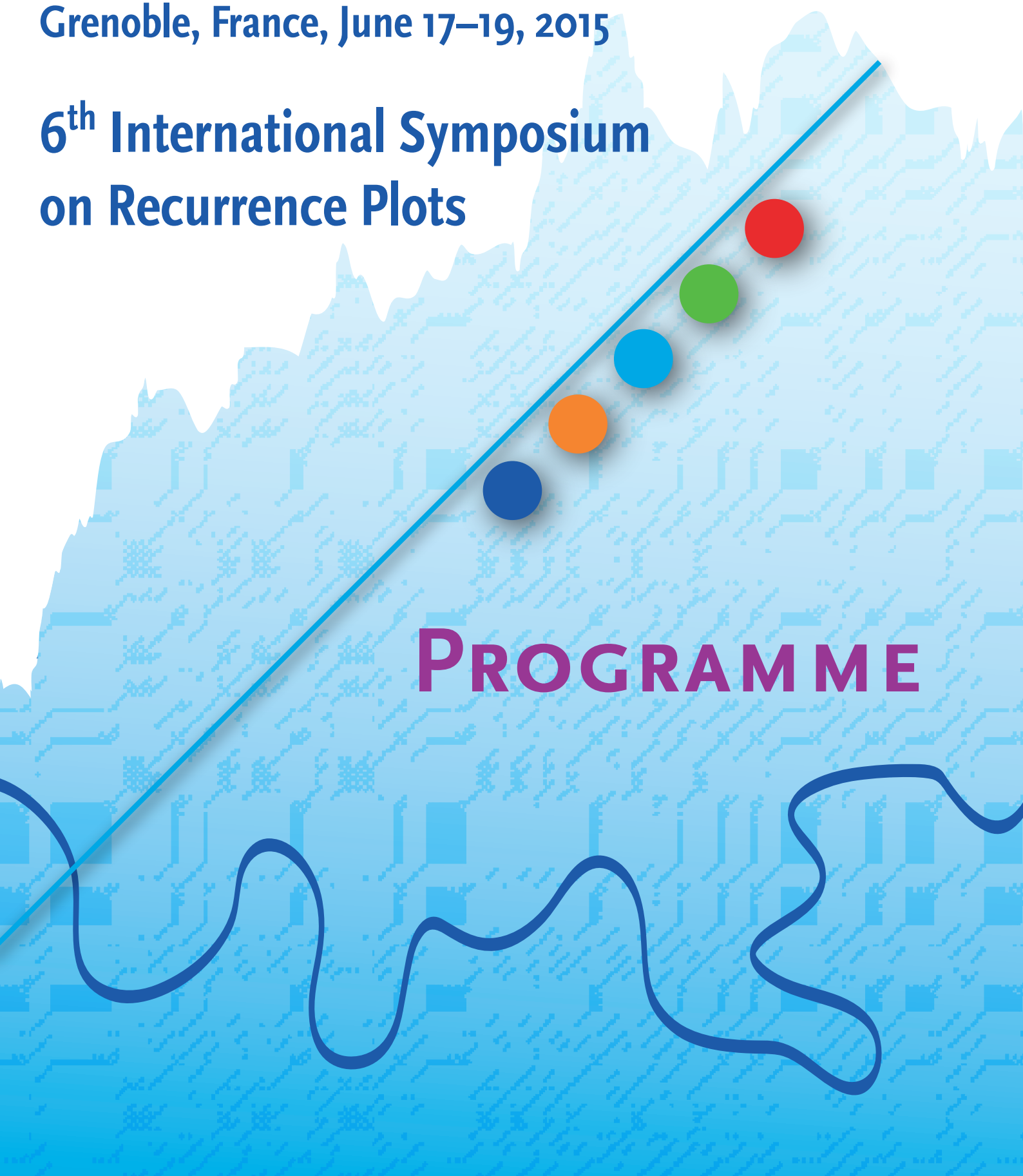
Grenoble, France, June 17–19, 2015

6th International Symposium on Recurrence Plots



Programme

Scientific and Organisational Committee

Cornel Ioana[1]
Norbert Marwan[2]
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Aims

Since 1992, recurrence plots (RP) and its recurrence quantification (RQA) have become important research tools in the analysis of short, noisy and non-stationary data. Theoretical work on and practical applications of RPs have reached considerable maturity and the popularity of these methods continues to expand into diverse areas such as physiology, astrophysics, biochemistry, finance, and meteorology, to name a few.

The symposium is designed to encourage the exchange of knowledge and strategies among scientists investigating different classes of complex phenomena by means of recurrence analysis. Theoretical and experimental results using recurrences: (1) show how RPs can capture subtle underlying dynamics of complex systems; (2) demonstrate the linkage of RPs to dynamical properties; (3) provide ways to study phase-synchronization and perform complex network analyses. To this end, sophisticated recurrence methodologies possesses a utility for Complex Systems Analysis in which scientists from various disciplines are tackling similar questions and face the common challenge of extracting structural/functional patterns from the systems of varying complexity.

Applications of the RP analysis, in connection with traditional well-known research activities of Grenoble's scientific community (environment observation, biomedical researches, physics, etc.), will be an important aspect of the symposium, accentuating the interdisciplinary behavior of the RP domain.

We hope everybody will enjoy the meeting and find new inspirations and cooperations.

Location

The symposium will be held at the Université Joseph Fourier Grenoble Campus in Saint Martin D'Heres Cedex. A campus map can be found at the last page of this booklet.

Lectures

The lecture room is in the GIPSA-lab, Lecture hall "Mont Blanc" (building D, 2nd floor) Posters and discussion will be in the Welcome hall of the GIPSA-lab.

Practical Workshop

In a practical workshop, hands-on sessions on RQA feature extraction and pattern recognition as well as a practical application of the CRP Toolbox for MATLAB will be offered. The workshop will take place in the computer lab in the ISEE (Image and Signal for Energy and Environment) hall, in the same building and at the same level as the GIPSA-lab.

Lunch

Lunch will be served in the "Chartreuse" room of GIPSA-lab.

Social Events

Thursday, June 18

For Thursday, 19:30, we have organised a dinner at the restaurant "Chez le Pèr' Gras" located at the Grenoble Bastille. Participation requires an already done pre-registration.

Saturday, June 20

Saturday we will have an excursion to the La Grave/ Meije Glaciers and a visit of the "Vizille" castle. Departure is 9:30 in Grenoble downtown and arrivial in Grenoble between 17:00 and 17:30. Details will be shared Friday.

Presentations

The speakers have to upload their presentation to the computer in the lecture hall in advance of their talk (in the morning of the day of their talk). The time for the talk is 17 min, plus 3 min discussion (invited talks are 40 min, plus 5 min discussion).

Both MacOS and Windows machines will be available, installed with standard presentation software (PowerPoint, Acrobat, Preview, and Keynote). You may also bring your own computer or presentation device provided that it is fitted with the appropriate VGA output and that you are capable of installing and testing the machine prior to the scheduled session time.

Collection of Presentations

We will provide a platform for sharing the presentations after the symposium in a secure way (password protected web site, secured pdf documents). We will ask the authors of the presentations to give a written permission for this purpose during the symposium. Without such a written permission, presentation files on the presentation computer will be deleted after the symposium.

Note

The symposium will adhere to the rules of good scientific and ethical practice. This means that it is not allowed to copy presentations from the presentation computer. It is also forbidden to take photographs of oral presentations and presented posters without explicitely given permission of the presenter.

Oustanding Poster Award

All posters displayed at the meeting will be evaluated by a committee for an award recognizing excellence in presentation and significance in contribution to nonlinear science. The evaluation criteria comprise the poster display, the significance of the study, and the clarity of the oral presentation including the ability to answers questions.

Program

Tuesday, August 13th

17:00 Registration reception (until 19:30)
GIPSA-lab welcome hall

Wednesday, June 17th

8:00 Registration & pay for registrations
In front of the GIPSA-lab lecture hall "Mont Blanc"

Introduction

9:00 Opening

Methodological Aspects I

9:10 **Peter beim Graben**, Axel Hutt:
Keynote Lecture Analyzing event-related brain potentials through recurrence grammars

9:55 **M. Victoria Caballero**, Mariano Matilla, Manuel Ruiz:
Symbolic Recurrence Plots

10:15 **Diogo C. Soriano**, F. I. Fazanaro, R. Attux, R. Suyama:
Estimating Algorithmic Complexity of Dynamical Systems and Time Series Using Recurrence Plots

10:35 *Coffee/tea break*

11:10 **Fausto Guzzo da Costa**, Ricardo Arajo Rios, Rodrigo Fernandes de Mello:
Applying dynamical system tools to detect concept drift on data streams

11:30 **Olivier Le Bot**, C. Gervaise, J. I. Mars:
Detection of deterministic transient signals in white Gaussian noise by statistical analysis of similarity matrix coefficients

11:50 **Cindy Bernard**, Angela Digulescu, Alexandre Girard, Cornel Ioana:
Multi-lag recurrence plot analysis for transient signal characterization

12:10 **Mike Sips**, Tobias Rawald, Carl Witt, Norbert Marwan:
Towards multi-scale RQA using Visual Analytics

12:30 *Group photo shoot*

12:45 *Lunch*

14:00 **Ramon Miralles**, Alicia Carrion, Guillermo Lara:
Computing the Delay Vector Variance using Recurrence Plots

14:20 **Hui Yang**, Gang Liu:
Self-organizing Topology of Recurrence-based Complex Networks

14:40 Mikhail Khotyakov, Jasper G. Franke, Jobst Heitzig, **Reik V. Donner**:
Recurrence network perspectives on driven chaotic systems: Understanding qualitatively different responses to deterministic and stochastic forcing

15:00 **Deniz Eroglu**, Thomas K. D. Peron, Nobert Marwan, Francisco A. Rodrigues, Luciano da F. Costa, Michael Sebek, Istvan Z. Kiss, Jürgen Kurths:
Entropy of weighted recurrence plots

15:20 *Coffee/tea break*

Applications in Engineering

16:00 **Adler**, Nowicki, Swirszcz, Tresser, Winograd::
Error diffusion algorithm on acute simplices

16:20 **Angela Digulescu**, Ion Candel, Guy D'Urso, Cornel Ioana, Alexandru Serbanescu:
New applications of transient signal processing techniques using the recurrence plot analysis

16:40 **Alicia Carrión**, Ramón Miralles, Guillermo F. Lara:
Scattering material characterization based on Recurrence Plots Quantification Analysis (RQA)

17:00 **Andrzej Rysak**, Grzegorz Górski, Roman Mosdorf, Grzegorz Litak:
The study of two-phase flow chandes using recurrence plots

Thursday, June 18th

8:50 Welcome & miscellaneous announcements

Methodological Aspects II

9:00 **Yoshito Hirata**:
Keynote Lecture Distances of point processes and recurrence plots for neuroscience, econophysics, and seismology

9:45 **Charles L. Webber, Jr.**:
Splayed Recurrence Analysis of Iterated Dynamical Systems

10:05 David Schultz, **Stephan Spiegel**, Norbert Marwan, Sahin Albayrak:
Approximation of diagonal line based measures in recurrence quantification analysis

10:25 *Coffee/tea break*

11:00 **Norbert Marwan**, Saskia Foerster, Jürgen Kurths:
Recurrence plot analysis of spatially extended high-dimensional dynamics

11:20 **Maik Riedl**, Jürgen Kurths, Norbert Marwan:
Spatial-temporal recurrence analysis based on a global measure of spatial similarity

Applications in Earth Science

11:40 Giovanna Zimatore, Gianpaolo Garilli, Maurizio Poscolieri, **Claudio Rafanelli**, Fabrizio Terenzio Gizzi, Maurizio Lazzari:
RQA application to AE time series from two Italian stations within the Apennines for crustal stress propagation assessment

12:00 **Francisco Cervantes-De la Torre**, J. I. Gonzalez-Trejo, S. B. Gonzalez-Brambila, C. A. Real-Ramirez:
Recurrence Plot Measures of Complexity and its application to Self-Potential Time Series

12:30 *Lunch*

13:40 **Mariola Kędra**, Łukasz Wiejaczka:
The role of retention reservoirs in altering the dynamics of river water temperatures (Polish Carpathians)

14:00 **Holger Lange**, Milan Flach, Thomas Foken, Michael Hauhs:
Recurrence Analysis of Eddy Covariance Fluxes

14:20 **Shaleen Jain**, Sudhir R. Jain:
Hydroclimatic change and nonstationarity: Data- and model-based exploratory analyses

14:40 **Lu Jianfei**:
Applications of RPs and RQA in coastal shallow groundwater along the northeast coast of Hainan, China

15:00 *Coffee/tea break*

15:30 Poster Session

19:30 *Social Event* Dinner at Chez le Pèr' Gras (Grenoble Bastille)

Friday, June 19th

8:50 Welcome & miscellanous announcements

Applications in Life Science

9:00 **Ricardo L. Viana**, S. R. Lopes, T. L. Prado, P. P. Galuzio, F. M. Neves, M. R. Pie, D. Toufen, Z. O. Guimarães-Filho, I. L. Caldas, J. Kurths:
Keynote lecture Recent developments in the application of recurrence plots to physical and biological systems

9:45 **Christian Heinze**, David Sommer, Martin Golz:
Automatic relevance determination of recurrence and spectral features of heart rate time series

10:05 **Rosangela Akemi Hoshi**, Luiz Carlos Marques Vanderlei, Carlos Marcelo Pastre, Moacir Fernandes Godoy:
Heart rate variability analyzed by Recurrence Plot: comparison by gender

10:25 *Coffee/tea break*

11:00 **Harald Krause**, Niels Wessel:
A Recurrence-plot-based Method for Detection and Quantification of Cardio-respiratory Coordination

11:20 **Veronica Romero**, Paula Fitzpatrick, R. C. Schmidt, and Michael J. Richardson:
Using cross-recurrence quantification analysis to understand social motor coordination in children with autism spectrum disorder

Applications in Economics and Financial Markets

11:40 **Catherine Kyrtsou**, Christina Mikropoulou:
Implications of noise-induced synchronization

12:00 Patrick Crowley, Catherine Kyrtsou, **Christina Mikropoulou**:
Financial Indicators and the Business Cycle: the Contribution of Recurrence Plot Analysis

12:20 Closing and poster award

12:40 *Lunch*

15:00 **Diogo Soriano, Norbert Marwan**:
Hands on session RQA feature extraction and pattern recognition, CRP Toolbox for MATLAB

Poster

Poster 1 **Ozgur Afsar**, Norbert Marwan, Jürgen Kurths:
Scaling relations from recurrence quantification analysis for the Logistic map at the edge of chaos: Connection with universal Huberman-Rudnick scaling law

Poster 2 **Shigeki Ikegawa**, Charles L. Webber, Jr.:
Recurrences of Converging and Diverging Trajectories near Borders in the Mandelbrot Set

Poster 3 **Hui Yang**, Yun Chen:
Heterogeneous Recurrence Analysis

Poster 4 Jasper G. Franke, **Reik V. Donner**:
Using Recurrence Networks to detect tipping points in Earth's climate history

Poster 5 **Cesar A. Real-Ramirez**, F. Cervantes-De la Torre, J. I. Gonzalez-Trejo:
Non-linear time series study of Dst index with recurrence plot

Poster 6 **George Tzagkarakis**, Thomas Dionysopoulos, Juliana Caicedo-Llano:
Estimation of the time-synchronization profile between market and volatility indices using cross-RQA: The S&P500 and VIX case

Poster 7 **Lipika Kabiraj**, Aditya Saurabh:
Application of Recurrence Plots to Combustion Dynamics

Poster 8 **Olivier Le Bot**, C. Gervaise, J. I. Mars, Y. Simard:
Time-delay estimation based on Cross Recurrence Plot and Joint Recurrence Plot for passive underwater acoustic source localization

Poster 9 **Grzegorz Litak**:
Responses of nonlinear energy harvester by means of recurrences

Poster 10 **Chiya Savari**, Rahmat Sotudeh-Gharebagh, Navid Mostoufi, Reza Zarghami:
Detection of Particle Size Changes in Fluidized Beds by Recurrence Plots Analysis Using Pressure and Acoustic Signals

Poster 11 **Moacir Fernandes Godoy**, Rosangela Akemi Hoshi:
Relationship between Recurrence Plot variables and other linear and nonlinear indices of Heart Rate Variability

Poster 12 Claudia Lerma, **G. Hortensia Gonzalez**, Oscar Infante:
Cross recurrence plot analysis of heart rate and systolic blood pressure during supine position and active standing in healthy adults

Poster 13 **Humberto Arce**, Ayari Fuentes, G. Hortensia Gonzalez:
T_2 as dynamical index in non-monotonic cardiac restitution curves

Poster 14 **Rosangela Akemi Hoshi**, Luiz Carlos Marques Vanderlei, Carlos Marcelo Pastre, Moacir Fernandes Godoy:
Application of Recurrence Plot analysis on recovery from maximal exercise

Poster 15 **Michal Javorka**, Zuzana Turianikova, Ingrid Tonhajzerova, Zuzana Lazarova, Barbora Czippelova, Kamil Javorka:
Recurrence plot as a tool to detect early cardiovascular dysregulation in obesity

Poster 16 **Shambhavi Srivastava**:
The stochastic and the deterministic nature of recurrence in the DNA and its contribution to the evolution of the DNA

Poster 17 **Bruno G. Straiotto**, D. C. James, P. J. Seeley:
Recurrence quantification of electromyographic data for continuous and intermittent squat exercise

Poster 18 **Ralf F. A. Cox**:
Quantifying the dynamics of children's individual and interactive behaviour

Poster 19 **Mary Lauren Malone**, Michael J. Richardson:
The Social Coordination Dynamics of Deception

Poster 20 **Hugo Palacios**:
The spatial distribution of behavior under fixed time scheduled water/food deliveries

Poster 21 **Veronica Romero**, Lillian Rigoli, Kevin Shockley, Gregory J. Funke, Adam J. Strang, Michael J. Richardson:
How Control Asymmetries Influence the Dynamics of Joint-Action

Abstracts

Error diffusion algorithm on acute simplices

Adler, Nowicki, Swirszcz, Tresser, Winograd

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Error diffusion is a continuous to discrete conversion. In color printing (which inspired our study) it provides an online and greedy way to print point by point one out of only a few colors to get the impression of the full palette. The algorithm can be represented as iterations of a piecewise affine map in a d-dimensional space, where the pieces are Voronoi regions of a convex polytope. I will present some results, when the polytope is an acute simplex and the input parameter (the color to be printed) is a constant mixture of the cartridge colors. In this case the absorbing set is a (usually non-convex) polytope which happens to be a fundamental set for the lattice generated by the simplex.

Scaling relations from recurrence quantification analysis for the Logistic map at the edge of chaos: Connection with universal Huberman-Rudnick scaling law *Poster*

Ozgur Afsar, Norbert Marwan, Jürgen Kurths

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Huberman-Rudnick universal Lyapunov scaling law is a kind of predictive capability if a system become chaotic through a sequence of period doublings, then one could be predict how it will be as a function of the control parameter [*R.C. Hilborn, Chaos and Nonlinear Dynamics (Oxford University Press, NewYork, 1994)*]. As chaos threshold is approached within this scaling law, it is fact that the Lyapunov exponent exhibits a power law behaviour depending to distance of the chaos threshold ($a - a_c$) possessing the a universal critical exponent with $\nu = \ln 2 / \ln \delta \simeq 0.45$ (δ is the Feigenbaum constant) [*B. A. Huberman and J. Rudnick, PRL* **45** *(1980) 154*]. We numerically introduce the new relationships and scaling laws related to the recurrence rate (RR), the average length of the diagonal lines ($\langle L \rangle$), the determinism (DET) and exponantial divergence of phase space trajectory (DIV) as the measures from Recurrence Quantification Analysis (RQA) as we approach the chaos threshold of the logistic map with Huberman-Rudnick scaling procedure. After we determine the critical values (RR_c, $\langle L \rangle_c$, DET_c and DIV_c) of these measures on the chaos threshold of the logistic map, firstly, we verify that a scaling law of type $|RR - RR_c| \propto (a - a_c)^{\alpha}$ is evident with the critical exponent $\alpha = 0.47 \pm 0.01$. Secondly, we show that the quantity $\langle L \rangle$ scales as $|\langle L \rangle - \langle L \rangle_c| \propto (a - a_c)^{\beta}$, where the exponent is $\beta = 0.46 \pm 0.02$. Thirdly, we numerically verify that DET exhibits a scaling law of type $|DET - DET_c| \propto (a - a_c)^{\gamma}$, where the exponent is $\gamma = 0.27 \pm 0.01$. Finally, we numerically show relation between the Huberman-Rudnick universal Lyapunov scaling law and Divergence scaling which behaves as $\lambda \propto (a - a_c)^{\nu}$ and $DIV \propto (a - a_c)^{\kappa}$, where the exponents are $\nu = 0.449 \pm 0.001$ and $\kappa = 0.50 \pm 0.03$.

T_2 as dynamical index in non-monotonic cardiac restitution curves *Poster*

Humberto Arce, Ayari Fuentes, G Hortensia Gonzalez

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The action potential duration (APD) restitution curve of cardiac cells or activation-recovery intervals (ARI) in the entire human ventricle have been used to characterize the recovery or restitution of their electrical properties [1]. The restitution curve represents the relationship between an APD/ARI and the preceding diastolic interval. The "restitution hypothesis" states that a slope of the APD/ARI recovery curve > 1 may leads to alternans, wavebreaks, and transitions from ventricular tachycardia to ventricular fibrillation (VF), even in a ventricle without preexisting repolarization heterogeneity (IBID). A subset with non-monotonic profile has been previously described among different experimental types of recovery curves. In the present work we model a recovery curve using an exponential function plus a gaussian function, with parameters estimated from experimental data [1]. Following the approach proposed by Trulla et al. [2], we produced a bifurcation diagram by iterating the map produced with these combined functions as we increase the bifurcation parameter, in this case, pacing time. We explored 60 Gaussian heights embedded in the same exponential function and, for each one of these cases; we calculated the Lyapunov exponents and obtained the maximal diagonal inverse and the T_2 index for each recurrence plot. The results obtained with these indexes are qualitatively similar, meaning that all they show the dynamical bifurcation pattern occurring in this system. Particularly rich in information is the T_2 bifurcation (biparametric) diagram, as it is possible to observe that the bifurcation diagram is almost symmetric, which happens because the emerging patterns for lower gaussian regions are preserved in higher gaussian ones, but doubling the zones they cover and moving away from each other. This is particularly evident for periodic windows intercalated between chaotic regions. Also, the region of pacing times where there is chaotic behavior grows as the recovery curve is farther from the monotonic realization. After comparing with rhythm diagrams for monotonic APD/ARI recovery curves it is possible to consider that in this case complex rhythms appear for higher pacing times, implicating bigger vul-

nerability of cardiac tissue with non-monotonic APD/ARI recovery curves. The dynamical bifurcation diagram calculated based on trulla's scheme is very quickly obtained which may be helpful in designing clinically oriented applications.

References:

[1] Yue A M, Franz Mir, Roberts P, P Morgan, John M (2005) J Am Coll Cardiology 46

[2] Trulla L L, A Giuliani, JP Zbilut, and CL Webber Jr (1996) Phys. Lett. A 223

Analyzing event-related brain potentials through recurrence grammars

Peter beim Graben and Axel Hutt

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The identification of neural correlates of cognitive, affective and emotional states is a pertinent problem in computational neuroscience. Inspired by Dietrich Lehmann's idea to segment EEG or ERP time series into brain microstates (Lehmann et al. 1987, 2009), beim Graben & Hutt (2013, 2015) developed an algorithm for the detection of recurrence domains of complex dynamical systems from time series. Our approach exploits the characteristic checkerboard texture of recurrence domains exhibited in recurrence plots. In phase space, recurrence plots yield intersecting balls around sampling points that could be merged into cells of a phase space partition. We constructed this partition by a rewriting grammar applied to the symbolic dynamics of time indices. However, two open problems remained unsolved: (1) how to determine the optimal size of intersecting balls; and (2) how to cluster recurrence domains from different trials together. In my resentation, I suggest a maximum entropy principle as solution for (1), while problem (2) could be solved by phase space clustering according to the Hausdorff distances of partition cells. I will motivate these techniques by simulated ERP data from a Lotka-Volterra model and by ERPs obtained from a psycholinguistic experiment (beim Graben & Hutt 2015).

References:

- Lehmann, D.; Ozaki, H. & Pal, I. (1987). EEG alpha map series: brain micro-states by space-oriented adaptive segmentation. Electroencephalography and Clinical Neurophysiology, 67, 271 - 288.
- Lehmann, D.; Pascual-Marqui, R. D. & Michel, C. (2009). EEG microstates Scholarpedia, 4, 7632.
- beim Graben, P. & Hutt, A. (2013). Detecting recurrence domains of dynamical systems by symbolic dynamics. Physical Review Letters, 110, 154101.
- beim Graben, P. & Hutt, A. (2015). Detecting event-related recurrences by symbolic analysis: Applications to human language processing. Proceedings of the Royal Society London, A373, 20140089.

Multi-lag recurrence plot analysis for transient signal characterization

Cindy Bernard, Angela Digulescu, Alexandre Girard, Cornel Ioana

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Transients are encountered in many real-life applications such as electrical discharges in solar panel or electric network, hydraulic shocks in pipeline systems, etc. Due to their nonstationarity and their wide frequency content, it is really difficult to characterize them. Nevertheless, their monitoring is of great interest as it can reveal malfunctioning activities of the system. Recurrence plot analysis has been proved really useful for time series analysis in many fields of applications. However, no method has been proposed to automatically select the time delay and the embedding dimension m parameters. Most of the time, those parameters (that highly depend on the application) are determined by trials which makes it difficult to design data-driven algorithms. In this paper, we propose a method to study transients where the user does not need to choose the time delay parameter. The technique involves the calculation of phase space diagrams for different values of time-delay and $m = 2$. Parameters are then extracted from each representation and studied according to the variation of the time delay. Different parameters have been designed for this purpose:

- By considering phase space diagrams as scatterplots, elliptic modeling can be fitted. Three parameters are then extracted for each representation: the angle of the ellipse, the major and minor semi-axes.
- Another approach would consider the bounding box of phase space diagrams. The four intersections with the box are recorded.
- The diagrams can also be seen as curves, then, one can study the evolution of the area covered by the curve.

Those methods are designed to enlighten similarities between transients such as dilation and amplitude modification. Let us imagine the case of an electric discharge occurring in a cable. Due to the propagation trough the medium that can be modeled as a nonlinear filtering, the two signals are not identical, which makes difficult the using of cross-correlation or other traditional signal processing tools. Due to their nonstationarity, it is also difficult to characterize them with time-frequency analysis. The techniques proposed by this paper are tested for real signal and the results prove their capacity to enlighten transient similarities based on phase space diagrams.

Symbolic Recurrence Plots

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The technique of recurrence plots was proposed by Eckmann et al. as a graphical tool to study the time dependence behavior of any time series without making any a priori assumption on the generator system. In order to quantify the most important features of a recurrence plot, Zbilut and Webber, and Marwan have, over the last ten years, developed the Recurrence Quantification Analysis (RQA). For that, it is crucial to fix a real number ϵ that introduces some noise in the analysis. We propose the use of symbolic recurrence plot. This tool doesn't need to fix the value ϵ. Given a vectorial time series the encoding provided by the symbolization map s which assigns to every element of vectorial time series a symbol, that is its ordinal pattern. Given the symbolization map s we define the indicator function $I(\cdot)$. This function is 1 if the symbol of two elements of vectorial time series is the same and 0 otherwise. For each value of $(t;k)$ in the plane or we can represent $I(\cdot)$ by a black or colour point when the indicator function is 1 (where the colour would depend on the symbol, each symbol a different colour). Then the indicator function $I(\cdot)$ informs about when the time series re-visit each one of $m!$ areas determined by $m(m-1)/2$ hyperplanes and therefore it can be a useful tool to study the dynamic structure of the series. We show examples of the usefulness of symbolic recurrence plots to detect periodicities, randomness, or deterministic chaos. In addition we propose measures from theses graphics as the proportion of points which has assigned the same symbol by s. But the most important thing is that we don't need fix the parameter ϵ ad hoc .

Scattering material characterization based on Recurrence Plots Quantification Analysis (RQA)

Alicia Carrión, Ramón Miralles, Guillermo F. Lara

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The versatility of the Recurrence Plots (RP) is widely known. However, this powerful tool has never been used before for the characterization of the porosity of cement pastes. In this work the Recurrence Plots Quantification Analysis (RQA) is proposed to extract information about the combination of coherent reflections in scattering material grains with respect to the rest of incoherent noises that typically appear in non-destructive testing (NDT) using ultrasonic. RP reconstruction based on the angular distance is a non-parametric technique commonly used in chaos theory that does not require making any kind of assumptions about attenuation profiles. In highly scattering media (low SNR), it has been shown theoretically that the degree of determinism (diagonal lines) allows material characterization. The experimental results obtained in this work with 16 cement probes of 4 different porosities demonstrate the ability of this technique to do classification. It has also been shown that, in this particular application, the measurement of determinism can be used as an indicator of the percentages of porosity of the test samples with great accuracy.

Recurrence Plot Measures of Complexity and its application to Self-Potential Time Series

F. Cervantes-De la Torre, J. I. Gonzalez-Trejo, S. B. Gonzalez-Brambila, C. A. Real-Ramirez.

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Since 1992, the self-potential time series studied in this work have been recorded at a seismically active region located near the trench of the Mexican South Pacific Coast. In that period of time, one great event with $M = 7.4$ (September 14, 1995) has occurred in the monitored zone. Because that event is classified as a large one, we are studying the registered signals obtained it by using non-linear techniques, such as, Recurrence Plot Measures of Complexity.

Quantifying the dynamics of children's individual and interactive behaviour *Poster*

Ralf F. A. Cox

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The temporal variability in children's behaviour constitutes a rich source of information about the origins of that behaviour, as well as about learning and development. This information is essential for unravelling how children's actions are synchronized with those of other people, as in social interaction, or coordinated in a specific task, as during problem solving. In addition, it provides a framework for conceptualizing and understanding how behaviour emerges en develops from the interaction of body, brain and environment. By thoroughly studying the behaviour as it unfolds over time, employing nonlinear time-series techniques such as recurrence quantification analysis (RQA), it is possible to reveal this information from the noisy measurements. The poster will present examples of the application of RQA on categorical time series of children's behaviour.

Financial Indicators and the Business Cycle: the Contribution of Recurrence Plot Analysis

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The particular characteristics of the latest persistent episode of financial distress revived the interest in investigating the power of financial indicators to predict peaks and troughs of the business cycle. Among the best candidate variables are the stock of money, as measured by the monetary aggregate M2, and the stock market as represented, in the case of US, by the SP500 index. Since the relationship between the financial and economic sectors is quite complex, the need to utilize appropriate techniques which do not suffer from well-documented estimating errors and computational biases becomes more than ever relevant. With the aim of making both an empirical and theoretical contribution, beyond the mainstream econometric methodology, we propose an alternative line of research based on the recurrence plot (RP) analysis. Thus, we employ the multivariate extension of RPs along with the Line of Synchronization (LOS). Besides the visual inspection of the simple and cross-recurrence plots, we focus on the nonlinear bivariate measure of Shannon entropy, which is able to capture synergetic dynamics between the variables being analyzed. The entropy deals with the complexity in the RP. For uncorrelated noise, it takes small values, indicating low complexity while for more complex processes it raises progressively during phase transition regimes i.e. prior to the ongoing tipping point. This feature renders the entropy a robust early warning indicator. To the best of our knowledge this paper is the first work attempting to establish, through the implementation of the RP technique, a link between the underlining dynamics of main financial indicators and the phases of the business cycle, so as to prevent from output deterioration by taking appropriate intervention actions.

The data set consists of monthly time series (the longest available) for the US real money supply and the S&P500; the US industrial production is chosen as a proxy of the business cycle. Our conclusions shed light on the quest for potential costs derived from the inclusion of real M2 among the LEI components. They also confirm recent reports of the Conference Board according to which the M2 has missed the 2001 and 2007 recessions, exerting a negative pressure on the Composite Leading Index. On the other hand, the entropy results for the SP500 index are in line with those of Gao and Hu (2014) supporting that upward estimates precede the NBER announcements of recessions.

New applications of transient signal processing techniques using the recurrence plot analysis

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Transient signals are signals with short duration and broad spectrum which are often present in various industrial applications such as turbine regime changes, electrical arches generated in photovoltaic panels or in electric cables, etc. In order to ensure the safety of such systems, it is very important that these signals can be detected, located and characterized in order to prevent an eventual irreversible damage. This paper presents new tools derived from the concept of Recurrence Plot Analysis and applied to some real applications related to power systems. Two of the applications concern the detection, localization and characterization of the electrical partial discharges measured in photovoltaic panels and in electrical cables, respectively. While the detection and the localization of the partial discharges are achieved through the exploration of the characteristics of the recurrence matrix building a well suited energy detector, their characterization is obtained using the multi-lag recurrence plot analysis, a new concept which uses the 2D phase space representation. The multi-lag recurrence plot analysis tools investigate the evolution of the signals in the phase space using the elliptic modeling and the polar coordinates representation.

Another application refers to the characterization of the water hammer effect using an ultrasonic sensing system placed on a pipe line. The acoustic effect induced to the sensors is detected using the recurrence plot analysis concept and, then, the time of flight of the signals is computed. Hereby, the pressure variation performed by the water hammer phenomenon into the pipe line is determined and compared with the variation measured by the pressure sensor placed in the pipe. An error under 2% was obtained, the recurrence plot analysis method proving to be a much better approach in comparison to state of the art methods in hydraulics or signal processing.

The fourth application refers to the detection and characterization of a rotational vortex rope using acoustic sensors in active configuration. The recorded signals are investigated through the quantification of the diagonal lines and the exploit of their frequency content. Results confirm the existence of the rotational vortex rope and highlight its evolution.

Weighted Recurrence Plot

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Phase-space binning and using information in the bins is the standard method to establish complexity of a dynamical system. Methods such as the Shannon entropy, the Hausdorff dimension, the Kolmogorov complexity etc., can be used to quantify transitions between different dynamical regimes. In order to create a recurrence plot, we divide the phase space into equidistant but overlapping bins. The information in the bins shows us similar features as in the mentioned measures before. Here we suggest a method based on weighted recurrence plots and show that the associated Shannon entropy is positively correlated with the largest Lyapunov exponent. We demonstrate the potential on a prototypical example as well as on experimental data of a chemical experiment.

Using Recurrence Networks to detect tipping points in Earth's climate history *Poster*

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In the last years the existence of tipping elements in the Earth's climate system has gained increased attention. Here, tipping behavior refers to dynamical transitions of some subsystem leading to a qualitatively different state. In the light of the recent debate on possible regime shifts due to global climate change it is necessary to understand if, when and where such transitions have occurred in the past in order to assess possible future risks.

As tipping of climate elements should be accompanied by changes in the nonlinear dynamics (e.g., due to bifurcations or noise-induced transitions), methods from nonlinear time series analysis can lead to additional insights regarding the existence of past transitions. In this work, we study the capabilities of recurrence network analysis to reveal complex signatures of past nonlinear regime shifts. The potentials and limitations of these novel approaches are systematically compared with those of classical early warning indicators like increasing autocorrelation, variance, etc. We illustrate the performance of the different methods for synthetic time series exhibiting tipping point behavior as well as different paleoclimate time series.

Relationship between Recurrence Plot variables and other linear and nonlinear indices of Heart Rate Variability *Poster*

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The knowledge of heart rate recurrence analysis is not widely diffused in the literature and, as a suitable method for short and non-stationary time series evaluation, it deserves special attention. Thus, trying to clarify the physiological meaning of Recurrence Plot's (RP) variables, it seems reasonable to evaluate the correlation between them and more commonly used indices of heart rate variability (HRV), making this the aim of this study.

Methods: 83 male, young and healthy subjects underwent 30 minutes of supine rest, with spontaneous breathing, while their heart rate was continuously recorded beat-to-beat. 1000 R-R intervals were extracted from the most stable segment of time series and heart rate Recurrence Rate (%RR), Determinism (%DET), Laminarity (LAM), and Shannon Entropy (SE) were analyzed by Visual Recurrence Analysis software, using the following parameters: dimension 10, radius 70, line 2 and delay 1. Kubios HRV analysis, was used for SDNN, RMSSD, LF, HF, SD1 and SD2 determination while Total DFA, $\alpha 1$ and $\alpha 2$ was calculated by DFA software. Pearson's correlation test was performed and considered significant when P value was lower or equal to 0.05.

Results: All RP's variables significantly correlated with parasympathetic indices (RMSSD, HF and SD1), total DFA and $\alpha 1$, but the highest and most expressive correlations were found between: %RR and RMSSD ($r = -0.542$, $P < 0.0001$), HF ($r = -0.475$, $P < 0.0001$), SD1 ($r = -0.424$, $P < 0.0001$), total DFA ($r = 0.712$, $P < 0.0001$) and $\alpha 1$($r = 0.334$, $P = 0.002$); and DET correlated with RMSSD ($r = -0.58$, $P < 0.0001$), HF ($r = -0.531$, $P < 0.0001$), SD1 ($r = -0.445$, $P < 0.0001$), DFA ($r = 0.488$, $P < 0.0001$) and $\alpha 1$($r = 0.384$, $P = 0.0003$).

Conclusion: Our results suggest that the percentage of recurrence points (%RR) and the portion of these recurrence points that align into diagonal lines (%DET) presented higher relationship with parasympathetic modulation and fractality.

Applying dynamical system tools to detect concept drift on data streams

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The modeling of data stream plays an important rule to detect changes in its behavior over time, which are also referred to as concept drift. The detection of such changes is important in order to obtain information about the phenomenon which produced the stream. Current studies on concept drift estimate probability distributions assuming data are statistically independent and produced by linear and stationary process. As next step, they compare the estimatives of probability distributions to issue a concept drift. In this work, we consider data streams as a mixture of deterministic and stochastic components and present a new definition for concept drift which is related to how the dynamics of data changes over time. The stream dynamics is analyzed by reconstructing consecutive windows of data streams into the phase space, using Takens' immersion theorem. Then, we compare the obtained attractors using the Cross-Recurrence Plot and Recurrence Quantification Analysis to detect concept drift. In this new approach, the concept change is thus characterized by the deterministic behavior found after the reconstruction of data windows in phase space. The advantage of this approach is that it is capable of finding out similarities between dynamical systems rather than only compare estimations of probability distributions. In experiments, data streams were produced by non-linear and stationary/non-stationary processes with different types and levels of noise. The proposed algorithms were compared to well-known algorithms from literature by using three metrics: Missed Detection Rate (MDR), Mean Time to Detection (MTD) and Mean Time between False Alarms (MTFA). Results confirm that the algorithms from literature proceed according to an always-detecting approach, creating several false alarms; or by a never-detecting one, creating no alarms at all. On the other hand, the proposed algorithms detected most of the concept drifts, presenting few false alarms. Thus, we consider the algorithms based on our approach more adequate to scenarios in which one needs a better balance among all three metrics considered. As limitation, our algorithms present greater time complexity when compared to others. As future work we intent to assess the proposed algorithms in real-world data streams with chaotic influences as well as work on their time complexities.

Automatic relevance determination of recurrence and spectral features of heart rate time series

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We present a machine-learning framework that determines the most relevant measures of recurrence quantification analysis (RQA) for the discrimination of heart rate time series (each averagely 23 h long) from two different groups: the NSR2 database contains 54 recordings of heart beat annotations from healthy subjects, whereas the CHF2 database contains 29 recordings of patients suffering from congestive heart failure (CHF).

Per subject, heart rate time series were divided into non-overlapping segments, where segment lengths of 2, 4, and 8 min were tested. Time-delay τ and embedding dimension m were estimated by determining the first local minimum of mutual information and false nearest neighbors, respectively, for all segments. The resulting distributions indicated $\tau = 7$ and $m = 5$ as appropriate global values for time-delay embedding. Recurrence threshold ε was defined by the following consideration: based on an ECG sampled at 128 Hz, the quantification noise e of R-to-R intervals is 7.8 ms. It was assumed that Îţ should be at least five times greater than the observed noise level, thus: $\varepsilon > 5e > 0.039$ s ≈ 0.04 s. With such τ, m, and ε, RQA was computed for all segments.

To compare RQA against other heart rate features, 20 frequency bins between 0.0 and 0.4 Hz (based on the Lomb-Scargle periodogram) were calculated for every segment as well.

The learning vector quantization (LVQ) is an artificial neural network for classification. It has been extended to the generalized relevance LVQ (GRLVQ) which simultaneously learns relevance factors λ for the input variables. Multiple hold-out cross validation was used to estimate classification performance. After finishing training mean relevances were determined by averaging across all subjects.

The best classification for all features was achieved at a segment length of 8 min, where frequency bands (classification error: 16.1 $\pm$ 0.5 %) clearly outperformed RQA (27.4 $\pm$ 0.5 %). Relevance factors show length of longest vertical & diagonal line as well as recurrence time of 2nd type as the only three relevant RQA measures. The relevance distribution of frequency bands is less distinct; still, 0.22$\pm$0.24 Hz (within the high-frequency band) is the most relevant band before very-low-frequency bands. A combination of spectral and recurrence features yielded an intermediate classification (19.5 $\pm$1.3 %), where very same RQA measures maintained their dominant relevance rank.

Distances of point processes and recurrence plots for neuroscience, econophysics, and seismology

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In the real world, there are many examples of point processes, for which we can obtain a series of events. Distances for point processes provide a convenient platform such that time series data sampled with a fixed sampling interval and point processes can be analyzed in the same manner seamlessly. In this platform, recurrence plots become an interface for understanding the underlying dynamics intuitively. I will demonstrate the effectiveness of the platform using examples of neural activity, earthquakes, and their influence to the foreign exchange markets.

Application of Recurrence Plot analysis on recovery from maximal exercise *Poster*

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Recurrence plots has been described as suitable for the analysis of non- stationary and short data series, therefore it seems reasonable to use this technique to assess conditions in which it is hard to find a stationary signal and the responses are fast and acute, like during physical activity. However, up to date, there is no registered study using this technique to evaluate exercise and recovery. Thereby, the aim of this study is to observe Recurrence Plot's variables of healthy subjects throughout recovery period after high intensity exercise.

Methods: Twenty eight subjects first performed a Peak Oxygen Consumption Test and, on the following day, the Time Limit Test and recovery assessment. Previous to the exercise, they lay down for 30 minutes for resting data collection and then underwent constant velocity exercise at 100% of maximal velocity until exhaustion. Immediately after the exercise cessation, the participants kept a supine position for 120 minutes recovering passively. HR and R-R intervals were recorded during the whole process and we used windows lengths of 256 beats at the end of baseline and at each 10 minutes of recovery to be analyzed by the Visual Recurrence Analysis software.

Results: At baseline the median values of Recurrence Rate, Determinism, Entropy and Lmean were, respectively, 25.1%, 97.2%, 2.9 and 8.6 beats. Ten minutes after the exercise, all these variables showed significant increase until 80 minutes. After that, no significant difference was found between recovery moments and baseline, but only at 120 minutes we found values very close to pre-exercise levels.

Conclusions: Using Recurrence plot as a variable to assess exercise and recovery seems a suitable method. The variables behaved in a similar way, increasing right after the exercise and showing recovery at same moment, which suggests coherency among them. We may conclude that after maximal exercise, the complexity is restored after 80 minutes.

Heart rate variability analyzed by Recurrence Plot: comparison by gender

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Heart rate variability analyzed by Recurrence Plot: comparison by gender There are several physiological differences between men and women and the autonomic nervous system (ANS) modulation seems to be one of them. Although several studies have analyzed heart rate variability (HRV) linear indices and heart rate (HR) complexity in both sexes, there is still discordance about gender differences in autonomic behavior and also none of these studies applied Recurrence Plot analysis.

Objectives: The aim of this study was to verify if there are quantitative differences in recurrence plot between healthy and young men and women.

Methods: 158 subjects (78M and 80W) underwent 30 minutes of supine rest, with spontaneous breathing, while their heart rate was continuously recorded beat-to-beat. 1000 R-R intervals were extracted from the time series most stable segment and analyzed by Visual Recurrence Analysis software using the following parameters: dimension 10, radius 70, line 2 and delay 1. Unpaired student t test was performed to detect differences between the groups and P values lower or equal to 0.05 were considered significant.

Results: Both groups were statistical homogeneous on age ($M = 21.55 \pm 2.31$ vs. $W = 21.66 \pm 2.79$, $P = 0.785$). Differences between sexes were not found in any of analyzed recurrence plot's variables and the mean values for men and women were, respectively: Recurrence Rate $23.12 \pm 6.36\%$ vs. $24.00 \pm 6.14\%$, $P = 0.375$; Determinism $96.88 \pm 1.55\%$ vs. $97.06 \pm 1.34\%$, P=0.427; Laminarity 85.06 ± 16.92 vs. 83.32 ± 19.79, $P = 0.553$; Entropy 4.27 ± 0.38 vs. 4.35 ± 0.34, $P = 0.137$; Max Line 237.46 ± 188.74 vs. 302.92 ± 232.09, $P = 0.054$.

Conclusion: Unlike some studies which reported that HRV and complexity is lower in women than in men, our results suggest that the complexity of men and women is equivalent in this age group.Thus we conclude that cardiac autonomic activity and its complexity are not gender dependent.

Recurrences of Converging and Diverging Trajectories near Borders in the Mandelbrot Set *Poster*

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The Mandelbrot (M) set is an infinitely deep mathematical structure consisting of recurring patterns and miniaturized M-sets at all scales. The entire M-set and with all of its diminutive derivatives exist within the complex plane of constant $C(C_{real}, C_{imag})$ in the iterated equation: $Z = Z \cdot Z + C$. If the complex variable Z converges toward the M-attractor, point C is considered a member of the M set. But if Z diverges from the M-attractor after N iterations, point C falls outside of the M-set.

In this study, Z dynamics were examined near the border of seven different regions of the M-set. Region A was the central cardioid itself. Regions B, C and D were smaller and smaller cardioids above the central cardioid. Regions E, F and G were smaller and smaller cardioids to the left of the central cardioid. Variable Z_{real}, Z_{imag} was consistently seeded to 0, 0 and parameter C was systematically adjusted within border vicinities to give long Z dynamics (up to 5000 points) for converging and diverging Z values.

Z dynamics were studied by cross recurrence and joint recurrence quantifications (Z_{real} vs. Z_{imag}). Recurrence quantifications of converging trajectories were compared with diverging trajectories of points very close to M-set borders in C space. Subtle differences could be detected between the two dynamics over the first 1000 points. These initial parts of the dynamics were many cycles prior to the diverging Z trajectory exploding off to infinity. This study shows that RQA strategies can be used to detect subtle dynamical differences between trajectories attracted to or repelled from the Mandelbrot chaotic attractor.

Hydroclimatic change and nonstationarity: Data- and model-based exploratory analyses

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Changes in the planetary climate and hydrologic cycle manifest in a range of environmental systems, such as riverine and lake systems. Short length historical records offer important clues regarding past and ongoing changes, abrupt shifts, and transitions. In this study, we use lake, streamflow and climate records to explore the nature of interannual and longer-term variability. Of particular interest are the changes in the seasonal cycle of streamflow and lake ice-out. We use recurrence plots to investigate the extent to which periodicities and phase shifts are coherent and propagate across relevant variables and seasons. Some practical implications for environmental sustainability are also discussed.

Recurrence plot as a tool to detect early cardiovascular dysregulation in obesity *Poster*

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Obesity is accompanied by many severe complications including various cardiovascular disorders. An impairment of cardiovascular control by autonomic nervous system could be one of the possible links between obesity and development of cardiovascular complications. In our previous study, we have shown that recurrence quantification analysis (RQA) measures derived from recurrence plots with fixed percentage of recurrence points constructed from spontaneous heart rate and systolic blood pressure oscillations are sensitive to changes in autonomic tone (decrease of parasympathetic and increase of sympathetic activity) induced by postural change. The aim of this study was to test the sensitivity of RQA measures against other linear and nonlinear time series analysis tools in detection of early autonomic dysregulation in young obese subjects.

Continuous recordings of beat-to-beat systolic blood pressure and RR intervals from ECG were obtained from 40 obese subjects (25 female, age 14.2 [13.1–16.1] (median [interquartile range]) years) and gender and age matched non-obese control subjects. In addition to linear measures (time and frequency domain) we performed recurrence quantification analysis (RQA) and multiscale entropy (MSE) analysis for both signals.

While no significant differences in heart rate and systolic blood pressure dynamics were detected by linear measures and MSE, analysis of recurrence plots with a fixed percentage of recurrence points from RR intervals time series showed significant differences – indices trapping time and maximal length of vertical from RQA were significantly higher in obese compared to control group.

We conclude that heart rate and blood pressure control by autonomic nervous system is relatively well preserved in young obese subjects. However, novel recurrence quantification analysis measures are able to detect early subtle abnormalities in cardiac autonomic control in obese subjects indicating a decreased control system complexity.

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Application of Recurrence Plots to Combustion Dynamics *Poster*

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The paper is a summary of recent activities on the application of recurrence plots and recurrence quantification analysis to three very important aspects in combustion systems: combustion noise, combustion instability and the occurrence of extreme events, namely, flashback and blowout. In practical systems, these three aspects involve a complex interaction between multiple physical processes, such as, combustion, acoustics, and hydrodynamics. As such, phase space reconstruction based analysistextemdash specifically recurrence analysistextemdash is most suited for analyzing data resulting from such highly unsteady phenomena with multiple time scales.

In each of the applications, it is shown that recurrence plots and recurrence quantification analysis provides a basis for results and inferences that conventional analysis could not uncover. Specifically, for combustion noise, recurrence plots can be used for comparing noise generation from turbulent flames at different conditions and for identifying transient occurrence of coherent flame dynamics. For combustion instability, recurrence plots helped in the identification of a dynamical state that, at first, appeared to be a series of random events. Finally, an application of recurrence plots for the detection of undesirable sudden events in a combustion system is shown.

The application of recurrence plots to combustion systems is a new and ongoing investigation. Further efforts are required to adopt this class of analysis methods together with conventional techniques, such that additional information obtained could be incorporated in modeling and prediction of the said aspects.

The role of retention reservoirs in altering the dynamics of river water temperatures (Polish Carpathians)

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Water temperatures are an important environmental factor for aquatic biota. The range of temperature values and their dynamical changes through different temporal scales, from diurnal to annual ones, influence the life conditions for fish and other aquatic organisms. The main objective of the paper is the determination of the role of mountain reservoirs operating in the course of rivers in altering the dynamics of river water temperatures. Water and air temperatures, measured some distance below a group of two reservoirs functioning on a mountain river, are analysed for the period covering the time before and after reservoirs construction. The reservoirs (Czorsztyn-Sromowce WyÅijne on the Dunajec River) are designed to fulfil mainly flood control and electricity generation.

In order to establish the impact of the considered reservoirs on water temperature changes below these reservoirs, the relationship between water and air temperature should be taken into account for the same time interval, as the air temperature largely determines the river water temperature in the same location.

Using recurrence and cross-recurrence quantification analyses, the daily water and air temperatures in KroÅŻcienko locality (22 km downstream of the reservoirs) were studied for the period 1978âĂŞ2012 (35 hydrological years), with the division into pre-dam and post-dam periods. The conducted analyses revealed that reservoirs have significantly altered the temperature dynamics of water flowing out of them compared to the pre-dam period.

Recurrence network perspectives on driven chaotic systems: Understanding qualitatively different responses to deterministic and stochastic forcing

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Recent numerical results have demonstrated that especially the transitivity properties of recurrence networks change markedly when a chaotic system is coupled with another one (Donner et al., 2015). This effect has been attributed to the role of network transitivity as a generalized notion of fractal dimensions (Donner et al., 2011), which changes when introducing additional degrees of freedom via coupling to an external driver or even bidirectional interactions. However, present scientific literature lacks a detailed discussed on how exactly the geometric properties of attractors quantified by fractal dimensions change in such a case.

In order to systematically understand the geometric impact of external forcing, we numerically study the response of recurrence network transitivity when coupling two structurally similar chaotic systems, taking time-discrete and continuous

as well as dissipative and Hamiltonian systems into account (Khotyakov, 2014). Our results demonstrate that different types of systems can behave essentially different as the coupling strength is increased, and that the previously reported increase of the transitivity dimension of the driven system at intermediate coupling strengths prior to the onset of synchronization (Donner et al., 2015) is no universal feature.

In addition, we consider the special case of a single chaotic system subject to additive noise. We analytically show that the fractal dimension of the driven system increases sharply to an integer value for even infinitesimally small noise (Khotyakov, 2014). Using recurrence networks with a large number of vertices (corresponding to an arbitrarily fine spatial coverage of the attractor), we numerically confirm these analytical results, demonstrating that stochastically forced chaotic systems behave essentially different from such driven by another deterministic system in terms of their geometric organization in phase space.

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A Recurrence-plot-based Method for Detection and Quantification of Cardio-respiratory Coordination

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As a presentation and analysis tool for cardio-respiratory coordination (CRC) the coordigram was developed by Riedl et al. [1]. Originally the fourier components of the distribution of heartbeats before and after an respiratory onset where used to quantify CRC. In this work a new recurrence plot based method to analyse and quantify CRC is presented. This method can also be applied in case of strong irregularities during one respiratory cycle as in presence of strong respiratory sinus arrhythmia where the results of the original method will be distorted.

The advantage of this recurrence-plot-based method is the ability to quantify the coupling direction and strength.

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Implications of noise-induced synchronization

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Economic and financial systems are unstable by nature. Both endogenous and exogenous forces drive this instability. Apart from the interest in quantifying the effects of various types of noise, apprehending the underlying behavioural characteristics that determine the nature of disturbances constitute a crucial factor as well. Recent empirical research has highlighted the contribution of investors' heterogeneity and risk appetite to real market fluctuations. Thus, noise takes a new dimension within a globalised financial environment by incorporating more interesting features than the equilibrium approach of EMH initially suggested. Acting as a mirror of trading activity, noise may force interdependence and contagion. In this sense, the concept of noise-induced synchronisation can provide precious information about the connectivity mechanism. Noise-induced synchronisation explains how two independent nonlinear oscillators can synchronise due to a common noisy forcing. In practice, when this phenomenon becomes active several questions may arise concerning the root cause of this relationship. The presence of stylised facts (such as heteroskedasticity and seasonality) in real data is a clear demonstration of the altering liaisons that may emerge.

Our goal in this paper is to investigate the way that noise might synchronise two uncoupled systems via the implementation of an aggregated index of connectivity, namely the Correlation of Probability of Recurrence (CPR). We control for the statistical significance of empirical findings using the Twin Surrogates technique recently introduced by Thiel et al., (2006) and applied by Goswami et al., (2012). The simulation experiment is built on three bivariate Mackey-Glass systems: i) a deterministic version, ii) a stochastic version with common heteroskedastic noise, and iii) a seasonal version of the second process. The estimated CPR value shows the existence of synchrony-breaking in the first case of the uncoupled oscillators. Incorporating identical noise terms leads to high CPR, a result that it is equally confirmed for the seasonal model.

As the analysis indicates, the contribution of the common heteroskedastic noise to the synchronicity between two nonidentical processes sheds light on the importance of the trading mechanism producing such type of structures in real markets. To

better understand the evolving dynamics when noise forcing is in place, the methodology is employed to a stochastic bivariate system consisting of pure heteroskedastic noises. The obtained CPR values suggest strong synchronisation, validating our hypothesis of noise-driven connectivity. We conclude with a short application to real time series, suggesting insightful policy implications.

Recurrence Analysis of Eddy Covariance Fluxes

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The eddy covariance (EC) method is one key method to quantify fluxes in biogeochemical cycles in general, and carbon and energy transport across the vegetation-atmosphere boundary layer in particular. EC data from the worldwide net of flux towers (Fluxnet) have also been used to validate biogeochemical models. The high resolution data are usually obtained at 20 Hz sampling rate but are affected by missing values and other restrictions. In this contribution, we investigate EC fluxes using Recurrence Analysis (RA). High resolution data from one site and fluxes calculated at half-hourly resolution from eight locations provide a set of very long time series to analyze. After Fluxnet standard gapfilling pretreatment, we calculate properties and indicators of the recurrent structure based both on Recurrence Plots as well as Recurrence Networks. Time series of windows-based RA measures are presented. Their interpretation is guided by three different questions: (1) Is RA able to discern periods where the (atmospheric) conditions are particularly suitable to obtain reliable EC fluxes? (2) Is RA capable to detect dynamical transitions (different behavior) beyond those obvious from visual inspection? (3) Does RA contribute to an understanding of the nonlinear synchronization between EC fluxes and atmospheric parameters, which is crucial for both improving carbon flux models as well for reliable interpolation of gaps? (4) Is RA able to recommend an optimal time resolution for measuring EC data and for analyzing EC fluxes? (5) Is it possible to detect non-trivial periodicities with a global RA? We will demonstrate that the answers to all five questions is affirmative, and that RA provides insights into EC dynamics not easily obtained otherwise.

Detection of deterministic transient signals in white Gaussian noise by statistical analysis of similarity matrix coefficients

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Over the past decades, recurrence plot analysis has become a popular tool for analyzing dynamical systems. As recurrence plots show different patterns that depend on the state of the system (random, deterministic, chaotic), several approaches have been proposed in the literature to quantify and distinguish between these different states. Most of existing methods rely on metrics called recurrence quantification analysis (RQA), to decide whether the time series is random or deterministic.

In this presentation, we propose a new detection scheme that only relies on the analysis of the statistical distribution of the similarity matrix coefficients, to decide whether the measured signal is a white Gaussian noise or a deterministic transient [1]. Our hypothesis is that if the measured time series is a white Gaussian noise, then the similarity matrix coefficients will follow a certain distribution, whereas if the measured time series contains a deterministic transient, the similarity matrix coefficients will follow another distribution.

First, we make some analytical development to derive the mathematical expressions of the expected distribution for the similarity matrix coefficients, when the input signal is a white Gaussian noise. Then, we compare this analytic distribution with the empirical distribution obtained for a given unknown measured signal. This comparison is equivalent to a goodness-of-fit test and is achieved using divergence measures. Finally, the value of this divergence measure is compared to a detection threshold in order to decide whether the analytical and empirical distributions look alike or not, and so if the measured signal is a noise only or deterministic.

The performances of the proposed detector are assessed by use of receiver operating characteristic (ROC) curves. Deterministic signals to be detected are pure cosines and impulses. Influences of parameters like the embedding m, the similarity measure and the divergence measure on the performances are discussed. Finally, the proposed detector is compared with that of the energy detector and the matched filter detector, which are commonly used is signal processing. The results of this performance analysis show that the proposed detector outperforms the energy detector, giving a probability of detection 10% to 50% higher, and has a similar performance to that of a matched-filter detector.

References:

[1] O. Le Bot (2014), Détection, localisation, caractérisation de transitoires acoustiques sous-marins, PhD Thesis, Université de Grenoble

Time-delay estimation based on Cross Recurrence Plot and Joint Recurrence Plot for passive underwater acoustic source localization. *Poster*

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Passive acoustic localization of underwater sources, like cetaceans, is generally based on a two steps approach. First step consists in a time-delay estimation (TDE), which aims at measuring the relative time difference of arrival (TDOA) of the signal on spatially separated sensors. Second step consists in determining the position of the source from a set of estimated TDOA related to the array geometry, by using a spatial inversion algorithm. In this presentation we only focus on the first step.

The most popular method for time-delay estimation in underwater acoustic is the cross-correlation. However, this method has some weaknesses when the signal of interest is mixed in high-level background noise and propagate in reverberant and dispersive environment that warp the waveform of the signals received at different sensors. In such conditions, the cross-correlation gives poor and unreliable estimates of the time-delay, particularly if a low percentage of samples look alike on the different sensors.

In this presentation, we propose to use Cross Recurrence Plot (CRP) and Joint Recurrence Plot (JRP) to estimate the time-delay. First, we identify samples that are recurrent on the different sensors, by calculating the CRP and the JRP between pairs of sensors. Then, we use recurrence quantification analysis (RQA) to estimate the time-delay. Several RQA metrics such as the longest diagonal line Lmax , the longest curved trace, the diagonal-wise tau-recurrence rate, the recurrence rate and the joint probability of recurrence are considered for this purpose. The most reliable RQA metric for TDE is determined through performance analysis tests involving simulated signals with known time-delay. The influence of the embedding dimension m, of the delay tau and of the recurrence threshold on the performances of the TDE are also discussed. Finally, the proposed method is validated on real data recorded at sea by a hydrophone array and containing cetacean and fish vocalizations.

Cross recurrence plot analysis of heart rate and systolic blood pressure during supine position and active standing in healthy adults *Poster*

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Background: Heart rate (HR) and systolic blood pressure (SBP) are closely related through several mechanisms that preserve cardiovascular stability during daily challenges such as active standing (AS). Recurrence quantitative analysis of beat-to-beat HR and SBP has shown that AS changes HR and SBP dynamics towards more persistent states (e.g. higher determinism and laminarity). The interrelation between beat-to-beat HR and SBP time series have been studied with many methods but not with cross recurrence plots (CRP). Aims: To describe the interrelation between HR and SBP through CRP analysis, both during supine position (SP) and AS.

Non-invasive blood pressure recordings were obtained from 19 healthy volunteers (ages between 20 and 40 years old) during SP and AS. HR and SBP time series were obtained during 15 minutes in each position. The embedding delay was calculated from the maximum absolute value of the cross correlation between each pair of HR and SBP time series. The estimated embedding dimension was < 10 in all time series (false nearest neighbors' method). Therefore CRPs were obtained with embedding dimension = 10, the embedding delay estimated for each pair of time series, and a fixed recurrence rate < 7%. All quantitative CRP indexes had normal distribution (p > 0.05, Kolmogorov-Smirnov tests). Mean values of the CRP indexes were compared between SP and AS with paired t tests.

The embedding delay was similar in both positions: SP = -1.42 ± 3.78 vs AS = -0.47 ± 6.59 beats ($p = 0.47$). CRP were characterized by high determinism in SP (0.93 ± 0.01) and AS (0.95 ± 0.01, $p < 0.01$) and relatively short mean diagonal length 5.74 ± 0.34 (SP) vs 6.01 ± 0.37 (AS), $p = 0.01$. Compared to SP, AS increased Shannon's entropy (2.43 ± 0.08 vs 2.49 ± 0.08, $p = 0.01$), laminarity (0.77 ± 0.14 vs 0.90 ± 0.07, $p < 0.01$), trapping time (3.18 ± 0.72 vs 3.59 ± 0.64, $p < 0.01$), maximum vertical lines (28.08 ± 11.83 vs 34.73 ± 10.55, $p = 0.03$), and both recurrence time type 1 (9.08 ± 1.11 vs 9.99 ± 0.03, $p < 0.01$) and type 2 (20.75 ± 6.45 vs 29.36 ± 6.54, $p < 0.01$).

Conclusions: CRP analysis of HR and SBP beat to beat time series shows a deterministic interrelation between them. We found a high determinism with very low dispersion for this association. The interrelation strength increases during the physiological stress by AS.

Responses of nonlinear energy harvester by means of recurrences *Poster*

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We examine the modal response of mono- and bis-table electromechanical energy harvesting devices based on characterisation of the experimental time series. Different models of the energy harvesting system based on nonlinear mechanical resonator and energy transducers as piezoelectric and electromagnetic are used. To identify the dynamics of the response of the studied harvesting structure and the associated voltage output we used the Fourier spectrum and Recurrence Quantification Analysis (RQA).

Applications of RPs and RQA in coastal shallow groundwater along the northeast coast of Hainan, China

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In this paper, based on daily average water table and conductivity data gained from 3 groundwater-monitoring wells sited along the northeast coast of Hainan province of China, RPs and RQA are employed to analyze the inner dynamical structures and parameters. Impacts of different RR values on overall topology structures and results of RQA are also discussed. Furthermore, how selection of minimum length of diagonal and vertical structures affects DET and LAM are considered. The results show that: 1) Recurrence Plots of water table subsystems are similar as a whole, which contain obvious disrupted structures. While apparent differences can be found out among conductivity subsystems with disrupted or drift structures or both. Wholeness of topology structures of different systems or subsystems implied in RPs doesn't rely on the same certain RR values. Appropriate RR value derived from trial methods may be more objective. 2) Compared with determinism, intermittency is more clearly in both water table and conductivity systems under the same recurrence rate. However, the gap between determinism and intermittency narrows when RR rises. To the contrary, L is always longer than TT which may indicate that prediction dependent on L can go further than that on TT. And the increase of RR will expand the lead. As for shapes of curves, similarity does exist between DET and LAM, L and TT when they describe the same subsystem. This may be explained as inner connections between diagonal and vertical structures. In addition, relative relationships measured by diagonal or vertical structures among different subsystems are accordant whatever recurrence rate is. Further speaking, selection of ε only enlarges or narrows the gap among subsystems. 3) RQA results of RR$\approx$10% show that distinctions of vertical structures are less obvious than diagonal structures among subsystems of both water table and conductivity systems. It means that intermittency on phase space trajectories among different subsystems seems alike while spatial distributions of trajectories differ much. Compared with water table system, more significant differences of vertical and diagonal structures exist among subsystems of conductivity. There is even order of magnitude differences when L, Lmax, DIV are considered. 4) Long diagonal or vertical structures can only be small probability events. Short diagonal and vertical structures are more decisive to DET and LAM. When considering decay rate of DET and LAM, differences among water table subsystems are much smaller than that of conductivity subsystems.

The Social Coordination Dynamics of Deception *Poster*

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On average, lies comprise one quarter of conversational content, most of which go undetected. Detecting deception is an important skill for therapists, health professionals, lawyers, salespeople, parents and teachers. Recognizing dishonesty can also aid military and law enforcement professionals in maintaining public safety. Major challenges of deception research include identifying the behavioral processes that differentiate truthful and deceptive interactions, and determining how these processes are modulated by properties of the social environment. Despite decades of research, however, it remains unclear how the coordinated behavior of liars differs from that of truth tellers. This lack of understanding may be due to the historic challenge of objectively capturing and quantifying the time-evolving and adaptive nature of human motor behavior during complex social interactions. Given recent advances in unobtrusive data collection methods and nonlinear time- and event-series analysis methods, however, it is now possible to objectively determine and evaluate these dynamics. In particular, recurrence quantification analyses are able to pull forward seemingly invisible and non-obvious aspects of complex social motor coordination and interpersonal behavioral order.

We present data from a study examining the dynamic structure, complexity, and stability of social motor coordination that occurs between co-actors during a series of covert deception tasks. Several nonlinear time-series analyses, including cross-

and joint-recurrence, were used to quantify the behavioral movement and linguistic data, as well as assess certain aspects of coordination (e.g., amount, strength, duration, and manner) between paired participants. Collectively, the results imply that these methods may provide the ability to identify differences in the behavior of liars.

Recurrence-bassed Raman spectra analysis for monitoring of chemotherapy leukemia treatment *Poster*

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The use of Raman spectroscopy to analyze blood biochemistry and hence distinguish between normal and abnormal blood was investigated. Blood samples were obtained from 6 patients who were clinically diagnosed with leukemia and 6 healthy volunteers. The imprint was put under the microscope and several points were chosen for Raman measurement. All the spectra were collected by a confocal Raman micro-spectroscopy (Renishaw) with a NIR 830 nm laser. It is shown that the serum samples from patients with leukemia and from the control group can be discriminated when recurrence-bassed analysis is applied to their Raman spectra. The preliminary results suggest that Raman Spectroscopy could be a new technique to study the degree of damage to the bone marrow using just blood samples instead of biopsies, treatment very painful for patients.

Recurrence plot analysis of spatially extended high-dimensional dynamics

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Recurrence plot based measures of complexity are capable tools for characterizing complex dynamics. We show the potential of selected recurrence plot measures for the investigation of spatially extended high-dimensional dynamics by applying them to data from the Lorenz96 model. The recurrence plot based measures are able to qualitatively characterize typical dynamical properties such as chaotic or periodic dynamics. Moreover, we demonstrate its power by analyzing satellite image time series of vegetation cover with contrasting dynamics as a spatially extended and potentially high-dimensional example from the real world.

Computing the Delay Vector Variance using Recurrence Plots

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The Delay Vector Variance (DVV) technique is frequently used for detection and characterization of nonlinearities. This technique has been successfully applied in a large number of situations: EEGs, financial data, etc. On the other hand the Recurrence Plots (RP), alongside with the Recurrence Quantification Analysis (RQA), can also be used for the same purpose with similar good results. In fact, it is easy to show that there exists a clear geometrical relationship between these two techniques, and it is easy to compute the DVV using RP concepts. This relationship also works the other way around, and it is possible to use some of the ideas in the DVV technique to create better, and less parameter dependent RQA tests, that could be used for nonlinear detection and characterization. This work formulates these relationships and proposes a technique, using the presented ideas that can be employed to distinguish nonlinearities in oscillatory signals.

The spatial distribution of behavior under fixed time scheduled water/food deliveries *Poster*

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As part of the studies of the psychological phenomenon as a dynamic system, within the theoretical framework proposed by Ribes and LÃşpez at Behavior Theory (1985), an experiment was conducted on rats, using experimental preparation Schoenfeld Box for the study of contextual interbehavioral function, specifically the case interruption, and RP-RQA for data analysis. In the study, the effects of water and/or food deliveries on the location of the behavior of rats were evaluated. Fixed time programs controlled deliveries of water and/or food, in two or/and four dispensers, located one for each wall of the experimental box. Eight experimental subjects were assigned into four subgroups. The difference between subgroups was the order of exposure to couplings programs. Within cycles, delivery schedules were coupled concurrently or sequentially and the availability of water and/or food, is scheduled for limited or unlimited. The results are reported.

Non-linear time series study of Dst index with recurrence plot *Poster*

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The Dst or Disturbance storm time index is a measure of geomagnetic activity used to assess the effect of magnetic storm. Solar storm can disrupt communication and navigational equipment, damage satellites, and even cause blackouts by damaging power plant and electrical grid components. On March 13th, 1989, a geomagnetic superstorm ($Dst = -589$nT) occurred, affecting power systems of Canada and United States contries, resulting in a major power outage for the majority of Quebec region and the northeastern of United States. Central and southern Sweden also experienced power losses. Because our civilization has evolved into a technology dependent society. Today a solar storm of this magnitude or greater could produce a global catastrophe. In this work we used the recurrence plot series to characterize the dynamic of the time serie (Dst).

Spatial-temporal recurrence analysis based on a global measure of spatial similarity

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The analysis of spatial-temporal data is still a methodological question of current research, e.g. in earth science. In this work an extension of the recurrence plot is suggested in order to track regime shifts in spatial patterns. For this purpose, the global state, i.e. all data in one time step, is compared to each other by means of a similarity measure that is known from tracking algorithms. This routine consists of a digitalization, blurring and bin wise comparison of the single global states. In its roughest version, the algorithm is equivalent to the kappa-statistic which is widely used to assess similarities of spatial pattern in ecosystems. The use of this similarity measure in the framework of recurrence plots enables a visualization and quantification of the temporal evolution of the spatial extended system. In the end, the extended recurrence plot and its quantification allows a detection of changes in the spatial-temporal dynamic of the observed system.

How Control Asymmetries Influence the Dynamics of Joint-Action *Poster*

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Previous research has revealed that the behavioral dynamics of joint-action can naturally emerge from the physical and informational constraints that define a shared task-goal. The emergence of complementary actions, or synergistic coordination in control also appear to be a natural part of such behavior, and are often an inherent aspect of robust and highly flexible joint-action performance. The aim of the current study was to explore these latter aspects of joint-action behavior. More specifically, we examined the interpersonal coordination and control distribution that emerged between two individuals performing a virtual labyrinth ball-control game under different conditions. Key manipulations involved whether control was symmetrical (i.e. both individuals had full control of the board tilt), asymmetrical (i.e. one with control of the x-axis of tilt and the other with control of the y-axis of tilt), or unbalanced (i.e. one joystick had full control of the y-axis of tilt, but only $1/2$ the gain control of the x-axis of tilt, and vice versa). Data on a solo individual two-handed version of the task was also collected for comparison purposes. Cross-recurrence quantification analysis (CRQA) revealed that the patterns of synergistic coordination that emerged were the same for pairs and individuals, and that both pairs and individuals maintained task success by mutually adapting the coordination and control dynamics across the different task manipulations.

Using cross-recurrence quantification analysis to understand social motor coordination in children with autism spectrum disorder

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Interpersonal motor coordination is considered to be an integral part of maintaining successful social interactions. In fact, research has shown that simply coordinating one's movements with another actor can influence rapport, feelings of connection and feelings of social competence. Past research has also found that deficits in social motor coordination are associated with psychological dysfunction such as schizophrenia and borderline personality disorders. However, the potential association between interpersonal motor coordination and autism spectrum disorder (ASD) has not been studied. In the current exper-

iment, children who had been previously diagnosed with ASD and typically developing children were asked to synchronize their movements with those of an experimenter in three different tasks: object tapping, pointing and interpersonal hand-clapping. Both the experimenter's and the participants' wrist movements were captured and compared to each other using cross-recurrence quantification analysis (CRQA). The results reveal differences in the way children with ASD and those who are typically developing synchronize with an experimenter in various social tasks. In general, children diagnosed with autism showed less percent recurrence than their typically developing counterparts, however the differences between the two groups were task dependent.

The study of two-phase flow chandes using recurrence plots

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The mixture flowing in a small-diameter channel can create different flow structures which depend on several parameters such as the channel diameter, viscosity, surface tension, liquid density and phase ratio. In the case under study, a two-phase flow is formed by air and water mixed in various proportions. The two-phase mixture is passed through a circular mini-channel with a diameter of 2 mm. By increasing the relative volume of gas, one can obtain different flow structures, from bubbles, slugs, and churns – up, to annular flow. The dynamics of the flow may be further complicated by a laminar or turbulent flow of the liquid phase. Changes in the flow dynamics are analysed in order to obtain information about the transformations of the flow structure. The flow dynamics and its structures are determined using recurrence plot analysis and the sliding window technique. To assess changes in the structure and dynamics of the flow, a function is computed which depends on the mutual distance of the RR(e) lines in the compared windows.

Detection of Particle Size Changes in Fluidized Beds by Recurrence Plots Analysis Using Pressure and Acoustic Signals *Poster*

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Recurrence plot (RP) and recurrence quantification analysis (RQA) were used for inspecting the hydrodynamic status of fluidized beds for detection of particle size changes. Pressure fluctuations and acoustic emission signals of a lab-scale fluidized bed were recorded at various superficial gas velocities and particle size distributions. RQA variables (determinism, laminarity, recurrence rate, entropy) of both pressure and acoustic signals were calculated. It was found that patterns within RP of pressure and acoustic signals, and subsequently the RQA variables, change with particle size distribution. The results showed that small changes in particle size distribution can be detected by this method and acoustic signals are more sensitive to the particle size changes. This study confirms that using acoustic signals and applying RP and RQA analysis can be used for detection of agglomeration in fluidized beds.

Approximation of diagonal line based measures in recurrence quantification analysis

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Given a trajectory of length N, recurrence quantification analysis (RQA) traditionally operates on the recurrence plot, whose calculation requires quadratic time and space ($O(N^2)$), leading to expensive computations and high memory usage for large N. However, if the similarity threshold ε is zero, we show that the recurrence rate (RR), the determinism (DET) and other diagonal line based RQA-measures can be obtained algorithmically taking $O(N \log(N))$ time and $O(N)$ space. Furthermore, for the case of $\varepsilon > 0$ we propose approximations to the RQA-measures that are computable with same complexity. Simulations with autoregressive systems, the logistic map and a Lorenz attractor suggest that the approximation error is small if the dimension of the trajectory and the minimum diagonal line length are small. When applying the approximate determinism to the problem of detecting dynamical transitions we observe that it performs as well as the exact determinism measure.

Towards multi-scale RQA using Visual Analytics

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Time series often capture a variety of sub processes on different temporal scales. Applying the recurrence quantification analysis (RQA) to time series describes the behavior of all processes simultaneously. In many application scenarios, users want to restrict the RQA only on relevant processes. Therefore, there is increasing interest to extract relevant processes from time series.

Previous work has shown that multi-scale methods, such as wavelet transformation, are capable of isolating relevant processes. Our research goal is to extent the traditional RQA into a multi-scale RQA method. Our current research efforts show that multi-scale RQA involves two major challenges. First, the decomposition of a time series produces a huge set of time series; each time series is associated with a particular temporal scale. Second, users need to locate the temporal scales at which relevant processes operate. To address these two challenges, we currently work on a Visual Analytics approach that combines multi-scale decomposition, the fast computation of RQA for all temporal scales, and the clustering of these RQA results.

In our presentation, we will discuss the three main components of our Visual Analytics approach. First, our approach supports a broad range of multi-scale methods. Second, our fast RQA computation is based on subdividing the RQA computation and distributing the computational work across multiple graphics processing units. Third, the clustering of RQA measures allow users to focus on characteristic RQA results. We will present our latest research efforts and discuss the challenges involved to extent traditional RQA into a multi-scale method.

Estimating Algorithmic Complexity of Dynamical Systems and Time Series Using Recurrence Plots

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Complexity outlines a non-unified concept that has been approached from different theoretical frameworks, which, however, can be commonly understood in terms of two main lines. The first one relies on revealing the randomness structure of an object (e.g., a random variable), being strongly supported by Shannon information theory. The second tries to describe the complexity of an object by means of the length of the shortest program that can explain the object (the observed sequence) in accordance with the idea of algorithmic complexity (AC) proposed by Kolmogorov in the context of computer science.

From the standpoint of nonlinear dynamics and time series analysis, complexity has been analyzed by means of Lyapunov exponents or even by the "fingerprint" patters obtained in the recurrence plots (RP). In fact, the latter approach is interesting, once that it provides a two-dimension binary structure – the recurrence matrix – for which is possible to define distinct measures associated with the distribution or organization of the diagonals (the classical recurrence quantification analysis – RQA-metrics).

In this work, two different measures are presented for estimating the algorithmic complexity upper bound of an RP based on ZIP and Ziv-Lempel-Welch coding strategies. Employing the logistic map, it is shown here that these AC upper bounds are highly correlated to classical RQA metrics and can also distinguish stochastic and deterministic signals. As an application, it can be shown that these new measures offer an alternative solution to the blind source separation problem in the context of deterministic signals, which is in agreement with the previous performance obtained by classical RQA and with the conceptual framework established by Pajunen. Finally, as a major contribution, this work aims to widen the idea of complexity associated with a RP, positioning it in the context of information theory and computer science paradigms. In fact, the possibility of analyzing complexity from different perspectives in an RP has many implications and, therefore, deserves careful attention.

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The stochastic and the deterministic nature of recurrence in the DNA and its contribution to the evolution of the DNA *Poster*

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In this work, I will show how to create a Markov model for the DNA that allows us to analytically calculate the statistics of recurrence of many group of words. This model is constructed by encoding the DNA nucleotides into symbolic sequences (words) and creating a 2D symbolic map for the DNA. We then partition the symbolic map or space in sub-regions, each sub-region representing a group of words that share symbolic similarities. A partition of order -T of the symbolic space of the DNA is done by verifying information-theoretical quantities that specify that this partition, composed of many subregions, has Markov properties, in the sense that for some sub-regions, representing some groups of words, words belonging to a group will repeat again after T nucleotides, and the correlation between two words belonging to one of these groups will be approximately zero. These sub-regions that provide the Markov properties of the DNA are responsible for the stochastic nature of the DNA and provide a simple way to analytically calculate the statistics of recurrence of many group of words. The remaining sub-regions, representing other group of words whose correlation between words does not decay after T-nucleotides represent the group of words that provide the dynamical deterministic nature of the DNA. In

this work, I will show how the stochastic and the deterministic nature of the DNA contributes to the genes, coding and non-coding regions of the DNA, and provide an explanation for the evolution of the DNA from simple organisms to the Human genome in terms of how the recurrence of the DNA has become more or less memoryless.

Recurrence quantification of electromyographic data for continuous and intermittent squat exercise *Poster*

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Introduction: Understanding how individual muscles behave when stressed by various types of movement can have important applications in relation to exercise and for individuals whose movement is compromised by disease or ageing. The objective of this study was to examine two upper leg muscles during continuous and intermittent movement. This was achieved using standard electromyography (EMG) techniques and application of recurrence quantification analysis (RQA). Methods: Four subjects (28 ± 5 year; 76 ± 14 kg; 1.7 ± 0.1 m (mean $\pm$ SD)) performed wall squat and up-down squat exercise to fatigue. EMG activity of the vastus lateralis and rectus femoris muscles of the dominant leg were recorded for the two conditions at 1000 Hz and raw EMG data were band pass filtered at 20-500 Hz. The signals were locally normalized for each condition and submitted to RQA to identify the behaviour of these muscles in the two different tasks in particular relation to fatigue.

Results: A conventional set of RQ parameters were determined. Values averaged over non-fatigued and fatigued states were: %rec 2.3; %det 48; %lam 59; entropy 1.4. The average ranges for these quantities were: %rec 2.8; %det 59; %lam 48; entropy 1.5. Transitions from non-fatigued to fatigued states resulted in the average changes: %rec +0.8; %det +9; %lam +8; entropy +0.2. These differences were normally statistically significant or highly significant ($p < 0.05$) though not for %rec. Changes in parameter values varied with muscle and participant. In some cases the progressions in values from non-fatigued to fully fatigued states were uniform, in some cases saltatory.

Conclusion: Whilst the recorded EMG signals and the results of this nonlinear analysis are generally in accord with a conventional view of muscle fatigue, they appear to reveal additional complexity in fatigue processes.

Estimation of the time-synchronization profile between market and volatility indices using cross-RQA: The S&P500 and VIX case *Poster*

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In financial markets, volatility refers to the amount of uncertainty or risk about the size of changes in a market index. With the implied volatility representing the expected volatility of a stock over the lifetime of an option, the success of a trading strategy can be significantly enhanced by tracking accurately the implied volatility changes. Most importantly, variations in implied volatility can cause losses even when a correct prediction for a stock's direction is available. This fosters the need to design improved algorithmic tools for extracting the time-synchronization profile between a given market index and the associated implied volatility. In particular, traders of options and volatility often rely on methods that compare and track the actual volatility of the market using various look-back periods (such as, 10-day, 1-month, and 3-months) to the forward volatility, as expressed by an appropriate volatility index, to help determine whether options are relatively cheap or expensive. The majority of existing techniques rely either on statistical or stochastic models, whilst in both cases the models are applied on the original one-dimensional time series. On the other hand, the typical correlation, which is widely used to identify potential interrelations between the indices, uncovers only a relationship, whereas it cannot provide a conclusive explanation for such a relationship. Furthermore, correlation does not reveal how and which variable influences the other. In our study, we advance existing solutions for identifying the temporal interdependence between a given time series of index returns and the associated volatility index. To this end, our proposed approach relies on a cross-recurrence quantification analysis (cross-RQA) for extracting both the underlying dynamics of a given market and volatility indices pair, along with their time-synchronization profile. The main advantage of cross-RQA is that it enables a more generic, and noise robust, non-linear analysis of small-scale structures in a time series ensemble, by employing time-delay embedding in higher-dimensional spaces. A performance evaluation on the S&P500 Index and its associated CBOE Volatility Index (VIX), which is calculated as a weighted average of implied volatilities of various options on the S&P500 Index, reveals the enhanced capability of cross-RQA in estimating accurately a temporal mapping between S&P500 and VIX values. This mapping could be further exploited in developing flexible models on both indices simultaneously, thus being able to accommodate their joint evolution, or in designing time-consistent methods to calibrate models of index returns and options.

Recent developments in the application of recurrence plots to physical and biological systems

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Recurrence plots and their quantification became a modern tool in nonlinear data analysis, currently being used in a myriad of scientific disciplines, a diversity that characterizes the Recurrence Plot Workshop since its beginning. In this presentation I will review recent work done in Brazilian research institutions, focusing on physical and biological applications of recurrence plots and recurrence quantification analysis. Firstly I will present some applications of recurrence quantification analysis to data analysis in a fusion plasma, namely turbulent fluctuations in the plasma edge of Tokamak Chauffage Alfvén Brésilien tokamak, which is a magnetic confinement plasma machine [1]. A similar analysis was performed in a low-density plasma device called Helimak (University of Texas) [2]. In the second place we consider a system of biological interest, which is a experimental study of ant activity patterns, in which the recurrence quantification analysis was able to reveal changes between random and deterministic spatial patterns in different ant species and castes. Finally we consider an extension of the recurrence plot technique devised to investigate spatial patterns in one and two dimensions at fixed time (spatial recurrence plots) [3]. This method is able to characterize small structures in mammographies using a relatively small computer time, making it a potentially interesting tool for the use of physicians diagnosing possible structures related to breast cancer [4].

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Splayed Recurrence Analysis of Iterated Dynamical Systems

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Splayed Recurrence Analysis (SRA) is a new method for identifying and quantifying recurrent events in iterated systems. The technique is fully applicable to difference equations, Poincare sections of continuous time series, and independent random events. Inspiration for SRA comes from American roulette wheel gaming. It has been postulated that non-random wheel determinism is introduced by unbalanced wheels (mechanical) and non-random repeated motions of house spinners (human).

American roulette has 38 unique slots into only one of which the ball can land on each play. Sequential slot landing positions (Y) are plotted as a function of the rank ordered spin attempts (X). Lines are passed through all possible pairs of points in the plot and extrapolated to the border, denying circular wheel wrap-around. Any points falling exactly on these extended lines are scored as recurrent points. Because long gaps are often found between legal points (hits), the points are necessarily splayed out along the many linear trajectories comprising the entire plot.

Two specific parameters govern the behavior of recurrent events: the number of sequential plays (epoch length) and the maximal number of possible landing positions (vocabulary size). All legal points are contained and constrained within the matrix $HITS[Y, X]$. The vocabulary size for roulette is fixed at 38, but can be modified to any number to accommodate other systems. No embedding procedures are necessary and radius filtering is handled by downsizing the vocabulary maximum. The number of recurrent points increases with decreasing vocabulary size (Y) and/or increasing epoch length (X).

SRA strategies were applied to natural random numbers, American roulette data, chaotic models, and natural phenomenon. No differences could be detected for roulette data and naturally occurring random processes. But SRA was able to detect deterministic structures in mathematically chaotic systems as well as in eruption times of the Old Faithful geyser. Much more work is required to fine tune SRA strategies (theory) as well as apply the methodology to numerous other iterated systems (practice).

Heterogeneous Recurrence Analysis *Poster*

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Recurrence is one of the most common phenomena in natural and engineering systems. Process monitoring of dynamic transitions in nonlinear and nonstationary systems is more concerned with aperiodic recurrences and recurrence variations. However, little has been done to investigate heterogeneous recurrence variations and link with the objectives of process monitoring and anomaly detection. Notably, nonlinear recurrence methodologies are based on homogeneous recurrences, which treat all recurrence states in the same way as black dots, and non-recurrence is white in recurrence plots. Heterogeneous recurrences are more concerned about the variations of recurrence states in terms of state properties (e.g., values and relative locations) and the evolving dynamics (e.g., sequential state transitions). This paper presents a novel approach of heterogeneous recurrence analysis that utilizes a new fractal representation to delineate heterogeneous recurrence states in multiple scales, including the recurrences of both single states and multi-state sequences. Further, we developed a new set of heterogeneous recurrence quantifiers that are extracted from fractal representation in the transformed space. To that end, we integrated multivariate statistical control charts with heterogeneous recurrence analysis to simultaneously monitor two or more related quantifiers. Experimental results on nonlinear stochastic processes show that the proposed approach not only captures heterogeneous recurrence patterns in the fractal representation, but also effectively monitors the changes in the dynamics of a complex system.

Self-organizing Topology of Recurrence-based Complex Networks

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With the rapid technological advancement, network is almost everywhere in our daily life. Network theory leads to a new way to investigate the dynamics of complex systems. As a result, many methods are proposed to construct a network from nonlinear time series, including the partition of state space, visibility graph, nearest neighbors and recurrence approaches. However, most previous works focus on deriving the adjacency matrix to represent the complex network and extract new network-theoretic measures. Although the adjacency matrix provides connectivity information of nodes and edges, the network geometry can take variable forms. The research objective of this article is to develop a self-organizing approach to derive the steady geometric structure of a network from the adjacency matrix. We simulate the recurrence network as a physical system by treating the edges as springs and the nodes as electrically charged particles. Then, force-directed algorithms are developed to automatically organize the network geometry by minimizing the system energy. Further, a set of experiments were designed to investigate important factors (i.e., dynamical systems, network construction methods, force-model parameter, nonhomogeneous distribution) affecting this self-organizing process. Interestingly, experimental results show that the self-organized geometry recovers the attractor of a dynamical system that produced the adjacency matrix. This research addresses a question, i.e., what is the self-organizing geometry of a recurrence network?, and provides a new way to reproduce the attractor or time series from the recurrence plot. As a result, novel network-theoretic measures (e.g., average path length, and proximity ratio) can be achieved based on actual node-to-node distances in the self-organized network topology. The paper brings the physical models into the recurrence analysis and discloses the spatial geometry of recurrence networks.

RQA application to AE time series from two Italian stations within the Apennines for crustal stress propagation assessment

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RQA has been applied to investigate relationships between Acoustic Emissions (AE) gathered on the field and the dynamics of crustal seismic processes.

The paper describes the application of RQA to the AE in the Earth's crust. The AE time series, 30 sec. of sampling rate, at the Savoia di Lucania (Potenza, Italy – 40.57°N, 15.56°E, hereafter Savoia), within a Project with Basilicata Region, and at Orchi (Perugia, Italy 43.02°N, 12.78°E), far 320 km each other, within the Apennines, highly seismic mountain along the Italian peninsula. The AE sensors are stuck in Orchi to a natural rock and in Savoia to a reinforced concrete pillar of a building. The AE data were collected by piezoelectric transducers at 25 kHz (LF-AE) and at 150 kHz (HF-AE). The AE signal amplitude varies with the acoustic impedance, related to local crustal stress conditions and sensitive to fracture density, water content, a.s.o.

The signals have been recorded from September 18th, 2014 to February 2nd, 2015. In the same time interval, earthquakes occurred within 300 km from AE stations and with Magnitude > 3 have been considered. To highlight the crustal stress propagation, two different analysis procedures are carried out: RQA and Fractal Analysis (FA). The fractal dimension parameter D is calculated by BCM Method, by which it is possible to characterize the spatial distribution of the AE sources.

The second technique, RQA, allows studying the changes in correlation structure of the observed phenomenon; a relevant increase of correlation is known to precede the catastrophic event in many different systems ranging from physiology to economy. The aim of this work is to validate those RQA descriptors that can explain the characteristics of the AE signals and identify anomalies to be related to crustal stress.

The results obtained are:

1. a 95% r-Pearson correlation, in HF-AE, between Savoia and Orchi; in spite of their distance and different geotectonic setting.
2. a relevant correlation between the parameters of FA and RQA during the whole period of monitoring.
3. a rapid slope variation both in FA and RQA, few days before earthquakes events;
4. in Orchi 67% of earthquakes fall in a minimum of DET for RQA.

These encouraging results, suggest new scenarios in RQA applications, and in order to confirmed, it needs to get an AE station network. Finally, it will be possible to optimize the analytical approach to confirm the capability of AE as being seismic events precursor.

DIRECTION to GIPSA-lab

ROADMAP

The laboratory is located in the building of the ENSE3 Grenoble Institute of Technology
This university is located in the Grenoble Campus (town of Saint Martin d'Hères).

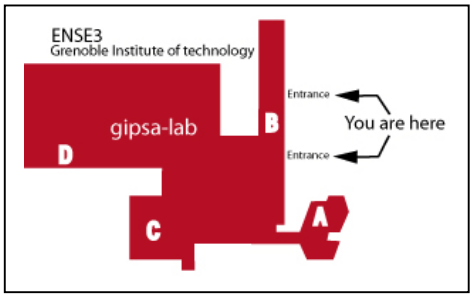
Building B 3th floor : direction of GIPSA-lab
Building B 3th floor : Speech and Cognition Department
Building B 2nd floor : Control Systems Department
Building D 1st floor : Images-Signal Department

BY CAR

Coming from Chambéry (highway A41)

Bypass Exit N°1 - Domaine universitaire

1- At the roundabout, turn right and stay on the right lane
2- At the roundabout, go straight (av. de Vignate)
3- At the roundabout, turn right (rue de la Piscine)
4- At the end of this street, turn left (av. de la Chimie)
5- Go straight on the av. de la Chimie until the end
6- At the crossroad, enter the car park opposite
7- You have 2 doors to enter the building
8- Access to upper floors via the central staircase



Coming from Lyon (highway A48) or from Sisteron (highway A480)

Direction of Chambery/Rocade Sud
EXIT N°1 - Domaine universitaire

1- At the roundabout (of the exit), go around to go left (pass under the bypass)
2- At the roundabout, go straight (av. de Vignate)
3- At the roundabout, turn right (rue de la Piscine)
4- At the end of this street, turn left (av. de la Chimie)
5- Go straight on the av. de la Chimie until the end
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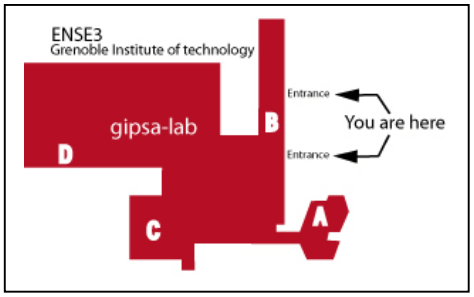
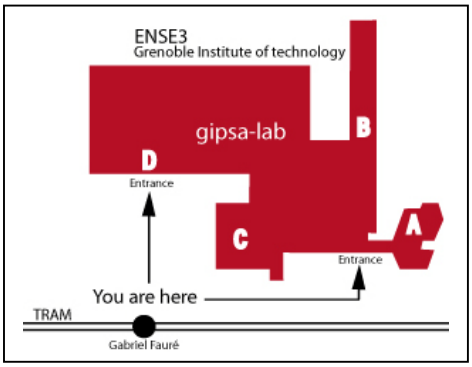


BY TRAM

Coming from the train station of Grenoble or the city center

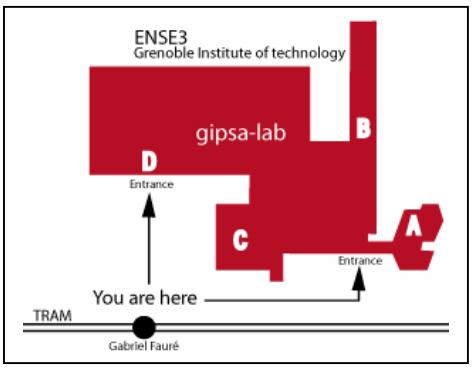
Take Tram B
Direction Gières/Plaine des sports/Universités



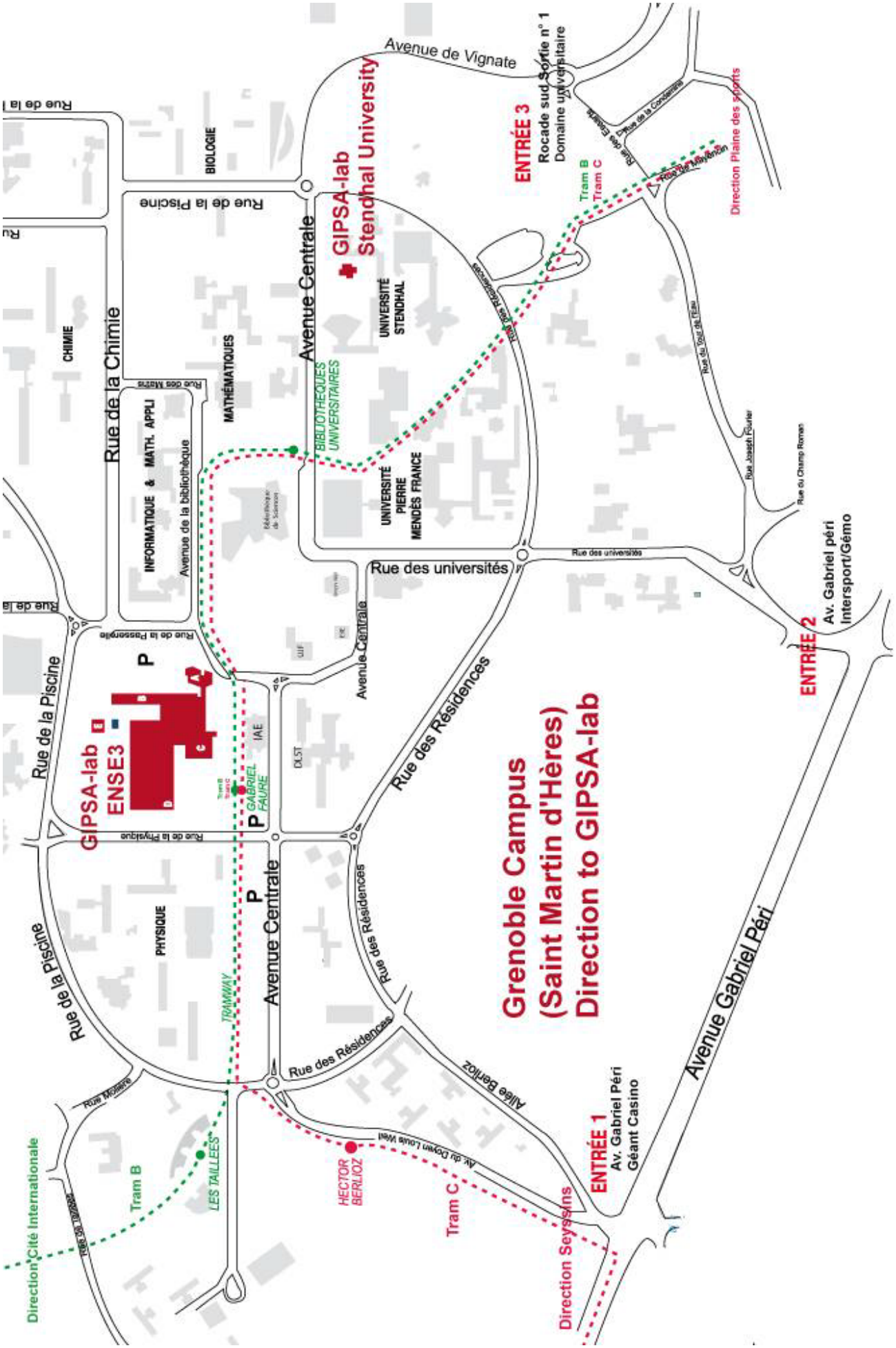
1- Get off at the stop Gabriel Fauré
2- Cross the Tram tracks
3- If you go to the Images-Signal Department (building D) : take the pedestrian walkway in front of the Tram stop, enter through the door at the end of this way and go up to the first floor.
4- If you go to another Department or the direction of Gipsa-lab, after crossing the Tram tracks, continue right along the tracks to the main entrance of building A and go up to the floors.

Coming from the train station of Gières

Take Tram B or C
Direction Cité internationale or Seyssins le Prisme



1- Get off at the stop Gabriel Fauré
2- If you go to the Images-Signal Department (building D) : take the pedestrian walkway in front of the Tram stop, enter through the door at the end of this way and go up to the first floor.
3- If you go to another Department or the direction of Gipsa-lab, go backwards parallele with the Tram tracks to the main entrance of building A (on you left) and go up to the floors.



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