Preface

The modern field of orbit determination (OD) originated with Kepler's interpretations of the observations made by Tycho Brahe of the planetary motions. Based on the work of Kepler, Newton was able to establish the mathematical foundation of celestial mechanics. During the ensuing centuries, the efforts to improve the understanding of the motion of celestial bodies and artificial satellites in the modern era have been a major stimulus in areas of mathematics, astronomy, computational methodology and physics. Based on Newton's foundations, early efforts to determine the orbit were focused on a deterministic approach in which a few observations, distributed across the sky during a single arc, were used to find the position and velocity vector of a celestial body at some epoch. This uniquely categorized the orbit. Such problems are deterministic in the sense that they use the same number of independent observations as there are unknowns.

With the advent of daily observing programs and the realization that the orbits evolve continuously, the foundation of modern precision orbit determination evolved from the attempts to use a large number of observations to determine the orbit. Such problems are over-determined in that they utilize far more observations than the number required by the deterministic approach. The development of the digital computer in the decade of the 1960s allowed numerical approaches to supplement the essentially analytical basis for describing the satellite motion and allowed a far more rigorous representation of the force models that affect the motion.

This book is based on four decades of classroom instruction and graduate-level research. The material has been derived from and shared with numerous colleagues and students. In addition to the contributions of these individuals, the material has been influenced by the approaches used at the NASA Jet Propulsion Laboratory (JPL) to fulfill Earth and planetary navigation requirements and at the NASA Goddard Space Flight Center (GSFC) and the Department of Defense Naval Surface Weapons Center in applications of satellite tracking to problems in geodesy, geodynamics, and oceanography. Various implementations of the techniques described have been accomplished over the years to meet the requirements to determine the orbit of specific spacecraft.

This book is focused on developing data processing techniques for estimating the state of a non-linear dynamic system. The book contains six chapters and eight appendices, each covering a unique aspect of the OD problem. Although the concepts will be discussed primarily in the context of Earth-orbiting satellites or planetary transfers, the methods are applicable to any non-linear system and have been applied to such widely diverse problems as describing the state of economic systems, chemical processes, spacecraft attitude, and aircraft and missile guidance and navigation.

In Chapter 1, the inherent characteristics of the OD problem are introduced in the context of a very simple dynamic problem. The concepts of the dynamic system and its associated state are introduced. The fact that essentially all observations are non-linear functions of the state variables and the complexities associated with this are discussed. The classical or well-determined problem and the over-determined problem are described as examples of the approaches used in the following chapters.

Chapter 2 lays the background for the OD problem by introducing the relevant elements of orbital mechanics. The concept of perturbed two body motion and its role in the description of orbital motion is discussed. The fundamental forces acting on the satellite are described, especially within the context of an accurate description of the orbit. Finally, the definitions of the coordinate systems used to describe the motion and the time conventions used to index the observations and describe the satellite position are given.

Chapter 3 describes the various types of observations that are used to measure the satellites motion. This includes ground-based systems such as laser and radiometric, as well as space-based measurements from the Global Positioning System. Error sources and media corrections needed for these observation types also are described. In the problem of orbit determination, the observations described in this chapter will be the input to the estimation methodologies in the following chapters.

In Chapter 4, the orbit problem is formulated in state space notation and the non-linear orbit determination problem is reduced to an approximating linear state estimation problem by expanding the system dynamics about an *a priori* reference orbit. This concept allows application of an extensive array of mathematical tools from linear system theory that clarify the overall problem and aid in transferring the final algorithms to the computational environment. Chapter 4 also introduces the important concept of sequential processing of the observations, and the relation to the Kalman Filter, and relates the algorithm to the observation and control of real time processes.

Chapter 5 addresses issues related to the numerical accuracy and stability of the computational process, and formulates the square root computational algorithms. These algorithms are based on using a series of orthogonal transformations to operate on the information arrays in such a way that the requirement for formation of the normal equations is eliminated. The approach is used to develop both batch and sequential data processing algorithms.

Chapter 6 explores the very important problem of assessing the effect of error in unestimated measurement and force model parameters. The effects of incorrect statistical information on the *a priori* state and observation noise are examined and the overall process is known as consider covariance analysis.

The eight appendices provide background and supplemental information. This includes topics such as probability and statistics, matrix algebra, and coordinate transformations.

The material can be used in several ways to support graduate or senior level courses. Chapters 1, 3, and 4, along with Appendices A, B, F, and G provide the basis for a one-semester OD class. Chapters 5 and 6, along with Appendix A, provide the basis for a one-semester advanced OD class. Chapter 2 could serve as supplemental information for the first semester class as well as an introductory orbit mechanics class. Each chapter has a set of problems selected to emphasize the concepts described in the chapter.

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Web Sites

Relevant information can be found on the World Wide Web (www). However, the www does not provide a stable source of information comparable to a published document archived in a library. The following list of www sites was valid just prior to the publication date of this book, but some may no longer be functional. Use of readily available search engines on the www may be useful in locating replacement or new sites.

- Ancillary Information for *Statistical Orbit Determination*

  Academic Press
  http://www.academicpress.com/companions/0126836302

  Center for Space Research (CSR, University of Texas at Austin)
  http://www.csr.utexas.edu/publications/statod

  Colorado Center for Astrodynamics Research
  (CCAR, University of Colorado at Boulder)
  http://www-ccar.colorado.edu/statod

- Online Dissertation Services

  UMI (also known as University Microfilms)
  http://www.umi.com/hp/Products/Dissertations.html

- Satellite Two Line Elements (TLE)

  NASA Goddard Space Flight Center
  http://oig1.gsfc.nasa.gov (registration required)

  Dr. T. S. Kelso
  http://celestrak.com

  Jonathan McDowell's Home Page
  http://www.planet4589.org/space/

- Earth Orientation, Reference Frames, Time

  International Earth Rotation and Reference Frames Service (IERS)
  http://www.iers.org

  Observatoire de Paris Earth Orientation Center
  http://hpiers.obspm.fr/eop-pc/

  IERS Conventions 2003
  http://maia.usno.navy.mil/conv2003.html

  National Earth Orientation Service (NEOS)
  http://maia.usno.navy.mil

  International Celestial Reference Frame (ICRF)
  http://hpiers.obspm.fr/webiers/results/icrf/README.html

  International Terrestrial Reference Frame (ITRF)
  http://lareg.ensg.ign.fr/ITRF/solutions.html

  U. S. Naval Observatory Time Service
  http://tycho.usno.navy.mil/

- Space Geodesy Tracking Systems

  International GPS Service (IGS)
  http://igscb.jpl.nasa.gov

  International Laser Ranging Service (ILRS)
  http://ilrs.gsfc.nasa.gov

  International VLBI Service for Geodesy and Astrometry (IVS)
  http://ivscc.gsfc.nasa.gov

  International DORIS Service (IDS)
  http://ids.cls.fr/

- Global Navigation Satellite Systems

  GPS
  http://gps.losangeles.af.mil/

  GLONASS
  http://www.glonass-center.ru/

  GALILEO
  http://www.europa.eu.int/comm/dgs/energy_transport/galileo/

Web pages for particular satellite missions are maintained by the national space agencies.