Ian G. Cumming | Frank H. Wong

digital processing of SYNTHETIC APERTURE RADAR DATA

Algorithms and Implementation

CD-ROM INCLUDED

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To our wives, Linda and Mabel, who patiently stood by us through the many years of preparation of this book

In memory of my parents, aunts, and uncles, who impressed on me the value of education and curiosity, and who supported me through my many years of education (Ian Cumming)

In memory of my grandmother, Madame Lee Kam Lin, who, through no fault of her own, received no education while living through one of the most tumultuous periods in China's history, but did value the importance of education (Frank Wong)

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Foreword

The introduction of spaceborne synthetic aperture radar (SAR) into Earth remote sensing can be dated back to the SEASAT mission in 1978—a 100-day episode that opened a door and enabled us to catch a glimpse of the potential of SAR imaging. However, it was not until the 1991 launch of ERS-1 that SARs began to continuously orbit the Earth and deliver images on a reliable, operational basis from aboard remote sensing satellites. Data continuity, which has become indispensable to environmental monitoring and global change research, is guaranteed by national and international space programs where radar remote sensing is of high priority.

Many new applications, never before dreamed of, have been developed since then. The most exciting one is SAR interferometry, where the coherent nature of the complex SAR image is exploited to measure topography, motion, or structural decorrelation of the Earth's surface. At present, with the availability of more than 13 years of continuous SAR data, long-term studies are possible and decadal signals can be observed, be they indicators of land subsidence of 1 mm per year or of variations in ocean wave systems. Up to 100 SAR images of the same area often need to be processed, precisely registered, and evaluated to obtain a single result.

This has all become possible because SAR processing made a significant leap from the optical bench to the world of digital signal processing (DSP). Only in the digital world are processed SAR images accessible in a convenient and reproducible way; their large dynamic range remains undistorted, their phase is carefully preserved, and the set of possible signal processing operations is not limited by physical restrictions. Also, digital SAR processing continually benefits from the inflationary increase in computing power that we have been and still are experiencing. In the beginning, supercomputers or dedicated DSP hardware were required; today, a SAR image can be processed on a notebook computer in a reasonable time. The tempting possibilities of digital processing, plus the ever-growing SAR data availability and user interest, stimulated SAR processor developments at many research institutes and commercial companies. Several new algorithms have been designed to accommodate high resolution, high bandwidth, and high phase accuracy requirements, as well as sophisticated imaging modes.

SAR image formation and data processing are different from many other remote sensing techniques, since the imaging process is coherent. The most natural way to describe such a system and its signals is by complex-valued functions. Hence, signal processing, rather than image processing, provides the appropriate tools. SAR processing needs DSP, but DSP also profits from SAR. The SAR imaging principle and the processing algorithms on their own have become an attractive class of DSP methods that can be transferred to other fields. The concepts of SAR constitute a general imaging principle of a caliber quite comparable to tomography; hence SAR signal processing is well worth studying from an educational point of view.

Having said this, it is surprising that only a very small number of books are available to describe digital processing for remote sensing SARs in a comprehensive manner. Up until now, knowledge in this field has been dispersed throughout journal papers, conference proceedings, internal reports, and patents. Therefore, this book by Professor Cumming and Dr. Wong is special.

First, it is written by the developers of the first digital SAR processor for remote sensing and, therefore, builds upon the longest possible experience. Second, it collects the current knowledge on SAR algorithms, and represents it in a coherent signal processing based terminology. It differs from classical radar books in that it approaches the subject from the processing viewpoint rather than from the physical radar world. By focusing on the important class of satellite SARs with their relatively small squint and aperture, some of the concepts — and sometimes baggage — inherited from conventional radar can be simplified and described in a clearer fashion. It is common experience that, even though a technology has been fully developed, it takes longer for its exposition to be clearly established. This book demonstrates that SAR processing algorithms have reached this level of maturity. This is not only true for the stripmap imaging mode algorithms, but also for the more recent ScanSAR algorithms. I hope that in a later edition of the book spotlight imaging will also be included.

It is evident that the authors have well-honed teaching skills and are not holding back any of their knowledge (Ian Cumming is a professor and Frank Wong is a sessional lecturer at the University of British Columbia). I have known both authors for several years and have always appreciated their dedication to explaining complicated matters in an instructive and easy-to-understand way. Their book is a step-by-step, concise yet complete, illustrative course in SAR processing, following a straight, logical line. The reader is taken on a guided tour, starting from a review of relevant signal processing fundamentals, passing the traditional range Doppler algorithm, reaching the most recent class of chirp scaling methods, and finally arriving at the field of processing parameter estimation. All these stations are supported by numerous examples and illustrations. A set of SAR data provided on a CD-ROM allows the reader to achieve valuable hands-on experience with the processing algorithms.

I am sure that university teachers, postgraduate students, and engineers — whether novices or SAR processing experts — will appreciate this book. Personally, I would have saved myself quite some effort had I had access to a book like this when I entered the field of SAR processing.

Richard Bamler, Director
Remote Sensing Technology Institute
German Aerospace Center, DLR
Oberpfaffenhofen
December 2004

Preface

Scope of the Book

We have written this book to record our experiences in processing synthetic aperture radar (SAR) data for remote sensing applications. Most of the material has been published previously in technical literature, but is gathered together here for the first time in a single reference work.

Our SAR work began at MacDonald Dettwiler (MDA) in 1977, in designing a digital processor for SEASAT data. The work continued with processors developed for SIR-B, ERS-1, ERS-2, RADARSAT-1, and ENVISAT. Several airborne SAR processors were built, the most recent being a dual-frequency, polarimetric, interferometric system. The work continues to this day, with the development of the current RADARSAT-2 processor. This book is an attempt to record the knowledge gained in this work during the last 27 years.

When we began our work, coherent optical SAR processors were the existing technology. Coming from digital sonar backgrounds, it was a natural extension to apply digital signal processing (DSP) principles to SAR data. Although there had undoubtedly been work on digital processors in the military, we were unaware of any such developments, so we had a clean slate upon which to develop our SAR processor ideas.

Our experience has been mainly with the class of SARs that we refer to as "remote sensing" SARs. These SARs make an image of the Earth's surface for applications such as mapping, geology, oceanography, forestry, agriculture, and the like. Their resolutions are typically in the order of a few meters to a few tens of meters, and swath widths are in the order of 2000 to 8000 samples, covering up to 150 km in ground range (even larger swaths with ScanSAR).

There are significant differences between the processing of satellite and airborne SAR data, and it is difficult to build a processor with enough generality to handle both types of data successfully. As satellite data is more publicly available, we usually describe the algorithms from this point of view. When we can provide a simple explanation without disturbing the flow of the book, we point out some differences with airborne data processing.

This book addresses SAR processing from a DSP perspective. It does not dwell upon radar systems principles, except those needed to understand the properties of recorded SAR data.

Prospective Audience

The book is primarily directed towards practicing engineers working with SAR data, or research engineers designing new processing algorithms. Most of the technical information needed to understand and design high quality and/or high throughput SAR processors is presented in some detail. Some of the pertinent DSP principles are included to help those without a strong DSP background.

In addition to processor designers, the book may also be of interest to applications specialists who need to understand some of the properties of the SAR data to help in their image interpretation.

Digital SAR processing is a fascinating application of DSP principles. Indeed, a SAR processor uses a large proportion of the algorithms described in standard DSP textbooks, and even adds a few new concepts. For this reason, the book should be of interest to senior or postgraduate students studying DSP, who wish to learn from an advanced example of applying DSP to a practical application.

Errors, Misprints, and Omissions

The authors apologize for any errors that may be present in the book, and would be grateful to have them brought to their attention.

We have tried to quote the most relevant and precedent references for the various technical issues. In many cases, we have used the references most familiar to us, which means that in some cases our own writings have been given more prominence than they deserve. We will be grateful to have other references pointed out to us.

Acknowledgments

We would like to acknowledge four groups of people who have been essential to the writing of this book. First, the many people with whom we have worked over the years. Among them, John MacDonald, company founder and visionary, who has always been a strong source of inspiration and support. He believed in us, and gave us the resources to build the first commercial digital SAR processor in 1977, when many people thought it could not be done. John Bennett, who was our group leader through the first 10 years, was usually one step ahead of us with ideas and insight. Other members of the original team included Robert Deane, Robert Orth, Pietro Widmer, and Pete McConnell, with whom we shared many ideas in the course of unraveling the mysteries of SAR data processing.

As our market in SAR processors grew, many people joined the MDA team, and most are still working at MacDonald Dettwiler in the SAR group. Some of the people who have made significant technical contributions to SAR processing include David Stevens, Gordon Davidson, Martie Goulding, Paul Lim, and Tim Scheuer.

Most of our work has been sponsored by Canadian and European government organizations, especially the Canada Center for Remote Sensing, the Canadian Space Agency, and the European Space Agency. We have always had close technical ties with our customers, and we would especially like to thank Keith Raney, Laurence Gray, Paris Vachon, and Bob Hawkins of the Canadian agencies; and Rudolph Okkes, Jean-Claude DeGavre, and Yves Desnos of ESA for the many fruitful collaborations we have enjoyed.

Two other agencies stand out as being influential. While we have only occasionally worked directly with them, many algorithms have been developed in parallel, and much has been learned from each other's work. This includes JPL, with Charlie Wu, Michael Jin, Dan Held, Paul Rosen, and Richard Carande developing technology pertinent to this book. Also, there is the German Aerospace Research Center, DLR, where Richard Bamler, Hartmut Runge, Michael Eineder, Alberto Moreira, Rolf Scheiber, and Josef Mittermeier have done seminal work in SAR processor algorithm design. In particular, we are very grateful to Richard Bamler, who has kindly provided the foreword for the book. Their names will appear throughout the reference lists we quote for various algorithm developments.

Second, we would like to thank people who contributed material to the book. Kjell Magnussen of MDA was very helpful in defining the Earth/satellite geometry models. We are grateful to Professor Fabio Rocca of the Politecnico di Milano, who gave us a few extra insights on the ωKA algorithm. Dr. Riccardo Lanari of IREA-CNR in Napoli was very helpful in providing an explanation of the modified SPECAN algorithm, and Paul Rosen of JPL provided an SRTM image for this section. Bob Hawkins of CCRS provided two Convair-580 airborne radar images. Gordon Staples provided many RADARSAT images, as well as the raw data CD. A number of graduate students in the Radar Remote Sensing Group at UBC, including Shu Li, Millie Sikdar, Kaan Ersahin and Yewlam Neo, helped by reading the chapters and providing some programs to read the RADARSAT data and estimate Doppler parameters for some of the figures for Chapters 12 and 13.

Third, we would like to thank the many people who reviewed the manuscript during various stages of its preparation. Ian Cumming was enjoying a sabbatical year at DLR during the first part of the writing, and many individuals were very helpful in reviewing early stages of the work. Near the end of the writing, Juergen Holzner of DLR did a very detailed review of the manuscript. Frank Wong spent a leave of absence in the Department of Electrical Engineering at the National University of Singapore, when a couple of the earlier chapters were written. Back at home, there were more reviewers, including Bernd Scheuchl and Yewlam Neo of UBC, Dave Alton of the University of Calgary, and Martie Goulding, Paul Lim, and Norm Goldstein of MDA.

As to style, our proofreader, Eunice Ludlow, spent many hours making sure that a semitechnical reader had a fair chance of understanding most of the sentences. She was diligent in telling us where to put commas in, and did not let us get away with sentences more than three lines. Thanks also to Rebecca Allendorf and the anonymous Artech House proofreaders, who did a diligent job persuading us to conform to a uniform style in the manuscript.

Finally, our families deserve medals for their support, patience, and tolerance of our intense, irregular working schedules.

An Airborne SAR Image

On to the book — but first let's start off with a SAR image, taken by the Canada Center for Remote Sensing C-band polarimetric airborne radar on the Convair-580. The image was taken over the UBC Westham Island test site on September 30, 2004.

The scene center is 49.2° N, 123.1°W. The swath width is 10 km, and the image was formed by the on-board real-time processor with seven looks, with a nominal radiometric correction. The four polarimetric channels are combined to form the black and white image displayed in Figure A.1.

The first real-time digital SAR processor built by MacDonald Dettwiler was delivered to CCRS in 1979, and installed on the Convair-580. This image was made by the second real-time processor, which replaced the first model in 1986.

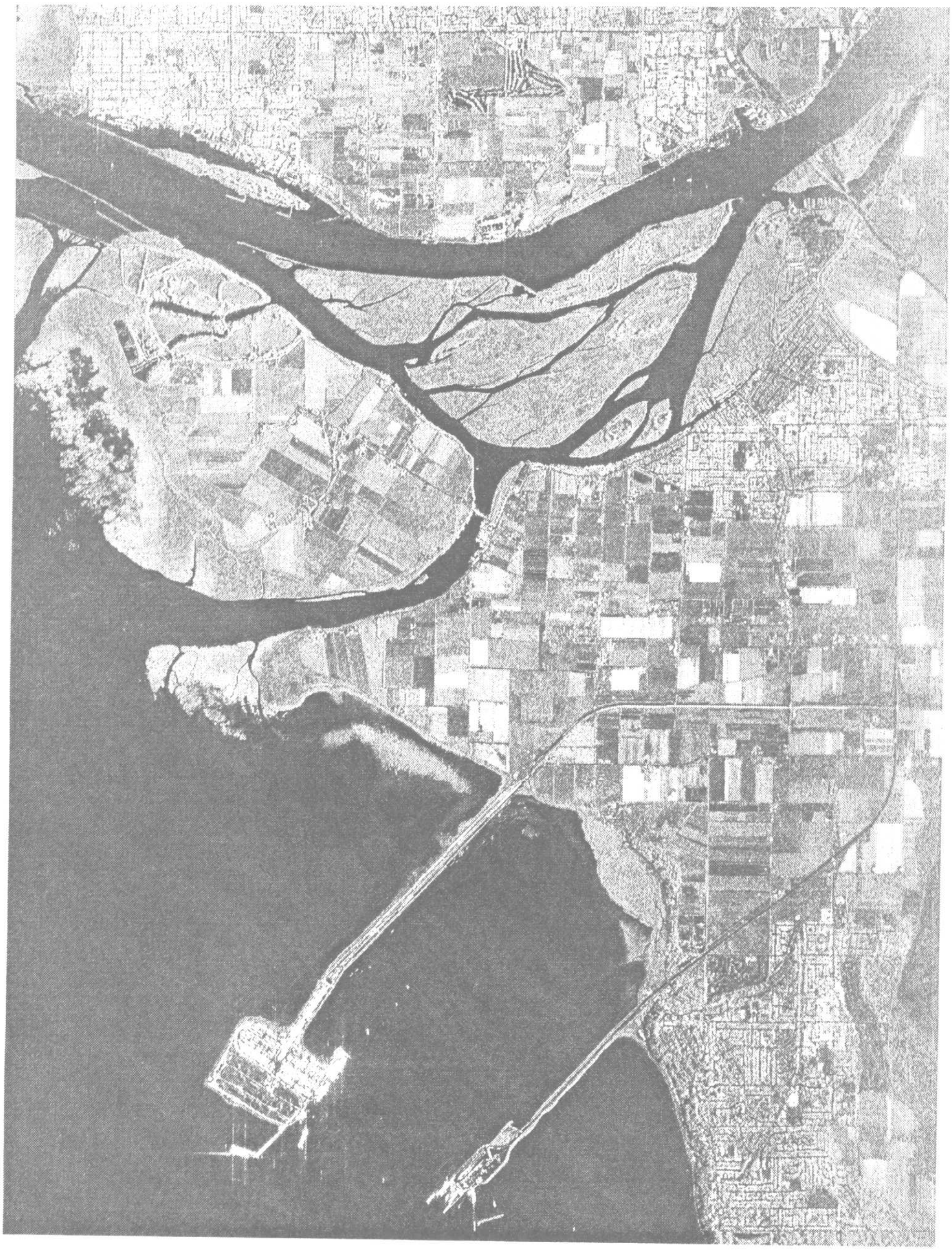

Figure A.1: Convair-580 real-time processed image of the Ladner area of Delta, BC. (Courtesy of Bob Hawkins of CCRS.)

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