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Committee for
Space Data Systems

REPORT CONCERNING SPACE
DATA SYSTEM STANDARDS

NAVIGATION DATA— DEFINITIONS AND CONVENTIONS

CCSDS 500.0-G-1

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FOREWORD

This Report contains technical material to supplement the CCSDS Recommendations for the standardization of spacecraft navigation data generated by CCSDS Member Agencies. The topics covered herein include radiometric data content, spacecraft ephemeris, planetary ephemeris, tracking station locations, coordinate systems, and attitude data. This Report deals explicitly with the technical definitions and conventions associated with inter-Agency cross-support situations involving the transfer of ephemeris, tracking, and attitude data.

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1 INTRODUCTION

1.1 PURPOSE AND SCOPE

Spacecraft navigation data are exchanged between Consultative Committee for Space Data Systems (CCSDS) member Agencies during cross-support of space missions. The purpose of this document is to establish a common understanding for the exchange of spacecraft navigation data.

Types of navigation data exchanged, and discussed in this document, include:

- properties and measurements of spacecraft dynamics;
- ground station information;
- environmental models;
- radiometric data.

1.2 APPLICABILITY

This document applies to navigation data exchanged in the following cases:

- flight-to-ground;
- ground-to-flight;
- ground-to-ground;
- flight-to-flight.

This document serves as a guideline for the development of compatible, inter-Agency standards for the exchange of spacecraft navigation data.

1.3 REFERENCES

The following documents are referenced in this Report. At the time of the publication the indicated editions were valid. All documents are subject to revision, and users of this Recommendation are encouraged to investigate the possibility of applying the most recent editions of the documents indicated below. The latest issues of CCSDS documents may be obtained from the CCSDS Secretariat at the address indicated on page i.

[1] *Procedures Manual for the Consultative Committee for Space Data Systems*. CCSDS A00.0-Y-7. Yellow Book. Issue 7. Washington, D.C.: CCSDS, November 1996.

[2] D. McCarthy. *IERS Technical Note 21*: *IERS Conventions (1996)*. Frankfurt am Main. Germany: IERS, 1996. [http://maia.usno.navy.mil/conventions.html]

[3] “The Introduction of the Improved IAU System of Astronomical Constants, Time Scales and Reference Frame into the Astronomical Almanac.” Supplement section, pp. S1-S39, in *The Astronomical Almanac*. Washington, DC and London: GPO and HMSO, 1984.

[4] http://www.ngs.noaa.gov/CORS/itrf.html
[possibly http://www.ngs.noaa.gov/CORS/Coords.html]

[5] O. Montenbruck and E. Gill. *Satellite Orbits: Models, Methods, and Applications*. New York: Springer, 2000.

[6] B. W. Parkinson and J. J. Spilker, eds. *Global Positioning System: Theory and Practice.* Volumes 163 and 164 of *Progress in Astronautics and Aeronautics*. Washington, DC: American Institute of Aeronautics and Astronautics, Inc., 1996

[7] E. D. Kaplan, ed. *Understanding GPS: Principles and Applications*. Norwood, MA: Artech House, 1996

[8] H.H. Fromm and R. Lucas. “The European Contribution to GNSS-2: A Status Report on the Technical Preparations.” International Conference on the European GNSS-2 System, European Space Agency, 1998.

[9] W. Gurtner and G. Mader. “Receiver Independent Exchange Format Version 2.” *CSTG GPS Bulletin* Vol.3, No.3, Rockville, MD: National Geodetic Survey, September/October 1990.

[10] T. D. Moyer, “Formulation for Observed and Computed Values of Deep Space Network (DSN) Data Types,” JPL Publication 00-07, Jet Propulsion Laboratory, Pasadena, California, 2000.

2 SCOPE OF NAVIGATION

2.1 GENERAL

This section briefly describes the spacecraft navigation process, and defines terms relevant to this process.

2.2 NAVIGATION

2.2.1 DEFINITION

The word 'navigate' is derived from the Latin words *navis*, meaning ship, and *agere*, meaning to move or direct. The common definition of navigation establishes that it is the science of getting a craft or person from one place to another.

2.2.2 SPACECRAFT NAVIGATION PROCESS

The spacecraft navigation process is comprised of three steps:

1) A set of measurements is acquired.

2) The set of measurements is used to calculate the trajectory, flight path, and/or attitude of the spacecraft.

3) The future state is predicted using the updated trajectory estimate.

Figure 2-1 depicts the spacecraft navigation process, which can take place either in real time or near-real time.

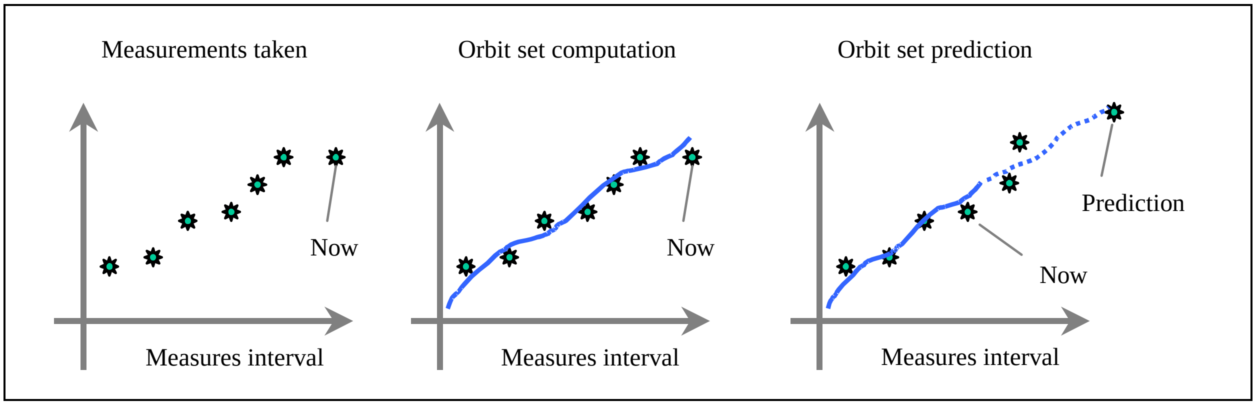


Figure 2-1: Real-Time or Near–Real Time Navigation Process

2.3 DEFINITIONS OF SPACECRAFT NAVIGATION TERMS

In order to establish a solid Recommendation for the exchange of spacecraft navigation data among Agencies, it is important to clearly define terms relevant to this process. These terms are as follows:

Navigation is the process used to find the present and imminent future position, orbit and orientation of a spacecraft using a series of measurements. For purposes of this document, CCSDS Subpanel 1J includes orientation and maneuver information as part of the spacecraft navigation process.

Guidance is the process of defining a path to move a spacecraft from one point to another.

Control is the process to maintain a spacecraft within the prescribed path and attitude.

The responsibilities for guidance and control are outside of the scope of this Report.

3 NAVIGATION MESSAGE EXCHANGE FRAMEWORK

3.1 GENERAL

This section describes the elements, characteristics, and major groupings of navigation message exchanges, as well as the data types involved in these exchanges.

3.2 TERMS AND DEFINITIONS

Agency Center: Facility used for executing commands to spacecraft, as well as monitoring telemetry, tracking, flight dynamics, and other engineering parameters. Data may be exchanged between agency centers by operations staff (e.g., via facsimile), or by servers across a computer network common to both the broadcasting and acquiring agents.

Navigation Session: The interchange of data between participants for navigation purposes.

Participant: An entity which has the ability to acquire or broadcast navigation messages. Consider all the possible participants that an agency has which can participate in a navigation message exchange. These participants can be arranged into three categories, as depicted in figure 3-1.

Spacecraft: Hardware in orbit about any body, as a single entity or as part of a set (such as constellations or formations). Spacecraft also includes assets in operations at, or in close proximity to, a remote body; these participants are referred to as *in situ* assets, and can include rovers, landers, aircraft, etc. Navigation messages to/from these participants are exchanged digitally, and are usually optimized in response to bandwidth, power, or message format constraints.

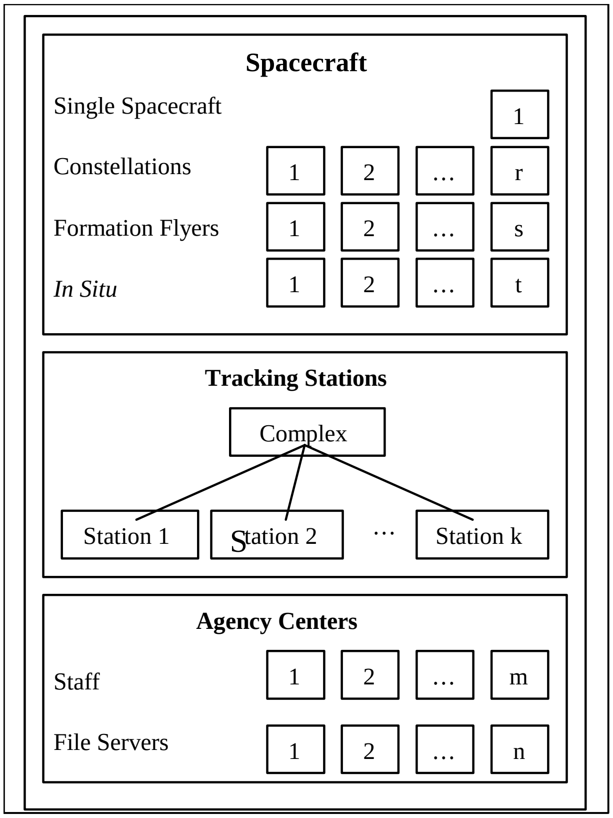


Figure 3-1: Agency Participants

Tracking Station: Ground-based facility used to monitor the location of spacecraft. Some agencies have multiple stations operated by a central entity, referred to as the complex.

3.3 NAVIGATION DATA CATEGORIES

For the purpose of organization in this report, the navigation data types exchanged by participants are grouped into three categories:

a) **Property** of a participant is a data type that allows describing the physical characteristics of that participant.

b) **Measurements** are data types collected specifically to improve the knowledge of properties.

NOTE – Any piece of information can be treated as a property or a measurement; the distinction is in how the information is used.

c) **Ancillary Information** is any data type used for the correct interpretation of measurements and properties.

3.4 NAVIGATION DATA AND NAVIGATION MESSAGE

Navigation Data: A set of measurements, properties, and ancillary information exchanged between participants during a navigation session.

Navigation Message: A particular arrangement of the navigation data whose structure and content are the subjects of CCSDS Subpanel 1J’s Recommendations.

Figure 3-2describes the roles of navigation data versus navigation messages.

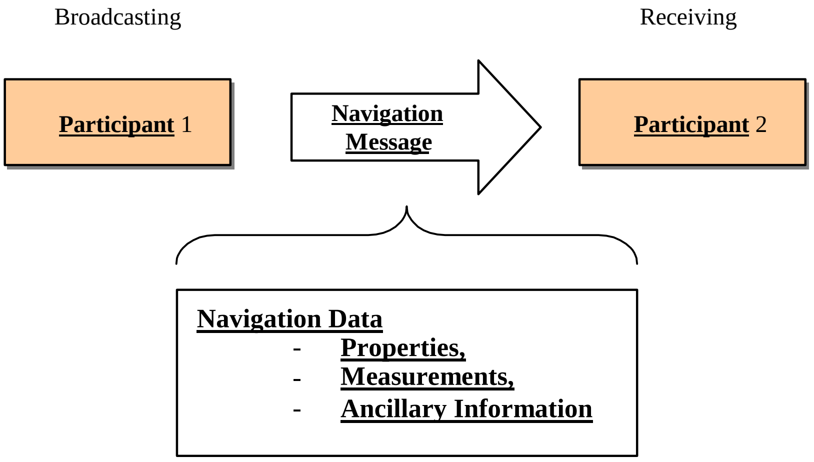


Figure 3-2: Navigation Message Exchange Definitions

3.5 NAVIGATION EXCHANGE DATA TYPES

Tables 3-1 through 3-3 contain a list of the most typical measurement, property, and ancillary information data types currently exchanged. For current and future Recommendations, the units recommended can come from these tables; in most cases, the International System of units (SI) will be used. However, there are cases where it is not possible to convert raw measurements from hardware-specific units to SI units without risking some degradation of measurement quality. For example, for Doppler and range measurements collected during periods when the transmitter frequency is time varying, a conversion to SI units is only possible with accurate trajectory information. In this case, the recommendation is for the participating agencies to agree upon a hardware-specific unit.

Table 3-1: Typical Measurement Data Types

Type	Units
Range	km
Range rate	km/s
Light Time	sec
Variable Transmitter Range	Range Units
Antenna Tracking Angles	deg
Doppler (coherent)	Hz
Doppler (non-coherent)	Hz
Variable Transmitter Doppler	-
Allan variance	-
Integrated Doppler count	-
Quality of measurements	-
IMU output	deg/s^2

Table 3-2: Typical Property Data Types

Type	Units
Position	km
Angular Velocity	deg/s
Linear Velocity	km/s
Angular acceleration	deg/ s^2
Acceleration	km/s^2
Attitude	deg
Attitude rate	deg/s
Length	m
Moment of Inertia	kgm^2
Force	kgm/ s^2
Torque	kgm^2/ s^2
Mass	kg
Energy, work, or heat	kgm^2/ s^2
Power	kgm/s^3
Pressure	kgm/ s^2
Temperature	K
Transmitter delay	ms
Receiver delay	ms
Surface	m^2
Antenna angles	deg
Oscillator frequency	MHz
Ballistic coefficient	m^2/kg
Aerodynamic coefficient	-
Reflectivity	-

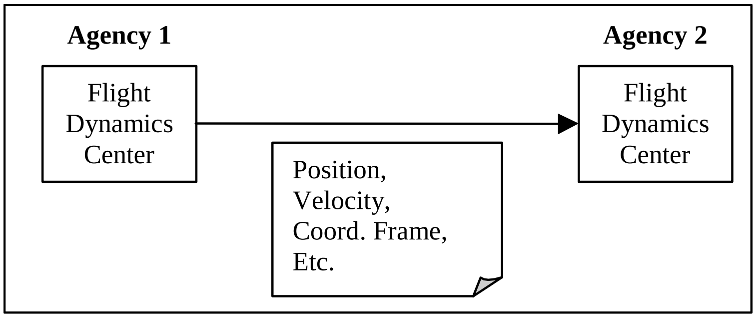
Table 3-3: Typical Ancillary Information Data Types

Type	Units
Physical constants	Depends on constant
Transmitter ID	-
Receiver ID	-
Epoch	-
Co-ordinate system description	-
Time system description	-
Quality of property	-

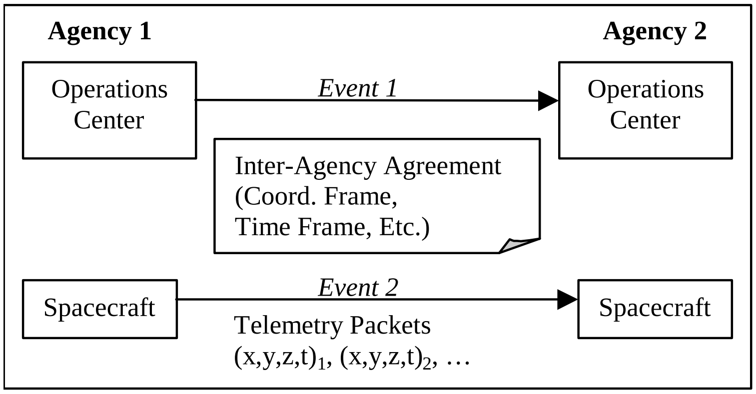
3.6 NAVIGATION DATA EXCHANGE CHARACTERISTICS

This Report describes a framework for the exchange of messages between any two types of participants (see subsection 3.2 and figure 3-1). It is not possible to describe every possible navigation session in detail, but navigation sessions generally have the following three general characteristics:

a) **Navigation sessions may be divided so as to accommodate constraints on data rates or availability of relevant information.** For example, for launch support of a spacecraft, spacecraft state vectors could be exchanged between operations centers of two agencies. This exchange may take the form of an ASCII file or electronic FAX. The text contains (1) the relevant property information (the position and velocity of the spacecraft); and (2) all of the necessary ancillary information needed to interpret the position and velocity of the spacecraft (coordinate frame, time, time frame, spacecraft ID, etc.). All of the information needed to unambiguously interpret the property information is sent in one event. In a second example, it may be necessary to send spacecraft position updates from one spacecraft to another in real time. Due to bandwidth limitations on the telemetry, it may not desirable to send any other ancillary information at that time. In that case, the participating agencies must agree on the coordinate frames, time frames, etc., beforehand, and commit these pieces of information to an interagency document. This document, in fact, becomes part of the overall navigation session as depicted in figure 3-3.



(a) Spacecraft state vectors between agencies



(b) Spacecraft relative position information between spacecraft

Figure 3-3: Examples of Navigation Sessions

b) **Navigation messages may utilize a CCSDS-recommended shorthand to convey ancillary information.** The shorthand developed in each case should be unambiguous, flexible and extensible. For example, in the case described in part (a) of figure 3-3, the coordinate frame can be an ASCII string, such as ‘Earth Centered True of Date’. It is possible to assign each coordinate frame a unique ASCII string, but there is a loss of extensibility with that approach, and in some cases the required number of bits of information may be prohibitive. It is also possible to assign a unique ID number to each coordinate frame; this approach would result in a fairly compact message, but the resulting order of coordinate frame IDs would have little physical meaning. (Shorthand conventions for commonly used data types are reviewed in section 4.)

c) **The content of a navigation session may be governed by more than one CCSDS Recommendation.** For example, if one agency is to provide another with the time history of the position of a sensor or antenna on a spacecraft, there are three pieces of information that need to be exchanged, each with its own protocol: (1) the time history of the spacecraft trajectory or orbit; (2) the position of the sensor or antenna with respect to the spacecraft center of mass (given most likely in a spacecraft fixed frame); and (3) the attitude history of the spacecraft. Although the content of these pieces come from different Recommendations, the information itself can be sent at one time or in separate events (see figure 3-4).

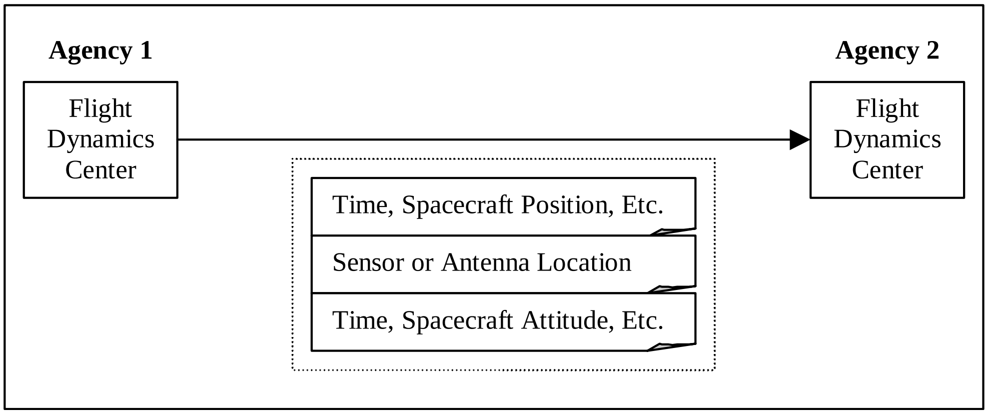


Figure 3-4: Navigation Session Using Multiple CCSDS Recommendations

3.7 NAVIGATION DATA EXCHANGE SCENARIOS

3.7.1 GENERAL

Ideally, every CCSDS Recommendation should apply to every type of navigation message exchange described previously in this section. However, it is clear that widely used formats and protocols which we consider strong candidates for CCSDS recommendation cannot presently cover the entire range of exchanges. Nevertheless, Agencies can benefit by promoting some of these formats at the present time. Therefore, the set of exchanges to which a recommendation applies needs to be defined. As new recommendations are proposed, new exchange scenarios will be defined in future versions of Subpanel P1J documents.

3.7.2 GROUND-TO-GROUND SCENARIO

CCSDS Subpanel 1J has defined **ground-to-ground** exchanges as the set of exchanges between any two non-spacecraft participants.

3.7.3 GROUND-TO-FLIGHT SCENARIO

CCSDS Subpanel 1J has defined **ground-to-flight** exchanges as the set of exchanges between any one spacecraft participant and a non-spacecraft participant.

3.7.4 FLIGHT-TO-FLIGHT SCENARIO

CCSDS Subpanel 1J has defined **flight-to-flight** exchanges as the set of exchanges between any two spacecraft participants.

4 ANCILLARY DATA

4.1 RATIONALE

This section describes the ancillary data types, which are the pieces of information needed to interpret measurements and properties of navigation participants. In general, ancillary information makes it possible to take properties or measurements and incorporate them correctly into numerical computations. In some cases, very detailed modeling information is passed along so that measurements and properties can be used in state-of-the-art, high-fidelity computations. For each ancillary data type covered, descriptions of formats and systems supported by member agencies are included in a unified manner.

4.2 QUALITY

For some exchanges, it may be desirable to include the uncertainty of the transmitted data. This uncertainty information is referred to as data **quality**. Quality specifications will be made in the individual recommendations. In addition, there are many constants used in navigation which have uncertainty values that are agreed upon in the international community; in this case, the user should refer to the relevant governing document.

4.3 COORDINATE FRAME IDENTIFICATION

4.3.1 GENERAL

This subsection defines coordinate system terms and describes commonly used specifications.

4.3.2 COORDINATE SYSTEM DEFINITIONS

A **coordinate frame** is defined as an associated set of mutually orthogonal Cartesian axes (referred to as x, y, and z).

The **reference plane** is the x-y plane in a coordinate frame.

The **reference direction** is the direction of the x-axis.

The **frame origin** is the common origin of the Cartesian axes.

4.3.3 COORDINATE SYSTEM SPECIFICATIONS

4.3.3.1 Specifying (1) the frame origin of the Cartesian axes, (2) the reference direction, and (3) the reference plane (or its normal direction, the z-axis direction) is sufficient to unambiguously define a coordinate frame. Frame origins are either (1) the center of mass of a participant (spacecraft, ground station, etc.), (2) the center of mass of a natural body, or (3) the center of mass of a set of bodies (referred to as the barycenter). For this discussion the origin will remain constant over time. The reference direction and reference plane normal are vectors that can be defined in one of these ways:

- point to a fixed direction in inertial space (e.g., toward a quasar);
- be parallel to the distance vector between one object and another;
- be parallel to an object's velocity vector;
- point from the origin through the intersection of two defined planes;
- be parallel to an object's spin axis; or
- be normal to an object's orbit.

4.3.3.2 In many cases, the reference plane is the equator or orbit plane of a natural body. In those cases, the motions of the equator or orbit plane are explicitly computed. A natural body's equatorial bulges can be perturbed by the gravitational attraction of other natural bodies; this causes variations in the orientation of the equatorial plane. Also, the perturbative effects of natural bodies on each other cause variations in the orientation of their orbit plane. Long term motions that can be treated as though they are secular are known as **precession** motion; short periodic motions are referred to as **nutation**. When the natural body's equator and ecliptic are defined as being represented by the precession motions only, these are referred to as **mean** directions. Those affected by both precession and nutation are referred to as **true** directions. Directions fixed at the time corresponding to a fundamental reference are referred to as values at the **epoch**, while those referring to instantaneous moments are referred to as **values of date**.

4.3.3.3 With the information contained in 4.3.3.2, it is possible to specify any form of coordinate reference system about any form of participant. In current practice, however, the vast majority of navigation messages between Agencies only use a small subset of the possibilities, some of which are described in the following sections.

4.3.4 INTERNATIONAL CELESTIAL REFERENCE SYSTEM (ICRS)

4.3.4.1 General

In 1991 the International Astronomical Union (IAU) established the International Celestial Reference System (ICRS) as the fundamental inertial coordinate system (reference [2]). The origin of the ICRS is defined as the solar system barycenter within a relativistic framework, and its axes are fixed with respect to distant extragalactic radio objects.

4.3.4.2 International Celestial Reference Frame (ICRF)

The practical realization of the ICRS is designated the International Celestial Reference Frame (ICRF), which is jointly maintained by the International Earth Rotation Service (IERS) and the IAU Working Group on Reference Frames (reference [2]). The fundamental plane of the ICRF is closely aligned with the mean Earth equator at J2000, and the origin of right ascension is defined by an adopted right ascension of the quasar 3C273 to closely match the vernal equinox at J2000. The Hipparcos star catalogue is an optical realization of the ICRS.

4.3.4.3 International Terrestrial Reference System (ITRS)

Complementary to the ICRS, the International Terrestrial Reference System (ITRS) provides the conceptual definition of an Earth-fixed reference system (reference [2]). Its origin is located at the Earth's center of mass (including oceans and atmosphere), and its unit of length is the SI meter. The orientation of the IERS Reference Pole (IRP) and IERS Meridian (IRM) is consistent with the previously adopted Bureau International de l'Heure (BIH) system at epoch 1984.0, as well as the former Conventional International Origin (CIO). The time evolution of the ITRS is such that it exhibits no net rotation with respect to the Earth's crust. The International Terrestrial Reference Frame (ITRF) is a realization of the ITRS. New versions of the ITRF are published annually and exhibit global differences on the centimeter level.

4.3.4.4 Development Ephemerides

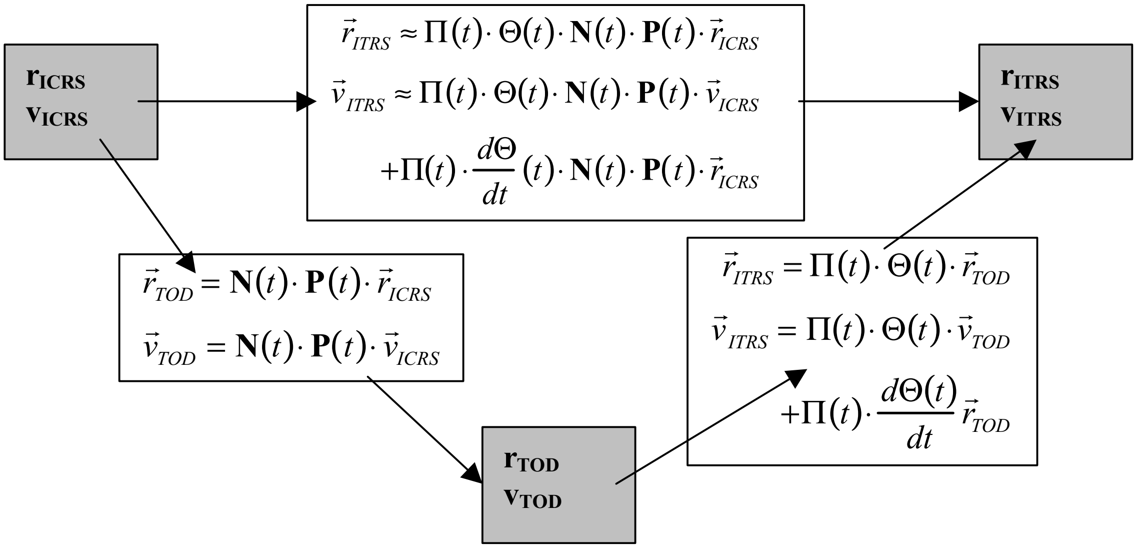
The Jet Propulsion Laboratory provides a series of solar system ephemerides. The Development Ephemerides (DE) are publicly available, and DE405 ephemerides are currently most widely used for general applications. All data are referred to the ICRF. The difference between the dynamical J2000 reference frame and the ICRF is at a level of 0.01 arcsec, and determined with an accuracy of 0.003 arcsec (reference [5]).

4.3.4.5 True of Date (TOD) Coordinate System

The True of Date (TOD) coordinate system is frequently used for astrodynamical applications.

4.3.4.6 Relationships Among Common Reference Frames

The transformations for position vectors (**r**) among the ICRS, the ITRF, and the TOD coordinate systems are performed in figure 4-1. With the simplification $\dot{\mathbf{\Pi}}(t) \approx \dot{\mathbf{N}}(t) \approx \dot{\mathbf{P}}(t) \approx 0$, which is applicable in the framework of navigation data exchange, the transformations of velocity vectors (**v**) among these frames is also shown.



where:

Π: Polar Motion Transformation Matrix
Θ: Earth Rotation Transformation Matrix
N: Nutation Transformation Matrix
P: Precession Transformation Matrix

$$\frac{d\Theta(t)}{dt} = \omega_E \cdot \begin{pmatrix} 0 & 1 & 0 \\ -1 & 0 & 0 \\ 0 & 0 & 0 \end{pmatrix} \cdot \Theta(t)$$

and ω_E is the (time dependent) Earth angular velocity. Details for these transformations are contained in reference [2].

Figure 4-1: Relationships Among Coordinate Frames of Interest

4.4 TIME

4.4.1 RATIONALE

The exact definition and understanding of time systems is essential for:

- the modeling of satellite orbits and attitude;
- exchange of navigation data; and
- satellite ground operations.

This subsection provides definitions of time scales relevant to navigation messages (reference [2]). The relative differences between time frames appear as (1) step functions (for example, when leap seconds are added); or (2) monotonically increasing differences (when relativistic effects are added); or (3) periodic differences (due to solar system dynamics).

4.4.2 TIME SCALES

4.4.2.1 Differences Between Time Scales

Figure 4-2 provides an overview of the differences between the most relevant time scales described in references [[2]] and [5].

NOTE – Periodic terms in Barycentric Coordinated Time (TCB) and Barycentric Dynamical Time (TDB) have been exaggerated by a factor of 100 to make them discernible.

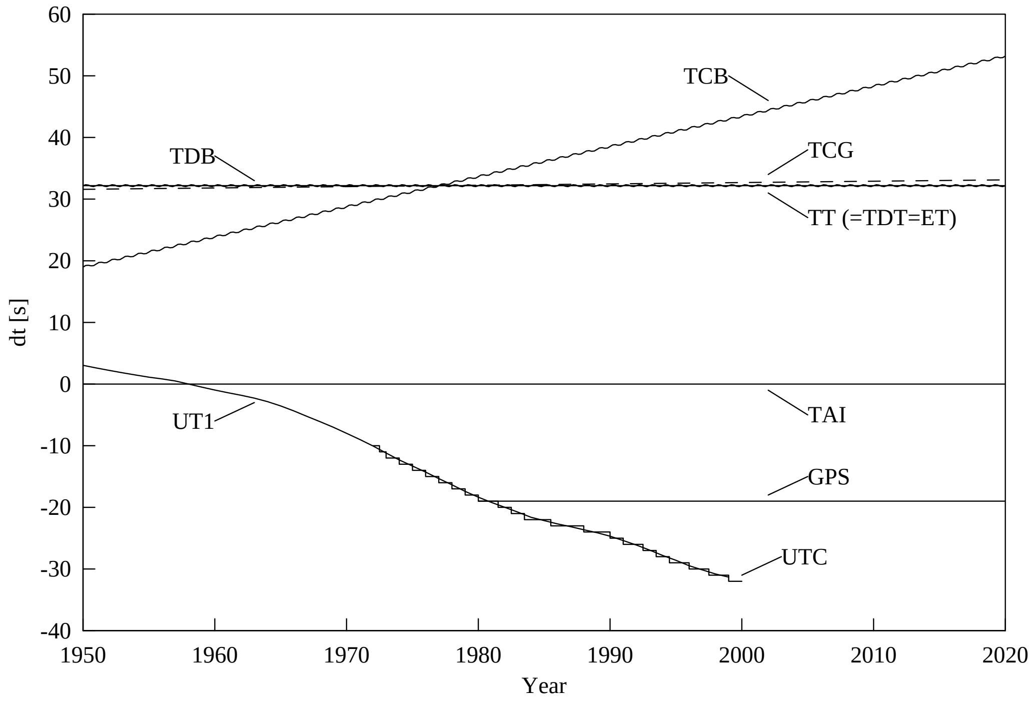


Figure 4-2: Differences Between Relevant Time Scales Between 1950 and 2020

4.4.2.2 Time Scales for Earth Orbiting Satellites

4.4.2.2.1 Terrestrial Time

Terrestrial Time (TT), previously known as Terrestrial Dynamical Time (TDT), is a conceptually uniform time scale that would be measured by an ideal clock on the surface of the geoid. TT is measured in days of 86400 SI seconds.

4.4.2.2.2 International Atomic Time

International Atomic Time (TAI) provides the practical realization of a uniform time scale based on atomic clocks and agrees with TT, except for a constant offset of 32.184s and the imperfections of existing clocks.

Between TAI and TT the following relation holds:

TAI = TT - 32.184s

4.4.2.2.3 Global Positioning System Time

Global Positioning System (GPS) time is an atomic time scale like TAI, but differs in the chosen offset and the choice of atomic clocks used in its realization.

The origin of GPS was arbitrarily chosen as:

GPS = UTC on 1980 January 6.0, i.e., GPS time differs from TAI by a constant offset of:

GPS = TAI(GPS) - 19s

4.4.2.2.4 Greenwich Mean Sidereal Time

Greenwich Mean Sidereal Time (GMST) is defined as the Greenwich hour angle of the mean vernal equinox of date.

4.4.2.2.5 Universal Time

Universal Time (UT1) is today's realization of a mean solar time, which is derived from GMST by a conventional relation.

4.4.2.2.6 Coordinated Universal Time

Coordinated Universal Time (UTC) is tied to TAI by an offset of integer seconds (leap seconds) which is regularly updated to keep UTC in close agreement with UT1) (within 0.9s). Leap seconds may be introduced on January 1 and July 1, as well as on April 1 and October 1).

At the beginning of the year 2000, the difference between UTC and TAI was

UTC - TAI = -32s

4.4.2.3 Time Scales for Interplanetary Missions

4.4.2.3.1 Barycentric Dynamical Time (TDB)

Barycentric Dynamical Time (TDB) is the independent variable of current barycentric solar system ephemerides. This time was introduced by the IAU in 1976 and defined to deviate from the TDT (which is now identical with TT) by periodic terms (≈2 ms) only (reference [3]).

4.4.2.3.2 Barycentric Coordinated Time

Barycentric Coordinated Time (TCB) is the relativistic time coordinate of the 4-dimensional barycentric frame. TCB and TDB exhibit a scale difference of

$$L_B = 1.5505197487 \cdot 10^{-8}$$

which results in a secularly increasing difference of

$$\mathrm{TCB} - \mathrm{TDB} \approx 46.7\mathrm{s/cy}\ (\mathrm{year}-1977.0)$$

4.4.2.4 Relationships Between Time Scales

Figure 4-3 depicts the relationships between the time scales.

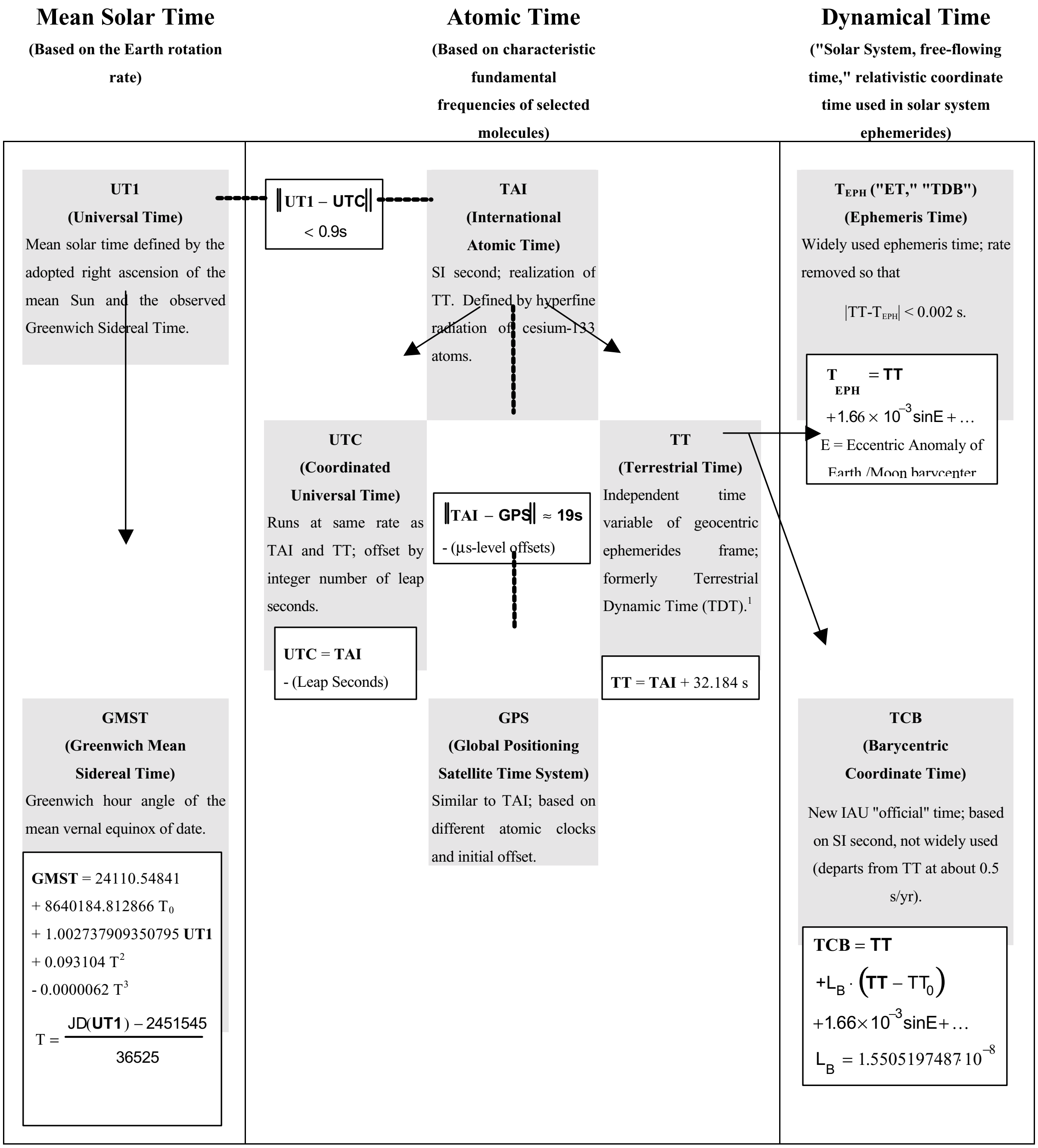


Figure 4-3: Relationships Among Time Scales

4.5 ASTRODYNAMIC CONSTANTS

Examples of astrodynamic constants exchanged for navigation purposes include the vacuum speed of light, Greenwich Mean (GM), and reference dimensions for Earth and other solar system bodies. Unless otherwise specified, the international community uses values recommended by the IERS.

4.6 ENVIRONMENTAL MODELS

Along with astrodynamic constants, mathematical models have been derived to compute effects on measurements, as well as effects on the equations of motion. Unless otherwise specified, the international community uses models recommended by the IERS.

5 PROPERTIES

5.1 RATIONALE

There are many possible ways to group the physical attributes of spacecraft, rovers, and tracking stations that are needed for navigation. This section first discusses the simplest physical attributes, and then introduces progressively more sophisticated attributes (see table 5-1).

Table 5-1: Property Data Types

Property Data Type Grouping	Definition	Example Data Types
Point Source	The attributes that can be associated with an object when it is treated as a point source.	Position Velocity Acceleration
Three-Dimensional Object	The attributes that can be associated with an object when it is treated as a three-dimensional object.	Orientation Angles Angular Velocity
Physical	The attributes which are physical characteristics of the spacecraft in its entirety.	Spacecraft Mass Moments of Inertia Solar Rad. Press. Area Solar Rad. Press. Coefficient Aerodynamic Drag Area Aerodynamic Coefficient
Hardware	The attributes which are physical characteristics of a specific sub-assembly on a spacecraft.	Solar Panel Area, Bus Area Mass Flow Rate Transmitter Delays Receiver Delays Oscillator Frequency Oscillator Stability

5.2 POINT SOURCE PROPERTIES

5.2.1 SURFACE STATION LOCATIONS

Spacecraft tracking and communications are made possible by a network of fixed ground stations located around the world. Whenever an orbiting spacecraft passes across the field of coverage of a ground station, it collects tracking data which allows determination of the spacecraft position and velocity. In this category we also consider the location of surface rovers and remote stations.

For surface tracking stations, the station coordinates and uncertainties are commonly defined based on the ITRF (reference [4]), using Cartesian coordinates. The reference point described by the coordinates is usually independent of its pointing direction. Pointing-dependent corrections, if significantly larger than the location uncertainty, are specified separately.

5.2.2 STATE VECTORS AND ORBITAL ELEMENTS

The motion of a satellite around a central body may be described by various sets of parameters. In subsections 5.2.2.1 and 5.2.2.2, short definitions are given for the most commonly used representations.

5.2.2.1 State Vector

The time-dependant spacecraft position (km) and velocity vectors (km/s)

$$\vec{r}(t) = \begin{pmatrix} x(t) \\ y(t) \\ z(t) \end{pmatrix} \quad \text{and} \quad \dot{\vec{r}}(t) = \begin{pmatrix} \dot{x}(t) \\ \dot{y}(t) \\ \dot{z}(t) \end{pmatrix}$$

are usually given in the 6-dimensional representation of the state vector

$$\vec{Y}(t) = \begin{pmatrix} x(t) \\ y(t) \\ z(t) \\ \dot{x}(t) \\ \dot{y}(t) \\ \dot{z}(t) \end{pmatrix}$$

in a specified coordinate system at a specific epoch.

5.2.2.2 Classical Keplerian Elements

For some purposes it may be convenient to use the classic osculating Keplerian elements (table 5-2v), which are an equivalent representation of the state vector at a specified epoch.

Table 5-2: Classical Keplerian Elements

Parameter	Symbol	Unit
Semi-major Axis	a	km
Eccentricity	e	–
Inclination	i	deg
Right Ascension of Ascending Node	Ω	deg
Argument of Perigee	ω	deg
True Anomaly	υ	deg

NOTE – The application of the Keplerian elements does not make sense for special cases (e.g., $i = 0$, $e \geq 1$).

For some applications (e.g., orbit maintenance of remote sensing satellites), mean Keplerian elements are used which are generated by averaging the osculating elements over one or more revolutions.

5.2.3 ORBIT MANEUVERS

5.2.3.1 Thrust Forces

The motion of a spacecraft is affected by natural forces. Spacecraft motion may also be affected by the action of an onboard thruster system. Thrusters are frequently applied for orbit control, attitude control or a combination of both, and exhibit a variety of performance levels and burn durations. The mathematical model used for trajectory prediction must factor in the impact of thrust forces on maneuvers, as well as the impact of maneuvers on spacecraft orbit.

5.2.3.2 Impulsive Maneuvers

In many cases thrust forces may be modeled as impulsive maneuvers. These are described by a velocity vector $\Delta\vec{v}$, applied to the spacecraft at a specified epoch with a burn duration $\Delta t = 0$.

5.2.3.3 Simplified Modeling of Extended Orbit Maneuvers

For extended maneuvers, a simplified model with the assumptions of constant thrust and mass flow rate is sufficient in most cases.

With

$\vec{F}$: Thrust force vector (assumed as constant during the maneuver)
$|\dot{m}|$: Mass flow rate (assumed as constant during the maneuver)
Δt: Maneuver burn duration
m_0: Spacecraft mass at start of the maneuver

the total velocity increment experienced by the spacecraft is computed in this case as follows:

$$\Delta\vec{v} = -\frac{\vec{F}}{|\dot{m}|} \cdot \ln\left(1 - \frac{|\dot{m}| \cdot \Delta t}{m_0}\right) .$$

5.2.3.4 Exact Modeling of Extended Orbit Maneuvers

In cases of high precision orbit computation, an exact numerical modeling of the time-dependent functions of thrust and mass flow rate is applied.

5.2.4 EPHEMERIS REPRESENTATIONS OF TRAJECTORIES

Under the proper conditions, state vectors and orbital elements allow for the use of a propagation technique (analytical or numerical) to interpret the position and velocity at times different from the specified epoch. Another manner to represent a trajectory is to use a tabular format, with state vectors at pre-determined time intervals. This format (referred to as an ephemeris representation) allows for the use of interpolation techniques to interpret the position and velocity at times different from the tabular epochs.

5.3 ATTITUDE

5.3.1 DEFINITIONS

The attitude of a rigid body is its orientation in a 3-dimensional space at a given time. Participant attitude is the orientation, at each time, of a participant with respect to a known reference (e.g., celestial objects, frame, etc.). Attitude motion describes the attitude evolution around its centre of mass.

5.3.2 ATTITUDE DETERMINATION

Attitude determination is the process of computing a set of parameters that describe this orientation using measurements. The process of attitude determination also includes checking the measurements of the various onboard attitude sensors for any sign of physical deterioration, improper configuration, or changes in calibration or alignment. All available attitude measurements can be processed to compute a best-estimate time history of spacecraft attitude. This history is called definitive attitude. Most spacecraft now carry Onboard Computers (OBC) with the capability of computing the spacecraft's own attitude parameters.

5.3.3 TRANSFER OF SPACECRAFT ATTITUDE

The transfer of spacecraft attitude data from one Agency to another is useful to:

- ensure scientific observations of specific targets;
- maximize solar energy collection for onboard power usage;
- ensure successful on-orbit, de-orbit, or rendezvous and orbit maneuver operations;
- ensure successful attitude maneuver operations;
- ensure and evaluate efficient ground/onboard communications links connected with the onboard antenna pattern.

5.3.4 ATTITUDE REPRESENTATIONS

Several attitude representations are available, and the choice of a particular representation is generally suited to the attitude stabilisation mode of the spacecraft. Examples of representations include:

- single axis (spinned);
- three axis;
- gravity gradient;
- uncontrolled;

Due to this wide domain of configuration it is convenient to use a single representation to describe the status of the attitude. This mathematical representation of a rigid body is called a ‘quaternion’. As it is non-ambiguous and singularity free, it is the most convenient for attitude kinematics, and is used for every attitude stabilisation mode.

The attitude elements needed at a given time are as follows:

- time of application;
- quaternion at this time;
- description of body frame;
- description of reference frame.

NOTE – The following definition use an inertial reference frame (J2000, for example) and a connected body frame.

The attitude of the body frame with respect to the reference frame is represented by a unique rotation around a vector u, which is invariant in both frames, with an angular amplitude Φ. The vector u is oriented in such a way that makes Φ positive directly around the u vector in the movement from reference frame to body frame.

The attitude quaternion is defined by a 4-dimension vector Q (Q0,Q1,Q2,Q3) with:

- Q0 = cos(Φ/2)
- Q1 = e1*sin(Φ/2)
- Q2 = e2*sin(Φ/2)
- Q3 = e3*sin(Φ/2)

Where Φ is the rotation angle between the reference frame and the body frame and e1, e2, and e3 are the components of the unit rotation vector u in the body axis (or in the reference frame) with the relation

$$Q0*Q0 + Q1*Q1 + Q2*Q2 + Q3*Q3 = 1$$

We also define the conjugate quaternion Q^T =(Q0,Q1,Q2,Q3).

With

xi the components of a vector in the reference frame, with x i= (xi1,xi2,xi3)
xf the components of a vector in the body frame, with xf = (xf1,xf2,xf3)

We define the associated quaternions:

$$\boldsymbol{Xi} = \begin{pmatrix} 0 \\ \boldsymbol{xi}1 \\ \boldsymbol{xi}2 \\ \boldsymbol{xi}3 \end{pmatrix} \text{ and } \boldsymbol{Xf} = \begin{pmatrix} 0 \\ \boldsymbol{xf}1 \\ \boldsymbol{xf}2 \\ \boldsymbol{xf}3 \end{pmatrix}$$

Xf and Xi are linked by

Xf = Q * Xi * Q^T and Xi = Q^T * Xf.* Q.
(Those products are defined by the quaternion's algebra.)

This link can also be expressed using a rotation matrix M.

$$\boldsymbol{xf} = \boldsymbol{M} \cdot \boldsymbol{xi}$$

$$\boldsymbol{M} = \begin{pmatrix} 2(\boldsymbol{q}_0^2 + \boldsymbol{q}_1^2) - 1 & 2(\boldsymbol{q}_1\boldsymbol{q}_2 + \boldsymbol{q}_0\boldsymbol{q}_3) & 2(\boldsymbol{q}_1\boldsymbol{q}_3 - \boldsymbol{q}_0\boldsymbol{q}_2) \\ 2(\boldsymbol{q}_1\boldsymbol{q}_2 - \boldsymbol{q}_0\boldsymbol{q}_3) & 2(\boldsymbol{q}_0^2 + \boldsymbol{q}_2^2) - 1 & 2(\boldsymbol{q}_2\boldsymbol{q}_3 + \boldsymbol{q}_0\boldsymbol{q}_1) \\ 2(\boldsymbol{q}_1\boldsymbol{q}_3 + \boldsymbol{q}_0\boldsymbol{q}_2) & 2(\boldsymbol{q}_2\boldsymbol{q}_3 - \boldsymbol{q}_0\boldsymbol{q}_1) & 2(\boldsymbol{q}_0^2 + \boldsymbol{q}_3^2) - 1 \end{pmatrix}$$

5.4 PHYSICAL PROPERTIES

5.4.1 PARAMETERS

The parameters for the simplified models discussed in subsections 5.4.2 and 5.4.3 are parameters are as follows: C_R, A_R, C_D, A_D (within the Orbit Parameters Message [OPM]).

5.4.2 SOLAR RADIATION PRESSURE (SIMPLIFIED MODEL)

The absorption or reflection of photons associated with solar radiation causes a spacecraft to accelerate. For most applications of navigation data exchange, a simplified model which assumes that the surface normal of the spacecraft is pointing to the Sun is sufficient to account for the effect of solar radiation. The following model for the acceleration of a satellite due to solar radiation pressure may be used:

$$\ddot{\vec{r}}_R = -C_R \frac{A_R}{m} \frac{\Phi}{c} \frac{\vec{r}_S}{r_S^3} AU^2$$

where:

C_R: Solar radiation pressure coefficient
A_R: Effective satellite cross section for solar radiation pressure
m: Spacecraft mass
Φ: Solar flux at 1 AU (≈ 1367 Wm^{-2})
c: Velocity of light
$\vec{r}_S$: Vector spacecraft-Sun
AU: Astronomical unit

5.4.3 ATMOSPHERIC DRAG (SIMPLIFIED MODEL)

For low altitude satellites, the interaction of particles from the central body's atmosphere with the spacecraft surface causes an acceleration. For most applications of navigation data exchange, a simplified model which assumes a spherical shape of the satellite with a unique surface is sufficient to account for the effect of atmospheric drag. The following model for the acceleration of a satellite due to atmospheric drag may be used:

$$\ddot{\vec{r}}_D = -\frac{1}{2} C_D \frac{A_D}{m} \rho \cdot v_r^2 \frac{\vec{v}_r}{v_r}$$

where:

C_D: Drag coefficient
A_D: Effective satellite cross section for drag
m: Spacecraft mass
ρ: Atmospheric density at spacecraft location
$\vec{v}_R$: Velocity of spacecraft relative to atmosphere

5.5 HARDWARE PROPERTIES

Hardware properties are associated with a particular subsystem of the entire spacecraft, and not the vehicle as a whole. For example, in addition to the effective areas defined in 5.4 for the entire spacecraft for solar radiation and aerodynamic drag calculations, area information may be exchanged for individual components of significance on the vehicle (such as a solar panel or parabolic antenna). Other examples include the mass flow rate (which can depend on the engines or thrusters being used for a particular maneuver), transmitter and receiver delays (which can be a function of the transponder or transceiver being used), and oscillator frequency and stability (multiple frequency standards can exist on a single spacecraft).

6 MEASUREMENTS

6.1 RATIONALE

Spacecraft navigation is based on measurements of velocity, distance, and angular direction. Data for orbit determination is obtained from telemetry or radar tracking signals.

6.2 MEASUREMENT DATA TYPES

6.2.1 ANGLES

Tracking stations at various locations around the Earth track a single spacecraft simultaneously. Each station makes high-rate recordings of the downlink's wave fronts while maintaining precise timing data. Stations also record the pointing angles of their antennas, which slew directly to the position of any extragalactic object, when that position is accurately known. The antennas then slew back to the spacecraft. Correlation and analysis of the recorded data yields a very precise triangulation from which both angular position and radial distance may be determined.

6.2.2 RADIOMETRIC/TRACKING DATA

6.2.2.1 General

Spacecraft tracking is the process used to determine where a spacecraft is located in its orbital trajectory at a particular time. Tracking data is obtained from the spacecraft in flight as it passes within the field of signal acquisition from one participant to another.

6.2.2.2 Range

Range is the measurement of distance between the flying spacecraft and another participant (or other participants).

6.2.2.3 Range Rate

Range rate is the measurement of relative velocity between the flying spacecraft and other participant(s). Normally the integrated Doppler count is converted to range-rate in a suitable way.

6.2.2.4 Phase

Phase is the relative measure of the alignment of two waveforms of similar frequency, expressed in degrees from 0 to 360.

6.2.3 ACCELERATION

Body acceleration is measured by accelerometers and other devices.

6.3 GPS

The Navigation Satellite Timing and Ranging System (NAVSTAR) and the Global Navigation Satellite System (GLONASS) provide several observable quantities to the user's receivers, including the code, the carrier, etc. From the phase of the code, the receiver can extract the pseudorange. From the frequency of the carrier, the receiver can extract the Integrated Doppler Count. Apart from these observables, the receiver can get the GPS system time. The relevant GPS measurement is referred to as the PVt (Position, Velocity and time) measurement.

7 SATELLITE-BASED GLOBAL NAVIGATION SYSTEMS

7.1 OVERVIEW

There is a growing dependency in space applications on Global Navigation Systems (GNS) such as GLONASS, NAVSTAR, and the Galileo Space Segment (GalileoSAT).

The development of these three satellite-based systems represents a huge change in the technology of navigation and positioning. GLONASS was developed in Russia, NAVSTAR was developed in the U.S, and GalileoSAT is now being developed by the European Space Agency (ESA). Although these systems were initially planned for military purposes, the civil sector (non-military) has quickly recognized their potential in the areas of civil aviation, marine and ground navigation, spacecraft navigation, and surveying and geodesy. The development of products and services has opened a new market with rapid growth.

Several factors make GNSs attractive to spacecraft navigation:

- Coverage: These systems offer almost complete coverage for spacecraft with Low Earth Orbit (LEO) orbits, and reasonable coverage for spacecraft with High Earth Orbits (HEO) orbits.
- Accuracy: All these systems can or will provide accuracy in orders of magnitude better than conventional ground tracking (references [6], [7]and [8]).
- Integrity: The systems are guaranteed to function continuously without performance degradation.
- Price: The degraded signals of both NAVSTAR and GLONASS are available without charge.

7.2 NAVSTAR

The U.S. GPS system, NAVSTAR, is managed by the United States Air Force (USAF). The NAVSTAR satellite constellation is composed of 27 satellites deployed in near-elliptical orbits around the Earth. The satellites are located in 4 orbital planes, with 6 active satellites per plane.

7.3 GLONASS

GLONASS is operated by the Air Command of the Russian military, and it is similar to NAVSTAR. GLONASS is comprised of 24 satellites having 3 orbital planes, with 8 satellites per plane. However, GLONASS uses Frequency Division Multiple Access (FDMA) to broadcast data, whereas NAVSTAR uses Code Division Multiple Access (CDMA).

7.4 GALILEOSAT

In 1999, ESA approved the development of GalileoSAT, which is expected to be fully operational by the year 2008. GalileoSAT will be interoperable with NAVSTAR. The GalileoSAT constellation will consist of a medium-Earth orbit satellite constellation and a number of geostationary satellites, plus some other local complements. GalileoSAT will carry both commercial and non-commercial signals.

7.5 EXCHANGE OF GNS MEASUREMENTS

The Receiver Independent Exchange (RINEX) format is used for the exchange of GNS measurements in ground-to-ground scenarios (reference [9]).

ANNEX A

GLOSSARY

This annex provides a glossary of spacecraft navigation terminology.

Agency Center: Facility used for executing commands to spacecraft, as well as monitoring telemetry, tracking, flight dynamics, and other engineering parameters.

Ancillary Information: A data type used to interpret measurements and properties.

Attitude: The direction in which a spacecraft is oriented in space.

Control: The process used to maintain a spacecraft within its prescribed path and attitude.

Coordinate frame: An associated set of mutually orthogonal Cartesian axes (referred to as x, y, and z).

Doppler: The apparent change in the frequency of a signal caused by the relative motion of the transmitter and receiver.

Eccentricity: The ratio of the distance from the center of an ellipse to its focus to the semi-major axis.

Ephemeris: A list of (accurate) positions and velocities of a satellite as a function of time.

Epoch: Epoch signifies the beginning of an era (or event) or the reference date of a system of measurements.

Flight-to-flight: The set of exchanges between any two spacecraft participants.

Frame origin: The common origin of the Cartesian axes.

Global Positioning System (GPS): A highly accurate, global satellite navigation system based on a constellation of 29 satellites orbiting the earth at a very high altitude. In addition to navigation data, the system also provides very precise time data.

Ground-to-ground: The set of exchanges between any two non-spacecraft participants

Ground-to-flight: The set of exchanges between any one spacecraft participant and a non-spacecraft participant.

Guidance: The process of defining a path to move a spacecraft from one point to another.

Inclination: The angle between the orbital plane of a body and its equatorial plane.

Measurements: Data types collected specifically to improve the knowledge of properties.

Navigation: The process used to find the present and imminent future position, orbit and orientation of a spacecraft using a series of measurements. For purposes of this document, CCSDS Subpanel 1J includes orientation and maneuver information as part of the spacecraft navigation process.

Navigation Data: A set of measurements, properties, and ancillary information exchanged between participants during a navigation session.

Navigation Message: A particular arrangement of the navigation data whose structure and content are the subjects of Subpanel 1J's Recommendations.

Navigation Session: The interchange of data between participants for navigation purposes.

Nutation: The short-period oscillations in the motion of the pole of rotation of a freely rotating body that is undergoing torque from external gravitational forces. Nutation of the Earth's pole is difined in terms of components in obliquity and longitude.

Orbit: The path followed by a celestial body.

Orbital elements: A set of parameters describing any astronomical or spacecraft orbit.

Participant: An entity which has the ability to acquire or broadcast navigation messages.

Perigee: The point in an orbit of closest approach to the Earth (i.e., at this point the geometric distance between Earth and the orbiting body is at a minimum).

Polar motion: Motion of the instantaneous axis of the rotation of the Earth with respect to the solid body of the Earth. Irregular but more or less circular motion with an amplitude of about 15m, and a main period of about 430 days (called Chandler Wobble).

Precession: The change in orientation of a spinning body's rotational axis.

Property: A data type that describes the physical characteristics of a participant.

Quality: Uncertainty information about a participant or a measurement.

Quaternion: A mathematical representation of a rigid body.

Range rate: The rate of change of range between the satellite and receiver. The range to a satellite changes due to satellite and observer motions. Range rate is determined by measuring the Doppler shift of the satellite beacon carrier.

Receiver Independent Exchange Format (RINEX): A set of standard definitions and formats to promote the free exchange of GPS data and facilitate the use of data from any GPS receiver with any software package.

Reference direction: The direction of the x-axis.

Reference plane: The x-y plane in a coordinate frame.

Right ascension of ascending node: The angular distance measured from the vernal equinox, positive to the east, along the celestial equator to the ascending node.

RINEX: See Receiver Independent Exchange Format.

Tracking Station: Ground-based facility used to monitor the location of spacecraft. Some agencies have multiple stations operated by a central entity, referred to as the complex.

ANNEX B

ABBREVIATIONS AND ACRONYMS

BIH	Bureau International de l'Heure
CCSDS	Consultative Committee for Space Data Systems
CDMA	Code Division Multiple Access
CIO	Conventional International Origin
DE	Development Ephemerides
DSN	Deep Space Network
ESA	European Space Agency
FDMA	Frequency Division Multiple Access
GalileoSAT	Galileo Space Segment
GLONASS	Global Navigation Satellite System
GM	Greenwich Mean
GMST	Greenwich Mean Sidereal Time
GNS	Global Navigation System
GPS	Global Positioning System
HEO	High Earth Orbit
IAU	International Astronomical Union
ICRF	International Celestial Reference Frame
ICRS	International Celestial Reference System
IERS	International Earth Rotation Service
IRM	IERS Meridian
IRP	IERS Reference Pole
ITRF	International Terrestrial Reference Frame

ITRS	International Terrestrial Reference System
JPL	Jet Propulsion Laboratory
LEO	Low Earth Orbit
NAVSTAR	Navigation Satellite Timing and Ranging System
OBC	Onboard Computer
OPM	Orbit Parameters Message
PVt	Position, Velocity and time
RINEX	Receiver Independent Exchange Format
SI	International System of Units
TAI	International Atomic Time
TCB	Barycentric Coordinated Time
TDB	Barycentric Dynamical Time
TDT	Terrestrial Dynamical Time
TOD	True of Date
TT	Terrestrial Time
USAF	United States Air Force
UT1	Universal Time
UTC	Coordinated Universal Time