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Book Review

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Statistical Orbit Determination

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The authors state in the preface, "This book is focused on developing data processing techniques for estimating the state of a nonlinear dynamic system," with particular emphasis on "the field of orbit determination." Here, orbit determination means the process by which knowledge of a satellite's motion is obtained relative to the center of mass of the Earth in a specified coordinate system. The authors specifically emphasize noncelestial bodies, that is, objects placed into orbit by humans, since the nongravitational forces are significantly important. The stated intent of the book is to formulate and solve the orbit determination problem, which involves determining the best state estimate at some epoch using a combination of a mathematical model with observational data such as range, azimuth, and elevation.

The book comprises six chapters and eight appendices. The first chapter provides an introduction to orbit determination concepts, which includes a well-treated overview on the history of orbit determination. Chapter 2 presents the orbital dynamics equations of motion for two bodies, which includes a thorough treatise on both gravitational and nongravitational perturbations as well as common coordinate systems. Chapter 3 provides observations models, coupled with nonideal effects due to the atmosphere and other effects. Modern-day use of the GPS for low-Earth orbiting spacecraft is also shown. Chapter 4 focuses on mathematical techniques to estimate orbits, which include batch methods such as least squares, as well as sequential methods such as the Kalman filter. Typical error sources associated with satellite force models and measurement models are also discussed. Chapter 5 discusses issues related to the numerical accuracy and computational stability of the algorithms shown in Chapter 4, and formulates more stable algorithms based on square root computations. Chapter 6 provides an assessment of the effects of error in the unestimated measurement and force model parameters through a covariance analysis. The eight appendices provide background and supplemental information in the areas of probability and statistics, matrix concepts, various forms of the equations of motion, analytical theory of near-circular orbits, dynamic model compensation, and transformations between coordinate systems.

The book is aesthetically very well written. The chapters progress in a logical fashion. In particular, the first three chapters provide all the necessary background material to perform statistical orbit determination. The appendices are very complete with excellent reviews of probability and statistical theory as well as matrix algebra. The theory of statistical orbit determination relies heavily on estimation theory. The authors provide a thorough background review of this theory, starting with batch least squares and moving to sequential methods such as the extended Kalman filter (EKF). Several flowcharts of these algorithms are provided, which allows for easy mechanization of the relevant equations. Intrinsic with these algorithms is the statistical characteristics of the measurement errors with complete discussions on the concepts of minimum variance, maximum likelihood, and Bayesian estimation. Clearly, the authors used a deliberate and meaningful thought process in the preparation of this book.

Several practical discussions are given as well. For example, an excellent discussion is given on the combination of the Chandler and annual periods that result in a variation of the Earth's rotation rate. Several expressions for the relevant time systems are also shown. The authors also provide a complete analysis of various orbital perturbations such as oblateness effects, third-body effects, and relativistic effects. Furthermore, a significant effort is given on matrix factorization methods to overcome filter instabilities, which are often associated with the orbit determination problem. In particular, several orthogonal transformations are shown with numerical recipes. Sequential algorithms are also provided, including Potter's square root update, the *U-D* covariance factorization, and the square root information filter (SRIF). The detailed explanations of these variants provide a clear understanding of the overall programming aspects of each algorithm.

The intended audience includes first-year graduate or senior-level undergraduate students. Chapters 5 and 6 can also be used to form a basis for an advanced course. Several exercises and problem sets are provided at the end of each chapter. These range from simple analytical analyses to complex numerical problems and simulations. Several practical examples are scattered throughout the text as well. For example, several sections of Chapter 3 provide actual data plots for practical solutions to orbit determination using various measurements. These aspects enhance the pedagogical experience. Practicing engineers will also find the book useful. For example, "Consider Covariance Analysis" of Chapter 6 shows the impact of ignoring certain unknown or poorly known parameters on the overall estimation process, backed up with several explanatory examples. Clearly, the authors have invoked a "learn by doing" approach in preparing this book.

The book is very well produced with no obvious errors in the technical content. A thorough table of contents and index are provided. The references are numerous, which sufficiently back up the derived theory. On several occasions the authors give specific bibliographic references to enhance the particular discussions. Backup material is also provided through web links, several to actual satellite missions. Since most of these are maintained by national space agencies, they should be readily available for many years to come.

The book provides a solid theoretical foundation of the concepts with practical insights to various problems that arise during the solution process. The several examples shown in the text give a clear understanding of the concepts. A small section that shows results using actual data with the sequential matrix factorization algorithms of Chapter 5 would make the book truly exceptional. For example, numerical comparisons between the standard EKF and the SRIF would be particularly useful. Still, to this reviewer's knowledge, other books as thorough as this on the subject of statistical orbit determination are not currently available, which attests to the authors' effectiveness in providing a useful resource that builds upon the deterministic methods of Refs. [1,2]. In this regard the book should become an instant classic.

In summary, *Statistical Orbit Determination* successfully fills the gap between the theory of estimation and practical orbit determination applications in the face of uncertainties. The student should find this book to be an invaluable tool coupled with a solid theoretical framework in the classroom. The practicing engineer should find this book to be a useful reference for understanding the issues involved with practical orbit determination. Both the student and the practicing engineer will especially appreciate the several examples backed up with significant discussions. This book should be a valuable addition to an individual's collection or to an institution's library.

References

[1] Escobal, P. R., *Methods of Orbit Determination*, Krieger Publishing Company, Malabar, FL, 1976.

[2] Battin, R. H., *An Introduction to the Mathematics and Methods of Astrodynamics*, AIAA, New York, 1987.

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