CHAPTER ONE

Introduction

The present monograph is devoted to microwave imaging for diagnostic applications. As is well known, microwave imaging is a technique aimed at sensing a given scene by means of interrogating microwaves. This active technique—considered for a long time an *emerging technique*—has recently proved capable of providing excellent diagnostic capabilities in several areas, including civil and industrial engineering, nondestructive testing and evaluation (NDT&E), geophysical prospecting, and biomedical engineering.

To *localize*, *shape*, and *reconstruct* an unknown target located in an investigation domain and *surrounded* by measurement probes able to acquire the samples of the *scattered* field, several different approaches can be applied. Those considered in this book are *inverse scattering*–based procedures, which address the data inversion in several different ways depending on the target itself (e.g., strongly or weakly contrasted bodies, conducting objects) or on the imaging configuration and operation conditions.

Conceptually, the starting point for the development of these methods is formulation of the electromagnetic inverse scattering problem. A review of this important formulation constitutes Chapters 2 and 3 of this book and is described with engineering style and notations. In particular, the three-dimensional volume and surface scattering by dielectric and conducting targets is introduced, moving from Maxwell's equations to wave equations. The fundamental Fredholm integral equations, which are solved in most of the inverse scattering–based imaging procedures, are then derived in terms of the proper Green functions and tensors. Then, the two-dimensional scattering problem, in which the presence of infinite cylindrical scatterers is assumed, is addressed in detail, since it is of basic importance for the development of tomographic techniques.

In Chapter 3 the distinction between direct and inverse scattering problems is introduced. Moreover, the nonlinear formulation of the latter problem, in

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terms of the so-called data and state equations, is discussed and a related numerical solving procedure is outlined. Finally, the semianalytical solution for plane-wave scattering by a multilayer elliptic cylinder is derived. The importance of using canonical scatterers for testing numerical methods is well known. In addition, a stratified elliptic cylinder is a quite complex structure for representing a significant test for imaging procedures.

The aim of Chapter 4 is to clarify the *objectives* of the short-range imaging approaches considered and specify the geometric arrangements used for microwave tomography and other inspection modalities. Among them, scanning configurations, as well as the detection of buried objects in half-space domains and in cross-borehole configurations, are discussed. Chapter 4 also introduces the most significant approximations on the scattering model that are used in imaging applications. Essentially, these are the Born and the Rytov approximations for dielectrics and the Kirchhoff approximation for conductors. These approximations are discussed in detail, since they constitute the key assumptions of several qualitative reconstruction methods. Such methods are covered in Chapter 5. In particular, in Section 5.1, the *classification* of microwave imaging algorithms into *quantitative* and *qualitative* methods, which is highly arbitrary, is discussed. The chapter includes remarks on uniqueness, ill-posedness, and stability of the electromagnetic inverse scattering problem and introduces concepts such as generalized solutions, regularization, and other fundamental tools for handling the most critical theoretical and numerical aspects in the development of *inversion* techniques.

Two kinds of qualitative methods are considered in Chapter 5: procedures for object localization and shaping, and methods based on approximations. Concerning the former, the formulation of the linear sampling method is outlined, since this method has been found to be efficient when used not only autonomously but also in conjunction with other quantitative reconstruction techniques in order to devise hybrid inspection methods. As far as qualitative methods based on approximations are concerned, Chapter 5 reviews the *classical* diffraction tomography and iterative approaches based on Born-type approximations.

Chapter 6 is devoted to a description of quantitative deterministic reconstruction methods, which are aimed at retrieving the values of the electromagnetic parameters of the unknown scenario. As they are based on *exact* models, they are theoretically able to inspect any scatterers, even highly contrasted targets. Among the various quantitative methods proposed in the scientific literature, this book focuses on inexact Newton procedures, while the so-called distorted Born iterative method and gradient-based techniques are also discussed.

Significant emphasis is then given to quantitative stochastic reconstruction methods, which are based on probabilistic concepts and are in principle able to find an optimum solution to the inverse scattering problem when it has been recast into a global optimization problem. Simulated annealing, the genetic algorithm, differential evolution, particle swarm optimization, and ant colony optimization are discussed and compared in Chapter 7. In particular, the two main properties of stochastic reconstruction techniques are stressed throughout the chapter. In particular, these techniques allow a simple introduction of a priori information into the model (which is of major importance in practical applications) and can be very efficiently combined with other deterministic methods in order to exploit the specific features of the different techniques, improving the effectiveness of the inspection process. Actually, the possibility of devising hybrid methods (Chapter 8 is devoted to these methods) is of paramount importance in microwave imaging, since the development of specific application-oriented procedures and systems is fundamental to increase the efficiency of microwave imaging for real and practical applications in several advanced technological fields.

Chapter 9 deals with instrumentation for microwave imaging. Some proposed imaging apparatuses, aimed at fast and accurate measurement of the scattered field data, are described. In particular, prototypes of microwave axial tomographs and microwave cameras and scanners are discussed with reference to some significant solutions recently proposed. Insights into the so-called modulated scattering technique and the antennas used in microwave imaging systems are also discussed.

Civil, industrial, and medical applications are covered in Chapter 10, with detailed descriptions of several specific examples. Concerning the field of nondestructive evaluation and testing, the use of inverse scattering–based inspection approaches is analyzed with reference to materials evaluation, crack detection, and inspection of civil and industrial structures. Shallow subsurface detection is also addressed in that chapter. Furthermore, concerning the medical field, where the potentialities of microwave imaging are widely recognized, the chapter includes discussion of the assumptions made and results obtained by applying some of the imaging systems and reconstruction techniques considered.

In Chapter 11, some new directions of imaging strategies are briefly delineated. One of them is represented by the current trend of extending, to three-dimensional imaging, most of the inspection methods originally devoted to two-dimensional configurations. It is very encouraging to see the final utilization—thanks to the increased power of the current generation of computers—of a key property of electromagnetic imaging, namely, the possibility of factoring in the vector nature of the field. Other strategies and applications are also briefly mentioned in the chapter, including the use of amplitude-only input data or metamaterial slabs, as well as the recent proposal of using support vector machines for deriving basic parameters of unknown targets starting from field scattered data.

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