Microwave Imaging Techniques

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A volume in the Wiley Series in Remote Sensing, Jin Au Kong, Series Editor

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A WILEY-INTERSCIENCE PUBLICATION

JOHN WILEY & SONS, INC.

New York · Chichester · Brisbane · Toronto · Singapore

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Library of Congress Cataloging-in-Publication Data:
Steinberg, Bernard D.
Microwave imaging techniques / Bernard D. Steinberg, Harish M. Subbaram.
p. cm.—(Wiley series in remote sensing)
"A Wiley-Interscience publication."
Includes bibliographical references (p.
ISBN 0-471-50078-X
1. Microwave remote sensing. I. Subbaram, Harish M. II. Title. III. Series.
G70.4.S74 1991
621.36′78 – dc20 90-12941
CIP

Printed in the United States of America

10 9 8 7 6 5 4 3 2 1

MICROWAVE IMAGING TECHNIQUES

WILEY SERIES IN REMOTE SENSING

Jin Au Kong, Editor

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Steinberg and Subbaram · MICROWAVE IMAGING TECHNIQUES

To My Loving Wife Jacqueline, My Lifetime Companion, Inspiration, and Support

To My Parents M. R. Subbaram and Sharada Subbaram

PREFACE

This book is the third of a series dealing with large arrays and microwave imaging. The first book, *Principles of Aperture and Array System Design: Including Random and Adaptive Arrays* (Wiley, 1976), introduced the designers of communications and radar systems to the spatial domain. Its purpose was to bridge the gap between two disciplines, one practiced by the antenna designer and the student of electromagnetics, and the other by the student of statistical communication theory and system design. At the time that the book was written the antenna designer typically viewed the end point of his work as the single-port connector to the radio or radar set. A similarly narrow point of view was taken by the set designer, who considered his job to begin at that same connection. In short, the antenna designer dealt with the spatial problems and the set designer dealt with the temporal problems. The function of the antenna was to convert signals that were received simultaneously over space to a single time-varying waveform which the antenna delivered to the receiver. The receiver accepted the single time-varying waveform and provided the temporal processing or filtering. It was a simple division: spatial filtering, the job of the antenna designer; temporal filtering, the job of the set designer. A similar division of labor took place on transmission.

When interest in the phased array developed in the late 1960s and early 1970s, it became evident that system design should combine the spatial and temporal properties together rather than deal with them in serial fashion. A phased-array receiving antenna intrinsically has a multiport output. It is not essential that the ports be combined at RF and the output signal delivered as a single time-varying waveform to the single-port input of the receiver. The multiple output ports can be delivered directly to a multiport receiver. More powerful signal processing would then become available without the artificial constraint of spatial first, temporal next.

Treating the entire system as a combined spatial–temporal processor was strange at the time both to the electromagnetic and radar/communications communities. It was not strange, however, in the field of underwater sound, where spatio-temporal system design had been common for many years. The purpose of the book was to acquaint workers in radar and communications with the basic geometric properties of antennas and phased arrays, and the spatial properties of the radiation patterns. They were shown that their own tools—Fourier theory, convolution theory, linear systems theory, and the theory of stochastic processes—were the same basic tools that they needed to bridge the gap of understanding into the spatial domain. In short, they were adequately educated to deal with the spatial domain; they only needed exposure to the world of electric current excitations in an aperture and radiation fields and sidelobes and so forth.

The book had one more objective. The work of the Valley Forge Research Center of the University of Pennsylvania was focused on very high-resolution microwave imaging. Because of that fact the theory of the second part of the book dealt with the very large antenna arrays necessary to achieve high resolution, the problems of these arrays, and the properties of radiation fields that may result from very large antenna arrays. The thinned aperiodic array and the even more highly thinned random array were discussed and the mathematics of the random array was developed. Also, because very large arrays are intrinsically error-prone, considerable attention was given to tolerance theory for large systems.

While the first book provided the intellectual basis for the study of large antenna arrays, the second one, *Microwave Imaging with Large Antenna Arrays: Radio Camera Principles and Techniques* (Wiley, 1983), was a how-to-do-it book describing the intrinsic problems of large microwave systems and ways to overcome these problems. It demonstrated that it is possible to make very large antenna arrays that are highly distorted and highly thinned, and by using self-calibration procedures called adaptive beamforming to cause these arrays to produce microwave imagery as good as from diffraction-limited antennas. The second book amplified and extended the properties of the random array and developed the theory of diversity-combining as applied to random antenna arrays for the purpose of reducing their high sidelobe content.

The primary thrust of the second book was the achievement of high angular resolution in microwave imagery. The book recognized that high resolution was a necessary condition for high-quality imagery but that it was not a sufficient condition. It left the development of the subject "How To Make *Good* Microwave Pictures" to this book, for which that is an appropriate subtitle.

This book has two distinct parts. The first describes what microwave imagery is, how it is obtained, and what the problems are in obtaining good microwave images. This part consists of the first four chapters. The remaining eight chapters describe many techniques for enhancing image quality. Chapters 5 and 6 deal with ways for achieving diversity-combining of images. Chapter 7 introduces deconvolution for eliminating image artifacts and for the general improvement of image quality; it dwells mainly on a technique called CLEAN, which was first developed for radio astronomy. Chapters 8 and 9 discuss the self-calibration methods necessary for successful operation of very large arrays. Chapter 10 describes means for reducing the data-handling requirements of large, high-resolution phased-array systems. Chapter 11 treats the theory and practice of superresolution or non-Fourier processing of spatial data, extending it into the near field and applying it to microwave imaging for the purpose of enhancing the available resolution from a given aperture. Display techniques found useful at the Valley Forge Research Center end the book in Chapter 12.

Much but not all of the work described in this book came out of the Valley Forge Research Center. Faculty, students, and staff members who have contributed are Professors R. S. Berkowitz, C. N. Dorny, F. Haber, and S. H. Taheri (deceased); my students Drs. E. H. Attia, J. Tsao, H. Subbaram, Z. Liang, and B. Kang, and Mr. W. Lee and Ms. S. Patrick; and members of the technical staff Messers D. Carlson, W. Whistler, S. Seeleman, T. Seeleman, and W. Borders. The book itself is a joint effort with my student, now colleague, Dr. Harish Subbaram. Preparation and production of the finished manuscript was the responsibility of Mrs. Shirley Levy, to whom the authors are deeply grateful. Mr. Sam Seeleman, longtime site manager of VFRC and close friend, designed and constructed all the large, complicated antenna arrays, including the 83-m array that for the first time provided us with human-optical angular resolution at microwaves.

BERNARD D. STEINBERG

Philadelphia, Pennsylvania
April 1991

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INTRODUCTION TO MICROWAVE IMAGING

1-1 CATEGORIES OF MICROWAVE IMAGING SYSTEMS

Microwave imaging is picture-taking with long-wavelength microwave energy. The target or the scene to be imaged is illuminated by a microwave transmitter and the reflected or scattered energy is intercepted by the receiving antenna. The receiving system processes the microwave echoes much as the lens of a camera transforms the optical field at the lens into an image in the focal plane. A microwave source such as a radar transmitter plays the role that the sun does in optical photography.

Figure 1-1 shows the basic similarity between optical and microwave imaging: both require a source of radiation, a scattering or reflecting surface, and receivers. The images are entirely different, however, and the figure indicates one reason why this is so: the rough surface scatters optical waves while the same surface may be smooth to microwaves and produce specular reflections. This distinction and its consequences are discussed in Section 4-2.

Another difference between optical and microwave imaging is shown in Fig. 1-2. The camera images the boy in the boat from a position above the boat. The optical photograph is an angle–angle image. The distance dimension has been collapsed onto the image plane.

To achieve the same image orientation with a pulsed microwave system, the direction to the viewing equipment is rotated by 90°. The reason is that the image dimensions are range–angle. The radar transmitter launches a pulse (or a succession of pulses) toward the boat. The first echo to be received is from the stern of the boat; the last echo is from the fish. The range or distance dimension replaces one of the angular dimensions in the optical photo. The other dimension is angle or cross range. Resolution in this direction requires a

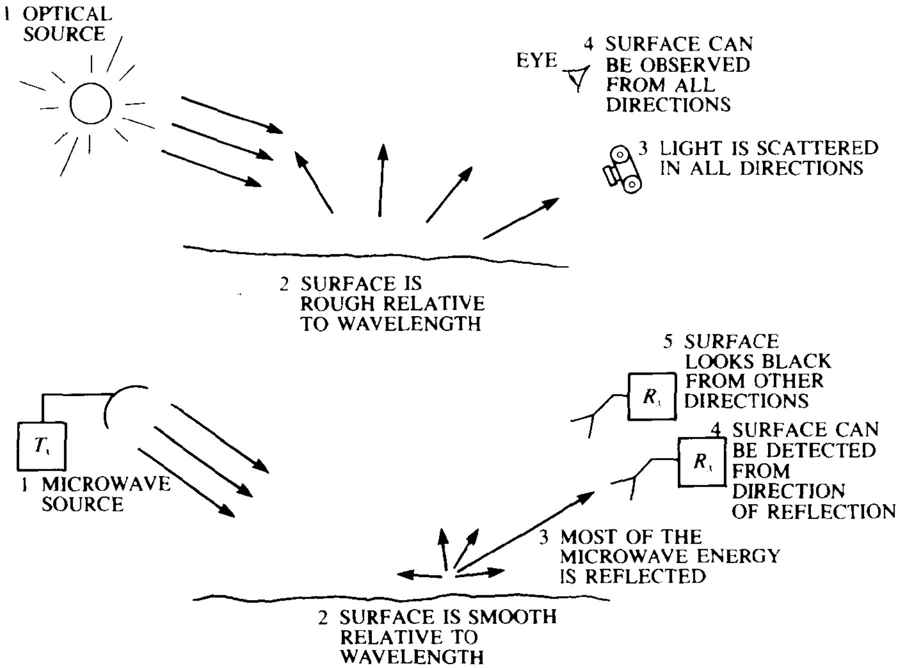

Figure 1-1 Short-wavelength light is scattered; long-wavelength microwave radiation is largely reflected. (From ref. [97])

large microwave aperture. This antenna, which usually is a phased array, and the image processor that follows it constitute the analog of the optical lens.

This book addresses terrestrial microwave imaging, which may be defined as picture-taking with microwaves at long distances on or near the surface of the earth. Another field of microwave imaging is radio astronomy, in which huge antenna arrays receive microwave radiation from cosmological sources and produce images displaying the distribution of sky brightness [117]. Still another field of microwave imaging research is work confined to the laboratory and the anechoic chamber. Here the targets are often scale models of full-size targets.

The three activities share many common theoretical tools and some experimental tools. The differences that result from the different natures of the targets and their distances, however, justify the distinction. For example, radio astronomy is a purely passive technique, whereas both terrestrial and laboratory microwave imaging require active transmitters. Each target of the radio astronomer (such as a star) is an energy source that generates and radiates energy in the microwave region. The targets or sources are not "seen" by reflected or scattered illumination. Because the sources themselves are active, the system—not having its own illuminator—is termed *passive*. Terrestrial and

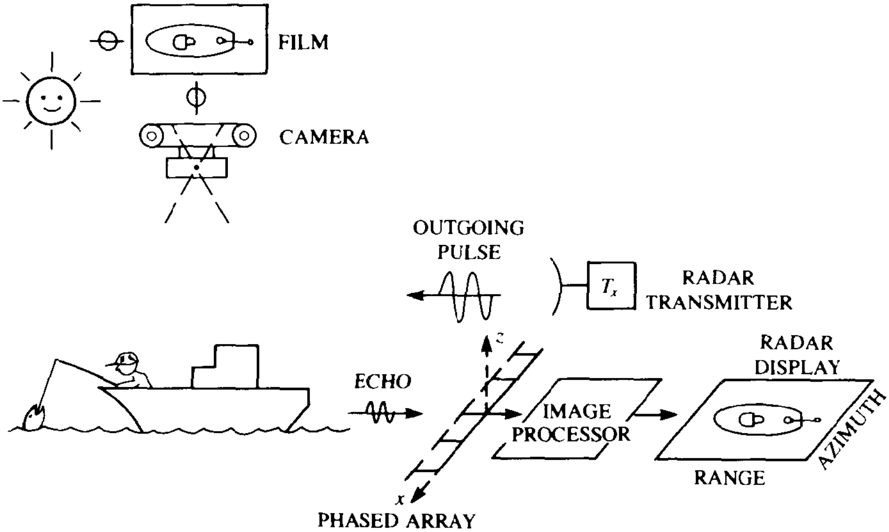

Figure 1-2 Aerial photograph and surface-to-surface microwave image provide the same view of the target. The camera's image plane is normal to the direction of the target, while the radar's image plane contains the target direction.

laboratory imaging systems, on the other hand, require transmitters and are called *active*.

Another distinction also results directly from the fact that radio astronomy targets are energy sources. Because they are physically independent of each other (stars, pulsars, quasars), their radiated waveforms are independent. As a consequence the radiation field at the receiving array is a time-varying field. By contrast, the radiation field at an array resulting from reflections from a radar transmitter is unchanged following each pulse transmission, provided only that the geometry of the target scene does not change. The radio astronomy radiation field is called *incoherent* or *noncoherent*. The microwave imaging field based upon an active transmitter is called *coherent*. This distinction affects the availability and choice of signal processing techniques used in forming the images.

Figure 1-3 illustrates the difference. On the left are shown two independent waveforms $f_1(t)$ and $f_2(t)$ from active sources. Their spherical radiation fields interfere in space and the complex sum arrives as a spatially and temporally varying wavefront, illustrated in the sketch as $e(x, t)$, at the radio astronomy antenna array. Because of the independence of the source waveforms, the spatial distribution of the energy at the antenna array varies continuously in time. The statistics of the radiation field do not vary, however. Consequently, from a time series of measurements made at each antenna, statistical averages of functions of these measurements can be estimated and these prove useful in image