Informational approach to the analysis of acoustic signals

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Abstract. The example of linguistic processing of acoustic signals of a seismic event would be an information approach to the processing of non-stationary signals. The method for converting an acoustic signal into an information message is described by identifying repetitive self-similar patterns. The definitions of the event selection indicators in the symbolic recording of the acoustic signal are given. The results of processing an acoustic signal by a computer program realizing the processing of linguistic data are shown. Advantages and disadvantages of using software algorithms are indicated.

1 Introduction

A method of signal processing that uses procedures of decomposition in non-orthogonal basis group of information processes' self-similarity mechanisms in the context of acoustic signals in cosmophysics is proposed. Scientific interest is caused by similarity of models of synergetics nonequilibrium systems with catastrophic events that occur in lithosphere and atmosphere. We expect to see this similarity in properties of signals caused by those events.

There is a feature of acoustic signals due to unsteadiness properties, notable episodic occurrence of energy anomalies, and frequent nonlinearity manifestation, which is generated by the dynamics of the nature of the source of such signals. Methods of preliminary processing that are traditionally applied to the signals, such as factorization, statistical accumulation and approximation methods often appear to be incorrect conversion operations or require strict restrictions on the dynamics of the frequency and time behaviour of the signal. During measurements caused by the seismic activity of acoustic signals, decomposition techniques in known basis functions are frequently used. In this case, a significant variability of the optimal set of decomposition elements from one measurement episode to another is detected due to previously named features of processed signals. In such cases, the incorrect application of spectral analysis often leads to erroneous conclusions [1]. In addition, the classical methods of isolating a useful time-localized seismic signal operate at a signal-to-noise ratio exceeding background noise several times. However, during the most part of the observation time it is impossible to detect weak signals that are harbingers

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of seismic events. As a rule, physical events in the geosphere, accompanying the accumulation of critical values of the parameters prior to the moment of a catastrophic event, have a low amplitude, frequently due to the significant diversity in the space of the source and receiver of the signal and the conditions of its propagation. Comparable in intensity with background, desired signal that has similar probabilistic characteristics with a masking background does not allow the effective use of classical spectral and correlation methods as well as popular non-orthogonal decompositions and neural networks. Nevertheless, a mixture of useful signal and background obviously carries in itself useful information. It should be expected that the nature of this useful signal and background should depend on the state of the environment, where seismic processes constantly change its isotropic and homogeneous properties. This affects the conditions for the propagation of acoustic waves, which is reflected in a variety of ways on the characteristics of the signal itself and is expressed in the form of additive-multiplicative phase-frequency distortions. Due to the local distribution of the inhomogeneous radiation boundaries of the signal source in space, there are also additional phase delays with respect to the point receiver. In such conditions, to obtain useful information, the task of detecting and recognizing seismic events is better to be considered not as a task of restoring (isolating) the original signal or isolating it from the background. But as a task of estimating the extent of the environment-induced change in the received message at various consecutive measuring moments including both a distorted "useful" signal, and a change in the background obtained at the point of reception.

2 Method of investigations

To decipher the received signal mixture plus background, we propose a methodology based on the principles of synergetics that allow considering received signal as a function of reflecting the reaction of the system in the process of its probabilistic transitions in the network of possible states of this system. In this case, to assess the current state of the system, it is advisable to apply an information approach to data analysis. In the considered practical case, the analysis of the received acoustic signals is depending on whether it will be changed in a certain time window. A search is carried out for some information units characterizing the signal, as well as the identification of characteristic consecutive episodes of amplitude-phase variability of the signal (patterns). The degree of changes in signal structure can be estimated by cyclic calculation of the increment of information entropy values based on the extracted patterns.

The stated representations are consistent with the well-known approach to describing the behaviour of a certain class of stochastic dynamical systems in the form of symbolic dynamics [2]. If the set of admissible states of the system is $\{Qi\}$ ($i = 1, 2, …$), then the result of consecutive N steps of the process can be written in the form of a Markov chain $Qi_1, Qi_2, … Qi_N$. Such a record is equivalent to describing its evolution in the language of "letters" $\{i_N\}$ of the corresponding "alphabet". Symbolic dynamics allows considering selected sequences as a set of "messages" or "texts" containing certain information.

For the use of symbolic dynamics in the presented study, the previously developed algorithms for the linguistic analysis of physiological signals were adapted [3]. These algorithms were used to convert an acoustic signal into a symbolic form and compose the message text.

To introduce the conducted research into the plane of practical application, we describe below the developed method of converting acoustic signals into text messages. Subsequently, the results of this transformation are guided by the search for general patterns conditioned by the cause-effect relationships of the electromagnetic processes events in the atmosphere with deformation processes that generate acoustic emission in the lithosphere. Earlier such a connection was confirmed [4, 5].

The method is realized by performing two stages. During the first stage, the acoustic signals are converted into text messages, and then, based on the results of processing, event objects are compiled. The transformation is carried out by using a priori information about the objectively established facts of a seismic event manifestation fixed at a certain point in time. The initial stage of the selection of event objects is performed by processing self-similar signal structures through the developed computer program of preprocessing the accumulated records of the acoustic signals of the IKIR archive. Preprocessing includes standard converting of files to an accessible data format, searching for characteristic signal patterns, removing redundant patterns, converting a signal into a message, highlighting an event alphabet, forming a linguistic event object.

The algorithm for searching for signal patterns is constructed from the well-known position of synergetics that near stable states the system describes self-similar trajectories that are expected to correspond to similar fragments of the reflecting behaviour of the signal system. For processing from the whole signal, we choose only local extremes, each of which can be described by two parameters: the amplitude and the time interval that has elapsed since the previous local extremum. Here we should agree that this choice of the signal description saves the most significant information about its amplitude-phase characteristic. Let some fragment of the signal with N extremes be presented by a set, consisting of pairs of numbers x_1, τ_1 x_2, τ_2 ... x_N, τ_N , where x_i is the value of the extremum amplitude and τ_i is the time shift with respect to the preceding extremum ($\tau_1 = 0$). We calculate the ratios for each of the extremes as follows:

$$r_{i,i+m} = \begin{cases} 1, x_i > x_{i+m} \\ 0, x_i \le x_{i+m} \end{cases} \qquad \omega_{i,i+m} = \begin{cases} 1, \tau_i > \tau_{i+m} \\ 0, \tau_i \le \tau_{i+m} \end{cases} \qquad m = 1...M(M \le N - i) \qquad (1)$$

where $r_{i,i+m}$ is logical comparison result of *i*-th and *i+m*-th values of the extremum amplitudes; $\omega_{i,i+m}$ is logical comparison result of *i*-th and *i+m*-th values of intervals between extremes. We order the series of such ratios in the form of square matrices for M ratios of amplitudes of extremes and time shifts between extremes. The resulting matrices will have a diagonal symmetry because of the algebraic symmetry property of the inequalities ($a > b$ implies $b > a$) and in this sense are redundant. Therefore, we will use only half of each of the constructed matrices, which we combine into one. Bearing in mind that, in accordance with rule (1), values on the main diagonal of each of the original matrices are zero, we obtain

$$D_i = \begin{pmatrix} 0 & \omega_{i,i+1} & \cdots & \omega_{i,i+(M-3)} & \omega_{i,(M-2)} \\ r_{i+1,i} & 0 & & & \omega_{i+1,i+(M-2)} \\ \vdots & & \ddots & & \vdots \\ r_{i+(M-3),i} & & & 0 & \omega_{i+(M-3),i+(M-2)} \\ r_{i+(M-2),i} & r_{i+(M-2),i+1} & \cdots & r_{i+(M-2),i+(M-3)} & 0 \end{pmatrix} \qquad (2)$$

Matrix (2) represents a specific code for the selected (*i*-th) extremum in the signal. This code characterizes extremum's amplitude and time position with respect to neighboring extremum to a depth M to the right. As a consequence of the application of the rules of the relation (1), the transformation of the signal fragment from the M extremes into the matrix (2) has the property of invariance to displacement operations, as well as to amplitude and temporal transpositions of the original signal. This important property of the matrix follows from the basic property of inequalities:

$a > b \Rightarrow a + c > b + c, \forall c$ for the time shift operation of the signal, and

$a > b$ *and* $c > 0 \Rightarrow ac > bc$ for compression and stretching operations.

As a result, each of the resultant matrix (2) can be associated graphically with some invariant waveform (pattern).

When searching for patterns in a signal, the following rule is applied: if for two selected non-coincident (intersection of possible) sequences of local extremes the corresponding matrices of the form (2) of the same order M coincide, then the hypothesis is assumed that such a matrix describes a stable form invariant in the signal. The matrix itself can be interpreted as a definite sign – *symbol*. A more stringent constraint can be applied, given the need for more coinciding matrices for three or more episodes of the signal. We call a given restriction K the statistical threshold for the existence of a symbol in a signal, below which all the occurring combinations should be considered as insignificant or null-symbols (Z).

Figure 1 shows an example of the conversion of a signal fragment. With the rules described in this fragment of the alarm message, two symbols are allocated that have been assigned a conditional names a and b with dimensions 5 and 7, respectively. Below are the invariants of the symbols (templates) ordered in the amplitude of the extremum – II and the magnitude of the interval between the extremes – III.

The sequential application of the above algorithm for allocating patterns to each consecutive local extremum allows us to select a certain set of symbols – *alphabet*. Let's call *the size of the alphabet* $D = |A|$ the total number of alphabet symbols found in the message.

For example, the alphabet of the alarm message shown in the figure 1 is $A = \{a, b\}$, $D = 2$.

The resulting alphabet allows you to convert the signal into symbolic form. Such a symbolic record will be referred to hereinafter as a message. For a symbol, the value equal to the dimension of the corresponding matrix M, will be called the *dimension of the symbol*. In figure 1, the message in the selected symbols of the alphabet A looks like "abba".

The next stage of data processing is the allocation of collected alphabets to groups of events of a certain class and the formation of event objects on their basis. The task is solved by methods of linguistic parsing of sequences of objects of events [6]. For this, a number of evaluation parameters are introduced.
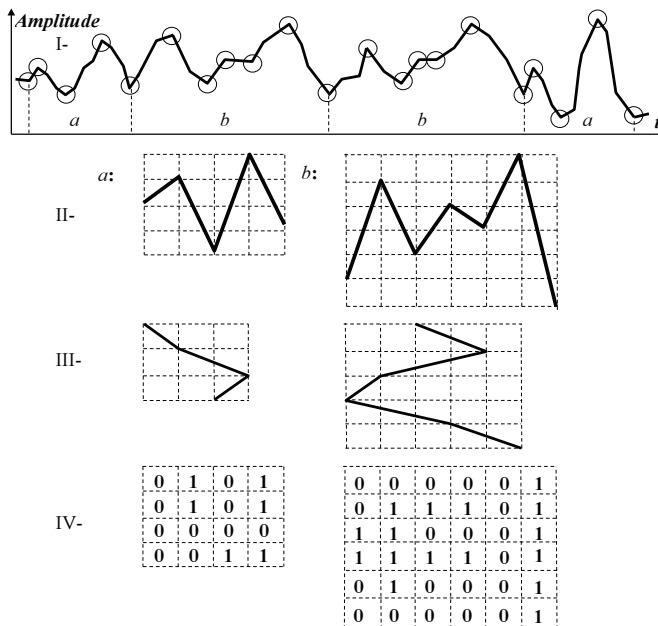

Fig. 1. Example of forming a matrix of relations for two patterns (a) and (b).

The frequency of the appearance of a symbol in the message is different and indicates the most preferable trajectory behaviour of the dynamic system. To estimate the frequency of the message, we will use the *probability of occurrence of the symbol a_i of the alphabet A*, which is equal to the ratio of the number of occurrences of the symbol in the message m to the total number of symbols in this message *N*.

$$P(a_i) = \frac{m}{N} \qquad (3)$$

From the point of view of information theory, indicator (3) is also an estimate of the information load per symbol of the alphabet. In accordance with the recommendations of the authors of symbolic dynamics [1], one should try to find connections at the level of the Markov chain of high orders, calculating the conditional probabilities of occurrence of combinations of symbols: $P(b \mid a) = P(ab)/P(a)$; $P(c \mid ab) = P(abc)/P(ab)$ … , where *a, b, c* are symbols of the alphabet $A = \{a, b, c…\}$ isolated from the signal. If we accept that in a certain stable state the set of events, characterizing the state of the system does not change over a long period, then it is logical to assume that the composition of the alphabet *A* of the perceived message, reflecting this set of events, and its dimension *N*, should also not vary. Change is allowed in the order of appearance of each of the message symbols or the order of the sequences of symbols indirectly reflecting some fluctuations in the state of the system. In other words, a hypothesis is put forward that within each stable state the system is able to generate only a fixed set of alphabet symbols of a certain dimension. If there is a change in the state of the system, this should entail a change in the set of events, which in turn should cause qualitative and quantitative changes in the alphabet composition that can be detected using elements of the theory of pattern recognition. Following the recommendations of the theory of pattern recognition [7], when developing the analysis apparatus, it is necessary to provide for the possibility of learning based on the accumulation of standards, which are some fixed sets of parameters for subsequent comparisons with the current set of parameters. In the case under consideration, these will be sets of parameters, consisting of alphabets, information on the probabilities of the appearance of symbols of different dimensions, which will be stored in the memory block of the linguistic signal analysis circuit.

The next parameter for evaluating the state of the system is the *alphabet size N*, which is the total number of alphabet symbols found in the message. Set $A = \{a_i\}$ and its dimension *N* for the model of the dynamic system can be linked with its stable state, when the trajectory moves near one or several nearby attractors, without going beyond the boundaries of their action. This state can be represented, for example, by a certain period of relaxation after a catastrophic event. Violation of stability in the system under the influence of external forces or currents can cause the system to transition to another stable state, in which the system, undergoing a qualitative transformation, will generate symbols of the alphabet, characteristic of another state. The manifestation of the variability of the system state can change the statistics of the appearance of the symbols of the original alphabet, and can also supplement it with new symbols, and/or lose some of the previous composition of the symbols. This is a prerequisite for the conclusion about the transitional state of the system at the semantic level.

3 Results of investigation and discussion

To demonstrate the operation of the method, we selected a file of acoustic observations from the IKIR archive, obtained from a vector receiver installed on Lake Mikijah, from Nord direction with duration of 15 minutes, on which a seismic event is recorded in the form of a visually observable sequence of pulses on February 5. The digitization rate of the signal was

48000Hz. Three fragments in duration 120 sec 2017 (figure 2 at the top) were cut out of file, and for comparison, the signal spectra corresponding to the fragments are presented (figure 2 at the bottom). The first fragment covers the interval immediately before the appearance of a visually identifiable series of pulses associated with a seismic event (A). The second fragment covers the observed impulse bursts of the signal (B). The third fragment represents the interval after 5 minutes after the marked seismic activity (C).

The figure shows an increase in the spectral power in the frequency range from 3 to 8 kHz with a rise in the maximum value at a frequency of approximately 4.5 kHz from -78 to -68 dB. The spectra before and after the seismic event practically differ neither in energy nor in the contour of the spectrum pattern.
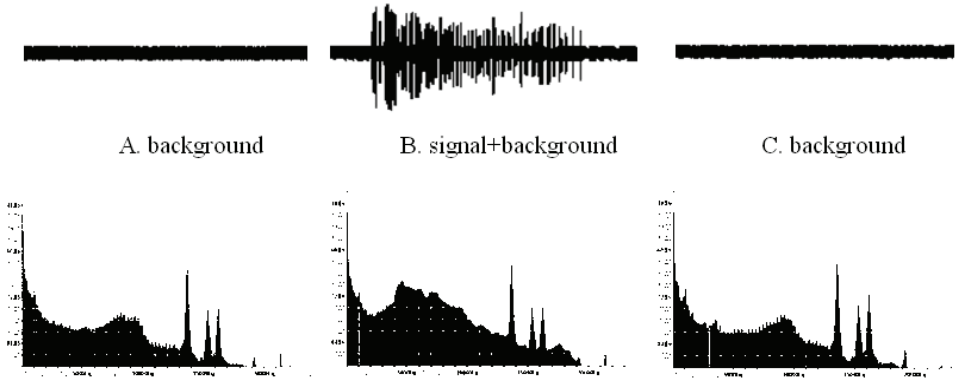
Fig. 2. Fragments of the recording of the channel N of the vector acoustic receiver, selected for linguistic processing at the top, and the corresponding Fourier spectra.

The linguistic processing of the presented signal fragments was carried out using the author's program of entropy-syntactic analysis of electrophysiological signals (ESAES ver. 3.0) [8]. The main window of the program with the result of processing the signal fragment is presented below (figure 3).
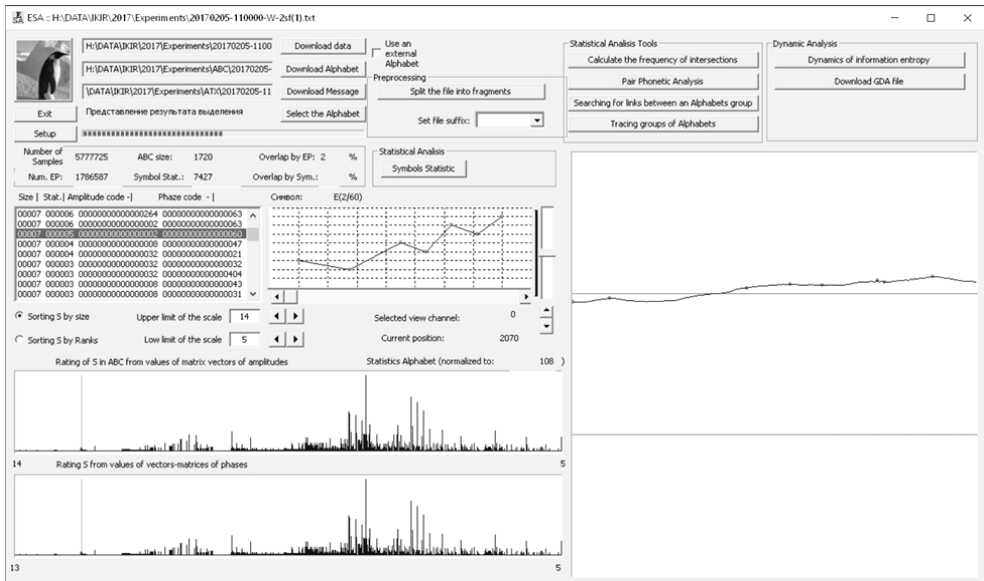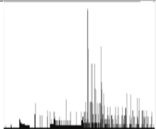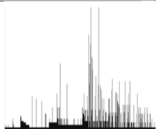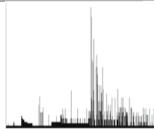

Fig. 3. Results of linguistic processing of a fragment of an acoustic background.

The program performs the decomposition of the signal into self-similar patterns, eliminates redundancy, calculates the statistics of the isolated symbols and compiles the alphabet. Additionally, it displays the ranking of the statistical values of the frequency of the alphabet symbols on the numerical axis of the symbol dimension values, which allows us to estimate indirectly the degree of randomness of the signal and to consider the most probable phase trajectories in the form of symbol templates of the selected alphabet.

The results of linguistic processing are tabulated.

Table 1. The results of the first stage of linguistic processing of the signal fragments presented in figure 2

	Fragment A (background 1)	Fragment B (signal+ background)	Fragment C (background 2)
Number of allocated local extremes	1083837	1073489	1085573
Dimension of Alphabets	1063	1092	1051
Sum of statistics	4358	4629	4537
Rank distribution of symbols of alphabets on values of symbols dimensions of			

For a better understanding of the self-similar structure of the signal, in figure 4 are derived templates (patterns) of isolated alphabet characters of different dimensions.
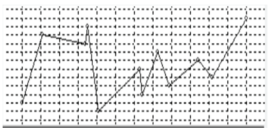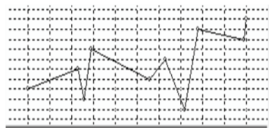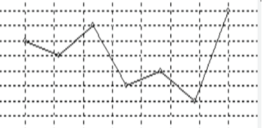
Size	12	10	9
Pattern			
Code	0000000000000016 0000000000000036	0000000000000064 0000000000000256	0000000000000032 0000000000000191

Fig. 4. Representation of indicators of linguistic processing used for analysis.

For carrying out comparative linguistic analysis, a utility is built into the computer program. With its help, operations on sets of symbols of compared alphabets are carried out **A (background 1)**, **B (signal+background)** и **C (background 2)**:

Table 2. Results of a comparative analysis of the signal messages alphabets presented in figure 2.

Operation	Formalization	Overlapping of sets in %	Illustration
Intersection A&C :	$C_1 = A \cap C$	50% / 49%	Figure 5
Intersection B&C :	$C_2 = B \cap C$	24% / 24%	Figure 6
Intersection B&A :	$C_3 = B \cap A$	25% / 25%	Figure 7

It can be seen that the alphabets of "background 1" and "background 2" are much more repeated over the elements of the set (figure 5) than the comparative estimates for the sets of

symbols of the alphabets "signal+background" – "background 2" (figure 6) and "signal+background" – "background 1"- (figure 7).
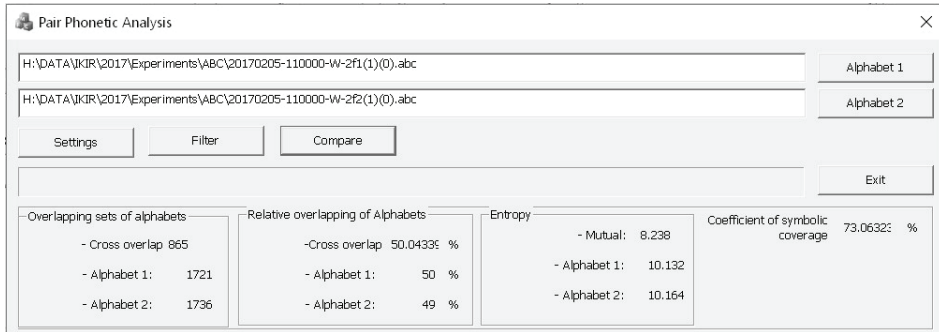

Fig. 5. Comparative analysis of the composition of the alphabets of background 1 and background 2.
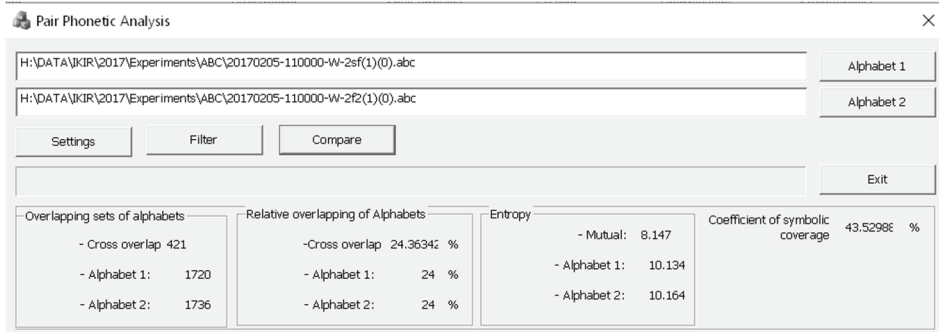

Fig. 6. Comparative analysis of the composition of the alphabets signal+background and background2.
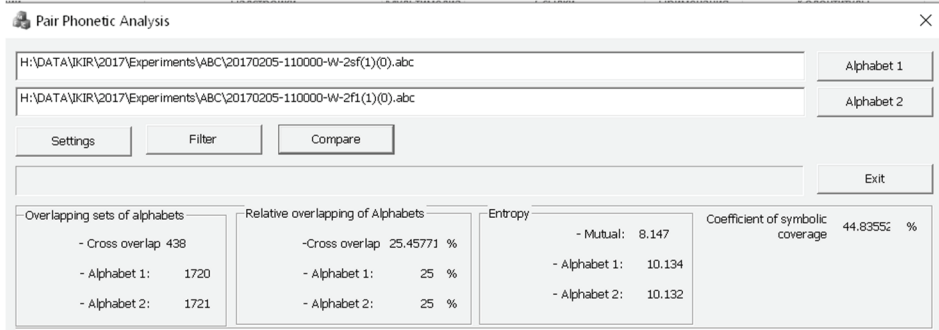

Fig. 7. Comparative analysis of the composition of the alphabets signal+background and background 1.

The presented statement of the foundations of the method, based on the information approach to the solution of the problem, corresponds to the idea of searching for the semantics of the detected structural changes in the signal, which is laid down by the phenomenon at the time of generation of this signal during a seismic event. The structure of the signal converted into a message is a reflection of the behavior of a nonlinear dynamic system, what a seismic event at least is, and the structure of the message is formed under the influence of the internal structure of a nonlinear dynamical system. Because of this, there is a way to recognize these influences and build models of system behavior. The last assumption allows us to consider cosmophysical processes from the standpoint of information theory, that is, to assess in detail

the dynamics of the behavior of such systems, and, therefore, to expect a more successful solution of the problems of recognizing their current state.

4 Conclusions

The presented example of the initial stage of linguistic processing is intended to show the principal differences between the information approach and the classical methods of signal preprocessing. Self-similar patterns are not a consequence of the application of functional decomposition. These structural elements preserve the amplitude-phase relationships of repeatedly occurring episodes of the original signal without imposing any time or frequency limitations. Moreover, because of the design features of the patterning based on the ratios of the amplitudes of local extremes and the time intervals between these extremes associated with them, patterns have the invariance property, and therefore, when looking for similarity, do not require scaling, in contrast to, for example, wavelet transform. In the algorithm for searching and extracting such signal structures, the elements of self-organization of the formation of alphabets are included, the elements of which do not have a functional connection, which allows us to describe the signal without estimating its stationarity.

Of course, the search for such patterns requires enormous computational costs. Therefore, the implementation of the approach itself becomes possible only with the availability of powerful computing tools, which is an essential drawback of the algorithm of linguistic processing used here.

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