System approach to identification of geopulses

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Abstract. A new system approach to the identification and systematization of geophysical pulses is described. It includes stages of detection, analysis, object and structural description, pulse classification. In order to identify the pulses in geoacoustic emission, we apply a method based on the calculation of adaptive threshold, the values of which are estimated by the results of signal root-mean-square deviation in a moving window of a defined size. The detected pulses are described and identified by an adaptive matching pursuit algorithm which allows us to decompose the pulse into linear combination of basic functions from a combined Gauss-Berlage dictionary with minimum spatial and time costs and with the required accuracy of constructed approximations. Within the framework of object approach, pulses are described by a combination of features such as the number of functions in a decomposition, function type, parameters etc. We present a method of reduction of innumerable diversity of identified pulses to a denumerable set of patterns. It is based on structural transformation of geoacoustic emission pulses with simultaneous automatic procedure of classification. The results obtained during the application of the described system approach to the analysis of geoacoustic signals are summarized in a Geophysical Signal Catalogue.

1. Introduction

Systematization of geophysical signals is the main part of a system approach to geophysical data processing. The diversity of methods and forms of geophysical data acquisition and representation is a subject to the legal basis of metrological support. When collecting data, one should meet the requirements, norms and rules of the applied measurement models according to established standardized methods. At the present time, there are governing documents in the field of investigation of geophysical signals. They determine the applied terminology and do not regulate long-term observation result representation. That complicates significantly the processing of great electronic storages of accumulated data and makes them inaccessible for wide scientific and engineering communities.

In view of this, the scientists from the Laboratory of Acoustic Research at the Institute of Cosmophysical Research and Radio Wave Propagation (IKIR) FEB RAS decided to develop a method to unify and automate the procedure of geophysical signal classification. Long-term observation data (2001-2018) were used as the experimental base for the research.

Based on the investigations which had been carried out earlier [1–12], we suggested applying a system approach for the investigation and description of geophysical pulses and for the formation of
Geophysical Signal Catalogue (hereafter Catalogue). In order to realize it, current scientific groundwork and experience in geoacoustic emission (GAE) signal investigation were applied during the first phase [10, 13–20]. The aim of the scientific-technical works realized at this stage was systematization and classification of GAE pulses on the basis of system approach to the investigation and description of the variety of forms (patterns) of these pulses.

The process of geophysical signal description is divided into three stages: pulse detection; pulse inner time-frequency structure analysis followed by detection of characteristic features; classification of pulse signal forms.

2. Methods and algorithms for data processing and analysis

At the first stage of GAE signal processing, single pulses were detected. Investigation of specific properties of geoacoustic signals allowed us to reduce the pulse detector threshold value by 3-5 dB for fixed probability of correct detection of pulses. The developed algorithm of the detector is called logical filtering (figure 1). Its main idea is that a signal fragment, detected by the detector threshold scheme, is tested for the completeness of a wavetail of local maxima and minima on its extension. If the length of a continuous sequence of local extrema discovered in a signal exceeds the defined value \( N \), then this signal fragment is taken as the required pulse. And vice versa, if the number of consecutive local extrema is less than the defined threshold \( N \), the signal fragment is equal to zero.

This simple algorithm turns to be quite effective owing to the physical peculiarities of GAE pulse generation since sedimentary rock fractions with non-uniform density become the sources of oscillations of different frequency, duration and amplitude under external force action. The specific character of the suggested algorithm does not affect calculation of extrema number in detected signal fragments.

**Figure 1.** Block diagram of logic filter algorithm.
Operation algorithm of the filter is the following:

- digitized GAE signal with the sampling frequency of 48 000 Hz is processed by a low-frequency filter with the cut-off frequency chosen according to an investigation task (from 12 000 Hz to 16 000 Hz). This operation allows us to suppress noise high-frequency component and to decrease the impact of its single peaks (block 1);
- threshold \( Th_k \) is calculated for the filtered signal \( s(n) \) in a moving window on the basis of root-mean-square deviation (RMS) of a signal (block 2). Threshold values are calculated in a moving window (without superposition) of a fixed length \( n \) by the formula
  \[
  Th_k = B \cdot \sigma_k ,
  \]
  where \( Th_k \) is a threshold in a window from \( k \)-th to \( k+n-1 \)-th sample, \( n \) is the window length in filtered signal samples, \( \sigma_k \) is the RMSD calculated in a window from \( k \)-th to \( k+n-1 \)-th sample, \( B \) is the experimentally determined parameter. In order to compensate the pulse impact on the threshold value, we chose a long window (more than 5 000 samples of a digitized signal, as a rule);
- the threshold value \( Th_k \) is compared with filtered signal sample value, then, based on the comparison results, a control signal \( x(n) \) is formed (block 3). In this case, \( x_i = 1 \) if the values of corresponding signal samples \( s(n) \) exceed the threshold value \( Th \) and, in the contrary case, \( x_i = 0 \).
- signals \( x(n) \) and \( s(n) \) from the delay line output arrive to block 4 which has the function to cut the GAE signal fragments according to the control signal values: if \( x_i \neq x_{i+1} \) then a new fragment is formed from \( s_{i+1} \);
- the obtained fragments of GAE signal \( \{s_k(n)\} \) come by turn to block 5 input, where local extrema (maxima and minima) of each fragment \( s_k(n) \) are determined and their number \( m_k \) is calculated;
- the number of local extrema \( m_k \) is compared with the set threshold value \( N \) equal to the length of a defined wavetail of local extrema (block 7). Thus, a decision is made on the identification of a fragment as GAE pulse or detector false response;
- in the first case, the fragment \( s_k(n) \) from a storage device, where signal fragments are stored until a decision is made (block 6), remains unchanged. In the second case, a zero signal is formed, its duration coincides with the omitted fragment that provides continuity of a sequence of output signal samples \( s_{\text{out}}(k) \) (block 8).

The results of calculation experiments showed that application of a logic filter allows us to reduce significantly the number of second-kind errors (detector false response) in the signal-noise ratio from 0 dB to 3 dB. The value of such a result is the increase of the first-order error (countdown). However, in practice, elimination of false responses makes it possible to select just those pulses which further form a dictionary of GAE pulse structural patterns.

At the next stage of processing, signals are standardized, centered and analyzed by sparse approximation methods.

Solution of sparse approximation problem assumes signal \( s(t) \) representation in the form of a linear combination of minimum possible number of functions (time-frequency atoms) \( g_m(t) \) from a preliminary selected basis (dictionary).

\[
 s(t) = \sum_{m=1}^{N} c_m g_m(t), \quad \|c\| \rightarrow \min,
\]  

(1)

where \( c \) is the decomposition coefficient vector.
Approximation accuracy and sparsity depends directly on a selected function dictionary. A dictionary, composed of modulated and shifted Gaussian and Berlage functions, is appropriate for GAE signal analysis.

Gaussian pulse is defined by analytical expression

\[ g(t) = A \cdot \exp(-B(t_{\text{end}}) \cdot \Delta \cdot t^2) \cdot \sin(2\pi ft), \]

where \( A \) is the amplitude chosen so that \( ||g(t)||_2 = 1 \); \( t_{\text{end}} \) is the atom length; \( f \) is the frequency from 200 to 20 000 Hz (recorded frequency range); \( B(t_{\text{end}}) \) is the parameter \( B \) limit value calculated by the formula

\[ B(t_{\text{end}}) = -4 \cdot \ln 0.05 \cdot t_{\text{end}}^2; \]

\( \Delta \) is the coefficient of parameter \( B \) variation relatively the limit value.

Berlage pulse is defined by analytical expression

\[ g(t) = A \cdot t^{n(p_{\text{max}})} \cdot \exp\left(-\frac{n(p_{\text{max}}) \cdot \Delta}{p_{\text{max}} \cdot t_{\text{end}}} t\right) \times \cos\left(2\pi ft + \frac{\pi}{2}\right), \]

where \( A \) is the amplitude chosen so that \( ||g(t)||_2 = 1 \); \( t_{\text{end}} \) is the atom length; \( p_{\text{max}} \) is the location of a maximum relatively atom length, \( p_{\text{max}} \in [0.01, 0.4] \); \( f \) is the frequency from 200 to 20 000 Hz; \( n(p_{\text{max}}) \) is the \( n \) parameter limit value calculated by the formula

\[ n(p_{\text{max}}) = \frac{\ln 0.05}{-\ln p_{\text{max}} - (p_{\text{max}})^{-1}} + 1; \]

\( \Delta \) is the coefficient of parameter \( n \) variation relatively the limit value.

Sparse approximation problem (1) is unsolvable for polynomial time. Exact solution algorithm requires complete enumeration of all possible function combinations from a dictionary, i.e. it has factorial complexity \( O(N!) \). In order to make the calculation faster, we applied the algorithm of approximate solution for sparse approximation problem by Matching Pursuit (MP). The algorithm was suggested in the paper [21]. The algorithm can be written in the form of the following procedure:

\[
\begin{align*}
R_0(t) &= s(t), \\
(m, h) &= \arg \max_{k,j} \langle g_k(t - \tau_j), R_i(t) \rangle, \\
R_{i+1}(t) &= R_i(t) - \langle g_m(t - \tau_h), R_i(t) \rangle \cdot g_m(t - \tau_h),
\end{align*}
\]

where \( R(t) \) is the residual, \( \tau \) is the function \( g(t) \) shift relatively a signal \( s(t) \).

The Matching Pursuit algorithm has significant disadvantages. Firstly, to provide decomposition sufficient accuracy, we need to apply dictionaries of larger sizes that entails power growth of algorithm execution speed. Secondly, as long as functions are selected from an unchangeable dictionary, the obtained decompositions differ by “rough” sampling in parameter space. In order to solve these problems, we suggested improving the classical algorithm so that we could make decomposition of the required accuracy on a dictionary of a limited size. Because function parameters having the highest scalar product with a signal are defined at each iteration of the algorithm, the matching pursuit iteration may be described in the form of a problem of search for function maximum of many variables

\[ F(\tau, \mathbf{p}) = \langle s(t), g(t - \tau, \mathbf{p}) \rangle \rightarrow \max_{\mathbf{p}}. \]
The main idea of the suggested improvements is the application of optimization methods to define the parameters $p$ of the function having the maximum scalar product with a signal. The developed algorithm was called “Adaptive Matching Pursuit” (AMP) [17; 22].

Thus, in the result of the analysis within the framework of the object approach, each signal may be an object with the following attributes, reflecting signal characteristic features:

- Length (samples).
- Date and time of signal recording (with the accuracy to ms).
- Number of functions contained in $N$ pulse.
- Resulting error (in %) calculated by the formula $ERR_N = \|R_N\| \cdot \|s(t)\|^{-1} \cdot 100\%$.
- The following items are given for each function:
  a. type (Berlage or Gaussian);
  b. shift $\tau$ (samples; if the value is negative a function is shifted to the left relatively a pulse);
  c. basic length (maximum possible function length, length and maximum location are calculated relatively this value);
  d. length $t_{end}$ (% relatively the basic length (c));
  e. maximum location for Berlage functions $p_{max}$ (% relatively the length (d));
  f. filling harmonic frequency $f$ (Hz);
  g. variability coefficient $\Delta$ (affects the envelope function steepness: the higher the value is the steeper the envelope is).

To automate the process of geoacoustic pulse characteristic feature detection, we apply “MP Complex” software. It includes four subsystems: dictionary generation subsystem “Dictionary Constructor”; signal analysis subsystem “MP Analyzer”; visualization subsystems “MP Visualisator” and “SIG View” [22].

The authors suggest the following GAE pulse model developed on the basis of signal sparse approximation:

$$
\begin{cases}
  s(t) = \sum_{n=1}^{N_1} \alpha_n g_n(t) + \sum_{n=N_1+1}^{N_1+N_2} \beta_n g_n(t) + R_N(t), \\
  \|R_N(t)\| \rightarrow \text{min}, \\
  \|\alpha\| + \|\beta\| \rightarrow \text{min}.
\end{cases}
$$

This model meets the following requirements:

- functions $g(t)$ belong to linear normalized space $L_2(R)$;
- dictionary $D = \{g(t)\}_{1 \leq i \leq K}$ is redundant;
- $g(t)$ are time shifted, modulated Gaussian and Berlage functions. Each atom is uniquely determined by a parameter set $p$: frequency $f$ and the parameters affecting pulse envelope form;
- atoms are standardized $\|g(t)\| = 1$;
- coefficients $\alpha, \beta$ and function parameters $p$ are identified by the matching pursuit algorithm.

Figure 2 illustrates the models of two GAE pulses. The number of atoms providing the model sufficient accuracy are determined by $ERR$ calculated by the ratio of residual norm to initial signal norm:

$$
ERR_N = \frac{\|R_N\|}{\|s\|} \cdot 100\%.
$$
The expansion is stopped when $ERR$ reaches the threshold value of 5%.

![Figure 2. Model examples of two GAE pulses (Wigner-Ville transform contours were calculated by level 0.2).]

In order to visualize the time-frequency structure of the models, we chose the Wigner-Ville transform as long as its time-frequency resolution depends minimally on the length of a signal under analysis.

$$P^s_\tau(\omega) = \frac{1}{\pi} \int_{-\infty}^{\infty} \left| s\left(\tau + \frac{t}{2}\right) \right| \left| s\left(\tau - \frac{t}{2}\right) \right| \exp(-i\omega t) dt.$$  

However, as long as the transform is nonlinear and is constructed on the bases of a quadratic function from the initial signal, than a strong interference component manifests in the mapping for additive signals. Thus, we decided to estimate the Wigner-Ville transforms for each atom included into the signal model (2) separately and to superimpose their mappings on each other on a time-frequency plane.

The described method for detection and analysis of geoacoustic signals allowed us to solve the problem of GAE pulse identification effectively. However, improving the measurement accuracy entails exponential increase of the applied computational recourses and causes combinatorially dependent diversity of acceptable forms of a signal that results in a serious problem of formation of a basic set of typical GAE pulses.

Solution of this problem is the application of an approach providing invariant transformation of signal model. The transformation is based on the representation of identified pulses in the form of amplitude-phase structure describing the relation of local extrema of these pulses. Such an approach allows us to represent a signal within the framework of a closed set without threshold values of amplitude quantization level and sampling period arising during the process of analogue signal
digitization. Transformation invariance is achieved by pulse reduction into a sequence of its local extrema and intervals between them. The transformation essence is illustrated in figure 3.

$$\begin{align*}
    r_{i,j} &= \begin{cases} 
    1, x_i > x_j, & i, j = 1, N; \\
    0, x_i \leq x_j, & i, j = 1, N; \\
    \end{cases} \\
    \omega_{i,j} &= \begin{cases} 
    1, \tau_i > \tau_j, & i, j = 1, N; \\
    0, \tau_i \leq \tau_j, & i, j = 1, N; \\
    \end{cases}
\end{align*}$$

(3)

where \( r_{i,j} \) is the result of logical comparison of \( i \)-th and \( j \)-th values of extremum amplitudes; \( \tau_{i,j} \) is the result of logical comparison of \( i \)-th and \( j \)-th interval values between the extrema. We put in order the series of such relations in the form of square matrices for \( N \)-relations \( r_{i,j} \) and \( \omega_{i,j} \). The obtained matrices are redundant owing to the algebraic property of inequality asymmetry (if \( a > b \), then \( b < a \)), thus, we will apply only halves of each of the matrices.

\[
R = \begin{bmatrix}
0 & r_{1,2} & \cdots & r_{1,N-1} & r_{1,N} \\
r_{2,1} & 0 & \cdots & r_{2,N-1} & r_{2,N} \\
\vdots & \ddots & \ddots & \ddots & \vdots \\
r_{N-1,1} & 0 & \cdots & 0 & r_{N-1,N-1} \\
r_{N,1} & r_{N,2} & \cdots & r_{N,N-1} & 0 \\
\end{bmatrix},
\]

(4)

\[
W = \begin{bmatrix}
0 & \omega_{1,2} & \cdots & \omega_{1,N-1} & \omega_{1,N} \\
\omega_{2,1} & 0 & \cdots & \omega_{2,N-1} & \omega_{2,N} \\
\vdots & \ddots & \ddots & \ddots & \vdots \\
\omega_{N-1,1} & 0 & \cdots & 0 & \omega_{N-1,N-1} \\
\omega_{N,1} & \omega_{N,2} & \cdots & \omega_{N,N-1} & 0 \\
\end{bmatrix}.
\]

(5)

Matrixes (4) and (5) describe signal segment (pulse) characterizing mutual position of local extrema. As a consequence of application of relation rule (3), transformation of a signal fragment from \( N \)-extrema into matrixes (4) and (5) has invariant property to shift operations as well as initial signal amplitude and time transposition. The obtained important property of insensitivity to matrix shift follows from inequality main property: if \( a > b \), then \( a + c > b + c \) for any \( c \) for the operation of signal time shift, and if \( a > b \) and \( c > 0 \), then \( a \cdot c > b \cdot c \) for signal transposition operation. In the result,
some graphic invariant of signal form (pattern) can be related to each obtained pair of matrixes (4) and (5). Such a description gives the information on signal structure in relations of its extrema. When applying the transformation, we can describe any fragment of a signal. An example of such structural description is illustrated in figure 4.

Figure 4. Examples of structural description of a signal fragment, obtained by author software “Registry”. At the top on the left is an episode of a digitized signal with a selected fragment; on the right is a matrix of selected fragment relations in symbols “greater than”, “less than” or “equal to”; at the bottom is a selected fragment pattern constructed on the basis of relational matrix.

Experiments to form a GAE pulse pattern set showed that the dimension of such a set exceeds the hundreds and thousands of patterns on the signals with the duration from 5 to 15 minutes. For quantitative estimate of pattern set changeability during the transitions from one state to another, we chose the estimate of static overlap degree of two adjoint states characterized by the following sets:

\[ K = \frac{|A_j \cap A_{j+1}|}{|A_j \cup A_{j+1}|} \times 100\% , \]

where \( A_j \) and \( A_{j+1} \) are the sets of \( j \) and \( j+1 \) states. For different time fragments of the signal, \( K \) estimate is 10-20%. Such a result is determined by the distortions caused by acoustic wave passage through heterogeneous medium changing the time-frequency portrait of an initial signal as well as by the noise impact which change significantly the amplitude ratios of local extrema wavetails. In order to change the situation, an algorithm for reduction of the detected pulse basic set was developed.

The foundation of the mechanism of GAE pulse basic set reduction is the procedure of determination of the coincidence degree of structural description matrixes comparable in order values. Matrixes \( A_{n \times n} \) and \( B_{m \times m} \) \((n \geq m)\) are comparable if \(0 \leq (n - m) / n \leq P\), where \( P \) is an empirically selected threshold. Comparison of matrixes of the same order is realized by the calculation of coincidences of their elements when superimposing the matrixes on each other. If order values are different \((n > m)\), \(n - m + 1\) comparisons are performed. In this case, at the first comparison the matrix of \( m \) order is inserted into the matrix of \( n \) order so that the first elements of first lines coincide. For further comparisons, the shift is made along a larger matrix diagonal that is the less-order matrix is shifted by one element to the right and downward. Based on the results of \( n - m + 1 \) comparison, the largest number of coincidences is chosen. This value is compared with the threshold calculated by
empirically obtained formula $S = g \cdot m^2$. If the largest number of coincidences exceeds the threshold $S$, the structures of the compared pulses are assumed to be close. In this case, occurrence frequency statistics of a pulse with structural matrix of a larger order increases by the value of occurrence frequency statistic of a matrix of less order. Pattern with the matrix of less order is removed from the alphabet of signal fragment under analysis. An example of comparison of two matrixes of orders 5 and 3 is shown in figure 5.

![Matrix Comparison](image)

**Figure 5.** Representation of operation sequence during the comparison algorithm of 5- and 3-order matrixes, respectively (explanation is in the text).

Application of the algorithm allowed us to reduce the dimensions of identified pulse sets by an order and to increase $K$ estimate to 80-90%.

3. Results

Observation data of IKIR FEB RAS were processed and analyzed by the described method. As an example, the results of processing of 15-minute fragment record from January 18, 2016 (“Karymshina” site, Kamchatka) are presented. We detected 21 GAE pulse with different structural matrixes with order values from 10 to 19 by the threshold scheme. Before the method was applied, the number of detected patterns coincided with the number of pulses. Each pattern described only one pulse. When the method was applied with threshold $g = 0.8$, the alphabet reduced to 6 patterns (reduction by 3.5 times). In this case, characteristic profile of pattern rank distribution with defined maxima up to 14 for the most frequently observed similar pulses (figure 6).

Figure 7 illustrates time-frequency representations of models for three pulses described by one pattern. It is clear from figure 7 that the models of these signals have similar structures.

A new approach has been proposed to describe the geoacoustic emission pulses structure and to create a Geophysical Signals Catalogue on its basis. During the process of realization of the described approach to describe GAE measurement results, we obtained unique data on the diversity, specification and characteristics of geoacoustic signals in near-surface rocks. To automate the description process of a pulse set included into the Catalogue, a software application “Registry” was written. Currently, the number of pulses included in the Catalogue is 40 284.

The developed method of geoacoustic pulse detection and identification uses indicators which are invariant to the amplitude and time transposition of the detected pulse forms. Thus, this method is fundamentally different from the techniques previously applied to study geoacoustic emission signals.
Figure 6. Initial signal fragment (a); order distribution of patterns before the method application, the number of described pulses is inside the squares (b); order distribution of patterns after method application (c).

Figure 7. Visualization of models of three GAE pulses (Wigner-Ville transform contours were calculated by level 0.2): pulse time forms (a); time-frequency structure models corresponding to them (b); pulse describing patterns (c).
4. Conclusions

- Based on the developed object description of pulses applying decomposition in a combined dictionary of Gaussian-Berlage functions, analyzed signals were decomposed into basic functions with high accuracy.
- Owing to the developed format of pulse characteristics representation in the form of a unified pattern, we demonstrated the possibility of graphic and self-explanatory description of GAE pulse set, their automatic search and sorting based on a defined pattern field set.
- By the means of structural description of selected pulses in the form of specific matrix-pattern, we demonstrated clearly the countability of geoacoustic pulse endless variety.
- In the result of geoacoustic signal processing applying the developed pattern, we created an object base for their further analytical examination in classes based on semantic information binding and detection of group properties.
- Finally, on the basis of object systematization by characteristic features and application of the object approach to data representation, Geophysical Signal Catalogue has been formed.

5. References

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