Project proposal: Factas (Functional Analysis for ConcepTion and Assessment of Systems)

1 Team members

The composition of the team is similar to the one of Apics:

Permanent members:

Laurent Baratchart (DR Inria);
Sylvain Chevillard (CR Inria);
Juliette Leblond (DR Inria);
Martine Olivi (CR Inria);
Fabien Seyfert (CR Inria, scientific leader).

Post-docs:

Vanna Lisa Coli (UCA$^{\text{Jedi}}$, ToMaT; joint supervision with CEPAM and Morpheme).

PhD Students:

Gibin Bose (Labex UCN@Sophia, ED STIC UCA; joint supervision with LEAT);
Sébastien Fueyo (UCA, ED SFA; joint supervision with McTao);
David Martínez Martínez (DGA-CNES, ED Xlim Limoges; joint supervision with Xlim);
Konstantinos Mavreas (MESR, ED STIC UCA).

Team assistant:

Marie-Line Meirinho (AI Inria).

2 Introduction: from Apics to Factas

This is a scientific proposal to create the Inria team Factas, by members of the former team Apics (reaching the end of its life cycle). Building on the positive appraisal of Apics by Inria's evaluation panel in 2018, the permanent staff members have decided to stay together as a team and present a new project updating the scientific objectives they pursued in the past few years.

The mathematical body of knowledge shared by the team members involves functional and harmonic analysis along with related fields like approximation theory, potential theory, Schur analysis or system and circuit theory. Our approach is to couple these theoretical tools with constructive optimisation techniques, and to demonstrate the efficiency of such a combination in selected application areas. The latter mainly comprise microwave electronics, notably the synthesis and tuning of circuital communication devices, as well as inverse problems in quasi-static electromagnetism, with applications to paleomagnetism in planetary sciences and imaging issues in electro- and magneto-encephalography (EEG and MEG for short) for functional and medical neurosciences. We try to balance theoretical and applied work without sacrificing any, a transverse positioning made possible by the complementary skills within the team, ranging from mathematical analysis to algorithm design and numerical optimisation, software design as well as some knowledge in microwave electronics, brain imaging and magnetometry. In all cases, the overall objective is to produce prototypical software tools for the user, dedicated to the application at hand.

The upcoming period will see a renewal of problems in the targeted application areas, mostly driven by technical evolution. For example, in microwave electronics, an emerging topic is the design of stability assessment techniques for active devices, such as amplifiers and oscillators. Their non-linearity and non-stationarity raise questions different from those encountered with passive systems. This forges new research directions involving some spectral theory of dynamical systems, and operator-valued approximation in the complex domain. Such questions already give rise to collaborations by members of FACTAS with the Inria team McTAO (Sophia Antipolis) and the team Elec at VUB (Brussels University). As another example, antennas is to us a new, timely subject of study for which we feel in position to develop design and tuning procedures. Indeed, for reasons of power efficiency, the co-conception of the pair filter-antenna is becoming increasingly important in order to approach impedance matching problems and thereby maximise the radiated power. Now, solving such matching problems in a near optimal manner *via* Schur analysis seems a realistic **mid-term objective** for the team. Moreover, the case of antenna arrays, which is still quite open, raises questions similar to those encountered in simultaneous matching problems for multiplexers, and is likely to be amenable to the same techniques. In this connection, obtaining a circuital model to describe the radiating phenomena characterising a given antenna, is a **long term objective** of FACTAS. The goal is to develop a complete circuit-based design and tuning procedure for antennas and their matching circuits, including the adjustment of the radiating diagram of such devices. Today, for reasons of complexity, the latter is usually handled separately from the circuital matching problem, whereas both questions are intimately connected. As regards more mature topics, like microwave filter tuning procedure, new challenges also arise when envisaging fully automated robot-tuning procedures. This poses new algorithmic problems, since tools at hand today were merely designed to assist engineers but not to stand in their place. Such problems will be tackled in collaboration with partners from LEAT (Antenna and Telecommunication Lab, UCA and CNRS, Sophia Antipolis), KTH (Stockholm) and the filter team MACAO at Xlim (Limoges University). Our industrial collaborations have relied until now on software transfer (RARL2, Presto-HF, Dedale-HF) to Thales Alenia Space, Flextronics, LGS-Innovation, as well as to the French SMB Inoveos with which we consider working on fully automated solutions. The FACTAS team aims at pursuing this transfer policy to foster dissemination of its ideas, techniques and algorithms among industrials stakeholders.

We now turn to inverse problemss. Our interest in inverse potential problems was initially motivated by the remark that, in 2-D, the derivative of a discrete potential is a rational function. Hence, a typical inverse potential problem in 2-D is to recover a rational function from values it takes on the boundary of the domain of analyticity. This example is basic to system identification from frequency data, and stresses a unifying link between our investigations on electronic circuits, paleomagnetism and biomedical imaging.

As regards paleomagnetism, an application field of fairly recent vintage to APICS that FACTAS means to pursue, the goal is to analyse magnetic properties of meteorites or planetary rock samples in order to shed light on the formation and history of the solar system, as well as on mechanisms underlying the Geodynamo that protects us from solar winds. In this connection, the development of extremely sensitive, superconducting scanning microscopes (SQUID) allows one to measure very weak fields, which is needed for such an endeavour, while new, optical sensors (QDM) are already coming into existence. These are developed, in particular, by our partners at the Department of Earth, Atmospheric and Planetary Sciences (EAPS) at MIT (Cambridge, MA, USA). Besides, the ANR-project "MagLune" coordinated by CEREGE-CNRS (Aix-en-Provence, France), which we are taking part in, is about designing a dedicated magnetometer to quickly estimate the magnetic moment of a great many samples of moon rocks, brought to Earth by NASA missions. Hence, it is fair to say that research in the area is driven by the technological development of new sensors. The techniques to address magnetisation recovery much depend on the geometry of the sample and of the measurement place. For instance, in the context of the MagLune project, one deals with volumic sources and measurements on a sphere, which draws a parallel with reconstruction techniques used in EEG, to be mentioned later on. Dwelling on this analogy, a **short term objective** is here to provide a software implementation of our method, suited for this particular application where the geometry differs only slightly from the EEG context. In contrast, our collaboration with the EAPS department at MIT and the department of mathematics at Vanderbilt University (Nashville, TN, USA) mainly focused, so far, on planar sample and measurements area. In this case, we introduced a Hardy-Hodge decomposition of vector fields to describe the nature of silent sources (*i.e.*, magnetisation producing no field) and derived techniques to evaluate the net moment of a sample. However, these turn out to be fairly sensitive to the noise of the sensor (in particular electronic drift), which affects their performance. A **short-term objective** will be to offset this adverse effect and obtain a software tool that could be transferred to MIT. As to recovery proper, we recently introduced notions of sparsity in this infinite-dimensional context, which seem promising to identify unidirectional or thinly supported magnetizations by regularising the total variation of the magnetisation. Another **short-term objective** is to implement and test them. In the longer term, our partners will get more and more interested in volumic (*e.g.*, parallelepipedic) samples, which raise new theoretical questions regarding silent sources. These will be considered on a **mid-to long-term scale**. Finally, let us mention that such techniques could also apply to global issues of current interest to geophysicists, like separating the crustal and core contributions in the Earth's magnetic field. This is the subject of ongoing collaboration with TU Freiberg (Germany). Moreover, the mathematical framework, consisting of Hardy spaces of harmonic gradients, is intimately connected with modal decomposition techniques we plan to use for the circuital modelling of antennas mentioned before.

A third application field concerns physiological imaging, more precisely the localisation of sources of electric activity in the brain from partial knowledge of the electric (EEG) or magnetic (MEG) field on the surface of the scalp. While EEG imaging has been considered by team members for some time, in collaboration with the ATHENA project team (Inria, Sophia Antipolis), MEG imaging is fresh to us. In recent years, our activity in this area has undergone new developments on which FACTAS will dwell. For instance, it is now possible to simultaneously record EEG and MEG signals, and a **mid-term challenge** is to couple them into a single recovery technique. As another example, correlating at different time instants the geometric information obtained from static localisation techniques should help detecting regions in the brain that get activated simultaneously. This **short to mid-term issue** is of interest in functional exploration. A natural home for such developments will be the software FindSources3D (FS3D) that we plan to transfer to the medical community, in particular our partners at INS (Aix-Marseille University, La Timone hospital). Yet another different goal in the **longer term** is to estimate conductivities, in order to better account for inhomogeneities. This is a weak version of the famous Calderón problem (weak because conductivities are assumed piecewise constant), but even then it is unclear how the knowledge of the Dirichlet-to-Neumann operator can yield the desired information in a constructive manner.

3 Technical positioning and objectives

3.1 Harmonic analysis and design of microwave devices

Summary

We describe below one of the two main areas investigated by the team, namely the

design and identification of microwave devices using harmonic analysis, complex approximation and circuital realisation techniques. We explain why matching problem in microwave electronics are naturally linked to analytic approximation problems in hyperbolic geometry and therefore can be tackled via Schur analysis. This accounts for the first short to mid-term objective of the team, namely the development of design procedures for matching circuits, to be cascaded with mismatched antennas or used to derive matching filters in the context of multiplexer design. Such a design, when considered on a large frequency bandwidth, is subject to dispersive effects that need to be taken into account during the realisation phase of previously computed optimal responses. The derivation of circuital realisation techniques involving frequency-dependent electromagnetic couplings, as opposed to narrow-band circuit for which coupling are considered frequency-independent, is another mid-term objective of ours. Yet another mid-to long term objective of the team is the consideration of design problems involving amplifiers, oscillators and antennas. This goes far beyond the application scope initially targeted by APICS, because such devices are active and generate new problems from the analytic viewpoint. In particular, assessing the stability of amplifiers from frequency data obtained by the recently developed harmonic-balance technique raises non-classical spectral-theoretic questions after linearisation of their non-linear dynamics, either around a functioning point or a periodic trajectory (in the so-called strong signal case). Whereas the nature of the singularities of the linearized transfer function around a point is now well understood, describing the singularities of the harmonic tranfer function (a periodic function valued in analytic functions) occurring in the case of a periodic trajectory is much of an open issue. It amounts to relate the spectrum of the monodromy of certain periodic delay-differential systems with the singularities of the Fourier coefficients of the multiplier asymptotically describing the system in the frequency domain. In this connection, the design of effective approximation techniques to locate these singularities (at least a subset thereof lying in a specified region of the complex plane), from simulations of the device in the frequency domain, is here our main, long-term objective. Finally, the study of scattering matrices for antennas in the time-harmonic regime, especially the nature of their singularities and the connection to the geometry of the antenna, is also on FACTAS's list. Identifying such matrices from measurements performed in an anechoic chamber, which involves analyzing functional expansions in spherical harmonics, is a long time objective that may be viewed as a generalization of harmonic transfer function identification in a 2-D (that is: spherical rather than circular) setting.

Introduction

The area of design and tuning of microwave communication devices, for which we developed skills within our team, has undergone a properly extraordinary expansion over the last twenty years under the impetus of terrestrial and space wireless communication development. The main driving forces here are the generalisation of the 4G standard, the upcoming 5G standard, the launching of *low-cost* low orbits constellations of communication satellites, and the emerging Internet of Things (IOT) which consists in connecting together a multitude of elementary communication terminals. These technological challenges call in particular for a sharp optimisation of the bandwidth occupancy of each terminal, for a complete automation of production of items that were till now manufactured singly, as well as reduced energy consumption of emitting, receiving, and amplification chains. In the same spirit as APICS, contributions by FACTAS will be concerned with the development of formalism, methods and algorithms to help fully automated, or at least computer assisted, design and tuning of such microwave components.

Hereafter, we get more specific about the technical framework. The functioning of devices we consider (filters, multiplexers, amplifiers) is ruled by Maxwell equations, that describe the wave propagation phenomenon taking place within them. Such devices are usually fed and interconnected by means of wave-guides or transmission lines in which only one mode can propagate at functioning frequencies. The free terminals of the lines constitute the input/output ports of the communication device. One can show that each port is entirely characterised by the knowledge of a modal harmonic tension which corresponds to impose the tangential electrical field at the endpoints of the line, and the knowledge of a modal harmonic current which corresponds to impose a tangential magnetic field [1, 2]. If, for example, modal tensions are imposed at all ports of the system, Maxwell equations allow us to compute all modal currents at the ports. The linear operator relating the vector of Fourier transforms of the modal tension to the one of modal currents is called the admittance matrix. The Cayley transform of the latter is the *scattering* matrix of the device, and its elements are functions of the frequency variable $s = j\omega$ that admit an analytic continuation in the right half-plane. Depending on the characteristics of the underlying system, they can be rational functions, delayed rational functionals or more general functions in a so-called Hardy space. The law of energy conservation is to the effect that the *scattering* matrix is unitary at each frequency and therefore an inner matrix: a fundamental object in Schur analysis. Therefore, one can easily figure out why the interconnection of elementary microwave circuits is intimately related to the hyperbolic geometry of the unit disk [3]. For example, ongoing work in the team on electronic matching problems recast the problem of maximizing energy efficiency in terms of minimising the hyperbolic distance to a reference behavious over a rational class of functions under Pick type interpolation constraints [4, 5].

Generally speaking, our contributions fall in two classes. The first one concerns design problems where the "best" transfer function in the sense for example of power transfer or selectivity is sought. The optimisation procedure is typically carried out over a functional class restricted by realisability constraints, passivity constraints, or topological constraints on the circuit induced by electrical considerations weighing the final implementation of the device. The second class of problems is system identification which is used by the team to design tools for diagnosis of microwave hardware from input/output frequency data, obtained through measurements or full-wave simulations. The objective here is either to extract a circuital model, whose analysis allows one to infer dimensional modifications to be made on the hardware, or else a stability/instability assessment in the case of active systems. This approach, the final aim of which is the computerised assistance or full automation of design and tuning of microwave elements, comes up at a time when cutting on the unit manufacturing cost is a priority. While realisations by Apics were mainly concerned with filters, which are elementary building blocks of every communication chain, Factas is enlarging this scope to multiplexers, antennas and the detection of instabilities in amplifiers and oscillators.

Below, we provide more details about the matching problems that we consider and specific objectives that we pursue in this area.

3.1.1 Matching problems and related Schur approximation problems

Matching problems occur when chaining a 2×2 scattering matrix S to a given load L (see Figure 1) which is not perfectly resistive. The purpose is usually to transmit as much power as possible to the load, which amounts to minimise the reflections after chaining when S is supposed to be loss-less. Matching problems classically occur when dealing with antennas, the input of which is seldom purely resistive. Indeed, when feeding the antenna with a signal, one wants to get sure that most of it is radiated to the free space and not reflected back to the input. But this is not the only situation where matching is crucial: in multiplexer design for example, each channel filter needs to be matched to the load formed by the rest of the multiplexer, namely the common wave-guide and the other channel filters. In a very general setting, matching problems occur each time two scatterers are connected together and the power transmission is important. Usually, one of these systems is designed already, and the remaining issue is to design the second one so as to obtain the best possible "match", that is, the maximum power transfer possible between the two systems. To fix ideas, let I be a compact interval of the frequency axis $\mathbb{R}$ where the transfer of energy to the load needs to be maximised. If we call G_{11} the reflection coefficient of the system obtained after closing port 2, the matching problem can be stated as:

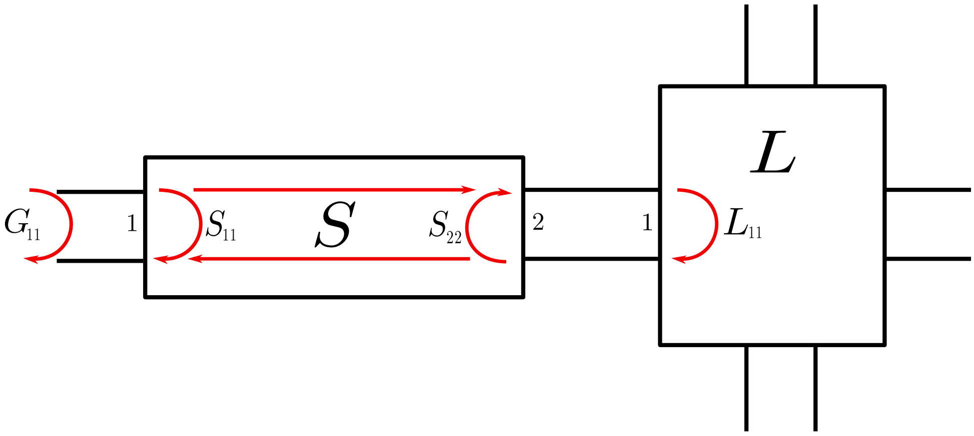


Figure 1: 2×2 scattering system plugged to a load L with reflection coefficient L_{11}

$$P_{\mathcal{H}}: \min_{S \in \mathcal{H}} \max_{\omega \in I} |G_{11}(\omega)| = \min_{S \in \mathcal{H}} \max_{\omega \in I} \left| \frac{\overline{S_{22}(\omega)} - L_{11}(\omega)}{1 - S_{22}(\omega) L_{11}(\omega)} \right| = \min_{S \in \mathcal{H}} \max_{\omega \in I} \delta(\overline{S_{22}(\omega)}, L_{11}(\omega))$$

where δ is the pseudo-hyperbolic distance, defined in the unit disk by:

$$\delta(u, v) = \frac{u - v}{1 - \overline{u} v},$$

and $\mathcal{H}$ is the class of all loss-less scattering matrices of maximal McMillan degree N. Bode, Fano and Youla [6, 7] developed in the sixties one an aesthetic approach to this problem based Darlington's 2×2 extension of the load. The latter is however quite rigid, and only allows one to compute specific types of global reflection G_{11}, like Tchebychev and Butterworth ones which are known to be far from optimal for the matching problem. Moreover this approach becomes untractable beyond very simple loads of degree one or two, and therefore was soon abandoned. It is currently replaced by heuristics in combinatorial circuital optimisation, an example of which is proposed by the company Optenni. In practice, the exponential complexity of such approaches restricts their use to relatively simple matching circuits, and offers no guarantee of optimality. We developed an interpolation-based approach to this problem [8], and more recently we introduced convex optimisation techniques on cones of functions [4, 5] in order to extend Youla's approach. This technique, which is a convex relaxation of the original problem dwelling on Nevanlinna-Pick constraints, yields lower bounds for $P_{\mathcal{H}}$ which seem to be the first ever obtained for finite degree, as opposed to those obtained by Fano, and later by Helton, for infinite dimension [3]. Bringing this approach to completion, along with a corresponding software, is a **short-term objective** of FACTAS. Using the results of this relaxation in order to initialise minimisation strategies for the original problem $P_{\mathcal{H}}$ is a **mid-term objective**, in line with a broader **mid to long-term** objective which is to solve approximation problems on an interval in the class of Schur (passive) rational functions of given maximal degree. While the cost function for matching is the pseudo hyperbolic distance, the problem can also be considered for the usual L^2 norm, and then it becomes an identification problem under passivity constraints. Solving this problem is a well-known bottleneck to characterise electronic components from their frequency measurements, as the use of the identified model in time domain simulations (for instance with Spice) requires passivity to make the computation stable. Note that, unlike approximation problems by a stable rational functions which are ill-posed on a compact frequency interval (a strict subset of the frequency interval), Schur rational approximation is well posed because the bound on the norm of the approximant regularises the approximation problem. By extending the rational Schur approximation problem to a loss-less rational matrix approximation problem, at the cost of doubling the size as in the Darlington extension process, we expect to be able to take advantage of the stratified manifold structure of loss-less rational matrices to approach the original issue algorithmically. Scalar as well as matricial versions of this question will be considered, as well as software implementation thereof. These will represent substantial extensions of the software RARL2 developed by Apics. Competitors here are all-round rational approximation engines, the best known of which today is certainly Vector Fitting. The latter, based on the interpolatory Cauchy method, has many issues. It may not converge, or converge to a function which is not even a local best approximant for the least square criterion it aims at minimising; it does not ensure stability of the approximant either, much less its passivity [9]. Moreover, for multi-ports systems, bounds on the McMillan degree of the approximant are not guaranteed, and typically require to be met some post processing imposing a dimension to the state, usually at the cost of worsening the quality of approximation. This approach rests on the paradigm that, when fed with ideal, noiseless stable passive rational data, the transfer function is perfectly recovered and that, by continuity of the criterion, the approximation error will remain acceptable in non-ideal situations. This does not reflect our practical experience, as electronic noise and undermodelling phenomena are co-substantial to most real-world identification problems, and hardly negligible. Note that the situation is paroxysmal for matching problems, as they consist in approximating unstable data ($\overline{S_{22}}$) by functions from a stable class. For all these reasons, we think our techniques might bring substantial improvement to the present state of the art solutions, and if successful will generate interest by practioners in the electronic community, as well as in mechanics where the notion of passivity is common in applications.

From the point of view of electronics, one objective is also to tackle matching problems relative to multi-port antennas, networks of antennas or multiplexers. In all these problems, several matching circuits have to be determined simultaneously at several ports of the system, while taking into account couplings effects between those ports. Such matrix matching problems are therefore strictly harder than the scalar ones, but preliminary results obtained for the synthesis of multiplexers show, using Brouwer's fixed point theorem, the existence of a "simultaneous matching point". Although this result is purely topological and by non-constructive, we are confident that important progress can be achieved in these areas by means of our techniques.

3.1.2 Broad-band circuital realisation techniques

The approaches to identification and matching problems proposed in the previous section allow us to determine the functional response of circuits to be identified or synthesised. Applications of these techniques are followed by a realisation step to obtain a circuital representation of the response, possibly subject to certain specifications. This decomposition in two steps, first a functional one and then a realisation procedure, lies at the heart of our approaches as opposed to direct circuital optimisation wich is carried out on the coordinates of elementary circuital elements. Our belief is that this functional step allows us to exploit the mathematical features of the underlying optimisation problem like convexity, manifold structure of transfer function, stability properties and soon We have therefore payed special effort to solve the realisation step for circuits made of coupled resonators with specific topologies, that are most commonly used in narrow band applications [10]. Our most salient contribution here is the software

Dedale-HF [11] based on algebraic geometry and effective computer algebra techniques, developed in collaboration with the former Inria team Salsa (now Polsys). In the coupled resonator model we seek, electromagnetic couplings are supposed independent of the frequency. The latter hypothesis is usually justified for narrow band applications like narrow pass-band filter with relative bandwidth of 1-3 %, but it is no longer valid for broader bands like those encountered in matching and in some filtering applications. A non trivial extension of our previous work is thus needed to handle dispersive couplings, both in synthesis and identification problems. This raises nontrivial issues such as identifiability of the coupling's dispersion, practical implementation of specific dispersive effects, and of course computability of circuit realisations including such effects that double the number of electrical parameters of the synthesis or identification problem under consideration. The state of the art in this direction today is to consider supernumerary spurious couplings in order to explain the discrepancy between measured data and model prediction: this leads in our opinion to misinterpretation of the phenomena at work in the identified device, which are mainly due to dispersive effects. In synthesis problems on mid or broad-band indeed, the dispersive nature of couplings needs to be considered and might also be used to the benefit of the designer as the use of resonating coupling irises to realise additional transmission zeros suggests [12]. The **mid-term objective** of the team is here to come up with a theoretical framework and a practical method to handle dispersive effects by means of the inclusion of frequency varying couplings that are usually considered constant in the coupled resonator circuits used in narrow band situations. This fundamental issue in circuit theory can be seen as an extension of Darlington's synthesis to arbitrary circuit topologies, and also comes up in other application fields like mechanics [13], where analogies between circuital elements and elementary mechanical devices raise similar realisability questions.

3.1.3 Tuning robot for filter manufacturing

Until now our methodology and tools Presto-HF [14] and Dedale-HF [11] have been transferred to various companies with the objective to assist technician and engineers during the manufacturing phase of their microwave hardware. More recently the french SMB Inoveos, after the acquisition of a license of Presto-HF [14], came to us with the project to build a prototype of an automatised tuning robot for filters tailored for the microwave industry. For the moment the company is setting up a financing strategy, involving the public investment bank BPI France: it is therefore to soon to assert that this project will really take place, at least within a bilateral collaboration with the company Inoveos. Scientifically the project raises several interesting questions we will be working on a **short to mid-term time scale**.

- While our tools permit the extraction of electrical circuit parameters from frequency measurements, a sensitivity chart is needed that relates electrical parameters to physical dimensions of the hardware. The best way to perform this calibration process in a robot driven application is completely open.

- For particular coupling topologies distinct sets of electrical parameters yield the same scattering matrix [10]. This leads to a non-univocal identification process where additional measuring strategies are necessary in order to identify the correct circuital realisation among a discrete set of equivalent circuits. Once a correct solution has been identified, a local tracking algorithm of this solution on a particular algebraic sheaf might be considered. Results and methodologies for particular electrical topologies have been obtained [15] in this direction: their implementation at the heart of a robotic application and for general classes of topologies remains a challenging topic.

- On a more prospective agenda the availability of massive tuning data sets for similar filters calls for use of AI strategies of unsupervised learning. We are not specialists of these topics, but they will be considered with care as a possible improvement of the time efficiency of our tuning solutions.

3.1.4 Stability diagnosis for microwave amplifiers

A **long-term goal** of the FACTAS team is to extend its functional methods to the analysis of other types of microwave devices than filters and multiplexers, namely antennas, amplifiers and oscillators. The last two types are active components that intrinsically entail a non-linear behaviour. This is due to the presence of transistors which exhibit saturation effects, and therefore induce input/output characteristics that are no longer proportional to the magnitude of the input signal. A central question arising in the design of amplifiers is their stability. The latter may be understood around a functioning point when no input but noise is considered, or else around a periodic trajectory when an input signal at a specified frequency is applied to the system and some noise is added. In the case of oscillators, a precise estimation of their oscillating frequency is crucial during the design process. For devices operating at relatively low frequencies, time domain simulations, based on the integration of the underlying non-linear dynamical system, answers these questions satisfactorily. However, for complex microwave amplifiers and oscillators, the situation is drastically different: the time step necessary to integrate the equations of transmission lines (which behave like a simple wire at low frequency) becomes so small that simulations are intractable in reasonable time. In addition, most linear components of such circuits are known through their frequency response, and so a preliminary, numerically unstable step is necessary to obtain their impulse response, prior to any time domain simulation.

Dwelling on the unstable/stable decomposition in Hardy Spaces, we recently developed a procedure to assess the stability or instability of the transfer function at hand, from evaluation on a finite frequency grid [16], that we further improved in [17] to address the design of oscillators, in collaboration with Smain Amari. A prototypical software library called Pisa [18] has been developed by our post-doctoral student A. Cooman to demonstrate the procedure. Since preliminary experiments are encouraging, a **mid- to long-term objective** of the team is to link together the width of the measurement band, the density of the measurement points, and the precision at which an unstable pole can be located at given distance from the imaginary axis in the complex plane. Extensions of our procedure to the strong signal case, where linearisation is considered around a periodic trajectory and produces a harmonic transfer functions (an analytic function with values in periodic functions), are also on the FACTAS list and require system theoretical developments.

Indeed, when stability is studied around a periodic trajectory, determined in practice by Harmonic Balance algorithms, linearization yields a linear time varying dynamical system with periodic coefficients and a periodic trajectory thereof. While in finite dimension the stability of such systems is well understood via the Floquet theory, this is no longer the case in this infinite dimensional setting when delays are considered. Dwelling on the theory of retarded systems, S. Fueyo's PhD work recently showed that, for circuits which are passive at very high frequency, the monodromy operator is a compact perturbation of a stable operator, and that only finitely many unstable points of its spectrum can occur. The **short term goal** is here to stress the link between this monodromy operators and the Harmonic Transfer Function of the circuit. A practical application of this result will be to generalise the previously described techniques, determining stability around a functioning point, into a stability assessment technique around periodic trajectories. This can be recast in terms of the finiteness of the number of abscissas of unstable poles of the Harmonic Transfer functions of the circuit. It would be very interesting to generalise such considerations to arbitrary circuits, whose structure is less well understood at present.

3.1.5 Circuit models for antennas

Our work on matching problems, initially devoted to multiplexer synthesis, led us to consider antennas as natural candidates for matching network techniques. In such questions the antenna is represented only by means of its reflection coefficient S_{11}: synthesising an efficient matching network results in that most of the power available at the generator is transmitted to the antenna, but no control is provided on how this power is radiated by the antenna. The radiation pattern of an antenna is usually obtained by means of heavy full wave simulations, and is usually dealt with independently from the circuital part of the antenna represented by the reflection coefficient. Still, in the course of the ANR research project Cocoram, it became clear that an efficient co-conception technique for an antenna and its matching circuits should also include a circuital model of the antenna reflecting its radiating properties, which can be co-designed simultaneously with the matching network . One way to do this is to model the antenna as a scattering system, having a feeding port and several radiating ports, each of which corresponds to a set of two spherical vector waves, traveling respectively inwards and outwards [19]. In this model the smallest sphere enclosing the antenna can be seen as the cross-section of a spherical waveguide having features similar to its cylindrical counterpart: orthogonal modes, cut-off, propagation and evanescence. In this framework the antenna admits a multidimensional scattering matrix taking into account its radiating nature, from which the global radiation pattern can be computed. A **long-term objective** of FACTAS is the derivation of circuital models that realise the full scattering matrix of an antenna, for instance as networks of resonators coupled coupled on the one hand to the feeding port of the antenna and on the other hand to radiating spherical vector modes. If more adapted, other families of radiating orthogonal modes may also be considered. The objective is here to gain insight of functioning mechanisms of the antenna, and to aid design by means of circuital analogies linking electronic parameters of the extracted circuit to some dimensional parameters of the antenna hardware. A collaboration with our colleagues from LEAT and KTH is getting started on this prospective but promising topic. A preliminary step will be to study efficient algorithms to decompose an electromagnetic field into vector spherical harmonics, is also relevant to the representation of harmonic gradients arising in inverse potential problems discussed in the next section.

3.2 Inverse potential problems

Summary

We now describe the second main area investigated by the team, namely inverse potential problems with applications to source recovery from electromagnetic measurements in the quasi-static limit. This is a timely issue, due to the readiness or coming into existence of new, extremely sensitive magnetic sensors.

Two application fields are specifically targeted: (i) biomedical imaging, especially the processing of EEG/MEG data to locate electric activity in the brain or to estimate the conductivity of tissues, (ii) Earth and planetary sciences, especially paleomagnetism where magnetization distributions of rock samples are to be reconstructed to get information on their past history, or Geomagnetism where the crustal and core fields of the Earth must be determined to understand the evolution of the Geodynamo.

We mostly consider inverse source problems associated with a Poisson-Hodge equation: $\Delta u = \operatorname{div} \mathcal{S}$, where the source term $\mathcal{S}$ is seeked from measurements of the potential u, or more commonly of the field ∇u. In some cases, a more general equation $\operatorname{div}(\sigma \nabla u) = \operatorname{div} \mathcal{S}$ must be considered, where σ is non-constant. As explained in the introduction, these are ill-posed problems that suffer non-uniqueness and

instability issues which need to be addressed, and the techniques anticipated by FACTAS to do so are the thread in what follows.

Section 3.2.1 is concerned with the problem of non-uniqueness which is connected with questions in geometric analysis (some of them related to the structure of scattering matrices for antennas discussed in Section 3.1.5). In this connection, the description of silent sources (responsible for non-uniqueness) is a short to mid term goal in standard functional settings, and a mid to long term goal when volumic sources are modeled by measures.

The next four sections discuss regularisation techniques as follows.

In Section 3.2.2, extremal problems for harmonic gradients are set forth to approach data transmission problems across nested shells, that arise when handling piecewise constant conductivities, for example in EEG. They can be seen as 3-D versions of holomorphic approximation problems mentioned in Section 3.1. Exploring this circle of ideas is a short to mid term goal with spherical models, a mid to long term goal in more complex geometric contexts.

Sections 3.2.3 and 3.2.4 present two different regularising approaches to non-uniqueness, making different extra-assumptions on the sources. The first deals with a discrete model for $\mathcal{S}$, and makes contact with rational approximation of holomorphic functions, a recurring technique also appearing in Section 3.1; investigating this research direction to treat jointly EEG and MEG data is a short to mid term goal. The second approach breaks new ground, making a measure-theoretic assumption on the support of the sources that serves as a notion of sparsity in this infinite-dimensional context. For sources lying on a surface, making use of this idea from the algorithmic viewpoint is a mid term goal. An in-depth analysis thereof for volumic sources is a long term goal.

Section 3.2.5 is concerned with weakening the inverse problem, looking for features of the source term (for instance averaged quantities like the net moment) that are uniquely defined by the potential, in which case non-uniqueness is no longer an issue. For the prototypical question of moment recovery, several kinds of estimators can be set up, depending on the range of measurements relative to the sample size and the signal to noise ratio. The case of extensive but noisy measurements is a short to mid term term goal. The case of reduced measurements involves regularisation techniques whose assesment is a mid to long term goal.

Other inverse problems of interest to the team, but endowed with relatively lower priority, are mentioned in Section 3.2.6.

Introduction

A prototypical inverse potential problems is to estimate the location and strength of a collection of sources from measurements of the field they generate. In its most basic form, the problem involves the Laplace operator. Namely, for u a solution to the Poisson-Hodge equation: $\Delta u = \operatorname{div} \mathcal{S}$, the question is to recover the source term $\mathcal{S}$ from measurements of the potential u, or often of the field ∇u, on a set Q of points in space, away from the sources. For electromagnetic potentials, such a model derives from Maxwell's equations in the quasi-static approximation, when the conductivity or permeability is constant. When the conductivity (or permeability) cannot be assumed constant, as is the case for instance in EEG inverse problems (see below), the Poisson equation generalises to its non-Euclidean analog $\operatorname{div}(\sigma\nabla u) = \operatorname{div} \mathcal{S}$ where σ is conductivity (or permeability). Since elliptic PDE quickly blur high frequencies when the distance to the sources increases, details of the latter are hard to reconstruct, which makes the problem ill-posed. Further difficulties arise from the fact that the forward operator, mapping $\mathcal{S}$ to the field ∇u restricted to the measurement place Q, may well have a non-trivial nullspace. In this case, there exist sources producing the zero field in the region of space where measurements are taken, and such sources are called silent. In the presence of silent sources, some irreducible uncertainty attaches to the recovery of $\mathcal{S}$, which has to be removed by either performing additional measurements or making extra-assumptions on the source term. Moreover, even if the nullspace reduces to zero, the range of the forward operator is usually dense but not complete in standard function spaces on Q, which entails that reconstructing ∇u from the measurements – which are incomplete in that they involve values on Q only – is not a stable process, and much less is recovering $\mathcal{S}$.

In EEG/MEG inverse problems, sources are primary currents supported on the brain, while the measurement set Q is a portion of the scalp. For EEG, the conductivity is non-constant, but may be assumed piecewise constant (the scalp, skull and brain all have different conductivities). For MEG, the permeability is often supposed to be constant. Geometrically, there are two kinds of models: 2-D source models distributed on the surface of the brain (usually assumed to point in the normal direction), and 3-D models where sources lie inside the brain. The latter aim at giving a simpler description, typically consisting of a few dipoles, that can in turn generate a 2-D model on the scalp by balayage.

For paleomagnetic inverse magnetisation problems, the source is the magnetisation and is supported on the rock sample, while measurements are typically made on a plane above the sample. Again there are two types of models: planar samples, which are really rocks sanded down to thin slabs, and volumic samples carrying a 3-D magnetisation.

All situations are subject to one or several of the three types of ill-posedness mentioned before, namely: (i) blur in high frequencies, (ii) non-triviality of the nullspace, (iii) incompleteness of the measurements. We should now mention a fourth one which is uncertainty in the measurements, most notably the drift inherent to electronic devices. Hereafter, we sketch lines of approach to circumvent these difficulties, and we sort them out according to the degree of complexity induced by the geometry and the regularisation techniques we plan to use.

3.2.1 Description of silent sources

Given some inverse potential problem, it is of basic importance to know about silent sources which is a main cause of ill-posedness (non injectivity). It is relatively easy to make regularising assumptions on the source term that rule out the possibility of silent sources: for instance we may suppose that sources in a volume are discrete, or that sources on a surface point in the normal direction. However, such assumptions may or may not be appropriate, depending on the physical context. When they are not, one faces the question of describing all possible silent sources.

For sources supported on a plane with measurements performed on a parallel plane, we did characterise silent ones in a general distributional context by introducing the so-called Hardy-Hodge decomposition [20] for vector fields. If the sample is compact such sources are divergence-free, otherwise a harmonic gradient from the side of the plane which is measured can be added. The result was extended in [21] to sources modelled by measures and supported on an open surface that needs not be planar.

One goal of FACTAS will be to obtain corresponding characterisations on closed surfaces or volumes. In the functional, say L^p, setting, this is a **short to mid-term objective**, because Hodge theory in degree 1 exists in Euclidean space and can be developed on a Lipschitz surface, while regularity theory for the Laplacian is well-developed in this context. But in the distributional framework, or even simply for measures, this is a **longer term objective** connected to deep issues in harmonic analysis, *e.g.*, the fact that the Riesz transforms of a measure are no longer measures in general.

3.2.2 Transmission of boundary data

Best constrained approximation issues in Hardy spaces is a recurring subject of research in the team, as it provides a suitable setting to regularise inverse problems of Cauchy type. Specifically, given partial Dirichlet-Neumann data on the boundary of a domain, one aims at estimating the values of the solution to Laplace equation (and of its normal derivative) on the whole boundary (which yields them on the domain itself). Though uniqueness is guaranteed when data are known on an open set of the boundary, such problems are classically ill-posed. To regularise them, we may introduce a norm constraint on that part of the boundary where no data are available (a Tychonov-like regularisation in the L^2 case).

In 2-D, such bounded extremal problems (BEP) were initially studied by APICS to identify microwave filters, and today they receive renewed interest from FACTAS in the context of impedance matching. Following progress made in [22], we shall pursue the study of BEP of mixed type on the circle, with a quadratic criterion and a uniform constraint, in the framework of the starting ANR project REPKA. A **short term objective** is to control oscillation of the solution at endpoints of the bandwidth, which is not an easy task, even for simple functions.

In space, similar problems arise in the data transmission step of EEG inverse source problems. Indeed, the conductivity can only be assumed to be piecewise constant (the skull has a lower conductivity than the brain and the scalp) and, assuming a spherical model of the head, we want to propagate the available data from the scalp to the surface of the brain by solving BEP in Hardy spaces of harmonic gradients on shell regions corresponding to the skull and the cerebrospinal fluid, see [23, 24]. This topic also comes close to the identification of transfer functions of antennas, see Section 3.1.5.

In the **longer term**, we want to address non-spherical geometries which remains a difficult issue. We also plan to study generalisations of our methods to non-constant but smooth conductivity, see [25, 26] where appropriate generalised Hardy spaces were studied in 2-D.

3.2.3 Discrete sources

The estimation of discrete source terms from available data, specifically when $\mathcal{S}$ is modelled as a linear combination of Dirac masses, is an important inverse problem, both from the theoretical and practical point of view. It appears in applications to medical imaging (EEG-MEG) and in Lunar paleomagnetism, when the primary cerebral current and the magnetisation are respectively modeled via pointwise sources. In both cases, we consider the restriction of the available data to planar cross-sections and we make use of best rational approximation to locate the 2-D singularities induced by the restriction. Those appear as multiple poles and branched singularities of the function to be approximated. For EEG data that correspond to measurements of the electrical potential, one should consider *triple* poles [23]; this will also be the case for MEG data. However, for (magnetic) field data produced by magnetic dipolar sources (linked to the PhD research of K. Mavreas and to the ANR project MagLune), one should consider poles of order five [27].

It is known that in rational approximation of given degree to an algebraic function on a contour encompassing the singularities, a positive proportion of poles of the approximants converges to the branchpoints when the degree goes large [28]. It is numerically observed that *multiple* poles only strengthen this nice behaviour (they quickly accumulate near the branched singularities), although there is no mathematical justification so far. This intriguing property, however, is definitely helping source recovery. It is used in order to automatically estimate the "most plausible" number of sources (numerically: up to 3 with current algorithms). The technique is implemented in the software FS3D (see also Section 4.4), where from planar singularities of the approximants, the 3-D sources are estimated in a final clustering step. It is also used in order to approximate the magnetic dipole location in Moon rocks, for which the clustering step is still under study.

The behaviour of best quadratic rational approximants with one multiple pole (of prescribed multiplicity) recently became the topic of further studies within the team. Assuming that the approximated function itself has a single multiple pole, we want to estimate the number and behaviour of the solutions of the corresponding critical point equation. This will be incorporated to the software RARL2 (**short-term**).

Furthermore, regarding EEG and MEG problems, renewed contacts with medical partners at INS convinced us that it is worth coupling our spatial source localisation techniques with time dependant informations, in order to resolve the ambiguity in the location of synchronous sources. Through the analysis of a singular value decomposition (SVD), involving an appropriate change of basis, this will allow one to automatically estimate the number of dipolar sources. We just began to consider the estimation of time correlated (delayed) sources, using the time component of the above factorisation. Magnetic data from MEG recently became available along with EEG data; indeed, it is now possible to use simultaneously both measurement devices, in order to measure simultaneously the electrical potential and a component of the magnetic field (its normal component on the MEG helmet, which may be assumed spherical). This should enhance the accuracy of our source recovery algorithms. Such developments will be pursued (**short- / mid-term**). In the **longer term**, we plan to generalise our results and algorithms for pointwise source recovery to non-spherical and more realistic geometries, see [29] for ellipsoidal situations. Last but not least, we consider the possibility of using gradients of discrete potentials in order to estimate pointwise sources directly in 3-D **long term**.

3.2.4 Sparse sources

For planar rock samples, which is the setup initially proposed by geophysicists at MIT, silent sources are now well understood [20], however recovery proper is still much of an open issue. Approaches based on prior discretization and l^2 regularisation or discrete Fourier techniques gave mixed results. One goal of FACTAS is to explore regularisation techniques adapted to specific assumptions of physical relevance. In particular, for planar magnetizations modelled by $\mathbb{R}^3$-valued measures, notions of sparsity and unidirectionality are proposed in [21]; more generally, the latter reference deals with magnetizations supported on so-called slender (slender means thin) sets (*i.e.*, the set has measure zero, each connected component of the complement has infinite measure). Here, sparsity is defined in measure geometric terms, requiring that the support of the magnetisation contains no arc (pure 1-unrectifiability), while unidirectionality, (or piecewise unidirectionality) is self explanatory and corresponds to some sort of sparsity directionwise. It is shown in [21] that sparse, as well as piecewise unidirectional magnetizations, can be approximately recovered for small enough noise, when the regularisation penalises the total variation of the magnetisation. This can be seen as a version of compressed sensing in an infinite-dimensional setting.

A **mid-term objective** of FACTAS is to make these results computationally effective. A **longer term objective** is to study 3-D analogs of the notion of sparsity in this context, as well as 2-D analogs on a closed surface which is relevant to EEG/MEG and geomagnetic inverse problems. We mention that unidirectionality is an assumption which makes good sense for igneous rocks from the physical viewpoint, for such rocks were formed by cooling down in an ambient field of which they keep record.

3.2.5 More general sources: estimating simpler averaged quantities

When sources are spread out, as pointed out already, it is generally impossible to recover their distribution from measurements, due to the uncertainty generated by silent sources. To stand a chance of recovering nevertheless the distribution, specific regularising assumptions can be made, like discreteness or unidirectionality as discussed in Sections 3.2.1 and 3.2.4. However, if such assumptions are not suitable (*i.e.*, if they do not produce convincing models), one may consider obtaining weaker type of information from the data.

For instance, instead of recovering the full distribution of sources, a possibility is to recover averaged quantities which depend from the field only and are not influenced by the addition of a silent source. An example is the net moment, *i.e.*, the integral of the magnetisation over the sample, which is an important piece of information to geophysicists. Still, estimating the net moment in an efficient and reliable manner is a difficult task. In the case where the sample is a compact parallelepiped and the field is measured on a sufficiently large square, we developed a method based on the known asymptotic behaviour of some integrals of the field. However, while the results are excellent on synthetic data, the practical behaviour on true data is much affected by the fact that the sensor slightly drift over time. A **short-term objective** will be to adapt our method to this issue. We setup another method, which is limited to 2-D samples but does not require to measure on a large area [30]; this method can also be adapted to compute spherical harmonic expansions of the crustal magnetic field in Geosciences [31]. It consists in solving a bounded extremal problem to compute a specific function ϕ which, when integrated against field measurements, yields an estimate of the net moment. Several improvements are required to make this method practically efficient: while we have a prototypical code to numerically estimate ϕ, it is too slow to allow for computations in realistic situations. Using a suitable basis of functions is a promising idea to improve it. We also intend to put special care to the careful rigorous computation of ϕ with explicit error bounds between the true theoretical solution of the bounded extremal problem ϕ and its numerical realisation. In the **longer term**, the formulation of the bounded extremal problem shall be modified in order to account for 3-D samples and for the expected sensitivity of the method to the drift of the sensor.

3.2.6 Other inverse problems

Imaging in archaeology. A recent **short-term** activity of the team is linked to image classification in archaeology in the framework of the project ToMaT "Multiscale Tomography: imaging and modelling ancient materials, technical traditions and transfers", funded by the Idex UCA$^{\text{JEDI}}$, and to the post-doctoral stay of V. L. Coli. This project brings together researchers in archaeological, physical, and mathematical sciences, with the purpose of modelling and detecting low level signals in 3-D images of ancient potteries. Indeed, archaeological analysis focuses on early stages of pottery manufacturing processes, while micro-computed tomography has recently been used to explore the micro-structure of ancient materials. The acquired data comprise 2-D and 3-D datasets at different resolutions, with specific characteristics related to each acquisition modality. The main challenge of this project is to overcome the lack of existing protocols to quantify observations. Specific shape recognition methods need to be developed using robust imaging techniques and shape recognition algorithms. We currently focus our investigation on the pores locations and we are considering several data processing treatments, such as multi-resolution processing and Hough transform, in order to evaluate their outcome when applied to these particular images. Together with the distribution of inclusions, different possibilities of investigation will be analysed as well, such as "a contrario" analysis and deep learning techniques.

Water waves. In collaboration with D. Clamond (UCA-UNS, Department of Mathematics), we intend on the **mid-term** to consider free boundary problems for water waves that consist in determining the wave profile from pressure measurements at the bed, in 2-D. Using conformal maps, such geometrical issues can be recast as bounded extremal problems for pseudo analytic functions.

Conductivity estimation. Inverse conductivity estimation issues were taken up in [32] for EEG related considerations, with a piecewise constant conductivity in a layered spherical head model. There, the conductivity of the intermediate layer (the skull) was to be determined from the available measurements and the knowledge of the source term. Uniqueness and constructive results were established. This could form the basis of an estimation scheme for more general (smooth, radial) conductivity coefficients, that could be discretized by a piecewise constant function (**mid- / long-term**). This is linked to more ambitious questions, related to Calderón inverse problem for discrete dataset.

4 Software and transfer strategy

The transversal nature of our scientific activity makes it necessary to develop a common language with our applicative partners. Joint publications, containing methodological as well as practical results obtained at hand of real word data, is one way of achieving this. Developing software dedicated to a specific application is another one, which lies at the origin of most realisations within Apics: RARL2 [33], Presto-HF [14], Dedale-HF [11], FindSources3D (FS3D) [34], and more recently Puma [35] and Pisa [18].

Our software production is structured in Matlab libraries. This choice is justified by several reasons:

- the simplicity and relative time-efficiency of this high-level language for the implementation of vector calculus based algorithms, relying on qualitative numerical routines (NAG, ...);
- the fact that most of our potential users rely on Matlab to develop their own numerical routines;
- the ease in developing user tailored graphical interfaces with Matlab: we usually do not develop user graphical interfaces for our libraries, but our users write their own ad hoc interface thanks to the aforementioned simplicity.

At the moment, we maintain 4 such Matlab libraries: RARL2 regrouping techniques for stable matricial rational approximation, Presto-HF regrouping procedures relative to extremal bounded problems in Hardy Spaces and their specialization to filter responses identification, Dedale-HF for circuital realisation procedures and FS3D containing functions to handle inverse dipolar potential problems in spherical geometry. Each of these libraries is maintained by at least one permanent member of the team under a version control tool (svn, git) and these libraries are of course interconnected. The rational approximation library RARL2 is a good example: its parametrisation of rational, matrix valued, stable transfer functions based on inner-outer factorisation and realisation theory is present in Presto-HF and FS3D. Unfortunately, it has led over years to specialised versions or branches of our rational approximation engine in each of the aforementioned software, that should ideally be integrated back into the core RARL2 library. This hasn't happened yet due to a lack of coding manpower but has been identified as an **objective**: a complete re-engineering of RARL2 is under discussion, in order to permit integration and maintenance of different specialised branches, and is on the software agenda of Factas. Evolutions of Presto-HF, Dedale-HF and FS3D are also planned (see below the specific sections for each library).

Regarding inverse potential problems, applications we made to geological studies of rocks did not lead so far to software tools, even though we have developed prototypical codes to test our ideas and algorithms. The difficulty here is twofold: first, we did not reach yet satisfying algorithmic solutions, and this is still on-going research; second, even though the underlying inverse potential problem is the same in several applications, the technical solutions developed to solve them strongly depend on the geometry of the measurements area and on the assumptions made on the nature of the sources. This leads to *ad hoc* solutions, not necessarily well-suited for the design and distribution of a more generic software tool. Nevertheless, the problem of computing averaged quantities (such as the net moment) seems of general interest to many applications and offers the advantage not to depend on assumptions on the nature of the sources. This observation lays ground for a **long term objective**, which consists in designing a robust *numerical magnetometer*: from measurements of (some components of) the magnetic field in one of the most usual geometries (say, planar or spherical), to provide an estimate of the net moment of the sources generating it.

The distribution policy of our libraries is rather opportunistic and depends on the targeted users and the will of the main developers of the software. Presto-HF is freely distributed to our academic partners and sold to industrial users after clearance of our IP department. The ancestor software hyperion (developed by the MIAOU and APICS team) was initially developed in connection with research contracts of CNES that first wanted to restrict its distribution to french industrial companies. We therefore opted for a distribution policy that enables to control who are the industrial end users. FS3D has a similar distribution policy. RARL2 access is free for any academic usage but a license needs to be signed by the user's institution prior to any access to the the code. Eventually Dedale-HF is freely downloadable from the web under a license that allows unlimited usage for academic purposes and requires the payment of a user license for industrial application. In practice there is no way to control for what purposes the software is used, meaning it is de facto in open access. We chose this distribution scheme because we wanted to convince the electrical community that the coupling matrix synthesis problem can effectively be solved by means of the Gröbner basis machinery and continuation techniques and this within computations times compatible with applications. We succeeded in this direction as our software has become the reference for solving complex coupling matrix synthesis problems but we lost control of its usage by industrial entities. We intend to maintain this opportunistic decision process for the distribution policy of our software.

Eventually note that we encourage our PhD and post-doc students with pronounced programming skills and taste to write their own software, as this has proven to be an excellent asset for their job search by illustrating practical outcomes of their work. This is for example the case of the software Puma and Pisa. Regarding these two tools, time will show whether they will be maintained and further developed by their authors and possibly by members of the team or some of their ideas adopted and transferred into core realisations of FACTAS.

We give in what follows a brief description of our main software production that can be further deepened by looking up the associated websites.

4.1 RARL2 [33]

Our core rational approximation engine for stable, matrix valued problems. As described above a re-engineering of the code structure is under study to permit the maintenance of several specialised branches. Algorithmically the software could benefit from future results on Schur rational approximation (see Section 3.1.1) and offer for example a guaranty on the passivity of the obtained approximant. Also, we would like to take the opportunity of the upcoming re-engineering to provide guarantees on the numerical quality of the code: control the floating-point errors, provide rigorous error bounds between the theoretical approximant (the one that would be computed if the data were perfect, and if an infinite number of iterations were performed) and the actually computed approximant, etc. The library would thus have a strong semantics on what it computes and to what accuracy, a feature absent of other rational approximation software so far.

4.2 Presto-HF [14]

Software library dedicated to the identification of scattering matrices of microwave devices, such as filters and multiplexers. A special attention has been given to the resolution of bounded extremal problems in the Hardy classes, and the identification of delay components induced by access guides or lines. The software has been transferred to various industrial (under purchase in this case) and academic partners and is central for the potential development of robot driven tuning procedure (see Section 3.1.3).

4.3 Dedale-HF [11]

Software library dedicated to the realisation of scattering matrix by means of coupled resonator circuits with specified coupling topologies, see Section 3.1.2.

4.4 FindSources3D (FS3D) [34]

FindSources3D is a software program dedicated to the resolution of inverse source problems in EEG, developed in collaboration with the E.P.I. Athena and the Center for Applied Mathematics, Mines ParisTech, Sophia Antipolis. From pointwise measurements of the electrical potential taken by electrodes on the scalp, FS3D estimates pointwise dipolar current sources within the brain in a spherical model (see Section 3.2.3). Numerical experiments with FS3D give very good results on simulated data and we are now engaged in the process of handling real experimental data, in collaboration with our partners at INS, La Timone hospital, Marseille. Together with refined approach for time / space signal separation, we will add the treatment of MEG data as another feature of the software FS3D (short-term), simultaneously or not with EEG. The version of the software FS3D currently under development takes as inputs actual time signals, and performs a suitable combination of the principal components, in order to separate the main independent time activities from the corresponding spatial (static) components, and to estimate correlated sources. This possibility seems to be quite a powerful feature of the software, not shared by distributed dedicated algorithms (like dipole-fit, or MUSIC) and tools (like FieldTrip).

5 Team's positioning and collaborations

5.1 Positioning with respect to other Inria teams

Regarding the activities on the conception of microwave systems, the teams of our Inria theme "Optimisation and control of dynamical systems" with which we share some thematic similarities are Non-A Post, Gaia, Disco, I4S and McTao. Factas and Non-A Post are both active in the field of dynamical systems identification. Non-A Post is interested in real time identification techniques for control purposes at hand of time domain measurements, while Factas considers systems where mostly frequency measurements are pertinent. The techniques from differential algebra used by Non-A Post are fundamentally different from ours, lying in functional analysis and approximation. Gaia, derived from Non-A, wants to develop symbolical-numerical methods for the study of dynamical systems, including the synthesis of controllers, and this again in the time domain. However part of its activity is dedicated to the analysis of finite dimensional time delay systems, a research area also shared by Disco. If Disco develops analysis methods for the control of systems known by their complete functional description, we are interested in the identification of this functional description for problems of microwave electronics, at hand of partial frequency measurements. I4S develops statistical identification methods in the context of modal analysis, which relates to identification problems of transfer functions, a problematic shared by Factas. Here again the inputs are in the time domain, and the identification techniques build on the stochastic paradigm where the system's model is supposed exact and the measurement noise is part of this model. FACTAS is interested in the optimal solving of some functional problems, where the approximation error entails a modelling error in addition to the measurement noise. Finally, we collaborate with McTAO on the study of stability assessment of time delay periodic systems. To the best of our knowledge we are the only teams at Inria, involved in the design and tuning of microwave communication devices and systems.

Research activities on inverse problems — taken in the broad sense of (approximately) solving large singular (or ill-conditioned) linear systems — concern most of the teams involved in image and signal processing, and part of those involved in statistical learning, of which some examples are CARMEN, MORPHEME, PANAMA, or PARIETAL. More specifically, FACTAS explores the well-posed character of inverse problems issued from Maxwell's equations in quasi-static or harmonic regime, and their regularisation by solving approximation issues in specific functional classes. The study of mathematical problems coming from this approach concern several teams at Inria, which we list hereunder. The 2D geometrical problems for Laplace operator addressed by SPHINX (which belongs to our Inria theme) with linear interpolation methods are close to some issues that we studied with harmonic and rational approximation techniques. The mathematical analysis of inverse problems is also considered by M3DISIM, together with applications to bio-mechanics and life sciences from the observer viewpoint. The team DEFI develops numerical methods in wave diffraction and scattering, based on factorisation, for obstacle determination and non-destructive control. Inverse problems of obstacle detection are also among the research topics of POEMS who handles them by developing regularisation strategies based on level surfaces methods coupled with Tychonov schemes. MAGIQUE-3D mainly considers inverse obstacle or coefficients determination problems, the latter being related to acoustic wave propagation for seismic, that are solved by optimising the integration method of the forward problem. This team also develops spectral methods. Notice that the approaches and results of DEFI, POEMS and MAGIQUE-3D could be useful to FACTAS in the context of its collaboration with the LEAT, in order to generalise some techniques for the determination of electrical parameters of materials envisaged today. Finally, ATHENA is devoted to medical brain imaging; this includes inverse Cauchy problems to which FACTAS would like to contribute, while we interact for a long time on inverse source and conductivity problems in EEG. While ATHENA handles these issues by optimising the numerical resolution of the associated discretized forward problem, we aim at developing methods from harmonic analysis and function theory.

5.2 Collaborators, users, competitors

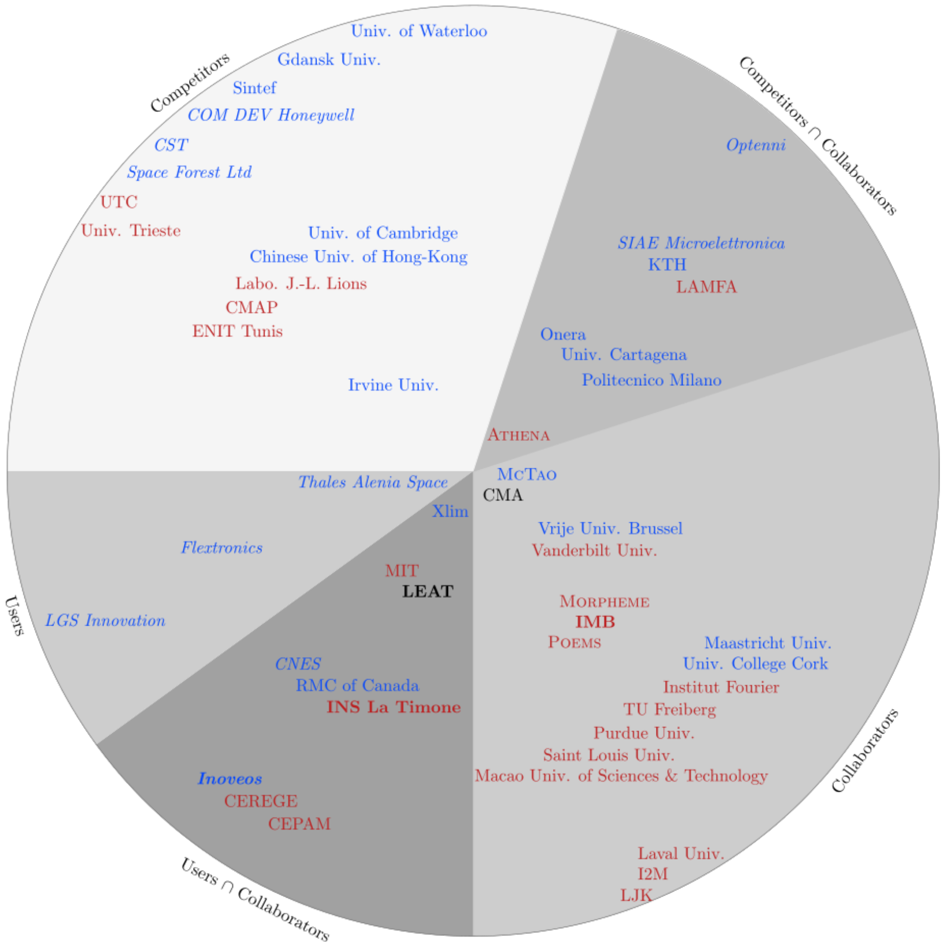
Figure 2 sums up the content of this section. We start with selected partners, *i.e.*, those that are the closest from the team (or that are expected to get closer soon) and for which we give some details. The section ends with actors with which we have interactions, but less strong.

Selected partners on design problems in microwave electromagnetism.

- McTAO team, Inria, Sophia Antipolis (contact: J.-B. Pomet). Collaboration on the stability of microwave amplifiers and the analysis of periodic time delay systems. One ongoing co-advised PhD.

- VUB (Vreije Universiteit Brussels) elec. department (contacts: Y. Rollain and G. Vandersteen). Collaboration around the synthesis of passive and active microwave devices. A co-advised PhD during the 2013-2016 period. Venue as a post-doc of a VUB student in 2017-2018.

- Xlim, MACAO team, Limoges University (contact: S. Bila). Long standing collaboration with a major French actor in microwave engineering. One ongoing co-advised PhD. Several ANR projects realised in common.



The institutions with which we have interactions. The colour indicates the topic (blue: microwave, red: inverse potential problems, black: regards both topics). Industrials appear in italic, while academic institutions are in roman. The distance to the centre indicates the proximity to the team. In bold: the collaborations expected to strengthen in the close future.

Figure 2: The institutions with which we have interactions. The colour indicates the topic (blue: microwave, red: inverse potential problems, black: regards both topics). Industrials appear in italic, while academic institutions are in roman. The distance to the centre indicates the proximity to the team. In bold: the collaborations expected to strengthen in the close future.

- CNES, microwave department, Toulouse. Our historical partner for microwave engineering matters.

- Royal Military College of Canada (contact: S. Amari). Collaboration on filter synthesis problems and more recently on the design of microwave oscillators.

- Inoveos Sarl, Brive La Gaillarde. Starting collaboration around the software Presto-HF, and possible full-automatic robotic tuning devices.

- Thales-Alenia Space, Toulouse. Regular collaboration, historical user of our tool Presto-HF.

- Onera, Toulouse (contact: C. Poussot-Vassal). Starting collaboration around questions of model reduction and stability analysis.

- Technical University of Cartagena, Spain (contact: A. Alvarez-Melcon). Collaboration on filters and antennas.

- Politecnico Milano, Italy (contact: G. Macchiarella). Collaboration on filters and multiplexers. A co-advised PhD during the 2009-2012 period.

Selected partners on inverse potential problems.

- Vanderbilt University, Department of Mathematics, USA (contacts: D. Hardin and E. Saff). Long term collaborators associated with our research with the MIT above.
- Institut de Mathématiques de Bordeaux (IMB) (contacts: K. Kellay and S. Kupin). Collaboration (recently tightened) in harmonic analysis and approximation theory. An ANR project (together with other partners) is starting. One co-advised PhD expected soon.
- MIT, Department of Earth, Atmospheric and Planetary Sciences, USA (contact: E. Lima). Long term collaborator on inverse magnetization issues in rocks. A former Inria Associate Team (period 2013-2018), an MIT-France seed fund and two NSF grants on the USA side.
- Institut de Neurosciences des Systèmes (INS), La Timone hospital, Marseille (contact: J.-M. Badier). Our hospital partner around inverse problems in EEG (prospectively in MEG), with which our contacts have recently tightened.
- Athena team, Inria, Sophia Antipolis (contacts: M. Clerc and T. Papadopoulo). Long standing collaboration on inverse EEG problems and development of the FindSources3D software.

Selected partners shared by both problematics.

- Laboratoire d'Électronique et Antennes et Télécommunications (LEAT), Sophia Antipolis (contacts: J. Y. Dauvignac, F. Ferrero, N. Fortino, C. Migliaccio). Collaboration on the conception of antennas and on wave imaging systems. One ongoing co-advised PhD. This collaboration is expected to take more importance in the close future.
- Centre de Mathématiques Appliquées (CMA), École des Mines ParisTech, Sophia Antipolis (contact: J.-P. Marmorat). Long term collaboration around RARL2 [33] and FindSources3D [34].

Other collaborators, users and competitors.

- In the domain of microwave systems, we have fairly close and regular collaborations with teams in system theory, among which KTH (Stockholm, J. Karlsson and P. Enquist), University of Maastricht (R. Peeters), University of Cork (B. Hanzon) and a friendly competition with University of Cambridge (U.K., team of M. Smith) and Irvine University (USA, T. Georgiou). From these teams, we are the only ones to strongly invest in the domain of microwave electronics. The main users of our tools are Flextronics (USA), Thales Alenia Space Spain & France and LGS-Innovation (USA). Some of our application competitors for computer assisted tuning applications are the company COM DEV Honeywell (Canada), the university of Waterloo, the simulation software manufacturer CST (Germany), the Chinese university of Hong-Kong (team of Ke-Li Wu), the polish company Space Forest Ltd and Gdansk University. On de-embedding questions of multiplexer, we collaborate with an ancient PhD of ours at SIAE Microelettronica (Italy, Milan, M. Oldoni). Sintef, which develops the Vector Fitting software, is probably the most noticeable competitor to RARL2. As to software dedicated to matching circuit determination, note the recent successful start of the start-up company Optenni from Finland triggered by antenna design problems for 4G and 5G, with which contacts are planned and might lead to collaborations. Our main assets here are the strong mathematical basis of our approaches, their systematic and proven nature, as opposed to heuristic methods of our competitors. Our weaknesses lie in the fact that we do not realise internally, at our lab, microwave devices. It is to alleviate for these, that we keep close and vivid collaborations with teams active in microwave system engineering, as well as keep contact with users of our tools from the academic or private sector.

- In the domain of inverse potential problems, we have ongoing collaborations on the national level with CEREGE (CNRS, Aix-en-Provence, J. Gattacceca and Y. Quesnel), the Institut de Mathématiques de Marseille (I2M, A. Borichev), the laboratory Jean Kuntzmann (LJK, Grenoble, F Triki and E. Bonnetier), the Institut Fourier (Grenoble, E. Russ), the POEMS team (Saclay, L. Bourgeois), and the department of mathematics and applied mathematics of Amiens (LAMFA, M. Darbas). On a rather different topic, we currently collaborate with the MORPHEME team and the CEPAM laboratory (CNRS, UCA, Nice) within the project ToMaT, funded by the Idex UCA$^{\text{JEDI}}$ (a post-doc currently co-advised). Some competitors at the national level are the Laboratory Jacques-Louis Lions (Sorbonne Université), the CMAP at Ecole Polytechnique, the University of Technology of Compiègne (UTC). At the international level, we have regular collaborations with the department of Geomathematics of Technical University of Freiberg (Germany, C. Gerhards), Macao University of Sciences and Technology (T. Qian and D. Pei), Purdue University at Indianapolis (USA, M. Yattselev), Laval University (Québec, Canada, J. Mashreghi) and St Louis University (USA, E. Pozzi). Let us also mention some teams which consider close questions, although with different approaches: SISSA (Univ. Trieste, Italy, E. Sincich), ENIT Tunis (LAMSIN, A. Ben Abda, M. Mahjoub).

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6 Curricula Vitae of permanent members

CV of Fabien Seyfert

Fabien Seyfert
30 bis Vieux Chemin de Gairaut
06100 Nice
Born 25/02/1970
Maried, 2 Children

Education and Professional Experience

2001-2019	Full research position (CR2 and CR1) at INRIA Sophia-Antipolis Habilitation à diriger les recherches
1998-2000	Research position at Siemens Munich, Discrete Optimization team
1994-1998	PhD in applied Mathematics and Agrégation de Mathématiques
1990-1993	Ecoles des Mines de St Etienne

Software

Presto-HF	Tuning of Microwave filters: `https://project.inria.fr/presto-hf/` Academic Users: Xlim, CNES, Univ. Erlangen, MIT, Univ. Sydney Corporate Users (via license purchase): Thales Alenia Space France & Spain, Thales Syst. Aeroportés, Flextronics (USA), LGS Innovations (US), Inoveos (France)
Dedale-HF	Circuital Synthesis Software for microwave filters: `https://www-sop.inria.fr/apics/Dedale/WebPages/` Users: Online distribution

Research

Author of 20 research articles, 40 communications in conferences with reading committee.

PhD Supervision

Co-superviser of the Phd's of V.Lunot, M. Oldoni (with Polytech Milano), M. Caenepeel (with VUB, Bruxelles), D. Martínez-Martínez (with Xlim, Limoges), G. Bose (with LEAT, Sophia-Antipolis).

Promotion of scientific activities

Member of the IEEE MTT-8 Technical Committee on Filters and Passive Components. Workshops organizer at the international conferences: International Microwave Symposium (IMS) and the European Microwave Week.

Grants

Co-organiser of the ANR (of type Astrid with DGA) Cocoram, of the ANR Filipix and in charge of 7 industrial contracts with CNES and 1 with Thales Alenia Space.

INRIA, 2004 route des Lucioles
06902 Sophia-Antiolis
France
☎ *04 92 38 78 77*
FAX *04 92 38 78 58*
✉ *martine.olivi@inria.fr*
🖱 *www-sop.inria.fr/members/Martine.Olivi/*

Martine Olivi

Education and Professional Experience

2010	**Habilitation à diriger des recherches**, *Université de Nice Sophia Antipolis*. Parametrization of rational lossless matrices with application to linear system theory.
1988-2019	**Full research position (CR1-CRHC)**, *INRIA*, Sophia-Antipolis.
1987	**PhD in commutative algebra**, *Université de Provence (Aix-Marseille I)*.
1985	**Agrégation de Mathématiques**.
1981-1983	**École Nationale Supèrieure des Mines de St-Etienne**.

Research

Author of 19 research articles, 33 communications in conferences with reading committee.
`http://www-sop.inria.fr/members/Martine.Olivi/publis.html`

Teatching and PhD Supervision

2005-2012	**Courses on Fourier Analysis**, *Polytech'Nice-Sophia*.
1990-2019	**Co-superviser of 6 PhD students**, *G. Bose (Inria-LEAT), D. Martinez-Martinez (Inria-Xlim), M. Caenepeel (Inria-VUB) , V. Lunot , P. Fulcheri, M. Cardelli*.

Responsabilities

2011-2019	**Chargée de Mission Médiation Scientifique**, *Inria-Sophia Antipolis Méditérannée*, and president of the committee MASTIC (Médiation et Animation Scientifique).
2011	**Organiser of the ERNSI workshop**, *European Research Network in System Identification*.

Software

RARL2 L^2 stable rational approximation `https://project.inria.fr/rarl2/`

- Component of the softwares PRESTO-HF and FS3D.
- Academic users : universities of Maastricht (Pays Bas), Cork (Irlande), Macau (Chine), Bruxelles (Belgique), BITS- Pilani Hyderabad Campus (Indes) and ONERA (Toulouse)
- Corporate Users (via PRESTO-HF) : Thales Alenia Space France & Spain, Thales Airbone Systems, Flextronics (USA), LGS Innovations (US), Inoveos (France)

Juliette LEBLOND *Curriculum Vitae*

Born November 8, 1963, Paris (two children).

40 avenue des Sources, 06370 Mouans–Sartoux.
Tel.: 06 84 22 60 24, 04 92 38 78 76. Fax: 04 92 38 78 58.
`juliette.leblond@inria.fr`, `http://www-sop.inria.fr/members/Juliette.Leblond/`

Education & professional experience:
- HDR (Mathematics), University Nice - Sophia Antipolis, 1998.
- PhD (Engineering Sciences), Nice University, 1989.
- Researcher at INRIA since 1990, DR1 since 2014 (teams Miaou, Apics, then Factas).

Publications: 38 articles in journals, 34 in proceedings of conferences; 5 recent ones:
- L. Baratchart, S. Chevillard, D. P. Hardin, J. Leblond, E. A. Lima, J.-P. Marmorat, Magnetic moment estimation and bounded extremal problems, Inverse Problems and Imaging, 13(1), 2019, to appear.
- S. Chevillard, J. Leblond, K. Mavreas, Dipole recovery from sparse measurements of its field on a cylindrical geometry, Symposium on Applied Electromagnetics and Mechanics (ISEM) 2017, Chamonix Mont Blanc, France, to appear in a special issue of the International Journal of Applied Electromagnetics and Mechanics.
- L. Baratchart, J. Leblond, F. Seyfert, Constrained extremal problems in H^2 and Carleman's formulas, Sbornik Math., 209(7), 922–957, 2018.
- M. Clerc, J. Leblond, J.-P. Marmorat, C. Papageorgakis, Uniqueness result for an inverse conductivity recovery problem with application to EEG, Rendiconti dell'Istituto di Matematica dell'Università di Trieste. An International Journal of Mathematics, special issue dedicated to Giovanni Alessandrini, 48, 2016.
- L. Baratchart, L. Bourgeois, J. Leblond, Uniqueness results for inverse Robin problems with bounded coefficients, J. Functional Analysis, 270(1), 2508–2542, 2016.

Software: Co-development of FindSources3D (FS3D), dedicated to inverse source problem in EEG, `http://www-sop.inria.fr/apics/FindSources3D/`.

Training: 12 PhD students, 6 post-doct., 2 young engineers, and internships.

Collective & administrative duties: Member of the Scientific Board (since 2011) and of the Commission Administrative Paritaire (CAP) DR of INRIA. Participation to PhD defense committees and to hiring committees for INRIA and Universities.

Promotion of scientific activities: Organisation of workshops and invited sessions at conferences. In 2018, co-organisation of an invited session at the conference IPMS (Malta), and of the spring school & workshop "Inverse problems and approximation techniques in planetary sciences", INRIA S. A. Participations and invitations at seminars, workshops, conferences.

Research grants: ANR REPKA (2019-2022); Idex UCA Jedi, ToMaT (2018-2020).

IDENTITE / PERSONAL DETAILS

Civilité/Title :	M.	Nom/Name :	Chevillard	Prénom/First name :	Sylvain
Ville/City :	Sophia Antipolis	Pays/Country :	France		

DOMAINE DE RECHERCHE / AREA OF RESEARCH

Mots-clefs libres / Free keywords

1. Rigorous computing
2. Numerical analysis
3. Mathematical aspects of computer science
4. Complex analysis

Autres compétences scientifiques / Other scientific skills :

Floating-point arithmetic

CURRICULUM VITAE

Fonction actuelle / Current fonction

Junior researcher (chargé de recherche)

URL page web personnelle / Personal webpage

http://www-sop.inria.fr/members/Sylvain.Chevillard

Position actuelle / Current position

Organisme public français / French public organisation

Organisme / Organisation	Laboratoire / laboratory	Code Unité	Code postal / Postcode	Ville / City
Inria	Factas project-team		06902	Sophia Antipolis

Organisme privé français / French private organisation

Siret	Etablissement	Direction/service	Code postal	Ville / City

Organisme étranger / Foreign organisation

Etablissement / Institution	Laboratoire / Laboratory	Ville / City	Pays / Country

Autre(s) activité(s) / Other activitie(s)

Oral examinations ("colles") in “classes préparatoires aux grandes écoles”

Position(s) antérieure(s) / Previous position(s)

De … à … / Since… to…	Ville (Pays) / Locality (Country)	Organisme / Organisation	Fonction
From 2009 to 2010	Nancy	Inria	Postdoc
From 2006 to 2009	Lyon	ENS	PhD student

Formation supérieure / Education

Master in Computer Science, Université Lyon 1

PhD from the doctoral school "Computer Science and Mathematics", Université de Lyon

PROJETS DE RECHERCHE FINANCES - RECOMPENSES / FUNDED PROJECTS - AWARDS

Co-coordinator of the Associate Team Inria-MIT Impinge (http://www-sop.inria.fr/apics/IMPINGE), 2013-2018

Participant of the Maglune project funded by the ANR (http://maglune.cerege.fr/)

PUBLICATIONS

1. S. Chevillard, J. Harrison, M. Joldes and C. Lauter. Efficient and accurate computation of upper bounds of approximation errors. In Theoretical Computer Science 412(16): 1523-1543, (2011).
2. S. Chevillard and M. Mezzarobba. Multiple-Precision Evaluation of the Airy Ai Function with Reduced Cancellation. In 21th IEEE SYMPOSIUM on Computer Arithmetic, pages 175-182, Los Alamitos, CA, April 2013. IEEE Computer Society.
3. L. Baratchart, S. Chevillard and T. Qian. Minimax principle and lower bounds in H^2-rational approximation. In Journal of Approximation Theory 206: 17-47, (2016).
4. L. Baratchart, S. Chevillard, D. Hardin, J. Leblond, E. A. Lima and J.-P. Marmorat. Magnetic moment estimation and bounded extremal problems. Inverse Problems & Imaging, 13(1):39-67, 2019.
5. L. Baratchart, S. Chevillard and J. Leblond. Silent and equivalent magnetic distributions on thin plates. In Harmonic Analysis, Function Theory, Operator Theory, and their Applications, Theta Series in Advanced Mathematics, pages 11–27. The Theta Foundation, 2017.

VALORISATION

brevets, licences, création d’entreprise, développement d’outils (dont logiciels), etc. / patent, licence, business creation, development of tool (including software), etc.

Development (together with C. Lauter) of the Sollya software tool (http://sollya.gforge.inria.fr) since 2006 (mainly written in C, about 150k lines of code)

Curriculum vitae

Laurent Baratchart, French citizen, born Sept. 5, 1955 in Cotonou (Bénin).

Education

- Graduated from Ecole Nationale Supérieure des Mines de Saint-Etienne (France), 1978.
- Agrégation de Mathématiques, 1981.
- Ph. D. from Ecole des Mines de Paris, 1982 (Prof. P. Bernhard, advisor).
- Thèse d'Etat in Mathematics, 1987 (Prof. A. Galligo, advisor).

Positions held

- 2000-present: Directeur de Recherche (DR1) at INRIA Sophia Antipolis Méditerranée.
- 1987–2000: Directeur de Recherche (DR2) at INRIA Sophia Antipolis Méditerranée.
- 1981–1987: Research fellow at INRIA (Rocquencourt & Sophia Antipolis Méditerranée).

Visiting Positions

- Fall 2017: invited Prof. at Vanderbilt University (Nashville, TN, USA).
- Fall 2009: invited Prof. at Vanderbilt University (Nashville, TN, USA).
- Spring 2006: invited Prof. at University of Cyprus.
- Spring 2003: *Mathematical System Theory* semester at Mittag-Leffler Institute (Djursholm, Sweden).
- Spring 1988: invited Prof. at University of Florida (Gainesville, USA).

Main Research Interests

Complex and Harmonic Analysis, Potential Theory, Approximation Theory, Orthogonal Polynomials, Inverse Problems, System Identification, Controlled Dynamical Systems.

Publications and Conferences

60 papers in international journals, 41 papers in referreed conference proceedings, 2 book chapters, 50 conferences on invitation, 10 as plenary speaker. Colloquium speaker at 7 foreign universities. Publication list at http://www-sop.inria.fr/members/Laurent.Baratchart/me.html

Teaching and supervision

Taught 13 graduate courses in Analysis, Potential Theory, Approximation and Inverse Problems at Nice, Marseille, Lille, Cyprus and Vanderbilt Universities. Supervised 16 Ph.D. students.

Institutional responsibilities

- Head of the teams MIAOU (1988–2003) and APICS (2004–2017) at INRIA Sophia-Antipolis Méditerranée.
- Editor for "Computational Methods and Function Theory" and "Complex Analysis and Operator Theory".
- Member of the program committee of 15 international conferences.
- Member of the *Commission d'évaluation* at INRIA for 6 years.
- Member of the *Commission de spécialistes (Mathematics)* at *Université de Provence* (2003–2005), *Université de Lille* (2008–2011) and *Université de Bordeaux* (2008–2011).

Grants

- Co-principal investigator (with E. Lima) of MIT-FRANCE seed fund "Ultra-high Sensitivity Magnetometry for Analyzing Ancient Rock Magnetism", 2015–2018.
- Head of ANR Grant 07-BLAN-0247-01 titled *Analyse Harmonique et Problèmes Inverses* (2007–2011), www.ahpi.math.cnrs.fr.
- Co-principal investigator (with E.B. Saff) of NSF grant INT-9417234
- Principal investigator of NATO Grant PST CLG 979703.
- Collaborator of NSF Grant "CMG Collaborative Research: Imaging Magnetization Distributions in Geological Samplings" (2009- 2012, coord. E.B. Saff and B. Weiss).
- Team leader in the TMR-program *European Research Network on System Identification* (1992-2000).

Industrial contracts

Scientist in charge of 18 industrial contracts with companies and agencies, including Dassault, CNES, Alcatel Alenia Space, Thomson TMX, Thalès.