

Standard

Astrodynamics – Propagation Specifications, Technical Definitions, and Recommended Practices

American National Standard

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American National Standard

Astrodynamics—Propagation Specifications, Technical Definitions, and Recommended Practices

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Approved 25 August 2010

American National Standards Institute

Abstract

This document provides the broad astrodynamics and space operations community with technical standards and lays out recommended approaches to ensure compatibility between organizations. Applicable existing standards and accepted documents are leveraged to make a complete—yet coherent—document. These standards are intended to be used as guidance and recommended practices for astrodynamics applications in Earth orbit where interoperability and consistency of results is a priority. For those users who are purely engaged in research activities, these standards can provide an accepted baseline for innovation.

American National Standard

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Foreword

One of the most significant scientific and technological accomplishments since the beginning of the space era is the successful deployment of space systems and the necessarily ingenious application of astrodynamics to support these systems. Astrodynamics has been developed by extending the knowledge accumulated since the first recorded investigations into the motions of heavenly bodies.

The outgrowth of civilian and military rocket system developments has led to the establishment and implementation of numerous space systems, related physical models, and astrodynamics theories, algorithms, and procedures. With the proliferation of different and independent space systems and advancements in technology and astrodynamics sciences, the interfacing needed to ensure interoperability within space operations has become more complex.

The ASD/CoS charter is to *"Identify, establish, and publish astrodynamics standards, guides, and recommended practices to ensure the continued enhancement of aerospace-wide efficiency and productivity to meet the scientific, technological and operational demands."* To accomplish the chartered goals, the strategy is to:

- Research and establish the up-to-date status of the astrodynamics standards and practices currently available.
- Identify scientific, technological, and operational programs and system elements that have a need for astrodynamics standards and consensus practices.
- Perform in-depth analyses of the existing standards and practices and develop recommendations for possible adoption and/or modifications as AIAA standards or practices.
- Develop definition of standards and adopt formal guidelines and requirements of standardization.
- Recommend and propose the areas where new standards, guides, and recommended practices are required. Additionally, identify areas where standards are currently not appropriate.
- Identify, develop, and document candidate new astrodynamics standards, guides, and recommended practices for consideration.
- Perform independent verification and validation, including solicitation of in-depth reviews within industry, academia, and government laboratories for all proposed and documented standards, guides, and recommended practices.
- Submit proposed standards, guides, and recommended practices to the Standards Executive Council for approval and publication.
- Maintain all relevant technical materials and standards.
- Maintain technical coordination with scientific and astrodynamics communities nationally and internationally.

To help provide coherent direction for its activities in identifying and selecting topics, the committee approved a set of criteria. Fundamentally, the committee has taken the view that the objective of an astrodynamics standard is to provide guidance on practices that will ensure and enhance interoperability between organizations. Following are the criteria that have been useful in selecting topics that achieve this objective:

- Scope: Does the topic relate to processes associated with describing the motion of orbiting bodies? Although rather evident, the committee has occasionally found itself considering topics that really fall within the purview of a different area or responsibility.

- Utility: Is the topic of wide concern to the majority of the astrodynamics community, and does it deal with the process of information exchange among members of that community? If a topic is of only minor relevance to the community, developing standards may not be particularly useful. Thus, such standards should aim at facilitating the broadest information exchange across the community.
- Alternatives (Ambiguity): Does the topic involve alternative ways of performing a process or accomplishing an objective? In cases where multiple alternatives exist, we tried to give guidance on the variability of applications, indicating what the community consensus is. Where only one commonly accepted alternative existed, we determined if there was any potential confusion in its application.
- Practicality: Can agreement be achieved on standardization? Despite meeting all the above criteria, insufficient consensus may demand not treating the topic.

The ASD/CoS initial effort, *Recommended Practice, Astrodynamics—Part I*, was chaired by Dr. Joseph J. F. Liu. A *Part II* document was initiated by Dr. Hamilton Hagar, but was never officially finished in its original form. The current document supersedes the *Part I* and *Part II* and forms a unified document, including specific treatment of standards and recommended practices. The current version focuses on propagation for Earth orbiting satellites.

At the time of approval, the members of the AIAA Astrodynamics Committee on Standards were:

David A. Vallado, Chair	Center for Space Standards & Innovation
Rich Burns	NASA
David Finkleman	Center for Space Standards & Innovation
Michael Gabor	Northrop Grumman
Felix Hoots	The Aerospace Corporation
T.S. Kelso	Center for Space Standards & Innovation
Steve Nerem	University of Colorado
Daniel Oltrogge	1Earth Research, LLC
Glenn Peterson	The Aerospace Corporation
Paul Schumacher	U.S. Air Force Research Laboratory
John H. Seago	Analytical Graphics, Inc.
P. Kenneth Seidelmann	University of Virginia
Fred Slane	Space Infrastructure, Inc.
Jerome R. Vetter	Johns Hopkins University Applied Physics Laboratory

The above consensus body approved this document in August 2010.

The AIAA Standards Executive Council (Vice President, Wilson Felder, Chairman) accepted the document for publication in August 2010.

The AIAA Standards Procedures dictates that all approved Standards, Recommended Practices, and Guides are advisory only. Their use by anyone engaged in industry or trade is entirely voluntary. There is no agreement to adhere to any AIAA standards publication and no commitment to conform to or be guided by standards reports. In formulating, revising, and approving standards publications, the committees on standards will not consider patents that may apply to the subject matter. Prospective users

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Introduction

The American Institute of Aeronautics and Astronautics (AIAA) Astrodynamics Committee on Standards (ASD/CoS) has developed this open set of voluntary standards and recommended practices applying to propagation of orbits about the Earth. This document provides the broad astrodynamics and space operations community with technical standards and lays out recommended approaches to ensure compatibility between organizations. Applicable existing standards and accepted documents are leveraged to make a complete—yet coherent—document. These standards are intended to be used as guidance and recommended practices for astrodynamics applications in Earth orbit where interoperability and consistency of results is a priority. For those users who are purely engaged in research activities, these standards can provide an accepted baseline for innovation.

This document describes the technical specifications and requirements that comply with established and accepted guidelines, practices, and technical intent for propagation in Earth orbit. There are numerous examples of recommendations for implementation and approved variations. Accompanying resources will include algorithm and software code examples, as well as corresponding test cases, to establish confidence in the resulting products.

The remainder of this document is organized to provide a complete picture of the Earth orbit propagation application:

- Section 4 provides a glossary of terms used in the standards document.
- Section 5 lists the accepted and agreed upon units, constants, coordinates, and time systems, as well as consideration of conversions and precision.
- Section 6 describes the accepted force models used for Earth orbit propagation applications. These force models include gravity, atmospheric drag, third-body perturbations, solar radiation pressure, tides, and other perturbative forces.
- Section 7 describes application of analytical, numerical, and semianalytical approaches to orbit propagation.
- Section 8 summarizes the references used in the development of this set of standards and Annex A provides informative references.

1 Scope

This document provides the broad astrodynamics and space operations community with technical standards and lays out recommended approaches to ensure compatibility between organizations. Applicable existing standards and accepted documents are leveraged to make a complete—yet coherent—document. These standards are intended to be used as guidance and recommended practices for astrodynamics applications in Earth orbit where interoperability and consistency of results is a priority. For those users who are purely engaged in research activities, these standards can provide an accepted baseline for innovation.

2 Tailoring

When viewed from the perspective of a specific program or project context, the requirements defined in this standard may be tailored to match the actual requirements of the particular program or project. Tailoring of requirements shall be undertaken in consultation with the procuring authority where applicable.

For this document, there are no specific tailoring actions as the document contains recommended practices and approaches that are intended to cover specific implementations.

NOTE Tailoring is a process by which individual requirements or specifications, standards, and related documents are evaluated and made applicable to a specific program or project by selection, and in some exceptional cases, modification and addition of requirements in the standards.

3 Applicable Documents

The following documents contain provisions which, through reference in this text, constitute provisions of this standard. For dated references, subsequent amendments to, or revisions of, any of these publications do not apply. However, parties to agreements based on this standard are encouraged to investigate the possibility of applying the most recent editions of the normative documents indicated below. For undated references, the latest edition of the normative document referred to applies.

ISO 8601 (2004)	<i>Data elements and interchange formats — Information interchange — Representation of dates and times</i>
ITU-R 460 (2002)	Recommendation 460
Department of Defense	NIMA TR8350.2, World Geodetic System, 1984
AIAA G-003C-2010	Guide to Reference and Standard Atmosphere Models

4 Vocabulary

4.1 Acronyms and Abbreviated Terms

AAS	American Astronautical Society
AFGP4	Air Force General Perturbations Version 4
AFSPC	Air Force Space Command
AIAA	American Institute of Aeronautics and Astronautics
APL	Applied Physics Laboratory
AU	Astronomical Unit

BC	Ballistic Coefficient
BCRS	Barycentric Celestial Reference System
BIPM	Bureau International des Poids et Mesures (International Bureau of Weights and Measures)
CCD	Charge-Coupled Device
CEP	Celestial Ephemeris Pole
CIO	Celestial Intermediate Origin
CIP	Celestial Intermediate Pole
CIRA	COSPAR International Reference Atmosphere, (CIRA 90)
CIRS	Celestial Intermediate Reference System
CNES	Centre National d'Etudes Spatiale (National Center for Space Studies)
COSPAR	Committee On Space Research
CSR	Center for Space Research
CTIM	Coupled Thermosphere-Ionosphere Model
DCA	Dynamic Calibration of the Atmosphere
DE200	Development Ephemeris 200
DMA	Defense Mapping Agency
DSST	Draper Semianalytic Satellite Theory
DTM	Drag Temperature Model
ECMWF	European Centre for Medium-Range Weather Forecasts
EGM	Earth Gravitational Model
EOP	Earth Orientation Parameters
ET	Ephemeris Time
EUV	Extreme Ultraviolet
FK5	Fifth Fundamental Catalog
GAST	Greenwich Apparent Sidereal Time
GCRF	Geocentric Celestial Reference Frame
GEM	Goddard Earth Model
GEO	Geosynchronous Earth Orbit
GMST	Greenwich Mean Sidereal Time
GMT	Greenwich Mean Time
GOST	Russian atmospheric model

GPS	Global Positioning System
GRAM	NASA/MSFC Global Reference Atmospheric Model (GRAM 90)
GRIM	GRIM is a concatenation of the first two letters of GRGS (group de recherches de geodesie spatiale, Toulouse/France) and "I" and "M" from IAPG Munich (institute of astronomical and physical geodesy, technical university of Munich). Both institutes jointly prepared the first GRIM gravity models under the lead of George Balmino (GRGS) and Christoph Reigber (IAPG).
GSFC	Goddard Space Flight Center
HPOP	High-Performance Orbit Propagator
HWM	Horizontal Wind Model
IAG	International Association of Geodesy
IAU	International Astronomical Union
ICRF	International Celestial Reference Frame
ICRS	International Celestial Reference System
IEEE	Institute of Electrical & Electronic Engineers
IERS	International Earth Rotation and Reference System Service
ISO	International Standards Organization
ISS	International Space Station
ITRF	International Terrestrial Reference Frame
ITRS	International Terrestrial Reference System
ITU-R	International Telecommunication Union Radiocommunication Sector
IUGG	International Union of Geodesy and Geophysics
J70	Jacchia atmospheric models (J64, J70, J71, J77)
JD	Julian Date
JERS	Japanese Earth Resources Satellite
JGM	Joint Gravity Model
JPL	Jet Propulsion Laboratory
JR71	Jacchia-Roberts atmospheric model
LEO	Low Earth Orbit
LOD	Length of Day
MET	Marshall Engineering Thermosphere
MJD	Modified Julian Date
MOD	Mean of Date
MSFC	Marshall Space Flight Center

MSIS	Mass Spectrometer Incoherent Scatter, (MSIS 00)
NASA	National Aeronautics and Space Administration
NCAR	National Center for Atmospheric Research
NGA	National Geospatial Intelligence Agency
NIMA	National Imagery and Mapping Agency
NIST	National Institute of Standards and Technology
NMC	National Meteorological Center
NORAD	North American Aerospace Defense Command
NRL	Naval Research Laboratory
NSWC	Naval Surface Warfare Center
NTP	Network Time Protocol
OD	Orbit Determination
OSU	Ohio State University
PEF	Pseudo Earth Fixed
PPT3	Position, Partial, and Time Version 3
RMS	Root Mean Square
SALT	Semi-analytical Liu theory
SAO	Smithsonian Astrophysical Observatory
SI	Système International d'Unités (International System of Units)
SGP	Simplified General Perturbations
SGP4	Simplified General Perturbations Version 4
SLR	Satellite Laser Ranging
SRP	Solar Radiation Pressure
SSC	Space Surveillance Center
STK	Satellite Tool Kit
TAI	Temps Atomique International (International Atomic Time)
TCB	Temps-Coordonnée Barycentrique (Barycentric Coordinate Time)
TCG	Temps-Coordonnée Géocentrique (Geocentric Coordinate Time)
TDB	Temps Dynamique Barycentrique (Barycentric Dynamical Time)
TDT	Temps Dynamique Terrestre (Terrestrial Dynamical Time)
TEG	Texas Earth Gravity model
TEME	True Equator, Mean Equinox

TIGCM	Thermosphere Ionosphere General Circulation Model
TIO	Terrestrial Intermediate Origin
TIRS	Terrestrial Intermediate Reference System
TOD	True of Date
TT	Terrestrial Time
USNO	U.S. Naval Observatory
UCAC	USNO CCD Astrographic Catalog
USM	Universal Semianalytical Method
USSA 76	Standard Atmosphere, (USSA76)
UT	Universal Time
UT Austin	University of Texas
UT1	Universal Time One
UTC	Coordinated Universal Time
VLBI	Very Long Baseline Interferometry
WGS	World Geodetic System

4.2 Terms and Definitions

For the purposes of this document, the following terms and definitions apply.

Albedo

the reflecting power or the ratio of the light reflected to light received

Altitude (h)

height where the geoid is often used as a reference surface

Anomalies (E , M , ν)

the angles describing the position of a body in a reference frame as independent variables (see *eccentric*, *mean*, and *true anomalies*)

a_p

planetary amplitude of geomagnetic activity (every 3 hours)

NOTE The daily average of the a_p values is given the symbol A_p .

Apoapsis

the point of an elliptic orbit farthest from the focus occupied by the central body

Apogee

the point of a geocentric elliptic orbit that is at the greatest distance from the center of the Earth

Apsidal Line

the line connecting the periapsis with the apoapsis

Apsis

the point on a conic section where the length of the radial vector is maximum or minimum

Argument of Latitude (u)

the angle between the line of nodes and the radial vector of an orbiting particle, regarded as positive when measured from the ascending node to the radial vector in the direction of motion of the satellite; also, the sum of the argument of periapsis and the true anomaly

Argument of Periapsis (ω)

the angle between the line of nodes and the periapsidal line measured in the direction of motion

Ascending Node

the point in the equatorial plane, or in general, in the reference plane, where the body passes from south to north of the reference plane (see *right ascension of the ascending node*)

Astrodynamics

branch of space science and engineering dealing with the motion of artificial bodies in space (see also *celestial mechanics*)

Astronomical Unit (AU)

the semimajor axis of Earth's orbit; equal to the radius of a circular orbit in which a body of negligible mass, free of perturbations, revolves around the Sun in $2\pi/k$ days, where k is the Gaussian gravitational constant

Atomic Clock

an electronic resonating device used for time-keeping that derives its basic frequency standard from the electromagnetic radiation associated with the transition between a specific pair of atomic energy levels

Autumnal Equinox

the direction and date when the fictitious Sun crosses the equatorial plane from North to South in its apparent motion along the ecliptic

Auxiliary Circle

a circle circumscribing an elliptic orbit and having a radius equal to the semimajor axis of the orbit

Azimuth (Az)

the angle measured clockwise from North along the horizon of the celestial sphere to the great circle passing through the point of interest and the zenith

Ballistic Coefficient (BC)

a parameter used to model the satellite characteristics that influence the perturbative acceleration due to drag on a satellite,

NOTE 1 $BC = C_D A / m$

where

- C_D is the drag coefficient,
- A is the effective frontal area, and
- m is the mass of the body.

NOTE 2 Recommended units are m^2/kg .

Barycenter

the center of mass of a system of bodies

Barycentric Dynamical Time (TDB)

a time scale which has the same rate and epoch as Terrestrial Time and is used as the time argument of ephemerides

NOTE It is called T_{eph} in some cases.

Celestial Ephemeris Pole (CEP)

the reference pole for nutation and polar motion

Celestial Equator

the projection of the Earth's equator on the celestial sphere

Celestial Intermediate Pole (CIP)

the reference pole of the IAU 2000A precession-nutation model

NOTE The motions of the CIP are those of the Tisserand mean axis of the Earth with periods greater than two days.

Celestial Mechanics

branch of dynamical astronomy dealing with the motion and dynamics of natural bodies in space

Celestial Sphere

a hypothetical sphere of indefinitely large radius upon which celestial bodies are projected. It is centered on the origin (e.g., Earth's center or Sun's center) of the associated spherical coordinate system

Central Body

the primary body that is being orbited

Centrifugal Force

the apparent force in a rotating system, deflecting masses radially outward from the axis of rotation

NOTE It is equal and opposite to the centripetal force that acts to keep a particle stationary in the rotating frame.

Conic Section

the intersection of a cone and a plane

NOTE 1 The four intersections related to Keplerian (two-body) orbital motion are the circle, the ellipse, the hyperbola, and the parabola.

NOTE 2 Two degenerate types of theoretical interest are a line and a point.

Coordinated Universal Time (UTC)

the time available from broadcast time signals, and the basis of civil times in the world

NOTE It differs from International Atomic Time (TAI) by an integral number of seconds and is maintained within ± 0.90 second of UT1 through the addition of leap seconds.

Coriolis Force

the apparent force attributed to a body in motion with respect to a rotating coordinate system

NOTE Coriolis force is experienced only by bodies with nonzero velocity in the rotating frame, unlike centrifugal force, which is independent of motion.

Covariance

a measurement of the tendency of two random variables to vary together

Cowell's Method

a process of special perturbations in which the total acceleration of an orbiting body is numerically integrated

Cross-section

the intersection of a three-dimensional object with a plane perpendicular to a particular reference direction

EXAMPLE The velocity direction.

Cross-track

see Sec. 5.5.8 for a discussion of satellite based coordinate systems

Date

day and time of day

Day (d)

an interval of time based on one rotation of the Earth

NOTE It is often subdivided into 86400 seconds, although the UTC day may be 86399, 86400, or 86401 SI seconds.

Declination (δ)

the angle between the celestial equator and a radius vector, regarded as positive when measured north from the celestial equator

Descending Node

the point in the equatorial plane, or in general, in the reference plane, where the body passes from north to south of the reference plane

Differential Correction

a process for correcting an initial estimate

NOTE It is used as an alternate name for orbit determination, estimation, least squares, and sequential batch operations.

Drag (D)

the retarding effect of the atmosphere on the motion of a body

Dynamical Astronomy

branch of astronomy dealing with the motion and dynamics of celestial bodies

NOTE It includes celestial mechanics, stellar dynamics, motion of binary stars, and positional astronomy.

Dynamical Time

the independent argument of dynamical theories and ephemerides (see *barycentric dynamical time* and *terrestrial time*)

Earth Rotation Angle

angle between the TIO and CIO measured along the intermediate equator of the Celestial Intermediate Pole

Eccentric Anomaly (E)

the angle at the center of an elliptic orbit, formed by the apsidal line and the radius vector drawn from the center to the point on the circumscribing auxiliary circle from which a perpendicular to the apsidal line will intersect the orbit and locate the body

Eccentricity (e)

term defining the specific shape of a conic section

NOTE 1 It is the ratio of the distance of a point on a conic section from the focus to the distance from the directrix.

NOTE 2 For ellipses — conic sections with an eccentricity of less than one—it is also the distance from the center of an ellipse to the focus divided by the length of the semimajor axis.

Eclipse

the obscuration of a celestial body caused by its passage through the shadow of another body

Ecliptic

the mean plane of Earth's orbit around the Sun

Elevation (E)

the angular distance of a point of interest above (+) or below (-) the horizon measured along the great circle passing through the point and the zenith

Ephemeris Time (ET)

the time scale used 1960-1984 as the independent variable in gravitational theories of the solar system later; subsequently replaced by dynamical time

Ephemeris

a table of locations (and rates) of natural or artificial bodies versus time

NOTE Its plural is "ephemerides", meaning multiple tables.

Epoch (t_0 or T_0)

a date that is usually prescribed as fixed and nonchanging, such as the date of the reference system to which celestial coordinates are referred, or a specific date to which an object's location has been referenced

Equator

the intersection of the surface of a body with the plane passing through the center of mass of the body, perpendicular to the axis of rotation

Equinox of Date

the instantaneous location of the equinox at a date, where the date may be changing according to a set of available observations or ephemeris

Equinox of Epoch

the instantaneous location of the equinox at an epoch that is usually prescribed as fixed or nonchanging

Extreme Ultraviolet Radiation (EUV)

high frequency ultraviolet radiation from the Sun that may have the most substantive influence on the density of the upper atmosphere of the Earth

Fictitious Mean Sun

an imaginary body having nearly uniform angular velocity in the plane of the Earth's equator; essentially the name of a mathematical formula that serves as the basis for mean solar time

Fiducial Direction

defining direction for a coordinate system

Flattening (f)

a measure of deviation of an ellipsoid from a spherical shape

NOTE 1 $f = (a-b)/a$

where

— a is the equatorial radius and

— b is the polar radius.

NOTE 2 Also known as oblateness, it is applied to a body generated by the rotation of an ellipse about its minor axis.

Fifth Fundamental Catalog (*FK5*)

a catalog of star positions prepared by the Astronomisches Rechen Institut in Germany and the basis for the IAU Reference System for J2000.0 from 1984-1998

Gaussian Gravitational Constant (*k*)

the gravitational constant expressed in terms of solar system units

NOTE It allows the motion of the planets to be accurately described without an exact knowledge of the scale of the solar system or the mass of the Sun and the planets.

General Perturbation Method (*GP*)

analytical or semianalytical solution of the differential equations describing a perturbed orbit

Geocenter ($\oplus$)

the center of mass of the Earth

Geocentric Coordinates

the latitude and longitude of a point on Earth measured as angles subtended at the center of Earth (see *latitude (geocentric)* and *longitude (geocentric)*)

Geoid

an equipotential surface of the Earth that most closely approximates the mean sea level of the open ocean

Geosynchronous Satellite

a satellite whose orbital period is one sidereal day

Gravitational Constant (*G*)

the constant of proportionality in Newton's Universal law of gravitation

Gravitational Parameter ($\mu = GM$)

the product of the mass of central body and the universal gravitational constant

Gravitational Potential (*U* or *V*)

a function whose gradient yields the gravitational force

Great Circle

the path of intersection, circumscribing a spherical surface, when a plane intersects the sphere's center

Great Circle Path

a geodesic (shortest distance between two points) along a sphere

Greenwich Apparent Sidereal Time (*GAST*)

Greenwich mean sidereal time corrected for the shift in the position of the mean equinox due to nutation

Greenwich Mean Sidereal Time (*GMST*)

the hour angle of the Greenwich meridian relative to the mean equinox

Greenwich Meridian

the meridian from which terrestrial longitude is measured, passing through the Royal Observatory in Greenwich, England

Height (*h*)

the distance measured above a reference surface along a perpendicular to that surface

Heliocentric

sun-centered

Horizon

a plane normal to the zenith, passing through the observer or object of interest; also, the limb of a nearby celestial body

Hour Angle (*HA*)

angular distance on the celestial sphere measured westward along the celestial equator from the meridian to the hour circle that passes through a celestial object

Hour Circle

a great circle on the celestial sphere that passes through the celestial poles and is, therefore, perpendicular to the celestial equator

Inclination

the angle between the orbital angular momentum vector and the equator, or XY plane

Inertial Reference Frame

an unaccelerated and nonrotating reference frame in which Newton's Laws are valid

NOTE The inertial qualifier is sometimes used with other quantities to indicate unaccelerated and nonrotating behavior, such as the inertial ecliptic.

International Celestial Reference Frame (*ICRF*)

a quasi-inertial reference frame defined based on the radio positions of 212 extragalactic sources distributed over the entire sky

NOTE The resulting International Celestial Reference Frame has been adopted by the International Astronomical Union as the fundamental celestial reference frame, replacing the FK5 optical frame as of 1998 January 1.

International Celestial Reference System (*ICRS*)

the set of prescriptions and conventions together with the modeling required to define at any time a triad of axes

NOTE 1 The System is realized by VLBI estimates of equatorial coordinates of a set of extragalactic compact radio sources, the International Celestial Reference Frame (ICRF).

NOTE 2 The ICRS can be related to the International Terrestrial Reference System (ITRS) by use of precession-nutation theory and corrected by Earth-orientation parameters.

International Terrestrial Reference Frame (*ITRF*)

the International Terrestrial Reference Frame is a set of points having three-dimensional Cartesian coordinates which realize an ideal reference system, the International Terrestrial Reference System (ITRS), as defined by the IUGG resolution No. 2 adopted in Vienna, 1991

International Terrestrial Reference System (*ITRS*)

a set of prescriptions and conventions, together with the modeling, required to define origin, scale, orientation and time evolution of a Conventional Terrestrial Reference System (CTRS)

NOTE The ITRS is an ideal reference system, as defined by the IUGG resolution No. 2 adopted in Vienna, 1991. The system is realised by the International Terrestrial Reference Frame (ITRF) based upon estimated coordinates and velocities of a set of stations observed by VLBI, LLR, GPS, SLR, and DORIS.

International Atomic Time (*TAI*)

the time scale of the Bureau International des Poids et Mesures of atomic time standards

NOTE The unit is the SI second.

In-track

see Section 5.5.8 for a discussion of satellite based coordinate systems

Invariable Plane

the plane containing the center of mass of the solar system and perpendicular to the angular momentum vector of the solar system

NOTE Sometimes known as the Laplacian plane.

J2000.0

standard epoch of the FK5 coordinate system (12^h TDB 2000 January 1)

NOTE JD = 2451545.0

Julian Date (*JD*)

the date measured as an interval since Greenwich noon, 1 January 4713 BC

K_p

planetary index of geomagnetic data

Laplacian Plane

for a system of satellites, the fixed plane relative to which the vector sum of the disturbing forces has no orthogonal component (see also *Invariable Plane*)

Latitude

the angular distance north (positive) or south (negative) of the primary great circle or plane, as on the Earth or the celestial sphere

Astronomical: the angle measured from the equatorial plane to the direction of gravity (plumb line) (ϕ_{as})

Celestial: the angle on the celestial sphere measured from the ecliptic plane to the radius vector from the observer to the point of interest (ϕ_{ecl})

Geocentric: the angle measured from the equatorial plane to a line to Earth's center of mass (ϕ_{gc})

Geodetic: the angle measured from the equatorial plane to the local normal to the reference spheroid (ϕ_{gd})

Leap Seconds

the one-second interval added or subtracted from the end of the UTC month to maintain UTC to within ± 0.90 seconds of UT1

Line of Nodes ($\bar{n}$)

the line connecting the ascending and descending nodes

Local Horizon

apparent horizon tangent to the position vector at a particular location

NOTE This can also be applied to satellite positions.

Longitude

the angular distance along the primary great circle measured eastward from the reference meridian, as on Earth or the celestial sphere

Astronomical: the angle measured from the plane of the Greenwich meridian to the plane perpendicular to the equatorial plane that contains the direction of gravity (plumb line) (λ)

Celestial: the angle on the celestial sphere measured eastward along the ecliptic from the dynamical equinox to the great circle passing through the point of interest and the ecliptic poles (λ)

Terrestrial: the angle measured from the plane of the Greenwich meridian to the plane through the polar axis and the radius vector from Earth's center of mass (λ_E)

Longitude of the Ascending Node

the angle measured eastward along the Earth's equator from the Greenwich meridian to the position of the ascending node with respect to the equator

Longitude of Perigee (ϖ)

the sum of the angles of the longitude of the ascending node and the argument of perigee

NOTE The general terminology is longitude of periapsis and the angle may be the addition of angles in separate planes if the orbit is inclined.

Low-Earth Orbit (LEO)

orbit below the near-Earth radiation belt (altitude approximately 3000 km)

NOTE 3000 km is an arbitrary point of differentiation.

Mean Anomaly (M)

the product of the mean motion and the interval of time since periapsis passage

NOTE An angular measure with a period equal to the period of the orbit.

Mean Elements

elements of an adopted reference orbit that approximates the actual perturbed orbit

Mean Equator and Equinox

the celestial reference system determined by ignoring small short-period variations in the motion of the celestial equator

NOTE 1 Mean Equator of date is defined as a specific instance of the secular precession of the Earth's rotational axis about the North ecliptic pole.

NOTE 2 Mean equinox of date is the intersection of the mean ecliptic and mean equatorial planes.

Mean Motion (n)

the value of a constant angular velocity required for a body to complete one revolution within one orbit period

Mean Sea Level

average level of the oceans determined through worldwide tide gauges and satellite observations

Meridian

the great circle between the North and South poles (terrestrial and celestial) which passes through the point directly above the observer

Modified Julian Date (MJD)

the Julian date minus 2400000.5

Nadir

the point on the celestial sphere diametrically opposed to the zenith

Newton's Universal Law of Gravitation

the gravitational force between bodies is proportional to the product of their masses and inversely proportional to the square of the distance between them

Node

either of the points at which the orbit intersects the reference plane

Nutation

the short-period oscillation of the pole of a gravitationally perturbed rotating body

NOTE 1 The oscillation occurs perpendicular to a central axis.

NOTE 2 For Earth rotation, it consists of the two components, nutation in celestial longitude ($\Delta\psi$) and nutation in obliquity ($\Delta\epsilon$).

Oblateness

see *flattening*

Obliquity (ϵ)

the angle between the mean equatorial and orbital planes

Orbit

the trajectory of a body subject to the gravitational force of a neighboring body or bodies

Orbit Determination

process of finding the orbit of a satellite by processing measurements of the object

Orbital Elements

a selected set of six variables describing the orbit

NOTE The classical orbital elements are:

- a (semimajor axis),
- e (eccentricity),
- i (inclination),
- Ω (right ascension of the ascending node),
- ω (argument of periapsis), and
- M_0 (mean anomaly at epoch).

Penumbra

the near or partial shadow cast by an eclipsing body (see also *umbra*)

Periapsis

the point of an orbit closest to the focus occupied by the attracting body

Perigee

the point of a geocentric orbit closest to the center of Earth

Period (P, T)

the interval of time required to complete one revolution in an orbit or one cycle of a periodic phenomenon, such as a cycle of phases

Periodic Motion

a motion which repeats itself in equal intervals of time

Periodic Variations

variations due to perturbations which can be expressed as periodic functions

Phase Space

a mathematical space with one point for every possible state of the system, having as many dimensions as there are degrees of freedom in the system

Polar Motion

the irregularly varying motion of Earth's pole of rotation with respect to Earth's crust

Precession

the uniformly progressing motion of the mean pole of rotation with respect to the celestial sphere

Propagator

a computational process predicting the state of a dynamical system at a time of interest based on a set of initial conditions

Proper Motion

the projection on the celestial sphere of the motion of a star relative to the solar system

Radial

see Section 5.5.8 for a discussion of satellite based coordinate systems

Radiation Pressure (p_{sr})

the pressure acting on a surface exposed to incident electromagnetic radiation caused by the momentum transferred to the surface by the absorption and/or reflection of the radiation

Random Errors

those errors that can be described only statistically; errors arising from events whose causes or specific times of occurrences cannot be explicitly predicted

Reference Orbit

an orbit that is used as a baseline for comparison

Reflectivity

measure of the amount of radiation that is not absorbed by an object

Revolution

one complete orbit around the central body

Right Ascension (α)

the angle between the vernal equinox and the projection of the radius vector on the equatorial plane, regarded as positive when measured eastward from the vernal equinox

Second

International System of Units (SI): the duration of 9192631770 oscillations of the radiation corresponding to the transition between two hyperfine levels of the ground state of the cesium-133 atom

Sectoral Harmonic Coefficients (J_{mm} , C_{mm} , S_{mm})

coefficients of the terms in the Legendre series expansion of the gravitational potential that depend only on the longitude

NOTE The degree equals the order.

Secular

constant change over time

Selenocentric

referred to the center of mass of the moon

Semianalytical Techniques

propagation techniques that combine analytical and numerical methods

Semimajor Axis (a)

the distance from the center of an ellipse or hyperbola to an apsis

Sidereal Time

a measure of time defined by Earth's diurnal rotation with respect to the vernal equinox

Solar Flux

solar radiation emanating from the Sun and influencing satellite in the drag regime

Solar Radiation Pressure

force exerted on a satellite from the particles originating from the Sun

Special Perturbation Method (SP)

numerical integration of the differential equations describing perturbed motion

Spherical Harmonics

mathematical representation of a complex surface or shape

NOTE 1 The Earth's gravity field is modeled through this technique. These are the coefficients in the associated Legendre series expansion of the gravitational potential (J_{nm}, C_{nm}, S_{nm}) .

NOTE 2 See also *zonal*, *sectoral*, and *tesseral harmonic coefficients*.

Spheroid

an oblate ellipsoid which closely approximates the mean sea level figure of Earth or the geoid.

NOTE A "spheroid" is an ellipsoid in which two of the three axes are equal; an "oblate spheroid" has the rotation of an ellipse about the minor axis; and, a "prolate spheroid" is the rotation of an ellipse about the major axis.

Standard Atmosphere

a static model of atmospheric density, pressure and temperature as a function of altitude that is accepted as a standard and used as a model to portray average values for these quantities

Standard Epoch

a date that specifies the reference system to which celestial coordinates are referred

State Vector

any set of parameters (e.g., position and velocity) which uniquely define an orbit at a selected epoch

Stationkeeping

the procedure necessary to maintain position (that is, either vehicle attitude or vehicle spatial position) after the space vehicle has been established on orbit

Stellar Dynamics

branch of astronomy dealing with the motion and dynamics of stars and stellar systems

Sun-synchronous Orbit

an orbit that precesses about the central body at the same mean angular rate as the central body orbits the Sun

Tangential

See Section 5.5.8 for a discussion of satellite based coordinate systems

Terrestrial Time (TT)

the independent argument for apparent geocentric ephemerides

NOTE 1 The unit is 86,400 SI seconds at mean sea level and $TT = TAI + 32.184$ s.

NOTE 2 Previously known as *terrestrial dynamic time*.

Terrestrial Longitude (λ_E)

the angle between the Greenwich meridian and the meridian of a geographic location, measured eastward along Earth's equator

Tesseral Harmonic Coefficients (J_{nm} , C_{nm} , S_{nm})

coefficients of the terms in the Legendre series expansion of the gravitational potential which depend on the latitude and longitude

NOTE Degree and order are not equal, and order is greater than zero.

Topocentric

referenced to a point on the surface of Earth

Tracking

the process of a sensor following a satellite while collecting observations of the satellite's relative position and velocity

Trajectory

the path describing the motion of an object as a function of time

Transverse

See Section 5.5.8 for a discussion of satellite based coordinate systems

Tropical Year

the period of time for the Sun to advance 360 degrees in longitude

True Anomaly (ν)

the angle at the focus (nearest the periapsis) measured from the apsidal line directed toward the periapsis to the radius vector of the orbiting body in the direction of motion

True Equator and Equinox

the celestial coordinate system determined by the instantaneous positions of the celestial equator and ecliptic

NOTE The Equator is often given an "of date" qualifier to specify the exact orientation.

True Equator and Mean Equinox

coordinate system formed by the projection of the mean equinox of date onto the true equator of date

NOTE This system is used exclusively with the SGP4 analytical propagation technique.

Two-body Motion

General: the dynamics of two gravitationally interacting point masses

NOTE Two-body dynamics refers to the situation where an orbit is propagated considering only the two bodies of interest, the satellite and the central body. Two-body orbit is used when referring to the orbit generated using only two-body dynamics. The two-body problem or model refers to the situation where only two bodies are present in the solution of propagating a satellite orbit.

Restricted: the modification of the general problem to the case when the mass of one of the bodies is much smaller than the other so that it does not influence the motion of the larger body

Umbra

the darkest part of the shadow cast by an eclipsing body in which all light from the source has been obscured

Universal Time (*UT*)

a measure of Earth-rotation angle, whose rate is based on the mean diurnal motion of the Sun, and is the basis of civil timekeeping

NOTE Coordinated Universal Time (UTC) is a particular form of Universal Time based on the SI second (see *Coordinated Universal Time (UTC)* Section 5).

Universal Time One (*UT1*)

a time scale based on rotational angle of the Earth's determined from astronomical observations

Variation of Parameters

perturbation technique in which the constants of the two-body orbit or of the analytical solution of an approximation to an actual problem are allowed to vary

Vernal Equinox

the direction where and the date when the Sun crosses the equatorial plane from South to North in its apparent motion along the ecliptic (its apparent longitude is zero); the ascending node of the ecliptic on the uniformly moving mean equatorial plane

Vertical

Astronomical: line parallel to the direction of gravity at the observation point (i.e., line normal to the geoid)

Geodetic: line normal to the surface of the reference spheroid and passing through the observation point

Year

time to complete one revolution of the Earth around the Sun

Anomalistic: the mean interval between successive passages of the Earth through perihelion

Tropical: the period of one complete revolution of the mean longitude of the sun with respect to the dynamical equinox

Zenith Distance

angle measured along the great circle on the celestial sphere from the zenith to the celestial object

Zenith (*z*)

for any given point, the intersection on the celestial sphere of the local vertical direction, which points opposite to the gravitational force at that point

Zonal Harmonic Coefficients (J_n)

The terms in the associated Legendre series expansion of the gravitational potential which depend only on the latitude

NOTE The order equals zero.

5 Units, Precision, Time, Constants, and Coordinates

The field of astrodynamics has a rich legacy of astronautical and astronomical terminology and practices. To produce effectively precise results, numerous definitions and specifications are required to operate within a framework of self-consistent coordinate and time systems. This section introduces some of these concepts, provides references that define some standard approaches, and recommends practices that aid in the sharing of data between organizations performing analyses.

5.1 Units

Standard units simplify the meaningful exchange of numeric data. The need is illustrated by numerous units historically used for the exchange of the orbital element semimajor axis: for example, kilometers, meters, statute miles, nautical miles, feet, Earth radii, or astronomical units. Another example, consistent

with ancient astronomical practice, is that angular measurements may be expressed in degrees of arc, arc minutes, arc seconds, and fractions thereof, whereas computing machinery will usually require angles expressed in radians.

Units of length, such as the SI meter, are defined in terms of the speed of light c and time interval Δt , that is, distance $d \equiv c\Delta t$. As the quantity Gm/c^2 has units of length, and assuming the values for c and the gravitational constant G remain the same in every frame of reference, the adopted masses of gravitating bodies (m) must also be compatible with the adopted units of time and length within the context of relativity.

5.1.1 Presentation of Units

Use of the International System of Units (SI) is recommended. Units should be described within the data itself, or via supplementary documentation, using conventional names or abbreviations, as recommended by National Institute of Standards (NIST). A few common exceptions exist, such as the use of angular degrees instead of radians, or “sec” instead of “s” as an alternate abbreviation for “seconds.” The retention of full precision (significant digits) is necessary when converting or rescaling units.

Canonical units are units normalized by specific parameters and constants. Canonical units are especially useful in celestial mechanics for academic developments and manual calculations, because many parameters of the equation normalize to unity to provide for simplified mathematical derivations and faster numerical evaluation. Excepting situations where they may be mandated by a specialized theory, the routine use of canonical units is no longer recommended in high-accuracy systems. The reason is that the absolute scaling of canonical units changes as system parameters or constants incrementally improve with time, resulting in unnecessary operational complications and incompatibilities later. Also, because some mathematical terms almost always appear in tandem, it is often unclear in software what specific variables may have been normalized, e.g., Gm versus m . Keeping track of proper units and discovering programming errors can be more difficult, because many canonical variables are unitless or lack named units.

5.1.2 Recommended Practice

- 1) Use SI units exclusively, or use units that are approved for use with SI, such as angular degrees. Canonical units cannot be generally recommended.
- 2) In all cases of numerical presentation, scale units and frames of reference should be clearly identified.

5.2 Precision, Accuracy, and Uncertainty

The concepts of accuracy and precision are easily confused. Accuracy describes how close an experimental outcome is to the true value, whereas precision describes mutual agreement amongst a population of experimental outcomes. High precision tends to infer a lack of random errors, and is related to the repeatability or reproducibility of a result, regardless of where truth is, while high accuracy implies a lack of systematic errors or bias relative to truth. As a result, precision can refer to the exactness of presentation, i.e., the number of significant digits to be retained from a result. Accuracy is more closely related to the error uncertainty of a single experimental outcome. Deviation is the difference of an actual outcome from an expected or desired outcome. Error is deviation from the truth outcome.

Often, astrodynamics systems are assessed by their ability to reproduce an expected result given specific inputs, such as a series of test cases advocated in this standard. *These types of tests tend to gauge precision rather than accuracy.* Claims of accuracy usually require some detached representation of truth, and, generally, describe a single outcome rather than a population. For example, as it pertains to measurement of atomic time and time interval, “precise time and time keeping” is the terminology most often encountered and accepted because atomic time is maintained according to the *relative* agreement of many atomic resonators with respect to each other, rather than an independent time scale of greater