Introduction

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Abstract. (Type abstract here)

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Reliable and detailed information about the Earth's subsurface is of crucial importance throughout the geosciences. Improved descriptions of the Earth's internal structure and composition are fundamental to better understand and predict physical processes within the Earth. Earth models are generally more reliable and practical if they unify multiple sources of information. This unification of geophysical, petrophysical, geological and geochemical aspects that span from theory, field measurements and laboratory experiments forms a truly multidisciplinary challenge. Herein, we consider primarily the combination of complimentary, yet possibly disparate, types of geophysical data in presence of geological and petrophysical constraints. The literature on this subject encompasses a wide variety of joint inversion, cooperative inversion and statistical post-inversion analysis methods, which come with different assumptions, advantages and challenges. We use the term *integrated imaging of the Earth* to not only designate this broad range of different approaches, but also as a possible name for this emerging branch of solid-Earth geophysics that has recently gained considerable attention within the geosciences.

This book reviews and synthesizes a variety of approaches, successes and challenges of integrated imaging of the Earth. The aim is to promote further understanding of the science involved, provide a coherent framework for practitioners and students, and to outline promising venues for future research. The book covers the fundamental theory and a broad range of applications at spatial scales that range from meters to 100s of kilometers. In the remainder of this chapter we discuss some of the issues common to all integrated approaches and provide some definitions of key terms. We then give a short overview of the content of the different chapters in this book and conclude with a brief look to the future. Given the already extensive literature on integrated approaches, we will not provide references for all aspects discussed in this introductory chapter. Instead we refer to individual chapters in this book which provide extensive references to the current literature.

1. Some definitions

A key question in integrated Earth imaging is how to best combine various geophysical methods and data to produce robust and consistent Earth models. Presently, there exists no consistent and widely adopted terminology to describe and classify different methodologies designed for this task. Here we provide a set of definitions that we hope will enable a more consistent usage in the literature. We have chosen these definitions to best fit with the usages preferred by the authors of the chapters of this book. In some cases, these choices represent a trade-off between historical and current usage trends.

Joint inversion, sometimes also termed *simultaneous inversion* (although we prefer the former), refers to approaches where different data types are inverted within a single algorithm, with a single objective function, and where all model parameters describing the property fields are adjusted concurrently throughout the inversion process. This stands in contrast to *cooperative inversion* approaches where single dataset inversions are performed, sequentially or in parallel, and information is shared between the different inversions. Note that this definition of cooperative inversion differs from the one offered by *Lines et al.* [1986] who used the term cooperative inversion to encompass both joint inversion and what we define as cooperative inversion. However, we argue that our definition is the most consistent with contemporary usage in the literature. We suggest the term *coupled inversion* to encompass both joint and cooperative inversion approaches.

Both joint and cooperative inversion share the same goal, that is, that the combination of multiple datasets will lead to improved resolution and more consistent inference of Earth properties. Currently there is no clear evidence to suggest that one of the two approaches is universally superior than the other and the approach needs to be chosen based on the context of the study at hand. Figure 1 shows generalized flow charts for joint and cooperative inversion algorithms that highlight the most important differences between the two approaches.

Cooperative inversion has the advantage that there is no need to explicitly define the relative weights of different data types and a cooperative approach may potentially have better convergence properties than joint inversions. Cooperative inversions may also be more practical when dealing with legacy data, or when it would be difficult to construct a feedback loop for one dataset, for example when incorporating seismic reflection or ground penetrating radar in the inversion. In this sense, many cooperative inversion strategies can be considered special cases of incorporating complex geological priors into the inversion (see also Chapter 5).

The main advantage of joint inversion is that the information provided by all data is considered simultaneously. This can potentially help to avoid inversion artefacts, because all methods contribute to the model evolution. Therefore spurious features are unlikely to appear in regions that several datasets are sensitive to. Also, approaches that parametrize the inversion in terms of petropysical properties, for example mineralogy or porosity, that simultaneously influence several geophysical parameters become joint inversion problems as changing one model parameter will influence the misfit for all datasets.

Within joint inversion approaches, we can identify different sub-categories. Single-property joint inversions combine different types of geophysical data that are sensitive to the same physical parameters. For example, receiver functions and surface waves are both sensitive to seismic velocity. This type of joint inversion is simplified because the different methods are naturally coupled through their common sensitivity to the same single physical property and no additional mathematical coupling measures are required. However, several complications can arise in practice. For example, controlled source electromagnetics (CSEM) and magnetotellurics are both sensitive to electrical conductivity within the Earth. In the MT case, the plane wave nature of the source leads to current flow that is largely horizontal in the absence of major lateral changes in conductivity. In contrast, CSEM dipole sources produce significant vertical components in the electric field and anisotropy must be considered. Similar arguments also apply to electrical resistivity tomography. Thus, a naive approach that neglects this complication and assumes an isotropic conductivity distribution may produce questionable results.

For multi-property joint inversions that combine, for example, electrical resistivity and seismic velocity, the manner in which these very different properties are coupled will have a large impact on the joint inversion and its ability to resolve different structures within the Earth. For this reason, a multitude of different coupling methods have been developed and we further divide multi-property joint inversion approaches into *structurally coupled* and *property coupled* approaches. Structural and property-based coupling approaches can also be applied in cooperative inversion strategies.

Property coupled joint inversion approaches directly link the different physical parameters that are inverted for. The coupling relationship can be obtained from local site-specific data (e.g. collected from boreholes, see Chapters 8 and 9) or by common petrophysical parameters such as porosity (see Chapter 9) or rock mineralogy (see Chapters 10 and 11 for examples). For the latter case, a petrophysical model can be used to calculate the necessary geophysical properties, e.g. conductivity and velocity. The theoretical foundations of these approaches are discussed in Chapter 3. Property coupled approaches must be tailored to the specifics of the dataset and region under investigation. As such, they require a detailed analysis of the data before the inversion can be performed and careful assessment of the inversion results. The reward for this is potentially improved resolution and direct information on quantities of geological interest.

Structurally coupled approaches focus on producing coincident boundaries or gradients within the different physical property models. The assumption of coincident physical property changes is often appropriate but is not generally valid (see Chapter 8 for an example). Chapter 4 describes different approaches for structural coupling in detail and many of the application chapters contain examples that use structural coupling. One of the main reasons for their popularity is their versatility, they need little or no adjustment for different applications, while still providing sufficient coupling between the geophysical methods. However, certain studies have shown that structural coupling may be insufficient for specific scenarios (see Chapters 8 and 9) and stronger property coupled approaches are required.

Post-inversion analysis methods are completely decoupled from the inversion process. They can be applied to the different models recovered by joint or cooperative inversion, or to co-located models obtained independently from single dataset inversions. They can even be applied to models generated by different groups of researchers. For independently generated models it is necessary to ensure that they have comparable parametrizations and resolution such that the features in each model can be related to one another. Chapter 5 gives an overview of different approaches for post inversion analysis of multiple models.

All the integrated imaging methods mentioned above move away from qualitative, subjective comparisons of different geophysical models. Instead they seek to utilize the different geophysical methods in a quantifiable and reproducible manner by defining mathematical relationships between different geophysical quantities. The difficulty in defining relationships between disparate geophysical parameters, such as seismic velocity and electrical conductivity, is reflected in the variety of different approaches that have been proposed to couple the different methods. Defining meaningful relationships is arguably the most important scientific challenge in integrated imaging of the Earth. As the examples presented in the different chapters of this book demonstrate, these relationships largely determine to what extent a given approach is applicable to a certain region and how much improvement we can expect compared to individual analyses.

2. Overview of chapter contents

This book contains contributions from leading researchers and covers the main aspects of integrated Earth imaging. The first part of the book deals with theory and the second with applications. The theory chapters contain the underlying mathematical and conceptual foundations. In Chapter 2 Mosegaard and Hansen consider the foundations of inversion and optimization methods that form the basis of most integrated imaging approaches with particular emphasis on statistical aspects of inverse methods. For deterministic inversion approaches *Nocedal and Wright* [1999] and *Menke* [2012] provide excellent introductions. It is shown how inverse problems can be formulated within a probabilistic framework using probability distributions that describe the various states of information or current knowledge about the system being studied (e.g., information on model parameters, data, physical relationships between model and data). Of particular importance when solving inverse problem is the choice of parameterization and it is discussed how solutions can be obtained that are independent of the choice of parameterization.

The discussion of inverse theory leads directly to the next necessary ingredient for joint and cooperative inversion approaches: the definition of a suitable coupling between the different methods. The mathematical background of different classes of coupling methods are covered in chapters 3 and 4, along with ways to incorporate them into integrated imaging approaches.

In chapter 3, Bosch introduces the general framework of lithological tomography to integrate multiple data sources and prior knowledge through statistical relationships. Formulating the posterior probability density function can be highly challenging when dealing with hierarchical models and multiple data sets. Bosch shows how direct acyclic graphs can greatly simplify this task. He then introduces the reader to typical lithological tomography problems in exploration and global-scale studies together with solution strategies based on either sampling (Markov chain Monte Carlo) or optimization (gradient) methods.

In chapter 4, Meju and Gallardo motivate and trace the history of structurally-based joint inversion. After a short discussion about data fusion and a review of alternative measures of common model structure, they focus on algorithms that use the cross-gradients function to enforce structural similarity between disparate physical properties. Field examples are provided both for near-surface and deeper exploration targets.

In Chapter 5, Paasche reviews different approaches for post-inversion integration of geophysical models obtained from either independent or coupled inversion. The various approaches can help identify structural features and classify relationships between physical properties. The post-inversion integration approaches of Chapter 5 ultimately ease the lithological interpretation of multiple geophysical models and substantially improve the information extraction from those models. Paasche provides the mathematical fundamentals for the approaches and demonstrates their application through illustrative examples.

Chapter 6 by Hansen et al. rounds off the theory section, where the problem of inferring information about the Earth is described as a probabilistic data integration problem. Probabilistic data integration requires that information is quantifiable in the form of a probability distribution. This can be achieved either directly through the specification of an analytical description of a probability distribution, or indirectly, through an algorithm that samples, a typically, unknown probability distribution. In this contribution methods are described for characterizing different kinds of information pertinent to Earth science and for making inferences from probability distributions that combine all available information. Methods are discussed that are capable of dealing with complex data integration problems.

While the theoretical foundation for joint inversion is common across applications, each specific application area faces its own set of challenges. The application chapters are roughly sorted by depth of investigation. We start with near-surface and hydrogeophysical applications (Chapter 7) that typically investigate the upper tens to hundreds of meters and have a long history of multi-method experiments. Linde and Doetsch provide a review of the coupled inverse modelling approaches that have played important roles in pushing hydrogeophysical applications towards increasingly challenging targets. Joint inversion with cross-gradient structural coupling is often favoured and has been applied successfully to a wide range of near-surface applications and geophysical data types. They also present significant work where the coupling involves hydrological flow- and transport simulators combined with petrophysical relationships that link hydrological state variables and geophysical properties. They conclude with a discussion of important challenges and suggest future research avenues. While the focus of Chapter 7 is on hydrogeophysical applications, Linde and Doetsch speak briefly on the potential of joint geophysical inversion to aid in archaeological investigations, civil engineering applications, and unexploded ordinance detection and discrimination.

Mineral exploration (Chapter 8) and hydrocarbon exploration (Chapter 9) focus on the upper hundreds of meters to few kilometers of the subsurface. Both areas of exploration have started to embrace integrated imaging approaches because of the potentially high economic benefits associated with new and improved techniques. The integrated imaging methods employed can be quite different in these two applications because of the different geological environments in which mineral deposits and hydrocarbon reservoirs are typically found. Imaging the sedimentary basins where hydrocarbons are found is traditionally performed with seismic methods and thus virtually all joint inversion approaches in this area include seismics. In contrast, seismic methods are costly and have proven more problematic for the hard-rock geology typically encountered in mineral exploration scenarios; there the focus is instead on electromagnetic and potential field methods.

In Chapter 8, Lelievre and Farquharson outline the aspects of mineral exploration that lead to difficulties with geophysical inversion and the need for integrated imaging approaches. They provide recommendations to practitioners for overcoming those challenges and they focus their review on joint and cooperative inversion approaches used in the field. They point out a great variety of possible geological scenarios, geophysical and geological data combinations available, and exploration questions posed: these provide ample interesting exploration problems where integrated imaging methods can be applied to potentially improve the success of mineral exploration projects. They emphasize that a solid understanding of physical property information is critical for directing joint and cooperative inversion strategies. They conclude by encouraging academic, government and industry cooperation towards further research and development of coupled inversion methods and software.

In Chapter 9, Moorkamp et al. describe the current state of the art in joint inversion for hydrocarbon exploration. An extensive amount of work has focused on maximizing the level of detail gained by the inversion by combining full-waveform and controlled source electromagnetic inversion approaches. Also, when investigating oil and gas reservoirs the porosity and permeability of the source rock are quantities of prime interest. Thus petrophysical approaches that formulate the inversion in terms of these quantities have been explored in some detail. The authors also present two detailed case studies associated with current areas of exploration interest. These illustrate practical issues associated with joint inversion and provide some recipes that can potentially be used in other application areas as well.

In Chapters 10 (lithosphere) and 11 (upper mantle and transition-zone), Afonso et al. and Zunino et al., apply much of the theory laid out in Chapter 2 with the goal of making inferences about the deep Earth using seismic, potential field, and electromagnetic methods. As a means of making inferences about the fundamental parameters of interest to basic Earth science, the studies invert directly for thermo-chemical and petrological quantities. The link between geophysical observables and thermo-chemical state is provided by thermodynamic concepts. The studies presented here rely on a self-consistent thermodynamic formalism for computing mantle mineral phase equilibria and physical properties from which quantitative inferences about the underlying processes that produce the observed variations in physical properties (e.g., seismic wave speeds, density, electrical conductivity) can be drawn. This ensures that temperature, composition, physical properties, and discontinuities associated with mineral phase transformations are anchored by laboratory-measured data of mantle minerals while permitting the use of inverse methods to sample a range of profiles of physical properties matching geophysical data. The advantage of this approach is that the inverse problem is formulated in terms of quantities of direct interest for geological interpretation and understanding Earth's evolution (geodynamic modelling). The main issues these approaches are facing are the high computational costs, the accuracy of laboratory measurements at high temperature and pressure and sparser sampling of the deep Earth by surface measurements. Nevertheless, results are encouraging and allow direct prediction of additional quantities of interest such as topography and heat flow.

One important area of application for integrated imaging approaches is absent from this compilation: exploration for geothermal resources is a field of strong research activity and high significance for securing energy supplies for the future. At present, integrated imaging of any form, be it joint inversion, cooperative inversion or integrated analysis is still quite sparsely used in this area. The limited work performed in this direction in the context of geothermal applications is highly innovative [e.g. *Bauer et al.*, 2012; *Revil et al.*, 2015] and highlights the advantages of integrated approaches. However, it seems that the methods have not yet been widely adopted by the community. We therefore consider imaging geothermal resources as a promising field for future developments.

3. Future developments

Both academic institutions and commercial providers are actively developing methodology and software for integrated Earth imaging. This dual interest is fundamental to ensure the development and implementation of new ground-breaking approaches. The interaction of scientific curiosity and commercial interests ensures significant funding and a balance between theoretically interesting approaches and direct applicability to concrete applications of Earth imaging. We argue that the collaboration between academia and industry is a prominent factor for past and future success of integrated imaging. However, the strong commercial interest in these methods also has its downsides. There is no doubt that important work remains unpublished for reasons of confidentiality and competitive advantage. Furthermore, there exists presently a multitude of patents for joint inversion of virtually any possible combination of geophysical datasets. We know from experience that the threat from these patents is not purely hypothetical: they have been and will continue to be barriers to the publication of open source joint inversion codes. We consider this most unfortunate as the exchange of computer codes helps to advance the field more rapidly. In the long term, such an exchange would also benefit the commercial providers that can integrate the advanced methods that evolve through this exchange into their products.

Overall, we see a bright future for integrated imaging approaches. As illustrated by the wide range of applications displayed in this book, coupled inversion and joint interpretation methods have established themselves in virtually all areas of solid-Earth geophysics. Various companies offer integrated interpretation and joint inversion as commercial services. This indicates that industry has recognized the added value that these approaches offer and is willing to collect a variety of data and bear the additional cost over traditional subsurface imaging methods. In academia, several large recent initiatives, such as US-Array and Sinoprobe, are collecting several types of geophysical data that enable integrated analyses. Furthermore, in recent years we have seen a shift in the types of publications on integrated approaches. Whereas earlier studies focused on the theoretical properties of the algorithms and used real data mostly as illustrative examples, various recent studies focus on the interpretation of the results and consider integration as a useful tool to achieve better results. This is a clear sign that integrated imaging has reached a certain level of maturity.

These developments do not imply that there is little to do for the future. Even though some coupling approaches, such as cross-gradient coupling, are widely used and significant practical experience has been gained with them, there are still only few systematic studies that rigorously compare the theoretical properties of different methods. Unfortunately, formal resolution analysis for complex models is still beyond reach due to the computational complexity of the problem. However, with the ever increasing speed of computer hardware it is only a question of time before this can be performed for complex models and multiple datasets. For petrophysical coupling approaches, only a very limited number of formulations has been explored. In exploration within sedimentary environments, for example, Archie's law is usually employed to link electrical conductivity to porosity and permeability even though it is known to be restricted to clean sandstones. Alternative and ideally more complete formulations that consider other factors such as clay content should be explored and can potentially further improve the results. Similar arguments hold for other application areas where experience has so far been limited to few geologic settings.

With growing interest in the field and larger number of researchers conducting integrated studies, we are optimistic that these issues and many others will be investigated. Being a truly multi-disciplinary field, these additional researchers ideally include not only Earth imaging specialists, but also geochemists, petrologists and geodynamicists. If we can combine all our knowledge of Earth in a consistent and systematic way, we have a unique opportunity to unravel some of the mysteries of our home planet.

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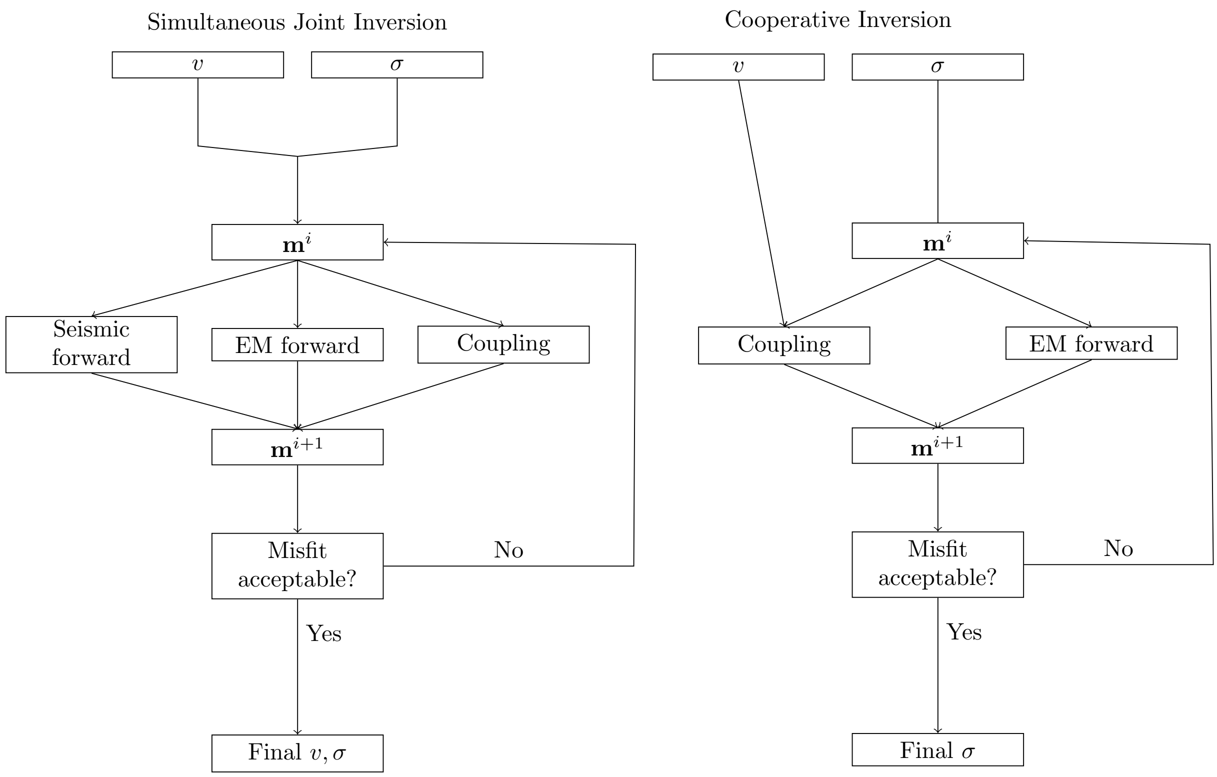

Figure 1. Generalized and simplified flowcharts for typical joint inversion algorithms (left) and cooperative algorithms (right) highlighting the main differences between the two approaches. We choose inversion of seismic velocity v and conductivity σ as an example. For simplicity we do not show regularization and how exactly the seismic velocities and conductivities are related to the model vector $\mathbf{m}$ in the inversion. This will depend on the type of coupling chosen and some examples can be found in the application chapters. The flowchart for the cooperative inversion is typically part of a larger algorithm that exchanges the roles of v and σ after each step or several iterations.