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Space systems — Orbit determination and estimation — Process for describing techniques

Systèmes spatiaux — Détermination et estimation de l'orbite — Processus pour la description des techniques

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Foreword

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The committee responsible for this document is ISO/TC 20, *Aircraft and space vehicles*, Subcommittee SC 14, *Space systems and operations*.

Introduction

This Technical Report prescribes the manner in which satellite owners/operators describe techniques used to determine orbits from active and passive observations and the manner in which they estimate satellite orbit evolution.

The same data inputs lead to different predictions when they are used in different models. Satellite owners/operators shall often accept orbit descriptions developed with physical models that others employ. The differences in orbit propagation as a result of using different physical models and numerical techniques can be significant. Safe and cooperative operations among those who operate satellites demand that each satellite owner/operator understand the differences among their approaches to orbit determination and propagation.

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Space systems — Orbit determination and estimation — Process for describing techniques

1 Scope

This Technical Report prescribes the manner in which orbit determination and estimation techniques are to be described so that parties can plan operations with sufficient margin to accommodate different individual approaches to orbit determination and estimation. This Technical Report does not require the exchange of orbit data nor does it prescribe a method of performing orbit determination. It only prescribes the information that shall accompany such data so that collaborating satellite owners/operators understand the similarities and differences between their independent orbit determination processes.

All satellite owners/operators are entitled to a preferred approach to physical approximations, numerical implementation, and computational execution of orbit determination and estimation of future states of their satellites. Mission demands should determine the architecture (speed of execution, required precision, etc.). This Technical Report will enable stakeholders to describe their techniques in a manner that is uniformly understood. Implementation details that can have proprietary or competitive advantage need not be revealed.

2 Symbols and abbreviated terms

BDRF	Bidirectional Reflectance Function
FPA	Flight Path Angle
GPS	Global Positioning System
HEO	High Earth Orbit
IOD	Initial Orbital Determination
LEO	Low Earth Orbit
LS	Least Squares
OD	Orbital Determination
RAAN	Right Ascension of the Ascending Node
RMS	Root Mean Square
SP	Sequential Processing
TLE	Two-line Elements
UTC	Coordinated Universal Time

3 Background

3.1 General

Satellite orbit determination (OD) estimates the position and velocity of an orbiting object from discrete observations. The set of observations includes external measurements from terrestrial or space-based sensors and measurements from instruments on the satellite itself. Satellite orbit propagation estimates the future state of motion of a satellite whose orbit has been determined from past observations. Though a satellite's motion is described by a set of ideal equations of motion representing physical hypotheses, the observations used in OD are subject to systematic and random uncertainties. Therefore, OD and propagation are probabilistic and can only approximately describe the satellite's motion. The degree of approximation that can be tolerated depends on the intended use of the orbital information.

A spacecraft is influenced by a variety of external forces, including terrestrial gravity, atmospheric drag, multibody gravitation, solar radiation pressure, tides, and spacecraft thrusters. Selection of forces for modelling depends on the accuracy and precision required from the OD process and the amount of available data. The complex modelling of these forces results in a highly nonlinear set of dynamical equations. Many physical and computational uncertainties limit the accuracy and precision of the spacecraft state that can be determined. Similarly, the observational data are inherently nonlinear with respect to the state of motion of the spacecraft and some influences might not have been included in models of the observation of the state of motion.

Satellite OD and propagation are stochastic estimation problems because observations are inherently noisy and uncertain and because not all of the phenomena that influence satellite motion are clearly discernable. Estimation is the process of extracting a desired time-varying signal from statistically noisy observations accumulated over time. Estimation encompasses data smoothing, which is statistical inference from past observations; filtering, which infers the signal from past observations and current observations; and prediction or propagation, which employs past and current observations to infer the future of the signal.

This Technical Report and related ISO documents employ the term "orbit data." Orbit data encompasses all forms of data that contribute to determining the orbits of satellites and that report the outcomes of orbit determination in order to estimate the future trajectory of a satellite. This includes observations of satellite states of motion either through active illumination, as with radars, or through passive observation of electromagnetic energy emitted or reflected from satellites, as with telescopes.

It is desirable to keep each space orbit standard as simple as possible, treating the form and content of orbit data exchange, description of the modelling approach, and other relevant but independent aspects individually. It is hoped that this will develop a sufficient body of standards incrementally, not complicating matters for which there is consensus with matters that might be contentious.

Most in the space community employ a variation of only a few major architectures. These architectures are cited in many texts and references that need not be enumerated in this document.

OD begins with observations from specified locations and produces spacecraft position and velocity, all quantities subject to quantifiable uncertainty.

3.2 Initial orbit determination

Initial OD (IOD) methods input tracking measurements with tracking platform locations, and output spacecraft position and velocity estimates. No a priori orbit estimate is required. Associated solution error magnitudes can be very large. IOD methods are sometimes nonlinear methods and are often trivial to implement. Measurement editing is typically not performed during IOD calculations because there are insufficient observations. Operationally, the OD process is frequently begun, or restarted, with IOD. IOD methods were derived by various authors: LaPlace, Poincaré, Gauss, Lagrange, Lambert, Gibbs, Herrick, Williams, Stumpp, Lancaster, Blanchard, Gooding, and Smith. Restarting techniques are most easily accomplished by using a solution from another technique.

3.3 Subsequent orbit determination

3.3.1 Least squares differential corrections

Least squares (LS) methods input tracking measurements with tracking platform locations and an a priori orbit estimate, and output a refined orbit estimate. Associated solution error magnitudes are by definition small when compared to IOD outputs. LS methods consist of an iterative sequence of corrections where sequence convergence is defined as a function of tracking measurement residual root mean square (RMS). Each correction is characterized by a minimization of the sum of squares of tracking measurement residuals. The LS method was derived first by Gauss in 1795 and then independently by Legendre.

3.3.2 Sequential processing

Sequential processing (SP) methods are distinguished from LS processing methods in that batches of data are considered sequentially, collecting a set of observations over a specified time interval and batch-processing one interval after the next. SP can be thought of as a moving time window whose contents are captured and processed at intervals, independent of previously processed batches of data. The analysis does not include process noise inputs and calculations. It is in no way equivalent to filter processing, in which each new observation is added to past observations, improving estimates in a rigorous, traceable manner.

3.3.3 Filter processing

Filter methods output refined state estimates sequentially at each observation time. Filter methods are forward-time recursive sequential methods consisting of a repeating pattern of time updates of the state of motion estimate and measurement updates of the state of motion estimate. The filter time update propagates the state estimate forward, and the filter measurement update incorporates the next measurement. The recursive pattern includes an important interval of filter initialization. Filter-smoother methods are backward-time recursive sequential methods consisting of a repeating pattern of state estimate refinement using filter outputs and backwards transition. Time transitions for both filter and smoother are dominated most significantly by numerical orbit propagators. The search for sequential processing was begun by Wiener, Kalman, Bucy, and others.

3.4 Required information for orbit determination

3.4.1 Observations

When observation data are communicated for collaborative or independent determination of satellite orbits, the observation types upon which that information is based shall be included. Several types of ground-based, airborne, and space-based sensor observations are routinely used in orbit determination. Table 1 describes the various observation types and sources.

Table 1 — Space surveillance observation product description

Content	Source
two angles and slant range	Radars
two angles	Baker-Nunn cameras, telescopes, binoculars, visual sightings
Azimuth	Direction finders
Time of closest approach	Radars, radio receivers [for transmitting (Doppler) satellites]
Range, angles, and rates	Radars
Pseudorange and carrier phase, as well as single, double, and triple differences of these basic measurement types	GPS or onboard inertial sensors
Direction cosines	Interferometric radars

3.4.1.1 Observation location information

When data are communicated for collaborative or independent determination of satellite orbits, the following information about the observation location and measuring devices shall be communicated:

- facility location latitude, longitude, altitude, and the reference from which such are measured, (e.g. WGS-84);
- tracking station identification (ID);
- elevation cutoff;
- measurement biases;
- transponder delay for downlinked information.

3.4.1.2 Satellite information

When data are communicated for collaborative or independent determination of satellite orbits, the following information about the satellite subject shall be included:

- a priori state estimate;
- tracking data ID;
- force model parameters;
- covariance matrix;
- general accelerations;
- transponder delay.

3.4.1.3 Estimation parameters and control

When data are communicated for collaborative or independent determination of satellite orbits, the following information about estimation parameters and control shall be included:

- estimation parameters;
- global force model controls;
- integration controls;
- database controls;
- observation uncertainties.

3.4.2 Tracking data selection and editing

When data are communicated for collaborative or independent determination of satellite orbits, the provider shall state whether data were edited and what the criteria were for tracking data selection.

3.4.3 Widely used OD schemes

When a widely used, consensus-validated, and authoritatively documented OD scheme is employed, the requirements of this Technical Report can be satisfied by citing that documentation and the specific parameter sets that the data provider employed within that scheme, which vary with scheme and version. Some widely used OD schemes that are acceptable are cited in Annex A. The list is not exhaustive.

3.4.4 Required information for orbit propagation or prediction

The following subclauses enumerate and decribe standard alternatives for information acceptable under this Technical Report.

3.4.4.1 Force models

Spacecraft are affected by several different conservative and non-conservative forces. Non-conservative phenomena dissipate spacecraft energy, for example by doing work on and heating the atmosphere.

3.4.4.1.1 Gravitation

Descriptions of an orbit propagation or prediction scheme shall include complete information about gravitational field characteristics employed. That description shall be based on the following formalism.

3.4.4.1.2 Earth gravity

The Earth's gravitational field shall be described in terms of a Jacobi polynomial expansion of finite order and degree. Jacobi polynomials are a complete, orthonormal set over the unit sphere. There are two angular degrees of freedom, equivalent to latitude and longitude. Any analytic function within that space can be represented by a weighted doubly infinite series of Jacobi polynomials.

3.4.4.1.2.1 Two-body motion

Two-body motion or Keplerian motion considers only the force of gravity from the Earth. Both the spacecraft and the Earth are considered point masses, with all mass concentrated at their centres of mass. This is the lowest- order zonal harmonic approximation.

3.4.4.1.3 Zonal harmonics

3.4.4.1.3.1 J2

The J2 perturbation (first-order) accounts for secular (constant rate over time) variations in the orbit elements due to Earth oblateness, mainly nodal precession and rotation of the semi-major axis of orbit elements that are otherwise those of unperturbed, Newtonian orbits. J2 is a zonal harmonic coefficient in an infinite Jacobi polynomial series representation of the Earth's gravity field. It represents the dominant effects of Earth oblateness. The even zonal harmonic coefficients of the gravity field are the only coefficients that result in secular changes in satellite orbital elements. The J2 propagator includes only the dominant first-order secular effects.

3.4.4.1.3.2 J4

The J4 perturbation (second-order) accounts for secular variations in the orbit elements due to Earth oblateness. The effects of J4 are approximately 1 000 times smaller than J2 and are a result of Earth oblateness.

3.4.4.1.3.3 Generalized zonal harmonics

It is impractical to determine the weights (coefficients) for a mathematically complete Jacobi polynomial series representation; therefore the series is truncated at meaningful (in terms of precision of the representation of the gravity field) order (latitudinal) and degree (longitudinal). If the order and degree are equal, the truncation is "square." Since gravitational and other perturbations are not necessarily symmetrical in latitude and longitude, the best approximation for a given application is not necessarily square. Static elements of the gravity field are the gravitation of the fixed portions of the distribution of the Earth's mass. The static gravity field is not uniform. Dynamic elements of the gravity are caused by the fluid elements of the Earth's core and by variations in the distribution of water. There are solid and ocean tides.