $\mu$s, $\tau_{LT} = 45.7$ $\mu$s, $\tau_{LK} = 109.8$ $\mu$s. As the sampling interval is 10 $\mu$s these delays mean correlation method is not effective because signals are shifted in time domain only to several samples.
Figure 7. Results of phase measurements for 19.8 kHz signal (a), phase difference time diagram (b) and histogram (d). A 250 ms fetch (c) of the carrier phase simultaneously detected by all receivers.

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