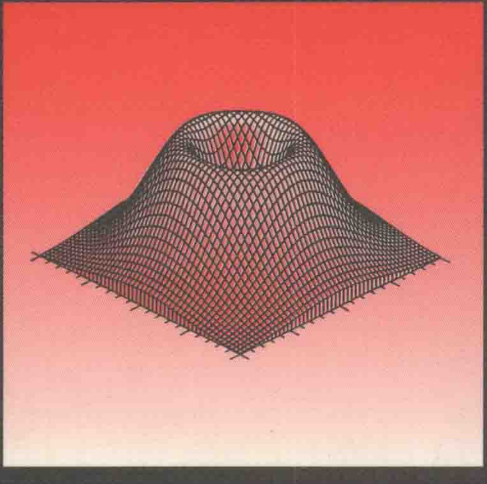
Bernd Jähne

Digital Image Processing

Concepts, Algorithms, and Scientific Applications

Third Edition



Springer

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Third Edition
with 168 Figures and 16 Color Plates

Springer-Verlag
Berlin Heidelberg NewYork
London Paris Tokyo
Hong Kong Barcelona Budapest

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ISBN 3-540-59298-9 3rd ed. Springer-Verlag Berlin Heidelberg New York
ISBN 3-540-56941-3 2nd ed. Springer-Verlag Berlin Heidelberg New York

Library of Congress Cataloging-in-Publication Data
Jähne, Bernd
Digital image processing: concepts, algorithms, and scientific applications /
Bernd Jähne. -- 3rd ed.
Includes bibliographical references and index.
1. Image processing -- Digital techniques. I. Title.
TA 1637.J34 1995
621.36'7--dc20

Printed in Germany

Typesetting: Camera ready by author
Printing: Mercedes-Druck, Berlin; Binding: Lüderitz & Bauer, Berlin
SPIN: 10498784 61/3020-5 4 3 2 1 0 - Printed on acid -free paper

Preface to the Third Edition

Digital image processing is a fascinating subject in several aspects. Human beings perceive most of the information about their environment through their visual sense. While for a long time images could only be captured by photography, we are now at the edge of another technological revolution which allows image data to be captured, manipulated, and evaluated electronically with computers.

With breathtaking pace, computers are becoming more powerful and at the same time less expensive, so that widespread applications for digital image processing emerge. In this way, image processing is becoming a tremendous tool to analyze image data in all areas of natural science. For more and more scientists digital image processing will be the key to study complex scientific problems they could not have dreamed to tackle only a few years ago. A door is opening for new interdisciplinary cooperations merging computer science with the corresponding research areas.

Many students, engineers, and researchers in all natural sciences are faced with the problem of needing to know more about digital image processing. This book is written to meet this need. The author — himself educated in physics — describes digital image processing as a new tool for scientific research. The book starts with the essentials of image processing and leads — in selected areas — to the state-of-the art. This approach gives an insight as to how image processing really works. The selection of the material is guided by the needs of a researcher who wants to apply image processing techniques in his or her field. In this sense, this book tries to offer an integral view of image processing from image acquisition to the extraction of the data of interest. Many concepts and mathematical tools which find widespread application in natural sciences are also applied in digital image processing. Such analogies are pointed out, since they provide an easy access to many complex problems in digital image processing for readers with a general background in natural sciences. The discussion of the general concepts is supplemented with examples from applications on PC-based image processing systems and ready-to-use implementations of important algorithms. Part of these examples are demonstrated with BioScan OPTIMAS, a high-quality image processing software package for PC-based image processing systems (BioScan, Inc., Edmonds, WA). A special feature of this book is the extensive treatment of three-dimensional images and image sequences. The synthetic images used for illustration were designed and computed with Caligari Broadcast (Octree Software, N.Y.) on a Commodore Amiga by AEON Verlag, Hanau, FRG.

After studying this book, the reader should be able to apply even quite complex digital image processing techniques in his or her research area. This book is based on courses given by the author since 1986 in the Physics Department and the Interdisciplinary Center for Scientific Computing at the University of Heidelberg. It is assumed that the reader is familiar with elementary matrix algebra as well as the Fourier transform. Wherever possible, mathematical topics are described intuitively making use of the fact that image processing is an ideal subject to illustrate even complex mathematical relations.

I am deeply indebted to the many individuals who helped me to write this book. I do this by tracing its history. In the early 1980s, when I worked on the physics of small-scale air-sea interaction at the Institute of Environmental Physics at Heidelberg University, it became obvious that these complex phenomena could not be adequately treated with point measuring probes. Consequently, a number of area extended measuring techniques were developed. Then I searched for techniques to extract the physically relevant data from the images and sought for colleagues with experience in digital image processing. The first contacts were established with the Institute for Applied Physics at Heidelberg University and the German Cancer Research Center in Heidelberg. I would like to thank Prof. Dr. J. Bille, Dr. J. Dengler and Dr. M. Schmidt cordially for many eye-opening conversations and their cooperation.

Then I contacted the faculty for computer science at Karlsruhe University and the Fraunhofer Institute for Information and Data Processing in Karlsruhe. I learnt a great deal from the course of Prof. Dr. H.-H. Nagel and Dr. R. Kories on "Algorithmic Interpretation of Image Sequences" that I attended in the summer term 1986.

In April 1989, a German edition of this book was published by Springer-Verlag. This is not a straightforward translation, but a completely revised edition with many augmentations, notably with many more practical examples, listings of important algorithms, a new chapter on shape, updated information on the latest image processing hardware, a new set of color tables, and countless small improvements.

I would like to express my sincere thanks to Dr. Klaus Riemer. He drafted several chapters of the lecture notes for my courses at Heidelberg University. He also designed a number of drawings for this book. Many individuals have reviewed various drafts of the manuscript. I would like to thank Robert I. Birenbaum, Thomas Fendrich, Karl-Heinz Grosser, Jochen Klinke, Dr. Dietmar Wierzimok and many others for valuable comments and suggestions on different parts of the manuscript. I am mostly grateful for the help of my friends at AEON Verlag. They sacrificed many night hours for proofreading, designing computer graphics, and providing general editorial assistance.

Many researchers and companies provided me with material from their research. The following list shows the many applications of digital image processing:

- Dr. K. S. Baker, Scripps Institution of Oceanography, La Jolla, California; R. C. Smith, University of California at Santa Barbara, California; O. B. Brown, Rosenstiel School of Marine and Atmospheric Science, University of Miami, Florida
- Dr. J. P. Burt, David Sarnoff Research Center, Princeton, New Jersey
- Dr. P. de Loor and Drs. D. van Halsema, Physics and Electronics Laboratory, TNO, Den Haag
- Dr. J. Dengler, Department of Medical and Biological Computer Science, German

Cancer Research Center, Heidelberg, and Dr. M. Schmidt, Alfred Wegener Institute, Bremerhaven

- Dr. W. Enkelmann, Fraunhofer-Institute for Information and Data Processing, Karlsruhe
- Prof. Dr. G. Granlund, Computer Vision Laboratory, University of Linköping
- Dr. R. Kories, Fraunhofer-Institute for Information and Data Processing, Karlsruhe
- Prof. Dr. E. C. Hildreth, Center for Biological Information Processing, Massachusetts Institute of Technology, Cambridge, Massachusetts
- Prof. Dr. A. C. Kak, School of Electrical Engineering, Purdue University, West Lafayette, Indiana
- Dr. K. Riemer and Dr. D. Wierzimok, Institute for Environmental Physics, University of Heidelberg
- Dr. B. Schmitt and Prof. Dr. D. Komitowski, Department for Histodiagnostics and Pathomorphological Documentation, German Cancer Research Center, Heidelberg
- J. Steurer, Institute for Communications Technology, Technical University of Munich
- Prof. Dr. J. Wolfrum and Dr. H. Becker, Institute for Physical Chemistry, University of Heidelberg
- Imaging Technology Inc., Woburn, Massachusetts, and Stemmer PC-Systeme GmbH, Munich
- Matrox Electronic Systems Limited, Dorval, Quebec, and Rauscher GmbH, Munich
- Techex Computer + Grafik Vertriebs GmbH, Munich

I would also like to thank Prof. Dr. K. O. Münnich, director of the Institute for Environmental Physics. From the beginning, he was open-minded about new ideas to apply digital image processing techniques in environmental physics. It is due to his farsightedness and substantial support that the research group "Digital Image Processing in Environmental Physics" could develop so fruitfully at his institute. Many of the examples shown in this book are taken from my research at Heidelberg University and the Scripps Institution of Oceanography. I gratefully acknowledge financial support for this research from the German Science Foundation, the European Community, the National Science Foundation (OCE89 11224), and the Office of Naval Research (N00014-89-J-3222). Most of this book has been written while I was guest professor at the Interdisciplinary Research Center for Scientific Computing at Heidelberg University. I would like to thank Prof. Dr. Jäger for his hospitality. I would also like to express my sincere thanks to the staff of Springer-Verlag for their constant interest in this book and their professional advice.

For the third edition, the proven and well-received concept of the first and second editions has been maintained and only some errors have been corrected. However, Appendix B (PC-Based Image Processing Systems) has been completely rewritten to accomodate to the considerable progress in hardware during the last two years. Again, I would like to thank all readers in advance for their comments on further improvements or additions. I am also grateful for hints on errors, omissions or typing errors which, despite all the care taken, may still have slipped attention.

La Jolla, California and Heidelberg, February 1995 — Bernd Jähne

Contents

1 Introduction

1.1 Digital Image Processing — A New Research Tool

From the beginning of science, visual observation has played a major role. At that time, the only way to document the results of an experiment was by verbal description and manual drawings. The next major step was the invention of photography which enabled results to be documented objectively. Three prominent examples of scientific applications of photography are astronomy, photogrammetry, and particle physics. Astronomers were able to measure positions and magnitudes of stars accurately. Aerial images were used to produce topographic maps. Searching through countless images from hydrogen bubble chambers led to the discovery of many elementary particles in physics. These manual evaluation procedures, however, were time consuming. Some semi- or even fully automated optomechanical devices were designed. However, they were adapted to a single specific purpose. This is why quantitative evaluation of images never found widespread application at that time. Generally, images were only used for documentation, qualitative description and illustration of the phenomena observed.

Nowadays, we are in the middle of a second revolution sparked by the rapid progress in video and computer technology. Personal computers and workstations have become powerful enough to process image data. They have also become cheap enough to be widely used. In consequence, image processing is turning from a specialized science in areas such as astronomy, remote sensing, electrical engineering, and computer science into a standard scientific tool. Applications in image processing have now been applied to virtually all the natural sciences.

A simple example clearly demonstrates the power of visual information. Imagine you had the task to write an article about a new technical system, for example, a new type of a solar power plant. It would take an enormous effort to describe the system if you could not include images and technical drawings. The reader of your imageless article would also have a frustrating experience. He would spend a lot of time trying to figure out how the new solar power plant worked and he might end up with only a poor picture of what it looked like.

Technical drawings and photographs of the solar power plant would be of enormous help for the reader of your article. First, he would immediately have an idea of the plant. Secondly, he could study details in the drawings and photographs which were not described in the text, but which caught his attention. Pictorial information provides much more details, a fact which can be precisely summarized by the saying that "a picture is worth a thousand words".

Another observation is of interest. If the reader later heard of the new solar plant, he could easily recall what it looked like, the object "solar plant" being instantaneously associated with an image.

1.2 Components of an Image Processing System

In this section, the technical innovations that enabled the widespread application of image processing in science are briefly reviewed. It will outline the capabilities of modern image processing systems and the progress in image sensors, image storage, and image processing.

1.2.1 Image Sensors

Digital processing requires images to be obtained in the form of electrical signals. These signals can be digitized into sequences of numbers which then can be processed by a computer. There are many ways to convert images into digital numbers. Here, we will focus on video technology, since it is the most common and affordable approach.

The milestone in image sensing technology was the invention of semiconductor photodetector arrays. There are many types of such sensors, the most common being the *charge coupled device* or CCD. Such a sensor consists of a large number of photosensitive elements. A typical high resolution CCD sensor (RS 170 norm) has 486 lines of 768 elements on a $10.5 \times 11\,\mu$m grid. During the accumulation phase, each element collects electrical charges, which are generated by absorbed photons. Thus the collected charge is proportional to the illumination. In the read-out phase, these charges are sequentially transported across the chip from sensor to sensor and finally converted to an electric voltage.

Semiconductor imaging sensors have a number of significant advantages:

- *Precise and stable geometry.* This feature simply results from the manufacturing procedure. Geometric distortion is virtually absent. More important, the sensor is stable in position, showing only a minor temperature dependence due to the low linear thermal expansion coefficient of silicon ($2 \cdot 10^{-6}$/K). These features allow precise size and position measurements. A new measuring technology named *videometry* is emerging. We might think that because of the limited number of sensor elements only quite coarse measurements are possible in comparison with other physical measurements. We will learn later, in section 17.4.5, that the positions of objects can be determined with accuracies well below a tenth of the distance between two sensor elements. This degree of accuracy can, of course, only be gained if the other components in the camera system do not introduce any significant error. Also, the geometric distortion caused by the camera lens has to be taken into consideration (section 2.2.4).

- *High sensitivity.* The quantum efficiency, i. e., the fraction of elementary charges generated per photon, is close to one. However, commercial CCDs cannot be used at low light levels because of the thermally generated electrons. But if CCD devices are cooled down to low temperatures, they are among the most sensitive imagers. Such devices are commonly used in astronomy and are about one hundred times more sensitive than photographic material.
- *Small and rugged.* A final advantage is the small size of the sensor and its insensitivity to external influences such as magnetic fields and vibrations.

Images are not restricted to visible light. Nowadays, imaging sensor systems are available for the whole range of the electromagnetic spectrum from *gamma radiation* to *radio waves.* In this way, the application range of digital image processing techniques has broadened enormously. To a large extent, this development has been initiated by astronomy. Astronomers have no other way to obtain knowledge about the distant objects they are studying than by measuring the faint emitted radiation. Thus it was natural that they developed and continue to develop sensors for the widest possible range.

These considerations lead us to the conclusion that a scientist using an image processing technique is not interested in the image brightness itself, but in specific physical, chemical, or biological characteristics of the objects he or she is studying. The electromagnetic radiation collected on the image plane is only used as a medium to learn about the features of interest.

The following example is taken from satellite oceanography. Plate 1a shows an image of the coastal Pacific in Southern California taken with the Coastal Zone Color Scanner (CZCS) in the visible green/blue range. The light emitted from the ocean surface water in this spectral region is basically determined by the chlorophyll concentration. Thus plate 1a directly shows the chlorophyll concentration in a pseudo color code as indicated in the color plate.

The same area was also observed by the NOA6 satellite at the same time in the far infrared. The radiation in this wavelength region is related to the ocean surface temperature (plate 1b). The temperature and chlorophyll concentration show similar spatial patterns which allow different water masses to be distinguished and ocean mixing and biological activities to be studied. Provided that the parameters can be determined accurately enough and without bias, the area extended measurements from satellites yield a much more detailed view of these processes than profiles taken from ships. Satellite images taken simultaneously in many different spectral regions, so-called *multichannel images*, have become a very valuable tool in *remote sensing.*

Microwaves and *radio waves* allow active remote sensing. These waves with wavelengths from meters to millimeters can be sent via an antenna onto the ocean surface. Because of the roughness of the sea surface, i. e., small-scale water surface waves, part of the emitted radiation is scattered back in all directions. Thus the power received by the satellite antenna contains a world of information about processes influencing the small-scale waves on the ocean surface [*de Loor and Brunsveld van Hulten*, 1978].

In the right margin of figure 1.1 in the mud-flats between the two islands, strong variations in the radar backscatter can be observed which first puzzled scientists considerably. Then it turned out that they were caused by a complex chain of interactions.

Figure 1.1: Radar image of the Dutch coast including the islands of Vlieland and Terschelling taken with the synthetic aperture radar of the SEASAT satellite on October 9, 1978 and evaluated by FVLR/GSOC. The resolution of the image is about 25 m. Image kindly provided by D. van Halsema, TNO, the Netherlands.

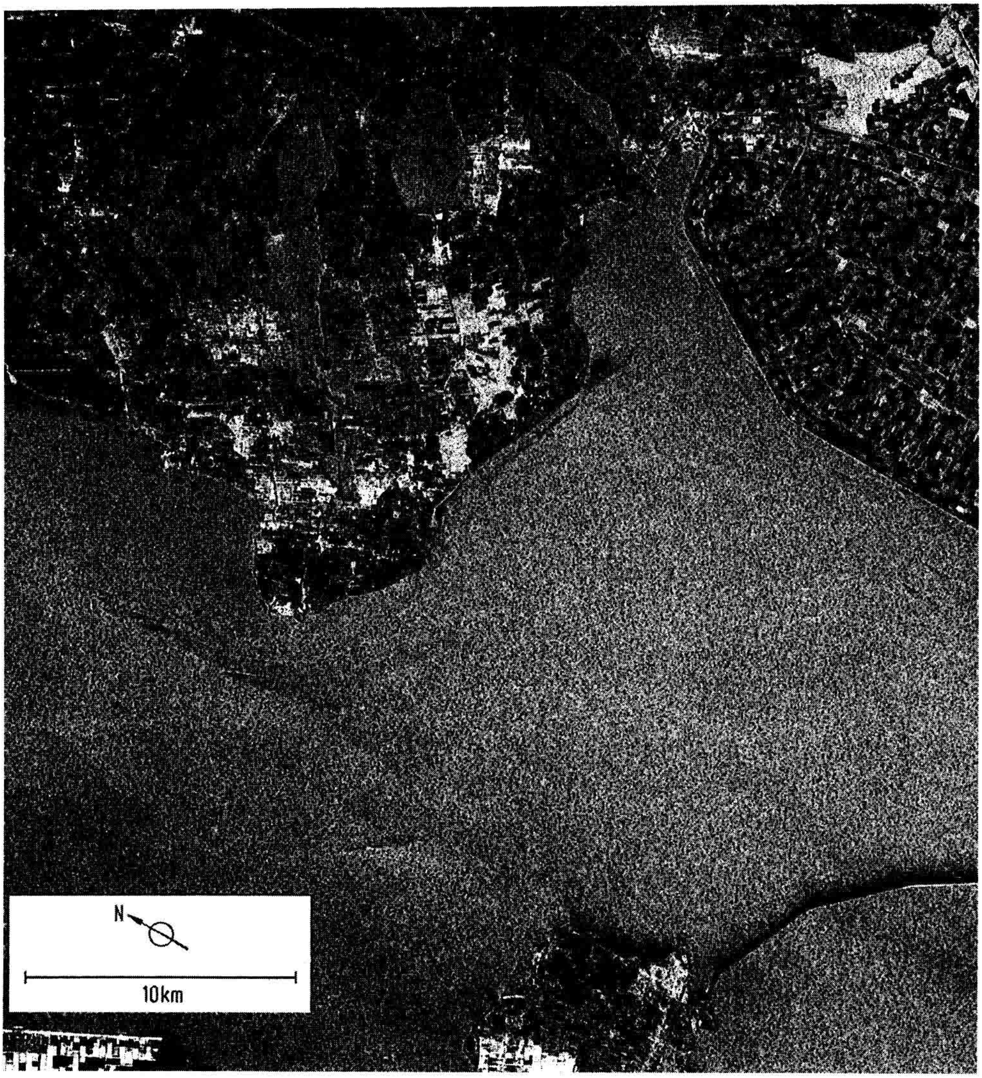

Figure 1.2: Another SAR-SEASAT image taken at the same day as figure 1.1 showing a sector of the Dutch Ijsselmeer. Image kindly provided by D. van Halsema, TNO.