

Essential Spaceflight Dynamics and Magnetospheric



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
Dordrecht / Boston / London

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