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ALGORITHM FOR AUTOMATIC DETECTION OF WHISTLERS IN REAL-TIME MODE

E.A. Malysh

Kamchatka State University by Vitus Bering, 683032, Petropavlovsk-Kamchatskiy, Pogranichnaya st., 4, Russia

E-mail: malysh_e_a@mail.ru

Algorithm for automatic detection of whistlers is described in the paper. It is based on the non-linear transformation of VLF signal spectrograms. In a converted spectrogram, a whistler graphic pattern is presented by a straight line, the recognition of which is an algorithmically simple task. Tests of the implementation of the algorithm showed that recognition can be carried out in real-time mode.

Key words: whistlers, lightning discharge, pattern recognition, automatic detection of whistlers.

Introduction

Whistlers are special radio signals of very low frequency (VLF) range generated in the result of propagation of an electromagnetic pulse of lightning discharge in the Earth plasmasphere along a field tube of the magnetic field.

A wave generated by pulse radiation penetrates into the Earth magnetosphere and comes back to a magnetically conjugate point where it may be registered. Trajectories of propagation of such waves are shown in Fig. 1.

During its propagation, a whistler suffers frequency dispersion: first, high-frequency components of a signal come, then the lower frequencies with a progressive delay. Forms of the dispersion curves significantly depend on the plasmasphere state, in particular, on electron concentration, that makes a whistler a natural indicator of the Earth plasmasphere state. Thus, investigation of whistlers is the urgent task for cosmic weather studies [5].

Graphic pattern of whistlers in VLF signal spectrograms

A whistler can be distinguished only on a dynamic spectrum of a signal. The actual pattern of a whistler in the dynamic spectrum is an acinaciform curve, the recognition of which is a difficult task due to its complicated geometric shape (Fig. 2). The acoustic pattern of such a signal is whistle that gaves the name "a whistler".

Malysh Ekaterina Alexandrovna – Assistent of Dept. Informatics, Vitus Bering Kamchatka State University.

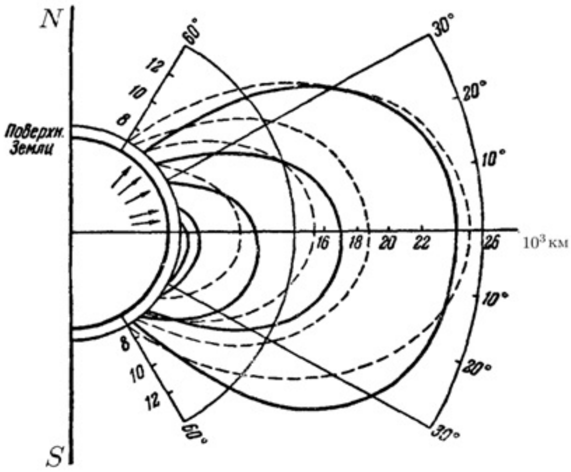

Fig. 1. Trajectories of whistler propagation (solid lines) and the Earth magnetic field tubes (dashed lines).

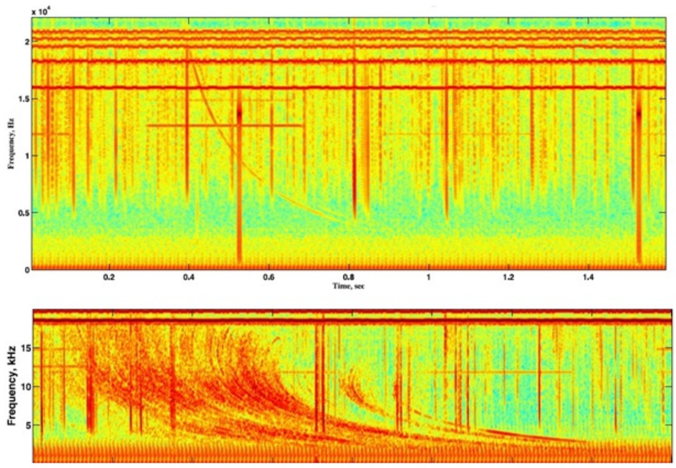

Fig. 2. Whistler characteristic pattern in spectral-time diagram. A single whistler in the top and a whistler group at the bottom.

In Kamchatka, IKIR FEB RAS stations record whistlers by a VLF direction-finder constructed by the institute staff. A signal received by the instrumentation is pre-processed and is saved as a wav file having the duration of 15 minutes.

Besides, to process whistler fluxes in real-time mode, we need a reliable computer-assisted system for whistler detection in a spectral-time diagram of a signal [2].

At present, IKIR has a recognition system based on neural networks and matching with a tamplate whistler [4]. However, the time of recognition in this system does not allow us to work in real-time mode. Thus, we had to develop a new algorithm for detection of whistlers in VLF signals.

Description of the algorithm

The idea of the algorithm is the nonlinear transformation of coordinate axes, the aim of which is the straightening of whistler curve in new coordinates. The formulas for this transformation are calculated on the basis of the theory of whistler propagation in the magnetosphere [1]. Detection of a "straightened" whistler is algorithmically a more simple task and it is more stable in the sense of calculation. After the recognition, whistler parameters are calculated back into the initial coordinates.

In general view, the algorithm includes three stages (Fig. 3):

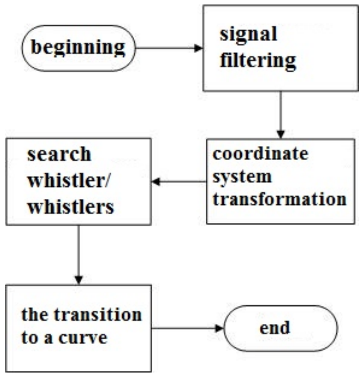

Fig. 3. Block-scheme of the algorithm for detection of whistlers in VLF signals.

1. «*Signal filtration*».

Three arrays are sent to the algorithm input, they are: frequency array $F(f_j), j = 1,...,n$, time array $T(t_i), i = 1,...,k$, and amplitude array $A(t_i, f_j)$. Filtration includes 2 steps:

Stap 1. All the points of amplitude array, the frequency of which is less than 1 kHz and more than 7 kHz, are zeroed.

Step 2. Looking through all the values of amplitude array $A(t_i, f_j)$, we choose the maximum. Than, we find some percentage from this maximum and leave only the points which exceed it $(A(t_i, f_j) = 1)$. All the rest of the points are zeroed. Thus, we have a filtered array, which contains the values «0» and «1», where «0» are the removed points and «1» are the points left after the filtration. Percentage is determined empirically. Therefore, the points corresponding to background noise are removed from the graph (Fig. 4).

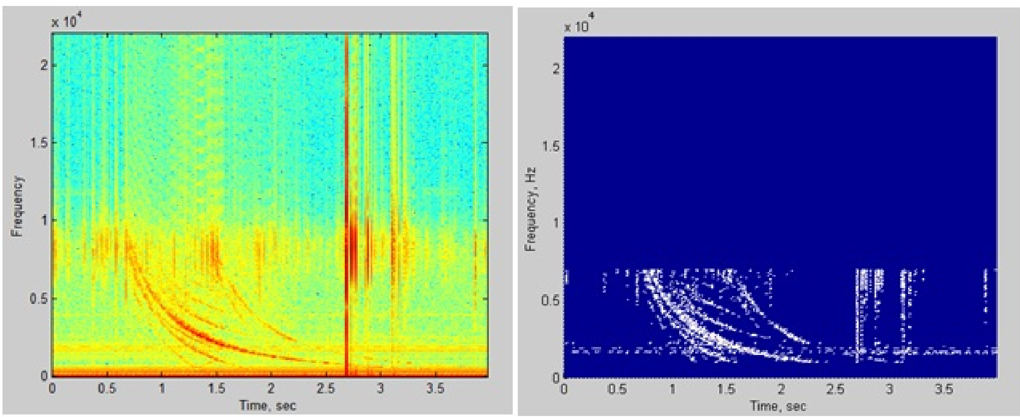

Fig. 4. To the left is the initial signal, to the right is the signal after the filtration, the remaining points are marked by the wight color.

2. «Transformation of coordinate system».

The following dependence of frequency at the given moment on time is known [1]:

$$t - t_0 = \frac{D}{\sqrt{f}} \tag{1}$$

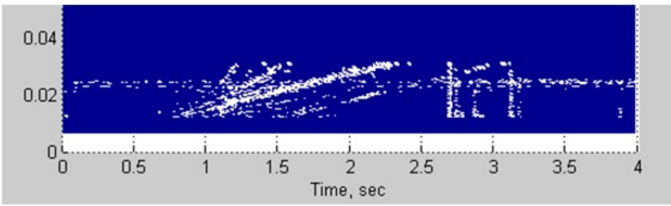

Fig. 5. Whistler pattern in coordinate system $(t, \frac{1}{\sqrt{f}})$.

Here t_0 is the moment of signal occurrence. Then, in the coordinate system $(t, \frac{1}{\sqrt{f}})$, straight lines, the presence of which is further recognized, should correspond to whistlers (Fig.5). At this step we transform the array $F(f_j)$ into a new one $F_{new} = \frac{1}{\sqrt{f}}$. We make an array with the dimension P to store filtered point coordinates. Thus, only separate points are left the number of which is less than in the initial array.

3. «Search for a whistler/whistlers».

In the new coordinate system, we go through all of the rest points $(t_i, \frac{1}{\sqrt{f_i}})$, where $i = 1...P$. For each point we calculate the distance D from the origin of coordinates to a straight line though this point and set at some angle $\varphi \in [0;90]$ (Fig. 6, a).

$$D = \sin\varphi t_i - \frac{\cos\varphi}{\sqrt{f_i}} \tag{2}$$

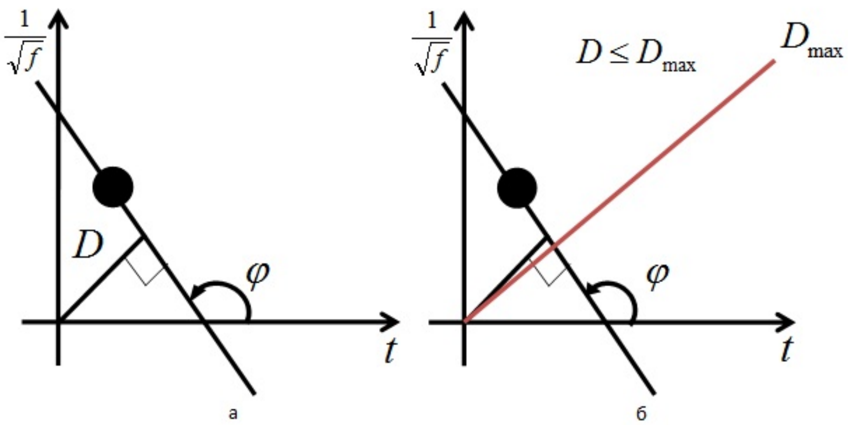

Fig. 6. Recognition of straight lines corresponding to whistlers.

Now we find the distance to the outermost point D_{max}, and any of the determined distances D will not exceed the distance to D_{max} (Fig. 6, б).

$$D_{max} = \sqrt{T(t_k)^2 + Fnew(\frac{1}{\sqrt{f_n}})^2} \tag{3}$$

We divide the interval $[0;D_{max}]$ by s equal segments and determine which segment contains D. We make a two-dimensional array $N(\varphi,s)$, the first value of which is the current angle φ, and the second one is the current segment (the one which contains distance D). For concrete values of the angle and the segment we increase the hit counter $(N(\varphi,s)++)$. Thus, the array $N(\varphi,s)$ will store the data on the number of points, the straight lines to which are set at a concrete angle φ and the distance to these points fall within a concrete segment s. The calculation is based on the fact that all the points of one straight line have the same angle of inclination and the same distance from the origin of coordinates to this straight line.

Then we analyze the obtained array. If the maximum is clear in the array, there is a whistler. If there are several maximums, the signal contains several whistlers. If there are not any maximums, there is no whistler (Fig. 7).

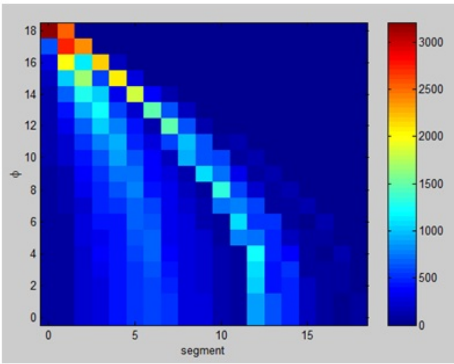

Fig. 7. Analysis of the obtained array, presence of a maximum at a point (0,18).

Maximum is a threshold value which is determined empirically.

4. «Transition to a "curve".

After the conclusions we return to the initial coordinate system.

Conclusions

That is the general idea of the detection algorithm. The algorithm was implemented as a software complex. At present, the developed program is being tested on real signals of VLF range. Realization of the algorithm showed that the posed task was solved, that is recognition of whistler patterns in real-time mode. Tests showed that it takes 4.5 minutes to process a 15-minute file. Next we plan to optimize the software complex to decrease the time for signal processing.

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