



Revista Mexicana de Física

ISSN: 0035-001X

rmf@ciencias.unam.mx

Sociedad Mexicana de Física A.C.

México

Ramírez-Rojas, A.; Cervantes de la Torre, F.; Angulo-Brown, F.
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Revista Mexicana de Física, vol. 58, núm. 1, junio-, 2012, pp. 104-109
Sociedad Mexicana de Física A.C.
Distrito Federal, México

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Study of geoelectrical time series in the natural time domain

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Recibido el 23 de Marzo de 2010; aceptado el 27 de Abril de 2011

In this work we present a case study of geoelectric time series collected at the Mexican Pacific coast, which is a very active seismic zone linked to the Middle American tectonic trench. The analysis of the data sets is by means of two methods: The so-called natural time domain (NTD) and the detrended fluctuation analysis (DFA). The analyzed signals are of seismo electric signals (SES) type previously reported in Greece prior to earthquakes (EQs) of relevant magnitude. In our case we analyze SES likely linked to two earthquakes of $M=6.6$ and $M=7.4$ respectively. In both cases we find that the correlations contained in the signals increase prior to the EQ-occurrences and the power spectrum calculated in NTD are consistent with studies previously reported.

Keywords: Geoelectric time series; signal electro seismic; natural time.

En este trabajo presentamos un caso de estudio series de tiempo geoelectricas colectadas en la costa del Pacifico Mexicano, la que se caracteriza por ser una zona sísmica muy activa asociada con la trinchera tectónica de América. El análisis de las bases de datos se realizó mediante dos métodos: El llamado dominio en tiempo natural (NTD) y el análisis de fluctuaciones sin tendencia (DFA). Las señales analizadas son del tipo señales electro-sísmicas (SES) previamente reportadas in Grecia antes de sismos de magnitud relevante. En nuestro caso analizamos SES probablemente ligadas con dos sismos de magnitudes $M=6.6$ y $M=7.4$ respectivamente. En ambos casos encontramos que la correlación contenida en las señales se incrementa antes de que ocurrieran los sismos, además el comportamiento de la potencias espectrales, en el dominio del tiempo natural, son consistentes con los estudios reportados.

Descriptores: Series de tiempo geoelectricas; señal electrosísmica; tiempo natural.

PACS: 91.30.P-; 91.30.Px; 89.75.Da

1. Introduction

It is well known that short-term earthquake prediction is one of the most debated topics within the Earth sciences. Between the set of dynamical variables associated with the seismicity, the electric and magnetic fields of the ground have played a relevant role in order to understand the seismic phenomena. Among the different dynamical properties observed in geoelectric signals, the $1/f$ behavior has been detected before some earthquakes (EQ's), describing long-range correlations, so that some authors have proposed correlations between patterns of self-potential fluctuations and the mechanism of preparation of earthquakes [1]. It has been experimentally observed that when some materials are under stress there appear mechanisms that generate electric signal emissions [2]. Among the mechanisms associated with the emission of electric signals are included the piezoelectric effect in quartz [3], the electrokinetic effects [4], point defects [5], emission of electrons [6], and the motion of charged dislocations [7]. In the context of precursor signals of EQ's, the so-called Seismic Electric Signals (SES) has been a polemic topic within the scientific community. The SES activity is de-

finied [8-10] as transient anomalies of low frequency (≤ 1 Hz) in the electric self-potential fluctuations monitored in seismically active regions displayed prior to EQ's occurrence since a few hours until some weeks before the main shock. SES have been reported in Greece [11-12], in Japan [13] and México [14]. One of the most important features of SES activity is their dichotomic nature. Dichotomous noise has been observed in a variety of physical systems like geodynamo model [15] thermal transitions between two states [16], ion currents fluctuations in membrane channels [17] and geoelectric time series [18]. Due to the complexity of the earth crust many authors have considered the seismicity as a critical phenomenon [19], and Varotsos *et al.* have argued [8] that SES signals are emitted when the stress reaches a critical value in the EQ focal area. The dichotomic nature of SES was focused by Varotsos *et al.* [8-10] by analyzing them based on a new time domain called Natural Time (NTD). This approach may constitute a novel contribution to short-term prediction [19]. Varotsos *et al.* [10] showed that artificial noises of dichotomic nature can be distinguished from SES in the natural time domain. Only the SES reveal long-range temporal correlations [9-10] indicating that the system is in a critical stage.



FIGURE 1. Location of Acapulco station and both EQ epicenters, EQ (M6.6) and EQ2 (M7.4).

stage. An important point regarding natural time analysis may be that it enables us to follow the dynamical evolution of a system and identify when it enters into a critical stage [20]. The geoelectrical time series monitored within the seismically active Mexican region located in the Guerrero-Oaxaca coast displayed dichotomous nature noises associated with two EQ's occurred in October 24, 1993 and September 14, 1995 respectively. In this work we present, as a case study, a preliminary analysis of our geoelectrical time series by computing the power spectrum in natural time. Our results are consistent with those previously reported by Varotsos. In order to compare our experimental data set, we have considered the Liebovitch and Thot chaotic model [21] emulating an ionic dichotomous signal. We also use the DFA method to analyze the same geoelectric datasets. The present paper is organized as follows: In Sec. 2 the data set acquisition is described, Sec. 3 is devoted to the methods of analysis. In Secs. 4 and 5 the results and concluding remarks are presented and finally the references are listed in Sec. 6.

2. Data

The monitored area is located along the South Pacific Mexican coast, near the Middle American trench which is the border between the Cocos and American tectonic plates where large earthquakes have been generated within this area (see map in Fig. 1). This region is characterized by its high seismicity and it is constituted of composite terrains with both undersea volcanic and sedimentary sequences [22]. The monitoring station was located at (16°50'N, 99°47'W) close to Acapulco city and the experimental set-up was based on the VAN methodology [11,12] where the electric self-potential fluctuations, ΔV , were monitored between two electrodes buried 2m into the ground and 50 m apart with sampling times $\Delta t = 2$ and 4 sec. In order to remove all the high frequency fluctuations linked with noise, the sampled data were filtered by a low-pass filter in the range: $0 < f < 0.125$ Hz. The self-potential monitoring station was set in continuous data acquisition as described in Ref. 23.

The analyzed signals recorded at Acapulco station are depicted in Fig. 2. The first one (ACA1) corresponds to a SES

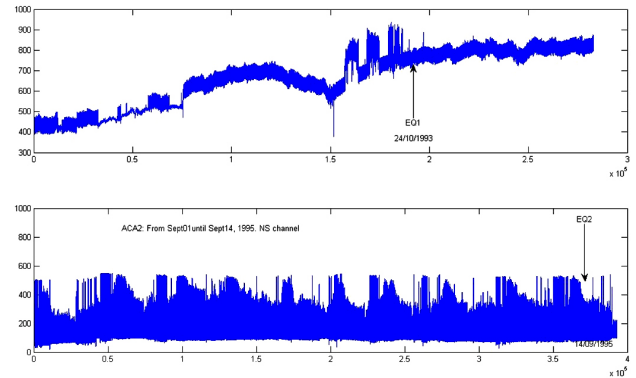


FIGURE 2. Time series analyzed. a) ACA1 time series and b) ACA2 time series. Both signals were monitored at Acapulco station.

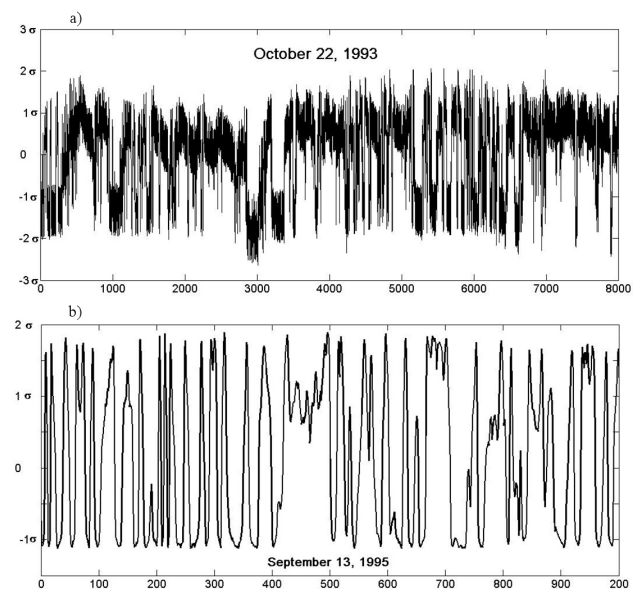


FIGURE 3. Excerpts of the analyzed time series displaying dichotomous features: a) SES activity of October 22, 1993 (ACA1). b) Segment of the signal monitored from April to September, 1995 (ACA2). In both cases the signals were normalized.

activity associated with the EQ of M6.6 (EQ1) occurred in October 24, 1993 with epicenter at (16.54°N, 98.98°W) (see Fig. 3) and the second one (ACA2) is associated with a M7.4 (EQ2) occurred in September 14, 1995 with epicenter at (16.31°N, 98.88°W) (Fig. 1). Excerpts taken from Fig. 2 showing dichotomous behavior are depicted in Fig. 3.

3. Methods

3.1. Detrended Fluctuation Analysis (DFA)

The DFA [24] has advantages over conventional methods because it permits the detection of long-range correlations embedded in a seemingly non stationary time series, and also avoids the spurious detection of apparent long-range correlations that are an artifact of non-stationarity. Briefly the DFA

algorithm is described as follows: Consider a time series $x(1), x(2), x(3), \dots, x(N)$. A new time series $\{y(k)\}$ is obtained by integration of the original time series,

$$y(k) = \sum_{i=1}^k (x(i) - x_{ave})$$

where x_{ave} is the average of the data set. Next, the integrated time series is divided into boxes of equal length n . For each box of length n , a least-squares line is fitted to the data, (representing the trend in each box: $y_n(k)$). Next, the integrated time series is detrended by subtracting in each box. The root mean-square fluctuation of this integrated and detrended time series is calculated by

$$F(n) = \sqrt{\frac{1}{N} \sum_{k=1}^N [y(k) - y_n(k)]^2} \quad (1)$$

This computation is repeated over many time scales (box sizes) to provide a relationship between $F(n)$, and the box size n . Typically $F(n)$ will increase with box size n . A linear relationship on a double log graph indicates the presence of scaling, that is:

$$F(n) \propto n^\alpha \quad (2)$$

The value of the scaling exponent α (Eq. 2), characterizes the correlation in a time series. For example white noise has $\alpha=0.5$. Two special cases are $\alpha=1$ corresponding to a $1/f$ noise and $\alpha=1.5$ to a Brownian noise. Values into the interval $0.5 < \alpha \leq 1$, indicate persistent long-range power-law correlations. In contrast, $0 < \alpha < 0.5$ indicates a different type of power-law correlation such that large and small values of the time series are more likely to alternate [25].

3.2. Natural time

The principle of natural time analysis is as follows [8-9]: In a time series of N events, the natural time defined as: $\chi_k = k/N$, it serves as an index for the occurrence of the k -th event. The aim is to study the evolution of the pair (χ_k, Q_k) , where Q_k denotes a quantity proportional to the energy released in the k -th event. For a dichotomous time series, Q_k has a clear meaning because it can be replaced by the duration of the k -th pulse.

The analysis is based in the normalized power spectrum $\Pi(\omega) \equiv |\Phi(\omega)|^2$ behavior; which is defined as [8-9]:

$$\Phi(\omega) = \sum_{k=1}^N p_k \exp(i\omega \frac{k}{N}) = \sum_{k=1}^N p_k \exp(i\omega \chi_k) \quad (3)$$

where

$$p_k = \frac{Q_k}{\sum_{k=1}^N Q_k} \quad (4)$$

And $\omega = 2\pi\phi$, where ϕ is called the natural frequency. In natural time analysis, the properties of $\Pi(\omega)$ (or $\Pi(\phi)$) are

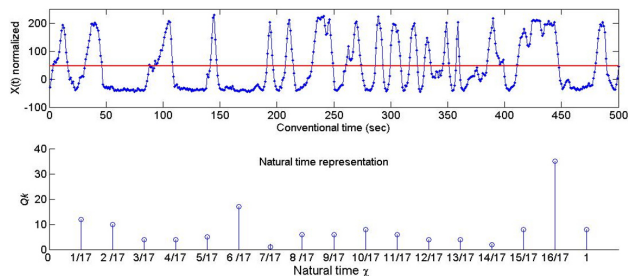


FIGURE 4. Time series in conventional time (above) and time series in natural time (below).

studied for continuous natural frequency range $0 < \phi < 0.5$. In this range $\Pi(\omega)$ (or $\Pi(\phi)$) reduces to a characteristic function for the probability distribution, p_k , and in the context of the probability theory, this means that statistical properties, such as variance, can be obtained by its derivatives at the origin [26]. By considering an uniform distribution of p_k values, Varotsos *et al.* modeled [8-10] a theoretical SES activity model (at critical stage) which has the following normalized power spectrum:

$$\Pi_{SES}(\omega) = \frac{18}{5\omega^2} - \frac{6 \cos \omega}{5\omega^2} - \frac{12 \sin \omega}{5\omega^3} \quad (5)$$

When $\omega \rightarrow 0$, Eq. (5) leads to

$$\Pi_{SES}(\omega) \approx 1 - 0.07\omega^2.$$

It reflects the fact that the variance of χ is given by

$$\kappa_{1_{SES}} = \langle \chi^2 \rangle - \langle \chi \rangle^2 = 0.07,$$

where

$$\langle f(\chi) \rangle = \sum_{i=1}^N p_i f(\chi_i)$$

[8-9].

4. Results

4.1. Detrended Fluctuation Analysis

Regarding the correlations within the mentioned time series, Fig. 5 and 6 display the α_{DFA} exponent values for ACA1 (SES activity prior M6.6) and ACA2 respectively. In our calculations no overlapping windows of length $N=6$ hr were considered. It can be observed that α values increase from $\alpha_{DFA} \approx 0.5$ (October 19) showing uncorrelated behavior until to attain $\alpha_{DFA} = 1.04$ (October 21), that is, long-range correlations of the $1/f$ type. The next days, α_{DFA} decreases until $\alpha_{DFA}=0.58$ (blue line in upper plot of Fig. 5). When the time series is shuffled the correlation is lost (green line in upper plot of Fig. 5).

The same analysis was performed for ACA2 (M7.4), the α_{DFA} exponents were calculated over windows of six hours from Sept. 01 until Sept. 14. In Fig. 6 this behavior is showed. For this time series a crossover appears showing two underlying dynamics one of them consisting in fractional Brownian motion (boxes of short length) and the other displaying a white noise associated with boxes of large length.

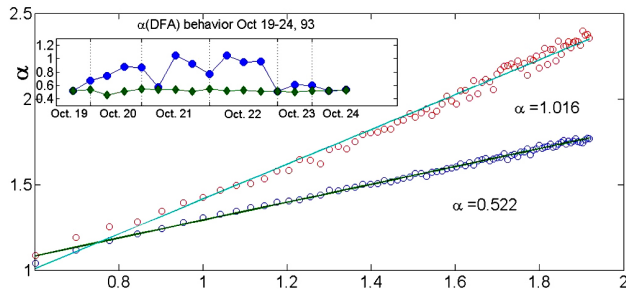


FIGURE 5. α_{DFA} -values behavior for the SES activity. Within the inset can be observed that long-range correlations appear around the SES signal indicating that the system enters to a critical stage (blue line). When the time series is shuffled the correlations disappear (green line).

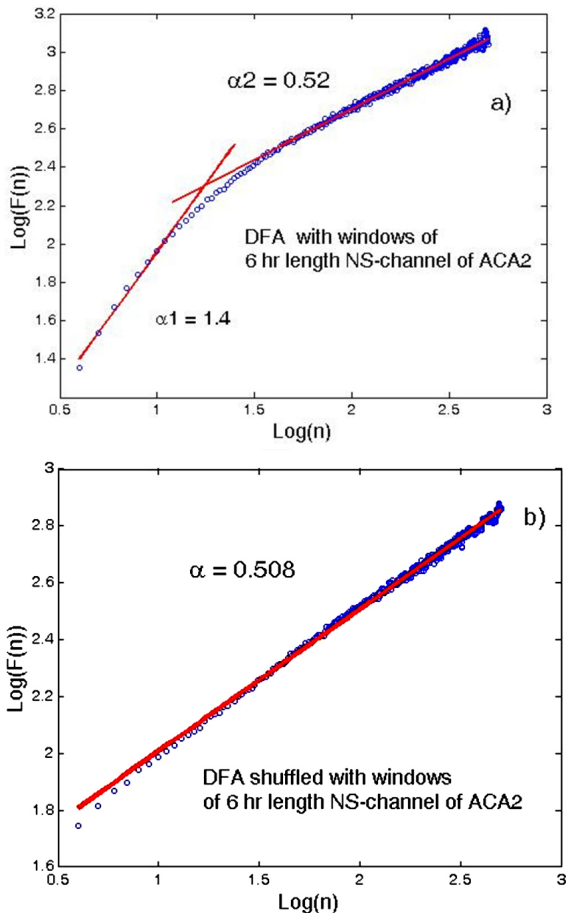


FIGURE 6. Example of α -values for EQ2 time series computed with windows of six hours, two behaviors are observed, a) before the crossover (small boxes) a fractional Brownian noises is displayed and a white noise for large boxes (after crossover). b) The shuffled time series is uncorrelated.

For the raw time series two α -values (α_1, α_2) are shown with a crossover while for the shuffled data the crossover does not appear. The distributions of α_1 and α_2 are in Fig. 7. In fact, in both cases it is possible to observe that SES activity as EQ2 time series display long-range correlations as a feature observed for systems in critical stage.

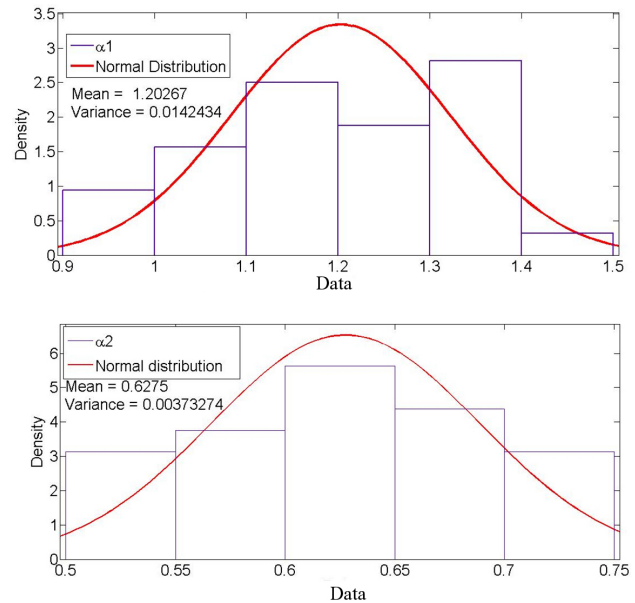


FIGURE 7. α_1 and α_2 distributions. α_1 is within a range of long-range correlations with mean value $\langle \alpha_1 \rangle = 1.202 \pm 0.0142$ and α_2 display short correlations with average values $\langle \alpha_2 \rangle = 0.627 \pm 0.0037$. A normal distribution is depicted for comparison.

4.2. Natural time analysis

We analyze two geoelectric time series, associated with a pair of main shocks, the first one corresponds to a possible SES observed since five days before the EQ1, and the second case is a dichotomous segment recorded before the EQ2. The corresponding segments are depicted in Fig. 2. The first one concerns to SES observed a few days before the $M_s = 6.6$ occurred in October 24, 1993. The distance between the EQ and Acapulco station is approximately 80 Km. The second case corresponds to the signal monitored in Acapulco station some days before the $M_s = 7.4$ EQ, occurred in September 14, (1995) with epicenter 112 Km away from Acapulco station. In order to compare our experimental data set, we also analyze a time series build from the Lievobitch and Thot chaotic map [21]. This mapping was proposed as a dynamical system in order to model ionic channels dynamics. This third case corresponds to a chaotic map proposed by Lievobitch and Thot as it is showed in Fig. 8. Some of their dynamical properties have been reported in Ref. 21.

We calculated the power spectrum in natural time of the three mentioned signals. For a comparison with the variance calculated for a SES theoretical model [10].

5. Concluding remarks

In this work we have analyzed three signals of dichotomic nature, two of them associated with two important EQ's occurred in October 24, 1993 and September 14, 1995 with $M6.6$ and $M7.4$ respectively, these geoelectrical signals were

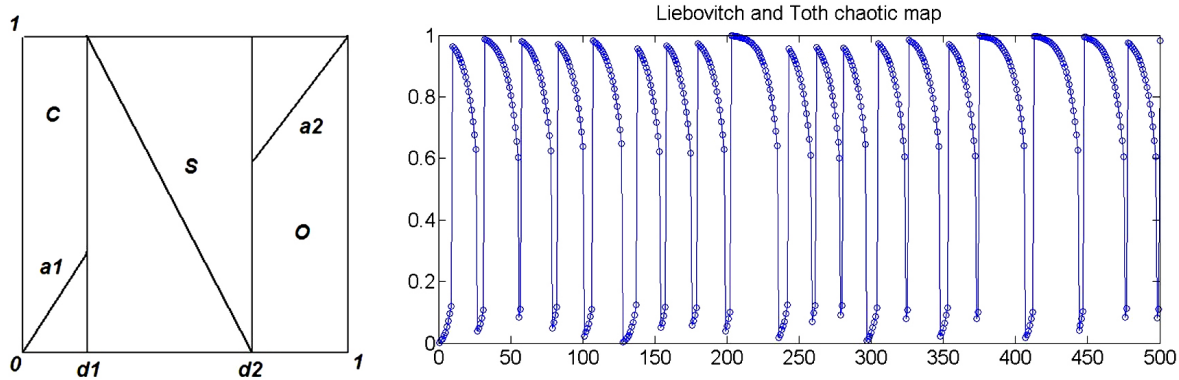


FIGURE 8. Liebovitch and Toht map and a segment of its time series.

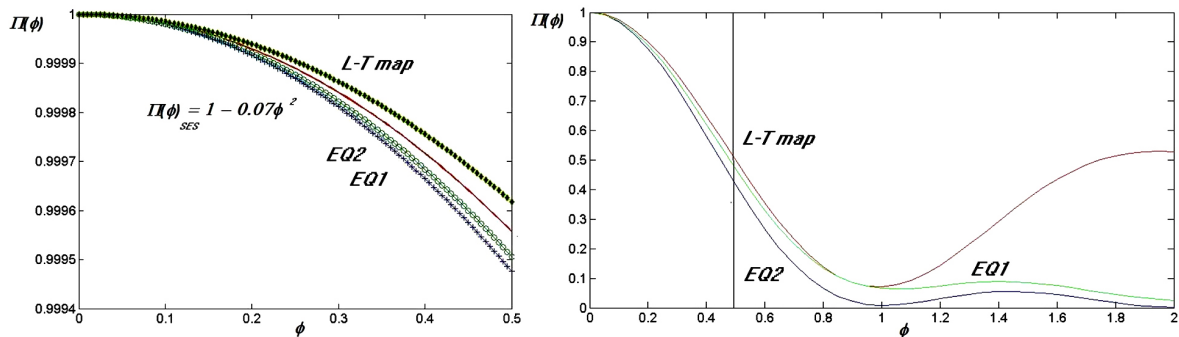


FIGURE 9. Power spectrum in the natural time. EQ1 and EQ2 curves are below the theoretical model for SES while the LT map curve, it is above. Such as it occurs in Ref. 10.

collected in a seismically active area located in the South Pacific Mexican coast. The third case corresponds to a time series obtained from the Liebovitch and Toht chaotic map which also displays dichotomic noise (see Fig. 8) [21]. The DFA results reflected temporal correlation of the geoelectric signals before their respective main shocks. For ACA1 (see Fig. 5), the inset displays the α_{DFA} -values. This behavior follows the sequence, white noise-long-range correlation-white noise suggesting that the system enters to a critical stage. For ACA2, α_{DFA} -values display crossover indicating two mixed dynamical behaviors (see Figs. 6 and 7), this result is consistent with other reported in Refs. 14 and 18. When the

signals are shuffled the correlations are lost. With regard the natural time analysis, in Fig. 9 the power spectrum is depicted. The spectrum analysis in the NTD seems to allow a classification of our both types of signals with respect to SES theoretical model, our SES type signals and the chaotic time series. For natural frequencies $0 < \phi < 0.5$ our SES type signals fall within the range reported by Varotsos *et al.* [8-10] with variance $\kappa_1 \approx 0.07$ and for chaotic time series $\kappa_1 \approx 0.08$. We consider that our results contribute to the development of the NTD method as a novel analysis tool for signals of dichotomic nature.

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