FOREWORD

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FOREWORD

Special section on electromagnetic characterization of buried obstacles

This *Inverse Problems* special section on electromagnetic characterization of buried obstacles contains a selection of 14 invited papers, involving 41 authors and 19 research groups worldwide\(^1\). We do not claim to have reached all the high-level researchers in the field, but we believe that we have made a fair attempt.

As illustrated by the variety of contributions included, the aim of this special section is to address theoretical and practical inversion problems (and the solutions thereof) that arise in the field of electromagnetic characterization of obstacles (artificial or natural) buried on the Earth or in planetary subsoil. Civil and military engineering, archaeological and environmental issues are typically among those within the scope of the investigation. An example is the characterization of a single (or multiple) obstacle(s) located near the interface or at shallow depths via electromagnetic means operating within relevant frequency bands. However, we also welcomed novel and thought-provoking investigations, even though their direct application to the real world, or even to laboratory-controlled settings, may still be far off.

Within this general mathematical and applied framework, the submitted papers focused on a combination of theoretical, computational and experimental developments. They either reviewed the most recent advances in a particular area of research or were an original and specialized contribution.

Let us now take the opportunity to remind the readers that this special section harks back (in addition to sharing some common contributors) to two special sections already published in the journal which possessed the same flavour of wave-field inversion and its many applications. They were ‘Electromagnetic imaging and inversion of the Earth’s subsurface’, which was published in October 2000 (volume 16, issue 5), and was co-ordinated by the Guest Editors, D Lesselier and T Habashy, and comprised 14 invited papers; and ‘Electromagnetic and ultrasonic nondestructive evaluation’, which was published in December 2002 (volume 18, issue 6), was organized by the Guest Editors, D Lesselier and J Bowler, and comprised 12 invited papers.

In particular in the latter special section, it was noted in the foreword that: ‘Much of the research effort in NDE (nondestructive evaluation) is aligned with the interests of the broader community of scientists and engineers who study inverse problems and their applications in areas such as geophysics, medical imaging, remote sensing or underwater acoustics, to mention but a few. Indeed, many of the basic methods adopted for NDE including tomography, synthetic aperture techniques and iterative inversions, under many guises, are widely used in these other areas’. In a similar fashion, the foreword of the former special section noted that: ‘Many developments have been driven by several new applications and some old ones, such as mathematical physics, atmospheric sciences, geophysical prospecting, quantum mechanics, remote sensing, underwater acoustics, nondestructive testing and evaluation, medical imaging, to mention only a few’.

\(^1\) Though this section consists of invited papers, the standard refereeing procedures of *Inverse Problems* have been rigorously observed.
One was confronted in these two previous special sections, as one is confronted today, with
the same difficult endeavour: a signal resulting from the interrogation of an object embedded
in some complicated medium by a probing radiation contains arcane, encoded information
about this object. Inversion is the procedure by which this signal is transformed into some
intelligible, decoded form in order to provide the user with some of this information. This
could be estimates of locations, volumes, boundaries, shapes, values, and distributions of
electromagnetic (elastic) constitutive parameters.

This endeavour forces us to go from mathematical theory to numerical solution meth-
ods, to validation from laboratory-controlled data, to processing of real-world data, and back
again. Unfortunately, we face critical configurations in practice. They require increasingly
sophisticated models, which exhaust most of our computational resources—notably due to the
three-dimensionally bounded objects in possibly vast and little known search zones. Furth-
more, we have to reckon with vector fields and dyadic Green functions, complex behaviours
of materials and often with severely incomplete and limited data. The latter limitation is a
severe one and is pervasive in the specific situation of buried objects in layered media, upon
which we focus in the special section.

In brief, this means that the solution methods must not be reduced to incremental improve-
ments over existing ones. They must be validated in-depth, have sound theoretical bases and
knowledge of the peculiarities and of the limitations of the measurements.

Naturally, this means that the technologically advanced sensors that are available nowa-
days, together with advanced computers, provide increasingly reliable data and powerful im-
plementations of solution methods. But as yet they do not provide us with the solution itself.
This is evident in the papers published today—they rely on rigorous analyses, clever insights
and much labour. Also, it is necessary to solve first and often simultaneously (within iterative
retrievals) a sequence of direct (forward) wave-field problems. This is needed to understand
the interaction, determine key parameters, estimate which models best fit our inversion needs
and acquire well-generated synthetic data for cost-effective preliminary testing of methods.

The 14 papers in this special section should do justice to the above, overall if not every
one individually. Ordered alphabetically, by the first author, the articles are as follows:

- A Baussard, E L Miller and D Lesselier, in ‘Adaptive multiscale reconstruction of buried
  objects’, seek to improve the speed and robustness of a nonlinear inversion (here limited to
  the case of two-dimensional objects in a half space) using a novel coarse-to-fine iterative
  strategy which involves a pyramid of B-splines of degree 3. In order to map the distribution
  of electromagnetic parameters sought, increasingly finer representations are progressively
  introduced in the areas of interest, i.e. those where the objects emerge from the background
  as the iterations go on. This was done following the testing of the improvement which
  such representations may or may not bring.
- N V Budko and R F Remis, in ‘Electromagnetic inversion using a reduced-order three-
  dimensional homogeneous model’, start from the idea of seeking an effective medium
  three-dimensional homogeneous scatterer which will be equivalent to the true one, with
  the assumption of a known target support. They then develop, and illustrate through
  a variety of numerical examples (including an inhomogeneous target), a model-based
  approach which involves the so-called Arnoldi decomposition and uses a reduced-order
  representation of the objective functional in order to avoid (in particular) the unusually
  high computational costs caused by repetitive solutions of the forward problem. This may
  have interesting applications in the low frequency limit.
  of a spheroidal-mode approach and a differential evolution algorithm for inversion of
  magneto-quasistatic data in UXO discrimination’, tackle the critical issue of the detection

and characterization of unexploded ordnance in conflict and training zones, using low-frequency probing tools (working in the quasistatic regime) available in the field. They address both the case of spheroidal objects and that of complex objects possibly included within spheroidal surfaces, and compute the coefficients of spheroidal field expansions that are characteristic of their magnetic response. From a library of coefficients, fast forward models are employed within a differential evolution approach in order to reconstruct in an effective fashion pertinent features of actual ordnances as shown from synthetic and measured data. Then, the detection and characterization problem can be made much simpler than the inverse problem.

- T J Cui, Y Qin, G-L Wang and W-C Chew, in ‘Low-frequency detection of two-dimensional buried objects using high-order extended Born approximations’, develop a full range of higher and higher approximations (starting from the Born one and encompassing the extended Born one, and then pursue beyond them both in a recursive fashion) in order to avoid solving the fully nonlinear problem for large contrasts of the sought obstacles. Then they show how these developments can be employed for such types of objects in lossy media at low enough frequency, yielding reliable images at the moderate computational expense of tackling a properly regularized linear inverse problem and recursively using the high-order approximations thereupon.

- A Dubois, K Belkebir and M Saillard, in ‘Localization and characterization of two-dimensional targets buried in a cluttered environment’, counter the clutter problem (so far only in a two-dimensional setting) via a combination of a hybrid iterative minimization—reduced to a modified gradient or to a Newton-type algorithm—and of the DORT (decomposition of the time reversal operator) method—which currently enjoys a number of developments for electromagnetic detection and numbering of buried objects. This novel combination enables one to synthesize waves that are focused onto the scatterers, an appropriate DORT-related objective functional being added or multiplied to the standard one minimized along the course of the iterations. In so doing, strong clutter, which usually tends to shadow the targets and/or produce severe artifacts, is overcome to a suitable extent.

- B Duchêne, A Joisel and M Lambert, in ‘Nonlinear inversions of immersed objects using laboratory-controlled data’, discuss the inversion of laboratory data that emulate buried objects in the ocean and where the data are very limited and the environment is highly attenuative. The forward model is employed with an integral equation approach. The inverse scattering algorithm uses the level set method as well as a binary specialized contrast source method. Though computationally intensive these approaches are expected to be effective whenever linearization of the inversion fails. Two types of antennae were tested out in the experiment, a small one and a larger one. It is found, in particular, that the smaller antenna reproduces the modelled result better than the larger one.

- X Feng and M Sato, in ‘Pre-stack migration applied to GPR for landmine detection’, investigate the testing of a ground penetrating radar with synthetic aperture, acquiring mid-point multi-offset data in the demanding situations (strong clutter) of inhomogeneous soil and rough ground and/or of steeply oblique landmines. This is done in practice with experimental data, and is thoroughly illustrated by numerical experiments in the framework of migration techniques. These techniques are tailored to provide an approximate but robust solution to the highly involved three-dimensional vector wave-field inversion problem which is relevant here.

- A Kirsch, in ‘The factorization method for Maxwell’s equations’, shows how the theory of the recently introduced and much considered factorization method can be developed in a sound theoretical fashion for the time-harmonic three-dimensional Maxwell system when far-field scattering patterns are known—by constructing a binary criterion which
tells whether, if a given point lies inside or outside an unknown obstacle, the shape of which is to be retrieved. The vector nature of the electromagnetic field is fully considered in this paper. This is investigated in depth both for a lossy obstacle (with lower-bounded imaginary part of the dielectric permittivity) and for a lossless one (albeit with smoothly varying dielectric permittivity). Useful comparisons with the linear sampling method are also made in the conclusion.

• A Massa, M Pastorino and A Randazzo, in ‘Reconstruction of two-dimensional buried objects by a differential evolution method’, cast the nonlinear inversion problem into the form of a global optimization problem. They combine properly weighted state (coupling) and data (observation) residuals and solve the problem by means of the differential evolution algorithm. Though limited at this stage to a two-dimensional setting and scalar fields, and to a limited exploration zone in space, the applicability of the procedure strongly relies on an appropriate strategy to construct trial solutions at low computational cost. Ways to achieve this strategy are studied and illustrated by the authors.

• G A Newman and P T Boggs, in ‘Solution accelerators for large scale three-dimensional electromagnetic inverse problems’, are interested in the solution of full vector three-dimensional inversion problems which involve a large number of unknowns, such as for monitoring oil recovery at diffusive frequencies. Much relies on properly preconditioning—an approximate Hessian was introduced to that effect via the solution of an approximate adjoint problem. They then propose two solution algorithms, known as the nonlinear conjugate gradient and the limited-memory quasi-Newton, and investigate their behaviour both in theory and via numerical experiments that are closely inspired by real-world applications.

• L-P Song and Q H Liu, in ‘Fast three-dimensional electromagnetic nonlinear inversion in layered media with a novel scattering approximation’, introduce within a full vector three-dimensional setting a source-dependent diagonal scattering tensor which leads them to a modelling method with a wider range of validity than the existing extended Born and other similar approaches. Then they show the efficiency of their model for electromagnetic imaging via an iterative inversion which involves carefully tuned regularization factors that are functions of the Fréchet sensitivity matrix.

• G L Wang, W C Chew, T J Cui, A A Aydiner, D L Wright and D V Smith, in ‘3D near-surface conductivity reconstruction by inversion of VETEM data using the distorted Born iterative method’, are preoccupied by the deciphering of data provided by the very early time electromagnetic (VETEM) system in the kHz to MHz range in order to reconstruct conductive structures in subsoils. A fast direct solver is introduced and used in the iterative reconstruction with a properly chosen regularization parameter. Yet this remains computationally expensive, as the authors illustrate. Through examples drawn from synthetic and real-world data, they retrieve the conductivity map of the search zone as a combination of sub-maps found separately, demonstrating its usefulness.

• Y Yu, B Krishnapuram and L Carin, in ‘Inverse scattering with sparse Bayesian vector regression’, develop on strong Bayesian foundations and statistical learning, a regression-based method in a vector framework (the sought parameters are in vector form), which preserves sparsity (only the most relevant examples from the training set are employed) and is appropriate for on-line decisions since here, in particular, all forward calculations are carried out beforehand. Once trained using synthetic and measured data, they apply the method to the retrieval of cubical targets buried in soil which are equivalent to the actual target.

• M S Zhdanov and A Chernyavskiy, in ‘Rapid three-dimensional inversion of multi-transmitter electromagnetic data using the spectral Lanczos decomposition method’,
work out a spectral Lanczos decomposition method in order to apply it to vector three-dimensional inversion (with present-day applications to mining exploration from helicopter-borne data along prescribed flight lines) using the localized quasilinear inversion previously introduced in the literature. This decomposition method has the advantage of providing a regularized solution for all values of the regularization parameter (which weighs in a data error and a model error, the latter with respect to some priors) at once. Synthetic and real data are shown to be amenable to useful retrievals in complex geological environments.

To conclude, we would like to thank all those involved in the preparation of this special section at the Institute of Physics for their dedicated work, and to thank all referees (there were many of them) for their thorough and timely reviews of the papers, which was not an easy task in view of the constraints we put on them and of the technical complexity of many of the contributions.

Special thanks should go to the Publisher, Elaine Longden-Chapman, and the Publishing Administrator, Kate Hooper, without whom none of this could have been done and, in particular, no deadlines met! The Editor-in-Chief, F A Grünbaum, and all the members of the Editorial Board, gave us the great opportunity to organize this section, and they should be thanked again for their kind support.

The last word of this introduction should, however, go out to the reader. We hope that he/she will appreciate the in-depth analysis of the electromagnetic retrieval of buried obstacles presented in the contributions of the special section, the variety of challenging issues dealt within and the cleverness of many of the solution methods proposed and investigated. We also know that many contributions will require from the reader a good level of multi-disciplinary expertise and sometimes quite considerable labour to get into the intricacies of the authors’ analyses. And, to tell the truth, we have often found ourselves, as Guest Editors, on the verge of being overwhelmed by the vast amount of knowledge required to understand and judge those intricacies. Ultimately, however, what should matter most now this special section is published is that some good light has been shed on many open and critical issues in the theoretical and applied field of electromagnetic inversion of buried obstacles. This is, in our opinion, very stimulating for those who are interested in this domain and who understand its relevance to many technical fields, as well as the integration of and synergy between such fields required to achieve a reliable result.

Guest Editors
Dominique Lesselier, Département de Recherche en Electromagnétisme, Laboratoire des Signaux et Systèmes (CNRS-SUPELEC-UPS), Supélec–Plateau de Moulon, 3 rue Joliot Curie, 91192 Gif-sur-Yvette cedex, France. E-mail: lesselier@lss.supelec.fr
Weng Cho Chew, Center for Computational Electromagnetics and Electromagnetics Laboratory, University of Illinois at Urbana-Champaign, 1406 West Green Street, Urbana, IL 61820-29991, USA. E-mail: w-chew@uiuc.edu