LOW-ENERGY LUNAR TRAJECTORY DESIGN

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July 2013

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Jeffrey Parker:
I dedicate the majority of this book to my wife Jen, my best friend and greatest support throughout the development of this book and always. I dedicate the appendix to my son Cameron, who showed up right at the end.

Rodney Anderson:
I dedicate this book to my wife Brooke for her endless support and encouragement.

We both thank our families and friends for their support throughout the process.

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FOREWORD

The Deep Space Communications and Navigation Systems Center of Excellence (DESCANSO) was established in 1998 by the National Aeronautics and Space Administration (NASA) at the California Institute of Technology's Jet Propulsion Laboratory (JPL). DESCANSO is chartered to harness and promote excellence and innovation to meet the communications and navigation needs of future deep-space exploration.

DESCANSO's vision is to achieve continuous communications and precise navigation—any time, anywhere. In support of that vision, DESCANSO aims to seek out and advocate new concepts, systems, and technologies; foster key technical talents; and sponsor seminars, workshops, and symposia to facilitate interaction and idea exchange.

The Deep Space Communications and Navigation Series, authored by scientists and engineers with many years of experience in their respective fields, lays a foundation for innovation by communicating state-of-the-art knowledge in key technologies. The series also captures fundamental principles and practices developed during decades of deep-space exploration at JPL. In addition, it celebrates successes and imparts lessons learned. Finally, the series will serve to guide a new generation of scientists and engineers.

Joseph H. Yuen, DESCANSO Leader

PREFACE

The purpose of this book is to provide high-level information to mission managers and detailed information to mission designers about low-energy transfers between the Earth and the Moon. This book surveys thousands of trajectories that one can use to transfer spacecraft between the Earth and various locations near the Moon, including lunar libration orbits, low lunar orbits, and the lunar surface. These surveys include conventional, direct transfers that require 3–6 days as well as more efficient, low-energy transfers that require more transfer time but which require less fuel. Low-energy transfers have been shown to be very useful in many circumstances and have recently been used to send satellites to the Moon, including the two *ARTEMIS* spacecraft and the two *GRAIL* spacecraft. This book illuminates the trade space of low-energy transfers and illustrates the techniques that may be used to build them.

ACKNOWLEDGMENTS

We would like to thank many people for their support writing this book, including people who have written or reviewed portions of the text, as well as people who have provided insight from years of experience flying spacecraft missions to the Moon and elsewhere. It is with sincere gratitude that we thank Ted Sweetser for his selfless efforts throughout this process, providing the opportunity for us to perform this work, and reviewing each section of this manuscript as it has come together. We would like to thank Al Cangahuala, Joe Guinn, Roby Wilson, and Amy Attiyah for their valuable feedback and thorough review of this work in each of its stages. We would also like to thank Tim McElrath for his feedback, insight, and excitement as we considered different aspects of this research.

We would like to give special thanks to several people who provided particular contributions to sections of the book. We thank Ralph Roncoli for his assistance with Sections 2.3 and 2.4, as well as his feedback throughout the book. Kate Davis assisted with Sections 2.6.3 and 2.6.11.3, most notably with the discussions of Poincaré sections. Roby Wilson provided particular assistance with Section 2.6.5 on the subject of the multiple shooting differential corrector. We would like to sincerely thank Andrew Peterson for his contribution to the development of Chapter 4. Finally, George Born and Martin Lo provided guidance for this research as it developed in

its early stages, leading to the authors' dissertations at the University of Colorado at Boulder.

Jeffrey Parker's Ph.D. dissertation (J. S. Parker, *Low-Energy Ballistic Lunar Transfers*, Ph.D. Thesis, University of Colorado, Boulder, 2007) provides the backbone to this manuscript and much of the dissertation has been repeated and amplified in this book. Much of the additional material that appears in this manuscript has been presented by the authors at conferences and published in journals. Such material has been reprinted here, with some significant alterations and additions. Finally, a number of additional journal articles and conference proceedings directly contributed to each chapter in the following list. In addition to their listing here, they are cited in text where the related material appears.

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Jeffrey S. Parker & Rodney L. Anderson

AUTHORS

Jeffrey S. Parker received his B.A. in 2001 in physics and astronomy from Whitman College (Walla Walla, Washington) and his M.S. and Ph.D. in aerospace engineering sciences from the University of Colorado at Boulder in 2003 and 2007, respectively. Dr. Parker was a member of the technical staff at the Jet Propulsion Laboratory (JPL) from January 2008 to June 2012. While at JPL he supported spacecraft exploration as a mission design and navigation specialist. He worked both as a spacecraft mission designer and as a navigator on the GRAIL mission, which sent two spacecraft to the Moon via low-energy ballistic lunar transfers. He supported India's *Chandrayaan-1* mission to the Moon, also as a mission designer and spacecraft navigator. Dr. Parker led the mission design development for numerous design studies and mission proposals, including missions to the Moon, near-Earth objects, the nearby Lagrange points, and most of the planets in the Solar System. At present, Dr. Parker is an assistant professor of astrodynamics at the University of Colorado at Boulder, teaching graduate and undergraduate courses in many subjects related to space exploration. His research interests are focused on astrodynamics and the exploration of space, including the design of low-energy trajectories in the Solar System, the optimization of low-thrust trajectories in the Solar System, autonomous spacecraft operations, and use of these engineering tools to provide new ways to achieve scientific objectives.

Rodney L. Anderson received his B.S. in 1997 in aerospace engineering from North Carolina State University at Raleigh and his M.S. and Ph.D. in aerospace engineering sciences from the University of Colorado at Boulder in 2001 and 2005, respectively. Upon the completion of his Ph.D., he worked as a research associate at the University of Colorado at Boulder conducting a study for the U.S. Air Force that focused on understanding the effects of atmospheric density variations on orbit predictions. Dr. Anderson has been a member of the JPL technical staff since 2010 where he has participated in mission design and navigation for multiple missions and continues to work on the development of new methods for trajectory design. His research interests are concentrated on the application of dynamical systems theory to astrodynamics and mission design. Some specific applications that he has focused on are the design of lunar trajectories, tour and endgame design in the Jovian system using heteroclinic connections, missions to near-Earth asteroids, and low-energy trajectories in multi-body systems. He has worked closely with multiple universities and has taught at both the University of Colorado at Boulder and the University of Southern California with an emphasis on the intersection of dynamical systems theory with astrodynamics.