JON HAMKINS SERIES EDITOR

JPL DEEP-SPACE COMMUNICATIONS AND NAVIGATION SERIES

SPACECRAFT OPTICAL NAVIGATION

WILLIAM M. OWEN JR.

WILEY

Spacecraft Optical Navigation

DEEP SPACE COMMUNICATIONS AND NAVIGATION SERIES

Issued by the Deep Space Communications and Navigation Systems
Center of Excellence, Jet Propulsion Laboratory
California Institute of Technology

Jon Hamkins, Editor-in-Chief

Published Titles in this Series

Radiometric Tracking Techniques for Deep-Space Navigation
Catherine L. Thornton and James S. Border

Formulation for Observed and Computed Values of Deep Space Network Data Types for Navigation
Theodore D. Moyer

Bandwidth-Efficient Digital Modulation with Application to Deep-Space Communications
Marvin K. Simon

Large Antennas of the Deep Space Network
William A. Imbriale

Antenna Arraying Techniques in the Deep Space Network
David H. Rogstad, Alexander Mileant, and Timothy T. Pham

Radio Occultations Using Earth Satellites: A Wave Theory Treatment
William G. Melbourne

Deep Space Optical Communications
Hamid Hemmati, Editor

Spaceborne Antennas for Planetary Exploration
William A. Imbriale, Editor

Autonomous Software-Defined Radio Receivers for Deep Space Applications
Jon Hamkins and Marvin K. Simon, Editors

Low-Noise Systems in the Deep Space Network
Macgregor S. Reid, Editor

Coupled-Oscillator Based Active-Array Antennas
Ronald J. Pogorzelski and Apostolos Georgiadis

Low-Energy Lunar Trajectory Design
Jeffrey S. Parker and Rodney L. Anderson

Deep Space Communications
Jim Taylor, Editor

Radio Science Techniques for Deep Space Exploration
Sami W. Asmar

Spacecraft Optical Navigation
William M. Owen Jr.

Spacecraft Optical Navigation

William M. Owen Jr.
Jet Propulsion Laboratory
California Institute of Technology
California, USA

WILEY

Published by John Wiley & Sons, Inc., Hoboken, New Jersey.
Published simultaneously in Canada.

Library of Congress Cataloging-in-Publication Data applied for:

Hardback ISBN: 9781119904434

Cover Design: Wiley
Cover Image: © Andrey Armyagov/Shutterstock

Set in 9.5/12.5pt STIXTwoText by Straive, Chennai, India

Contents

List of Figures

Preface

The book which you, my dear reader, are now holding in your hands represents not only the summation of the author's 40-year career at the Jet Propulsion Laboratory but also the accumulated wisdom, gained from experience, of many of my past and current colleagues. A brief autobiography may help provide some context for the rest of the material.

I was in high school when Mariners 6 and 7 flew past Mars and just out of college when the Vikings landed on it. I came to JPL in December 1979, after the Voyagers' encounters with Jupiter and before they flew past Saturn. I hired into what was then called the Optical Measurements Analysis Group, and they set me to work finding opportunities for optical navigation pictures for Galileo. At that time launch was scheduled for 1982, with a flyby of Mars, and I led a small effort to improve the positions of stars behind Mars before the flyby. (I still have some plates taken by the 48-inch Schmidt telescope at Palomar.) The launch slipped, and that work went for naught.

By 1985 I was finally supporting Voyager, not in operations but rather in star catalog development. Before the HIPPARCOS mission, the newest catalogs had been produced by the Yale University Observatory in the 1930s, and the uncertainties in the stars' proper motion had rendered their positions obsolete. The Voyager project, for each encounter, had a contract with Lick Observatory (by then managed by the University of California, Santa Cruz) to take glass plates, measure the stars on them, reduce the data, and produce an *ad hoc* catalog. Their state-of-the-art measuring engine was controlled by a PDP-8 minicomputer, but their setup required approximate plate coordinates for each image to be measured. A "survey machine," also connected to that computer, would project a small part of a plate onto a screen. There were crosshairs on the screen, a joystick to move the plate around, and a button (on a rack over to the side) labeled RECORD. I shall leave the rest of it to the reader's imagination. Suffice it to say that I surveyed eight plates for Uranus and enjoyed the experience so much that I repeated it for Neptune and for Galileo's flybys of Gaspra and Ida.

Changes to Voyager's approach sequence, coupled with a realization that the operations team could actually perform their tasks faster than originally planned, permitted us to schedule a few more late pictures. Those background stars lay outside the region we had catalogued, and I found myself writing to Southern Hemisphere observatories to request positions for these stars. The replies invariably began "Dear Dr. Owen," and not willing to make liars out of them, I went to grad school in fall 1986, studying astrometry under Heinrich Eichhorn, escaping just in time to support the Neptune flyby.

Since that time I have supported just about every mission that required optical navigation: Galileo (to a limited extent), Near Earth Asteroid Rendezvous (later renamed NEAR Shoemaker), Cassini, Deep Space 1, Stardust, Deep Impact, and New Horizons. I have also played a small role in some European missions, most notably Rosetta.

In the early 1990s I participated in some advanced studies to figure out how spacecraft navigation would work in the era of optical communication. Radio tracking data, so important for so many years, would be supplanted by a combination of LIDAR-style ranging and good old-fashioned optical astrometry, because a downlink laser would look just like a star in a telescope. We therefore started a groundbased astrometry campaign, first to characterize the instrument and camera, then to obtain data for the Galilean and Saturnian satellites, Mathilde and Eros, all in support of Galileo, Cassini, and NEAR. Our observations of Mathilde moved its orbit by something like eight standard deviations, a result that of course met with some resistance. David Dunham, now retired from APL but still active in the International Occultation Timing Association, was on NEAR's mission design team. He asked us for astrometry for one particular asteroid, (170) Maria, that was about to occult a star. We obliged, the predicted path of the occultation moved by 10 times its width, and someone in the revised path watched the event. This success gave the NEAR team the courage to accept our Mathilde astrometry, which also turned out to be correct.

The experience with Maria and Mathilde was the genesis of a collaboration with IOTA that would last twenty years.

All good things must end, so they say, and as I enter retirement it behooves me to thank all those who have helped me along the way:

- my supervisors, Ken Rourke, Tom Duxbury, and especially Steve Synnott;
- my graduate advisor, Heinrich Eichhorn, who taught this know-it-all even more than I thought possible;
- my many optical navigation colleagues over the years, particularly Ed Riedel, Bob Gaskell, and Nick Mastrodemos;
- my current management team, Ralph Roncoli and Tung-Han You, who have been holding my feet to the fire;

- David Berry, Bill Taber, and Dimitrios Gerasimatos, who provided financial support; and finally
- Richard Waldo Hambleton, my grandfather, who woke me up in the middle of one March night in 1960 to show me an eclipse of the moon.

Thank you, all of you.

Acknowledgement

The research described in this book was carried out at the Jet Propulsion Laboratory, California Institute of Technology, under contract to the National Aeronautics and Space Administration.