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ACS Without an Attitude

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This book is dedicated to the many students/colleagues that attended the lectures, whose active participation greatly improved the lectures and this book.

Preface

If you do a casual search for books that contain the word attitude in their title, you'll find yourself drowning in a sea of over 500 volumes. Of course, most of those books relate more to personal self-improvement than to spacecraft dynamics, but even when the subject is limited to the areas of aerospace and astrodynamics you'll still find a fair number of items from which to choose. So, what distinguishes this text from those many other candidates? This book attempts to de-emphasize the formal mathematical description of spacecraft onboard attitude and orbit applications in favor of a more qualitative, concept-oriented presentation of these topics (whether or not we ultimately achieved that goal is something we'll have to leave to you, dear reader, to decide). As such, it would most likely be described by an attitude control analyst as a (hopefully) amusing light read rather than an essential reference bible. And it certainly would not be the first text an Attitude Control Subsystem (ACS) flight software (FSW) designer would grab if he needed a specification of a Kalman filter algorithm. ACS Without an Attitude is instead intended for programmers and testers new to the field who are seeking a commonsense understanding of the subject matter they're coding and testing in the hope that they'll reduce their risk of introducing or missing the key software bug that causes an abrupt termination in their spacecraft's mission and their careers.

ACS Without an Attitude is organized in four major sections. Section One (Chaps. 1–3) contains the attitude, orbit, and dynamics background material required to understand the downstream spacecraft applications. Section Two (Chaps. 4 and 5) is a survey of the spacecraft sensors and actuators used to measure and control the spacecraft attitude and orbit. Section Three (Chaps. 6–11) examines how sensor data is combined with reference data to measure attitude and orbit, and how desired or commanded attitude parameters are compared with measured attitude parameters to determine what should be done to maintain the current pointing, or modify it to satisfy future needs. Finally, Section Four (Chap. 12) is a survey of mission characteristics and how attitude and orbit geometries are selected to accomplish mission objectives.

The information presented in these sections was originally collected to support an informal set of lectures in 1999 and 2000 instigated by my Branch Chief, Elaine

Shell (Flight Software Branch, NASA Goddard Space Flight Center), who also realized that bullet charts are an ineffective means to document information, hence this book. The following is a list of textbooks and documents I drew on (hopefully not too blatantly) while preparing for my talks, as well as additional references used when writing this book:

1. Spacecraft Attitude Determination and Control, edited by James R. Wertz, Kluwer Academic Publishers (1978).
2. Space Mission Analysis and Design, edited by Wiley J. Larson and James R. Wertz, Microcosm, Inc. and Kluwer Academic Publishers (1992).
3. Reducing Space Mission Cost, edited by James R. Wertz and Wiley J. Larson, Microcosm Press and Kluwer Academic Publishers (1996).
4. Satellite Technology and Its Applications, by P.R.K. Chetty, TAB Professional and Reference Books (1991).
5. An Introduction to the Mathematics and Methods of Astrodynamics, by Richard H. Battin, AIAA Education Series (1987).
6. Modern Inertial Technology Navigation, Guidance, and Control, by Anthony Lawrence, Springer (1998).
7. Modern Control Systems, by Richard C. Dorf and Robert H. Bishop, Addison-Wesley Publishing Company (1995).
8. Feedback Control of Dynamic Systems, by Gene F. Franklin, J. David Powell, and Abbas Emami-Naeini, Addison-Wesley Publishing Company (1991).
9. Modern Control Engineering, by Katsuhiko Ogato, Prentice-Hall (1997).
10. Goddard Trajectory Determination System (GTDS) Mathematical Theory, Revision 1, edited by A.C. Long, J.O. Cappellari, Jr., C.E. Velez, and A.J. Fuchs, NASA/GSFC Flight Dynamics Division Code 550 (1989).
11. Fundamentals of Astrodynamics, by Roger R. Bate, Donald D. Mueller, and Jerry E. White, Dover Publications, Inc. (1971).
12. Classical Mechanics, by Herbert Goldstein, Addison-Wesley Publishing Company (1950).
13. Fundamentals of Spacecraft Attitude Determination and Control, by Landis F. Markley and John L. Crassidis, Springer Science and Business Media (2014). (An excellent book for both subject history and in-depth mathematical analysis.)

In addition, here are some references targeted to specific topics discussed in the later chapters:

1. Hermite Polynomials, Legendre polynomials, and spherical harmonics: Mathematical Methods for Physicists (seventh edition), by G. Arfkin, H. Weber and F. Harris, Academic Press, Inc. (2013), Sect. 18.1.
2. Runge-Kutta integrator: Numerical Methods for Scientists and Engineers by R.W. Hamming, McGraw-Hill (1962).

One of the strengths of my original set of lectures was the participation of several of my NASA/GSFC Guidance, Navigation, and Control (GN&C) colleagues who supplemented (and often, and graciously, corrected) my presentations with material drawn from their extensive experience here at GSFC. And when my pitches started to drag a bit, they also helped liven things up by recounting some of their many war stories accumulated during their years of applying clean-cut mathematical algorithms to uncooperative real-life spacecraft. My crew of semi-regular experts included

1. Gary Welter
2. Landis Markley
3. Dave Quinn
4. Dave McGlew
5. Bruce Bromberg

As the years have rolled by since the first version of the manuscript, the material in the book has been updated many times, stimulated by new missions and new ACS technologies, as well as new teaching experiences gained repeating the course. Finally, as I reached the point I could no longer bear to edit the material again, Gary Welter, Dave Simpson, and Chris Rouff have ridden to the rescue to co-author with me this final version.

Lou Hallock—2010

Well … life goes on, including delays from other obligations. Lou passed the torch to us, his three amigos, when he retired in 2011, along with encouragement to put our own stamp on the book (sometimes with a “you broke it, you bought it” response to editorial suggestions). We’ve also corralled a couple of colleagues (Scott Starin and Tim McGee) to provide some review and feedback on the near-final text. (Our thanks to you both.) So, here is the multi-chef result, we think well-flavored—though some of you may find certain sections more “in your face” than “without an attitude”. Time to let it go. Enjoy.

Gary Welter, Dave Simpson and Chris Rouff—2016

Contents

Acronyms

ACE	Attitude Control Electronics
ACS	Attitude Control Subsystem
AOS	Acquisition of Signal
AST	Advanced Star Tracker
AU	Astronomical Unit
CCD	Charge-Coupled Device
CDR	Critical Design Review
CGRO	Compton Gamma Ray Observatory
CPU	Central Processing Unit
CSA	Celestial Sensor Assembly
CSS	Coarse Sun Sensor
CXO	Chandra X-Ray Observatory
DCM	Direction Cosin Matrix
DSCOVR	Deep Space Climate Observatory
DoD	Department of Defense
DOY	Day of Year
DSS	Digital Sun Sensor
ECI	Earth-centered Inertial
emf	Electromotive force
EOS	Earth Observing System
ESA	European Space Agency
ESA	Earth Scanner Assembly
FDF	Flight Dynamics Facility
FEEP	Field Emission Electric Propulsion
FES	Fine Error Sensor
FGS	Fine Guidance Sensor
FHST	Fixed-Head Star Tracker
FOG	Fiber Optic Gyro
FOV	Field of View
FSS	Fine Sun Sensor

FSW	Flight Software
GCI	Geocentric Inertial
GEO	Geosynchronous Earth Orbit
GMT	Greenwich Mean Time
GOES	Geostationary Operational Environmental Satellite
GPS	Global Positioning System
GSFC	Goddard Space Flight Center
GTDS	Goddard Trajectory Determination System
HCI	Heliocentric Inertial
HEAO-2	High Energy Astronomy Observatory-2
HGA	High-Gain Antenna
HRG	Hemispheric Resonating Gyro
HST	Hubble Space Telescope
ICOB	Inclined-Center-of-Box
IFOG	Interferometric Fiber Optic Gyro
IFOV	Instantaneous Field of View
IGRF	International Geomagnetic Reference Field
IR	Infrared
IRU	Inertial Reference Unit
ISEE-1	International Sun–Earth Explorer-1
IUE	International Ultraviolet Explorer
JD	Julian Day
JPL	Jet Propulsion Laboratory
JWST	James Webb Space Telescope
KSC	Kennedy Space Center
LISA	Laser Interferometer Space Antenna
LEO	Low Earth Orbit
LMSC	Lockheed Missiles and Space Company
LOS	Loss of Signal
L-R-C	Inductance Resistance Capacitance
LVA	Local Vertical Acquisition
MJD	Modified Julian Day
MT	Magnetic Torquer
MTB	Magnetic Torquer Bar
NASA	National Aeronautics and Space Administration
NCC	Network Control Center
NMR	Nuclear Magnetic Resonance
OBC	Onboard Computer
PD	Proportional–Derivative
PI	Proportional–Integral
PID	Proportional–Integral–Derivative
RFOV	Reduced Field of View
RG	Rate Gyro
RGA	Rate Gyro Assembly
RIG	Rate Integrating Gyro

RLG	Ring Laser Gyro
RPO	Revolution Per Orbit
RWA	Reaction Wheel Assembly
RXTE	Rossi X-ray Timing Explorer
SAMPEX	Solar Anomalous and Magnetospheric Particle Explorer
SDOF	Single-Degree-of-Freedom
SI	Science Instrument
SLP	Solar-Lunar-Planetary
SMM	Solar Maximum Mission
SOHO	Solar and Heliospheric Observatory
ST 5	Space Technology 5
TAI	International Atomic Time
TAM	Three-Axis Magnetometer
TDB	Barycentric Dynamical Time
TDT	Terrestrial Dynamical Time
TDOF	Two-Degree-of-Freedom
TDRS	Tracking Data and Relay Satellite
TDRSS	Tracking Data and Relay Satellite System
TFOV	Total Field of View
TONS	TDRSS Onboard Navigation System
TRIAD	Tri-Axial Attitude Determination
TRMM	Tropical Rainfall Measuring Mission
TT	Terrestrial Time
UT	Universal Time
UTC	Universal Time Coordinate
WMAP	Wilkinson Microwave Anisotropy Probe
YGC	Yaw Gyro Control