

COURS SPÉCIALISÉS 25

**LECTURES ON ELLIPTIC METHODS
FOR HYBRID INVERSE PROBLEMS**

**Giovanni S. Alberti
Yves Capdeboscq**

Société Mathématique de France

Comité de rédaction

Raphaël CÔTE
Cyril DEMARCHE
Romain DUJARDIN
Sophie GRIVAUX

Olivier GUICHARD
Thierry LÉVY
Bertrand MAURY
Alain VALETTE

Julie DÉSERTI (dir.)

Diffusion

Maison de la SMF
Case 916 – Luminy
13288 Marseille Cedex 9
France

christian.munusami@smf.emath.fr

AMS
P.O. Box 6248
Providence RI 02940
USA

www.ams.org

Tarifs 2018

Vente au numéro : 45 € (\$67)

Des conditions spéciales sont accordées aux membres de la SMF.

Secrétariat : Nathalie Christiaën

Cours Spécialisés

Société Mathématique de France

Institut Henri Poincaré, 11, rue Pierre et Marie Curie

75231 Paris Cedex 05, France

Tél : (33) 01 44 27 67 99 • Fax : (33) 01 40 46 90 96
coursspesmf@smf.ens.fr • <http://smf.emath.fr/>

© Société Mathématique de France 2018

Tous droits réservés (article L 122-4 du Code de la propriété intellectuelle). Toute représentation ou reproduction intégrale ou partielle faite sans le consentement de l'éditeur est illicite. Cette représentation ou reproduction par quelque procédé que ce soit constituerait une contrefaçon sanctionnée par les articles L 335-2 et suivants du CPI.

ISSN 1284-6090

ISBN 978-2-85629-872-5

Directeur de la publication : Stéphane SEURET

Ce cours a été effectué dans le cadre du Prix de la Fondation Sciences Mathématiques de Paris.

PREFACE

The starting point for these lectures is a course given in Paris between January and March 2014 as part of Chaire Junior of the Fondation Sciences Mathématiques de Paris. This book is designed for a graduate audience, interested in inverse problems and partial differential equations, and we have tried to make it as self-contained as possible.

The analysis of hybrid imaging problems relies on several areas of the theory of PDE together with tools often used to study inverse problems. The full description of the models involved, from the theoretical foundations to the most current developments, would require several volumes and is beyond the scope of these notes, which we designed of a size commensurate with a twenty hour lecture course, the original format of the course. The presentation is limited to simplified settings, so that complete results could be explained entirely. This allows us to provide a proper course, instead of a survey of current research, but it comes at the price that more advanced results are not presented. We have tried to give references to some of the major seminal papers in the area in the hope that the interested reader would then follow these trails to the most current advances by means of usual bibliographical reference libraries.

The physical model most often encountered in this book is the linear Maxwell system of equations. It is of foremost importance in the physics of inverse electromagnetic problems. Compared to the conductivity equation and the Helmholtz equation, the analysis of Maxwell's system is much less developed, and these lectures contain several new results which have been

established while writing this book. In the chapter discussing regularity properties, we focus on the Maxwell system of equations in the time harmonic case. Proofs regarding small volume inhomogeneities are given for Maxwell's system as well.

We introduce the inverse source problem from time-dependent boundary measurements for the wave equation from the classical control theory point of view, leaving aside many deep results related to the geometric control of the wave equation or the Radon transform, or recent developments concerning randomised data. Probabilistic methods are not used, random media are not considered, compressed sensing and other image processing approaches are not mentioned. All these questions would certainly be perfectly natural in this course, but would require a different set of authors. For many of these questions, we refer the reader to the relevant chapters of the Handbook of Mathematical Methods in Imaging [192] for detailed introductions and references.

The authors have benefited from the support of the EPSRC Science & Innovation Award to the Oxford Centre for Nonlinear PDE (EP/EO35027/1), and also of the ERC Advanced Grant Project MULTIMOD-267184. G. S. Alberti acknowledges support from the ETH Zürich Postdoctoral Fellowship Program as well as from the Marie Curie Actions for People COFUND Program. Y. Capdeboscq would like to thank the Fondation Sciences Mathématiques de Paris and the Laboratoire Jacques-Louis Lions for the remarkable support provided during his time spent in Paris in 2013-2014.

The authors would like to thank the anonymous referee. The manuscript review and the many helpful suggestions it contained have brought us to clarify and improve the presentation of several chapters.

CONTENTS

Preface	iii
1. Introduction	1
1.1. The electrical impedance tomography problem	2
1.2. Some hybrid problem models	6
1.3. Selected mathematical problems arising from these models	14
1.4. Outline of the following chapters	15
Part I. Mathematical tools	19
2. The observability of the wave equation	21
2.1. Introduction	21
2.2. Well-posedness and observability	22
2.3. On the relation with the Hilbert Uniqueness Method	30
2.4. Proof of Lemma 2.4	35
3. Regularity theory for Maxwell's equations	39
3.1. Introduction	39
3.2. Preliminaries	41
3.3. The main results	48
3.4. Well-posedness for Maxwell's equations	54

4. Perturbations of small volume for Maxwell's equations in a bounded domain	59
4.1. Introduction	59
4.2. Model, assumptions, and preliminary results	61
4.3. Main results	64
4.4. Proofs of Theorems 4.2 and 4.4	69
5. A case study of scattering estimates	79
5.1. Introduction	79
5.2. Main results	82
5.3. Bessel functions and solution of the transmission problem	85
5.4. Appendix on the $H_*^s(\mathbb{S}^{d-1})$ norms used in this chapter	98
6. The Jacobian of solutions to the conductivity equation	101
6.1. Introduction	101
6.2. The Radó-Kneser-Choquet theorem	102
6.3. The smooth case	104
6.4. The general case	112
6.5. Absence of quantitative Jacobian bounds in three and higher dimensions	113
7. Complex geometric optics solutions and the Runge approximation property	125
7.1. Introduction	125
7.2. Complex geometric optics solutions	127
7.3. The Runge approximation property	135
8. Using multiple frequencies to enforce non-zero constraints on solutions of boundary value problems	149
8.1. Introduction	149
8.2. Main results	153
8.3. Proofs of the main results	159
8.4. Quantitative unique continuation for holomorphic functions	164

Part II. Hybrid inverse problems	165
9. The coupled step in hybrid inverse problems	167
9.1. Magnetic resonance electric impedance tomography – current density impedance imaging	168
9.2. Acousto-electric tomography	169
9.3. Thermoacoustic tomography	171
9.4. Dynamic elastography	176
9.5. The thermoelastic problem	177
9.6. Photoacoustic tomography	179
10. The quantitative step in hybrid inverse problems	181
10.1. Current density impedance imaging	181
10.2. Acousto-electric tomography	187
10.3. Thermoacoustic tomography	191
10.4. Dynamic elastography	196
10.5. Photoacoustic tomography	199
Bibliography	203
Index	225

CHAPTER 1

INTRODUCTION

The inverse problems we discuss are the non-physical counterparts of physics based direct problems. A direct problem is a model of the link from cause to effect, and in this course we shall focus on direct problems modelled by partial differential equations where the effects of a cause are uniquely observable, that is, well posed problems in the sense of Hadamard: from an initial or boundary condition, there exists a unique solution, which depends continuously on the input data [109].

Inverse problems correspond to the opposite problem, namely to find the cause which generated the observed, measured result. Such problems are almost necessarily ill-posed (and therefore non physical). As absolute precision in a measure is impossible, measured data are always (local) averages. A field is measured on a finite number of sensors, and is therefore only known partially. One could say that making a measure which is faithful, that is, which when performed several times will provide the same result, implies filtering small variations, thus applying a compact operator to the full field. Reconstructing the cause from measurements thus corresponds to the inversion of a compact operator, which is necessarily unbounded and thus unstable, except in finite dimension. Schematically, starting from A , a cause (the parameters of a PDE, a source term, an initial condition), which is transformed into B , the solution, by the partial differential equation, and then into C , the measured trace of the

solution, the inversion from C to B is always unstable, whereas the inversion of B to A may be stable or unstable depending on the nature of the PDE, but $B \rightarrow A$ is often less severely ill posed than $C \rightarrow B$.

As a first fundamental example, let us consider the electrical impedance tomography (EIT) problem, also known as the Calderón problem in the mathematics literature.

1.1. The electrical impedance tomography problem

1.1.1. Measurements on the exterior boundary: the Calderón problem. — Let $\Omega \subseteq \mathbb{R}^d$ be a Lipschitz connected bounded domain, where $d \geq 2$ is the dimension of the ambient space.

We consider a real-valued conductivity coefficient $\sigma \in L^\infty(\Omega)$, satisfying

$$(1.1) \quad \Lambda^{-1} \leq \sigma(x) \leq \Lambda \quad \text{for almost every } x \in \Omega$$

for some constant $\Lambda > 0$.

Definition 1.1. — The *Dirichlet to Neumann map* is

$$\Lambda_\sigma : H^{1/2}(\partial\Omega) \longrightarrow H^{-1/2}(\partial\Omega), \quad \langle \Lambda_\sigma \varphi, \psi \rangle = \int_{\Omega} \sigma \nabla u \cdot \nabla v \, dx,$$

where $v \in H^1(\Omega)$ is such that $v|_{\partial\Omega} = \psi$ and $u \in H^1(\Omega)$ is the weak solution of

$$\begin{cases} -\operatorname{div}(\sigma \nabla u) = 0 & \text{in } \Omega, \\ u = \varphi & \text{on } \partial\Omega. \end{cases}$$

We need to “prove” this definition, because it apparently depends on the choice of the test function v . Given $v_1, v_2 \in H^1(\Omega)$ with the same trace, namely $v_1 - v_2 \in H_0^1(\Omega)$, from the definition of weak solution we have

$$\int_{\Omega} \sigma \nabla u \cdot \nabla (v_1 - v_2) \, dx = 0,$$

thus this definition is proper.