

Preface

There is a widespread belief that it is not space but time that in the end poses the greatest challenge in science. It is according to Gödel “that mysterious and seemingly self-contradictory being which, on the other hand, seems to form the basis of the world’s and our own existence”.

The basic scope of this monograph is to present the new view of time, termed natural time χ (from the Greek word “ $\chi\rho\acute{o}\nu\omicron\varsigma$ ” which means “time”), introduced by the authors in 2001. In this new view, time is *not continuous*, thus being in sharp contrast with the hitherto used conventional time t which is modeled as the one-dimensional *continuum* \mathcal{R} of the real numbers.

The results deduced to date on the basis of this new domain reveal that novel dynamical features hidden behind time series in complex systems can emerge upon analyzing them in natural time, but cannot when the analysis is carried out within the frame of conventional time. Furthermore, the analysis in natural time enables the study of the dynamical evolution of a complex system and identifies when the system enters a critical stage. Hence, it seems that natural time plays a key role in predicting impending catastrophic events in general.

The present monograph comprises three Parts:

Part I (Chapter 1) provides a review of the so-called seismic electric signals (SES) which are low-frequency ($\lesssim 1$ Hz) electric signals that precede earthquakes. A sequence of such signals, termed SES activity, constitutes the first example of a time series emitted from a complex system, like the Earth, to which natural time analysis has been applied.

Part II, consisting of the Chapters 2 and 3, sheds light on the foundations of natural time by providing the necessary mathematical background in each step. Furthermore, this Part describes how the analysis of a time series is made in the frame of natural time and explains how the entropy in natural time is introduced and calculated.

Part III, consisting of the six Chapters 4 to 9, presents examples of data analysis in natural time that have appeared to date (mainly in *Physical Review* and *Physical Review Letters*) in diverse fields, including Biology, Earth Sciences (Geophysics, Seismology), Environmental Sciences, Physics (Condensed Matter, Statistical Physics, Physics of Complex Systems) and Cardiology.

The contents of the nine Chapters can be summarized as follows.

Chapter 1 summarizes the mechanisms suggested to date for the SES generation as well as the physical properties of SES including those that SES are observed only at certain points of the Earth's surface called "sensitive points" and that their amplitude is interrelated with the magnitude of the impending earthquake. It is explained that these physical properties can be theoretically understood on the basis of Maxwell equations if we just consider that the earthquakes occur by slip on pre-existing faults, which constitute conductive paths in the solid Earth's crust. In addition, general background in Statistical Physics is provided on the basis of which we show that the observed SES activities exhibit *scale invariance* over four orders of magnitude. This is consistent with the pressure stimulated currents SES generation model proposed by Varotsos and Alexopoulos in the early 1980s based on thermodynamical grounds which (motivated the SES research in general and) suggests that SES are emitted when the stress in the focal region reaches a *critical* value, thus SES should be governed by *critical* dynamics.

In Chapter 2, we first present aspects advanced by such giants as A. Einstein, E. Schrödinger, W. Pauli, J. von Neumann, H. Weyl, and K. Gödel, in order to shed light on the crucial point that the continuity of conventional time is not demanded from *any* fundamental principle. We then introduce the natural time χ , which is *not* continuous, and indicate that its values, as well as those of the energy, form *countable* sets by using the set theory developed by Cantor. Furthermore, we demonstrate that natural time analysis is optimal for enhancing the signals in time-frequency space when employing the Wigner function and measuring its localization property. In other words, natural time analysis conforms to the desire to reduce uncertainty and extract signal information as much as possible. The normalized power spectrum $\Pi(\omega)$ is introduced in natural time, and its Taylor expansion leads, at low natural (cyclic) frequencies ω ($\omega \rightarrow 0$), to the expression $\Pi(\omega) \approx 1 - \kappa_1 \omega^2$ where the coefficient κ_1 is just the variance of natural time, i.e., $\kappa_1 = \langle \chi^2 \rangle - \langle \chi \rangle^2$. This quantity is useful in identifying the approach to a critical point as in the case of SES whose κ_1 value is shown to be 0.070. In addition, natural time analysis enables the distinction between the two origins of self-similarity, which is a challenging point when analyzing data from complex systems, i.e., whether self-similarity solely results from long-range temporal correlations (the process's memory only) or solely from the process's increments' infinite variance (heavy tails in their distribution).

In Chapter 3, we define the entropy S in natural time and show that the entropy S_- deduced from the natural time analysis of the time series obtained upon time reversal is in general different from S , thus the entropy in natural time does satisfy the condition to be "*causal*". Furthermore, the physical meaning of the change $\Delta S \equiv S - S_-$ of the entropy in natural time under time reversal, which is of profound importance for the study of the dynamical evolution of a complex system, is discussed. In addition, complexity measures are introduced that quantify the fluctuations of the entropy S and of the quantity ΔS upon changing the length scale as well as the extent to which they are affected when shuffling randomly the consecutive events.

Chapter 4 deals with the natural time analysis of all the measured SES activities which are shown to be characterized by very strong memory and their normalized power spectra $\Pi(\omega)$ versus ω fall on a *universal* curve having κ_1 value equal to 0.070. This curve coincides with the one obtained on theoretical grounds when assuming that SES are governed by *critical* dynamics. Concerning the distinction of SES activities from similar-looking

“artificial” (man-made) noise, we find that modern techniques of Statistical Physics, e.g., detrended fluctuation analysis (DFA), multifractal DFA, wavelet transform, *can* achieve such a distinction, but when they are *applied* in natural time. The entropy S in natural time as well as $\Pi(\omega)$ can also achieve such a distinction. Finally, the study of the fluctuations $\Delta\chi_l$ of the average value of natural time under time reversal versus the window length l , also achieves a distinction between SES activities and “artificial” noises.

In Chapter 5, we investigate the effect of significant data loss on the identification of a SES activity. In particular, the following two cases are treated. First, the effect of the random removal of data segments of fixed length on the scaling properties of SES activities. Second, the appearance of a periodic noise like in Japan, where the electric field measurements at some sites are seriously contaminated by high noise from 06:00 to 22:00 LT every day, i.e., around 70% data loss. We show that in both cases, when combining natural time analysis with DFA, the identification of a long duration SES activity becomes possible with probability around 70% even after severe data loss (e.g., 70–80%).

Chapter 6 is focused on the natural time analysis of the seismicity, a careful inspection of which reveals that the quantity κ_1 may be considered as an order parameter. This allows the determination of the constant b in the Gutenberg–Richter law for earthquakes, $N(\geq M) = 10^{a-bM}$, by applying the Maximum Entropy Principle. It leads to $b \approx 1$, which agrees with real seismic data. Studying the order parameter fluctuations relative to the standard deviation of its distribution, the scaled distributions of different seismic areas as well as that of the worldwide seismicity fall on a *universal* curve which also exhibits features similar to those in several critical phenomena. This curve changes upon randomly shuffling, which reflects that temporal correlations exist between the earthquake magnitudes (M). This is confirmed by applying DFA to the earthquake magnitude time series and upon employing either multifractal cascades in natural time or nonextensive statistical mechanics combined with natural time analysis. Finally, the probability density function $P(\kappa_1)$ versus κ_1 plot *before* mainshocks exhibits a significant bimodal feature. This is strikingly similar to the bimodal feature of the order parameter when approaching (from below) T_c in equilibrium critical phenomena.

In Chapter 7, assuming that the mainshock is a new phase, we show how natural time analysis enables the determination of the occurrence time of an impending major earthquake. Considering that the detection of a SES activity signifies that the system enters in the critical regime, the time series of the small earthquakes that occur in the candidate region to suffer the mainshock after the SES detection are analyzed in natural time. It is found that the variance κ_1 becomes equal to 0.070 a few days to around one week *before* the mainshock. This behavior, which exhibits spatial as well as magnitude threshold invariance, has been observed to date for *all* major earthquakes in Greece since 2001. For example, the occurrence time of the M_w 6.9 earthquake on February 14, 2008, which was the strongest earthquake to occur in Greece during the last 27 years, was publicly announced as imminent on February 10, 2008. The procedure has been also ascertained in the case of the volcanic-seismic swarm activity in 2000 in the Izu island region in Japan as well as in the M_s 7.1 Loma Prieta earthquake in California in 1989.

In Chapter 8, we apply natural time analysis to the time series of the avalanches in several self-organized criticality (SOC) models as well as to other dynamical models including a simple deterministic version of the “train” model for earthquakes introduced

by Burridge and Knopoff, the Olami–Feder–Christensen earthquake model, the 2D Ising model when quenching at temperatures close to but below T_c , which is qualitatively similar with the pressure stimulated currents SES generation model, a deterministic version of the original Bak–Tang–Wiesenfeld sandpile model and a generalized stochastic SOC model. In all these dynamical models, we find that the value $\kappa_1 = 0.070$ can be considered as quantifying the extent of the organization of the system at the onset of the critical stage. In addition, in this Chapter, we present the natural time analysis of the avalanches observed in laboratory experiments on three-dimensional piles of rice getting progressively closer to the critical state and on the penetration of the magnetic flux into thin films of high T_c superconductors. The results reveal κ_1 values around $\kappa_1 = 0.070$.

Chapter 9 deals with the natural time analysis of electrocardiograms and basically aims at identifying the risk of sudden cardiac death, which is a frequent cause of death and may occur even if the electrocardiogram seems to be strikingly similar to that of a healthy individual. Upon employing the fluctuations of the entropy in natural time, we find that sudden cardiac death individuals (SD) can be clearly distinguished from the truly healthy ones. Furthermore, by using complexity measures that quantify the change of the natural entropy fluctuations either by changing the time window length scale or by shuffling the “pulses” (heartbeats) randomly, we can achieve the classification of individuals into three categories: healthy, heart disease patients and SD. In addition, when considering the entropy change under time reversal, not only the SD risk can be identified, but also an estimate of the time of the impending cardiac arrest can be provided. Finally, a $1/f$ model in natural time is presented which is consistent with the progressive modification of heart rate variability in healthy children and adolescents. The model also results in complexity measures that separate healthy dynamics from heart disease patients as well as from SD.

For the reader’s convenience, the figures and the tables that refer to others than those included in this monograph, begin with small “f” and “t”. As for the Supplemental Material, cited as EPAPS document, it is freely available from www.aip.org/pubservs/epaps.html. Furthermore, bold face symbols correspond to vectors, as usual.

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Natural Time Analysis: The New View of Time
Precursory Seismic Electric Signals, Earthquakes and
other Complex Time Series

Varotsos, P.; Sarlis, N.V.; Skordas, E.S.

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