Inverse Problems

GUEST EDITORS' INTRODUCTION

Testing inversion algorithms against experimental data: 3D targets

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1. Presentation

One of the strengths of Institut Fresnel in Marseille, France, is the tight coupling which exists between experiments and theory. This is how the idea came about, inspired by the Ipswich database [1–4], of designing a new database containing results of controlled scattering experiments and making it available to the inverse problems community, thus giving researchers a further opportunity to test and validate their inversion algorithms against reliable experimental data. The experiments were carried out in the anechoic chamber of the Centre Commun de Ressources Micro-Ondes (CCRM), managed for this topic by the researchers of Institut Fresnel. This anechoic chamber is one of the microwave measurement setups that the institute is developing.

In the *Inverse Problems* special section entitled 'Testing inversion algorithms against experimental data' [5], the first results were reported through ten contributions from several research teams. For this inaugural opus, elongated homogeneous targets, to be assumed as two dimensional, were measured within a multi-frequency multi-static configuration. A detailed description of the measurement arrangement specific to this opus can be found in the introduction of the special section [5].

The success of the first opus was an encouragement to go further and to design new challenges for the inverse scattering community. Taking into account the remarks formulated by several colleagues, a second data set was provided with 'infinitely' long inhomogeneous targets measured in both transverse electric and transverse magnetic polarizations. This led to the second special section from *Inverse Problems*, entitled 'Testing inversion algorithms against experimental data: inhomogeneous targets' [6]. In the latter, 11 contributions from several research teams were included, reporting on a large diversity of inversion scattering techniques exploited to successfully reconstruct the profile of the inhomogeneous objects. A detailed description of the measurement configuration specific to this opus can be found in [7].

Then, the next step was to extend the database towards full three-dimensional (3D) problems, which represent the current challenge for the inverse scattering community. With this aim, a large effort has been made to be able to measure the scattered fields of 3D targets, in a meaningful yet computationally affordable way. This has led to the consideration of objects that, especially at the lower frequencies, were small as compared to the wavelength, thus posing the challenge of performing measurements characterized by a very low signal-to-noise ratio. Hence, several improvements have been obtained on the measurement system itself, as well as on the data processing part [8–10], making it now possible to extend the database to 3D targets, which is herein presented.

2. Content of the special section

For this third opus, the scattered fields of five dielectric targets have been measured. The first four targets are homogeneous but not necessarily with convex shape. The last one is a mysterious target, whose estimated position and overall size is only known to the experimental team. By doing this, the researchers have been able to test and calibrate their inversion schemes on the known targets before tackling the mysterious one. More details of the targets' characteristics and of the antennas can be found in the paper which opens this special section:

- J-M Geffrin and P Sabouroux, 'Continuing with the Fresnel database: experimental setup and improvements in 3D scattering measurements' [11],

wherein the description of the measurement procedure, the outline of the files and the data calibration which have been specifically developed for this 3D database are also provided.

Six teams have attempted to reconstruct the five targets from the measured fields provided by the Fresnel experimentalists and their results are gathered in the following papers:

- I Catapano, L Crocco, M D'Urso and T Isernia, '3D microwave imaging via preliminary support reconstruction: testing on the Fresnel 2008 database' [12];
- P C Chaumet and K Belkebir, 'Three-dimensional reconstruction from real data using a conjugate gradient-coupled dipole method' [13];
- J De Zaeytijd and A Franchois, '3D quantitative microwave imaging from measured data with multiplicative smoothing and value picking regularization' [14];
- C Eyraud, A Litman, A Hérique and W Kofman, 'Microwave imaging from experimental data within a Bayesian framework with realistic random noise' [15];
- M Li, A Abubakar and P M van den Berg 'Application of the multiplicative regularized contrast source inversion method on 3D experimental Fresnel data' [16];
- C Yu, M Yuan and Q H Liu, 'Reconstruction of 3D objects with multi-frequency experimental data with a fast DBIM-BCGS method' [17].

Even if the obtained reconstructions are slightly different in the various papers, all teams have succeeded in achieving a satisfactory characterization of the targets. As this has been done following different paths (processing tools and inversion strategies), we find it useful here to provide a synopsis of the global trends as well as the differences appearing between the various contributions.

Formalism

A first interesting point to note is that all the contributions consider a domain integral formalism to model the scattering problem. However, while most of them make use of the widely used electric field integral equation or contrast source integral equation formulation, two of them consider different models. In particular, Chaumet and Belkebir [13] adopt the coupled dipole method formulation which exploits the polarizability distribution, while Catapano *et al* [12] use the 'contrast source extended Born' model, a rewriting of the radiation operator that leads to the introduction of a 'modified' contrast function.

Inversion schemes

Being aimed at determining the permittivity profile distribution, all the contributions are based on an iterative minimization scheme. They are all Newton-type algorithms with either first-order derivatives scheme [12, 13, 15, 16] or second-order derivative ones [14, 17]. Born approximation is sometimes used to linearize the problem [15] or to simplify the gradient expression [13]. The second-order schemes are both based on the Gauss–Newton method either by using the distorted Born iterative method [17] or by directly the Gauss–Newton formalism [14].

With respect to the above, the only exception is the paper by Catapano *et al* [12] wherein a non-iterative scheme, the linear sampling method (LSM), is exploited to achieve a reconstruction of the targets morphology which is pedagogical to the subsequent quantitative imaging.

Data misfit and forward problem

Two types of data misfit cost functionals are encountered. In the modified gradient-type approaches developed by Catapano *et al* [12] and Li *et al* [16], both the coupling equation term and the observation equation term are present in the cost functional. This implies that the forward problem is implicitly hidden into the cost functional.

In the other proposed approaches, the data misfit term only contains the observation equation, with a constant weight proportional to the scattered field amplitude. The only exception is the work by Eyraud *et al* [15], wherein the distance between the measured data and the modelled ones is weighted taking into account the exact experimental noise and assuming weighting coefficients which vary with the total field amplitude. When the observation equation is the single misfit term, an explicit solution of the forward problem is required. To this end, iterative solvers using fast Fourier transform have been adopted in order to reduce the computation burden, such as the BCGS-FFT [17] or the 'marching-on-in' extrapolation technique [14].

Regularization of the inverse problem

In some contributions, the regularization is introduced directly into the cost functional expression. For instance, in [16, 17] the usual multiplicative regularization and additive Tichonov terms are considered, respectively, and their effects on the obtained reconstructed maps are observed. Conversely, two novel regularization terms have been introduced by De Zaeytijd and Franchois [14]. The first one is a multiplicative term which introduces a smoothing of the retrieved functional along the minimization process, while the second one is specifically designed to tackle piecewise-constant targets.

On the other hand, some approaches do not consider an explicit regularization term. For example, in [12], the regularization is enforced by means of a decomposition of the modified contrast in terms of Fourier harmonics. In [14–16], permittivity and conductivity bound constraints are applied during the iterative process. In a more general way, the exploitation of the knowledge on the targets' size and position (either gained from the database description or from a pre-processing step as in [12], together with an adequate starting point such as the back-propagated solution [12, 13, 16], can be seen as an implicit way of enforcing regularization, as they infer on the convergence of the iterative algorithm.

Way of processing the database

All the authors have directly taken the post-processed measured data provided by the experimental team as an entry to their inversion schemes, apart from [12] where an additional data filtering procedure has been applied.

Conversely, the multi-frequency and multi-polarization data provided by the database have been handled/exploited differently by the various contributors. As far as the first issue is concerned, the paper by Li *et al* [16] is the only one where multiple frequency data are simultaneously exploited, whereas in most of the other contributions frequency hopping schemes are adopted. Also, results from the use of data collected at a single frequency are reported by Chaumet and Belkebir [13], De Zaeytijd and Franchois [14], Eyraud *et al* [15]. Concerning the second point, most of the contributions have exploited the two supplied polarizations, either simultaneously or separately, whereas Yu *et al* [17] have considered one single polarization (the co-polar one). Also, Chaumet and Belkebir [13], and Li *et al* [16] have performed a comparison between the results arising from the two polarizations. It is also interesting to note that, in order to reduce the computational burden, some authors [12, 13] have applied the reciprocity condition to the database.

3. Conclusion

This special section contains the results of the application of several electromagnetic inverse scattering methods to the experimental database provided by the Institut Fresnel and constituted by three-dimensional dielectric targets. The reliable results obtained confirm both the high level of development achieved by the contributors as well as the accuracy of the database, which therefore stands as an independent tool for further testing and studies. As Guest Editors, we hope the reader will enjoy the special section and especially appreciate the *mysterious* target's trial!

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Guest Editors