
NoSAG21 Summer School and Conference
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# SUMMER SCHOOL PROGRAM

## Course 1: Mathematics of Deep Neural Networks: A First Introduction

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**Abstract**
This will be an introductive course to the mathematical foundation of Deep Neural Networks. One lecture will be devoted to the mathematical foundation of blockchain.

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## Course 2: Time-frequency perspectives

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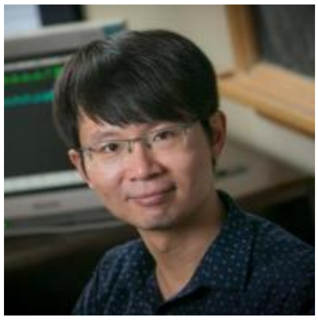
**Abstract**
Considering a number of issues related to different types of nonstationarities, time-frequency analysis will be introduced as a natural paradigm, and the main classical methods that have been developed since half a century for their analysis will be recalled. It will be discussed how time-frequency frameworks permit to address specific problems such as testing for nonstationarity, localizing chirps in the time-frequency plane, or disentangling multicomponent nonstationary signals. Some focus will be given to recent advances in spectrogram geometry, paving the way to filtering and denoising methods based on extremal points. Two typical examples that are naturally amenable to time-frequency approaches, namely gravitational waves and bat sonar, will be discussed in some detail, and a historical and epistemological perspective of the field will be provided.

## Course 3: Modern time series analysis via time-frequency analysis and complex analysis



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**Abstract**

Explosive advances in sensor technologies lead to explosive datasets being available in many fields, particularly the bio-medical field. Multimodal heterogeneous types of signals pile on an extra layer of difficulties on the data analysis mission. We focus on the high frequency time series in this lecture, and study its underlying intricate nature. We will introduce various signal processing techniques based on time-frequency (TF) analysis and complex analysis for the sake of extracting relevant information for practical usage. Theoretical and statistical analysis of the introduced techniques will be discussed based on real examples. Topics to cover include but not exclusively 1. synchrosqueezing transform; 2. de-shape short time Fourier transform; 3. Blaschke decomposition; 4. phase extraction; 5. statistical inference; 6. clinical applications. If time permits, how to combine these tools with differential geometry will be introduced. I will assume basic knowledge of Fourier analysis, complex analysis and probability.

# CONFERENCE PROGRAM

# Two novel Iterative Filtering algorithms

Giovanni Barbarino [1]

(1) Aalto University

The Empirical Mode Decomposition (EMD) was proposed as a decomposition method for non-stationary signals, but the presence of a number of heuristic and ad hoc elements makes it hard to perform a rigorous mathematical analysis.
The Iterative Filtering (IF) algorithm follows the same ideas of the EMD, computing the moving average through an iterated convolutional filtering on the signal, with the aim of singling out specific non-stationary components, usually identified by their instantaneous frequencies.
The rigid structure of IF lets us design a fast way to implement the Algorithm, and has been subjected to a rigorous analysis.
At the same time, the structure limits its scope of usage to signals presenting strictly separated and slowly changing frequencies; therefore, it has been relaxed in the Adaptive Local IF (ALIF) that widely expands the pool of possible applications, but at same time it loses most of IF's mathematical background and its fast implementation.
To compensate for the lacking background on the ALIF method, we introduce two new algorithms for which such analysis is possible.
The first, called Stable ALIF method, is always convergent, even in presence of noise, but it presents an increased computational cost with respect to ALIF.
The second, called Resampled IF method, is actually a modification of the fast IF algorithm, that preserves its convergence property, its fast implementation, and at the same time it sports flexibility properties similar to the ones of ALIF.

# Treatment of non-stationary noise signals for the detection and characterization of extrasolar planets

Aldo Stefano Bonomo [1]

(1) INAF - Osservatorio Astrofisico di Torino

One of the most common methods to detect and characterize extrasolar planets is the Doppler (or radial-velocity) method. It is based on the fact that a star is forced to orbit around the center of mass of the system by the gravitational perturbation of one or more hosted planets: the star periodically approaches and recedes from us. This wobble of the host star can be revealed through the variation of the stellar velocity along the line of sight (radial velocity) thanks to the Doppler effect. However, radial-velocity measurements can be affected by correlated noise associated with non-stationary variations due to stellar magnetic activity phenomena. Such variations may have amplitudes much higher than that of the searched planetary signals and are often modeled using Gaussian Process regression in Bayesian frameworks. I will describe the high efficiency but also the drawbacks of Gaussian Process techniques for the modeling of planetary signals in radial-velocity time series, and show that new/alternative approaches should also be explored.

# Turbulence in Space Plasma

Vincenzo Carbone [1]

(1) Università degli Studi dell'Aquila

Many decades of spacecraft flights convinced us that fluctuations of magnetic and velocity fields in space plasma at frequencies less than, say 0.1 - 1 Hz, can be interpreted, with a good approximation, in the framework of MHD turbulence. On the contrary, high-frequency fluctuations still represent a challenge for theoretical models. At these scales some kinetic plasma processes, as nonlinear wave-wave interactions, wave-particle couplings and collisionless dissipation are at work at the same time and scales. All the above phenomena have been roughly individually identified in spacecraft measurements, but contradictory interpretations can be found in literature.

# Mathematical innovations for advancement of super-resolved light microscopy and health assessment of endocrine glands in medicine

*Charles K. Chui* [1]

(1) Stanford University

The objective of this paper is to introduce and develop an innovative mathematical theory, along with effective methods and efficient computational schemes, for blind-source separation of composite modes (in terms of unknown linear combinations) of probability density function (pdf) components, with arbitrary parameters (such as shapes, scales and/or variances) but with distinct centers in the space domain Rd for any d  1 or distinct time-onsets in the time domain R. For applications to the spatial domain, we consider the "big data" problem of determining the number and locations of the point-masses, each of which is represented by some unknown rotation of some Gaussian pdf component with arbitrarily small and perhaps different values of the variance in the Cartesian coordinate orientation, and of recovering the rotation matrix of each (non-rotational invariant) Gaussian pdf component, by using discrete samples of the blind-source composite mode. The goal is to getting around the "resolution barrier" of Abbe/Rayleigh for the advancement of super-resolved light microscopy
in Bio-medicine. For applications to the time domain, we consider gamma pdf components of the composite mode, with arbitrary values of shape and scale parameters, but distinct time-onsets. The goal is to introduce a non-invasive tele-medicine tool for assessing the health of our endocrine glands by monitoring the initial force of hormone secretion, the amount of secreted hormone, and the time lag for the second secretion (or perhaps the third and fourth ones) from the same endocrine grand, again all from discrete time samples of the blind-source composite mode. This important information can be estimated by using values of the shape parameter, the scale parameter, and time-onsets, respectively, for each secretion.

# Complexity in the Earth's High-Latitude Ionosphere: the Field-Aligned Currents Filamentary Structure

Giuseppe Consolini [1]

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The dynamics of the ionospheric plasma in the polar regions of the Earth's ionosphere is very complex, displaying turbulent features, as well as, the formation of multiscale plasma structures. In this framework, the dynamics and the structure of the Field-Aligned Currents (FACs), which flow from the Earth's magnetosphere to the high-latitude ionosphere, plays a peculiar role in understanding several phenomena occurring in polar regions, such as, the ionospheric heating and the energy deposition during geomagnetic substorms and storms. In this brief talk, some recent results of the fluctuations of the magnetic and electric fields, as well as, of electron density in the high-latitude ionosphere where FACs flow, are presented and discussed. In particular, the multi scale character of these fluctuations are discussed in connection with the filamentary structure of the FACs.

# The minimal-norm RKHS solution of a system of first-kind integral equations in applied Geophysics

Patricia Diaz de Alba [1]

(1) Gran Sasso Science Institute

Electromagnetic induction techniques are often used to investigate the presence of conductive substances in the subsoil by non-destructive techniques. The main measuring device is the Ground Conductivity Meter (GCM) which is composed of two coils, a transmitter and a receiver. In this work we develop a numerical method for approximating the solution of a linear integral model which describes the interaction between the soil and the device in a reproducing kernel Hilbert space (RKHS). The model is typical of frequency domain electromagnetic induction (FDEM) methods in applied geophysics. The original problem is reformulated into a new one whose solution has the same smoothness properties of the original one. Then, the minimal-norm solution of such a model is computed through a numerical method that combines Riesz's theory with regularization tools. Numerical tests show the effectiveness of the proposed approach.

# Spectral and intermittency properties of kinetic plasma turbulence in the near-Sun and near-Earth solar wind

Luca Franci [1,2], Emanuele Papini [3,2], Alice Giroul [1], David Burgess [1], Petr Hellinger 4

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(2) INAF, Osservatorio Astrofisico di Arcetri, Firenze, Italy
(3) Dipartimento di Fisica e Astronomia, Università degli studi di Firenze, Sesto Fiorentino, Italy
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Spacecraft measurements by heliospheric missions provide evidence of a turbulent energy cascade in the solar wind. Plasma turbulence transfers energy via nonlinear couplings over a very extended range of scales, from large fluid ones down to those characteristic of the ions and the electrons, where it is eventually dissipated. Although different mechanisms can lead to energy dissipation in collisionless plasmas, there is no firm evidence or consensus on which is/are the most effective in the solar wind.
I will present results from high-resolution numerical simulations of plasma turbulence under different conditions, typical of both the near-Sun and the near-Earth environment. The spectral properties of the magnetic, density, and ion bulk velocity fluctuations are analysed and found to be in remarkable agreement with those observed by ongoing NASA missions. The intermittency properties and their evolution with the distance from the Sun are investigated by computing the probability distribution functions of the magnetic fluctuations and their scale-dependent kurtosis. A local intermittency measure analysis, performed by scanning the simulation box with a "virtual spacecraft", allows us to detect the location and properties of coherent intermittent structures, in order to infer their role in the plasma dynamics at kinetic scales. Our numerical results provide insightful information on both the physics at play and the strengths and limitations of this multiscale analysis technique.

# Time-frequency analysis: a tool for both signals and systems

Lorenzo Galleani [1]

(1) Politecnico di Torino

Time-frequency analysis reveals the inner structure of nonstationary signals, a structure often hidden in the separate domains of time and frequency. But signals are generated by systems, therefore, can time-frequency analysis be applied directly to systems, to reveal the mechanisms behind the generation of nonstationary signals? We show that this is indeed the case by discussing the time-frequency representation of a series of systems governed by differential equations.

# Multivariate Fast Iterative Filtering and Intrinsic Mode Functions for Time Delay Estimation Applied to Motion Estimation for Synthetic Aperture Sonar Imagery

Julia Gazagnaire [1], Pierre-Philippe Beaujean [2]

(1) Naval Surface Warfare Center
(2) Florida Atlantic University

Synthetic Aperture Sonar (SAS) provides the best opportunity for side-looking sonar mounted on unmanned underwater vehicles to achieve high-resolution images of underwater objects. However, SAS processing requires maintaining a coherent phase history over the entire synthetic aperture, driving strict constraints on resolvable platform motion. This has compelled the development of motion estimation and compensation techniques that use the received ping data, in addition to the onboard navigation solution, to resolve ping-to-ping platform motion. The most common approach is to use the redundant phase center (RPC) technique. Here the ping interval is set, such that a portion of the sonar array overlaps as the sensor moves forward. The time delay between the pings received on these overlapping elements is estimated using cross-correlation. These time delays are then used to infer the ping-to-ping vehicle motion. The accuracy of the motion estimation and compensation depends on the accuracy of this time delay estimation. Given the stochastic nature of the operational environment, some level of decorrelation between these two signals is likely, even with minimal residual platform motion. Furthermore, as the operational range of the sonar increases in relatively shallow waters, it is even more likely that multipath, reverberation and changes in the sound speed will corrupt and de-correlate the two signals. This could result in an inaccurate time delay estimation and cause image quality degradation.
In this research, two iterative signal decomposition methods suited for non-linear and non-stationary signals, are investigated for their potential to improve the time delay estimation. Huang et al [1] introduced the first algorithm of this kind, the Empirical Mode Decomposition (EMD). This method iteratively decomposes a signal into a finite sequence of simple components termed intrinsic mode functions (IMFs). The EMD algorithm considers the signal at the level of its local oscillations and the assumption is that the signal is composed of fast oscillations superimposed onto progressively slower oscillations. The Iterative Filter (IF) approach, developed by Lin, Wang and Zhou [2], builds on the EMD framework. It was able to address some shortcomings of the EMD algorithm, namely stability issues in the IMF generation and lack of a tractable mathematical formulation to ensure convergence.

The sonar signals considered in this research are complex baseband signals. Both the IF and EMD algorithms were designed to decompose real signals. However, the IF variant, the Multivariate Fast Iterative Filtering (MFIF) Algorithm [3] and the EMD variant, the Fast and Adaptive Multivariate Empirical Mode Decomposition (FA-MVEMD) algorithm [4], preserve both the magnitude and phase in the decomposition and hence were chosen for this analysis. As part of this research, the use of IMFs to improve the accuracy of the time delay estimates between overlapping RPC elements is investigated. The time delay estimation performances for simulated sonar signals, over a wide range of SNR are presented. The performance results are compared to the baseline, in which the time delay is estimated using the original non-decomposed signals. At a very low SNR, -15dB, knowing the theoretical value of the time delay, the results show a decrease in time delay estimation error of about 47 percent when using the MFIF to decompose the signals in pre-processing, as compared with the baseline estimation error. A decrease of 15 percent is observed relative to the baseline error when the FA-MVEMD is used to decompose the signals prior to the correlation.

Bibliography

[1] Huang, N. E., Shen, Z., Long, S. R., Wu, M.C., Shih, H. H., Zheng, Q., Yen, N. C., Tung, C. C., and Liu, H. H., "The empirical mode decomposition and the Hilbert spectrum for nonlinear and non-stationary time series analysis." Proceedings of the Royal Society of London. Series A: Mathematical, Physical and Engineering Sciences, 454(1971):903, 1998.

[2] Lin, L., Wang, Y., and Zho, H., "Iterative Filtering as an alternative algorithm for Empirical decomposition." Advances in Adaptive Data Analysis, 1(4): 543-560, 2009.

[3] Cicone, A., "Multivariate Fast Iterative Filtering for the decomposition of nonstationary signals." arXiv:1902.04860v1 [math.NA], 13 Feb. 2019.

[4] M. R. Thirumalaisamy, P. J. Ansell, "Fast and Adaptive Empirical Mode Decomposition for Multi-dimensional, Multivariate Signals", IEEE Signal Processing Letters, Vol. 25, No. 10, 2018.

# A Direct Time-frequency Method for Component Recovery of Multi-component Non-stationary Signals

Qingtang Jiang [1]

(1) University of Missouri-St. Louis

Recently a direct time-frequency method to recover a component of a multi-component non-stationary signal is proposed by Chui and Mhaskar. More precisely, a component is recovered by simply plugging the corresponding ridge of the signal separation operator (SSO), a variant of the short-time Fourier transform, to SSO. In this talk, firstly, we will show how this approach results in a more accurate component recovery formula when a linear chirp local approximation is applied. Secondly, we will discuss how the SSO approach leads to our most recently developed time-scale-chirp_rate (TSC_R) method to separate multi-component signals even with crossover instantaneous frequency curves. Our TSC_R maps a signal into a 3-dimensional space of time, scale and chirp-rate, as opposed to the traditional 2-dimensional space of time and scale. Demonstrative examples will also be presented.

# A Direct Time-frequency Method for Component Recovery of Multi-component Non-stationary Signals

Philippe Barbe [1], Antonio Cicone [2], Wing Suet Li [3], Haomin Zhou [3]

(1) LDC and CNRS, France (on leave)
(2) Università degli Studi dell'Aquila
(3) Georgia Institute of Technology

Iterative filtering methods were introduced around 2010 to improve definitions and measurements of structural features in signal processing. Like many applied techniques, they present considerable challenges for mathematicians to theorize their effectiveness and limitations in commercial and scientific usages. In this talk we recast iterative filtering methods in a mathematical abstraction more conducive to their understanding and applications. We also introduce a new visualization of simultaneous local frequencies and amplitudes. By combining a theoretical and practical exposition, we hope to stimulate efforts to understand better these methods. Our approach acknowledges the influence of Ciprian Foias, who was passionate about pure, applied, and applications of mathematics.

# Learning Interaction laws in particle- and agent-based systems

Mauro Maggioni [1]

(1) Johns Hopkins University

Interacting agent-based systems are ubiquitous in science, from modeling of particles in Physics to prey-predator and colony models in Biology, to opinion dynamics in economics and social sciences. Oftentimes the laws of interactions between the agents are quite simple, for example they depend only on pairwise interactions, and only on pairwise distance in each interaction. We consider the following inference problem for a system of interacting particles or agents: given only observed trajectories of the agents in the system, can we learn what the laws of interactions are? We would like to do this without assuming any particular form for the interaction laws, i.e. they might be "any" function of pairwise distances. We consider this problem both the mean-field limit (i.e. the number of particles going to infinity) and in the case of a finite number of agents, with an increasing number of observations, albeit in this talk we will mostly focus on the latter case. We cast this as an inverse problem, and study it in the case where the interaction is governed by an (unknown) function of pairwise distances. We discuss when this problem is well-posed, and we construct estimators for the interaction kernels with provably good statistically and computational properties. We measure their performance on various examples, that include extensions to agent systems with different types of agents, second-order systems, and families of systems with parametric interaction kernels. We also conduct numerical experiments to test the large time behavior of these systems, especially in the cases where they exhibit emergent behavior. This is joint work with F. Lu, J.Miller, S. Tang and M. Zhong.

# Space Weather, the question is not smooth: dealing with local roughness in Geospace dynamics

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(1) Istituto dei Sistemi Complessi del Consiglio Nazionale delle Ricerche (CNR-ISC)

Keywords: multi-scale statistical analysis, local fractal properties, time-scale analysis

*Clouds are not spheres, mountains are not cones, coastlines are not circles, and bark is not smooth, nor does lightning travel in a straight line. (B. Mandelbrot)*

The physics of plasma, that collects the laws ruling the Space Weather, is generally understood, and written, in terms of dynamical variables regarded as $C^\infty$ functions of space and time coordinates, i.e. the electric and magnetic fields, and the densities of the different chemical species I = 1, ..., N, both neutral and charged. Those $C^\infty$ variables undergo classical, celebrated equations of motion, as *Maxwell Equations* for $\boldsymbol{E}(\boldsymbol{x}, t)$ and $\boldsymbol{B}(\boldsymbol{x}, t)$, several *coupled Navier-Stokes-like fluid equation* for the velocity $\boldsymbol{v}_I(\boldsymbol{x}, t)$ of chemicals, and *continuity, or more general balance equations* for the chemical densities $\rho_I(\boldsymbol{x}, t)$. Such regular partial differential equations with integer order operators produce alsmost-everywhere smooth solutions, starting with smooth initial and boundary conditions. Yet, Nature provides us with geospatial time series in which the local variability of physical quantities rather shows an appearance that is rough, non-stationary, multi-scale structured and erratic. *In situ* data collected by satellites do look intrinsically noisy sequences, not to mention trans-ionospheric radio signals disturbed by plasma turbulence (scintillation). Of course, this fact does not invalidate the sacred equations mentioned for the fields ($\boldsymbol{E}$, $\boldsymbol{B}$, $\boldsymbol{v}_I$, $\rho_I$), but instead convince us that we are using smooth functions improperly: the space-time functions ($\boldsymbol{E}$, $\boldsymbol{B}$, $\boldsymbol{v}_I$, $\rho_I$) describing the local ionospheric state, indeed, are not the fundamental, microscopic dynamical variables of a deterministic system, but the collective outcome of what particles and groups of particles forming the plasma give rise to. What is wrong, then, is forgetting that ($\boldsymbol{E}$, $\boldsymbol{B}$, $\boldsymbol{v}_I$, $\rho_I$) are not properties of an otherwise empty space, but rather partial aspects of the emergent properties of the granular matter forming the plasma. In this presentation a short, necessarily partial and personal review will be given about both the theoretical ideas and the data analysis techniques trying to take into account the intrinsic local roughness of geospace quantities.

# Probing spacetime multiscale properties of plasma turbulence at sub-ion scales with Iterative Filtering

Emanuele Papini [1,5], Mirko Piersanti [2], Antonio Cicone [3,2], Luca Franci [4,5], Simone Landi [1,5]

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Turbulence in space and astrophysical plasmas is an intrinsic multiscale phenomenon, which involves nonlinear coupling across different temporal and spatial scales. As a result, the physical mechanisms responsible for the turbulent dissipation and the heating of the plasma below the proton characteristic scales remain largely unknown. In this work, we will present recent results from a statistical multiscale study of numerical simulations of plasma turbulence, performed employing Iterative Filtering (IF), a technique designed for the analysis of nonstationary nonlinear multidimensional signals. A spatial multidimensional IF decomposition reveals that turbulence at sub-proton scales is highly intermittent, formed by localized magnetic structures and/or perturbations organized in a filamented network where dissipation is enhanced. A further spatiotemporal analysis, performed by combining IF with Fourier methods, shows that such perturbations (with temporal frequencies smaller or comparable to the ion-cyclotron frequency) cannot be described in terms of wavelike interactions. Signatures of both whistler and kinetic Alfvén waves at high frequencies are also observed. However, their energetic contribution to the magnetic power spectrum is negligible. Implications of these results in the context of solar wind turbulence, together with potential applications of IF to spacecraft observations, will be discussed.

# An Inquiry into the Structure and Dynamics of Crude Oil Price Using the Fast Iterative Filtering Algorithm

Giovanni Piersanti [1]

(1) Università di Teramo

The identification of the temporal scales related to market activities is crucial for understanding the dynamics of international crude oil prices. Standard analysis techniques fail in producing consistently good results due to the non-linear behaviour of the oil market. To deal with this issue, an innovative approach based on the concurring application of a new non-linear data analysis method, Fast Iterative Filtering (FIF), and a multi-scale statistical analysis (Standardized Mean Test) is proposed. This approach proves to be able to separate automatically crude oil price data into three components: a long term trend, an intermediate or middle period behaviour, and a transitory or short-run behaviour. The economic meaning of each component is clearly identified as: high frequency variations, caused by normal supply-demand disequilibrium; medium term fluctuations, driven by geopolitical, financial, and technological shocks; a low frequency trend reflecting the global business cycle. All these results make the proposed approach a more performing tool for analysing oil price data structure and dynamics. Such a method, if coupled with different prediction techniques (e.g., ARIMA, ARCH, etc., or ANN, SVM, etc.), can potentially show higher performance than existing hybrid models in forecasting crude oil prices.

# Introduction to Infrared Thermography: A short review on the main "image processing" currently used

Stefano Sfarra [1]

(1) Università degli Studi dell'Aquila

General Principles of Infrared Thermography are presented in this seminar including passive and active approaches as well as the main image processing currently used in the research field. Along the presentation, various applications will be presented to the audience.

# Nonstationary and inhomogeneous signals visualized by 4DVD: Examples based on the 20th Century Reanalysis climate model

Sam Shen [1]

(1) San Diego State University

This presentation is a demonstration of the 4-Dimensional Visual Delivery (4DVD) technology www.4dvd.org, which is a software system designed to visually deliver big climate data at an extremely fast speed. The system visualizes and delivers netCDF climate data in a 4-dimensional space-time domain. It allows users to quickly visualize the data before making a download for further analysis. Users can use zoom in-and-out or other graphics options to help identify desired climate dynamics patterns. Data can eventually be downloaded for a spatial map of a given time and a historical climate time series of a given location after the map and time series are identified to be useful. In this way, the 4DVD software enables a user to quickly reach the core interested climate features without downloading the entire dataset in advance. This not only saves time and storage space, but also helps quickly explore the climate dynamics from observed data or climate model output. The fast speed of the 4DVD software system is achieved through optimally harnessing the technologies of distributed computing, database, and storage. We will use NOAA's 20$^{th}$ Century Reanalysis model data as examples to show the fields of temperature, U-wind, V-wind, pressure, relative humidity, precipitation rate, and more. These examples will demonstrate how to use 4DVD as an efficient tool for research, teaching, learning, and public outreach.

# Recent results and future challenges in ionospheric research addressed with modern signal processing techniques

Luca Spogli [1]

(1) Istituto Nazionale di Geofisica e Vulcanologia

Ionosphere is a dynamical system that shows a complex behaviour due to its non-linear coupling with the solar wind-magnetosphere system from above and with the lower atmosphere from below. Despite the climatological behaviour of the ionosphere is well understood and often ruled-out by first-principles equation, the aforementioned complexity manifests itself on a largely varying range of spatial and temporal scales. This makes the ionospheric modelling still challenging for the community, especially for its storm-time behaviour, short-to-medium-term predictability and effects on systems, like Global Navigation Satellite Systems (GNSS). The monitoring capability from ground and in-situ instruments grew fast in the recent years and provides a large variety of measurements and data concerning the physical properties of the ionospheric medium. Such precious amount of data, when properly investigate with modern processing technique for non-linear non-stationary signal, allows investigating scaling properties by means of the statistical momenta of each spatio/temporal scale at which the signal is studied. Moreover, resonant modes in ionospheric and related geophysical signals identified through signal processing techniques, like the recently introduced Iterative Filtering, allows speculating on the cause-effect mechanisms by investigating the lags and mutual interaction among the modes. This contribution is willing to review some recent results matured thanks to application of the Iterative Filtering technique and aims at highlighting future steps to improve the understanding and modelling capabilities of the ionosphere scale-dependent behaviour and of coupling with the other "spheres".

# Time-frequency filtering and time-frequency fading

Bruno Torresani [1]

(1) Aix-Marseille Université

Time-frequency filtering is routinely used in many signal processing applications, including among others the domains of audio, biomedical and geophysical signal processing. The standard practice is extend the usual linear time invariant filter to a given time-frequency domain, and therefore perform a pointwise multiplication of the time-frequency transform with a suitable transfer function, prior to resynthesis. The design of the transfer function is a key ingredient and is often ad hoc (the most common choices are binary or Wiener-type transfer functions), and is limited by time-frequency uncertainty principles.
In this talk we will review this problem from the point of view of time-frequency frame theory and shortly discuss the problem of time-frequency operator approximation. We will also introduce the "time-frequency fading" problem, namely the problem of constructing a time-frequency filter that optimally attenuates a prescribed time-frequency region (with a prescribed gain), and present applications to audio filtering. This part is a joint work with M. Krémé, C. Chaux and V. Emiya.

# Understanding causation via correlations and linear response theory

Angelo Vulpiani [1]

(1) Università di Roma "La Sapienza"

In spite of the (correct) common-wisdom statement correlation does not imply causation, a proper employ of time correlations and of fluctuation-response theory allows to understand the causal relations between the variables of a multi-dimensional linear Markov process. It is shown that the fluctuation-response formalism can be used both to find the direct causal links between the variables of a system and to introduce a degree of causation, cumulative in time, whose physical interpretation is straightforward. Although for generic non-linear dynamics there is no simple exact relationship between correlations and response functions, the described protocol can still give a useful proxy also in presence of weak nonlinear terms.

# A fast EEMD algorithm and decomposition quality criteria for paleo-climate signal analysis

Sébastien Wouters [1]

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We present a novel algorithm for Ensemble Empirical Mode Decomposition (EEMD) that splices the different noise-added realisations of a signal using even-odd extension, making it computationally more efficient than simply iterating the Empirical Mode Decomposition (EMD). Furthermore, the noise added is computed to cancel out perfectly, reducing the size of the ensemble to be performed, and making the resulting decomposition more representative of the initial signal. This algorithm is available in the R package DecomposeR (https://CRAN.R-project.org/package=DecomposeR), under the name 'extricate'. We propose a new methodology to further document the quality of any decomposition based on different concepts that we introduce: - Integrity quantifies to what extent the sum of the components is equal to the signal. It is defined as the averaged difference between (1) the signal, and (2) the summed components of the decomposition. EMD fulfils integrity by design, except for errors caused by floating-point arithmetic. Ensemble Empirical Mode Decomposition (EEMD) may fail to satisfy integrity unless noisy realisations are carefully chosen to cancel each other when averaging the realisations, which is performed in our 'extricate 'algorithm. - Parsimony checks that the decomposition does not generate components that heavily cancel each other out. We propose to quantify it as the ratio between (1) the cumulated absolute values of each component (except the trend), and (2) the cumulated absolute values of the signal (minus the trend). The trend should be ignored in the calculation, because an added trend decreases the parsimony estimation of a similar decomposition. - IMF departure (IMFD) quantifies the departure of each component to the definition of intrinsic mode functions (IMF), from which instantaneous frequency can reliably be computed. We define it as the exponential of the mean of the absolute differences of the logarithms of frequencies obtained using (1) a robust generalized zero-crossing method and (2) a more local method such as the Hilbert Transform. - Reversibility is the concept that all initial data points are preserved, even after linear interpolation of irregularly sampled data points. This allows to revert back to the original signal and discuss the significance of each data point. To facilitate reversibility we introduced the concept of quanta (smallest significative resampling interval) and an algorithm computing the highest common rational divisor of given values in R: 'divisor'. These concepts can be used to check any decomposition independently of how it was performed (i.e. a posteriori). Once the above-mentioned concepts are taken into account, the instantaneous frequencies, ratios of frequencies and amplitudes of the components can be computed and used

to understand signals. These concepts are particularly useful to process highly complex signals such as deep-time paleoclimatic ones, which can be affected by high levels of red noise, frequency modulation, and overprinting of parasitic signals, and are usually sampled irregularly. We further present a new theoretical concept: exchanging intensity between different components of a first prototype of decomposition, to further refine it. This would enable changing the characteristics of components, without compromising the integrity of a decomposition. We present this as an alternative to sifting, reducing the presence of riding wave without necessarily smoothing the amplitude modulation of components. This is useful in signals when amplitude modulation is of critical importance.

# Spectral Analysis of a Time Series: from Additive Perspective to Multiplicative Perspective

Zhaohua Wu [1]

(1) Florida State University

The study of trigonometric functions traces back to Hellenistic mathematicians such as Pythagoras, Euclid, and Archimedes. Many fundamental methods of analysis use trigonometric functions to describe and understand cyclical phenomena. It was Fourier in the early decades of the 19th century who pioneered the additive usage of trigonometric functions and first expressed various types of functions in terms of the sum of constant-amplitude constant-frequency trigonometric functions of different periods, now called the Fourier Transform. Unfortunately, Fourier's sum does not express nonlinear interactions between trigonometric components of different periods in its natural multiplicative way; leaving the spectral quantifications of nonlinear interactions in any dynamical system non-intuitive. In the last two decades, a multiplicative perspective of using trigonometric functions in quantifying nonlinear interaction in any time series was developed, pioneered by N. E. Huang's Empirical Mode Decomposition methodology. The most recent development in this line of research is a multi-dimensional spectral representation of a time series, which is termed here as the Huang Spectrum. Huang Spectral Analysis explicitly identifies the interactions among time-varying amplitude and frequency oscillatory components of different periods of a time series and quantifies nonlinear interactions explicitly. This paper introduces the intuitions and physical rationales behind the Huang Spectrum and Huang Spectral Analysis. Various synthetic and climatic time series with known time series characteristics are used to demonstrate the power of Huang Spectral Analysis.

# A Recurrent Neural Network and Differential Equation based Spatiotemporal Infectious Disease Model with Application to COVID-19

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The outbreaks of COVID-19 have impacted the world significantly. Modeling the trend of infection and real-time forecasting of cases can help decision making and control of the disease spread. However, data-driven methods such as recurrent neural networks (RNN) can perform poorly due to limited daily samples in time. We develop an integrated spatiotemporal model based on the epidemic system of differential equations and RNN. The former after simplification and discretization is a compact model of temporal infection trend of a region while the latter models the effect of nearest neighboring regions. The latter captures latent spatial information. We trained and tested our model on COVID-19 data in Italy and USA, and show that it outperforms existing temporal models (fully connected NN, ARIMA) in 1-day, 3-day, and 1-week ahead forecasting especially in the regime of limited training data. We also present a hybrid spatiotemporal regression and RNN framework for vector-borne disease prediction based on leishmaniasis data in Sri Lanka.

# Multiresolution Mode Decomposition: from Time-Frequency Analysis to Deep Learning

Haizhao Yang [1]

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This talk introduces the multiresolution mode decomposition (MMD) as a novel model for adaptive time series analysis. The main conceptual innovation is the

$$[\sum_{n=-N/2}^{N/2-1} a_n \cos(2\pi n\phi(t)) s_{cn}(2\pi N\phi(t)) + \sum_{n=-N/2}^{N/2-1} b_n \sin(2\pi n\phi(t)) s_{sn}(2\pi N\phi(t))]$$

introduction of the multiresolution intrinsic mode function (MIMF) of the form

to model nonlinear and non-stationary data with time-dependent amplitudes, frequencies, and waveforms. The multiresolution expansion coefficients $a_n$, $b_n$, and the shape function series $s_{cn}(t)$ and $s_{sn}(t)$ provide innovative features for adaptive time series analysis. For complex signals that are a superposition of several MIMFs with well-differentiated phase functions $\phi(t)$, two new approaches based on time-frequency analysis and deep learning are proposed to identify these MIMFs, their multiresolution expansion coefficients, and shape function series.

# IF2CNN: Towards non-stationary time series feature extraction by integrating iterative filtering and CNNs

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Time series is a common data type that appears in various fields. However, time series processing is still considered one of the most challenging problems in data mining because of its unique properties, such as noise and non-stationarity. In an effort to overcome these limitations, we present a framework, called IF2CNN, that integrates the iterative filtering (IF) method and convolutional neural networks (CNNs) for automatic feature learning for time series. First, IF is leveraged to decompose the raw non-stationary time series into intrinsic mode functions (IMFs), which are then converted into image format data. Second, CNN is designed to automatically learn features from the image format data, which can help to extract deep and global features of the time series. Besides, the use of IF and CNN technologies makes the proposed framework not only have the advantage of dealing with the non-stationarity of the time series, but also provides a good generalization ability for small training datasets. To evaluate the performance of IF2CNN, two different strategies are used to test the role of the derived features of CNN (called CNN features). The first strategy computes the feature importance through the methods based on decision trees, such as gradient boosting decision trees and random forest, and the other one tests the validity of the derived features by performing specific prediction tasks. Furthermore, three real datasets from different fields are used in our experiments. The results show that the CNN features have an overwhelming advantage in feature importance and significant improvements in prediction tasks.

# Equivariant Neural Network in Computer Vision and Scientific Computing

Wei Zhu [1]

(1) Duke University

Encoding symmetry information explicitly into the representation learned by a convolutional neural network (CNN) is beneficial for many computer vision and scientific computing tasks. I will present, in this talk, a scaling-translation-equivariant (ST-equivariant) CNN with joint convolutions across the space and the scaling group, which is shown to be both sufficient and necessary to achieve equivariance for the regular representation of the scaling-translation group ST . To reduce the model complexity and computational burden, we decompose the convolutional filters under two pre-fixed separable bases and truncate the expansion to low-frequency components. A further benefit of the truncated filter expansion is the improved deformation robustness of the equivariant representation, a property which is theoretically analyzed and empirically verified. Numerical experiments demonstrate that the proposed scaling-translation-equivariant network with decomposed convolutional filters (ScDCFNet) achieves significantly improved performance in multiscale image classification and better interpretability than regular CNNs at a reduced model size. Time permitting, I will also highlight the potential of equivariant neural networks in scientific computing by respecting conservation and symmetry constraint in physical models.

# POSTER SESSION

# Seismic Tomography of Southern Tyrrhenian by means of teleseismic data

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The topic of my work is a seismic tomography which has as object the investigation of Southern Tyrrhenian. This tomography was obtained by means of inversion of teleseismic data and an iterative computation of them to obtain the so-called residual that is the difference between the observed travel times and these theoretical travel times. The final tridimensional velocity model corresponds to that having the minimum residual. The entire process of operation of a seismic tomography is very relevant in order to investigate subduction zones. This is the case of the Southern Tyrrhenian oceanic back-arc basin. The subducting lithosphere has been mostly consumed along the Tyrrhenian-Apennine system has been consumed with the exception of the Calabrian arc sector. The Ionian subduction is documented by several previous works, included local seismic tomographies that have discovered the presence of high seismic velocity body beneath the Calabrian zone. The new seismic tomography, which derived from the inversion of travel times of teleseismic ray paths, travelling in the upper mantle at high depths. This kind of inversion could provide a good resolution to depth of 500-600 km, whereas previous local tomographies of Southern Tyrrhenian show results to depth of 250-300 km. The adopted database consists of 1929 teleseisms recorded in period 1990-2012 by 122 southern Italian seismic station directly connected to ISC (International Seismological Centre). The software FMTT was employed for the inversion of these arrival times. I have implemented a grid of 0-500 km in depth, 7°E-20°E in longitude and 35°-48° in latitude, with a grid spacing of 50 km in depth, 0.8 degrees in longitude and 0.4 degrees in latitude. Consequently, grid nodes are 10 in depth, 17 in longitude and 28 in latitude. I have implemented six iterations of this code, stopping it when there are not more significant changes in RMS and in variance of theoretical traveltimes. I have made 10 horizontal sections of final model from 50 km of depth to 500 km of depth, with an interval of 50 km of depth from each other. I have made 8 vertical sections, 4 NS vertical sections at fixed longitude respectively of 14°, 15°, 15.5° and 16° and 4 WE vertical sections at fixed latitude respectively of 39°, 39.5°, 40° and 40.5°. Finally, I have made 3 transversal sections, choosing as traces the same illustrated by Montuori et al. [1], for their teleseismic tomography of Southern Tyrrhenian. This work, together with contributions of Chiarabba et al. [2] and Calò et al. [3] is a fundamental landmark for the comparison of the results. Summarising, the horizontal sections show an evolution of the high velocity body that represents the Ionian slab. It is visible both at depth of 50 km and at depth of

100 km, beneath the Calabrian arc and extends to northern Sicily beneath the Aeolian arc with a maximum of 0.6-0.8 km/s. At depth of 250 km, the tomography evidences a sort of “transition” due to the absence of the Southern Tyrrhenian HVA and the occurrence of a low velocity region with maximum of -0.5 km/s scattered between the Aeolian Islands and Calabria. In the depth interval from 250 km to 400 km, there are two impressive high velocity areas in northern Sicily and along southern Campania with a value of 0.3 km/s, separated by a low velocity area (LVA) along the Calabrian arc and the Aeolian Islands in the range [0.4 ; 0.6] km/s. Extensions of HVAs and LVAs previously mentioned have been estimated by means of vertical and transversal sections. This evidence could be interpreted as the effect of a three-dimensional circulation of astenospheric flow provoked by slab roll-back. A new evidence from the tomography is the presence of a LVA in the [250 ; 400] km depth interval with an extension of 100-150 km that practically splits the Tyrrhenian slab into two parts, in Neapolitan region and in the southern Calabria-northern Sicily region. This evidence is partially in agreement with Chiarabba [2], that in in his work showed the presence of a “window slab” with an extension of 150 km, in a depth interval included between 100 and 300 km of depth. The presence of this “window slab” could be interpreted as a tear in which unperturbed mantle insert itself.

Bibliography

[1] C. Montuori et al, 2007 – Teleseismic tomography of the Southern Tyrrhenian subduction zone: new results from seafloor and land recordings – Journal of Geophysical Research – Vol. 112, No.B03311 doi: 10.1029/2005JB004114.

[2] C. Chiarabba et al, 2008 – The southern Tyrrhenian subduction zone: deep geometry, magmatism and Plio-Pleistocene evolution – Earth and Planetary Science Letters – Vol. 268, pp. 408-423 doi: 10.1016/j.epsl.2008.01.036.

[3] M. Calò et al, 2012 – Seismic velocity structures of southern Italy from tomographic imaging of Ionian slab and petrological inferences – Geophysical Journal International – Vol.191, No.2, pp. 751-764 DOI 10.1111/j.1365-246X.2012.05647.x.

# An EEMD-based denoising strategy for force measurements in water entry experiments

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The EEMD (Ensemble Empirical Mode Decomposition) is employed in order to reduce the background noise in non-stationary signals. The signals represent the forces measured during water impact tests of scaled fuselage models, mimicking the emergency water landing of aircraft (ditching). The tests are carried out in the main towing tank of the CNR-INM (Institute of Marine Engineering, Rome), where the fuselage models are towed at a horizontal speed of U=12 m/s, and the vertical trajectory is computer-controlled and realized by means of two linear servo-actuators. The vertical velocity at impact is V=0.45 m/s, reproducing the approach angle of an actual aircraft at ditching.
The measured data are characterized by a large amplitude broadband noise, which is associated with the vibrations of the carriage structure and with the interaction of the measuring system with the electro-magnetic fields generated by the carriage motors and their control systems.
The EEMD noise reduction method is based on a partial reconstruction of the non-stationary signal, which includes the residue, the signal-dominant modes and some noise-dominant modes. The latter modes are also processed using a thresholding procedure, which reduces the residual background noise and preserves the sharp features of the signal (pulses, ramps, peaks etc.).
The strategy is first developed and tested on a synthetic signal with a superimposed and known background noise and is then applied to some experimental signals. The latter signals are the forces measured during the vertical descent of the scaled fuselage in air, which accounts only for the inertial force, easily estimated from theory as a reference. Secondly, the actual water-entry tests are considered, which also include the hydrodynamics forces acting on the fuselage models during the water entry. These force contributions are of primary interest from a physical point of view and have to be distinguished from the background noise for a correct interpretation of the results. Thanks to its capabilities in keeping the sharp features of the signals while reducing the spurious oscillations, for the specific applications the EEMD denoising strategy has been found much superior to classical filtering methods, such as moving average filters and a low-pass FIR filters.