The Consultative Committee for Space Data Systems

Report Concerning Space Data System Standards

NAVIGATION DATA— DEFINITIONS AND CONVENTIONS

INFORMATIONAL REPORT VOLUME 1

CCSDS 500.0-G-3.9~~CCSDS 500.0-G-3.8~~vol1

GREEN BOOK

April 2015~~February 2015~~

AUTHORITY

Issue:	Informational Report, Issue 3.9~~Issue 3.8~~, Vol.1
Date:	April 2015~~February 2015~~
Location:	Washington, DC, USA

This document has been approved for publication by the Management Council of the Consultative Committee for Space Data Systems (CCSDS) and reflects the consensus of technical panel experts from CCSDS Member Agencies. The procedure for review and authorization of CCSDS Reports is detailed in the *Procedures Manual for the Consultative Committee for Space Data Systems*.

This document is published and maintained by:

CCSDS Secretariat
Office of Space Communication (Code M-3)
National Aeronautics and Space Administration
Washington, DC 20546, USA

FOREWORD

This CCSDS report, *Navigation Data – Definitions and Conventions*, contains background and explanatory material to supplement the CCSDS Recommended Standards for the standardization of spacecraft navigation data generated by CCSDS Member Agencies. It has been divided into two separate volumes. Volume 1 presents the conceptual framework and rationale for the exchange of navigation data, the definitions and conventions associated with inter-Agency cross-support situations involving the transfer of navigation data, as well as current and envisioned CCSDS Navigation Data Messages. The second volume deals explicitly with the technical definitions and conventions used widely within the navigation field.

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DOCUMENT CONTROL

Document	Title	Date	Status
CCSDS 500.0-G-1	Navigation Data—Definitions and Conventions	June 2001	Original issue, superseded
CCSDS 500.0-G-2	Navigation Data—Definitions and Conventions, Informational Report, Issue 2	November 2005	Current issue
CCSDS 500.0-G-2.11	Navigation Data—Definitions and Conventions, Informational Report, Issue 2.11	October 2009	Numerous minor updates, clarifications, corrections
CCSDS 500.0-G-2.12	Navigation Data—Definitions and Conventions, Informational Report, Issue 2.12	November 2009	Based on changes at CCSDS Fall 2009 Meetings
CCSDS 500.0-G-2.13	Navigation Data—Definitions and Conventions, Informational Report, Issue 2.13	January 2010	Comments received from members of WG.
CCSDS 500.0-G-2.14	Navigation Data—Definitions and Conventions, Informational Report, Issue 2.14	March 2010	Comments received from members of WG on local orbital frames sec 4.3.7.
CCSDS 500.0-G-3.1	Navigation Data – Definitions and Conventions, Informational Report, Issue 3.1	November 2010	Initial draft with the layout envisioned for the Navigation Data Definitions and Conventions document in preparation for version 4.0.
CCSDS 500.0-G-3.2	Navigation Data – Definitions and Conventions, Informational Report, Issue 3.2	April 2011	Addition of technical content with the new layout envisioned for version 4.0 of the Navigation Green Book.

CCSDS 500.0-G-3.3vol1	Navigation Data – Definitions and Conventions, Information Report, Issue 3.3, Vol.1	August 2011	Splitting the Navigation Green Book into two separate volumes. Volume 1 will contain most of the new technical content originally envisioned for version 4.0 of the Navigation Green Book.
CCSDS 500.0-G-3.4vol1	Navigation Data – Definitions and Conventions, Information Report, Issue 3.4, Vol.1	March 2012	Incorporated comments from the CCSDS Fall 2011 Navigation meetings held in Boulder, Colorado, and those comments received from multiple reviewers within the CCSDS Navigation Working Group (NWG).
CCSDS 500.0-G-3.5vol1	Navigation Data – Definitions and Conventions, Information Report, Issue 3.5, Vol.1	September 2012	Incorporated comments from the CCSDS Spring 2012 Navigation meetings held in Darmstadt, Germany, and those comments received from multiple reviewers within the CCSDS Navigation Working Group (NWG).
CCSDS 500.0-G-3.6vol1	Navigation Data – Definitions and Conventions, Information Report, Issue 3.5, Vol.1	March 2014	Incorporated comments from previous bi-annual CCSDS Navigation technical meetings, as well as comments received from multiple reviewers within the CCSDS Navigation Working Group (NWG).

CCSDS 500.0-G-3.7vol1	Navigation Data – Definitions and Conventions, Information Report, Issue 3.7, Vol.1	September 2014	Incorporated comments received from the chairman of the CCSDS Navigation Working Group (NWG), David Berry of NASA/JPL. Likewise, made several modifications to the document to meet the objectives of the Navigation Green Book volume 1 based on discussions taking place at previous bi-annual CCSDS technical meetings.
CCSDS 500.0-G-3.8vol1	Navigation Data – Definitions and Conventions, Information Report, Issue 3.8, Vol.1	February 2015	Incorporated comments received from members of the CCSDS Navigation Working Group (NWG). Several modifications to the document were made to meet the objectives of the Navigation Green Book volume 1 based on discussions taking place at previous bi-annual CCSDS technical meetings.
CCSDS 500.0-G-3.9vol1	Navigation Data – Definitions and Conventions, Information Report, Issue 3.9, Vol.1	April 2015	Incorporated comments received from members of the CCSDS Navigation Working Group (NWG). Several modifications to the document were made to meet the objectives of the Navigation Green Book volume 1 based on discussions taking place at previous bi-annual CCSDS technical meetings.

CONTENTS

Section Page

CONTENTS (continued)

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1 INTRODUCTION

1.1 PURPOSE AND SCOPE

Spacecraft navigation data is exchanged during cross support of space missions. The purpose of ~~volumes 1 and 2 of~~ this document is to establish a common understanding for the exchange of spacecraft navigation data. This exchange is facilitated through the use of the various navigation data messages defined in section 4~~)~~. Volume 1 presents the general definitions and terms of spacecraft navigation and flight dynamics, the conceptual framework and rationale for the exchange of navigation data, the definitions and conventions associated with inter-Agency cross-support situations involving the transfer of navigation data, as well as current and envisioned CCSDS Navigation Data Messages. Volume 2 deals explicitly with the technical definitions and conventions used widely to describe the properties, measurements and ancillary information of spacecraft dynamics required for navigation.

For purposes of this document, orbit, attitude, maneuver, and conjunction assessment information are considered integral parts of the spacecraft navigation process.

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

- Orbit data in the form of orbit elements or position and velocity of a spacecraft in Cartesian coordinates;
- Attitude data for either a spinning or three-axis stabilized spacecraft;
- Tracking data and ground system information;
- Conjunction Assessment data;
- Environmental models;
- Properties and measurements of spacecraft dynamics;
- Ancillary data required for the proper interpretation of properties and measurements within spacecraft navigation.

1.2 APPLICABILITY

This document serves as a guideline for the development and usage of international standards for the exchange of spacecraft navigation data.

1.3 STRUCTURE OF VOLUME 1

a) Section 1 (this section) provides an introduction including the purpose and scope, applicability and structure of this document.

b) Section 2 provides a brief overview of the spacecraft navigation and flight dynamics processes, as well as the definition of terms relevant to this process.

c) Section 3 provides foundational information regarding the navigation data message exchange architecture (definitions, paradigms, etc.).

d) Section 4 provides an overview of the CCDS Navigation Data Messages (NDMs), and introduces the current recommended and envisioned CCSDS standards for the exchange of navigation data.

e) Annexes A and B constitute a Glossary of Terms and a listing of Acronyms, respectively.

1.4 STRUCTURE OF VOLUME 2

a) Section 1 provides an introduction including the purpose and scope, applicability and structure of volume 1 and 2 of this document.

b) Section 2 provides a description of the ancillary data types needed to interpret the measurements and properties of navigation data correctly, such as details about coordinate systems, time systems, astrodynamic constants, environmental models, etc.

c) Section 3 specifies the physical attributes or characteristics of spacecraft, rovers, equipment, and tracking stations needed for navigation.

d) Section 4 introduces the measurements and data types necessary for orbit and attitude determination or that may be made during a navigation session.

e) Annexes A and B constitute a Glossary of Terms and a listing of Acronyms, respectively.

1.5 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, or from the CCSDS website (ref. [21]).

[1] *Organization and Processes for the Consultative Committee for Space Data Systems.* CCSDS A02.1-Y-4. Yellow Book. Issue 4. Washington D.C.: CCSDS, April 2014.

[2] B. D. Tapley, B. E. Schutz, and G. H. Born. *Statistical Orbit Determination.* Burlington, MA: Elsevier Academic Press, 2004.

[3] James R. Wertz, ed. *Spacecraft Attitude Determination and Control.* Astrophysics and Space Science Library 73. Dordrecht: D. Reidel, 1978.

[4] William G. Melbourne, "Navigation between the Planets," *Scientific American* 234 (June 1976): 58-64, 68-74.

[5] C. L. Thornton and J. S. Border. *Radiometric Tracking Techniques for Deep-Space Navigation*. Deep Space Communication and Navigation Series. Hoboken, N.J.: Wiley, 2003.

[6] *Attitude Data Messages*. Recommendation for Space Data System Standards, CCSDS 504.0-B-1. Blue Book. Issue 1. Washington, D.C.: CCSDS, May 2008.

[7] *Orbit Data Messages*. Recommendation for Space Data System Standards, CCSDS 502.0-B-2. Blue Book. Issue 2. Washington, D.C.: CCSDS, November 2009.

[8] *Tracking Data Message*. Recommendation for Space Data System Standards, CCSDS 503.0-B-1. Blue Book. Issue 1. Washington, D.C.: CCSDS, November 2007.

[9] *Time Code Formats*. Recommendation for Space Data System Standards, CCSDS 301.0-B-4. Blue Book. Issue 4. Washington, D.C: CCSDS, November 2010.

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[10] David Vallado, et al. “Revisiting Spacetrack Report #3.” In *Preceedings of the AIAA/AAS Astrodynamics Specialist Conference and Exhibit* (21-24 August 2006, Keystone, Colorado). AIAA 2006-6753. Reston, Virginia: AIAA, 2006. <http://centerforspace.com/downloads/files/pubs/AIAA-2006-6753.pdf>

[11] *XML Specification for Navigation Data Messages*. Recommendation for Space Data System Standards, CCSDS 505.0-B-1. Blue Book. Issue 1. Washington, D.C.: CCSDS, December 2010.

[12] David A. Vallado. *Fundamentals of Astrodynamics and Applications*. 4th~~3rd~~ Edition. Space Technology Library, 2013~~07~~.

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[13] *Conjunction Data Message*, Recommendation for Space Data System Standards, CCSDS 508.0-B-1. Blue Book. Issue 1. Washington, D.C.: CCSDS, June 2013.

[14] *Pointing Request Message*. Proposed Recommendation for Space Data System Standards, CCSDS 509.0-W-n. White Book. Issue n. Washington D.C: CCSDS, to be published.

[15] *Navigation Hardware Message*. Proposed Recommendation for Space Data System Standards, CCSDS 510.0-W-n. White Book. Issue n. Washington D.C: CCSDS, to be published.

[16] *Spacecraft Maneuver Message*. Proposed Recommendation for Space Data System Standards, CCSDS 511.0-W-n. White Book. Issue n. Washington D.C: CCSDS, to be published.

[17] *Navigation Data – Definitions and Conventions*. Report Concerning Space Data System Standards, 500.0-G-3. Green Book. Issue 3, Washington DC.: CCSDS, May 2010. (This document is only applicable during the transition phase from one to two volumes)

[18] *Navigation Data – Definitions and Conventions*. CCSDS Green Book. Issue 4, Volume 2. (This document is in progress)

[19] *CCSDS Publications Manual*. CCSDS A20.0-Y-4. Yellow Book. Issue 4. Washington D.C.: CCSDS, April 2014.

[20] Space Assigned Numbers Authority (SANA) website at http://sanaregistry.org.~~*Space Assigned Numbers Authority (SANA)—Role, Responsibilities, Policies, and Procedures.* CCSDS 313.0-Y-1. Yellow Book. Issue 1. Washington D.C.: CCDSD, July 2011~~.

-[21] CCSDS Publications website at http://public.ccsds.org/publications/default.aspx.

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 any object, a craft or person, from one place or orientation to another. In this document, ‘navigation’ shall be construed to mean the determination and prediction of the spacecraft orbit and attitude, which are specified by its translational and rotational motion, respectively.

2.2.2 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:

Orbit is defined by the translational motion of a spacecraft around a large central body due to the gravity forces of the larger mass acting on the spacecraft. The orbit of a spacecraft is the trajectory that does not, in the absence of perturbations, intersect with the central body. This trajectory is the path of the small mass, or spacecraft, orbiting the large central body through space. The orbit can be represented as position and velocity in a state vector, or as orbital elements as defined in Vol.2 of the Navigation Green Book (reference [17]) and reference [12]. There are other types of orbits that are affected by the gravity pull of two larger masses, ~~i~~e.~~eg~~. the moon and Earth; such that the spacecraft with an appropriate velocity will remain in the same position relative to the two larger bodies. These orbits are called Lagrange or libration point orbits.

Attitude is the orientation and/or pointing of a spacecraft and it is defined by its rotation relative to a defined reference coordinate system. The preferred attitude representation depends on the attitude stabilization mode of the spacecraft. For instance, the attitude of a spin stabilized spacecraft can best be represented by the attitude of a single axis either as a three-component unit vector or as a point on the unit celestial sphere. This representation sometimes includes the phase of rotation about that axis~~)~~. For three-axis stabilized spacecraft, the attitude can best be represented by a coordinate transformation from reference~~s~~ axes in inertial space to the spacecraft body frame. See Vol. 2 of the Navigation Green Book (reference [17]) and reference [3] for available attitude representations.

Orbital dynamics studies the changes in the position of all orbiting bodies, whereas **attitude dynamics** deals with changes in the orientation and pointing of the spacecraft. **Flight dynamics** is a term used to cover both orbital and attitude dynamics. It refers to the study of translational and rotational motion and control of a flying object, whether it is an aircraft or spacecraft. Within the aerospace industry, the flight dynamics term could be used for mission design and analysis as well as the support required for determining, controlling and maintaining the orbit and attitude of a spacecraft.

Orbit Determination and **Attitude Determination** are processes within Navigation to find the present and past positions and orientations of a spacecraft using a series of measurements. These two navigation processes fit a set of measurements to a physical model in some optimal way to obtain the best orbit and attitude solutions. Although they are related, these processes affect each other only weakly so they can generally be performed separately. For example, a nominal attitude can generally be used in drag models that affect orbit determination, and a predetermined ephemeris can generally be used in attitude determination. The~~se~~ results of these two processes are used to predict the imminent future position and orientation of the spacecraft.

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

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

The guidance, navigation and control terms above are commonly abbreviated to form **GN&C**. The **GN&C** term is used as a system or subsystem forming part of a spacecraft or aircraft. The GN&C system includes all the hardware (sensors and actuators) and software necessary for both onboard orbit and attitude determination and control.

The **Attitude Control System (ACS)** is part of GN&C and consists specifically of hardware and software for onboard attitude estimation and pointing control. The **Attitude Determination and Control System (ADCS)** term is sometimes used in lieu of ACS. The propulsion system is an essential element of GN&C and a complement for ACS within a spacecraft for attitude and/or orbit thruster control.

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

2.2.3 SPACECRAFT NAVIGATION PROCESSES

~~Beside~~ In addition to orbit and attitude determination introduced in section 2.2.2, maneuver planning and reconstruction for orbit and attitude control, conjunction assessment and collision risk analysis, and calibration of hardware used for navigation are also important processes within flight dynamics. In general estimation terms, all of these spacecraft navigation processes can take place either in real time, near-real time, or after the fact (also referred to as reconstruction), as illustrated in figure 2-1.

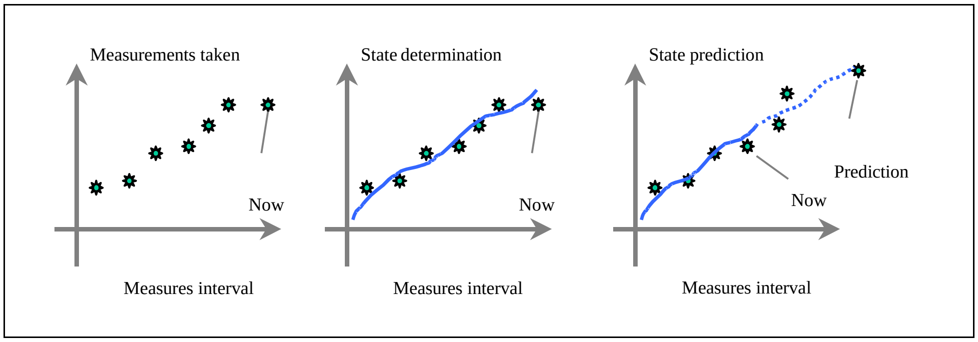


Figure 2-1: Navigation Estimation Process

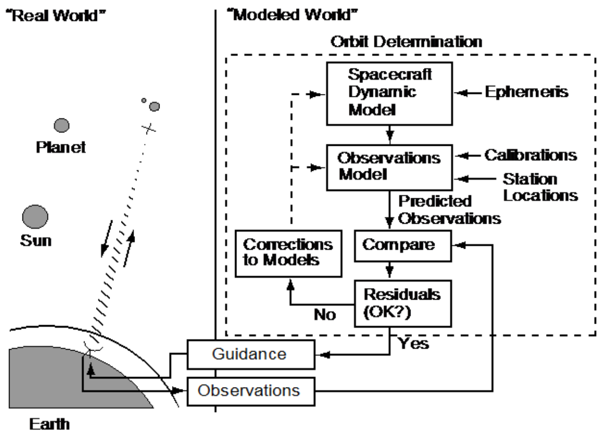
As an example, navigation data exchanged during orbit and attitude determination processes are the measurements or observations from navigation hardware, and orbit and attitude parameters or ephemeris described in section 4. These determination processes produce single orbit and attitude parameter or history solutions by fitting hardware measurements to a physical model. ~~These~~ This physical model represents the relationship between the measurements and the desired solution (position, velocity, attitude etc.). Often additional model parameters that affect the solution are also solved for to improve the navigation solution. Examples of such parameters are drag coefficients or gyro biases. The set of all parameters that is solved for is called the state of the system.

The more parameters in the state, and the more complex the model, the more data is needed to find a solution. Once a model with the dynamics is defined, data at different times may be used so there is generally more data available than the minimum needed to find a unique solution. In such 'over determined' cases, especially when the observations are uncertain, least-squares or other estimation techniques are used to find the best state to match the observations to the model solution.

For example, if one knows the position of a spacecraft, it is easy to compute the distance from the spacecraft to known points. The reverse process, computing the position of the spacecraft from a single distance measurement, does not give a unique solution. To obtain a unique solution, distances from several known points at one time are needed. Alternatively, distances from known points at different times or use of different types of data (e.g., velocity measurements) can be used. In order to use the time dependent differences, a model of the change of position of the spacecraft with time must be generated from the principles of physics. This model can be made more accurate by including perturbations in it, such as drag, and solving for parameters that help define the effect of these perturbations on the position as a function of time.

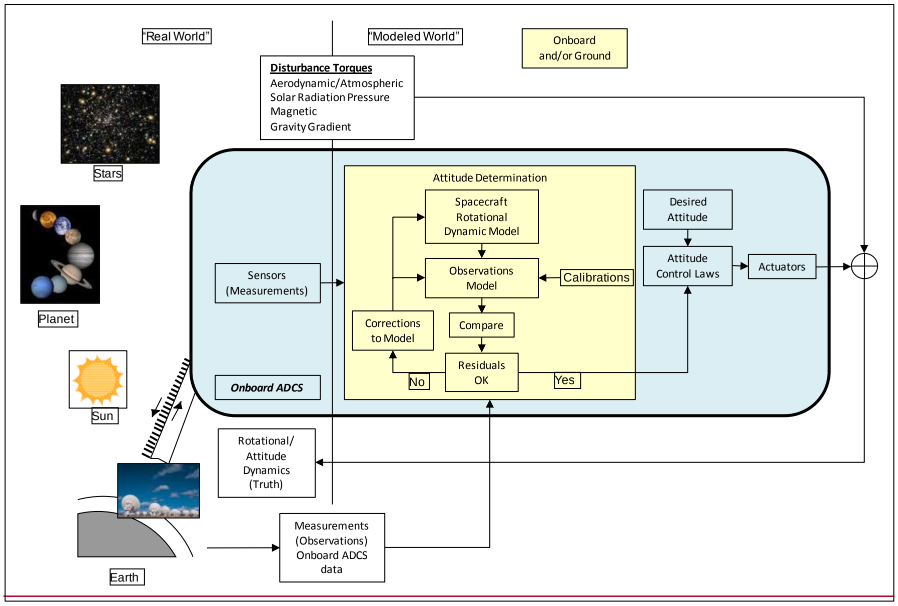
~~More detail of the navigation process for orbit and attitude determination, as well as Conjunction Assessment (CA) is illustrated in figures 2-2, 2-3, and 2-4.~~ The Conjunction Assessment (CA) process is just the result of the analysis of observations, and orbit and attitude solutions determined for more than one space object. ~~Figure 2-4 also shows the~~ The Orbit Data Message (ODM, see section 4.2.2) and Conjunction Data Message (CDM, see section 4.2.4) ~~as~~ are two key navigation data messages being exchanged as input to, and output of, the CA process, respectively. For the most part, the orbit and attitude determination processes can, however, be generalized to the following four steps:

1) A set of measurements is acquired.
2) The set of measurements is fit to a dynamic model to provide a solution state (cf. references [2], [3], [4], [5], and [12]), which is found by minimizing the differences between measurements and reference values corresponding to the measurements.
3) The solution state may be used in the model to predict the future state.
4) If necessary, the spacecraft state is altered at some future time:
   a) For trajectories/flight paths: 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’.
   b) For attitudes: A maneuver is performed to modify the spacecraft attitude, if necessary, to meet mission requirements and constraints. This process is called ‘attitude adjustment’.



The navigation process. Orbit determination is an iterative procedure for estimating the spacecraft trajectory and related physical parameters from a set of tracking data. Guidance involves the calculation of optimal maneuvers and commands needed to deliver the spacecraft to the desired target.

~~Figure 2-2: The Navigation Orbit Process~~



~~**Figure 2-3: The Navigation Attitude Process**~~

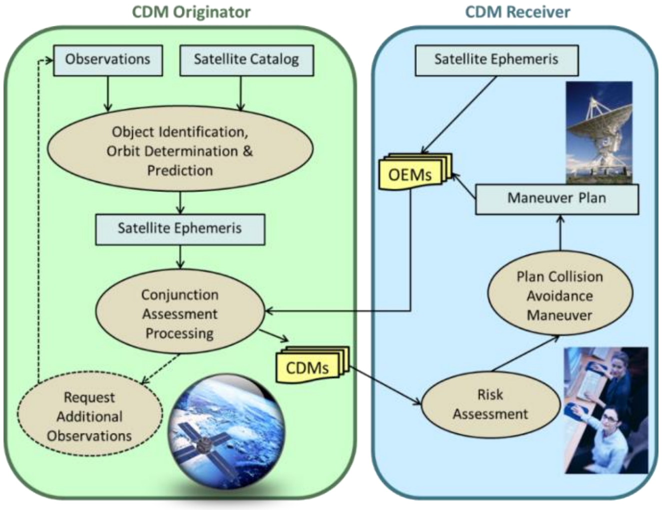


Figure 2-24: The Navigation Conjunction Assessment Process

3 NAVIGATION DATA MESSAGE EXCHANGE FRAMEWORK

3.1 GENERAL

This section describes the elements, characteristics, and major groupings of navigation data message exchanges.

3.2 TERMS AND DEFINITIONS

Property: An attribute or characteristic of an object or concept. In the context of this document, properties represent the physical attributes of spacecraft, rovers, equipment, and tracking stations that are needed for navigation.

Measurement: Quantitative data collected by an instrument specifically to improve the knowledge of properties. In the context of this document, measurements are quantities obtained from devices such as radio receivers, attitude sensors, etc.

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

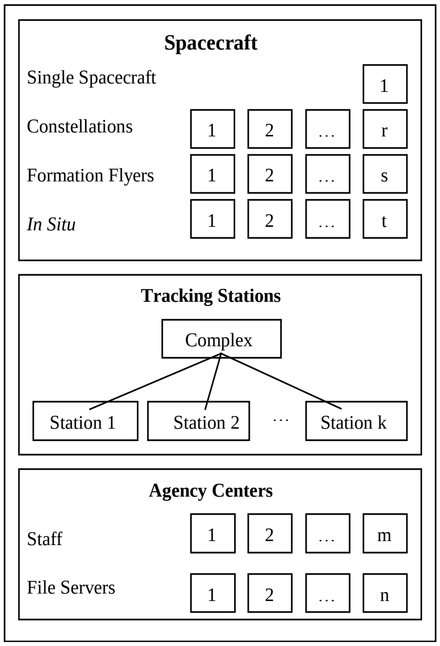


Figure 3-1: Participant Categories

Ancillary Information: Any data type needed to correctly interpret properties and measurements. In general, ancillary information makes it possible to take properties or measurements and incorporate them correctly into numerical computations.

Navigation Data: A set of measurements, properties, and ancillary information related to navigation.

Navigation ~~d~~Data ~~m~~Message: A particular arrangement of the navigation data whose structure and content are the subjects of CCSDS flight dynamics Recommended Standards.

Participant: An entity that has the ability to acquire or broadcast navigation data messages. Possible participants can be arranged into three categories, as depicted in figure 3-1.

Spacecraft: One type of participant defined as a single vehicle orbiting a celestial body or point, or as part of a set, such as constellations or formations. The term spacecraft also includes assets in operations at, or in close proximity to, a remote body. These types of participants are referred to as *in situ* assets, and consist of rovers, landers, aircraft, etc. Navigation data messages to/from these participants are exchanged digitally, and are usually optimized in response to bandwidth, power, or message format constraints.

~~Tracking~~ Ground Stations and Space Networks: One type of participant. These types of participants facilitate the spacecraft tracking and communications between the spacecraft and ground. Communications with the spacecraft are made possible by either a network of fixed ground stations located around the world, or a space network. Some spacecraft are equipped with the necessary navigation software and/or hardware to do onboard orbit determination and control with data from space networks or communication links. Ground-based facilities that provide tracking capabilities ~~facilities~~ are used to monitor the location of a spacecraft. Whenever an orbiting spacecraft passes across the field of view of a ground station, it is possible to collect tracking data that will be used for determining the spacecraft position and velocity. Some agencies have multiple stations operated by a central entity, referred to as complex.

~~**Ground Stations and Space Networks:** One type of participants. These types of participants facilitate the spacecraft tracking and communications between the spacecraft and ground. These communications are made possible by a network of fixed ground stations located around the world. Some spacecraft are equipped with the necessary navigation software and/or hardware to do onboard orbit and control with data from space networks or communication links.~~ **Agency Center:** One type of participant. An Agency Center includes the facilities~~,~~ used for the uplink of commands or software loads to the spacecraft, as well as for spacecraft telemetry monitoring, tracking, flight dynamics, and other engineering activities. Navigation data may be exchanged between agency centers by operations staff (e.g., via facsimile, email, FTP, etc.), or by servers across a computer network common to both the broadcasting and acquiring agents.

Navigation Session: The interchange of navigation data messages between participants.

3.3 NAVIGATION DATA AND NAVIGATION DATA MESSAGES

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

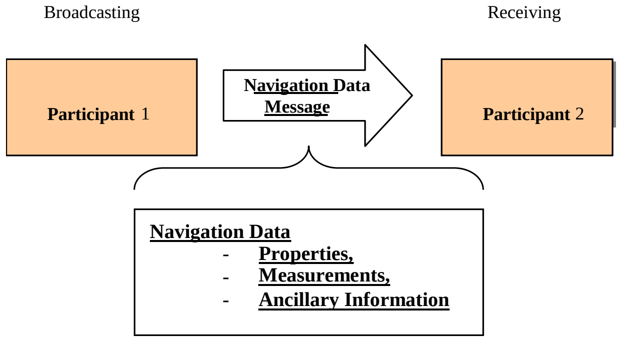


Figure 3-2: Navigation Data Message Exchange Definitions

Ideally, every navigation data message exchange will be covered by a CCSDS Recommended Standard related to flight dynamics~~ should apply to some type of navigation data message exchange described in this section~~. However, ~~it is clear that widely used formats and protocols that are considered strong candidates for ~~the completed CCSDS Recommended Standards cannot presently cover the entire range of exchanges. Subsection 4 introduces the current and proposed Recommended Standards for the exchange of navigation data. ~~Nevertheless, a~~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. ~~The following are the current exchange scenarios within the scope of CCSDS:

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

2. **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.

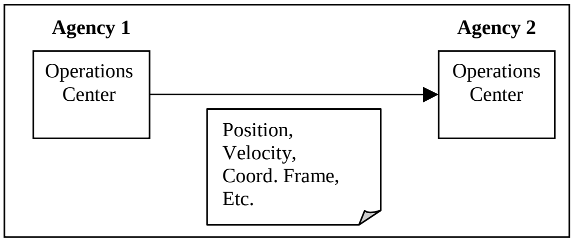
3. **Flight-to-flight** exchanges are defined as the set of exchanges between any two spacecraft participants.

Out of these exchange scenarios, navigation data is only exchanged ground-to-ground, ground-to-flight, and flight-to-ground at the time this document was written. The exchange of navigation data messages is most~~re~~ likely to take place after level-0 processing of spacecraft telemetry. In other words, spacecraft telemetry containing navigation data being downlinked to the ground is treated using separate CCSDS standards.

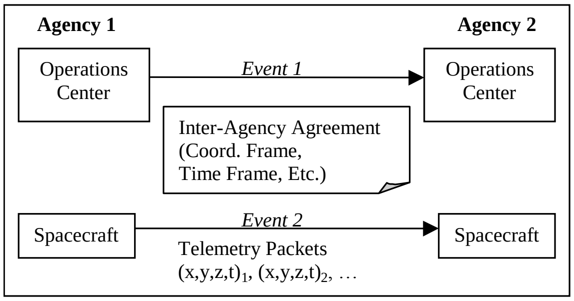
3.3.1 NAVIGATION DATA EXCHANGE CHARACTERISTICS

This section 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, state vectors (see references [17], [12], and [3]) could be exchanged between operations centers of two agencies. This exchange may be digital or through an image of the data (such as by 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~~system, 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 should 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 data messages may utilize a shorthand of a CCSDS Recommended Standard 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 Volume 2 of the CCSDS Navigation Green Book, reference [17].)

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).

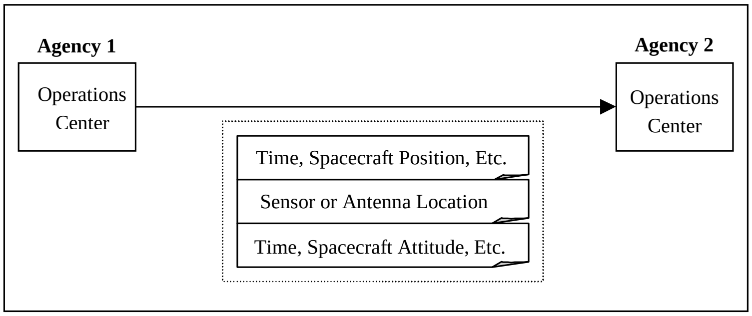


Figure 3-4: Navigation Session Using Multiple CCSDS Recommended Standards

4 CCSDS NAVIGATION DATA MESSAGES

4.1 GENERAL

This section provides an overview of the current and envisioned CCSDS Navigation Data Messages. It also reflects an application of the Navigation Data Message Exchange Framework descri~~pt~~bed in section 3.

The selection of navigation data formats and interfaces necessary for mission operations support is done very early during the development of the ground system. Standards are highly desirable for the correct interpretation and common understanding of the exchange of navigation data, with the purpose of facilitating communications within an agency and/or between agencies. Because interagency partnering in mission operations is becoming more widespread, standardization of navigation data formats facilitates interoperability between space agencies, where navigation functions for a mission of agency A could be performed by agency B, or vice-versa. In addition, standards for spacecraft navigation data could permit the reuse of software modules that read the input and generate the proper output products within the navigation process. This could facilitate an increased level of automation within the ground system.

There are currently four published standards for the exchange of spacecraft navigation data: the Attitude Data Message (ADM), Orbit Data Message (ODM), Tracking Data Message (TDM), and Conjunction Data Message (CDM). An overview of these standards will be provided in the subsequent subsections. The details of the ADM, ODM, TDM, and CDM are specified in references [6], [7], [8], and [13] respectively. The published standards are reviewed every 5 years. The three actions to be considered in the five year review are “reconfirm”, “retire”, or “revise”, as applicable (see reference [1]).

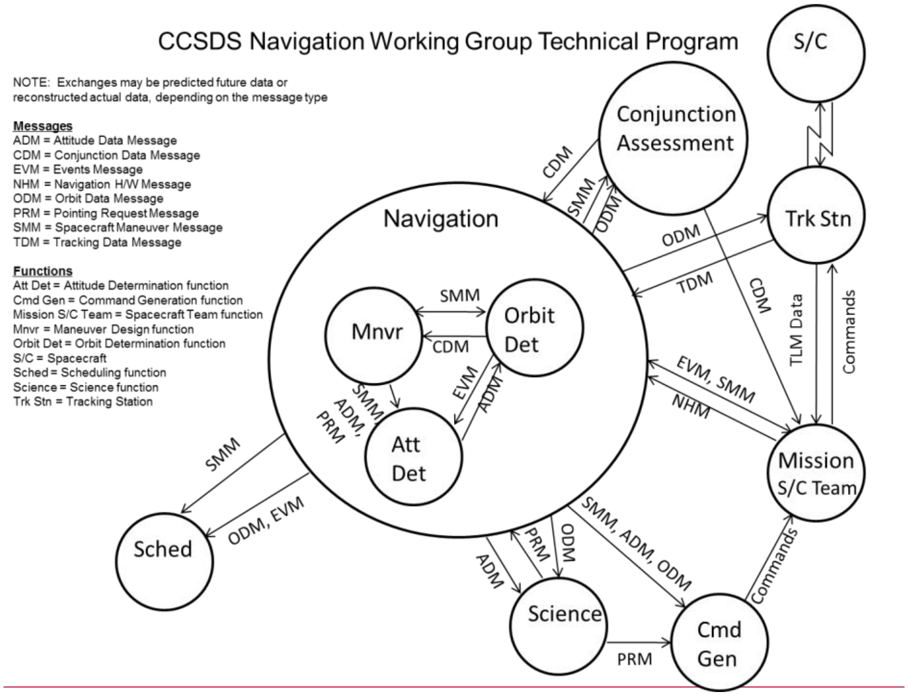
There are likewise several navigation data standards being developed and envisioned to fulfill and facilitate the execution and implementation of other navigation functions. Such standards under development are: Pointing Request Message (PRM, [14]), Navigation Hardware Message (NHM, [15]), and Spacecraft Maneuver Message (SMM, [16]). Also under consideration is a standard framework for the exchange of orbit and attitude events; this standard is tentatively named the “Event Messages (EVM).”

The objective of all navigation data messages (NDMs) is to minimize the burden during the implementation phase, by giving a specification and unambiguous interpretation of the input and output data for common navigation processes. The navigation data messages (NDMs) are means of transmitting information that relates to the navigation state of a spacecraft. The navigation state contains information about the position, orientation, and motion of the spacecraft. It is normally separated into an orbit sate and an attitude state. The orbit state represents the position of a spacecraft and the evolution of the position relative to an external coordinate frame. The attitude state represents the orientation of a spacecraft and may also represent the evolution of the orientation relative to an external coordinate frame. Each standard is developed to communicate the necessary data elements in a compact format that is readable to the human eye, as well as readable by computers to enable automation of navigation processes. The NDM standards are only applicable to the message format and content, but not to its transmission. The transmission method or mechanism used by the partners exchanging NDMs is beyond the scope of the standards and should be specified in ICDs. The message transmission could be based on a CCSDS data transfer protocol, file based transfer protocol such as SFTP, stream-oriented media, or other secure transmission mechanism. Once published by the CCSDS, all the CCSDS Navigation Standards are posted and available free of charge at the CCSDS website (reference [21]). ~~The navigation data messages (NDMs) are means of transmitting information that relates to the navigation state of a spacecraft. The navigation state contains information about the position, orientation, and motion of the spacecraft. It is normally separated into an orbit sate and an attitude state. The orbit state represents the position of a spacecraft and the evolution of the position relative to an external coordinate frame. The attitude state represents the orientation of a spacecraft and may also represent the evolution of the orientation relative to an external coordinate frame.~~ Here is a brief summary of all NDMs described in sections 4.2 and 4.3:

- The TDM contains information that can be used to determine the orbit state of a spacecraft.
- The ODM contains information that defines the orbit state of a spacecraft at one or more times.
- The ADM contains information that defines the attitude state of a spacecraft at one or more times.
- The NHM contains information that can be used to determine both the spacecraft attitude and orbit state. It also contains information that can be used for spacecraft maneuver reconstruction.
- The CDM contains information that defines the relationship between the orbit states of different space objects at different times.
- The PRM contains information on the desired attitude state of an object at one or more times.
- The SMM contains information on the transformation from one state (attitude or orbit) to another.

~~Figure 3-5 illustrates an example of how all the messages could be utilized in a mission operations environment. This figure illustrates the navigation data exchange and the direction of the information flow between the various functions that make up typical navigation operations. These functions may reside within one agency/organization or may be distributed across two or more agencies and/or organizations.~~

The remainder of this document provides a~~n~~ more detailed overview of the CCSDS navigation standards that have been published (see 4.2) and are under development (see 4.3).



~~Figure 4-1: Example of NDM Exchange and Direction of the Information Flow in a Mission Operarations Environment~~

4.2 PUBLISHED NAVIGATION DATA MESSAGES

4.2.1 TRACKING DATA MESSAGE (TDM)

The TDM (reference [8]) specifies a standard format for a single message type used in the exchange of spacecraft tracking data between space agencies. Such exchanges are used for distributing tracking data output from routine interagency cross-support in which spacecraft missions managed by one agency are tracked from a ground station managed by second agency. The standardization of tracking data formats facilitates orbit determination, as well as space agency allocation of sessions to alternate tracking resources and international cooperation in the provision of tracking services. Additionally, it increases the ability of space agencies to tolerate availability issues with their primary antennas.

The TDM standard is designed for the inter-agency exchange of the following tracking data types (see volume 2 of the Navigation Green Book, reference [17]):

- Ground based radio metric tracking data types~~ (see volume 2 of the Navigation Green Book, reference [17])~~:
  - Uplink and downlink (transmitted/received) frequencies
  - Range
  - Delta-DOR (Delta Differential One-way Ranging)
  - Range-rate
  - Differenced range
  - Doppler (one-way, two-way, three-way and four-way)
  - Differenced Doppler
  - Antenna angles
  - Interferometric types
  - Optical data (planned)
- Spacecraft-to-spacecraft Doppler and range
- Ancillary information needed to calculate the measurement residuals; such as meteorological data (weather), media delays/correction, and clock bias/drift measurements

The metadata section in the TDM contains keywords selected from a large number of available keywords that qualify the data section keywords and provide supplementary information that is necessary in order to interpret the data. There are a few metadata keywords that are required for every TDM; but in general, there are only a very small number because some of the metadata keywords would be meaningless for several data types. One of the most important metadata keywords, required in all TDMs, are the keywords that represent the participants (spacecraft, antennas, quasars, etc.) involved in a tracking data session. For any given TDM data type, the metadata keywords fall into three categories: required metadata, situation-specific required metadata, and completely optional metadata. The details for the full range of data types that may be exchanged via the TDM can be found in reference [8].

Because of the large amount of data typically collected during a tracking pass, the TDM is suited to inter-agency exchanges from one computer to another (e.g. file transfer) in an automated fashion. Based on the variety of data types, and the diversity of tracking systems existing in various agencies, a TDM should be supplemented by an ICD written jointly by the service provider and customer agency that discusses such things as tracking instrument locations, corrections that will or will not be applied to the data, the specific methods/mechanism of transferring data that will be supported, frequency of exchange, etc. While most agencies are transferring TDMs using a file-based transfer protocol, another CCSDS Working Group, the Cross Support Transfer Services (CSTS) Working Group, is in the process of developing a standard for real-time transfer of radiometric tracking data that will use the TDM as the data format.

The TDM has been assimilated into the operations environments of several of the CCSDS Member Agencies. A partial list of implementations follows. The TDM is the format used by NASA’s Jet Propulsion Laboratory (JPL) for providing tracking data from multiple European Space Agency (ESA) spacecraft (e.g. Mars Express, Venus Express, ROSETTA) by the Deep Space Network (DSN). The TDM has also been used for tracking data exchanges between JPL and the Indian Space Research Organization (ISRO) for the Mars Orbiter Mission.

4.2.2 ORBIT DATA MESSAGES (ODM)

The ODM (reference [7]) represents the orbit data for a single spacecraft and specifies the formats for use in transferring orbit information between space agencies, ~~and~~ commercial spacecraft operators, ~~or~~ and/or government spacecraft operators in a clear, concise and compact manner. The ODM may be one of the following three messages that serve different purposes: the Orbit Parameter Message (OPM), the Orbit Mean-Elements Message (OMM), and the Orbit Ephemeris Message (OEM). The OPM and OMM could be used in exchange scenarios that involve automated and/or human interaction; however, the OEM is best suitable for exchanges that require high level of automation for fast, frequent and reliable interpretation and processing of the data. Full details on the ODM can be found in reference [7].

The OPM specifies the orbital state (single position and velocity in Cartesian coordinates) or osculating Keplerian elements of a spacecraft at an instant of time; whereas the OMM specifies the characteristics of the spacecraft orbit expressed in mean Keplerian elements at a specified epoch. Neither the OPM nor OMM is designed for higher fidelity ~~dynamic modeling~~propagation. However, the OPM allows the user to specify simple parameters related to finite and instantaneous maneuvers, and provides simple parameters for the modeling of solar radiation pressure and atmospheric drag.

The OEM specifies the orbital state vectors at multiple epochs within a time range in a single message, and allows for the modeling of any number of gravitational and non-gravitational accelerations. The OEM represents the history or forecast (prediction) of the state vectors, which can be interpolated to obtain the spacecraft orbit position and velocity state at times other than those explicitly specified in the message (i.e. from the tabular epochs). ~~The OEM is the only ODM that supports a higher level of fidelity in the dynamic modeling.~~

One ~~advantage~~ feature of the ODM is that via the OMM it includes keywords and values to generate canonical NORAD Two Line Elements Sets (TLEs) for accommodating the needs of heritage users (see reference [10]). The 6x6 covariance matrix, which is optional for all the ODMs, reflects the uncertainties of the orbit solutions used to generate the states in the OEM, uncertainties of the orbit state in the OPM, and uncertainties of the mean Keplerian elements in the OMM.

~~Multiple OPM, OMM, or OEM messages may be provided in a message exchange session requiring different levels of ephemeris fidelity.~~ If ephemeris information of multiple spacecraft is being exchanged, then multiple OPM, OMM, or OEM messages ~~files~~ must be used (these could be packaged in a single file, if desired). ~~A difference in the exchange scenario is that the OPM and OMM do not accommodate high-fidelity dynamic modeling, whereas the OEM does.~~

~~Because the OMM is suited for directing antennas and planning contacts with satellites, the 6x6 covariance may be used to determine contact parameters that encompass uncertainties in predicted future states of orbiting objects of interest. The OMM, however, is not recommended for assessing mutual physical or electromagnetic interference among Earth orbiting satellites, developing collaborative maneuvers; or propagating precisely the orbits of active satellites, inactive man-made objects, and near-Earth objects. Conversely, the OPM could use the optional covariance matrix in the propagation process.~~

The ODM has been assimilated into the operations environments of several of the CCSDS Member Agencies. A partial list of implementations follows. The OEM is the format used by the European Space Agency (ESA) for submission of spacecraft ephemeris to NASA's Jet Propulsion Laboratory (JPL) for tracking of multiple ESA spacecraft (e.g. Mars Express, Venus Express, ROSETTA) by the Deep Space Network (DSN). The OEM has also been used to deliver the trajectories to the European Space Operations Centre (ESOC) for possible contingency tracking (e.g. Mars missions, SOHO). Additionally, the Japan Aerospace Exploration Agency (JAXA) used the OEM for DSN tracking of the SELENE spacecraft. The OPM has been implemented at ~~the DSN,~~ NASA/JPL Navigation, Deutsches Zentrum fur Luft-und Raumfahrt (DLR), Centre National d'Etudes Spatiales (CNES), and ESOC, and is used frequently for external support. The ODMs have also been implemented and used to support some projects within NASA Goddard Space Flight Center (GSFC). For instance, OEMs are used for owner/operator ephemerides in conjunction assessment by NASA GSFC for the Collision Avoidance Risk Assessment (CARA) process, ~~and~~ by the Joint Space Operations Center (JSpOC), and the Space Data Association. Several other implementations are likely to exist given the popularity and flexibility of the OEM.

The ODM is currently undergoing revision as a result of the mandatory CCSDS 5-year review. At present, it appears that there will be an additional message added to the ODM, but it is premature to provide details.

4.2.3 ATTITUDE DATA MESSAGES (ADM)

The purpose of the ADM recommended standard (reference [6]) is to delineate a format and keywords that allow the exchange of attitude information in an unambiguous manner. Even though the parameterization can take many forms, the information conveyed must at a minimum address the following to give an unambiguous attitude:

- Epoch of the attitude
- Coordinate system being transformed from (1)
- Coordinate system being transformed to (2)
- Attitude parameters

Depending on the particular parameterization of the attitude, additional information may be necessary to fully specify an unambiguous attitude. In addition to these parameters, the rotational rates of coordinate system 1 with respect to coordinate system 2 are needed to propagate the attitude.

The ADM recommended standard specifies two message formats for use in transferring spacecraft attitude information between space agencies: the Attitude Parameter Message (APM) and Attitude Ephemeris Message (AEM). Both ADMs provide the proper parameters for spin-stabilized and three-axis stabilized spacecraft. Each parameterization requires specification of different quantities, thus requiring a different set of keywords.

The APM consists of instantaneous attitude state and optional attitude maneuvers. It specifies the attitude state of a single object at an instant of time (an epoch). The recipient of the message requires the use of an attitude propagator or technique to determine the attitude at times different from the epoch. The recipient shall have, therefore, the proper modeling of spacecraft attitude dynamics, atmospheric torque, other internal and external torques (e.g. magnetic, gravitation, solar pressure, etc.), thrust or reaction wheel maneuvers, and attitude control to fulfill the accuracy requirements for a particular mission. For the propagation, additional ancillary information (spacecraft properties; such as inertia tensor, torque vectors, and maneuver planning data, if applicable) can be included in the message.

The AEM consists of a history or forecast of the spacecraft's attitude. The user or recipient of the AEM can interpolate the history/forecast to determine the attitude states at arbitrary times contained within the span of the ephemeris, but different from the tabular epochs. Because of the interpolation technique, a predictive AEM accommodates higher fidelity or precision dynamic modeling than is possible in the APM to allow for the modeling of any number of torques induced by flexible structures, more complex attitude movements, solar pressure, atmospheric torques, magnetic torques, etc.

The APM allows for modeling of any number of finite maneuvers, as well as simple modeling of solar pressure and atmospheric torque; the propagation technique leads to a higher level of effort for software implementation than for the AEM. When inertial reference frames are specified, the APM and AEM are self-contained and do not require additional information. If local orbital reference frames are specified, then an AEM or an APM must be used in conjunction with an OEM and or OPM, respectively.

Multiple APM or AEM messages may be provided in a message exchange session requiring different levels of precise modeling of the spacecraft dynamics to achieve the fidelity requirements. If attitude information for multiple spacecraft is being exchanged, then multiple APM or AEM messages must be used. Full details on the ADM can be found in reference [6]. Currently, ADMs ~~the implementation and use of ADMs is~~ are being ~~considered~~ used to support some mission operations within NASA Goddard Space Flight Center (GSFC), and the European Space Agency (ESA/ESOC).

4.2.4 CONJUNCTION DATA MESSAGE (CDM)

The CDM (reference [13]) specifies a standard message format for exchanging spacecraft conjunction information between providers of conjunction assessment (CA) results and spacecraft owners and operators. CA is the process of predicting conjunction events by comparing observations and orbit determination solutions for more than one space object. The CA results provide the closest point of approach or the local minimum in the difference between the position components of two space object trajectories.

~~Figure 2-4 provides more detail on~~ Within the overall CA processes, ~~. As seen in the figure,~~ the owner/operator of a spacecraft exchanges ODMs with the CA providers/CDM originators. Once the CA process or screening of conjunction events is completed, a CDM gets transmitted to the owner/operator of a spacecraft or group that performs the conjunction assessment risk analysis (CARA).

CARA considerations when assessing the risk include the conjunction geometry, collision probability and sensitivity, evolution and trends, solution quality, as well as mitigation strategies and maneuver evaluation. The assessment of each solution is based on the number of tracks and observations, last observations, sensor geometry and observability, fit span, residual acceptance, WRMS, ballistic coefficient, solar radiation pressure coefficient, energy dissipation rate, radar cross sectional area, force modeling (e.g. solid earth tides), and consistency between solutions. At a minimum, the CDM provides this information to analyze the conjunction event and determine the associated threat to the asset.

In summary, the CDM is the final product of CA results and intended to provide spacecraft owner/operators with information they can use to assess the risk of collision and design collision avoidance maneuvers if necessary. Therefore, the information exchanged within a CDM notifies the spacecraft operator(s) of possible conjunctions with another space object and enables consistent warning by different organizations employing diverse CA techniques. Conjunction information includes data types such as the identity of the affected objects, miss distance, probability of collision (POC), time of closest approach (TCA), closest approach relative position and velocity, Cartesian states of the affected objects at TCA, and a covariance matrix that reflects the uncertainty of the states. Full information describing the conjunction information contained in this message can be found in reference [13].

The JSpOC has fully implemented the CDM in operations. It is their primary means on notifying an operator of a conjunction assessment. It is also used in NASA JSC and GSFC operations.

4.3 NAVIGATION DATA MESSAGES IN DEVELOPMENT

4.3.1 POINTING REQUEST MESSAGE (PRM)

The PRM (reference [14]) will provide a common and standardized format for the exchange of pointing requests between the requestor and spacecraft owner/operators. These pointing requests allow the analysis and execution of changes to the spacecraft attitude or to the orientation of an articulated spacecraft component. The analysis may include operational constraint checks in detail due to the fact that the requestors may not necessarily know the spacecraft attitude. The requestors just want to point the spacecraft and describe their desire through a PRM. Processing of the PRM taking into account the trajectory, attitude, and desired target will determine whether or not the pointing is feasible.

The basic element of all pointing requests is the orientation or attitude of an object or the direction of an axis defined relative to this object at an instant of time. The object can be a spacecraft, or an instrument, sensor, antenna or articulated solar array mounted on a spacecraft. The attitude or axis direction can be defined either relative to inertial space or to another object. PRMs could be transmitted from scientists who operate an onboard instrument to the operator of the spacecraft. These could be referred to as science pointing requests. The following are examples of science pointing requests:

- point the boresight of an instrument onboard a planetary orbiter at the limb of the illuminated section of the planet
- point the onboard high gain antenna of a planetary orbiter at the earth such that the antenna beam passes through the planet’s atmosphere at a given altitude
- perform with the boresight of an instrument a raster scan of a target with a defined size, geometry, number of points and dwell time at each point

Another exchange of PRMs could be between service providers and users of relay communication satellites, e.g., Tracking and Data Relay Satellite System (TDRSS). Examples of such pointing requests are as follows:

- point the relay antenna of spacecraft 1 (which serves as relay) to spacecraft 2 (which uses the relay service) during a given time period
- point the relay antenna of a planetary orbiter to a lander or rover on the surface of the planet during a given time period
- point the relay antenna of a planetary orbiter to a lander on approach to the planet while it passes through a given altitude range.

4.3.2 NAVIGATION HARDWARE MESSAGE (NHM)

The NHM (reference [15]) will specify a standard message format for exchanging spacecraft hardware data that is essential to perform the underlying functions of navigation; such as, but not limited to, orbit and attitude determination, sensor calibrations used for navigation, and maneuver planning, execution and reconstruction. The NHM is intended to provide a uniform format for the transmission of the data from a ground system functional group that receives and unpacks spacecraft telemetry to any spacecraft functional ground that uses it for the navigation processes mentioned earlier.

The NHMs can be exchanged between space agencies or between users within an agency. Such exchanges are used for distributing hardware data output from an originator that receives spacecraft telemetry containing navigation hardware data to users. NHMs also allow for the performance analysis of the navigation hardware and the spacecraft navigation systems (i.e. GN&C and ACS) using the hardware data.

The standardization of hardware data formats facility space agency development of software to perform the navigation processes, as well as the desired monitoring and analysis functions.

Hardware data includes both raw data produced by the hardware and data that results from onboard processing of this raw data. Within navigation, the term “measurement” can be used to include both hardware measurements and processed hardware measurements. Data from payload sensors is excluded unless it is to be used for navigation purposes.

The following are examples of hardware that could be used for navigation:

- Sun Sensors for coarse attitude determination and control.
- Digital Sensors for more precise attitude determination and control.
- Earth Sensors (Horizon Sensors) for Earth pointing control.
- Star sensors that provide the horizontal and vertical positions of the stars in the field of view for fine attitude determination and control.
- Star trackers that provide autonomous attitude solutions (e.g. quaternion) as stars go in and out of, or stay in, the sensor field of view for fine attitude determination and control.
- Inertial Reference Units (IRUs) measuring the body rates or rotation motion of the spacecraft for attitude determination and control.

- Three-Axis Magnetometers for measuring the strength and direction of the magnetic field at a point in space for attitude determination and control, and momentum management.
- Accelerometers (sometimes included with the IRUs) measuring the translation and rotational accelerations of the spacecraft for attitude and orbit control.
- Satellite Global Navigation Systems (GNS) that provide accurate locations and precise time of the spacecraft or receiver determined from a constellation of spacecraft located around the globe for orbit determination and control.
- Thrusters for maneuvering the spacecraft, or orbit and attitude control. The thrusters for attitude control are also known as the reaction control system (RCS) of a spacecraft.
- Reaction wheels for attitude maneuvers and control.

4.3.3 SPACECRAFT MANEUVER MESSAGE (SMM)

The SMM (reference [16]) is foreseen to provide a spacecraft maneuver summary including information related to intentional changes to the spacecraft orbit and attitude states using actuators. The exchange of maneuver data between organizations is critical for the planning and calibration of spacecraft maneuvers.

Maneuver data is usually exchanged between the flight dynamics groups and flight operations teams. The planning information for maneuvers is often provided to a mission or flight operations team by the flight dynamics team for overall mission planning and conversion to spacecraft commands. After the execution of a maneuver, the results of a maneuver reconstruction and calibration are summarized and provided to spacecraft engineers and mission operations to evaluate the spacecraft performance. Examples of typical data included in a maneuver summary are:

- starting time and date (epoch) of the maneuver
- duration or stop time of the maneuver
- magnitude and direction of the Delta-V related to one or more coordinate systems and coordinate frames
- desired change in orbital parameter(s), such as delta apoapsis radius, delta inclination, delta longitude of the ascending node, etc
- desired change in the attitude state; such as delta pitch, roll and yaw, delta quaternion, or absolute target quaternion
- types of propulsion thrusters used and propulsion system configuration
- onboard attitude mode, e.g. Delta-V mode, Delta-H mode or Slew mode
- spacecraft mass at the beginning and end of maneuver or fuel usage
- propulsion system mode, pressure, temperature, duty cycles, thrust scale factor (efficiency)
- pulse width, jet start angle
- necessary info related to other actuators for the maneuver type

This message is not intended to represent non-intentional perturbations such as atmospheric drag, solar radiation pressure, or slews of articulated components mounted onboard the spacecraft. At the moment, this version of the book was written, the SMM was broken out into the maneuver planning message (SPM), maneuver design message (MDM), and maneuver analysis messages

(MAM). The specific messages or data within the SMM are exchanged based on the phase of the overall maneuver concept as illustrated in figure 4-6.

~~4.4 NAVIGATION DATA MESSAGES OVERLAP~~

~~The contents of particular messages sometimes require information that can be transmitted by other standard messages. An example of this is the Spacecraft Maneuver Message (SMM) in which the initial and final orbit states may be required and the same information can be represented in an Orbit Data Message (ODM). The information that is required in separate messages is generally that contained in either the ODM, for the orbit state, or the Attitude Data Message (ADM), for the Attitude state. The need for information in any message that may be represented in a different message results in an overlap of functionality among different messages and the possibility of differences in the representation of the same data in different messages.~~

~~In the following discussion the term “Input Standard” refers to the standard that requires the use of data that is defined in another standard--for example the SMM. “Output Standard” refers to that standard which currently defines the format of the data that will be used in the Input Standard--for example the ODM. The data that is needed by the Input Standard message and which can be represented by an Output Standard message is referred to as “Overlap Data.”~~

~~There is no formal limitation on the format in which Overlap Data may be represented in any standard but it is useful to provide recommendations of how Overlap Data should be treated in new Navigation Messages that contain it. Below is a description of three alternative methods of including data from a message defined by an Output Standard in a new Input Standard message along with a table of the advantages and disadvantages of each method.~~

1. ~~Independent Definition: The format of Overlap Data in the Input Standard message is defined without any reference to the Output Standard. This option essentially removes the use of on Output Standard.~~
2. ~~Common Definition: The Input Standard contains verbatim copies of some or all of the representations of the Overlap Data as it is defined in the Output Standard.~~
3. ~~Reference: The Input Standard includes a method of referring to an independent message that contains the Overlap Data as defined by on Output Standard.~~

~~Alternative~~	**~~Advantages~~**	**~~Disadvantages~~**
~~Independent Definition~~	~~1. Complete freedom to define the data format in a way that could be relevant to its use without having to adhere to a general standard.~~	~~1. Divergence of representations. Because the Input Standard and Output Standard contain independent representations of the same data there may be confusion in users of both message types.~~

~~Common Definition~~	~~1. Easy understanding. The same keywords, tags, and structures in one message are used in another.~~ ~~2. Some freedom. Messages that use overlap data may include only that subset of the definition that are relevant to the main message. For example an OPM may be defined but the portions of the ODM that define an OEM may be omitted.~~	~~1. Maintenance difficulty. Since the same format is defined in different standards, any change in one must be reproduced in the other. The need for coordination of standards means that if any standard is updated, all must be examined for possible update.~~
~~Reference~~	~~1. Minimal impact on the definition of the Input Standard.~~ ~~2. No impact on the definition of the Output standard.~~ ~~3. Simple to define and maintain.~~	~~1. A means must be included for a message using the Input Standard to refer to a message using the Output Standard.~~ ~~2. The existence and validity of the Overlap Data must be built into the software that reads the data defined by the Input Standard. In other words, software that reads the data defined by the Input Standard must include software that reads the data defined by the Output Standard.~~

~~4.5~~4.4 NAVIGATION DATA MESSAGES USE CASE EXAMPLES

This section will provide general examples of NDM use cases as input to and output ~~of~~ from navigation processes. ~~With the exception of the TDM, the exchange of NDMs usually occurs after level-0 processing of spacecraft telemetry, the TDMs are generated during contacts with ground stations that provide tracking services. At the moment this version of the book was written,~~ Note that NDMs ~~did~~ do not cover the format and/or transfer of spacecraft telemetry containing navigation data being downlinked to the ground. Other CCSDS standards provide the data format and transfer of spacecraft telemetry to the ground.

~~Figure 2-4 initially introduced t~~Although the use of ODMs and CDMs in the end-to-end Conjunction Assessment (CA) and Collision Avoidance Risk Assessment (CARA) processes was introduced in previous sections of this document,~~.~~ ~~F~~figure 4-2 below shows a higher level exchange scenario of ODMs and CDMs for these two processes. As seen in the figure, At least two ODMs are used to determine a conjunction, one ODM per object. If there is a high probability of collision, a CDM gets generated and provided to the owners and/or operators of the spacecraft. The CDM will then contain all the conjunction information to assess the risk of the collision and design an avoidance maneuver, if necessary. Therefore, both ODM and CDM exchanges are essential for CA.

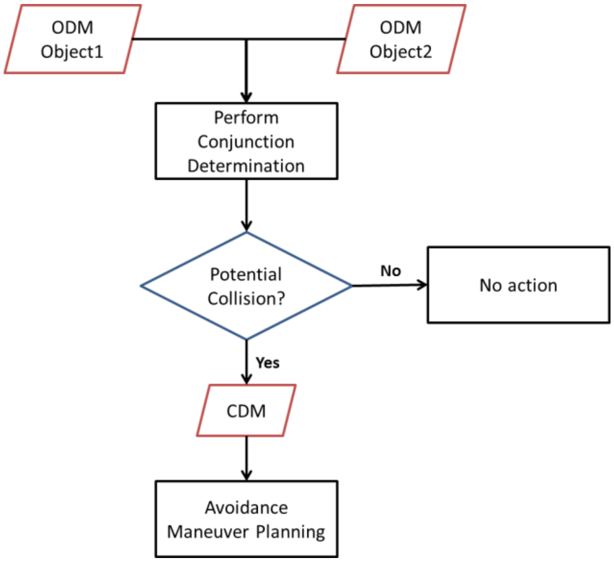


Figure 4-2: ODM and CDM Use Case Example

Two other navigation processes that require exchanges of multiple NDMs are orbit and attitude determination (see section 2.2.3). Orbit determination can be done either with tracking data from a TDM or orbit related hardware data provided in an NHM (e.g. GNS). On the contrary, only NHMs containing attitude sensor data (e.g. quaternion from star sensor, body rates from IRU, etc.) are ~~only~~ necessary for attitude determination. ODMs and ADMs are the spacecraft orbit and attitude state solutions computed during the determination process. Figure 4-3 depicts a diagram of the use of TDMs and NHMs as input for orbit determination, NHM as input for attitude determination, and ODMs and ADMs as the generated output of these two processes, respectively.

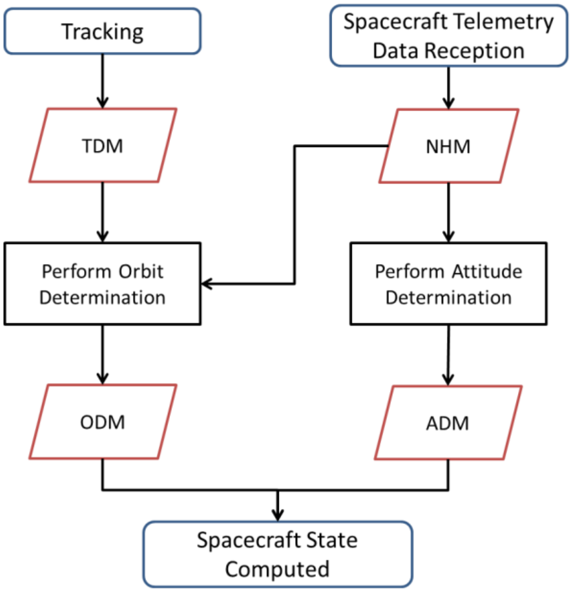


Figure 4-3: TDM, NHM, ODM, and ADM Use Case Example

As opposed to the previous use~~s~~ cases, which had to do with ~~the~~ message exchanges primarily for attitude and orbit determination processes, as well as conjunction assessment, the exchange of other messages are required for spacecraft orbit and attitude maneuver planning, execution, and reconstruction. These messages are the PRM and SMM. The PRM ~~does not~~ may ~~necessarily~~ be used ~~only~~ to request repointing the spacecraft to a different attitude, and ~~it can equally be used~~ for ~~the~~ orientation changes of spacecraft articulated instruments or appendages. As seen in figure 4-4, the PRM ~~gets exchanged~~is provided with the desired instrument pointing~~, which could also be the spacecraft attitude,~~ to the team that performs the maneuver planning and execution to achieve the final orientation.

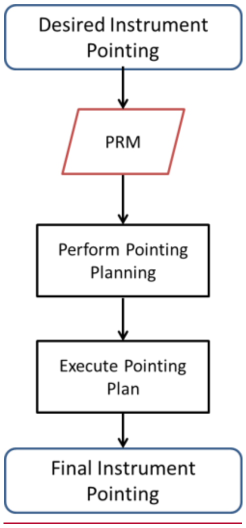


Figure 4-4: PRM Use Case Example

At a very high level, the use or exchange of SMMs is very similar to the PRMs, with the difference that the SMM is the result of the maneuver planning, as opposed to the request for a maneuver (see figure 4-5). Although the SMM is primarily used for execution and reconstruction of orbit maneuvers, in some cases it could be used for attitude maneuver planning and analysis, especially those maneuvers that are executed using thrusters (e.g. momentum control maneuvers for three-axis stabilized spacecraft or spin axis reorientation maneuvers for spin stabilized spacecraft), instead of other types of actuators, such as reaction wheels or magnetic torque bars.

Figure 4-6 shows the use of ODMs, ADMs and specific SMMs as integral parts of a maneuver concept. In this particular case, ODMs and ADMs are the outcome of maneuver reconstruction and analysis. They can also be predictions of orbit and attitude states used for the planning of maneuvers. The maneuver planning message (MPM), maneuver design message (MDM) and maneuver analysis message (MAM) are results obtained from the stages of maneuver planning, execution and reconstruction.

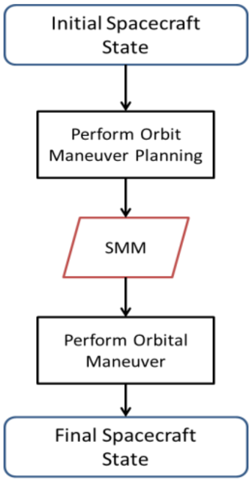


Figure 4-5: SMM Use Case Example

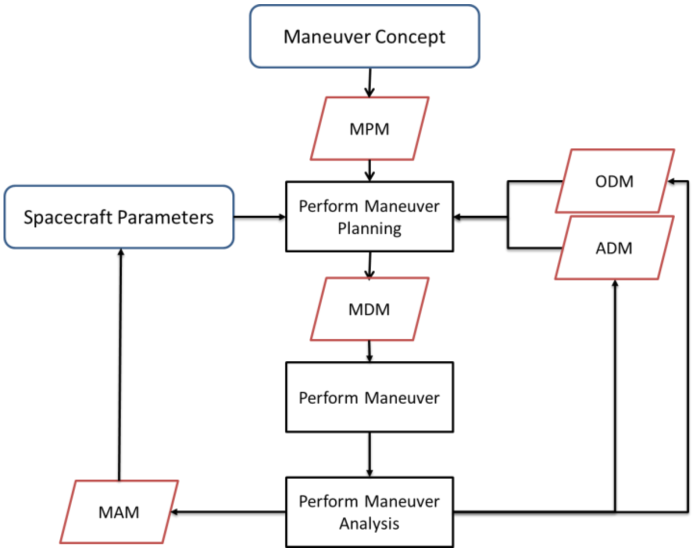


Figure 4-6: SMM, ODM and ADM Use Case Example

~~4.6~~4.5 NAVIGATION DATA MESSAGE FORMATS

The NDMs address the format and the approach for formatting each message. Currently, the NDMs use the KVN (Keyword Value Notation) and XML (Extensible Markup Language) formats. In the KVN format a keyword is specified, followed by an equals sign, followed by a value for the keyword (i.e., “keyword = value”); whereas the XML-based format relies on the document tags that specify how to organize the content. NDM tags in the XML format are usually equivalent to the keywords used in the KVN format.

Even though the KVN format is very useful and common in all computing architectures, the XML-based format has shown to be a better form of specifying ASCII data and a more convenient mechanism for web based architectures. Likewise, XML seems to be well suited to cover all possible needs of the NDMs due to limitations on the KVN format. The advantages, disadvantages and justification for using the XML instead of the KVN text files can be found in reference [11].

XML schemas for all of the Navigation Data Messages are available on the CCSDS SANA registry http://sanaregistry.org/r/ndmxml/ndmxml.html (ref. [20][20]).

~~4.6.1~~4.5.1 NAVIGATION DATA MESSAGE GENERIC STRUCTURE

There is much structural commonality within the suite of NDMs although they each address different information at their core. In general, each of the NDMs has a header and a body consisting of one or more segments, with the exception of the CDM. The body of the CDM consists of one relative metadata and data and two segments. Each segment is made of a metadata and data section. The common technical elements include the specification of time and coordinate systems, as well as the ancillary information regarding the nature or origin of a particular message; also, insofar as is possible, the units for all measurements in the NDMs are drawn from the International System of Units (SI). The information standardized across the NDMs involves the version number of the message, the date and time the message was created, a field for the agency creating the message, spacecraft/vehicle naming, and comments. With the exception of spacecraft/vehicle naming, the latter information that is common to all the NDMs gets included in the message in a section known as the header.

The contents in the metadata section, which follows the header in all NDMs, contain the keywords for the time system and reference frame being used in the message (if applicable), as well as all the information specific to each message. Reference [9] provides the CCSDS standard for the format of date and time regardless of what time system gets used in the NDMs. Volume 2 of the CCSDS Navigation Green Book, reference [17], provides a brief description of current time systems and reference frames used in navigation processes and messages.

ANNEX A

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GLOSSARY

This annex provides a glossary of spacecraft navigation terminology.

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

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

Attitude: Orientation of a given spacecraft reference frame with respect to another defined reference frame.

Bias: A fixed-offset error with respect to the ‘true’ value.

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

Doppler shift: The apparent change in the frequency of a signal caused by the relative motion of the transmitter with respect to the receiver.

Ephemeris: Within the context of this document, it is either a list of position and velocities of a spacecraft’s orbit and/or a list of orientation points of a spacecraft’s attitude as functions 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.

Global Navigation Systems (GNS): navigation systems that use a constellation of spacecraft located around the globe to provide their locations and precise time for navigation purposes.

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

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

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

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

Maneuver: within the context of this document, it is the planned and controlled change in the orbit and/or attitude of a spacecraft.

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, attitude 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 Data Message: A particular arrangement of the navigation data whose structure and content are the subjects of CCSDS Navigation Recommended Standards.

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

Orbit: The trajectory or path followed by a spacecraft and/or celestial body, typically a path around a central celestial body.

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

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 for navigation but not a particularly convenient physical interpretation.

Range: A measured or calculated distance between an observer and a spacecraft.

Range rate: The rate at which the range changes between the satellite and receiver. The range to a satellite changes due to satellite and observer motions. One method of determining range rate is by measuring the Doppler shift of the satellite beacon carrier.

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 such as landers or rovers.

Trajectory: The path followed by a spacecraft and/or celestial body in space.

Tracking Station: Space or ground-based facility used to track and/or communicate with the spacecraft. Some agencies have multiple stations operated by a central entity, referred to as the complex.

ANNEX B

ABBREVIATIONS AND ACRONYMS

ACS	Attitude Control System
ADM	Attitude Data Message
AEM	Attitude Ephemeris Message
APM	Attitude Parameter Message
CA	Conjunction Assessment
CARA	Collision Avoidance Risk Assessment
CCSDS	Consultative Committee for Space Data Systems
CDM	Conjunction Data Message
CNES	Centre National d’Etudes Spatiales
CSTS	Cross Support Transfer Services
DLR	Deutsches Zentrum fur Luft-und Raumfahrt
DOR	Differential One-way Range
DSN	Deep Space Network
ESA	European Space Agency
ESOC	European Space Operations Centre
FDC	Flight Dynamics Center
FTP	File Transfer Protocol
GNC (GN&C)	Guidance, Navigation and Control
GNS	Global Navigation System
GSFC	NASA Goddard Space Flight Center
ICD	Interface Control Document
JAXA	Japan Aerospace Exploration Agency

JPL	Jet Propulsion Laboratory
JSpOC	Joint Space Operations Center
KVN	Keyword Value Notation
NASA	National Aeronautics and Space Administration
NDM	Navigation Data Message
NHM	Navigation Hardware Message
NORAD	North American Aerospace Defense Command
NWG	Navigation Working Group.
OC	Operations Center
ODM	Orbit Data Message
OEM	Orbit Ephemeris Message
OMM	Orbit Mean-Elements Message
OPM	Orbit Parameter Message
POC	Probability of Collision
PRM	Pointing Request Message
SFTP	Secure File Transfer Protocol
SI	International System of Units
SMM	Spacecraft Maneuver Message
TCA	Time of Closest Approach
TDM	Tracking Data Message
TDRSS	Tracking and Data Relay Satellite System
TLE	Two-Line Elements
WG	Working Group
XML	Extensible Markup Language