Activity Report 2014

Project-Team GEOSTAT

Geometry and Statistics in acquisition data

RESEARCH CENTER
Bordeaux - Sud-Ouest

THEME
Optimization, machine learning and statistical methods

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Project-Team GEOSTAT

Keywords: Signal Processing, Multiscale Analysis, Complexity, Statistical Methods, Statistical Physics

Creation of the Team: 2009 November 01*, updated into Project-Team:* 2011 January 01.

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2. Overall Objectives

2.1. Overall objectives

Singularity exponent A measure of the unpredictability around a point in a complex signal. Based on local reconstruction around a point, singularity exponents can be evaluated in different ways and in different contexts (e.g. non-localized, through the consideration of moments and structure fonctions, trough the computation of singularity spectra). In GEOSTAT we study approaches corresponding to *far from equilibrium* hypothesis (e.g. microcanonical) leading to geometrically localized singularity exponents.

Singularity spectrum The mapping from scaling exponents to Hausdorff dimensions. The singularity spectrum quantifies the degree of nonlinearity in a signal or process, and is used to characterize globally the complexity of a signal.

Most Singular Manifold The set of most unpredictable points in a signal, identified to the set of strongest transitions as defined by the singularity exponents. From that set the whole signal can be reconstructed.

Adaptive Optics (AO) This term refers to a set of methodologies used, notably in Astromical observations, to compensate for the loss of spatial resolution in optical instruments caused by atmospheric turbulence.

Compact Representation Reduced representation of a complex signal (dimensionality reduction) from which the whole signal can be reconstructed. The reduced representation can correspond to points randomly chosen, such as in Compressive Sensing, or to geometric localization related to statistical information content (framework of reconstructible systems).

MMF Microcanonical Multiscale Formalism.

Sparse representation The representation of a signal as a linear combination of elements taken in a dictionary, with the aim of finding the most sparse possible one.

Optimal wavelet (OW). Wavelets whose associated multiresolution analysis optimizes inference along the scales in complex systems.

Universality class In theoretical physics, the observation of the coincidence of the critical exponents (behaviour near a second order phase transition) in different phenomena and systems is called universality. Universality is explained by the theory of the renormalization group, allowing for determination of the changes a physical system undergoes under different distance scales. As a consequence, different macroscopic phenomena displaying a multiscale structure (and their acquisition in the form of complex signals) can be grouped into different sets of universality classes.

GEOSTAT is a research project in **nonlinear signal processing**, with the fundamental distinction that it considers the signals as the realizations of complex dynamic systems. The driving approach is to understand the relations between complexity (or information content) and the geometric organization of information in a signal. For instance, for signals which are acquisitions of turbulent fluids, the organization of information is related to the effective presence of a multiscale hierarchy, of multifractal nature, which is strongly related to intermittency and multiplicative cascade phenomena; the determination of this geometric organization unlocks key nonlinear parameters and features associated to these signals; it helps understanding their dynamical properties and, as a consequence, their analysis. Specific advances are obtained in GEOSTAT in using this type of statistical/geometric approach to get validated dynamical information of signals acquired in Universe Sciences, e.g. Oceanography or Astronomy. The research in GEOSTAT encompasses nonlinear signal processing and the study of emergence in complex systems, with a strong emphasis on geometric approaches to complexity. Consequently, research in GEOSTAT is oriented towards the determination, in real signals, of quantities or phenomena, usually unattainable through linear methods, that are known to play an important role both in the evolution of dynamical systems whose acquisitions are the signals under study, and in the compact representations of the signals themselves. Research in GEOSTAT is structured in two parts:

- Theoretical and methodological aspects in nonlinear signal processing.
- Applicative aspects which encompass biomedical data (heartbeat signal analysis with IHU LIRYC, biomedical applications in speech signal analysis) and the study of universe science datasets.

The theoretical objectives are:

- multiscale description in terms of multiplicative cascade (essential in the characterization of turbulent systems).
- Excitable systems (cardiac electrophysiology): study of intermittency phenomena. Accessible objective: theoretical derivation of optimal wavelets.

The methodological tools used in reaching these objectives place GEOSTAT in the forefront of nonlinear signal processing and complex systems. We cite: singularity exponents [59][6], how these exponents can be related to *sparse representations* with reconstruction formulae [12] [60][12] [12], [4], the comparison with embedding techniques, such as the one provided by the classical theorem of Takens [57], [50], the use of Lyapunov exponents, how they are related to intermittency, large deviations and singularity exponents, various forms of entropies, persistence along the scales, *optimal wavelets* [5], comparison with other approaches such as Compressive Sensing, and, above all, **the ways that lead to effective numerical and high precision determination of nonlinear characteristics in real signals**. The MMF (Multiscale Microcanonical Formalism) is one of the ways to partly unlock this type of analysis, most notably w.r.t. singularity exponents and reconstructible systems [10]. We presently concentrate our efforts on it, but GEOSTAT is intended to explore other ways [46]. Presently GEOSTAT explores new methods for analyzing and understanding complex signals in different applicative domains through the theoretical advances of the MMF, and the framework of **reconstructible systems** [58]. Derived from ideas in Statistical Physics, the methods developed in GEOSTAT provide new ways to relate and evaluate quantitatively the *local irregularity* in complex signals and systems, the statistical concepts of *information content* and *most informative subset*. That latter notion is developed through the notion of *transition front* and *Most Singular Manifold*. As a result, GEOSTAT is aimed at providing *radically new approaches* to the study of signals acquired from different complex systems (their analysis, their classification, the study of their dynamical properties etc.). A common characteristic of these signals, which is related to *universality classes* [53] [54] [51], being the existence of a *multiscale organization* of the systems. For instance, the classical notion of *edge* or *border*, which is of multiscale nature, and whose importance is well known in Computer Vision and Image Processing, receives profound and rigorous new definitions, in relation with the more physical notion of *transition* and fits adequately to the case of chaotic data. The description is analogous to the modeling of states far from equilibrium, that is to say, there is no stationarity assumption. From this formalism we derive methods able to determine geometrically the most informative part in a signal, which also defines its global properties and allows for *compact representation* in the wake of known problematics addressed, for instance, in *time-frequency analysis*. In this way, the MMF allows the reconstruction, at any prescribed quality threshold, of a signal from its most informative (i. e. most unpredictable) subset, and is able to quantitatively evaluate key features in complex signals (unavailable with classical methods in Image or Signal Processing). It appears that the notion of *transition front* in a signal is much more complex than previously expected and, most importantly, related to multiscale notions encountered in the study of nonlinearity [55]. For instance, we give new insights to the computation of dynamical properties in complex signals, in particular in signals for which the classical tools for analyzing dynamics give poor results (such as, for example, correlation methods or optical flow for determining motion in turbulent datasets).

3. Research Program

3.1. Multiscale description in terms of multiplicative cascade

GEOSTAT is studying complex signals under the point of view of *nonlinear* methods, in the sense of *nonlinear physics* i.e. the methodologies developed to study complex systems, with a strong emphasis on multiresolution analysis. Linear methods in signal processing refer to the standard point of view under which operators are expressed by simple convolutions with impulse responses. Linear methods in signal processing are widely used, from least-square deconvolution methods in adaptive optics to source-filter models in speech processing. Because of the absence of localization of the Fourier transform, linear methods are not successful to unlock the multiscale structures and cascading properties of variables which are of primary importance as stated by the physics of the phenomena. This is the reason why new approaches, such as DFA (Detrented Fluctuation Analysis), Time-frequency analysis, variations on curvelets [56] etc. have appeared during the last decades. Recent advances in dimensionality reduction, and notably in Compressive Sensing, go beyond the Nyquist rate in sampling theory using nonlinear reconstruction, but data reduction occur at random places, independently of geometric localization of information content, which can be very useful for acquisition purposes, but of lower impact in signal analysis. One important result obtained in GEOSTAT is the effective use of multiresolution analysis associated to optimal inference along the scales of a complex system. The multiresolution analysis is performed on dimensionless quantities given by the *singularity exponents* which encode properly the geometrical structures associated to multiscale organization. This is applied successfully in the derivation of high resolution ocean dynamics, or the high resolution mapping of gaseous exchanges between the ocean and the atmosphere; the latter is of primary importance for a quantitative evaluation of global warming. Understanding the dynamics of complex systems is recognized as a new discipline, which makes use of theoretical and methodological foundations coming from nonlinear physics, the study of dynamical systems and many aspects of computer science. One of the challenges is related to the question of *emergence* in complex systems: large-scale effects measurable macroscopically from a system made of huge numbers of interactive agents [48], [45], [61], [52]. Some quantities related to nonlinearity, such as Lyapunov exponents, Kolmogorov-Sinai entropy etc. can be computed at least in the phase space [46]. Consequently, knowledge from acquisitions of complex systems (which include *complex signals*) could be obtained from information about the phase space. A result from F. Takens [57] about strange attractors in turbulence has motivated the determination of discrete dynamical systems associated to time series [50], and consequently the theoretical determination of nonlinear characteristics associated to complex acquisitions. Emergence phenomena can also be traced inside complex signals themselves, by trying to localize information content geometrically. Fundamentally, in the nonlinear analysis of complex signals there are broadly two approaches: characterization by attractors (embedding and bifurcation) and time-frequency, multiscale/multiresolution approaches. Time-frequency analysis [47] and multiscale/multiresolution are the subjects of intense research and are profoundly reshaping the analysis of complex signals by nonlinear approaches [44], [49]. In real situations, the phase space associated to the acquisition of a complex phenomenon is unknown. It is however possible to relate, inside the signal's domain, local predictability to local reconstruction and deduce from that singularity exponents (SEs) [10] [6]. The SEs are defined at any point in the signal's domain, they relate, but are different, to other kinds of exponents used in the nonlinear analysis of complex signals. We are working on their relation with:

- properties in universality classses,
- the geometric localization of multiscale properties in complex signals,
- cascading characteristics of physical variables,
- optimal wavelets and inference in multiresolution analysis.

The alternative approach taken in GEOSTAT is microscopical, or geometrical: the multiscale structures which have their "fingerprint" in complex signals are being isolated in a single realization of the complex system, i.e. using the data of the signal itself, as opposed to the consideration of grand ensembles or a wide set of realizations. This is much harder than the ergodic approaches, but it is possible because a reconstruction formula such as the one derived in [58] is local and reconstruction in the signal's domain is related to predictability. This approach is analogous to the consideration of "microcanonical ensembles" in statistical mechanics.

Nonlinear signal processing is making use of quantities related to predictability. For instance the first Lyapunov exponent λ_1 is related, from Osedelec's theorem, to the limiting behaviour of the response, after a time t, to perturbation in the phase space $\log R_\tau(t)$:

$$\lambda_1 = \lim_{t\to\infty} \frac{1}{t}\langle \log R_\tau(t)\rangle \tag{1}$$

with $\langle\cdot\rangle$ being time average and R_τ the response to a perturbation [46]. In GEOSTAT our aim is to relate such classical quantities (among others) to the behaviour of SEs, which are defined by a limiting behaviour

$$\mu\left(\mathcal{B}_r(\mathbf{x})\right) \;=\; \alpha(\mathbf{x})\, r^{d+h(\mathbf{x})} \;+\; o\left(r^{d+h(\mathbf{x})}\right)\;\; (r\to 0) \tag{2}$$

(d: dimension of the signal's domain, μ: multiscale measure, typically whose density is the gradient's norm, $\mathcal{B}_r(\mathbf{x})$: ball of radius r centered at $\mathbf{x}$). For precise computation, SEs can be smoothly interpolated by projecting wavelets:

$$\mathcal{T}_\Psi \mu(\mathbf{x}, r) = \int_{\mathbb{R}^d} \mathrm{d}\mu(\mathbf{x}') \frac{1}{r^d} \Psi\left(\frac{\mathbf{x} - \mathbf{x}'}{r}\right) \tag{3}$$

(Ψ: mother wavelet, admissible or not), but the best numerical method in computing singularity exponents lies in the definition of a measure related to predictability [16]:

$$h(\mathbf{x}) = \frac{\log \mathcal{T}_\Psi \mu(\mathbf{x}, r_0) / \langle \mathcal{T}_\Psi \mu(\cdot, r_0) \rangle}{\log r_0} + o(\frac{1}{\log r_0}) \tag{4}$$

with: r_0 is a scale choosen to diminish the amplitude of the correction term, and $\langle \mathcal{T}_\Psi \mu(\cdot, r_0) \rangle$ is the average value of the wavelet projection (mother wavelet Ψ) over the whole signal. Singularity exponents computed with this formula generalize the elementary "gradient's norm" in a very statistically coherent way across the scales.

SEs are related to the framework of reconstructible systems, and consequently to predictability. They unlock the geometric localization of a multiscale structure in a complex signal:

$$\mathcal{F}_h = \{\mathbf{x} \in \Omega \ \mid \ h(\mathbf{x}) = h\}, \tag{5}$$

(Ω: signal's domain). This multiscale structure is a fundamental feature of a complex system. Indeed, let us take the explicit example of a signal which is an acquisition of a 3D turbulent fluid. The velocity field of the flow, $\mathbf{v}(\mathbf{x}, t)$, is a solution of the Navier-Stokes equations. Fully Developped Turbulence (FDT) is defined as the regime observed when the Reynolds number $R \to \infty$, R being defined as the ratio of "viscous diffusion time" by "circulation time": $R = \frac{LV}{\nu}$,L and V being respectively characteristic length and velocity of the flow. The phase space of the associated dynamical system is infinite dimensional, while the dynamics of the flow possess one or more finite dimensional attractors. In the case of FDT, particles of the fluid in the continuum which are trapped around KAM invariant manifolds undergo random perturbations in their motion which accounts for the "boost" observed in turbulent diffusion. From there comes the observed behaviour for the energy spectrum (the law $\mathcal{E}(\mathbf{k}) \sim |\mathbf{k}|^{-5/3}$ within the inertial range), an observation that was the starting point of the Kolmogorov K41 theory, but is still not directly mathematically related from the Navier-Stokes equations. Intermittency is observed within the inertial range and is related to the fact that, in the case of FDT, symmetry is restored only in a statistical sense, a fact that has consequences on the quality of any nonlinear signal representation by frames or dictionaries.

The example of FDT as a standard "template" for developing general methods that apply to a vast class of complex systems and signals is of fundamental interest because, in FDT, the existence of a multiscale hierarchy (i.e. the collection of sets $\mathcal{F}_h$ of equation 5) which is of multifractal nature and geometrically localized can be derived from physical considerations. This geometric hierarchy of sets is responsible for the shape of the computed singularity spectra, which in turn is related to the statistical organization of information content in a signal. It explains scale invariance, a characteristic feature of complex signals. The analogy from statistical physics comes from the fact that singularity exponents are direct generalizations of *critical exponents* which explain the macroscopic properties of a system around critical points, and the quantitative characterization of *universality classes*, which allow the definition of methods and algorithms that apply to general complex signals and systems, and not only turbulent signals: signals which belong to a same universality class share common statistical organization. In GEOSTAT, the approach to singularity exponents is done within a microcanonical setting, which can interestingly be compared with other approaches such that wavelet leaders, WTMM or DFA. During the past decades, classical approaches (here called "canonical" because they use the analogy taken from the consideration of "canonical ensembles" in statistical mechanics) permitted the development of a well-established analogy taken from thermodynamics in the analysis of complex signals:

if $\mathcal{F}$ is the free energy, $\mathcal{T}$ the temperature measured in energy units, $\mathcal{U}$ the internal energy per volume unit $\mathcal{S}$ the entropy and $\widehat{\beta} = 1/\mathcal{T}$, then the scaling exponents associated to moments of intensive variables $p \to \tau_p$ corresponds to $\widehat{\beta}\mathcal{F}$, $\mathcal{U}(\widehat{\beta})$ corresponds to the singularity exponents values, and $\mathcal{S}(\mathcal{U})$ to the singularity spectrum.

The singularity exponents belong to a universality class, independently of microscopic properties in the phase space of various complex systems, and beyond the particular case of turbulent data (where the existence of a multiscale hierarchy, of multifractal nature, can be inferred directly from physical considerations). They describe common multiscale statistical organizations in different complex systems [55], and this is why GEOSTAT is working on nonlinear signal processing tools that are applied to very different types of signals. The methodological framework used in GEOSTAT for analyzing complex signals is different from, but related to, the "canonical" apparatus developed in recent years (WTMM method, wavelet leaders etc.). In the microcanonical approach developed, geometrically localized singularity exponents relate to a "microcanonical" description of multiplicative cascades observed in complex systems. Indeed, it can be shown that p-dissipation at scale r associated to a fixed interval $]p, p + \Delta p[$, $\epsilon_r^{(p,\Delta p)}$, behaves in the limit $\Delta p \to 0$ as

$$\epsilon_r^{(p)} = \lim_{\Delta p \to 0} \epsilon_r^{(p,\Delta p)} = \left(\epsilon_r^{(\infty)}\right)^{h(p)/h_\infty} \tag{6}$$

which indicates the existence of a relation between the multiscale hierarchy and the geometric localization of the cascade in complex systems.

The GEOSTAT team is working particularly on the very important subject of *optimal wavelets* which are wavelets ψ that "split" the signal projections between two different scales $\mathbf{r_1} < \mathbf{r_2}$ in such a way that there exists an injection term $\zeta_{r_1/r_2}(\mathbf{x})$, independent of the process $\mathcal{T}_\psi[\mathbf{s}](\mathbf{x}, \mathbf{r})$ with:

$$\mathcal{T}_\psi[\mathbf{s}](\mathbf{x}, \mathbf{r_1}) = \zeta_{r_1/r_2}(\mathbf{x})\mathcal{T}_\psi[\mathbf{s}](\mathbf{x}, \mathbf{r_2}) \tag{7}$$

($\mathbf{r_1} < \mathbf{r_2}$: two scales of observation, ζ: injection variable between the scales, ψ: optimal wavelet). The **multiresolution analysis** associated to optimal wavelets is particularly interesting because it reflects, in an optimal way, the cross-scale information transfer in a complex system. These wavelets are related to persistence along the scales and lead to multiresolution analysis whose coefficients verify

$$\alpha_s = \eta_1 \alpha_f + \eta_2 \tag{8}$$

with α_s and α_f referring to child and parent coefficients, η_1 and η_2 are random variables independent of α_s and α_f and also independent of each other.

For example we give some insight about the collaboration with LEGOS Dynbio team [1] about high-resolution ocean dynamics from microcanonical formulations in nonlinear complex signal analysis. LPEs relate to the geometric structures linked with the cascading properties of indefinitely divisible variables in turbulent flows. Cascading properties can be represented by optimal wavelets (OWs); this opens new and fascinating directions of research for the determination of ocean motion field at high spatial resolution. OWs in a microcanonical sense pave the way for the determination of the energy injection mechanisms between the scales. From this results a new method for the complete evaluation of oceanic motion field; it consists in propagating along the scales the norm and the orientation of ocean dynamics deduced at low spatial resolution (geostrophic from altimetry and a part of ageostrophic from wind stress products). Using this approach, there is no need to use several temporal occurrences. Instead, the proper determination of the turbulent cascading and energy injection mechanisms in oceanographic signals allows the determination of oceanic motion field at the SST or Ocean colour spatial resolution (pixel size: 4 kms). We use the Regional Ocean Modelling System (ROMS) to validate the results on simulated data and compare the motion fields obtained with other techniques [17].

[1] http://www.legos.obs-mip.fr/recherches/equipes/dynbio.

3.2. Excitable systems

Highly promising results are obtained in the application of nonlinear signal processing and multiscale techniques to the localization of heart fibrillation phenomenon acquired from a real patient and mapped over a reconstructed 3D surface of the heart. The notion of *source field*, defined in GEOSTAT from the computation of derivative measures related to the singularity exponents allows the localization of arrythmic phenomena inside the heart [7].

In speech analysis, we use the concept of the Most Singular Manifold (MSM) to localize critical events in domain of this signal. We show that in case of voiced speech signals, the MSM coincides with the instants of significant excitation of the vocal tract system. It is known that these major excitations occur when the glottis is closed, and hence, they are called the Glottal Closure Instants (GCI). We use the MSM to develop a reliable and noise robust GCI detection algorithm and we evaluate our algorithm using contemporaneous Electro-Glotto-Graph (EGG) recordings.

4. Application Domains

4.1. Application domains

As mentioned above, applicative aspects in GEOSTAT encompass biomedical data (heartbeat signal analysis with IHU LIRYC, biomedical applications in speech signal analysis) and the study of universe science datasets. GEOSTAT's objectives in analysis of biomedical data hinge on the following observations:

- The analysis and detection of cardiac arrhythmia and pathological voice disorders is a paradigm in nonlinear methodologies applied to these types of signals.
- The classical hypothesis under linear approaches are confronted with strong nonlinearities, aperiodicity and chaotic phenomena present in theses signals.
- Existing nonlinear approaches are lacking physiological interpretation.

Our objective in this part is to propose new measures based on low-level transition characteristics, these transition phenomena being related to general concepts associated to predictability in complex systems.

5. New Software and Platforms

5.1. Fluex

Participants: Rémi Paties [correspondent], Hussein Yahia, Joel Sudre.

- Previous software engineer Denis Arrivault has delivered the first Fluex package in December 2013, consisting of a core implementation under Gforge of the Microcanonical Multiscale Formalism in the form of C++ classes, for 1D, 2D 3D and 3D+t general signals. The Fluex project is carried on in 2014 by Rémi Paties. Contact: remi.paties@inria.fr.
- The Fluex project has been supported by the FLUEX ADT.

5.2. Platforms

5.2.1. Plafrim

GEOSTAT has participated financially in the acquisition of a computing server SGI UV2000 for PLAFRIM through funding with the OPTAD project (Conseil Région Aquitaine).

6. New Results

6.1. Highlights of the Year

Paper **Spanning the Scales of Granular Materials through Microscopic Force Imaging** by N. Brodu *et al.* accepted in **Nature Communications** (will appear in 2015).
BEST PAPER AWARD :
[36] **Complexity analysis of experimental cardiac arrhythmia in IEEE TENSYMP 2014**. B. XU, S. BINCZAK, S. JACQUIR, O. PONT, H. YAHIA.

6.2. Super-resolution for Earth Observation data

Participants: Hussein Yahia, Joël Sudre, Oriol Pont, Véronique Garçon, Dharmendra Singh.

References: [17], [30], [28], [38], [29].
With partners at LEGOS and in the framework of the OPTIC associated team (7.4.1), we are developping the novel super-resolution approaches for Universe Sciences data. New results are obtained for ocean dynamics, partial pressures pCO_2 between the ocean and the atmosphere, and data fusion.

6.3. Fast and Accurate Texture Recognition with Multilayer Convolution and Multifractal Analysis

Participants: Hicham Badri, Hussein Yahia, Khalid Daoudi.

Reference: [25].
A fast and accurate texture recognition system is presented. It consists in extracting locally and globally invariant representations of a given texture image. The mapping from the locally to the globally invariant representation is based on a scale-invariant method via the calculation of singularity exponents. The final descriptor is extracted from the distribution of these exponents and leads to a more accurate descriptor compared to the popular box-counting method. We also propose to use a combination of the generative PCA classifier together with multi-class SVM as well as a synthetic training strategy. Experiments show that the proposed solution outperforms existing methods on three challenging public benchmark datasets, while being computationally efficient.

6.4. Fast Image Edge-Aware Processing

Participants: Hicham Badri, Hussein Yahia, Driss Aboutajdine.

Reference: Article *Fast Edge-Aware Processing via First Order Proximal Approximation* by H. Badri, H. Yahia, D. Aboutajdine, accepted with minor revision in **IEEE Transactions on Visualization & Computer Graphics**, will be in HAL in 2015.
We present a framework for fast edge-aware processing of images and videos. This is an extension of our previous SIGGRAPH Asia 2013 paper. The proposed approach uses non-convex sparsity on the gradients of the latent smooth image to better preserve sharp edges. We develop tools based on first order proximal estimation for fast processing. We also propose fast and efficient numerical solutions based on separable filters estimation, which enables our method to perform fast high-quality smoothing on large-scale images. Extensive experiments show that the proposed method produces high-quality smoothing compared to state-of-the-art methods, while being fast and simple to implement.

6.5. Cardiac arrhythmia induced by mild hypothermia in vitro – a pitchfork bifurcation type process

Participants: Binbin Xu, Oriol Pont.

Reference: [20].

The neurological damage after cardiac arrest constitutes a big challenge of hospital discharge. The mild therapeutic hypothermia (MTH) (34°C - 32°C) has shown its benefit to reduce this type of damage. However, it can have many adverse effects, among which the cardiac-arrhythmia-generation-a-posteriori (CAGP) can represent up to 34%. Our study with a cardiac culture in vitro showed that at 35°C the CAGP can be induced. The process of MTH can be represented by a Pitchfork bifurcation, which could explain the different ratio of arrhythmia among the adverse effects after this therapy. This nonlinear dynamics suggests that a variable speed of cooling / rewarming, especially when passing 35°C, would help to decrease the ratio of post-hypothermia arrhythmia and then improve the hospital output.

6.6. Characterizing the dynamics of cardiac arrhythmia

The dynamics of cardiac arrhythmia is quite complex. Better understanding its mechanism can help to improve the treatment. In vitro cultures of cardiac cells which has similar parameters as cell of human's heart represent valuable tool and model to study this issue.

6.6.1. by Complexity Analysis

Participants: Binbin Xu, Oriol Pont.

References: [36], [39].
Stochastic approaches provide a type of methods to characterize cardiac arrhythmia, aimed at quantifying the statistical properties of the time series. Complexity analysis such as Approximate Entropy (ApEn) and Sample Entropy (SampEn), are particularly useful to analyze time series in electro-cardiology in which the signals are characterized by their high regularity in normal condition in contrast to irregularity in pathological cases. It is shown that ApEn and SampEn can not only serve as a discrimination index, but also provide another parameter which showed doubling phenomenon. It proves in other terms that bifurcation happens in case arrhythmia. See figure 1.

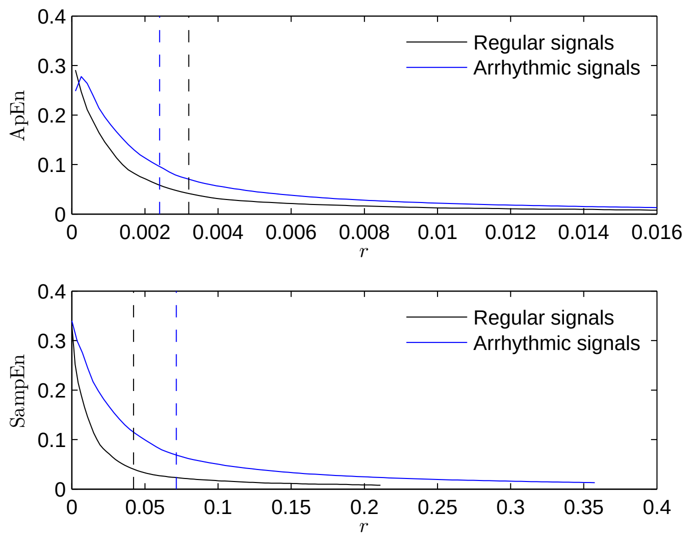

Figure 1. Illustration of ApEn / SampEn analysis for normal and arrhythmic electrical field potential.

6.6.2. by Phase Space Reconstruction

Participants: Oriol Pont, Binbin Xu.

References: [19], [40], [22].
Phase space reconstructions of electrical field potential signals in normal and arrhythmic cases are performed by characterizing the nonlinearity of these signals. The phase space reconstructions highlight attractors, whose dimension reveals that they are strange, depicting a deterministic dynamics of chaotic nature in the in vitro model. The electrical activity of the heart consists of nonlinear interactions emerging as a complex system. Electrocardiographic imaging provides a full spatiotemporal picture of the electric potential on the human epicardium. Rhythm reflects the connection topology of the pacemaker cells driving it. Hence, characterizing the attractors as nonlinear, effective dynamics can capture the key parameters without imposing any particular microscopic model on the empirical signals. A dynamic phase-space reconstruction from an appropriate embedding can be made robust and numerically stable with the methods developed in the team. With these, we have been able to show how both the phase-space descriptors and those of the a priori unrelated singularity analysis are able to highlight the arrhythmogenic areas on cases of atrial fibrillation. See figure 2.

Figure 2. Illustration of phase space analysis of normal and arrhythmic electrical field potential.

6.7. The origin of the myth FitzHugh-Nagumo model

Participants: Binbin Xu, Oriol Pont.

Reference: [37].
History became legend. Legend became myth. Derived from the pioneer ionic Hodgkin-Huxley model and due to its simplicity and richness from a point view of nonlinear dynamics, the FitzHugh-Nagumo model (FHN) is one of the most successful simplified neuron / cardiac cell model. 60 years later, there exist many variations of this model whose parameters (ε, γ and α) are often used in biased conditions. The related results would be questionable. This study showed that α controls the global dynamics of FHN. $\alpha > 0$, the cell is in refractory mode and does not respond to external stimulation; if $\alpha < 0$, the cell is excitable. ε controls the main morphology of the action potential generated. γ influences barely AP, it showed linear relationship with the period and duration of AP. Though it can be freely chosen for excitable cell, but smaller values are recommended.

6.8. Pathological Speech Analysis

Participants: Khalid Daoudi, Vahid Khanagha, Blaise Bertrac, Safa Mrad, Ashwini Jaya Kumar.

References: [14], [13], [26], [27].

We applied our recent results in nonlinear speech analysis to the filed of pathological speech detection and classification. We presented new insights in the task of normal-vs-pathological voice classification using the widely used Kayelemetrics database. In particular, we showed that hat one single parameter, derived from matching pursuit decomposition of speech, allow perfect discrimination between normal and dysphonic voices of these database. This result raises some important questions on the way this task is generally addressed. Using our GCI detection algorithm, we also proposed new definitions of standard voice perturbation measures (jitter, shimmer...) which lead to significantly higher classification accuracy. Our new measures have the strong advantage to avoid the usual periodicity and linearity assumptions. On the other hand, we started investigating the task of discrimination between Parkinson's and healthy voices. Our phonetic segmentation algorithm has potentially the ability to detect vowel onset and offset regions which have different structures in Parkinson's voices that in healthy ones. This preliminary result is promising and we are continuing research in this direction.

6.9. Statistics and detection of most unpredictable points in data sets

Participants: Nicolas Brodu, Hussein Yahia, Suman-Kumar Maji.

References: [21], [16].

The assumption that local regularity amounts to predictability can be challenged, depending on the model that one may use to make predictions. A statistical framework, "computational mechanics", has been explicitly designed over the past 30 years, that precisely formalizes notions of causality and predictability within discrete data sets. Patterns with similar causal influence on the data are clustered in equivalence classes. Taken together, these classes form a Markovian automaton by definition, since no extra information is needed from other classes to (statistically) predict the influence of a group of patterns on the rest of the data set. These automata are defined at the lowest data description scale, but it has been suggested that sub-automata (thus clusters at larger scales) form an ideal coarse-graining of the system in terms of predictability (thus also descriptive power). The theory is also deeply rooted in statistical physics, offering a unique perspective on how macroscopic variables could be derived from a microscopic description of a studied system. Preliminary results are promising and show that, for example, edges may be detected in images with a precursor continuous implementation of the theory extension under construction. In order to make more progress, advanced statistical and computational developments are necessary to carry this work. In order to facilitate this development, N. Brodu has submitted a Marie-Curie outgoing fellowship that, if accepted, would allow to partner with Australian leaders on statistics and data processing (University of Melbourne, department of Mathematics).

6.10. Image Reconstruction from Highly Corrupted Gradients

Participants: Hicham Badri, Hussein Yahia, Driss Aboutajdine.

Reference: [23].

Surface-from-Gradients (SfG) is an important step in many imaging applications. It consists in reconstructing an image/surface from corrupted gradient fields, which results in an ill-posed problem. We propose to use sparsity to regularize the problem. We use sparsity in the gradient field together with a robust norm on the data-fitting term (CVPR 2014). In a work in porgress, we make use of a non-local regularization that manipulates non-local similar patches of the corrupted gradient and forcing them to be low-rank. The two approaches significantly outperform previous optimization-based SfG methods on both synthetic and real data.

6.11. Local/Non-Local Noisy Image Deconvolution

Participants: Hicham Badri, Hussein Yahia.

Reference: [24].

Image deconvolution is a standard step in many imaging applications. Sparse local regularization has shown to be fast but tends to over-smoothing images. On the other hand, non-local priors that manipulate similar patches produce better results but tend to be much slower. In this paper, we combine both local and non-local methods in one framework to offer both good quality image reconstruction and computational efficiency in the presence of noise. By studying the non-local singular values of the image patches, we show that the non-local patches tend to be much similar in the blurred version of the image. We thus use low-rank estimation to first estimate a blurred but noise-free image. Secondly, we show that this denoising step introduces outliers in the deconvotion model and propose anefficient optimization method to tackle this problem. Experiments show that the proposed method poduces comparable results to non-local methods while being more computationally efficient.

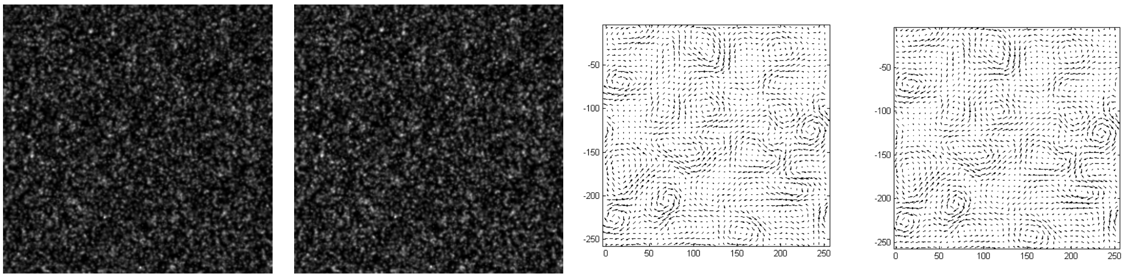

Figure 3. Motion estimation using the proposed method. From left to right: image sequences (2 images, at t and $t+1$ respectively) the ground-truth and the estimated flow (errors, from left to right : MSE=0.063, AAE=3.562, EPE=0.100).

6.12. Detection and dynamics of coastal upwelling

Participants: Ayoub Tamim, Khalid Daoudi, Hussein Yahia, Joël Sudre, Driss Aboutajdine.

References: [18], [34], [35], [33].
An unsupervised classification method is developed for the coarse segmentation of Moroccan coastal upwelling using the Sea Surface Temperature (SST) satellite images. The algorithm is used to provide a seasonal variability of upwelling activity in the southern Moroccan Atlantic coast using 70 Sea Surface Temperature (SST) images of the years 2007 and 2008. The performance of the proposed methodology has been validated by an oceanographer, showing its effectiveness for automatic delimitation of Moroccan upwelling region. We have also explored the applicability of the Fuzzy c-means (FCM) clustering, using an adaptive cluster merging, for the problem of detecting the Moroccan coastal upwelling areas in SST satellite images.

6.13. Nonlinear signal processing for adaptive optics

Participants: Suman-Kumar Maji, Hussein Yahia, Thierry Fusco.

Reference: [31].
The work developped by PhD student Suman Kumar Maji on nonlinear approaches to phase reconstruction in adaptive optics has been presented at the SPIE Astronomical Telescopes + Instrumentation, one of the great events in the field.

6.14. Turbulent Flow Estimation

Participants: Hicham Badri, Hussein Yahia.

We use singularity exponents (SE) to regularize the problem of turbulent flow estimation under the assumption that the brightness constancy constraint holds also for (SE). We also use weighted filtering (Lucas–Kanade's solution) and sparsity on the data-fitting term to improve robusteness to outliers. The proposed motion estimation is built on a Gaussian pyramid and uses the theory of warping for a better estimation of large displacements. Experiements on synthetic data show that the proposed method outperforms sophisticated methods while being simple. See figure 3.

6.15. Adaptive Transfer Real Image Restoration

Participants: Hicham Badri, Hussein Yahia.

Image restoration is a very challenging task in low-level vision and is extensively used in many imaging applications. Sparsity in various forms (dictionary learning, low-rank estimation,...) has shown to be the key for succesful image denoising. However, the standard noise model used to validate the results is mainly Gaussian and uniform, with known standard deviation. Unfortunately, these assumptions do not hold for real camera noise. Instead of using sparsity to model the singular values of non-local clean similar patches, we use a learning model that trains a mapping between the noisy and ground-truth clean singular values. The training is performed on real camera noise, contrary to previous methods. Experiments show that the proposed method signficantly outperforms previous denoising works on real non-uniform noise and does not require estimating the standard deviation of the corruption. See figure 4.

Figure 4. Image restoration demonstration on a severely corrupted image. The proposed method leads to a much better resotration quality compared to the standard BM3D method. From left to right: Ground-Truth, Noisy image, BM3D (20.46 dB), Proposed (22.25 dB).

6.16. Augmented Lagrangian for Fast Multi-Sparse Optimization

Participants: Hicham Badri, Hussein Yahia, Khalid Daoudi.

Sparsity has become one of the most important notions in many imaging applications. We address in this paper the problem of multi-sparse optimization, when the energy to minimize contains multiple sparse terms instead of a single one. We show that applying off-the-shelf proximal-based solvers such as ADMM results in a high computational cost due to the complexity of the resulting sub-problems in the case of multi-sparsity. We propose an efficient extension of ADMM for multi-sparse optimization, we study its convergence and complexity and show how it can be applied to computer vision problems. Experiments show that the proposed solver is not only computationally efficient, but also leads quickly to higher-quality results compared to the popular half-quadratic solver.

6.17. On the Fly Hybrid Video Denoising

Participants: Hicham Badri, Hussein Yahia.

Video denoising is a standard pre-processing step in many imaging applications. Non-local methods such as the BM3D method adapted to videos have shown to produce good quality results, but these methods require multiple frames to produce a temporally coherent result, especially when the amount of noise is high. On the other hand, using a hybrid camera, we can get clean images of the scene. However, these images suffer from low-temporal coherence. We present a new approach to video denoising which consists in learning a mapping between the clean images and their corresponding noisy frames and propagate denoising to intermediate frames. To improve temporal coherency, we use a fast method method to sparsify the temporal gradient. Experiments on high-resolution videos show that the proposed method produces good quality on the fly video denoising while being computationally efficient.

7. Partnerships and Cooperations

7.1. Regional Initiatives

- Project VAD-MMF with Conseil Régional Aquitaine: *Voice Activity Detection using the Multiscale Microcanonical Formalism*, 2012-2015.
- Project CAVERNOM with Conseil Régional Aquitaine: *Cardiac Arrhythmia Complexity and Variability by means of Robust Nonlinear Methods*, 2015.

7.2. National Initiatives

- ICARODE [2013-2016]. Participants : Hussein Yahia, Oriol Pont, Véronique Garçon, Joel Sudre, Antonio Turiel, Christine Provost [LOCEAN]. 4-year contract, CNES-NASA funding, started 2013. Title: *ICARODE: Integration and cascading for high resolution ocean dynamics*. Project leader: H. Yahia.
- IHU LIRYC and CRA DIAFIL project [2012-2014]. Post-doctoral fellow: B. Xu. Project leaders H. Yahia and O. Bernus.
- REGION AQUITAINE PROJECT "OPTAD". Participants : H. Yahia, S. Kumar Maji. Project leader: H. Yahia.

GEOSTAT is a member of the GDRs ISIS and PHENIX.

7.3. European Initiatives

7.3.1. Collaborations in European Programs, except FP7 & H2020

Program: ESA (European Spatial Agency) Support to Science Element.

Project acronym: OceanFlux.

Project title: High resolution mapping of GHGs exchange fluxes.

Duration: 09/2011 - 09/2014.

Coordinator: C. Garbe.

Other partners: : IWR (University of Heidelberg), LEGOS (CNRS DR-14), GEOSTAT (Inria), KIT (Karlsruher Institut fur Technologie, Frankfurt), IRD, Université Paul Sabatier.

Abstract: The EBUS (Eastern Boundary Upwelling Systems) and OMZs (Oxygen Minimum Zone) contribute very significantly to the gas exchange between the ocean and the atmosphere, notably with respect to the greenhouse gases (hereafter GHG). Invasion or outgasing fluxes of radiatively-active gases at the air-sea interface result in coupled or decoupled sink and source configurations. From in-situ ocean measurements, the uncertainty of the net global ocean-atmosphere CO2 fluxes is between 20 and 30%, and could be much higher in the EBUS-OMZ. Off Peru, very few in-situ data are available presently, which justifies alternative approaches for assessing the fluxes. GHG vertical column densities (VCD) can be extracted from satellite spectrometers. The accuracy of these VCDs need to be very high in order to make extraction of sources feasible. To achieve this accuracy is extremely challenging, particularly above water bodies, as water strongly absorbs infra-red (IR) radiation. To increase the amount of reflected light, specular reflections (sun glint) can be used on some instruments such as GOSAT. Also, denoising techniques from image processing may be used for improving the signal-to-noise ratio (SNR). GHG air-sea fluxes determination can be inferred from inverse modeling applied to VCDs, using state of the art modeling, at low spatial resolution. For accurately linking sources of GHGs to EBUS and OMZs, the resolution of the source regions needs to be increased. This task develops on new non-linear and multiscale processing methods for complex signals to infer a higher spatial resolution mapping of the fluxes and the associated sinks and sources between the atmosphere and the ocean. Such an inference takes into account the cascading properties of physical variables across the scales in complex signals. The use of coupled satellite data (e.g. SST and/or Ocean colour) that carry turbulence information associated to ocean dynamics is taken into account at unprecedented detail level to incorporate turbulence effects in the evaluation of the air-sea fluxes. We will present a framework as described above for determining sources and sinks of GHG from satellite remote sensing. The approach includes resolutions enhancements from nonlinear and multiscale processing methods. The applicability is validated against ground truth observations and numerical model studies.

7.4. International Initiatives

7.4.1. Inria Associate Teams

7.4.1.1. OPTIC

Title: Optimal inference in Complex and Turbulent data

International Partner (Institution - Laboratory - Researcher):

IITR (INDE)

Duration: 2014 - 2017.

See also: https://optic.bordeaux.inria.fr/. The associated team is supported by Inria and IFCAM.

The OptIC associated team targets the extension and development of a strong collaboration between Inria GEOSTAT team and INDIAN INSTITUTE OF TECHNOLOGY ROORKEE Dept of Electronics and Computer Engineering (Prof. D. Singh's group) on non-linear Signal Processing for Universe Sciences, with a strong emphasis on data fusion in Earth Observation and monitoring. Non-linear Physics puts strong evidence of the fundamental role played by multiscale hierarchies in complex and turbulent data: in these data, the information content is statistically localized in geometrical arrangements in the signal's domain, while such geometrical organization is not attainable by classical methods in linear signal processing. This is one of the major drawbacks in the classical analysis of complex and turbulent signals. The goal of this associated team is to show that inference of physical variables along the scales of complex and turbulent signals can be performed through optimal multiresolution analysis performed on non-linear features and data extracted from the signals, resulting in novel and powerful approaches for data fusion between different acquisitions (in temporal/spatial/spectral resolutions). This program needs both strong expertise in the physical processes beyond the acquisitions and the application of non-linear physics ideas on the behavior of the acquired physical phenomena. The proposal will focus on specific applications in Earth Observation and monitoring for which the Indian partner has developed a very strong expertise, notably in its knowledge and use of the physical processes in remote sensing acquisitions. This partnership is an extremely interesting and high potential collaboration between two teams which focus separately either on the acquisition of the physical processes or their analysis by Complex Systems and non-linear physics methodologies. The recent results obtained in super-resolution by GEOSTAT promises strong applications to a much wider range of Universe Sciences problems, notably with a strong emphasis on data fusion between the physical variables acquired on related but different acquisitions. OptiC builds on a collaboration between Inria and IIT ROORKEE teams, added with partners in Universe Sciences and earth observation (ONERA, CNRS) already involved in research actions with GEOSTAT.

7.4.2. Participation In other International Programs

- IFCAM (India), in cooperation with OPTIC associated team (7.4.1): Indo-French Centre for Applied Mathematics (IFCAM) project [2014-2017]. Title: Optimal inference in complex and turbulent data. 3-year contract, IFCAM funding, started 2014. Partners: GEOSTAT and IIT ROORKEE (INDIA).

7.5. International Research Visitors

7.5.1. Visits of International Scientists

- Professor Dharmendra Singh, IIT Roorkee, in the framework of the OPTIC associated team, visited GEOSTAT in June 2014.

7.5.1.1. Internships

- Ashwini Jaya Kular. Master 2 intern from Apr to Oct 2014.
- Jiri Mekyska, PhD student at Brno university (Czech republic), spent the month of June at GEOSTAT. His internship was funded by the Joseph Fourier grant.

7.5.2. Visits to International Teams

H. Yahia (2 weeks) and N. Brodu (2 weeks) visited IIT Roorkee in 2014, to work in the framework of the OPTIC associated team.

8. Dissemination

8.1. Promoting Scientific Activities

8.1.1. Scientific events organisation

8.1.1.1. General chair, scientific chair

H. Yahia and K. Daoudi are members of the scientific committee of the ISIVC 2014 conference.

8.1.1.2. Reviewer

K. Daoudi has been reviewer for INTERSPEECH, ICASSP and for the "The Icelandic Research Fund" project.

8.1.2. Journal

8.1.2.1. Member of the editorial board

- H. Yahia is a member of the editorial board of the open access journal *Frontiers in Fractal Physiology*.
- H. Yahia has been a member of Elsevier’s *Digital Signal Processing* from 2011 until mid 2014.
- H. Yahia is the editor in chief of the *Frontiers Research Topic* "theoretical physics and signal processing", to be organized in 2015 with P. Ivanov (Boston University) and A. Turiel (ICM-CSIC).

8.1.3. Conseil National des Universités

H. Yahia, member, section 61.

8.2. Teaching - Supervision - Juries

8.2.1. Seminars, presentations

- H. Yahia has given a presentation at the **Séminaire Cristolien d'Analyse Multifractale** (SCAM), headed by S. Jaffard: *Exposants de singularité en formalisme microcanonique et analyse multirésolutions quasi-optimale*, Jan 16, 2014.
- H. Yahia was invited to make a presentation: *Edges, transitions, criticality: novel nonlinear characterizations of low-level transition features in signal processing and applications to cross-scale inference in complex signals* at the ISIVC 2014 conference http://www.i3e.ma/isivc2014/keynote.php.
- O. Pont was invited to make a presentation: *Cardiodynamic Complexity: Electrocardiographic Characterization of Arrhythmic Foci*, [22].
- K. Daoudi was invited by Dr. Jon Gudnason to give a lecture on nonlinear speech analysis at Reykjavik university, Iceland.
- H. Badri has made a presentation at *Journées de l'EDMI* (Bordeaux - France), November 2014.
- H. Badri has made a presentation in the MANAO team: *Recovering Gradient Fields with Multi-Sparse Priors* March 26, 2014.
- H. Badri has made presentation at the "Signal-Image" seminar, co-organized by IMS-IMB-LaBRI in the framework of Labex CPU, May 15, 2014.
- GEOSTAT has invited A. Bijaoui, astronomer Emeritus to give a seminar for the Inria BSO centre, June 3rd, 2014.

8.2.2. Courses, summer schools

1. Mediterranean School of Complex Networks - (Salina, Sicily), June 9-13, attended by H. Badri.
2. WIPO intellectual property certificate attended by H. Badri.
3. University Teaching 101 - Johns Hopkins University certificate attended by H. Badri.

8.2.3. Teaching

Licence : H. Badri, C2I course, 32 hours, L1 level, Bordeaux I University, France.

Master : K. Daoudi was invited by the Moroccan CNRST within the FINCOME'2014 program (http://www.fincome.cnrst.ma/) to give a 20 hours lecture on speech processing at the Master2 InfoTelecom of the faculty of science of Rabat (http://www.fsr.ac.ma/MIT/).

8.2.4. Juries

H. Yahia was a member of the PhD Jury of S. Chef (Le2I, UMR CNRS 6306, Laboratoire Electronique, Informatique et Image), defended November 25, 2014. Title: *Contribution à l'analyse de signaux acquis par émission de photons. Dynamique pour l'étude de circuits à très haute intégration*. Jury:

- S. Binczak, professeur université de Bourgogne (directeur de thèse),
- S. Jacquir, maitre de conférence université de Bourgogne (co-encadrant),
- F. Morain-Nicolier, IUT de Troyes, (rapporteur),
- K. Sanchez, docteur ingénieur CNES, (examinateur),
- L. Torres, professeur LIRMM, (rapporteur),
- H. Yahia, chargé de recherche Inria Bordeaux (examinateur).

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[2] V. KHANAGHA, K. DAOUDI, H. YAHIA. *Detection of Glottal Closure Instants based on the Microcanonical Multiscale Formalism*, in "IEEE Transactions on Audio, Speech and Language Processing", December 2014, https://hal.inria.fr/hal-01059345

[3] V. KHANAGHA, K. DAOUDI, H. YAHIA. *Efficient and robust detection of Glottal Closure Instants using Most Singular Manifold of speech signals*, in "IEEE Transactions on Acoustics Speech and Signal Processing", 2014, forthcoming, https://hal.inria.fr/hal-00802014

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