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Report Concerning Space Data System Standards

**NAVIGATION DATA—
DEFINITIONS AND
CONVENTIONS**

INFORMATIONAL REPORT

CCSDS 500.0-G-2

GREEN BOOK

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FOREWORD

This Report contains technical material to supplement the CCSDS Recommended Standards 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. This version of the Green Book contains expanded material regarding spacecraft attitude data and radiometric tracking data.

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CONTENTS

<u>Section</u>	<u>Page</u>
1 INTRODUCTION.....	1-1
1.1 PURPOSE AND SCOPE.....	1-1
1.2 APPLICABILITY.....	1-1
1.3 STRUCTURE OF THIS DOCUMENT.....	1-1
1.4 REFERENCES.....	1-2
2 SCOPE OF NAVIGATION.....	2-1
2.1 GENERAL.....	2-1
2.2 NAVIGATION.....	2-1
2.3 DEFINITIONS OF SPACECRAFT NAVIGATION TERMS.....	2-3
3 NAVIGATION MESSAGE EXCHANGE FRAMEWORK.....	3-1
3.1 GENERAL.....	3-1
3.2 TERMS AND DEFINITIONS.....	3-1
3.3 NAVIGATION DATA CATEGORIES.....	3-2
3.4 NAVIGATION DATA AND NAVIGATION MESSAGE.....	3-2
3.5 NAVIGATION EXCHANGE DATA TYPES.....	3-3
3.6 NAVIGATION DATA EXCHANGE CHARACTERISTICS.....	3-4
3.7 NAVIGATION DATA EXCHANGE SCENARIOS.....	3-7
4 ANCILLARY DATA.....	4-1
4.1 RATIONALE.....	4-1
4.2 QUALITY.....	4-1
4.3 COORDINATE FRAME IDENTIFICATION.....	4-1
4.4 TIME.....	4-8
4.5 ASTRODYNAMIC CONSTANTS.....	4-12
4.6 ENVIRONMENTAL MODELS.....	4-13
4.7 ANTENNA TYPES.....	4-13
5 PROPERTIES.....	5-1
5.1 RATIONALE.....	5-1
5.2 POINT SOURCE PROPERTIES.....	5-2
5.3 ATTITUDE.....	5-5
5.4 PHYSICAL PROPERTIES.....	5-11
5.5 HARDWARE PROPERTIES.....	5-12

CONTENTS (continued)

<u>Section</u>	<u>Page</u>
6 MEASUREMENTS	6-1
6.1 RATIONALE.....	6-1
6.2 MEASUREMENT DATA TYPES.....	6-1
6.3 GPS	6-8
6.4 ATTITUDE MEASUREMENT DATA TYPES.....	6-8
7 SATELLITE-BASED GLOBAL NAVIGATION SYSTEMS	7-1
7.1 OVERVIEW	7-1
7.2 NAVSTAR.....	7-1
7.3 GLONASS.....	7-1
7.4 GALILEO	7-2
7.5 EXCHANGE OF GNS MEASUREMENTS.....	7-2
ANNEX A GLOSSARY	A-1
ANNEX B ABBREVIATIONS AND ACRONYMS	B-1

Figure

2-1 The Navigation Process	2-2
2-2 Real-Time or Near-Real-Time Navigation Process	2-3
3-1 Agency Participants	3-1
3-2 Navigation Message Exchange Definitions.....	3-2
3-3 Examples of Navigation Sessions.....	3-5
3-4 Navigation Session Using Multiple CCSDS Recommended Standards.....	3-6
4-1 Relationships among Common Reference Frames	4-5
4-2 Local Orbital LVLH Frame	4-6
4-3 Local Orbital TNW Frame.....	4-7
4-4 Local Orbital QSW Frame.....	4-8
4-5 Differences between Relevant Time Scales between 1950 and 2020	4-9
4-6 Relationships among Time Scales	4-12
5-1 Classical Keplerian Orbit Orientation Angles	5-3
5-2 Rigid Body Angular Momentum	5-9
6-1 Δ DOR Observation Geometry	6-6
6-2 Differenced Range	6-7

CONTENTS (continued)

<u>Table</u>	<u>Page</u>
3-1 Typical Measurement Data Types	3-3
3-2 Typical Property Data Types	3-4
3-3 Typical Ancillary Information Data Types.....	3-4
5-1 Property Data Types	5-1
5-2 Classical Keplerian Elements	5-3

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. For purposes of this document, orientation and maneuver information are included as part of the spacecraft navigation process.

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

- properties and measurements of spacecraft dynamics;
- ground station information;
- environmental models;
- tracking data;
- spacecraft attitude data;
- orbital elements;
- ancillary data required for spacecraft navigation.

1.2 APPLICABILITY

This document applies to navigation and attitude 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 and attitude data.

1.3 STRUCTURE OF THIS DOCUMENT

- a) Section 2 provides a brief overview of spacecraft navigation.
- b) Section 3 provides foundational information regarding the components of a message exchange architecture (definitions, paradigms, etc.).

- c) Section 4 provides details about coordinate frames, time systems, astrodynamic constants, environmental models, and other ancillary concepts important in spacecraft navigation.
- d) Section 5 discusses properties of the entities that participate in a navigation data exchange.
- e) Section 6 discusses the types of measurements that may be made during a navigation session.
- f) Section 7 briefly discusses satellite based global navigation systems such as GPS, GLONASS, GALILEO.
- g) Annexes A and B constitute a Glossary of Terms and a listing of Acronyms, respectively.

1.4 REFERENCES

The following documents are referenced in this Technical Report. At the time of the publication the indicated editions were valid. All documents are subject to revision, and users of this Technical Report 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-9. Yellow Book. Issue 9. Washington, D.C.: CCSDS, November 2003.
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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 four steps:

- 1) A set of measurements is acquired.
- 2) The set of measurements is used to determine the trajectory, flight path, and/or attitude of the spacecraft at a given time or over an interval of time (cf. references [13], [20], and [21] and figure 2-1).
- 3) The future state is predicted by propagation models using the updated estimate from step 2.
- 4) A spacecraft propulsive maneuver is performed to correct the trajectory, if necessary, to meet mission requirements and constraints. This process is called ‘flight path control’.

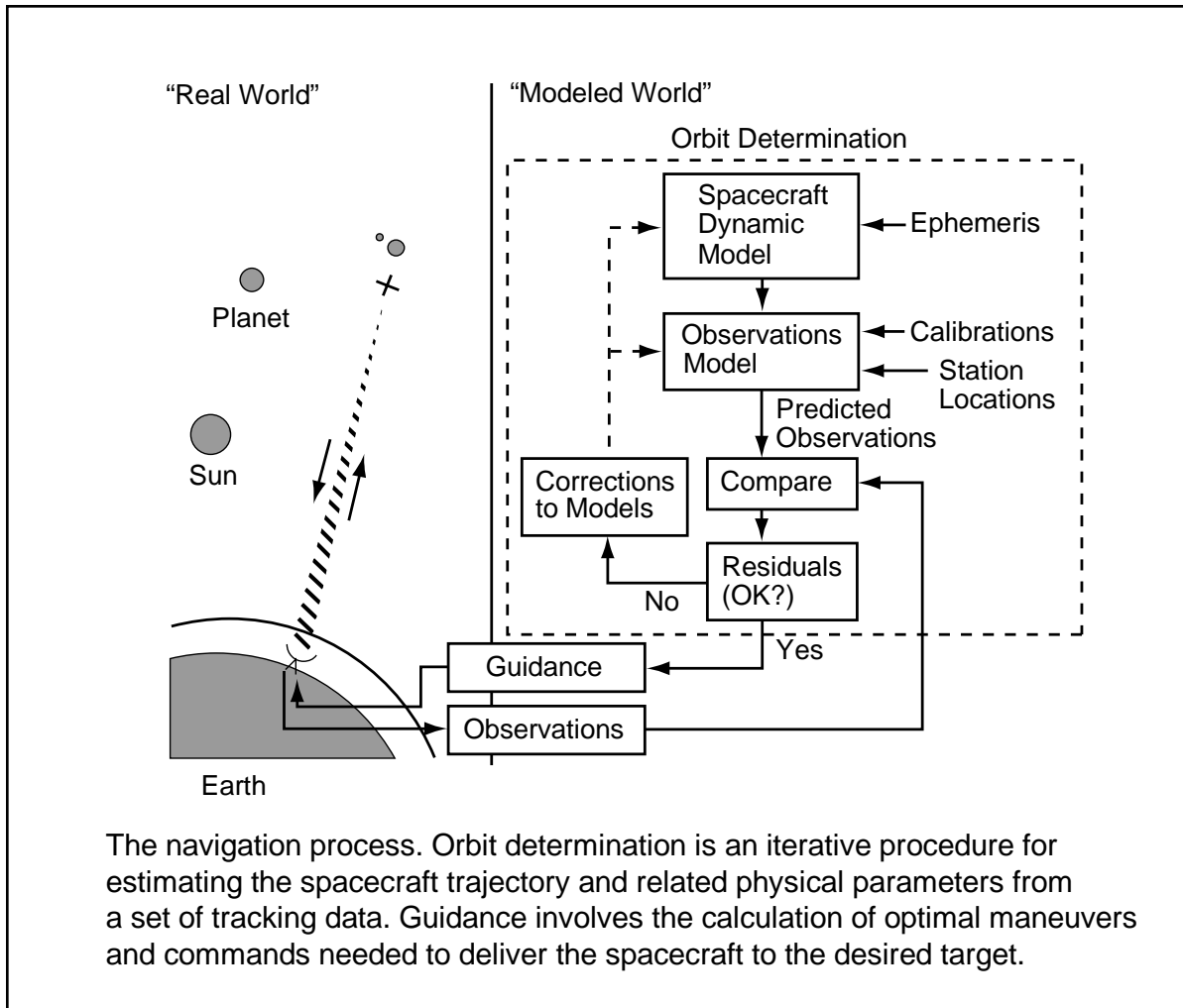


Figure 2-1: The Navigation Process

Figure 2-2 depicts the spacecraft navigation process, which can take place either in real time, near-real time, or after the fact (also referred to as reconstruction).

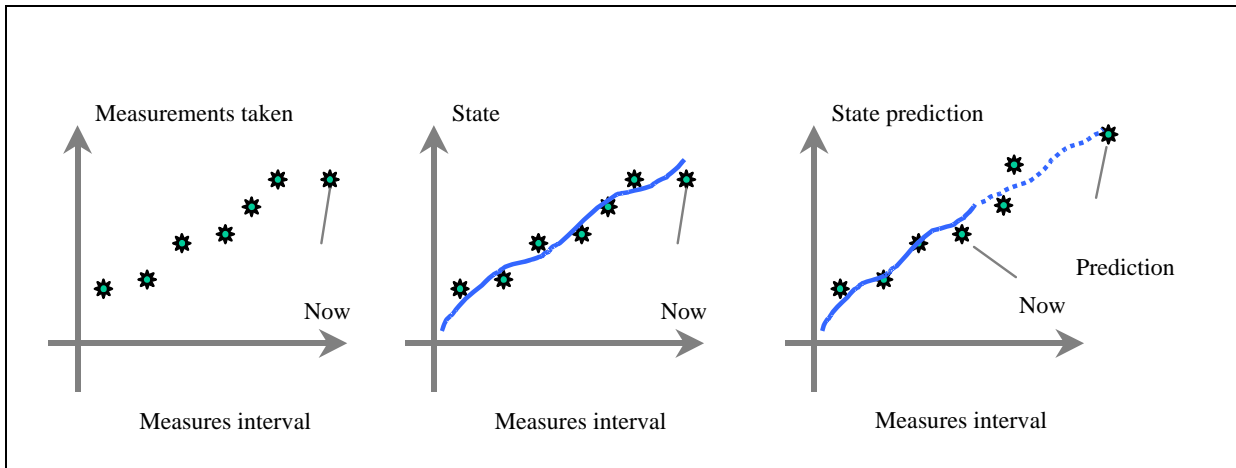


Figure 2-2: Real-Time or Near-Real-Time Navigation Process

2.3 DEFINITIONS OF SPACECRAFT NAVIGATION TERMS

In order to establish a solid standard 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.

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 for 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 that has the ability to acquire or broadcast navigation messages. Possible agency participants can be arranged into three categories, as depicted in figure 3-1.

Spacecraft: A vehicle in orbit about any celestial body or celestial point, as a single entity or as part of a set (such as constellations or formations). Spacecraft also include 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.

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.

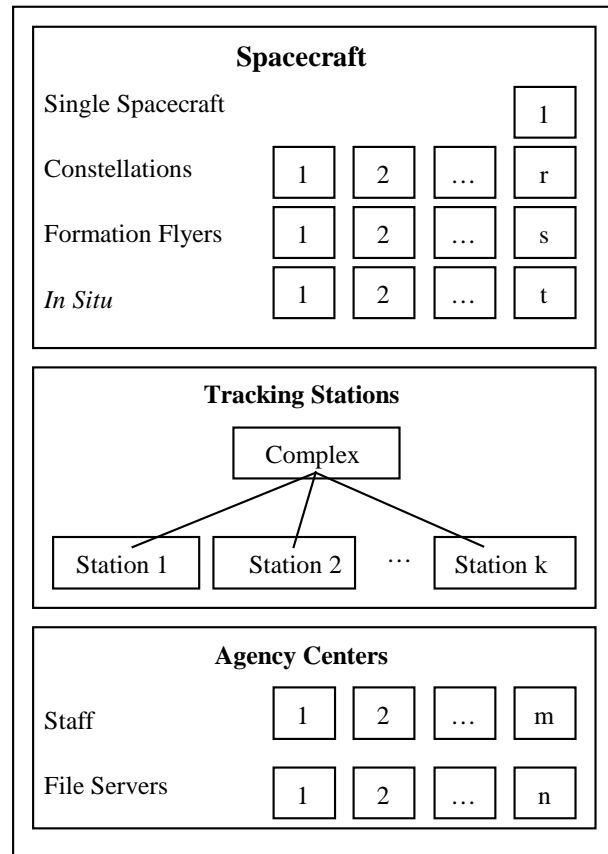


Figure 3-1: Agency Participants

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 flight dynamics Recommended Standards.

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

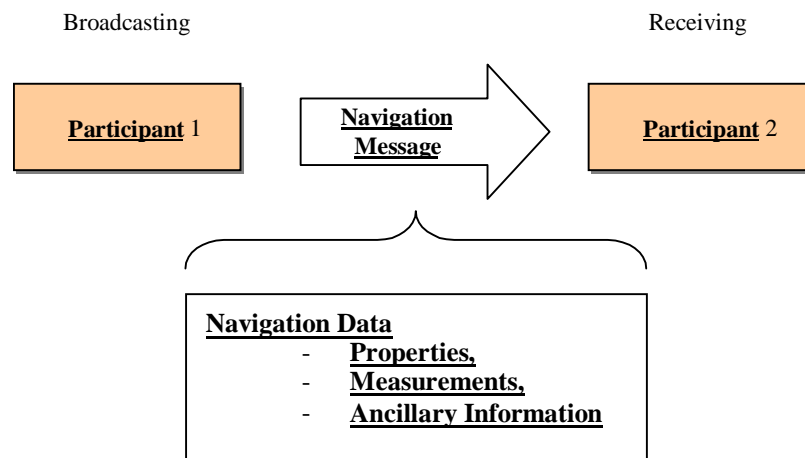


Figure 3-2: Navigation Message Exchange Definitions

3.5 NAVIGATION EXCHANGE DATA TYPES

Tables 3-1 through 3-3 contain lists of the most typical measurement, property, and ancillary information data types currently exchanged. For current and future Recommended Standards, it is preferable to use the units 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	s
Variable Transmitter Range	Range Units
Angles (antenna tracking, sun sensor, star sensor, gyro package, horizon sensor, videometers, etc.)	deg
Doppler (coherent)	Hz
Doppler (non-coherent)	Hz
Variable Transmitter Doppler	-
Integrated Doppler count	-
Quality of measurements	-
IMU output	deg/s ²
magnetometers	μT

Table 3-2: Typical Property Data Types

Type	Units	Alternate Units
Position	km	
Angular Velocity	deg/s	
Linear Velocity	km/s	
Angular acceleration	deg/ s ²	
Acceleration	km/s ²	
Length	m	
Moment of Inertia	kgm ²	
Force	kgm/ s ²	N
Torque	kgm ² / s ²	N*m
Mass	kg	
Energy, work, or heat	kgm ² / s ²	N*m
Power	kgm/s ³	W
Pressure	kg/ ms ²	hPa
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	-	
Angles	deg	
Angle rate	deg/s	
Angular drift	deg/ s ²	
Magnetic field components	μT	

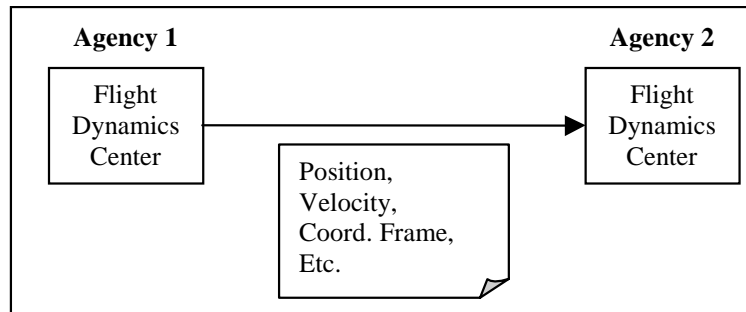
Table 3-3: Typical Ancillary Information Data Types

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

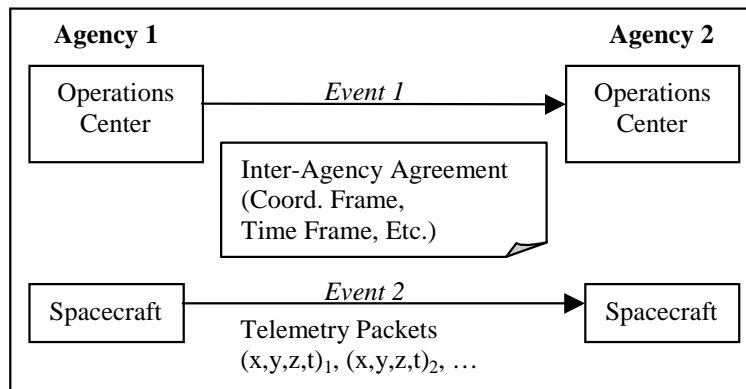
3.6 NAVIGATION DATA EXCHANGE CHARACTERISTICS

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 or attitude of the spacecraft); and (2) all of the necessary ancillary information needed to interpret the position and velocity or attitude 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 or orientation updates from one spacecraft to another in real time. Because of bandwidth limitations on the telemetry, it may not be 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 Interface Control Document (ICD). 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 Recommended Standard.** 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 Recommended Standards, the information itself can be sent at one time or in separate events (see figure 3-4).

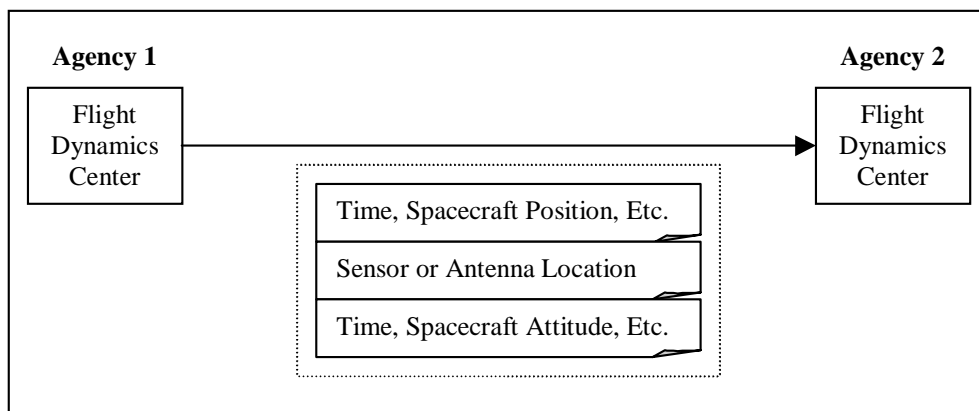


Figure 3-4: Navigation Session Using Multiple CCSDS Recommended Standards

3.7 NAVIGATION DATA EXCHANGE SCENARIOS

3.7.1 GENERAL

Ideally, every CCSDS Recommended Standard should apply to every type of navigation message exchange (orbit, attitude, tracking) described previously in this section. However, it is clear that widely used formats and protocols that are considered strong candidates for CCSDS Recommended Standard 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 Recommended Standard applies needs to be defined. As new Recommended Standards are proposed, new exchange scenarios will be defined in future versions of CCSDS flight dynamics documents.

3.7.2 GROUND-TO-GROUND SCENARIO

Ground-to-ground exchanges are defined as the set of exchanges between any two non-spacecraft participants.

3.7.3 GROUND-TO-FLIGHT AND FLIGHT-TO-GROUND SCENARIOS

Ground-to-flight and **flight-to-ground** exchanges are defined as the set of exchanges between any one spacecraft participant and a non-spacecraft participant.

3.7.4 FLIGHT-TO-FLIGHT SCENARIO

Flight-to-flight exchanges are defined 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 Recommended Standards. In addition, navigation uses many constants having 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 xy 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. Also called 'center name'.

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 define a coordinate frame unambiguously. Frame origins are generally either (1) the center of mass of a participant (spacecraft, ground station, etc.), (2) the center of mass of a natural body, (3) the center of mass of a set of bodies (referred to as the barycenter), or (4) the object position on orbit at each given time for local frame. Other frame origins are possible for special purposes. 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 or orbit of the spacecraft. 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 use only 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 (references [2] and [14]). 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 (reference [16]).

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) are 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 Solar System Ephemerides

The Jet Propulsion Laboratory provides a series of solar system ephemerides. The Development Ephemerides (DE) are publicly available; see reference [11] for the ephemerides currently most widely used for general applications. All data are referred to the ICRF (references [2] and [14]). 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. The mean equator and equinox of a given date define a Mean-of-Date (MOD) coordinate system, which includes the effects of precession but not the effects of nutation. A given date's true equator and equinox, which can be obtained by applying nutation to the mean values, define a True Of Date (TOD) coordinate system.

4.3.4.6 Greenwich True of Date (GTOD) Coordinate System

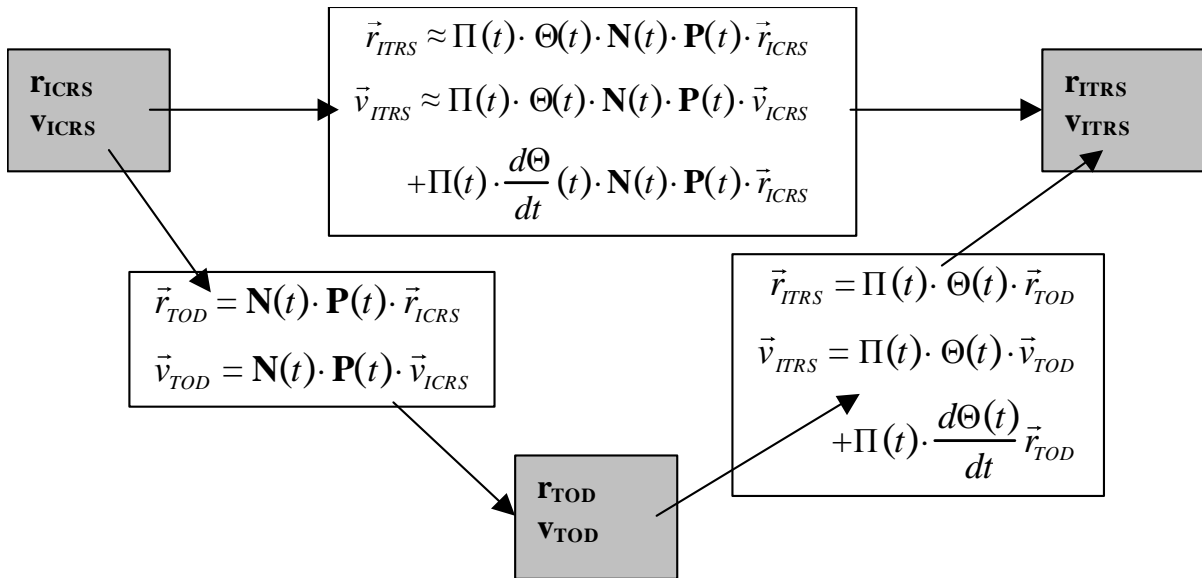
The Greenwich True of Date (GTOD) (geographic) coordinate system is a rotating, right-handed, Cartesian system with the origin at the center of the Earth. The orientation of this system is specified with:

- The xy plane is the Earth's true of date Equator.
- The z axis is directed along the Earth's true of date rotational axis and is positive north.
- The positive x axis is directed toward the prime meridian.
- The y axis completes a right-handed system.

Greenwich True of Date is also referred to as 'True of Date Rotating (TDR)' or 'Greenwich Rotating Coordinate Frame (GCR)'.

4.3.4.7 Relationships among Common Reference Frames

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



where:

- Π : Polar Motion Transformation Matrix
- Θ : Earth Rotation Transformation Matrix
- \mathbf{N} : Nutation Transformation Matrix
- \mathbf{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 Common Reference Frames

4.3.5 BODY FRAME SPECIFICATIONS

Just as there are various coordinate frames attached to an orbit for convenience, a coordinate frame is established to define the physical geometry of the spacecraft body. There is no restriction on this frame (except for orthogonality) as its purpose is to make convenient the definition of mechanical components, science instruments, and forces and torques. Some examples of these coordinate frames are as follows:

- a) center of frame placed at the center of mass or center of gravity and aligned along the principal axes of inertia;
- b) center of frame placed at an arbitrary location on or near the spacecraft body and oriented for the purpose of defining the location of mechanical equipment and/or science instruments;

- c) center of frame placed at center of mass or center of gravity and oriented to define roll, pitch and yaw similar to the definition for aircraft.

Note that if a reference frame is not centered on the center of gravity (usually coincident with the center of mass) then care must be taken when specifying forces and torques to be applied.

4.3.6 LOCAL ORBITAL FRAME

4.3.6.1 General

Important reference frames defined using the orbital position and velocity at a given time are used for attitude estimation and attitude control.

4.3.6.2 Local Orbital Frame (LVLH)

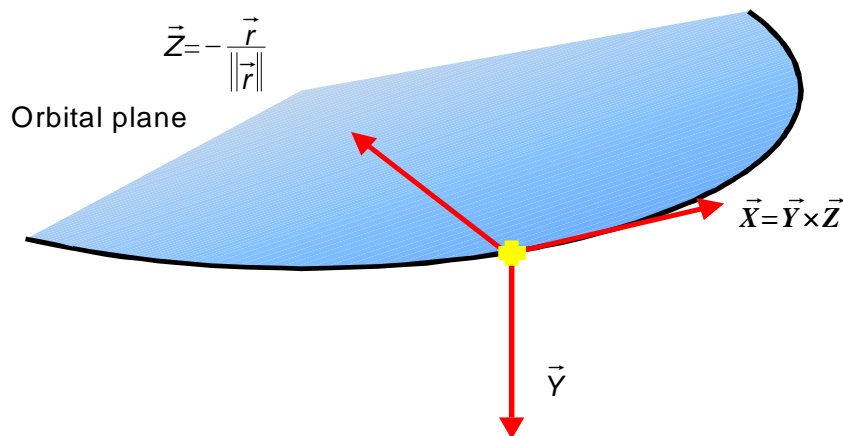


Figure 4-2: Local Orbital LVLH Frame

‘LVLH’ stands for ‘Local Vertical Local Horizontal’.

Frame origin : spacecraft gravity center

\vec{Z} : unit vector collinear and opposite sign of geocentric satellite position (planet center, spacecraft gravity center)

\vec{Y} : unit vector collinear and opposite sign of the orbital kinetic momentum (normal to orbit plane)

\vec{X} : unit vector equal to $\vec{Y} \times \vec{Z}$

4.3.6.3 Local Orbital Frame (T,N,W)

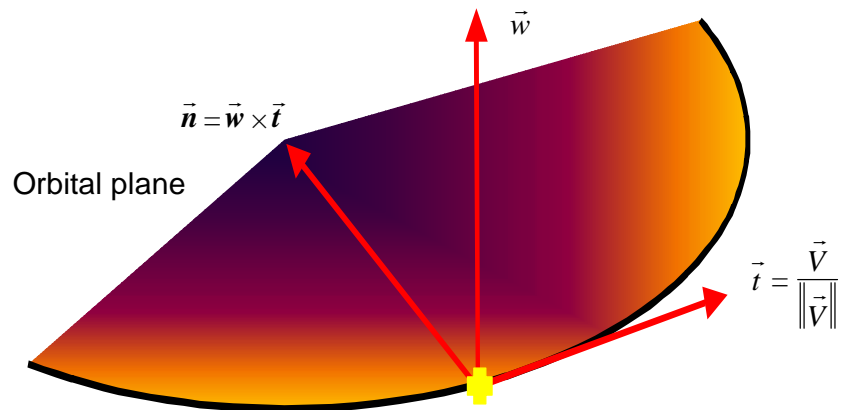


Figure 4-3: Local Orbital TNW Frame

In ‘TNW’, T stands for tangential, N for normal, and W for the Greek omega (ω) denoting the axis of angular momentum.

Frame origin : spacecraft gravity center

\vec{t} : unit vector collinear to absolute orbital velocity

\vec{w} : unit vector collinear to orbital kinetic momentum (normal to orbit plane)

\vec{n} : unit vector equal to $\vec{w} \times \vec{t}$

4.3.6.4 Local Orbital Frame (Q,S,W) or RTN (Radial, Transverse, Normal)

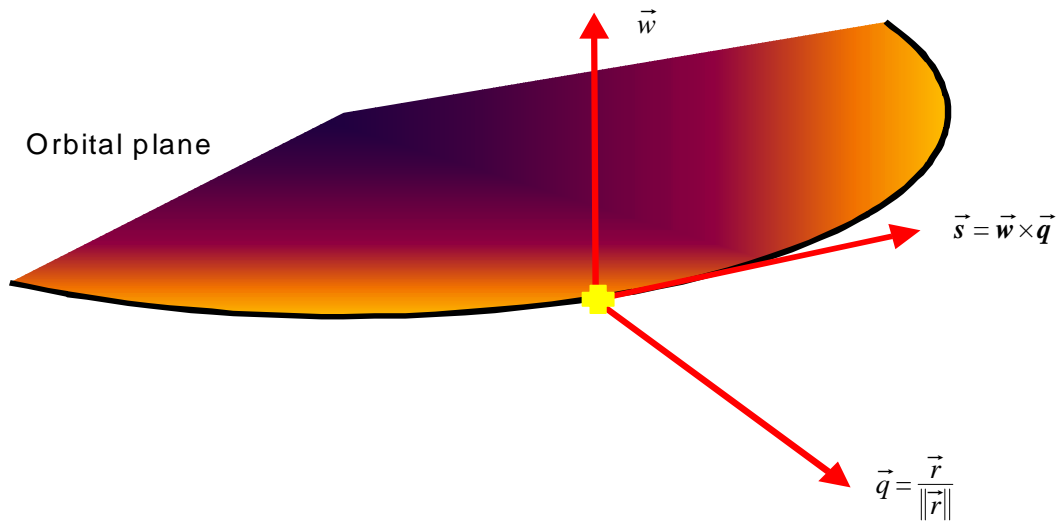


Figure 4-4: Local Orbital QSW Frame

Frame origin : spacecraft gravity center

Q : unit vector collinear to geocentric satellite position (planet center, spacecraft gravity center) (R)

W : unit vector collinear to the orbital kinetic momentum (normal to orbit plane) (N)

S : unit vector equal $\vec{w} \times \vec{q}$ (T)

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 4-5 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.

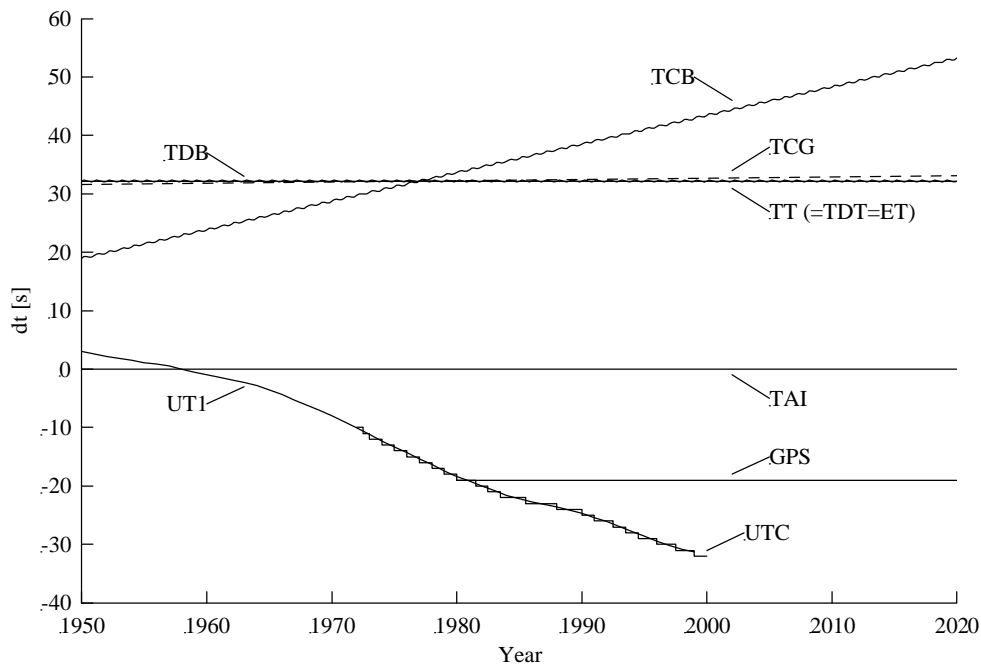


Figure 4-5: Differences between Relevant Time Scales between 1950 and 2020

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:

$$\text{TAI} = \text{TT} - 32.184\text{s}$$

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:

$$\text{GPS} = \text{TAI}(\text{GPS}) - 19\text{s}$$

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 an atomic time scale, based on the performance of atomic clocks. It is tied to TAI by an offset of integer seconds (called 'leap seconds'), which is regularly updated to keep UTC in close agreement with UT1 (within 0.9s). Since atomic clocks are more stable than the rate at which the Earth rotates, leap seconds are needed to keep the two time scales in agreement. Although it is possible to have a negative leap second (a second removed from UTC), so far, all leap seconds have been positive (a second has been added to UTC). Based on what we know about the Earth's rotation, it is unlikely that we will ever subtract a second. The International Earth Rotation Service (IERS) notifies the world when a leap second is to be added or subtracted, which is done only at the end of June or December. See references [5], [32], [33], and [34].

When no leap second is to occur, the clocks count time over the transition from one day to the next as follows:

23:59:58 23:59:59 00:00:00 00:00:01 UTC no leap second

To add a leap second, the clocks are made to count time at the transition from June 30 to July 1 or the transition from December 31 to January 1 as follows:

23:59:58 23:59:59 23:59:60 00:00:00 UTC positive leap second

If a leap second were to be subtracted, the clocks would count time as follows:

23:59:58 00:00:00 00:00:01 UTC negative leap second

At the beginning of the year 2005, the difference between UTC and TAI was

$$\text{UTC} - \text{TAI} = -32\text{s}$$

At the end of the year 2005, an additional leap second is scheduled to be added, making the difference between UTC and TAI -33s.

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 (references [3] and [15]).

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

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

4.4.2.4 Relationships Between Time Scales

Figure 4-6 depicts the relationships between the time scales.

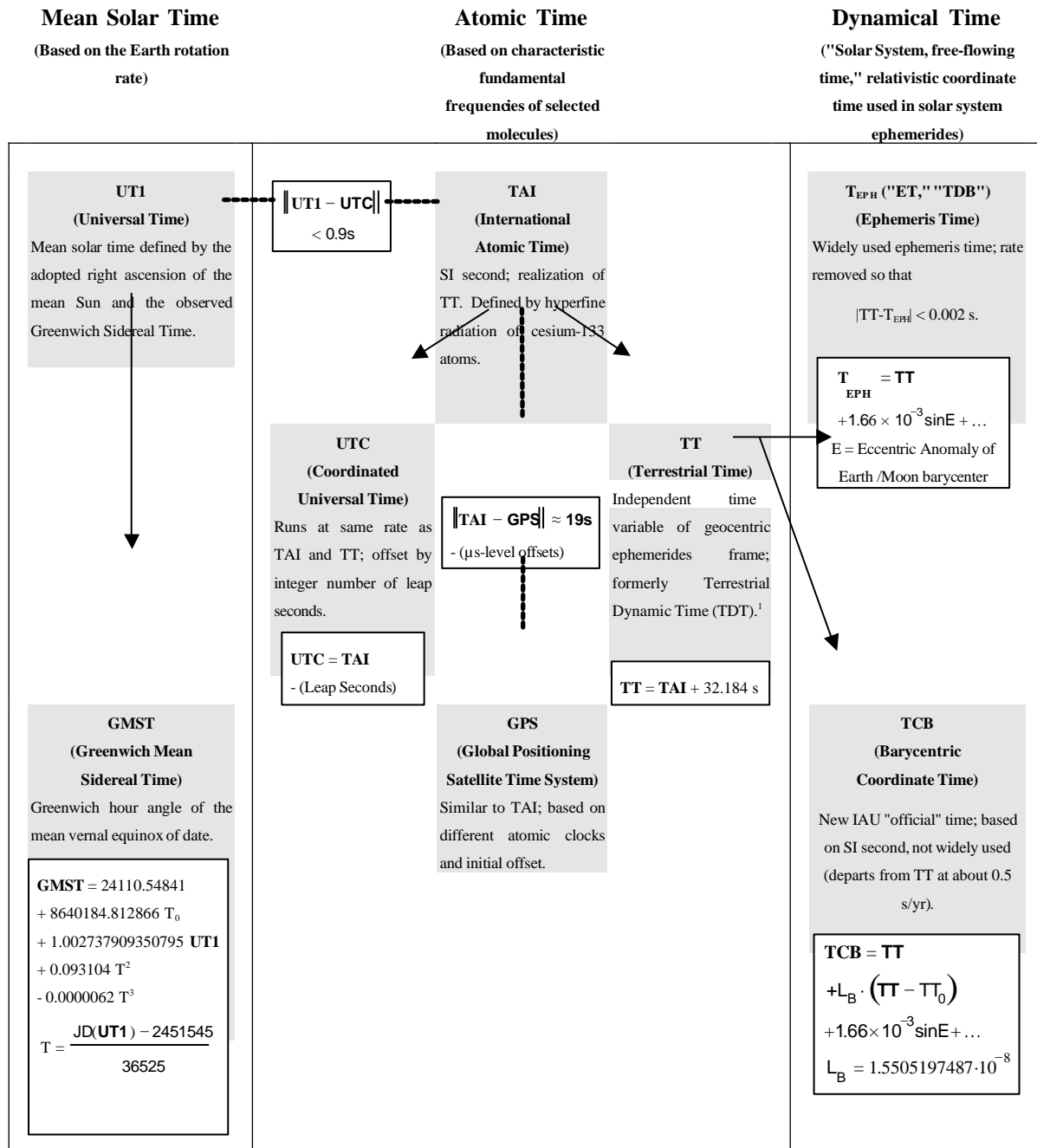


Figure 4-6: Relationships among Time Scales

4.5 ASTRODYNAMIC CONSTANTS

Examples of astrodynamical 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 (www.iers.org).

4.6 ENVIRONMENTAL MODELS

Along with astrodynamical 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 (www.iers.org).

4.7 ANTENNA TYPES

4.7.1 GENERAL

Several different antenna types are used in the process of collecting the tracking data that is used in the navigation process. For understanding the differences in these antenna types, some background is helpful. (See references [28], [29], [30], and [31].)

4.7.2 BACKGROUND TERMS FOR ANTENNA TYPES

The locations of objects in the sky are described in terms of the ‘celestial sphere’, a virtual sphere of infinite radius that surrounds the Earth. The center, pole and equatorial plane (reference plane) of the celestial sphere are the same as those of the Earth.

Declination (DEC) represents the angle formed between the center and a vector pointing to the object, expressed in degrees from 90 to -90. Positive declination angles represent objects north of the reference plane of the celestial sphere, and negative declination angles represent objects south of the reference plane.

Right ascension (RA) is conceptually equivalent to longitude. It measures how far the object is away from the zero point of the celestial reference plane (i.e., the vernal equinox). The right ascension may be expressed either in degrees from 0 to 360; or in hours, minutes, and seconds, where an hour of RA is 15 degrees of sky rotation. Together, the RA and DEC uniquely specify the inertial position of an object on the celestial sphere.

An object’s hour angle (HA) is the time dependent distance in hours, minutes, and seconds westward along the celestial equator from the observer’s meridian to the object’s RA. The HA is zero when the object is on the observer’s meridian.

A keyhole is an area in the sky where an antenna cannot track a spacecraft because the required angular rates would be too high. Mechanical limitations may also contribute to keyhole size.

4.7.3 EQUATORIAL OR RADEC MOUNT

An equatorial mount or RADEC antenna mount is designed with one mechanical axis parallel to the Earth's axis. To track an object, the antenna is pointed toward the object's known HA and DEC and then rotated about the antenna's polar axis as the Earth rotates during the rest of the tracking pass. The antenna structure design is latitude dependent.

4.7.4 THE X-Y MOUNT

In an X-Y antenna, X-angular movement is about a ground-fixed horizontal axle and Y-angular movement is about a perpendicular axle that rotates with X motion. The Y axle varies from a vertical to horizontal to inverted vertical orientation as X rotates through its range of motion. This configuration cannot directly swivel in azimuth as can an antenna having an AZEL mount. The X-Y mount can rotate freely in any direction from its upward-looking zenith central position.

An X-Y-mounted antenna is mechanically similar to a RADEC antenna. X-Y mounted antennas can have one of two types of configuration. These are XSYE and XEYN, whose characteristics are shown in the following table:

X-Y Configuration	Keyholes	X-Axis Point	Y-Axis Point	Best For
XSYE	east/west horizon	south	east	objects in polar orbits
XEYN	north/south horizon	east	north	objects in lower inclination orbits

4.7.5 AZIMUTH-ELEVATION (AZEL) CONFIGURATION

An azimuth-elevation (AZEL) design antenna locates a point in the sky by azimuth (AZ) in degrees eastward (clockwise) from true north, and elevation (EL) in degrees above the horizon. The AZEL fundamental design is not location dependent.

The AZEL mount has two perpendicular axes. The azimuth movement is about a ground-fixed vertical axle and elevation movement is about a perpendicular horizontal axle that rotates with azimuth motion. The keyhole in an AZEL system is near the zenith position.

5 PROPERTIES

5.1 RATIONALE

There are many possible ways to group the physical attributes of spacecraft, rovers, equipment, 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 (e.g., attitude)	The attributes that can be associated with an object when it is treated as a three-dimensional object.	Orientation Angles Angular Velocity Quaternion
Physical	The attributes that 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 that 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 Earth sensor Gyro Star sensor Sun sensor Magnetometer Thrusters

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, the ground station can collect tracking data that 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

5.2.2.1 General

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.

5.2.2.2 State Vector

The time-dependent 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.

5.2.2.3 Classical Keplerian Elements

For some purposes it may be convenient to use the classic osculating Keplerian elements (table 5-2), 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 Pericenter	ω	deg
True Anomaly	v	deg

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

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

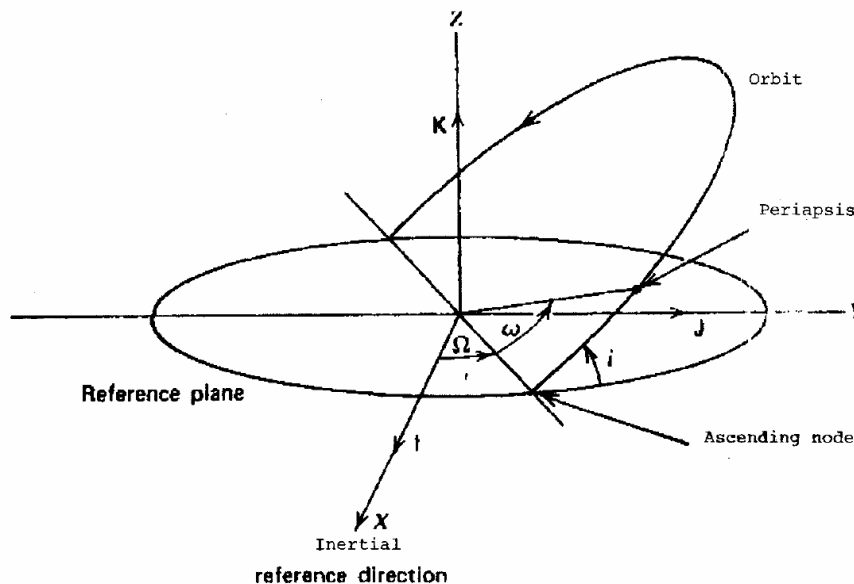


Figure 5-1: Classical Keplerian Orbit Orientation Angles

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, a more refined 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 GENERAL

The attitude of a spacecraft is its orientation in space. The motion of a rigid body is specified by its position, velocity, attitude, and attitude rotation. Understanding the attitude requires knowing: how it is determined/estimated, how it is controlled, and how its future rotation is predicted. See references [17] and [23]. This document seeks to address the determination/estimation and prediction of attitude. Attitude control is not in the scope of this document.

5.3.2 DEFINITIONS

The attitude of a rigid body is the orientation of a body-connected frame in a 3-dimensional space at a given time, with respect to a defined reference frame. 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 center of mass in a defined reference frame.

5.3.3 ATTITUDE ESTIMATION

Attitude estimation is the process of computing a set of parameters that describe this orientation using measurements (generally onboard measurements). The process of attitude estimation 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.

5.3.4 ATTITUDE REPRESENTATIONS

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

- single axis (spinning);
- three axis;
- gravity gradient;
- uncontrolled.

Because of this wide domain of configuration it is convenient to use a single representation to describe the status of the attitude (see reference [24] for a survey of attitude representations). 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 stabilization 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 definitions 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 \mathbf{u} , which is invariant in both frames, with an angular amplitude Φ . The vector \mathbf{u} is oriented in such a way that makes Φ positive directly around the \mathbf{u} vector in the movement from reference frame to body frame.

At this rotation is associated a unit quaternion $Q = \{ \cos(\Phi/2), \bar{U} \sin(\Phi/2) \}$.

This gives the following relation between a vector X and its transformation X' :

$$\bar{U} = Q * \bar{U}' * Q^T$$

The attitude quaternion is defined by a 4-dimension vector $Q (Q_C, Q_1, Q_2, Q_3)$ with:

- $Q_C = \cos(\Phi/2)$;
- $Q_1 = e_1 * \sin(\Phi/2)$;

- $Q2 = e2 * \sin(\Phi/2)$;
- $Q3 = e3 * \sin(\Phi/2)$.

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 \mathbf{u} in the body axis (or in the reference frame) with the relation

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

We also define the conjugate quaternion $Q^T =$

$$\begin{pmatrix} QC \\ Q1 \\ Q2 \\ Q3 \end{pmatrix}$$

With

- x_i the components of a vector in the reference frame, with $\mathbf{x}_i = (x_{i1}, x_{i2}, x_{i3})$
- x_f the components of a vector in the body frame, with $\mathbf{x}_f = (x_{f1}, x_{f2}, x_{f3})$

x_f and x_i are linked by

$$x_f = Q * x_i * Q^T \text{ and } x_i = Q^T * x_f * Q.$$

(These products are defined by the quaternion algebra.)

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

$$\mathbf{x}_f = M \cdot \mathbf{x}_i$$

$$M = \begin{pmatrix} 2(q_c^2 + q_1^2) - 1 & 2(q_1 q_2 + q_c q_3) & 2(q_1 q_3 - q_c q_2) \\ 2(q_1 q_2 - q_c q_3) & 2(q_c^2 + q_2^2) - 1 & 2(q_2 q_3 + q_c q_1) \\ 2(q_1 q_3 + q_c q_2) & 2(q_2 q_3 - q_c q_1) & 2(q_c^2 + q_3^2) - 1 \end{pmatrix}$$

The following formulae give the relations for the associated quaternion:

$$\begin{aligned} q_c &= +/- (M_{11} + M_{22} + M_{33} + 1)^{1/2} \\ q_1 &= 1/4 * q_c (M_{23} - M_{33}) \\ q_2 &= 1/4 * q_c (M_{31} - M_{13}) \\ q_3 &= 1/4 * q_c (M_{12} - M_{21}) \end{aligned}$$

This matrix can be used to elaborate a set of attitude angles like Euler's (Roll Pitch Yaw) giving the rotation angles around X=1=roll, Y=2=pitch, Z=3=yaw axes. The rotation order must be defined to have a set of values consistent with the desired rotation.

For example if the rotation order is ψ around axis 3, Θ around axis 2, ρ around axis 1 the Cardan angles ψ Θ ρ can be obtained by the following relations:

$$\begin{aligned}\Psi &= \arctan\left(\frac{2(q_c^2 + q_1^2) - 1}{2(q_1 q_2 + q_c q_3)}\right) \\ \Theta &= -\arcsin\left(\frac{2(q_1 q_3 - q_2 q_c)}{2(q_c^2 + q_3^2) - 1}\right) \\ \rho &= \arctan\left(\frac{2(q_c^2 + q_3^2) - 1}{2(q_1 q_2 + q_c q_3)}\right)\end{aligned}$$

NOTE – The angles Ψ ρ are undefined if $\cos(\Theta) = 0$.

Note that the transformation matrices above, while assuming a particular order of scalar (QC) and vector (Q1, Q2, Q3) portions of the quaternion, are invariant as it is an expression to transform a vector between the two frames of the quaternion. If one were to attempt quaternion multiplication, then order of the quaternion vector is of prime importance.

Another method of expressing 3-axis attitude is given in terms of roll, pitch, and yaw (R, P, Y) coordinates. However, the definition of roll, pitch, and yaw axes vary from mission to mission and often even change within a mission (reference [23]). In determining rotations or rotation rates about these axes, care must be taken to define the axes, which are often misunderstood. Using quaternions avoids the need to use R, P, Y attitude representation and its resulting complexity.

5.3.5 EPHEMERIS REPRESENTATIONS OF ATTITUDE

Under the proper conditions, attitude states allow for the use of a propagation technique (analytical or numerical) to interpret the orientation of an object connected frame at times different from the specified epoch. Another manner to represent attitude is to use a tabular format, with attitude states at pre-determined time intervals. This format (referred to as an ephemeris representation) allows for the use of interpolation techniques to interpret the attitude at times different from the tabular epochs.

5.3.6 ATTITUDE DYNAMICS

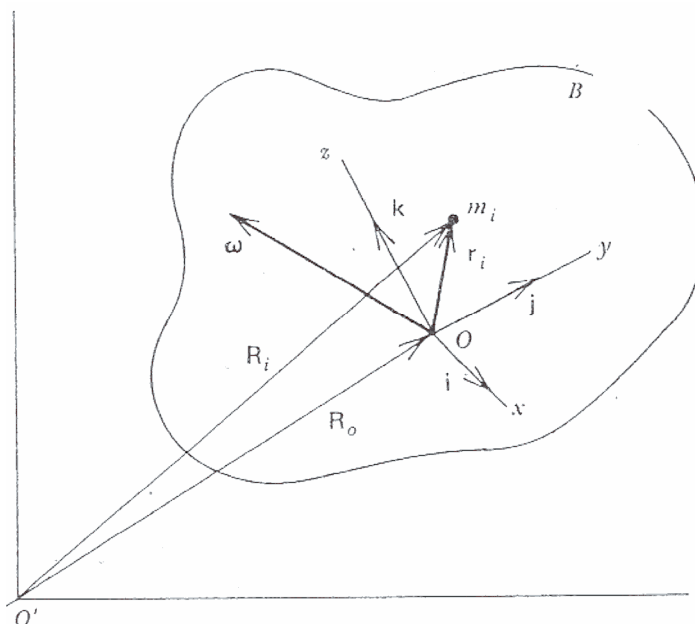


Figure 5-2: Rigid Body Angular Momentum

Consider the situation of figure 5-2 in which the rigid body B contains the body-fixed x, y, z coordinate system attached at the center of mass, O. The angular momentum is

$$\mathbf{h} = \int_B \mathbf{r} \times (\boldsymbol{\omega} \times \mathbf{r}) dm$$

where $\boldsymbol{\omega}$ denotes the instantaneous angular velocity vector of the rotating x, y, z coordinate system. The angular momentum may be written in matrix form as

$$\mathbf{h} \equiv \begin{bmatrix} h_x \\ h_y \\ h_z \end{bmatrix} = \begin{bmatrix} I_x & -I_{xy} & -I_{xz} \\ -I_{xy} & I_y & -I_{yz} \\ -I_{xz} & -I_{yz} & I_z \end{bmatrix} \begin{bmatrix} \omega_x \\ \omega_y \\ \omega_z \end{bmatrix} = \mathbf{I}\boldsymbol{\omega}$$

where

$$I_x = \int_B (y^2 + z^2) dm, \quad I_y = \int_B (x^2 + z^2) dm, \quad I_z = \int_B (x^2 + y^2) dm$$

$$I_{xy} = \int_B xy dm, \quad I_{xz} = \int_B xz dm, \quad I_{yz} = \int_B yz dm$$

I_x, I_y, I_z are the moments of inertia of the body about the x, y, z axes, respectively, I_{xy}, I_{xz}, I_{yz} are the products of inertia of B, and the matrix \mathbf{I} is known as the inertia matrix or the inertia

tensor. Thus, any rigid body is characterized by a set of constants I_x , I_y , I_z , I_{xy} , I_{xz} , and I_{yz} for the purpose of analyzing the angular momentum and, ultimately, attitude control. Therefore, the torque vector satisfies Euler's Equation,

$$\boldsymbol{\tau} = \frac{d\mathbf{h}}{dt} = \mathbf{I}\dot{\boldsymbol{\omega}} + \boldsymbol{\omega} \times \mathbf{I}\boldsymbol{\omega}$$

which equals zero in a torque-free environment. Thus, parallel to the conservation of linear momentum in orbital mechanics, the principle of conservation of angular momentum states that angular momentum remains constant in magnitude and direction in inertial space, if the body is not acted on by any external torques.

The kinetic energy

$$T = \frac{1}{2} \boldsymbol{\omega}^T \mathbf{I} \boldsymbol{\omega}$$

is reminiscent of the familiar

$$T = \frac{1}{2} m v^2$$

of particle dynamics with the angular velocity playing the role of the linear velocity and the inertia matrix being the analog of the mass for rotational systems.

A principal axis is any axis $\hat{\mathbf{P}}$ such that the resulting angular momentum is parallel to $\hat{\mathbf{P}}$ when the spacecraft rotates about $\hat{\mathbf{P}}$. If the principal axes are used as the coordinate axes of the spacecraft x , y , z reference frame (see figure 5-2), the inertia matrix is the diagonal matrix of eigenvalues (characteristic values), called the principal moments of inertia. (See references [17], [25], [26], and [27].)

5.3.7 ATTITUDE PREDICTION

Attitude prediction is the process of forecasting the orientation of the spacecraft by using dynamical models to extrapolate the attitude history. Propagation is the process of using the dynamic equations of motion (EOM) and mathematical models of environmental torques to model the attitude for an extended period of time. Environmental torques that are typically included are gravity gradient, aerodynamic torque (if applicable), solar pressure, differential gravity and self gravity. The choice of torques to include in a model depends on the location of the spacecraft in inertial space.

Differential and self gravity arise from gravity forces acting on a particular point in space, and these will eventually be dominant terms if the spacecraft is far enough away from a gravity source, such as a planet, sun, or moon.

To propagate the attitude of a spacecraft, a simple algorithm is typically followed:

- 1) Estimate the environmental torques on the body.
- 2) Integrate the momentum equation to determine the new momentum state.
- 3) Recover the rate from the new momentum state.
- 4) Propagate the attitude quaternion.

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 as follows: C_R , A_R , C_D , A_D (within the Orbit Parameters Message [OPM]). The meanings of these parameters are defined below.

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 that assumes 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 ($\approx 1367 \text{ Wm}^{-2}$)
- 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 that 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
- 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 tracking radio frequency signals, telemetry or radar tracking signals, and a variety of other sources (references [10] and [12]). Spacecraft attitude estimation and control are based on onboard measurements of directions using different kinds of detectors. Data for attitude estimation is obtained from spacecraft telemetry.

6.2 MEASUREMENT DATA TYPES

6.2.1 ANGLES

Many tracking stations are able to measure the angles from a ground station to a spacecraft. These angles are a fundamental data type for orbit determination in many missions, particularly in launch support (initial acquisition, LEOP) and at other times when the spacecraft is close to the Earth. The angles measured in this fashion are only useable in the proximity of Earth. The angles help to measure plane-of-sky position.

6.2.2 RADIOMETRIC TRACKING DATA

6.2.2.1 General

The ground-based measurements used to navigate spacecraft are derived from the radio link between the spacecraft and the tracking stations on the Earth (cf. references [13], [20], and [21]). Spacecraft tracking is the process that provides the measurements (observables) needed to determine where the spacecraft is located (its ephemeris) in its 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. The primary navigation measurements that are obtained by the radio system are range along the line of sight, range-rate, and Delta-Differential One-Way Range (Δ DOR). Note that these three data types are complementary since range and range rate provide line-of-sight information while Δ DOR adds the orthogonal (plane-of-sky) directions. Other data types include differenced range, differenced Doppler, Differenced Range Versus Integrated Doppler (DRVID), and Pseudo Noise (PN) Ranging.

6.2.2.2 Uplink and Downlink

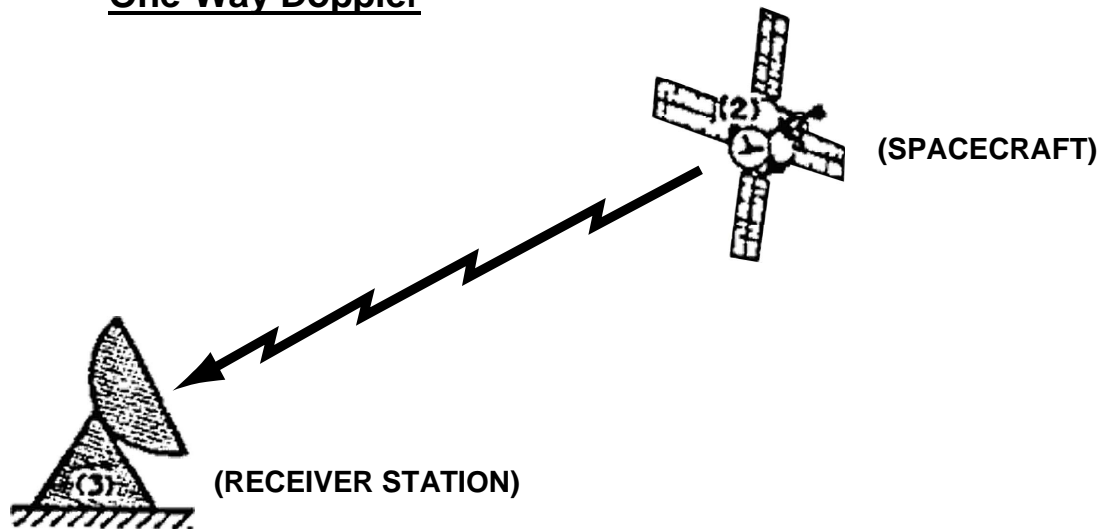
The radio signal transmitted from the Earth to a spacecraft is known as uplink. The transmission from spacecraft to the Earth is downlink. Uplink or downlink may consist of a pure RF tone, called a carrier. Such a pure carrier is useful in many ways, including radio science experiments. On the other hand, carriers may be modulated to carry information in

each direction. Commands may be transmitted to a spacecraft by modulating the uplink carrier. Telemetry containing science and engineering data may be transmitted to the Earth by modulating the downlink carrier (reference [28]).

6.2.2.3 One-Way, Two-Way, Three-Way Data

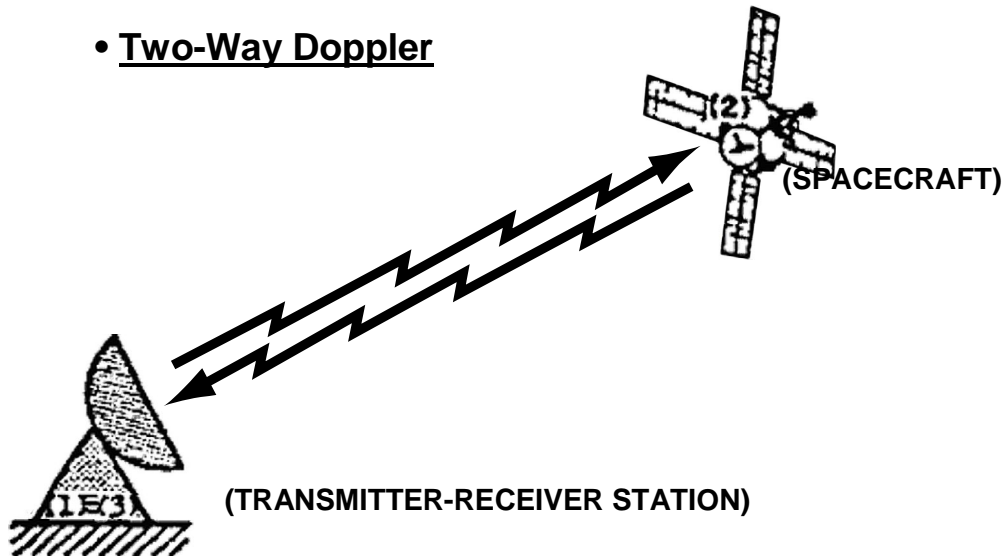
When an Earth-based station is only receiving a downlink from a spacecraft, the communication is called 'one-way'. When the station is sending an uplink that the spacecraft is receiving at the same time a downlink is being received at the Earth, the communications mode is called 'two-way'.

- **One-Way Doppler**



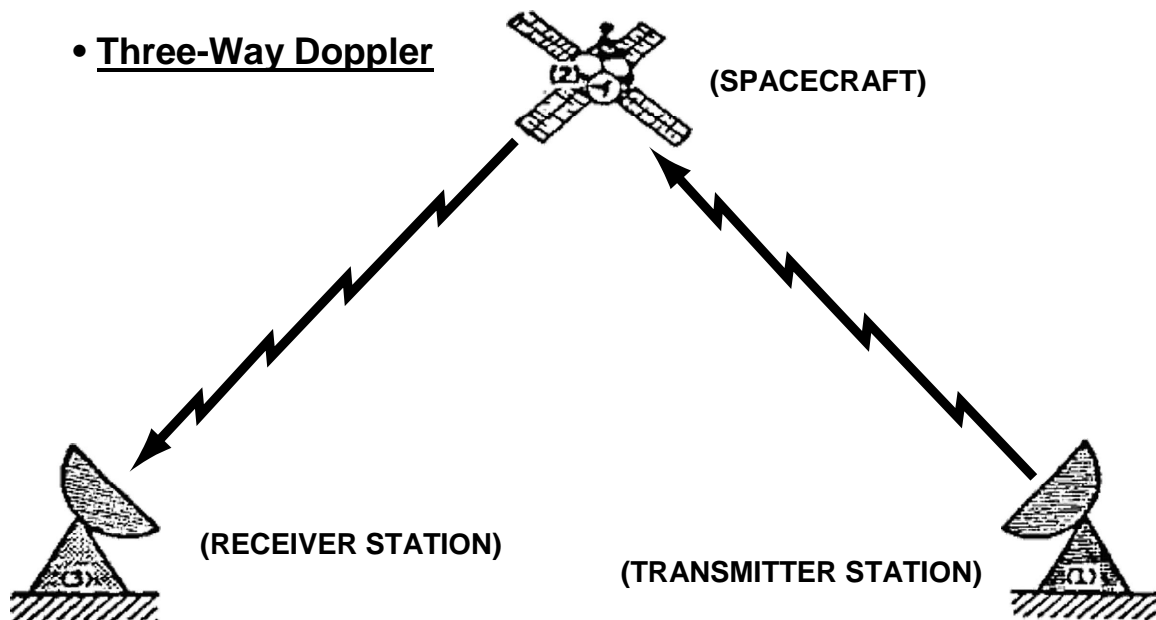
The communications mode is still called one-way even when an uplink is being received by the spacecraft, but the full round-trip light time has not elapsed. Consider the following situation: The station is receiving downlink and watching telemetry that shows the state of the spacecraft's own receiver. As long as the spacecraft's receiver is not receiving the uplink, communications are called 'one-way'. After the spacecraft's receiver has locked onto the uplink, it is 'two-way'.

• Two-Way Doppler



‘Three-way’ data results when a station is receiving downlink, but a different station is providing the uplink. The Round-Trip Light Time (RTLTL) must have elapsed since the other station’s uplink began. The same situation with respect to the uplink exists for two-way and three-way communication, i.e., one One Way Light Time (OWLT) after the spacecraft receiver locks on the uplink signal, the ground will detect the three-way signal. If telemetry is arriving at a station from the spacecraft, and the spacecraft’s receiver is still in lock on the uplink provided by another station, the communications are ‘three-way’.

• Three-Way Doppler



6.2.2.4 Four-Way Data

Data is referred to as ‘four-way’ if there are four directed edges and three nodes or six directed edges and four nodes in the communications trail. In the former scenario, a signal might be sent from a ground-based station to a relay satellite, on to another satellite, back to the relay satellite, and then back to the same ground-based station. In the latter scenario, the signal might be sent from the station on the ground to a relay station, on to another satellite, and to a different ground-based station.

6.2.2.5 Coherence

Aside from carrying the information modulated on the downlink as telemetry, the carrier itself is used for tracking and navigating the spacecraft, as well as for carrying out some types of science experiments such as radio science or gravity field mapping. For each of these uses, an extremely stable downlink frequency is required, so that Doppler shifts on the order of fractions of a Hertz may be detected out of many GHz, over periods of many hours. But it is currently impossible for any spacecraft to carry the massive equipment required to maintain such frequency stability. Spacecraft transmitters are subject to wide temperature changes, which cause their output frequency to drift. The solution is to have the spacecraft generate a downlink that is coherent to the uplink it receives.

This coherent signal is generated on the Earth with the aid of a hydrogen-maser-based frequency standard in an environmentally controlled room, sustained by an uninterruptible power supply. This maser is used as a reference for generating an extremely stable uplink frequency for the spacecraft to use, in turn, to generate its coherent downlink. (It also supplies a signal to the master clock that counts cycles and distributes UTC time.) Its stability is equivalent to the gain or loss of 1 second in 30 million years.

Once the spacecraft receives the stable uplink frequency, it multiplies that frequency by a predetermined constant (the ‘turnaround ratio’), and uses that value to generate its downlink frequency. In this way, the downlink enjoys all the extraordinarily high stability in frequency that belongs to the massive, sensitive equipment that generated the uplink. It can thus be used for precisely tracking the spacecraft and for carrying out precision science experiments. The reason a spacecraft’s transponder multiplies the received frequency by a constant is to assure the downlink it generates will not cause interference with the uplink being received.

Hence, one-way data is non-coherent, while the others are coherent. The spacecraft carries a low-mass oscillator to use as a reference in generating its downlink for periods when an uplink is not available, but it is not highly stable, since its output frequency is affected by temperature variations. Some spacecraft carry an Ultra-Stable Oscillator (USO), but even the USO has nowhere near the ideal stability of a coherent link.

6.2.2.6 Range

Range is the distance along the line of sight between the flying spacecraft and another participant or participants. A range measurement is obtained by determining the round-trip time of the radio signal, after accounting for delays from the ionospheric, tropospheric, and solar plasma media and onboard instrument and ground-based antenna system, plus clock drift on the spacecraft and at the stations.

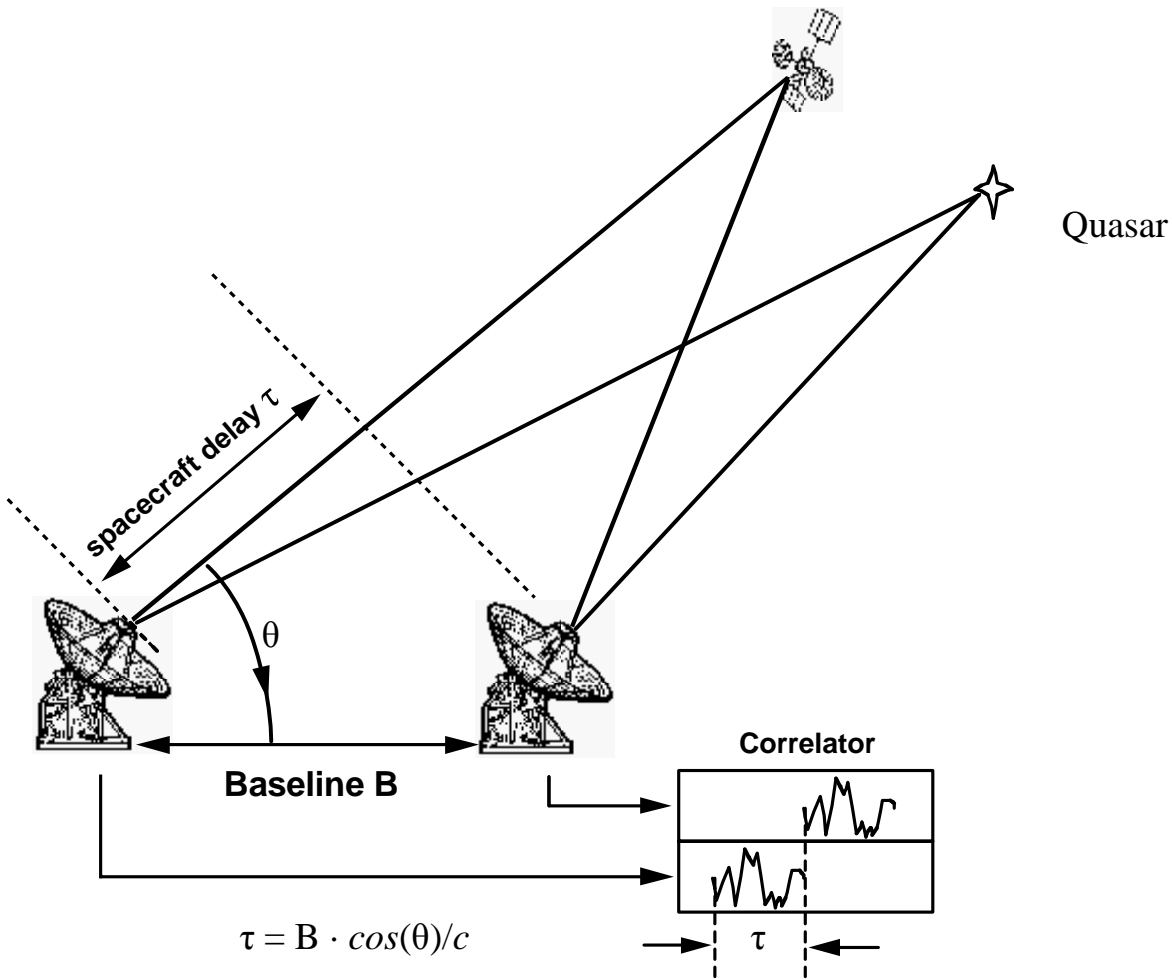
6.2.2.7 Range-Rate

The spacecraft topocentric range rate is obtained from the Doppler shift in the frequency of the radio signal produced by the relative motion along the line of sight from the station to the spacecraft. Because the spacecraft is moving with respect to the Earth, the onboard radio system receives an electromagnetic wave whose frequency differs from the one transmitted from the ground. The frequency of the received signal is increased if the spacecraft is moving toward the Earth and decreased if the spacecraft is receding. Doppler accuracies are often given in terms of radial velocity, but the fundamental measurement is range change.

The simplest Doppler measurement is the one-way (non-coherent) mode, in which the frequency of the signal received by the tracking station is compared with the best estimate of the frequency of the signal sent by the onboard oscillator. The most accurate measurements are obtained in the two-way coherent mode, for which the transmitting and receiving stations, and hence the frequency standards, are the same. If the receiving station on the Earth is different from the station that uplinked the signal to the spacecraft, the tracking mode is called three-way. The three-way mode is employed where: (1) the round-trip light time (RTLTL) is large enough that the transmitting station rotates out of sight of the spacecraft before the signal returns to the Earth, and, therefore, a second station must be employed to receive the signal; or (2) continuous tracking of a spacecraft is desired across the transition from the view period of one tracking complex to the view period of another.

6.2.2.8 Delta-Differential One-Way Range

The Delta-Differential One-Way Range (Δ DOR) data type provides angular information in the plane-of-sky orthogonal to the line-of-sight direction. 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. This data type measures geometric delay of the signal by cross-correlating the signal from two stations and performs a double-differencing to cancel a large portion of common error sources such as instrumental effects, clock errors, media effects, and baseline uncertainties. The result is a very precise triangulation from which angular position in the plane-of-sky may be determined. The Δ DOR observing geometry is shown in figure 6-1.



Credit: C.D. Edwards, J.S. Border, J.E. Patterson

Figure 6-1: Δ DOR Observation Geometry

6.2.2.9 Differenced Range

Simultaneous reception of ranging signals by two complexes during view period overlaps can provide a measure of angular position. Such a measurement type might be considered when the spacecraft is at a low declination (δ), because the uncertainty in the declination determined from other data types is proportional to $1/\sin\delta$. This data type is referred to as differenced two-way and three-way range and is illustrated in figure 6-2. The limiting errors for these observables are uncalibrated biases due to clock offsets and instrumental delays at the two stations. This data type is operationally difficult because of the round-trip light time and the uplink handover from one station to the other. Furthermore, as the time between two-way measurements increases, the differenced observables are increasingly contaminated by uncalibrated space plasma and other line-of-sight delay variations.

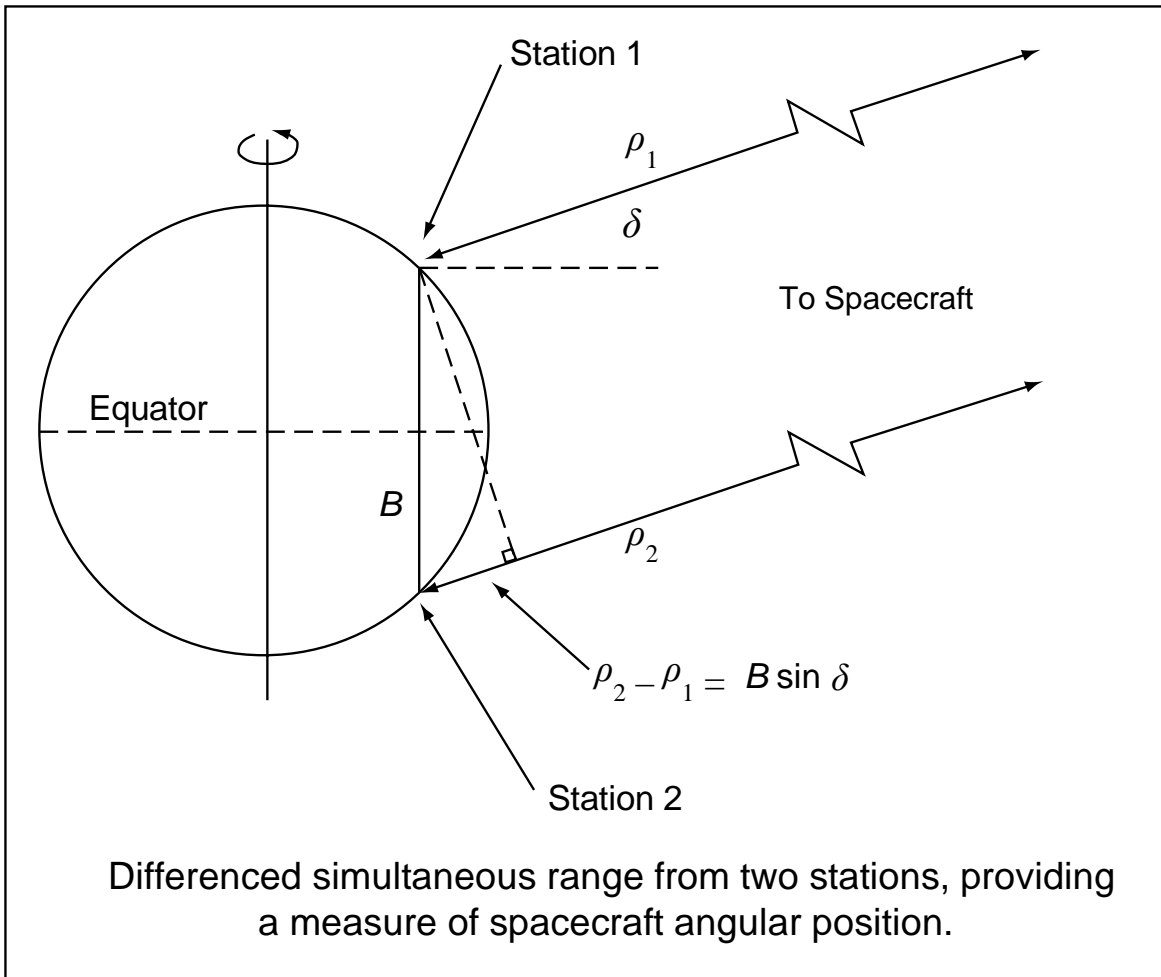


Figure 6-2: Differenced Range

6.2.2.10 Differenced Doppler

Doppler signals received simultaneously by two complexes during view-period overlaps can be differenced to produce the data type known as differenced Doppler. For a planetary orbiter, the orientation of the orbit plane about the line of sight from the Earth to the planet is not determined from Doppler or range measurements as accurately as the other components of state. The orientation component may be directly observed by Doppler data acquired simultaneously at two stations and then differenced. For two spacecraft in orbit about the same planet, which may be observed simultaneously in the same beamwidth of Earth-based tracking antennas, differential measurements may dramatically improve orbit accuracy for both spacecraft.

6.2.2.11 Combined Range, Doppler and Interferometric Tracking Data

Combining range and interferometric observables is an alternative to using long, continuous Doppler arcs for cruise navigation. In this method, the three components of spacecraft position are directly measured in just a few minutes. Doppler data may then be applied to infer better force models of the spacecraft's dynamics without the problem of aliasing model parameters into weakly observed spacecraft state components. Simultaneously fitting all data types leads to improved navigation reliability and robustness. Range measurements with sub-meter accuracy would have application to the relative tracking of planetary orbiters, rovers, and landers (cf. reference [22]).

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.

6.4 ATTITUDE MEASUREMENT DATA TYPES

Many kinds of attitude detectors are available, and the spacecraft equipment depends mainly on the mission. At this time, however, there is no CCSDS standard for exchange of attitude measurements; rather, the current Recommended Standards apply to transfer of attitude state and/or attitude ephemeris. Agency-specific processes use attitude data measurements to produce attitude states and attitude ephemerides, which are the subject of CCSDS Recommended Standards.

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 (Galileo).

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 Galileo 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 the use of a GNS attractive for spacecraft navigation:

- Coverage: These systems offer almost complete coverage for spacecraft with Low Earth Orbit (LEO) trajectories, and reasonable coverage for spacecraft with High Earth Orbit (HEO) trajectories.
- 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 reliable and typically function continuously without performance degradation.
- Price: The degraded signals of both NAVSTAR and GLONASS are available without charge to civilian users.

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 24 operational satellites deployed in near-circular orbits around the Earth. The satellites are located in four orbital planes, with six active satellites per plane. NAVSTAR uses Code Division Multiple Access (CDMA) to broadcast data.

7.3 GLONASS

GLONASS is operated by the Air Command of the Russian military, and it is similar to NAVSTAR. GLONASS is composed of 24 satellites having three orbital planes, with eight satellites (seven active and one on-orbit spare) per plane. GLONASS uses Frequency Division Multiple Access (FDMA) to broadcast data (reference [18]).

7.4 GALILEO

In 1999, ESA approved the development of Galileo, which is expected to be fully operational by the year 2008. Galileo will be interoperable with NAVSTAR. The Galileo constellation will consist of a medium-Earth orbit satellite constellation and a number of geostationary satellites, plus some other local complements. Galileo will carry both commercial and non-commercial signals (reference [19]).

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.

Apocenter: The point in an orbit at the greatest distance from the central body (i.e., at this point the geometric distance between the central body and the orbiting body is at a maximum).

Attitude: Orientation of the body reference frame with respect to a defined reference frame.

Attitude Equipment: Equipment onboard a spacecraft that is used to take measurements of the spacecraft attitude.

Barycenter: The center of mass of a collection of bodies, e.g., the solar system barycenter.

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

Clock Bias: A fixed-offset error of a clock from the ‘true’ time.

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 ($e = c/a$).

Ephemeris: A list of (accurate) positions and velocities or attitudes 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.

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

Frame origin: The common origin of the Cartesian axes. Applicable keyword is ‘CENTER_NAME’ in the navigation Blue Books.

Global Positioning System (GPS): A highly accurate, global satellite navigation system based on a constellation of 24 operational 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 the reference xy plane of the coordinate system being used (often the equatorial plane of the central body).

In situ assets: Spacecraft in operations at or in close proximity to a remote body; these participants can include rovers, landers, aircraft, etc.

Mean anomaly: The product of mean motion (average angular velocity) and the time since pericenter passage in an elliptical orbit.

Mean motion: The average angular velocity in an elliptical orbit.

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, orientation and maneuver information are included 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 CCSDS flight dynamics Recommended Standards.

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 defined 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.

Osculating elements: The elements at a specified time t of the Keplerian orbit that describe the flight path the spacecraft would follow if all perturbing forces were suddenly removed at the time t .

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

Pericenter: The point in an orbit of closest approach to the central body (i.e., at this point the geometric distance between the central body 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 4-component attitude representation for a rigid body. Quaternions have convenient mathematical properties but not a particularly convenient physical interpretation.

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 compatible software package.

Reference direction: The direction of the x axis.

Reference plane: The xy 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.

Semimajor axis: One-half the straight-line distance between the pericenter and apoapsis points in an orbit.

Spacecraft: A vehicle in orbit about any celestial body or celestial point, as single entities or as part of a set (such as constellations or formations). This category also includes *in situ* assets.

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.

True anomaly: The central angle between the position vector and the (reference) pericenter vector in an orbit.

ANNEX B

ABBREVIATIONS AND ACRONYMS

ALT	Altitude
AZ	Azimuth
AZEL	Azimuth and Elevation antenna configuration
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
DEC	Declination
DSN	Deep Space Network
EL	Elevation
ESA	European Space Agency
FDMA	Frequency Division Multiple Access
Galileo	Galileo Space Segment
GLONASS	Global Navigation Satellite System
GM	Greenwich Mean
GMST	Greenwich Mean Sidereal Time
GNS	Global Navigation System
GPS	Global Positioning System
HA	Hour angle
HEO	High Earth Orbit
IAU	International Astronomical Union

ICD	Interface Control Document
ICRF	International Celestial Reference Frame
ICRS	International Celestial Reference System
IERS	International Earth Rotation and Reference Systems 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
LVLH	Local Vertical Local Horizontal
NAVSTAR	Navigation Satellite Timing and Ranging System
OBC	Onboard Computer
OPM	Orbit Parameter Message
OWLT	One Way Light Time
PV _t	Position, Velocity and time
RA	Right Ascension
RADEC	Right Ascension (or Hour Angle) and Declination antenna
RINEX	Receiver Independent Exchange Format
RTL _T	Round Trip Light Time
SI	International System of Units
TAI	International Atomic Time
TCB	Barycentric Coordinated Time
TDB	Barycentric Dynamical Time
TDT	Terrestrial Dynamical Time

CCSDS HISTORICAL DOCUMENT
CCSDS REPORT CONCERNING NAVIGATION DATA—DEFINITIONS AND CONVENTIONS

TOD	True of Date
TT	Terrestrial Time
USAF	United States Air Force
UT1	Universal Time
UTC	Coordinated Universal Time
XEYN	X-east and Y-north antenna configuration
XSYE	X-south and Y-east antenna configuration
X-Y	X-Y antenna mount such as XEYN or XSYE
Δ DOR	Delta-Differential One-Way Range data type
δ	declination