Activity Report 2018

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

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2. Overall Objectives

2.1. Overall Objectives

GEOSTAT is a research project which investigates the analysis of some classes of natural complex signals (physiological time series, turbulent universe and earth observation data sets) by determining, in acquired signals, the properties that are predicted by commonly admitted or new physical models best fitting the phenomenon. Consequently, when statistical properties discovered in the signals do not match closely enough those predicted by accepted physical models, we question the validity of existing models or propose, whenever possible, modifications or extensions of existing models. We will give, in the sequel, a detailed example of this approach and methodology.

An important aspect of this methodological approach is that we don't rely on a predetermined "universal" signal processing model to analyze natural complex signals. Instead, we take into consideration existing approaches in nonlinear signal processing (wavelets, multifractal analysis tools such as log-cumulants or micro-canonical multifractal formalism, time frequency analysis etc.) which are used to determine the micro structures or other micro features inside the acquired signals. Then, statistical analysis of these micro data are determined and compared to expected behaviour from theoretical physical models used to describe the phenomenon from which the data is acquired. From there different possibilities can be contemplated:

- The statistics match behaviour predicted by the model: complexity parameters predicted by the model are extracted from signals to analyze the dynamics of underlying phenomena. Examples: analysis of turbulent data sets in Oceanography and Astronomy.
- The signals displays statistics that cannot be attainable by the common lore of accepted models: how to extend or modify the models according to the behaviour of observed signals ? Example: electrical activity of heart signal analysis (see infra).

GEOSTAT is a research project in nonlinear signal processing which develops on these considerations: it considers the signals as the realizations of complex extended dynamical systems. The driving approach is to describe 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 may be related to the effective presence of a multiscale hierarchy of coherent structures, 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 understand their dynamical properties and their analysis. We use this approach to derive novel solution methods for super-resolution and data fusion in Universe Sciences acquisitions [12]. Another example can be found in signal analysis of the electrical activity of the heart, where we find the distribution of activation points in a signal during episodes of atrial fibrilation (with strengthening from feature selection and Bayesian learning see below). 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.

Signals studied in GEOSTAT belong to two broad classes:

- Acquisitions in Astronomy and Earth Observation.
- Physiological time series.

3. Research Program

3.1. General methodology

Fully Developed Turbulence (FDT) Turbulence at very high Reynolds numbers; systems in FDT are beyond deterministic chaos, and symmetries are restored in a statistical sense only, and multi-scale correlated structures are landmarks. Generalizing to more random uncorrelated multi-scale structured turbulent fields.

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).

Sparse representation The representation of a signal as a linear combination of elements taken in a dictionary (frame or Hilbertian basis), with the aim of finding as less as possible non-zero coefficients for a large class of signals.

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 the determination of the changes followed by structured fluctuations under rescaling, a physical system is the stage of. The notion is applicable with caution and some differences to generalized out-of-equilibrium or disordered systems. Non-universal exponents (without definite classes) exist in some universal slowing dynamical phenomena like the glass transition and kindred. As a consequence, different macroscopic phenomena displaying multiscale structures (and their acquisition in the form of complex signals) may be grouped into different sets of generalized classes.

Every signal conveys, as a measure experiment, information on the physical system whose signal is an acquisition of. As a consequence, it seems natural that signal analysis or compression should make use of physical modelling of phenomena: the goal is to find new methodologies in signal processing that goes beyond the simple problem of interpretation. Physics of disordered systems, and specifically physics of (spin) glasses is putting forward new algorithmic resolution methods in various domains such as optimization, compressive sensing etc. with significant success notably for NP hard problem heuristics. Similarly, physics of turbulence introduces phenomenological approaches involving multifractality. Energy cascades are indeed closely related to geometrical manifolds defined through random processes. At these structures' scales, information in the process is lost by dissipation (close to the lower bound of inertial range). However, all the cascade is encoded in the geometric manifolds, through long or short distance correlations depending on cases. How do these geometrical manifold structures organize in space and time, in other words, how does the scale entropy cascades itself ? To unify these two notions, a description in term of free energy of a generic physical model is sometimes possible, such as an elastic interface model in a random nonlinear energy landscape : This is for instance the correspondence between compressible stochastic Burgers equation and directed polymers in a disordered medium. Thus, trying to unlock the fingerprints of cascade-like structures in acquired natural signals becomes a fundamental problem, from both theoretical and applicative viewpoints.

To illustrate the general methodology undertaken, let us focus on an example conducted in the study of physiological time series: the analysis of signals recorded from the electrical activity of the heart in the general setting of Atrial Fibrillation (AF). AF is a cardiac arrhythmia characterized by rapid and irregular atrial electrical activity with a high clinical impact on stroke incidence. Best available therapeutic strategies combine pharmacological and surgical means. But when successful, they do not always prevent long-term relapses. Initial success becomes all the more tricky to achieve as the arrhythmia maintains itself and the pathology evolves into sustained or chronic AF. This raises the open crucial issue of deciphering the mechanisms that govern the onset of AF as well as its perpetuation. We have developed a wavelet-based multi-scale strategy to analyze the electrical activity of human hearts recorded by catheter electrodes, positioned in the coronary sinus (CS), during episodes of chronic AF. We have computed the so-called multifractal spectra using two variants of the wavelet transform modulus maxima method, the moment (partition function) method and the magnitude cumulant method (checking confidence intervals with surrogate data). Application of these methods to long time series recorded in a patient with chronic AF provides quantitative evidence of the multifractal intermittent nature of the electric energy of passing cardiac impulses at low frequencies, *i.e.* for times ($>\sim 0.5$ s) longer than the mean interbeat ($\simeq 10^{-1}$s). We have also reported the results of a two-point magnitude correlation analysis which infers the absence of a multiplicative time-scale structure underlying multifractal scaling. The electric energy dynamics looks like a “multifractal white noise” with quadratic (log-normal) multifractal spectra. *These observations challenge concepts of functional reentrant circuits in mechanistic theories of AF*. A transition is observed in the computed multifractal spectra which group according to two distinct areas, consistently with the anatomical substrate binding to the CS, namely the left atrial posterior wall, and the ligament of Marshall which is innervated by the ANS. These negative results challenge also the existing models, which by principle cannot explain such results. As a consequence, we go beyond the existing models and propose a mathematical model of a denervated heart where the kinetics of gap junction conductance alone induces a desynchronization of the myocardial excitable cells, accounting for the multifractal spectra found experimentally in the left atrial posterior wall area (devoid of ANS influence).

3.2. Multiscale description in terms of multiplicative cascade, application to Earth observation signals

The research described in this section is a collaboration effort of GEOSTAT, CNRS LEGOS (Toulouse), CNRS LAM (Marseille Laboratory for Astrophysics), MERCATOR (Toulouse), IIT Roorkee, Moroccan Royal Center for Teledetection (CRST), Moroccan Center for Science CNRST, Rabat University, University of Heidelberg. Researchers involved:

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The analysis and modeling of natural phenomena, specially those relevant to geophysical sciences, are influenced by statistical and multiscale phenomenological descriptions of turbulence; indeed these descriptions are able to explain the partition of energy within a certain range of scales. A particularly important aspect of the statistical theory of turbulence lies in the discovery that the support of the energy transfer is spatially highly non uniform, in other terms it is *intermittent* [67]. 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 [64] 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 [34], [60]. Some quantities related to nonlinearity, such as Lyapunov exponents, Kolmogorov-Sinai entropy etc. can be computed at least in the phase space [35]. 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 Takens-81 about strange attractors in transition turbulence has motivated 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. 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 [13] and to deduce relevant information associated to multiscale geophysical signals [14]. A multiscale organization is a fundamental feature of a complex system, it can be for example related to the cascading properties in turbulent systems. We make use of this kind of description when analyzing turbulent signals: intermittency is observed within the inertial range and is related to the fact that, in the case of FDT (fully developed turbulence), 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 $\mathcal{F}_h$ 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. During the past decades, canonical approaches 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 [30]. The research goal is to be able to determine universality classes associated to acquired signals, independently of microscopic properties in the phase space of various complex systems, and beyond the particular case of turbulent data [54].

3.3. Excitable systems: analysis of physiological time series

The research described in this section is a collaboration effort of GEOSTAT, CNRS LOMA (Laboratoire Ondes et Matière d'Aquitaine) and Laboratory of Physical Foundation of Strength, Institute of Continuous Media Mechanics (Perm, Russia Federation).

AF is an arrhythmia originating in the rapid and irregular electrical activity of the atria (the heart's two upper chambers) that causes their pump function to fail, increasing up to fivefold the risk of embolic stroke. The prevailing electrophysiological concepts describing tachy-arrhythmias are more than a century old. They

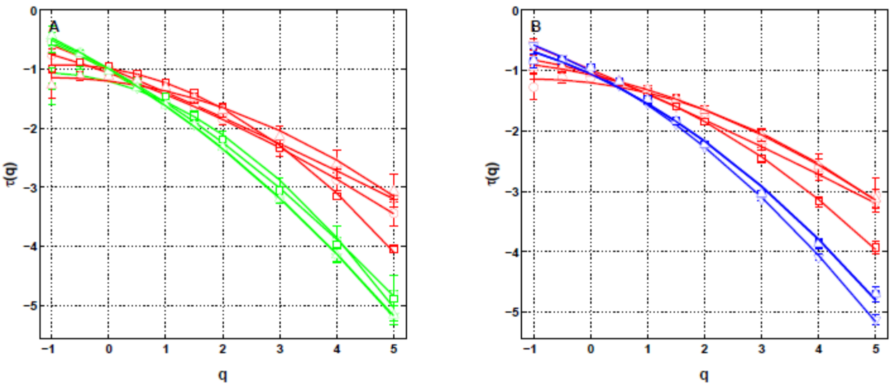

Figure 1. $\tau(q)$ spectra of local impulse energy time-series recorded along the CS vein at the electrodes Pt2 (red), Pt3 (blue) and Pt5 (green). The curves represent quadratic polynomial fit of the data. (A) The symbols correspond to the reference Patient 1 (chronic AF,$\bigtriangledown$), and to Patients 2 (chronic AF, $\circ$) 3 (paroxysmal AF, $\square$) and 4 (persistent AF, $\bigtriangleup$). (B) The symbols correspond to the reference Patient 1 ($\bigtriangledown$) and to three different time-series for Patient 4 ($\circ$,$\square$,$\bigtriangleup$) recorded at different periods of time preceding ablation procedure.

involve abnormal automaticity and conduction [53]. Initiation and maintenance are thought to arise from a vulnerable substrate prone to the emergence of multiple self-perpetuating reentry circuits, also called "multiple wavelets" [58], [59]. Reentries may be driven structurally, for instance because of locally high fibrous tissue content which badly conducts, or functionally because of high spatial dispersion of decreased refractoriness and APD [57]. The latter is coined the leading circle concept with the clinically more relevant notion of a critical "wavelength" (in fact the length) of the cardiac impulse [29], [63], [61], [33]. The related concept of vulnerability was originally introduced to uncover a physiological substrate evolving from normality to pathology. It was found in vulnerable patients that high rate frequency would invariably lead to functional disorder as cardiac cells would no longer properly adapt their refractoriness [32]. Mathematical models have managed to exhibit likewise phenomena, with the generation of breaking spiral waves in various conditions [50], [55]. The triggering role of abnormal ectopic activity of the pulmonary veins has been demonstrated on patients with paroxysmal AF resistant to drug therapy [49], but its origin still remains poorly understood. This region is highly innervated with sympathetic and parasympathetic stimulation from the ANS [65], [66], [31]. In particular, Coumel et al. [41], [40] have revealed the pathophysiological role of the vagal tone on a vulnerable substrate. It is frequently observed that rapid tachycardia of ectopic origin transits to AF. This is known to result from electrical remodeling. As described for the first time by Allessie et al. [28], remodeling is a transient and reversible process by which the impulse properties such as its refractory period are altered during the course of the arrhythmia, promoting its perpetuation: "AF begets AF" [68]. Under substantial beating rate increase, cells may undergo remodeling to overcome the toxicity of their excessive intercellular calcium loading, by a rapid down regulation (a few minutes) of their L-type calcium membrane current. Moreover, other ionic channel functions are also modified such as the potassium channel function, inducing a change in the conduction properties including the conduction velocity. The intercellular coupling at the gap junction level shows also alterations of their connexin expression and dispersion.

Wavelet-based methods (WTMM, log-cumulants, two point scale correlations), and confidence statistical methodology, have been applied to catheter recordings in the coronary sinus vein right next to the left atria of a small sample of patients with various conditions, and exhibit clear multifractal scaling without cross-scale correlation, which are coined "multifractal white noise", and that can be grouped according to two anatomical regions. One of our main result was to show that this is incompatible with the common lore for atrial fibrillation based on so-called circuit reentries. We used two declinations of a wavelet-based multi-scale method, the moment (partition function) method and the magnitude cumulant method, as originally introduced in the field of fully developed turbulence. In the context of cardiac physiology, this methodology was shown to be valuable in assessing congestive heart failure from the monitoring of sinus heart rate variability [51]. We develop a model such that the substrate function is modulated by the kinetics of conduction. A simple reversible mechanism of short term remodeling under rapid pacing is demonstrated, by which ionic overload acts locally (dynamical feedback) on the kinetics of gap junction conductance. The whole process may propagate and pervade the myocardium via electronic currents, becoming desynchronized. In a new description, we propose that circuit reentries may well exist before the onset of fibrillation, favoring onset but not contributing directly to the onset and perpetuation. By contrast, cell-to-cell coupling is considered fundamentally dynamical. The rationale stems from the observation that multifractal scaling necessitates a high number of degrees of freedom (tending to infinity with system size), which can originate in excitable systems in hyperbolic spatial coupling. See figure 1.

3.4. Data-based identification of characteristic scales and automated modeling

Data are often acquired at the highest possible resolution, but that scale is not necessarily the best for modeling and understanding the system from which data was measured. The intrinsic properties of natural processes do not depend on the arbitrary scale at which data is acquired; yet, usual analysis techniques operate at the acquisition resolution. When several processes interact at different scales, the identification of their characteristic scales from empirical data becomes a necessary condition for properly modeling the system. A classical method for identifying characteristic scales is to look at the work done by the physical processes, the energy they dissipate over time. The assumption is that this work matches the most important action of each process on the studied natural system, which is usually a reasonable assumption. In the framework of time-frequency analysis [46], the power of the signal can be easily computed in each frequency band, itself matching a temporal scale.

However, in open and dissipative systems, energy dissipation is a prerequisite and thus not necessarily the most useful metric to investigate. In fact, most natural, physical and industrial systems we deal with fall in this category, while balanced quasi-static assumptions are practical approximation only for scales well below the characteristic scale of the involved processes. Open and dissipative systems are not locally constrained by the inevitable rise in entropy, thus allowing the maintaining through time of mesoscopic ordered structures. And, according to information theory [48], more order and less entropy means that these structures have a higher information content than the rest of the system, which usually gives them a high functional role.

We propose to identify characteristic scales not only with energy dissipation, as usual in signal processing analysis, but most importantly with information content. Information theory can be extended to look at which scales are most informative (e.g. multi-scale entropy [39], ε-entropy [38]). Complexity measures quantify the presence of structures in the signal (e.g. statistical complexity [43], MPR [56] and others [45]). With these notions, it is already possible to discriminate between random fluctuations and hidden order, such as in chaotic systems [42], [56]. The theory of how information and structures can be defined through scales is not complete yet, but the state of art is promising [44]. Current research in the team focuses on how informative scales can be found using collections of random paths, assumed to capture local structures as they reach out [37].

Building on these notions, it should also possible to fully automate the modeling of a natural system. Once characteristic scales are found, causal relationships can be established empirically. They are then clustered together in internal states of a special kind of Markov models called ϵ-machines [43]. These are known to be the optimal predictors of a system, with the drawback that it is currently quite complicated to build them properly, except for small system [62]. Recent extensions with advanced clustering techniques [36], [47], coupled with the physics of the studied system (e.g. fluid dynamics), have proved that ϵ-machines are applicable to large systems, such as global wind patterns in the atmosphere [52]. Current research in the team focuses on the use of reproducing kernels, coupled possibly with sparse operators, in order to design better algorithms for ϵ-machines reconstruction. In order to help with this long-term project, a collaboration with J. Crutchfield lab at UC Davis was initiated in 2017.

3.5. Speech analysis

Phonetic and sub-ponethic analysis: We developed a novel algorithm for automatic detection of Glottal Closure Instants (GCI) from speech signals using the Microcanonical Multiscale Formalism (MMF). This state of the art algorithm is considered as a reference in this field. We made a Matlab code implementing it available to the community (link). Our approach is based on the Microcanonical Multiscale Formalism. We showed that in the case of clean speech, our algorithm performs almost as well as a recent state-of-the-art method. In presence of different types of noises, we showed that our method is considerably more accurate (particularly for very low SNRs). Moreover, our method has lower computational times does not rely on an estimate of pitch period nor any critical choice of parameters. Using the same MMF, we also developed a method for phonetic segmentation of speech signal. We showed that this method outperforms state of the art ones in term of accuracy and efficiency.

Pathological speech analysis and classification: we made a critical analysis of some widely used methodologies in pathological speech classification. We then introduced some novel methods for extracting some common features used in pathological speech analysis and proposed more robust techniques for classification.

Speech analysis of patients with Parkinsonism: with our collaborators from the Czech Republic, we started preliminary studies of some machine learning issues in the field essentially due the small amount of training data.

4. Application Domains

4.1. Sparse signals & optimisation

This research topic involves **Geostat** team and is used to set up an InnovationLab with I2S company

Sparsity can be used in many ways and there exist various sparse models in the literature; for instance minimizing the l_0 quasi-norm is known to be an NP-hard problem as one needs to try all the possible combinations of the signal's elements. The l_1 norm, which is the convex relation of the l_0 quasi-norm results in a tractable optimization problem. The l_p pseudo-norms with $0 < p < 1$ are particularly interesting as they give closer approximation of l_0 but result in a non-convex minimization problem. Thus, finding a global minimum for this kind of problem is not guaranteed. However, using a non-convex penalty instead of the l_1 norm has been shown to improve significantly various sparsity-based applications. Nonconvexity has a lot of statistical implications in signal and image processing. Indeed, natural images tend to have a heavy-tailed (kurtotic) distribution in certain domains such as wavelets and gradients. Using the l_1 norm comes to consider a Laplacian distribution. More generally, the hyper-Laplacian distribution is related to the l_p pseudo-norm $(0 < p < 1)$ where the value of p controls how the distribution is heavy-tailed. As the hyper-Laplacian distribution for $0 < p < 1$ represents better the empirical distribution of the transformed images, it makes sense to use the l_p pseudo-norms instead of l_1. Other functions that better reflect heavy-tailed distributions of images have been used as well such as Student-t or Gaussian Scale Mixtures. The internal properties of natural images have helped researchers to push the sparsity principle further and develop highly efficient algorithms for restoration, representation and coding. Group sparsity is an extension of the sparsity principle where data is clustered into groups and each group is sparsified differently. More specifically, in many cases, it makes sense to follow a certain structure when sparsifying by forcing similar sets of points to be zeros or non-zeros simultaneously. This is typically true for natural images that represent coherent structures. The concept of group sparsity has been first used for simultaneously shrinking groups of wavelet coefficients because of the relations between wavelet basis elements. Lastly, there is a strong relationship between sparsity, nonpredictability and scale invariance.

We have shown that the two powerful concepts of sparsity and scale invariance can be exploited to design fast and efficient imaging algorithms. A general framework has been set up for using non-convex sparsity by applying a first-order approximation. When using a proximal solver to estimate a solution of a sparsity-based optimization problem, sparse terms are always separated in subproblems that take the form of a proximal operator. Estimating the proximal operator associated to a non-convex term is thus the key component to use efficient solvers for non-convex sparse optimization. Using this strategy, only the shrinkage operator changes and thus the solver has the same complexity for both the convex and non-convex cases. While few previous works have also proposed to use non-convex sparsity, their choice of the sparse penalty is rather limited to functions like the l_p pseudo-norm for certain values of $p \geq 0.5$ or the Minimax Concave (MC) penalty because they admit an analytical solution. Using a first-order approximation only requires calculating the (super)gradient of the function, which makes it possible to use a wide range of penalties for sparse regularization. This is important in various applications where we need a flexible shrinkage function such as in edge-aware processing. Apart from non-convexity, using a first-order approximation makes it easier to verify the optimality condition of proximal operator-based solvers via fixed-point interpretation. Another problem that arises in various imaging applications but has attracted less works is the problem of multi-sparsity, when the minimization problem includes various sparse terms that can be non-convex. This is typically the case when looking for a sparse solution in a certain domain while rejecting outliers in the data-fitting term. By using one intermediate variable per sparse term, we show that proximal-based solvers can be efficient. We give a detailed study of the Alternating Direction Method of Multipliers (ADMM) solver for multi-sparsity and study its properties. The following subjects are addressed and receive new solutions:

- **Edge aware smoothing**: given an input image g, one seeks a smooth image u "close" to g by minimizing:

$$\underset{u}{\operatorname{argmin}} \; \frac{\lambda}{2}\|u-g\|_2^2 + \psi(\nabla u)$$

where ψ is a sparcity-inducing non-convex function and λ a positive parameter. Splitting and alternate minimization lead to the sub-problems:

$$\begin{aligned}
(\text{sp1}) \quad &: \quad v^{(k+1)} \longleftarrow \underset{v}{\operatorname{argmin}} \; \psi(v) + \frac{\beta}{2}\left\|\nabla u^{(k)} - v\right\|_2^2 \\
(\text{sp2}) \quad &: \quad u^{(k+1)} \longleftarrow \underset{u}{\operatorname{argmin}} \; \lambda\|u-g\|_2^2 + \beta\left\|\nabla u - v^{(k+1)}\right\|_2^2.
\end{aligned}$$

We solve sub-problem (sp2) through deconvolution and efficient estimation via separable filters and warm-start initialization for fast GPU implementation, and sub-problem (sp1) through non-convex proximal form.

- **Structure-texture separation**: gesign of an efficient algorithm using non-convex terms on both the data-fitting and the prior. The resulting problem is solved via a combination of Half-Quadratic (HQ) and Maximization-Minimization (MM) methods. We extract challenging texture layers outperforming existing techniques while maintaining a low computational cost. Using spectral sparsity in the framework of low-rank estimation, we propose to use robust Principal Component Analysis (RPCA) to perform robust separation on multi-channel images such as glare and artifacts removal of flash/no-flash photographs. As in this case, the matrix to decompose has much less columns than lines, we propose to use a QR decomposition trick instead of a direct singular value decomposition (SVD) which makes the decomposition faster.

- **Robust integration**: in many applications, we need to reconstruct an image from corrupted gradient fields. The corruption can take the form of outliers only when the vector field is the result of transformed gradient fields (low-level vision), or mixed outliers and noise when the field is estimated from corrupted measurements (surface reconstruction, gradient camera, Magnetic Resonance Imaging (MRI) compressed sensing, etc.). We use non-convexity and multi-sparsity to build efficient integrability enforcement algorithms. We present two algorithms : 1) a local algorithm that uses sparsity in the gradient field as a prior together with a sparse data-fitting term, 2) a non-local algorithm that uses sparsity in the spectral domain of non-local patches as a prior together with a sparse data-fitting term. Both methods make use of a multi-sparse version of the Half-Quadratic solver. The proposed methods were the first in the literature to propose a sparse regularization to improve integration. Results produced with these methods significantly outperform previous works that use no regularization or simple l_1 minimization. Exact or near-exact recovery of surfaces is possible with the proposed methods from highly corrupted gradient fields with outliers.

- **Learning image denoising**: deep convolutional networks that consist in extracting features by repeated convolutions with high-pass filters and pooling/downsampling operators have shown to give near-human recognition rates. Training the filters of a multi-layer network is costly and requires powerful machines. However, visualizing the first layers of the filters shows that they resemble wavelet filters, leading to sparse representations in each layer. We propose to use the concept of scale invariance of multifractals to extract invariant features on each sparse representation. We build a bi-Lipschitz invariant descriptor based on the distribution of the singularities of the sparsified images in each layer. Combining the descriptors of each layer in one feature vector leads to a compact representation of a texture image that is invariant to various transformations. Using this descriptor that is efficient to calculate with learning techniques such as classifiers combination and artificially adding training data, we build a powerful texture recognition system that outperforms previous works on 3 challenging datasets. In fact, this system leads to quite close recognition rates compared to latest advanced deep nets while not requiring any filters training.

5. Highlights of the Year

5.1. Highlights of the Year

- Technology transfer and socio-economic impact: InnovationLab i2S-GEOSTAT. Three year contract with I2S company on the transfert of award winning H. Badri PhD results (AFRIF PhD price in 2016). The contract is being transformed in 2018 in the form of an Inria Innovation Lab. The Innovation Lab is focused on non convex optimization methods in image processing and digital acquisition devices. People involved in GEOSTAT: H. Yahia, N. Brodu, K.Daoudi, M. Martin, A. Zebadua. Budget: 900 000 € on 3 years. The InnovationLab is intended at transferring non-convex optimization methods to solve efficiently the fundamental steps of an imaging acquisition chain built by i2S company. In particular, the following thematics receive new algorithmic solutions through proximal operators and non-convex optimization:
  - Image smoothing
  - Image denoising
  - Efficient block-matching implementation
  - Denoising through learning
  - Low rank transfert
  - Debayerisation
  - Image stitching
  - Deconvolution
  - 3D reconstruction from corrupted gradients
  - Super-resolution
  - Image enhancement

  This InnovationLab is operated by GEOSTAT researchers, 1 PhD, 2 post-docs and 1 engineer. C++ libraries are developed and transferred into the algorithmic chain at i2S.
- Research results done by GEOSTAT and LEGOS on greenhouse gases partial pressures at the atmosphere/ocean interface layers put forward on ESA site. Read : "Increasing the effective resolution of not well-resolved Essential Ocean Variables".

- IFCAM (Indo-French Center for Applied Mathematics) project accepted: "Generalization for land cover classification" by Dharmendra Singh and Nicolas Brodu.

6. New Software and Platforms

6.1. Fluex

KEYWORDS: Signal - Signal processing
SCIENTIFIC DESCRIPTION: Fluex is a package consisting of the Microcanonical Multiscale Formalism for 1D, 2D 3D and 3D+t general signals.
FUNCTIONAL DESCRIPTION: Fluex is a C++ library developed under Gforge. Fluex is a library in nonlinear signal processing. Fluex is able to analyze turbulent and natural complex signals, Fluex is able to determine low level features in these signals that cannot be determined using standard linear techniques.

- Participants: Hussein Yahia and Rémi Paties
- Contact: Hussein Yahia
- URL: http://fluex.gforge.inria.fr/

6.2. FluidExponents

KEYWORDS: Signal processing - Wavelets - Fractal - Spectral method - Complexity
FUNCTIONAL DESCRIPTION: FluidExponents is a signal processing software dedicated to the analysis of complex signals displaying multiscale properties. It analyzes complex natural signals by use of nonlinear methods. It implements the multifractal formalism and allows various kinds of signal decomposition and reconstruction. One key aspect of the software lies in its ability to evaluate key concepts such as the degree of impredictability around a point in a signal, and provides different kinds of applications. The software can be used for times series or multidimensional signals.

- Participants: Antonio Turiel and Hussein Yahia
- Contact: Hussein Yahia
- URL: svn+ssh://fluidexponents@scm.gforge.inria.fr/svn/fluidexponents/FluidExponents

6.3. classifemo

KEYWORDS: Classification - Audio
FUNCTIONAL DESCRIPTION: Classifies vocal audio signals. Classifemo extracts characteristics from vocal audio signals. These characteristics are extracted from signals of different type: initially these were emotion databases, but it can also process signals recorded from patients with motor speach disorders. The software can train usual classifiers (SVM, random forests, etc) on these databases as well as classify new signals.

- Participants: Khalid Daoudi and Nicolas Brodu
- Contact: Khalid Daoudi
- URL: https://allgo.inria.fr/app/emotionclassifierprototype

6.4. superres

Super-Resolution of multi-spectral and multi-resolution images
KEYWORD: Multiscale
SCIENTIFIC DESCRIPTION: This resolution enhancement method is designed for multispectral and multiresolution images, such as these provided by the Sentinel-2 satellites (but not only). Starting from the highest resolution bands, band-dependent information (reflectance) is separated from information that is common to all bands (geometry of scene elements). This model is then applied to unmix low-resolution bands, preserving their reflectance, while propagating band-independent information to preserve the sub-pixel details.

FUNCTIONAL DESCRIPTION: This super-resolution software for multi-spectral images consists of: - A core C++ library, which can be used directly - A Python module interface to this library - A Java JNI interface to the library - An end-user Python script for super-resolving Sentinel-2 images - An end-user plugin for the widely used SNAP software of the ESA.

- Participant: Nicolas Brodu
- Contact: Nicolas Brodu
- URL: http://nicolas.brodu.net/recherche/superres/index.html

6.5. EdgeReconstruct

Edge Reconstruction With UPM Manifold
KEYWORDS: 2D - Fractal - Signal processing
FUNCTIONAL DESCRIPTION: EdgeReconstruct is a software that reconstructs a complex signal from the computation of most unpredictible points in the framework of the Microcanonical Multifractal Formalism. The quality of the reconstruction is also evaluated. The software is a companion of a paper published in 2013: https://hal.inria.fr/hal-00924137.

- Contact: Suman Kumar Maji
- URL: https://geostat.bordeaux.inria.fr/index.php/downloads.html

6.6. ProximalDenoising

KEYWORDS: 2D - Image filter - Filtering - Minimizing overall energy - Noise - Signal processing - Image reconstruction - Image processing
SCIENTIFIC DESCRIPTION: Image filtering is contemplated in the form of a sparse minimization problem in a non-convex setting. Given an input image I, one seeks to compute a denoised output image u such that u is close to I in the L2 norm. To do so, a minimization term is added which favors sparse gradients for output image u. Imposing sparse gradients lead to a non-convex minimization term: for instance a pseudo-norm Lp with $0 < p < 1$ or a Cauchy or Welsh function. Half-quadratic algorithm is used by adding a new variable in the minimization functionnal which leads to two sub-problems, the first sub-problem is non-convex and solved by use of proximal operators. The second sub-problem can be written in variational form, and is best solved in Fourier space: it takes the form of a deconvolution operator whose kernel can be approximated by a finite sum of separable filters. This solution method produces excellent computation times even on big images.
FUNCTIONAL DESCRIPTION: Use of proximal and non quadratic minimization. GPU implementation.

RELEASE FUNCTIONAL DESCRIPTION: This software implements H. Badri PhD thesis results.

- Authors: Marie Martin, Chiheb Sakka, Hussein Yahia, Nicolas Brodu, Gabriel Augusto Zebadua Garcia and Khalid Daoudi
- Partner: Innovative Imaging Solutions I2S
- Contact: Hussein Yahia
- URL: https://gitlab.inria.fr/marmarti/i2s_geostat_C

7. New Results

7.1. Excitable systems

Participants: G. Attuel, E. Gerasimova-Chechkina, F. Argoul, H. Yahia, A. Arnéodo.

In a companion paper (I. Multifractal analysis of clinical data), we used a wavelet-based multiscale analysis to reveal and quantify the multifractal intermittent nature of the cardiac impulse energy in the low frequency range (2 Hz during atrial fibrillation (AF). It demarcated two distinct areas within the coronary sinus (CS) with regionally stable multifractal spectra likely corresponding to different anatomical substrates. The electrical activity also showed no sign of the kind of temporal correlations typical of cascading processes across scales, thereby indicating that the multifractal scaling is carried by variations in the large amplitude oscillations of the recorded bipolar electric potential. In the present study, to account for these observations, we explore the role of the kinetics of gap junction channels (GJCs), in dynamically creating a new kind of imbalance between depolarizing and repolarizing currents. We propose a one-dimensional (1D) spatial model of a denervated myocardium, where the coupling of cardiac cells fails to synchronize the network of cardiac cells because of abnormal transjunctional capacitive charging of GJCs. We show that this non-ohmic nonlinear conduction 1D modeling accounts quantitatively well for the "multifractal white noise" dynamics of the electrical activity experimentally recorded in the left atrial posterior wall area. We further demonstrate that the multifractal properties of the numerical impulse energy are robust to changes in the model parameters.

Publication: Frontiers in Physiology (in review forum).

7.2. Multiscale description in terms of multiplicative cascade, application to Earth observation signals

Participants: I. Hernandez-Carrasco, V. Garçon, J. Sudre, C. Garbe, H. Yahia.

A new methodology has been developed in order to improve the description of the spatial and temporal variability of not well-resolved oceanic variables from other well-observed high-resolution oceanic variables. The method is based on the cross-scale inference of information, incorporating the common features of different multifractal high-resolution variables into a coarser one. An exercise of validation of the methodology has been performed based on the outputs of coupled physical-biogeochemical Regional Ocean Modeling System adapted to the eastern boundary upwelling systems at two spatial resolutions. Once the algorithm has been proved to be effective in increasing the spatial resolution of modeled partial pressure of CO_2 at the surface ocean (pCO_2), we have investigated the capability of our methodology when it is applied to remote sensing data, focusing on the improvement of the temporal description. In this regard, we have inferred daily pCO_2 maps at high resolution (4 kms) fusing monthly pCO_2 data at low resolution (100 kms) with the small-scale features contained in daily high-resolution maps of satellite sea surface temperature and Chlorophyll-a. The algorithm has been applied to the South Eastern Atlantic Ocean opening the possibility to obtain an accurate quantification of the CO_2 fluxes in relevant coastal regions, such as the eastern boundary upwelling systems. Outputs of our algorithm have been compared with in situ measurements, showing that daily maps inferred from monthly products are in average 6 μatm closer to the in situ values than the original coarser monthly maps. Furthermore, values of pCO_2 have been improved in points close to the coast with respect to the original input data.

Publication: IEEE Transactions on Geoscience and Remote Sensing, HAL.

7.3. Multiscale description in terms of multiplicative cascade, application to Earth observation signals

Participants: H. Yahia, V. Garçon, J. Sudre, C. Maes.

We evidence and study the differences in turbulence statistics in ocean dynamics carried by wind forcing at the air-sea interface. Surface currents at the air-sea interaction are of crucial importance because they transport heat from low to high latitudes. At first order, oceanic currents are generated by the balance of the Coriolis and pressure gradient forces (geostrophic current) and the balance of the Coriolis and the frictional forces dominated by wind stress (Ekman current) in the surface ocean layers. The study was conducted by computing statistical moments on the shapes of spectra computed within the framework of microcanonical multi-fractal formalism. Remotely sensed daily datasets derived from one year of altimetry and wind data were used in this study, allowing for the computation of two kinds of vector fields: geostrophy with and geostrophy without wind stress forcing. We explore the statistical properties of singularity spectra computed from velocity norms and vorticity data, notably in relation with kurtosis information to underline the differences in the turbulent regimes associated with both kinds of velocity fields.

Publication: Frontiers of Information Technology & Electronic Engineering , Springer, 2018, 19 (8), HAL.

7.4. Multiscale description in terms of multiplicative cascade, application to Earth observation signals

Participants: A. El Aouni, K. Daoudi, H. Yahia, K. Minaoui.

We study coherent vortex detection from particles trajectories analysis and surface mixing and biological activity in the north african upwelling.

Publications: SIAM Conference on Nonlinear Waves and Coherent Structures HAL and AGU Ocean Sciences Meeting 2018 HAL.

7.5. Data-based identification of characteristic scales and automated modeling

Participants: N. Brodu, G. S. Phartiyal, D. Singh, H. Yahia.

Low-rankness transfer for denoising Sentinel-1 SAR images. Published in the 9th International Symposium on Signal, Image, Video and Communications ISIVC, Rabat, 2018, HAL.

A mixed spectral and spatial Convolutional Neural Network for Land Cover Classification using SAR and Optical data. Published in EGU General Assembly, Vienna, 2018, HAL.

Inferrence of causal states from time series for empirical modeling at prescribed scales. The goal of this research is to recover physical systems internal states from data and build a model of their evolution. Clustering together data with the same causal effets leads to consistent internal states: each measured data inferred to match the same state has by definition the same consequence, hence the same functional role. The theory behind this is well established, with major steps in the 80's by Jim Crutchfield. This leads to computational mechanics and epsilon-machines in the discrete case. The theory has however always suffers from computationability issues and it is very hard to apply in practice on large systems and real data. N. Brodu has made (unpublished) progress in 2018 in this theory, showing links between epsilon-machines and stochastic processes in the continuous case. The goal is to form a new class of algorithms drawing on the continuous representation, which would not suffer from the explicit discretization steps needed by current algorithms. N. Brodu has initiated a collaboration with Jim Crutchfield in 2017 and hope to further enhance that collaboration in 2019. This plan was presented to the reviewers during the team evaluation and deemed to be of high priority.

7.6. Speech analysis

Participants: G. Li, K. Daoudi, J. Klempir, J. Rusz, B. Das.

In the early stage of disease, the symptoms of Parkinson's disease (PD) are similar to atypical Parkinsonian sydromes (APS). The early differential diagnosis between PD and APS is thus a very challenging task. It turns out that speech disorder is an early and common symptom to PD and APS. The goal of reserach is to develop a digital marker based on speech analysis in order to assist the neurologists in their diagnosis.

Publication: IEEE-ICASSP - 2018 IEEE International Conference on Acoustics, Speech and Signal Processing, Apr 2018, HAL.

7.7. InnovationLab with I2S, sparse signals & optimisation

Participants: M. Martin, A. Zebadua, S. Sakka, N. Brodu, K. Daoudi, A. Cherif [I2S], J. L. Vallancogne [I2S], A. Cailly [I2S].

During 2018 A. Zebadua was involved for the first time in the use of non-convex optimization methods and proximal operators, to solve inverse problems in image processing. Within the framework of the joint project with i2s, his main task was to work together with the research engineers to understand, implement, adapt and reduce the execution time of the algorithms developed by H. Badri in his doctoral thesis. These algorithms were developed in a scientific context, it was, therefore, necessary to adapt them to an industrial context with practical constraints.

S. Sakka has been implementating of the demosaicing algorithm to reconstruct a full-color image from raw images acquired by scanning. Colors are generated by a mask of Bayer. This algorithm uses the Hamilton Method and the Edge aware smoothing algorithm. He has been performing benchmarks for performance and quality test, and has written the technical report about the demosaicing algorithm. S. Sakka has been implementing iterative algorithms for linear system resolution useful for inpaitnig image processing algorithm.

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C. Sakka has been participating in the GPU Technology Conference organized by Nvidia in Munich and attending the NVIDIA Deep Learning School, and A. Zebadua has been participating to the winter school itwist18 in optimization from November 19th to 20th in Marseille.

M. Martin studied and made comparison between two methods : EAS (Edge Aware Smoothing) algorithm and LRT (low rank transfer) for denoising. She has been writing technical report to choose with I2S the best method : more efficient, less time. M. Martin has also been implementing denoising in C++ with librairy opencv and gpu. She has been setting up code sharing with I2S on gitlab Inria

8. Bilateral Contracts and Grants with Industry

8.1. Bilateral Contracts with Industry

Preparation of the InnovationLab with I2S company, official starting scheduled after 1st 2019 COPIL in January 2019.

9. Partnerships and Cooperations

9.1. National Initiatives

- ANR project *Voice4PD-MSA*, led by K. Daoudi, which targets the differential diagnosis between Parkinson's disease and Multiple System Atrophy. The total amount of the grant is 468555 euros, from which GeoStat has 203078 euros. The duration of the project is 42 months. Partners: CHU Bordeaux (Bordeaux), CHU Toulouse, IRIT, IMT (Toulouse).
- PhD grant for G. Singh from IIT Roorkee, under co-supervision with D. Singh (IIT Roorkee).
- The PHC-Toubkal project "Caractérisation multi-capteurs et suivi spatio-temporel de l'Upwelling sur la côte atlantique marocaine par imagerie satellitaire", led by K. Daoudi, is in its second year. The partners in this project are: Faculté des sciences de Rabat, Centre Royal de Télédetection Spatiale, Mercator-Ocean and GEOSTAT.
- GEOSTAT is a member of ISIS (Information, Image & Vision) and AMF (Multifractal Analysis) GDRs.

- GEOSTAT is participating in the CNRS IMECO project *Intermittence multi-échelles de champs océaniques : analyse comparative d'images satellitaires et de sorties de modèles numériques*. CNRS call AO INSU 2018. PI: F. Schmitt, DR CNRS, UMR LOG 8187. Duration: 2 years.

9.2. European Initiatives

9.2.1. Collaborations in European Programs, Except FP7 & H2020

GENESIS Program: supported by Deutsche Forschungsgemeinde (DFG) and the Agence national de recherche (ANR). *GENeration and Evolution of Structures in the ISm.* Duration: start 1.5. 2017, 3 years. Coordinator: N. Schneider (I. Physik, Cologne). Other partners: Cologne (R. Simon, N. Schneider, V. Ossenkopf, M. Roellig), LAB (S. Bontemps, A. Roy, L. Bonne, F. Herpin, J. Braine, N. Brouillet, T. Jacq), ATN Canberra (Australia), LERMA Paris (France), MPIfR Bonn (Germany), CEA Saclay (France), ITA/ZAH Heidelberg (Germany), Institute of Astronomy, Cardiff (UK), ESO (Germany, Chile), CfA Harvard (USA), IPAG Grenoble (France), Argelander Institut Bonn (Germany), CASS San Diego (USA), University of Sofia (Bulgaria). Web site: link.

9.3. International Initiatives

9.3.1. Inria International Partners

9.3.1.1. IFCAM: Generalization for land cover identification. Geostat and the Indo-French Centre For Applied Mathematics

Land cover classification from satellite imagery is an important application for agriculture, environmental monitoring, tracking changes foremergency, etc. The typical methodology is to train a machine learning algorithm to recognize specified classes (urban, forest, fields, etc...) over regions of interest and classify new images when they become available. Yet, the generalization ability of such systems often not accounts for spatial consistency. High scores are obtained on the reference points, but nearby points of the same class are incorrectly classified. Local context, pixels around the selected one, may help in recovering that spatial consistency and increase the recognition rate. This may also induce spurious patterns and overfit the learning algorithm, which is especially the case for with Convolutional Networks trained on limited number of data. This proposal investigates how to use local context and how to best sample the data in order to provide the best generalization ability. Data will be sampled on reference locations and used for training and validation.

PIs: N. Brodu (Geostat) and D. Singh (IIT Roorkee).

Duration: 3 years. Starting 2018.

9.4. International Research Visitors

9.4.1. Visits of International Scientists

- S. Bogning Dongue [CNRS, from Dec 2018]
- K. Minaoui [Rabat University, Jul 2018]

10. Dissemination

10.1. Promoting Scientific Activities

10.1.1. Scientific Events Selection

10.1.1.1. Chair of Conference Program Committees

- K. Daoudi is Special Session Chair for the The 9th International Symposium on Signal, Image, Video and Communications ISIVC 2018, link.

- H. Yahia is Publication Chair for the The 9th International Symposium on Signal, Image, Video and Communications ISIVC 2018, link.

10.1.2. Journal

10.1.2.1. Member of the Editorial Boards

- H. Yahia is Review Editor for the journal Fronteirs in Physiology (Fractal Physiology).
- H. Yahia is Guest Editor of Springer Nature, Special Issue on Marine Information Technology, Volume 19, Issue 8, August 2018.

10.1.3. Invited Talks

- Seminars: K. Daoudi gave a seminar in July 2018 at FORTH in Greece. Title: "Speech-based differential diagnosis of Parkinsonism".

10.1.4. Scientific Expertise

- H. Yahia has been expert for the CNRS Momentum call.

10.2. Popularization

- C. Sakka, A. Zebadua, N. Brodu and H. Yahia have been participating in the demonstration made by I2s company during the Celebration of the 10 years of the center and presenting results of the demosaicing method applied to digital images.

10.2.1. Interventions

- GEOSTAT has been participating to the 10 years Inria celebration, in the form of a demonstration with I2S company.

11. Bibliography

Major publications by the team in recent years

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