

# Contents

## I. Seismic Electric Signals

<b>1. Introduction to Seismic Electric Signals</b>	<b>3</b>
1.1 Data collection and the telemetric network	3
1.2 Distinction of SES from noise	8
1.2.1 Distinction of SES from magnetotelluric (MT) changes	8
1.2.2 Distinction of SES from noise of electrochemical origin	10
1.2.3 Distinction of SES from “artificial” (man-made) noise. The $\Delta V/L$ criterion	10
1.3 SES physical properties	12
1.3.1 Lead time of SES. Other electrical precursors	13
1.3.2 Interrelation between SES amplitude and EQ magnitude	15
1.3.3 SES polarity and the ratio of the two SES components	16
1.3.4 SES sensitive sites. Selectivity effect	18
1.3.5 Determination of the epicenter and magnitude of an impending mainshock from the SES data	19
1.3.6 Magnetic field variations associated with SES	20
1.3.7 Magnetic field variations associated with the precursory short-duration electric pulses	22
1.4 Scale invariance of SES activities and their associated magnetic field variations	23
1.4.1 Long-Range Correlations. Background	24
1.4.2 Detrended fluctuation analysis (DFA)	25
1.4.3 DFA of long duration SES activities	27
1.4.4 DFA of the magnetic field variations that accompany SES activities	28
1.5 Criticality, complexity and fractals. An introduction	30
1.5.1 Introductory note on fractal dimension and self-similarity. Fractional Brownian motion and fractional Gaussian noise	30
1.5.2 Critical phenomena and fractality	35
1.5.3 Non-equilibrium critical dynamics. The scaling hypothesis	36

1.5.4	Current aspects on the non-equilibrium driven dynamics. Dynamic phase transitions . . . . .	37
1.6	Physical mechanisms suggested for the generation of SES . . . . .	38
1.6.1	Introduction. Views on seismogenesis and classes of SES generation models . . . . .	38
1.6.2	Pressure (stress) stimulated currents (PSC) model . . . . .	40
1.6.3	Charged dislocation mechanism . . . . .	47
1.6.4	The deformation-induced charge flow mechanism . . . . .	52
1.6.5	Teisseyre's model on the precursory electric signals generation related with dislocation dynamics . . . . .	55
1.6.6	The peroxy defects model . . . . .	55
1.6.7	The model of the large-scale motion of lattice defects . . . . .	56
1.6.8	SES generation mechanisms based on electrokinetic phenomena . . . . .	57
1.6.9	SES generation mechanisms when assuming the earthquake rupture as critical point . . . . .	64
1.6.10	Other SES generation mechanisms . . . . .	65
1.7	Explanation of the selectivity effect and other SES properties . . . . .	66
1.7.1	The model for the explanation of the selectivity effect . . . . .	66
1.7.2	Analytical studies related to the explanation of the SES properties . . . . .	69
1.7.3	Direction of the maximum principal stress with respect to the neighboring earthquake fault . . . . .	75
1.7.4	Explanation of the SES properties based on analytical studies . . . . .	76
1.7.5	Electric field numerical calculations explaining the selectivity effect . . . . .	79
1.7.6	Magnetic field calculations . . . . .	85
1.7.7	The physical background of the $\Delta V/L$ criterion to distinguish SES from noise . . . . .	89
1.7.8	Explanation of the difference between SES polarization and MT polarization . . . . .	95
1.8	Transmission of electric signals in dielectric media: time- and frequency-dependence . . . . .	97
1.8.1	The propagation regime and the diffusion regime of electromagnetic fields. Isotropic and homogeneous medium . . . . .	97
1.8.2	Electric field from a dipole current source lying close to a conductive path. Frequency dependence . . . . .	100
1.8.3	The electric signal recorded at a remote site. Time domain . . . . .	101
1.8.4	Discussion on the explanation of the SES detectability and selectivity . . . . .	103
1.8.5	Discussion on the time-difference between the SES electric field variation and the associated magnetic field recordings . . . . .	105
	References . . . . .	109

## II. Natural Time Foundations

<b>2. Natural Time. Background</b>	119
2.1 Introduction to natural time	119
2.1.1 Time and not space poses the greatest challenge to science	120
2.1.2 Definition of natural time	121
2.1.3 The “uniform” distribution	122
2.2 Time reversal and natural time	123
2.2.1 Interconnection of the average value of natural time with the effect of a small linear trend on a “uniform” distribution	124
2.2.2 Quantification of the long-range dependence from the fluctuations of the average value of natural time under time reversal	124
2.3 Characteristic function. Mathematical background	128
2.3.1 Definition of the characteristic function	128
2.3.2 Properties of the characteristic function	129
2.4 The normalized power spectrum $\Pi(\omega)$ or $\Pi(\phi)$ and the variance $\kappa_1$ of natural time	130
2.4.1 The normalized power spectrum for the “uniform” distribution	133
2.4.2 The normalized power spectrum of seismic electric signals	134
2.5 Distinction of the origins of self-similarity	138
2.5.1 The two origins of self-similarity. Background	139
2.5.2 The expectation value of $\kappa_1$ when a (natural) time window of length $l$ is sliding through a time series	139
2.5.3 The case when the increments of the time series of $Q_k$ are positive i.i.d. random variables of finite variance	143
2.5.4 The value of $\kappa_1$ when a (natural) time window is sliding through power law distributed energy bursts	143
2.5.5 Conclusions	146
2.6 Origin of the optimality of the natural time representation	146
2.7 Is time continuous?	150
2.7.1 Differences between natural time and conventional time on the basis of set theory	150
2.7.2 Proof of the cardinality of the set of the values of natural time	153
2.7.3 Is natural time compatible with Schrödinger’s point of view?	153
2.7.4 Conclusions	154
References	155
<b>3. Entropy in Natural Time</b>	159
3.1 The entropy in dynamical systems and the advantages of its use	159
3.2 Entropy in natural time. Definition	161
3.3 Properties of the entropy in natural time	161
3.3.1 Background material	162
3.3.2 The positivity of $\kappa_1$ and $S$	163
3.3.3 The concavity of $\kappa_1$ and $S$	164

3.3.4	Lesche stability (or experimental robustness) of $\kappa_1$ and $S$ . . . . .	165
3.3.5	A more general theorem for entropic functionals in natural time . . . . .	168
3.4	Entropy under time reversal . . . . .	169
3.4.1	Definition of the entropy in natural time under time reversal . . . . .	169
3.4.2	The case when the increments of the time series of $Q_k$ are positive i.i.d. random variables of finite variance . . . . .	170
3.4.3	Fractional Brownian motion time series . . . . .	170
3.4.4	An on–off intermittency model . . . . .	173
3.4.5	The case of signals that exhibit short-range temporal correlations . . . . .	175
3.4.6	Interrelation between $\delta S$ and $\sigma/\mu$ in the case of p.i.i.d. . . . .	175
3.5	The change $\Delta S$ of the entropy in natural time under time reversal . . . . .	180
3.5.1	Evaluation of $\Delta S_l$ when a (natural) time window of length $l$ is sliding through a time series . . . . .	180
3.5.2	Interrelation of $\sigma[\Delta S_l]$ and $\sigma/\mu$ in the case of p.i.i.d. . . . .	181
3.5.3	A simple example in which the meaning of the entropy change $\Delta S$ under time reversal seems to emerge clearly . . . . .	183
3.6	Complexity measures using the entropy in natural time . . . . .	184
3.6.1	Complexity measures that make use of the fluctuations of the entropy $S$ in natural time . . . . .	184
3.6.2	Complexity measures that make use of the change $\Delta S$ of the entropy in natural time under time reversal . . . . .	185
	References . . . . .	185

### III. Natural Time Applications

4.	Natural Time Analysis of Seismic Electric Signals . . . . .	191
4.1	Dichotomous time series. Markovian and non-Markovian processes . . . . .	192
4.1.1	Difference between natural time analysis and earlier studies of dichotomous time series. The Markovian process . . . . .	192
4.1.2	Non-Markovian character of SES activities and “artificial” noises . . . . .	193
4.1.3	Markovian dichotomous time series. Spectral analysis and detrended fluctuation analysis (DFA) . . . . .	195
4.2	Normalized power spectrum of SES activities. The universality emerged in natural time . . . . .	199
4.2.1	Normalized power spectrum of SES activities and “artificial” noises in natural time. A universality for SES activities . . . . .	199
4.2.2	Distinction of SES activities from “artificial” noises based on the normalized power spectrum . . . . .	201
4.3	Superiority of applying Hurst (R/S) analysis in the natural time domain . . . . .	202
4.3.1	Conventional Hurst analysis . . . . .	202
4.3.2	Hurst analysis of the time series of durations of the “high”- and the “low”-level states. Hurst analysis in natural time . . . . .	205
4.4	Superiority of applying detrended fluctuation analysis (DFA) in the natural time domain . . . . .	207

4.4.1	DFA of the original time series . . . . .	207
4.4.2	DFA of the time series of durations of the “high”- and the “low”-level states. Superiority of applying DFA in natural time . . . . .	208
4.5	Superiority of applying multifractal detrended fluctuation analysis (MF-DFA) in the natural time domain . . . . .	210
4.5.1	Monofractals and multifractals. The necessity for multifractal analysis . . . . .	210
4.5.2	Multifractal detrended fluctuation analysis. Background . . . . .	211
4.5.3	Multifractal detrended fluctuation analysis in natural time compared to that in conventional time . . . . .	212
4.6	Superiority of applying the wavelet transform in natural time . . . . .	213
4.6.1	The wavelet transform, background. Comparison of the estimators of scaling behavior . . . . .	213
4.6.2	The wavelet-based methods of estimating scaling behavior in natural time compared to that in conventional time . . . . .	218
4.7	Combining the normalized power spectrum analysis and multifractal analysis in natural time. The K-means clustering algorithm . . . . .	220
4.7.1	Combining the variance $\kappa_1$ and the generalized Hurst exponent $h(2)$ . . . . .	220
4.7.2	The K-means clustering algorithm . . . . .	221
4.7.3	Comments on the differences in the memory and the variance $\kappa_1$ among electric signals of different nature . . . . .	222
4.8	The fluctuation function $F(q) = \langle \chi^q \rangle - \langle \chi \rangle^q$ and the entropy $S$ in natural time . . . . .	222
4.8.1	Classification of electric signals based on the function $F(q) = \langle \chi^q \rangle - \langle \chi \rangle^q$ versus $q$ in various types of electric signals . . . . .	222
4.8.2	Classification of electric signals based on the entropy $S$ in natural time . . . . .	224
4.8.3	Classification of electric signals by the complexity measures using the fluctuations of the entropy in natural time . . . . .	225
4.9	Using the entropy $S_-$ or the fluctuations of natural time under time reversal . . . . .	226
4.9.1	Distinction of SES activities from “artificial” noises based on the entropy in natural time under time reversal . . . . .	226
4.9.2	Distinction of SES activities from “artificial” noises on the basis of the fluctuations of natural time under time reversal . . . . .	228
4.10	Summary of the criteria in natural time for the distinction of SES activities from noise . . . . .	230
4.11	Procedure to analyze a long-duration SES activity in natural time . . . . .	231
	References . . . . .	233

<b>5. Natural Time Investigation of the Effect of Significant Data Loss on Identifying Seismic Electric Signals</b> .....	237
5.1 Introduction .....	237
5.2 Identification when removing randomly noise-contaminated data segments of fixed length .....	238
5.3 Identification upon significant periodic data loss. The case of Japan ....	243
References .....	244
<b>6. Natural Time Analysis of Seismicity</b> .....	247
6.1 Earthquake scaling laws .....	248
6.2 The order parameter and the universal curve for seismicity. The $b$ value of the G-R law from first principles .....	249
6.2.1 The order parameter proposed for seismicity .....	249
6.2.2 Universal curve for the seismicity in various regions .....	254
6.2.3 Similarity of fluctuations in correlated systems including seismicity .....	257
6.2.4 The pdf of the order parameter of seismicity. The $b$ -value of the Gutenberg–Richter law deduced from first principles .....	259
6.2.5 Multifractal cascades in natural time and the case of seismicity .	261
6.3 Temporal correlations in real seismic data .....	264
6.3.1 Temporal correlations upon changing the magnitude threshold in a catalog .....	268
6.3.2 The strength of temporal correlations as a function of the EQ inter-occurrence time .....	269
6.4 Order parameter fluctuations of seismicity before and after mainshocks	270
6.4.1 Feature of the pdf of the order parameter for seismicity. DFA of earthquake magnitude time series .....	270
6.4.2 Prediction scheme by quantifying the bimodal feature of the pdf of the order parameter $\kappa_1$ for seismicity before mainshocks ....	274
6.4.3 Concluding remarks .....	278
6.5 Nonextensivity and natural time: the case of seismicity .....	278
6.5.1 Non extensivity and earthquakes. The generalization of the Gutenberg–Richter law .....	279
6.5.2 Combining nonextensivity with natural time analysis .....	281
6.5.3 Discussion of the results obtained from the combination of nonextensivity with natural time analysis .....	284
6.5.4 Conclusions from the combination of nonextensivity with natural time analysis of earthquakes .....	285
References .....	286
<b>7. Identifying the Occurrence Time of an Impending Mainshock</b> .....	291
7.1 Determination of the time-window of the impending mainshock by analyzing in natural time the seismicity after the initiation of the SES activity .....	291

7.1.1	The <i>preliminary</i> procedure to determine the occurrence time of the impending mainshock .....	293
7.1.2	The <i>updated</i> procedure to determine the occurrence time of the impending mainshock .....	300
7.2	What happened before all earthquakes in Greece with $M_s(ATH) = 6.0$ or larger since 2001. The cases of the major earthquakes with magnitude $M_w 6.4$ or larger since 1995 .....	303
7.2.1	The major Grevena-Kozani $M_w 6.6$ earthquake on May 13, 1995 .....	304
7.2.2	The major Eratini-Egion $M_w 6.5$ earthquake on June 15, 1995 ..	309
7.2.3	The major Aegean $M_w 6.5$ earthquake on July 26, 2001 .....	313
7.2.4	The major $M_w 6.7$ earthquake in southern Greece on January 8, 2006 .....	318
7.2.5	The two major $M_w 6.9$ and $M_w 6.5$ earthquakes in southwestern Greece on February 14, 2008 .....	320
7.2.6	$M_w 6.4$ earthquake in the Peloponnese on June 8, 2008 .....	324
7.3	Summary of all SES predictions issued along with all earthquakes of magnitude $M_w \geq 6.0$ in Greece since 2001 .....	326
7.4	The volcanic-seismic swarm activity in 2000 in the Izu Island region, Japan .....	327
7.4.1	Natural time analysis of the precursory electric signals .....	327
7.4.2	Natural time analysis of Izu 2000 seismicity subsequent to the initiation of the SES activity .....	330
7.4.3	Main conclusions from the study of the Izu 2000 case .....	333
7.5	Results from California: the $M_s 7.1$ Loma Prieta earthquake on October 18, 1989 .....	334
	References .....	337
<b>8.</b>	<b>Natural Time Analysis of Dynamical Models .....</b>	<b>341</b>
8.1	Is self-organized criticality (SOC) compatible with prediction? Recent aspects. The models analyzed here in natural time .....	342
8.2	Natural time analysis of the Burridge & Knopoff “train” earthquake model .....	343
8.2.1	The earthquake model proposed by Burridge & Knopoff. The “train” model. Introduction .....	343
8.2.2	Natural time analysis of the “train” model .....	345
8.3	Natural time analysis of the Olami–Feder–Christensen (OFC) earthquake model .....	349
8.3.1	The Olami–Feder–Christensen model. Introduction .....	349
8.3.2	Natural time analysis of the Olami–Feder–Christensen model ..	350
8.3.3	The predictability of the OFC model based either on the mean energy or on the interrelation between the $\kappa_1$ value and the exponent of the inverse Omori law .....	358
8.3.4	The predictability of the OFC model on the basis of the change $\Delta S$ of the entropy in natural time under time reversal .....	360
8.3.5	Summary of the results .....	362

8.4	Explanation of $\kappa_1 = 0.070$ for critical systems on the basis of the dynamic scaling hypothesis .....	363
8.4.1	Natural time analysis of the 2D Ising model quenched close to, but below, $T_c$ . The qualitative similarity to the original SES generation model .....	365
8.4.2	The original Bak–Tang–Wiesenfeld sandpile SOC model and its fully deterministic version. Natural time analysis .....	368
8.4.3	Natural time analysis of the mean field case .....	370
8.5	Natural time analysis of time series of avalanches observed in laboratory experiments .....	371
8.5.1	Time series of avalanches observed in ricepiles .....	371
8.5.2	Time series of magnetic flux avalanches observed in high $T_c$ superconductors. A generalized stochastic directed SOC model ..	373
	References .....	377
<b>9.</b>	<b>Natural Time Analysis of Electrocardiograms .....</b>	<b>381</b>
9.1	Natural time analysis of the RR, QRS and QT time series .....	381
9.1.1	Introduction .....	381
9.1.2	The quantities $\delta S$ and $\delta S_{shuf}$ . The non-Markovianity of electrocardiograms .....	384
9.1.3	Distinction between healthy humans and sudden cardiac death ones by means of either $\delta S(QT)$ or the ratio $\delta S_{shuf}/\delta S$ of the RR or QRS intervals .....	389
9.2	Complexity measures of the RR, QRS and QT intervals in natural time to classify sudden cardiac death individuals, heart disease patients and truly healthy ones .....	393
9.2.1	Introduction .....	393
9.2.2	Distinction of sudden cardiac death individuals (SD) from truly healthy ones (H) .....	395
9.2.3	Comparison of the present results in natural time with those deduced from the Approximate Entropy (AE) or the Sample Entropy (SE) to distinguish SD from H .....	404
9.2.4	The procedure for identifying SD among other individuals that include healthy ones and heart disease patients .....	404
9.2.5	Distinction of heart disease patients from H .....	410
9.2.6	Complementarity of the complexity measures for identifying sudden cardiac death individuals (SD) .....	410
9.2.7	The estimation errors in the procedure for identifying SD .....	413
9.3	Summarizing the conclusions for identifying sudden cardiac death individuals (SD) upon considering the error levels .....	415
9.3.1	Summary of the conclusions for distinguishing SD from H ....	415
9.3.2	Summary of the conclusions for identifying SD among individuals that also include heart disease patients and H .....	416



9.4 The change  $\Delta S$  of the entropy in natural time under time reversal: identifying the sudden cardiac death risk and specifying its occurrence time ..... 417

9.4.1 Specifying the occurrence time of the impending cardiac arrest by means of  $\Delta S$ ..... 417

9.4.2 Identifying the sudden cardiac death risk by means of complexity measures based on  $\Delta S$  ..... 420

9.4.3 Summary of the findings based on  $\Delta S$  and their tentative explanation ..... 422

9.5 Heart rate variability (HRV) and  $1/f$  “noise”. A model in natural time that exhibits  $1/f$  behavior ..... 423

9.5.1 The  $1/f$  “noise”. Background ..... 423

9.5.2 An evolution model in natural time that exhibits  $1/f$  behavior ... 425

9.5.3 The  $1/f$  model proposed and the progressive modification of HRV in healthy children and adolescents ..... 429

9.5.4 The complexity measures obtained from the  $1/f$  model and their comparison with HRV data ..... 431

References ..... 432

**Index** ..... 437

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.

2011, XXIV, 452 p., Hardcover

ISBN: 978-3-642-16448-4