ESSENTIAL SPACEFLIGHT DYNAMICS AND MAGNETOSPHERICS

THE SPACE TECHNOLOGY LIBRARY

Published jointly by Microcosm Press and Kluwer Academic Publishers

An Introduction to Mission Design for Geostationary Satellites, J.J. Pocha
Space Mission Analysis and Design, 1st edition, James R. Wertz and Wiley J. Larson
Space Mission Analysis and Design, 2nd edition, Wiley J. Larson and James R. Wertz
Space Mission Analysis and Design, 3rd edition, James R. Wertz and Wiley J. Larson
Space Mission Analysis and Design Workbook, Wiley J. Larson and James R. Wertz
Handbook of Geostationary Orbits, E.M. Soop
Spacecraft Structures and Mechanisms, From Concept to Launch, Thomas P. Sarafin
Spaceflight Life Support and Biospherics, Peter Eckart
Reducing Space Mission Cost, James R. Wertz and Wiley J. Larson
The Logic of Microspace, Rick Fleeter
Space Marketing: A European Perspective, Walter A.R. Peeters
Fundamentals of Astrodynamics and Applications, David A. Vallado
Influence of Psychological Factors on Product Development, Eginaldo S. Kamata

The Space Technology Library Editorial Board

Managing Editor: **James R. Wertz**, *Microcosm, Inc., El Segundo, CA*

Editorial Board:

- Val A. Chobotov**, *The Aerospace Corporation (retired)*
- Michael L. DeLorenzo**, *United States Air Force Academy*
- Roland Doré**, *International Space University, Strasbourg, France*
- Robert B. Giffen**, *United States Air Force Academy (retired)*
- Gwynne Gurevich**, *Microcosm, Inc.*
- Wiley J. Larson**, *United States Air Force Academy*
- Tom Logsdon**, *Rockwell International (retired)*
- Landis Markley**, *Goddard Space Flight Center*
- Robert G. Melton**, *Pennsylvania State University*
- Keiken Ninomiya**, *Institute of Space & Astronautical Science, Japan*
- Jehangir J. Pocha**, *Matra Marconi Space, Stevenage, England*
- Frank J. Redd**, *Utah State University*
- Malcolm D. Shuster**, *University of Florida*
- Gael Squibb**, *Jet Propulsion Laboratory*
- Martin Sweeting**, *University of Surrey, England*

Essential Spaceflight Dynamics and Magnetospherics

by

Boris V. Rauschenbakh

*Department of Theoretical Mechanics,
Moscow Institute of Physics and Technology, Moscow, Russia*

Michael Yu. Ovchinnikov

*Keldysh Institute of Applied Mathematics,
Russian Academy of Sciences, Moscow, Russia,
and Department of Theoretical Mechanics,
Moscow Institute of Physics and Technology, Moscow, Russia*

Susan McKenna-Lawlor

*Space Technology Ireland Ltd,
National University of Ireland,
Maynooth, Co. Kildare, Ireland*

KLUWER ACADEMIC PUBLISHERS

NEW YORK, BOSTON, DORDRECHT, LONDON, MOSCOW

eBook ISBN: 0-306-48027-1
Print ISBN: 1-4020-1063-X

©2004 Kluwer Academic Publishers
New York, Boston, Dordrecht, London, Moscow

Print ©2003 Kluwer Academic Publishers
Dordrecht

All rights reserved

No part of this eBook may be reproduced or transmitted in any form or by any means, electronic, mechanical, recording, or otherwise, without written consent from the Publisher

Created in the United States of America

Visit Kluwer Online at: <http://kluweronline.com>
and Kluwer's eBookstore at: <http://ebooks.kluweronline.com>

This book is dedicated to our esteemed parents

*Victor Yakovlevich Rauschenbakh and Leontina Fedorovna
Rauschenbakh*

*Yuriy Fedorovich Ovchinnikov and Antonina Spiridonovna
Ovchinnikova*

*James Christopher McKenna and Margaret McKenna, née
Keane*

*with deep appreciation of their endless love, guidance and
inspiration.*

Preface

The present book **Essential Spaceflight Dynamics and Magnetospherics** describes, in the first instance, some of the key aspects of celestial mechanics and spaceflight dynamics. We begin with classical two and three body problems illustrative of the aesthetic aspects of applying analytical methods of investigation to celestial mechanics. Then, osculating orbital elements are introduced as well as analysis techniques sufficient to evaluate the influence of various disturbing forces on spacecraft. Next a theory of manoeuvres is outlined and the methodology of making interplanetary trajectory corrections. Ideas involving various approaches to orbital element determinations using measured data are also considered.

The forces applied to a spacecraft can result in the development of torques that influence attitude motion and the effects of the most important of these are described in terms of equilibrium positions, periodic motions, steady-state and transient motions. Also considered is the problem of attitude control of a spacecraft using active and/or passive methods of orientation and stabilization. In addition, a more advanced treatment of the development of attitude control systems is provided.

A description of the Earth's magnetic and gravitational fields allows us to clarify the relationship between natural features of the Earth's environment and the requirements of mission design, orbit construction and approaches to attitude control. A detailed Addendum provides an overview of circumstances on the Sun that render interplanetary space a very hazardous environment for spacecraft and for 'man in space'. The influence of this environment on spacecraft performance and survival is then presented, together with an outline of some of the mitigating strategies that can be invoked. A feature of the Addendum is the indication it provides of the challenges that the

next generation of space experiments will pose to mission designers. It is accompanied by a separate set of references since it refers to ongoing work in space physics rather than to classical material.

A set of appendices contain mathematical tools useful in making derivations and in obtaining formulae, but without the inclusion of detailed numerical data. There are many suitable reference books that provide material in this regard, some of which are listed in the references to individual Chapters. Other references relevant to the Chapters are contained in footnotes.

While it is assumed that readers of this book are familiar with mathematical analysis, differential equation theory, analytical mechanics and the theory of stability, the intention of the authors in Chapters 1 – 13 is to describe the main aspects of celestial mechanics and spaceflight dynamics without the use of complex mathematical formulae or the provision of examples of associated problem solving. This approach (breadth as opposed to depth) is for those readers who will deal in a general way only with space related topics. Chapters 14 – 22, which employ a more mathematically advanced treatment, are intended for readers interested at a specialist level in attitude dynamics and in the development of attitude control systems.

In the first fourteen chapters diagrams are frequently used to illustrate features of introductory spaceflight and attitude dynamics in lieu of complicated formula. In this regard, those innovative diagrams that were drawn manually by our co-author Boris Rauschenbakh, who died in 2001, are used in his memory with minimum changes. Only their inscriptions were rendered into English and, in some cases, an arrow over a letter or bold font was introduced to indicate a vector symbol. We hope that these visual presentations, with the historical dimension they provide through their association with Academician Rauschenbakh, will be attractive to those who are beginners in the area of astrodynamics, as well as to those who are already specialists, for whom they can serve to illuminate subtle details and provide new insights. The addition in footnotes of short historical biographies reflects the role of several centuries of international mathematicians in the achievement of space navigation and control.

The content concerned with spaceflight dynamics sprang initially from two courses of lectures for B.Sc., M.Sc. and Ph.D. students presented at the Moscow Institute of Physics and Technology. This

material has been significantly expanded here as well as modulated by the practical experience of the authors in developing international space projects in engineering, control, mechanics, and space physics over a period extending from the early days of this discipline up to the present time.

It is a pleasure to thank our associates, colleagues and friends for their support during the preparation of this book, and for the many important general discussions and personal contacts with them that stimulated new ideas and contributed a depth of experience. Among those we would particularly like to acknowledge in this regard are D.Okhotsimsky, V.Sarychev, N.Trukhan, V.Pen'kov, V.Sazonov, V.Rauschenbakh, I.Ritous and V.Kozminikh, all of whom made greatly valued inputs. Also, we extend our thanks to V.Beletsky, F.Graziani, M.Hapgood and M.Dryer who read our manuscript and made several important remarks.

Michael Yu.Ovchinnikov,
Moscow, Russia
ovchinni@keldysh.ru

Susan McKenna-Lawlor
Maynooth, Ireland
stil@may.ie

About the Authors

Rauschenbakh, Boris Victorovich (1915-2001). Doctor of Technical Science, Member of the Russian Academy of Sciences and the International Academy of Astronautics. One of the founders of practical cosmonautics in Russia. Worked in the 'Energia' Enterprise with Sergey Koroljev and later occupied the Chair of Theoretical Mechanics at the Moscow Institute of Physics and Technology.

Ovchinnikov, Michael Yurjevich, Doctor of Science in Physics and Mathematics at the Keldysh Institute of Applied Mathematics of the Russian Academy of Sciences and also a Professor at the Moscow Institute of Physics and Technology. Expert in mechanics, spaceflight dynamics and attitude control for small satellites.

McKenna-Lawlor, Susan, Emeritus Professor at the National University of Ireland, Maynooth. Guest Professor of the Chinese Academy of Sciences. Doctorate in Space Physics. Director of Space Technology Ireland, Ltd. Pioneering experiments flown on European, American, Russian and Chinese Space Agency Missions. Member of the International Academy of Astronautics. Recipient of the Tsiolkovsky Medal for Cosmonautics.

Table of Contents

Preface	v
About the Authors	ix
1 Two-Body Problem	1
1.1 Equations of Motion	1
1.2 Integral of Energy	4
1.3 The Area Integral	5
1.4 Laplace's Integral	7
1.5 Kepler's Laws	11
1.6 Kepler's Equation	13
2 Qualitative Analysis of Orbits	17
2.1 Orbit Evolution	17
2.2 Orbital Transfer	18
2.3 SC Braking in the Atmosphere	19
2.4 Interplanetary Flight	20
2.5 Circular Velocity	20
2.6 Escape Velocity	23
2.7 Hyperbolic Escape Velocity	23
3 Perturbed Motion	25
3.1 The n -Body Problem	25
3.2 Planetocentric Form of Equations	28
3.3 The Three-Body Problem	30
3.3.1 The Lagrange and Euler Cases	30
3.4 Restricted Three-Body Problem	33
3.4.1 Hill's Surface	34
3.4.2 Singular Points of a Zero-Velocity Surface	39

4	Gravispheres	43
4.1	Sphere of Attraction	44
4.2	Sphere of Influence	45
4.3	Kislik Gravisphere	50
5	Osculating Elements	57
5.1	Reference System and Orbital Elements	57
5.2	Equations of Perturbed Motion	60
5.2.1	Introduction of Osculating Elements	61
5.2.2	Definition of the ‘Main Operation’	62
5.2.3	Equations for Osculating Elements	62
5.2.4	Transformation to the Argument of Latitude	69
6	Braking in the Earth’s Atmosphere	71
6.1	Qualitative Analysis	71
6.2	The Descending SC ‘Paradox’	76
7	Terrestrial Nonsphericity	79
7.1	Introduction to Models	79
7.2	Oblateness of the Gravitational Field	81
7.3	Calculation of Perturbing Accelerations	84
7.4	Evolution of the Equatorial Orbit	86
7.5	Precession of the Inclined Orbit	88
7.6	Clarification of ‘Inconsistency’	90
7.7	Orbits with Specific Inclinations	92
8	SC in the Field of Two Centers	97
9	Elements of Manoeuvring Theory	103
9.1	Statement of the Problem	103
9.2	Orbital Plane Orientation Changing	108
9.3	In-plane Manoeuvres	111
9.3.1	Effect of a Tangent Pulse ΔV_T	112
9.3.2	Effect of a Normal Pulse ΔV_S	114
9.3.3	Manoeuvre of Landing a SC	115
9.3.4	Change of the Period of SC Revolution	117

10 Trajectory Corrections	119
10.1 SC Motion Close to a Target Planet	120
10.2 Segment of a Nominal Trajectory	122
10.3 Properties of the Correction	124
10.4 Two-parameter Correction	126
10.5 Optimum Correction Point	127
10.6 Singularity of the Correction Matrix	129
10.7 Correction Using the Singular Matrix	131
11 Rendezvous Manoeuvring	133
11.1 Control-Free Relative Motion	133
11.2 Approaches to Rendezvous Manoeuvring	135
12 Gravity-Assist Manoeuvre	139
12.1 Description of the Manoeuvre	139
12.2 Application for Interplanetary Missions	143
12.3 Inclination Change of the Orbit	145
13 About Orbit Determination	149
13.1 Least Square Method	150
13.2 Concept of Recurrent Methods	152
14 Introduction to Attitude Control	155
14.1 Types of Attitude Control Systems	155
14.2 Scheme for SC Active Attitude Control	160
14.2.1 Estimation of Propellant Consumption	162
14.2.2 Effect of a Constant Perturbing Torque	165
14.3 SC Gyros for Attitude Control	169
14.3.1 Bounded Angular Momentum of a SC	170
14.3.2 Unbounded Angular Momentum of a SC	171
15 Gravity-Gradient Torque Effect	173
15.1 General Assumptions	173
15.2 Reference Systems	175
15.3 Kinematic Relationships	178
15.4 Gravity-Gradient Torque	179
15.5 Equations of SC Motion	183

16 SC Motion in a Circular Orbit	185
16.1 Planar Motion of a SC	185
16.2 SC Equilibrium Positions	192
16.3 Sufficient Conditions for Stability	195
16.4 Necessary Conditions for Stability	197
17 SC Motion in an Elliptical Orbit	201
17.1 Equation of Planar SC Motion	201
17.2 Linear Librations	203
17.2.1 Stability of the Solution of Mathieu's Equation	205
17.3 Non-linear Librations	207
17.4 Periodic Motion of a SC	209
17.4.1 Solutions for Slightly Elliptical Orbits	209
17.4.2 Numerical Investigation	212
18 Spinning Axisymmetric SC	219
18.1 Equations of Motion	219
18.2 Stationary Motions of a SC	221
18.3 Conditions of Stability	224
19 Equilibrium of a Gyrostat	227
19.1 Equations of Motion	227
19.2 Particular Cases of Equilibrium Positions	229
20 Effect of Aerodynamic Torque	233
20.1 General Assumptions	233
20.2 Atmospheric Density Approximation	237
20.3 Effect of the Earth's Rotation	240
20.4 Equilibrium Positions	242
21 SC in the Geomagnetic Field	247
21.1 The Geomagnetic Field	247
21.2 Models of the Geomagnetic Field	250
21.2.1 Dipole Terms ($n=1$)	250
21.2.2 Quadrupole Terms ($n=2$)	253
21.2.3 Octupole Terms ($n=3$)	254
21.3 Equations of Motion	255
21.4 SC Planar Motion	259
21.4.1 Asymptotic Solution	259

21.4.2 Numerical Construction of Periodic Solutions	260
21.4.3 Investigation of Stability	265
21.5 SC Spatial Motion	268
22 Motion of a SC under Damping	275
22.1 Equations of Motion	276
22.2 Fast Time. Equations of Motion in Standard Form	280
22.3 Averaging the Equations of Motion	283
22.4 Two Orthogonal Rods	285
22.4.1 Case without Hysteresis Rods	286
22.4.2 Case of Weak Damping	287
Appendices	291
A Method of van der Pol	291
B Periodic Equations	293
C Poincare's Method	297
Bibliography	299
Addendum. The Space Environment	303
A.1 Solar Activity and Near Earth Space	303
A.1.1 The Sun and the Solar Wind	303
A.1.2 Co-rotating Interaction Regions	304
A.1.3 The Solar Cycle	305
A.1.4 Solar Flares	307
A.1.5 Coronal Mass Ejections	307
A.1.6 Prediction of Proton Events	309
A.1.7 Numerical Modeling	310
A.1.8 The Earth's Magnetosphere	312
A.1.9 Particle Populations in the Magnetosphere	315
A.1.10 Galactic Cosmic Rays	315
A.1.11 The Van Allen Belts	316
A.1.12 Particle Motion in the Geomagnetic Field	318
A.1.13 The South Atlantic Anomaly	320
A.1.14 Magnetic Storms	320
A.1.15 External Magnetic Field Models	323

A.1.16	Relativistic Electrons	325
A.1.17	Thermospheric Heating	327
A.1.18	Atmospheric Drag	327
A.1.19	Solar Radiation Pressure	330
A.1.20	Solar Sailing	332
A.1.21	Perturbing Effects on Orbiting SC	332
A.1.22	Drag Free SC and their Applications	334
A.2	The Environment and SC Performance	337
A.2.1	Electronics and Energetic Particle Radiation	337
A.2.2	Models of near Earth Energetic Particles	339
A.2.3	Radiation Models for Mission Evaluations	340
A.2.4	SC Charging	342
A.2.5	SC Contamination	347
A.2.6	Sputtering from SC Surfaces	348
A.2.7	Corrosive Oxygen	348
A.2.8	Thermal Problems	350
A.2.9	Ambient Electric and Magnetic Fields	351
A.3	Overview of In-Orbit Disturbances	352
A.3.1	Surface and Internal Charging	356
A.3.2	Phantom Commands	358
A.3.3	Total Ionizing Dose and Single Event Effects	359
A.3.4	Solar Cell Degradation and Displacement Damage	359
A.3.5	Loss of Attitude Control/Orientation	360
A.3.6	Loss of Signal Phase and Amplitude Lock	360
A.3.7	Solar Radio Interference	361
A.3.8	Orbit Decay	361
A.3.9	Biological Effects	362
A.3.10	Interplanetary Conditions	364
A.4	Beyond the Solar System	365
List of References for Addendum		367
Index of Scientists Cited in Footnotes		375
Index		377
List of Figures		391
List of Tables		397