The Consultative Committee for Space Data Systems

Report Concerning Space Data System Standards

NAVIGATION DATA— DEFINITIONS AND CONVENTIONS

INFORMATIONAL REPORT VOLUME 1

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GREEN BOOK

September 2014~~2~~

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FOREWORD

This CCSDS report, *Navigation Data – Definitions and Conventions*, ~~has been divided into two separate volumes. The Green Book~~ contains ~~the~~ 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CCSDS 500.0-G-1	Navigation Data—Definitions and Conventions	June 2001	Original issue, superseded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 NAV Green Book volume 1 based on discussions taking place at previous bi-annual CCSDS technical meetings.

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1 INTRODUCTION

1.1 PURPOSE AND SCOPE

Spacecraft navigation data is exchanged between ~~Consultative Committee for Space Data Systems (CCSDS) Member Agencies~~ 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 data messages defined in diverse navigation data messages (see section 3~~3.3.2~~). 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 applies to navigation data exchanged in the following cases:~~

~~– flight-to-ground;~~

~~– ground-to-flight;~~

~~– ground-to-ground.;~~

~~– flight-to-flight.~~

This document serves as a guideline for the development of ~~compatible, inter-Agency~~ 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 **Error! Reference source not found.**~~2~~ provides a brief overview of spacecraft navigation process and flight dynamics, and provides the definition of terms relevant to this process. It also provides an overview of the physical assets of flight dynamics.

c) Section 2~~3~~ provides foundational information regarding the ~~navigation message~~navigation data messagenavigation data message exchange architecture (definitions, paradigms, etc.). It also introduces the current recommended and envisioned CCSDS standards for the exchange of navigation data.

d) Annexes ANNEX A~~A~~ and ANNEX B~~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.

[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.

~~*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.~~

[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.

[10] David Vallado, et al. "Revisiting Spacetrack Report #3." In *Preceedings of the AIAA/AAS Astrodynamics Specialist Conference and Exhibit* (21-24 August 26, 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.* 3rd Edition. Space Technology Library, 2007.

~~[13] *Navigation Data – Definitions and Conventions*. CCSDS Green Book. Issue 4, Volume 2. (This document is in progress)~~

[13~~14~~] *Conjunction Data Message*, Proposed for Space Data System Standards, CCSDS 508.0-B~~R~~-1. ~~Red Book~~Blue Book. ~~-~~Issue 1. Washington, D.C.: CCSDS, ~~March~~ June 201~~2~~3.

[14~~15~~] ~~*Spacecraft Perturbation Message*. Proposed for Space Data System Standards, CCSDS 507.0-W-n. White Book. Issue n. Washington, D.C: CCSDS, April 2010.~~

[15~~16~~] *Pointing Request Message*. Proposed Draft Recommended Standard for Space Data System Standards, CCSDS 509.0-W-n. White Book. Issue n. Washington D.C: CCSDS, August 2012.

[16~~17~~] *Navigation Hardware Message*. Proposed Draft Recommended Standard for Space Data System Standards, CCSDS 510.0-W-n. White Book. Issue n. Washington D.C: CCSDS, July 2012.

[17~~18~~] *Spacecraft Maneuver Message*. Proposed Draft Recommended Standard for Space Data System Standards, CCSDS 511.0-W-n. White Book. Issue n. Washington D.C: CCSDS, April 2012.

[18~~19~~] *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)

[19~~13~~] *Navigation Data – Definitions and Conventions*. CCSDS Green Book. Issue 4, Volume 2. (This document is in progress)

[20~~2~~] *CCSDS Publications Manual.* CCSDS A20.0-Y-4. Yellow Book. Issue 4. Washington D.C.: CCSDS, April 2014.

[21~~2~~] *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.

[22~~2~~] *CCSDS Implementation Conformance Statements.* Yellow Book. Issue 1. Washington D.C.: CCSDS, April 2014.

[23~~2~~] CCSDS Publications website at http://public.ccsds.org/publications/default.aspx.

2 ~~NAVIGATION MESSAGE~~NAVIGATION DATA MESSAGENAVIGATION DATA MESSAGE EXCHANGE FRAMEWORK

2.1 GENERAL

This section describes the elements, characteristics, and major groupings of ~~navigation message~~navigation data messagenavigation data message exchanges~~, as well as general information about the data types involved in these exchanges. This section also provides an overview of the current and envisioned CCSDS Navigation Data Messages~~.

2.2 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.

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 Message~~Navigation data messageNavigation data 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 message~~navigation data

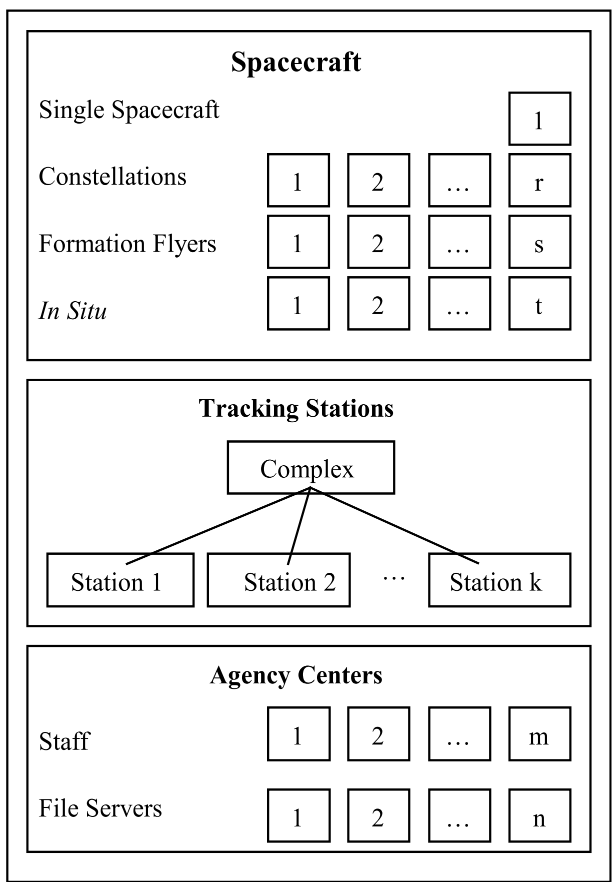


Figure 2-1: Participant Categories

messagenavigation data messages. Possible participants can be arranged into three categories, as depicted in figure 2-13-1.

Spacecraft: One type of participant (see section 2.3.2.1) defined as a single vehicle orbiting a celestial body or point, or as part of a set, such as constellations or formations. Navigation messageNavigation data messageNavigation data messages to/from these participants are exchanged digitally, and are usually optimized in response to bandwidth, power, or message format constraints.

Tracking Station: One type of participant (see section **Error! Reference source not found.**2.3.2.2).

Agency Center: One type of participant (see section **Error! Reference source not found.**2.3.2.3). An Agency Center includes the facilities, such as the MOC Operations Center (OC) and/or a Flight Dynamics Center (FDC), used for executing commands to the spacecraft, as well as for monitoring telemetry, tracking, flight dynamics, and other engineering parameters. 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 messagenavigation data messagenavigation data messages between participants.

2.3 NAVIGATION DATA AND NAVIGATION MESSAGENAVIGATION DATA MESSAGE

Figure 2-23-2 describes the roles of navigation data versus navigation messagenavigation data messages.

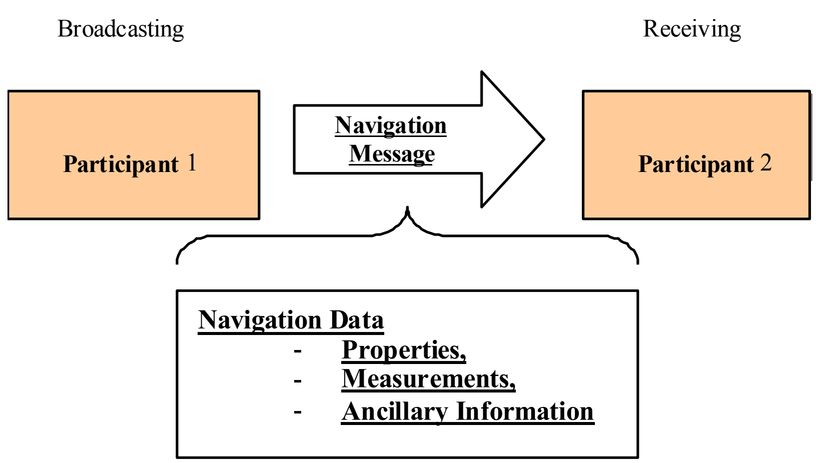


Figure 2-2: Navigation MessageNavigation data message Exchange Definitions

Ideally, every CCSDS Recommended Standard related to flight dynamics should apply to some type of navigation messagenavigation data message exchange described 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. Subsection 33.3.2 introduces the current and proposed Recommended Standards for the exchange of navigation data. 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. The following are the current navigation data 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 and flight-to-ground at the time this document was written.

2.3.1 NAVIGATION DATA

This section provides a description of the data types and characteristics of navigation messagenavigation data message exchanges.

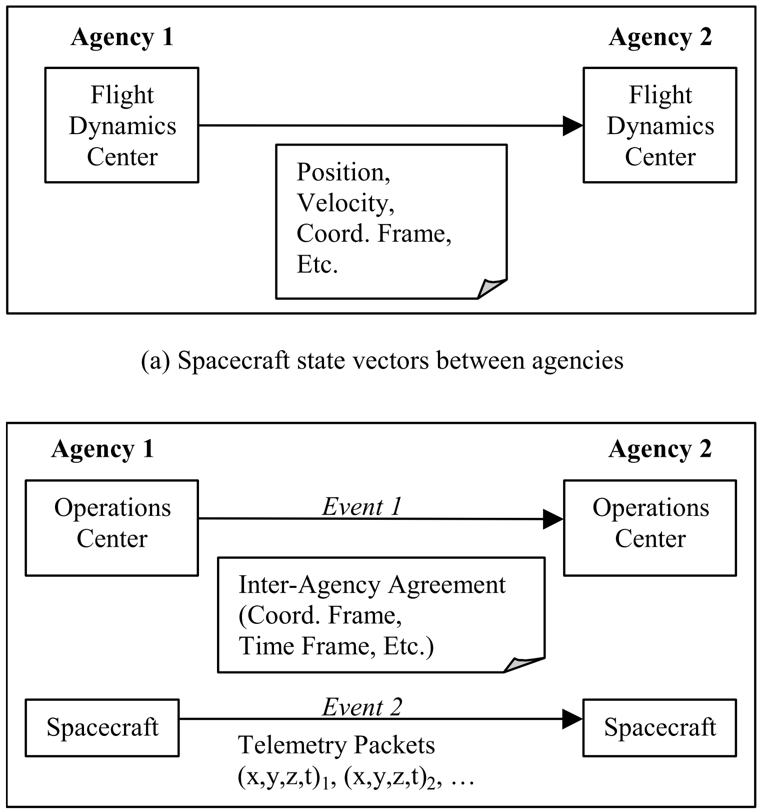
2.3.1.1 NAVIGATION EXCHANGE DATA TYPES

Volume 2 of the CCSDS Navigation Green Book, reference [45], provides a description of ancillary data, measurements and properties currently exchanged. For current and future Recommended Standards, it is preferable to use the units from the tables in each of the standards; in most cases, the International System of units (SI) will be used.

2.3.1.22.3.1 NAVIGATION DATA EXCHANGE CHARACTERISTICS

This Report section describes a framework for the exchange of messages between any two types of participants (see subsection 2.23.2 and figure 2-13-1). 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 (see reference [1819, 13]) 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, 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 2-33-3.



(b) Spacecraft relative position information between spacecraft

Figure 2-3: Examples of Navigation Sessions

b) **~~Navigation message~~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 2-33-3, 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 [1819, 13].)

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 2-43-4).

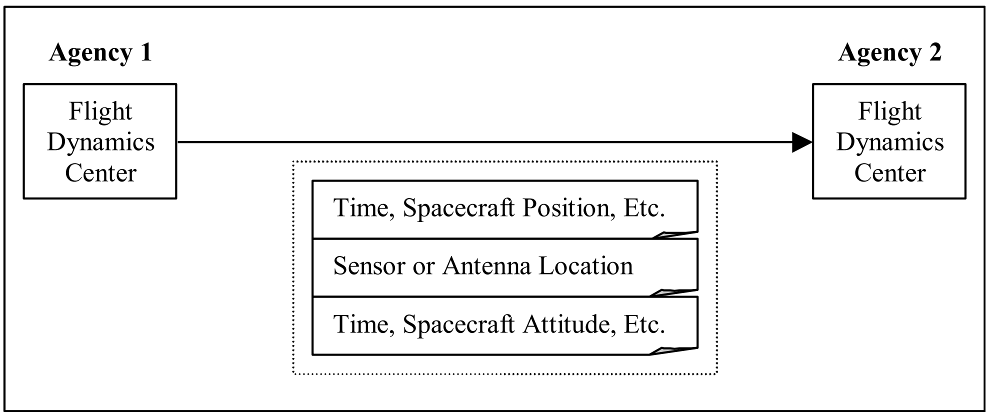


Figure 2-4: Navigation Session Using Multiple CCSDS Recommended Standards

~~2.3.2~~3 CCSDS NAVIGATION DATA MESSAGES

3.1 GENERAL

This section provides an overview of the current and envisioned CCSDS Navigation Data Messages.

The ~~definition~~ 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 essential 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 ~~and benefits~~ interoperability between space agencies, where ~~flight dynamics or~~ 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 ~~potentially enable~~ facilitate a level of automation within the ground system.

There are currently ~~three~~ four ~~(43)~~ published standards for the exchange of spacecraft navigation data: ~~T~~the Attitude Data Message (ADM), Orbit Data Message (ODM), ~~and~~ 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, ~~and~~ TDM, and CDM are specified in references [6], [7], ~~and~~ [8], and [13~~14~~] respectively. There are several navigation data standards being developed and envisioned to fulfill and facilitate the execution and implementation of other ~~flight dynamics~~ navigation functions ~~within the navigation process~~. Such standards under development are: ~~Conjunction Data Message (CDM, [14]),~~ Pointing Request Message (PRM, [15~~16~~]), Navigation Hardware Message (NHM, [16~~17~~]), and Spacecraft Maneuver Message (SMM, [17~~18~~]). The published standards are reviewed ~~and possibly updated~~ every 5 years ~~according to CCSDS processes [1]~~. The three actions to be considered in the five year review are “reconfirm”, “retire”, or “revise”, as applicable (see reference [1]). ~~Reconfirm, retire, or revise. (reference to the CCDSD Organization and Procedures).~~

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 ~~orbit, attitude and tracking~~ common ~~flight dynamics and/or~~ navigation processes. 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 ~~the generation and ingest of input and output navigation data products of navigation processes in an automated manner~~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 ~~or by following a CCSDS standard on transmission~~. The message transmission could be based on a CCSDS data transfer protocol, file~~d~~ 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 [20]).

Figure 3-1~~Figure 3-5~~ illustrates an example of how all the messages ~~are intended to~~ could be utilized in a mission operations environment. ~~Although this document applies to navigation data exchange between two or several participants; whether it is flight-to-ground, ground-to-flight, ground-to-ground, and flight-to-flight (see sections 3.2and 3.3), the intent in figure 3-5 is to~~ This figure illustrates the navigation data exchange and the direction of the information flow between the various functions that make up typical navigation operations. ~~once the data gets downlinked from the spacecraft to the ground and processed by the Telemetry, Tracking and Commanding (TT&C) system. As seen in the figure, the navigation data messages are transferred between multiple functions within the same agency or residing in separate space agencies to perform the flight dynamics functions required to support mission operations. The data format being communicated between the spacecraft and tracking sessions are controlled by other CCSDS standards and are outside of the CCSDS Navigation Domain.~~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 an overview of the CCSDS navigation standards that have been published and are under development.

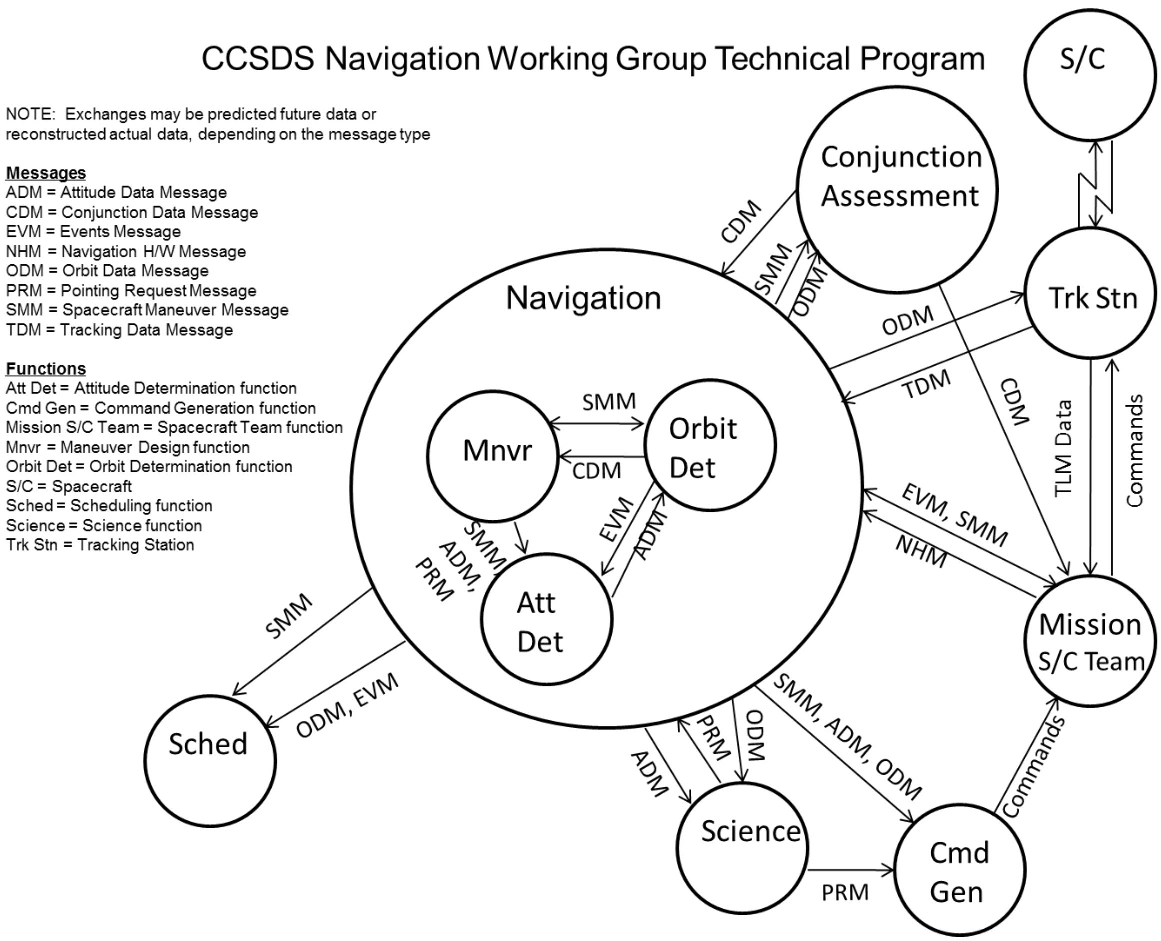


Figure 3-~~15~~: Example of NDM Exchange and Direction of the Information Flow in a Mission Operarations Environment ~~(note: excludes flight-to-flight)~~

~~2.3.2.1~~3.2 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 the availability issues with their primary antennas.

The TDM standard is designed for the inter-agency exchange of the following tracking data types:

- Ground based radio metric tracking data types (see volume 2 of the Navigation Green Book, reference [18~~19~~, 13]):
  - 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
- 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 ~~could~~ 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.

~~2.3.2.2~~3.3 ORBIT DATA MESSAGES (ODM)

The ODM (reference [7]) represents the orbit data for a single spacecraft and specifies the formats for use in transferring ~~the~~ orbit information between space agencies and commercial or government spacecraft operators in a clear, concise and compact manner. The ODM is divided into three separate messages that serve different purposes: ~~T~~the Orbit Parameter Message (OPM), the Orbit Mean-Elements Message (OMM), and the Orbit Ephemeris Message (OEM). ~~These three messages represent the orbit data for a single spacecraft. The ODM standard specifies the formats for use in transferring the orbit information between space agencies and commercial or government spacecraft operators in a clear, concise and compact manner. Even though t~~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].

~~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 files must be used. A difference in the exchange scenario is that the OPM and OMM do not accommodate high-fidelity dynamic modeling, as opposed to whereas the OEM does.~~

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 ~~require~~ is designed for higher fidelity dynamic modeling. However, the OPM ~~is the only ODM that~~ allows the user to specify parameters ~~for information~~ related to finite and instantaneous maneuvers, and provides simple parameters ~~and allows~~ 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 ~~required~~ a higher level of fidelity in the dynamic modeling.

One advantage 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 files must be used. 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 European Space Operations Centre (ESOC)~~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 ~~European Space Operations Centre (~~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),

~~2.3.2.3~~3.4 ATTITUDE DATA MESSAGES (ADM)

The ~~intent~~ purpose of the ADM recommended standard (reference [6]) is to ~~discuss how the parameterization of the attitude is represented for proper interpretation and 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). 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 files must be used. Both ADMs provide the proper parameters for both spin-stabilized and three-axis stabilized spacecraft. Each parameterization requires specification of different quantities, thus requiring a different set of keywords. Full details on the ADM can be found in reference [6].

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 or 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 attitude ephemeris, and 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.

Even though 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 files must be used. Full details on the ADM can be found in reference [6].

Currently, the implementation and use of ADMs is being considered to support mission operations within NASA Goddard Space Flight Center (GSFC).

~~2.3.2.4~~3.5 CONJUNCTION DATA MESSAGE (CDM)

The CDM (reference [13~~14~~]) ~~will specify~~specifies the format of a standard message for exchanging spacecraft conjunction information between ~~data~~ providers of conjunction assessments (CA) and spacecraft owners and operators. The information exchanged within a CDM notifies the spacecraft operator(s) of possible conjunctions ~~between objects in space~~ 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~~14~~].

~~2.3.2.5~~3.6 POINTING REQUEST MESSAGE (PRM)

The PRM (reference [15~~16~~]) will allow ~~the exchange of information related to pointing~~ the analysis of requests ~~of~~ to point a spacecraft between space agencies and operators. Pointing requests include changes of the spacecraft attitude or to the orientation of an articulated spacecraft component.

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 ~~between~~ 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.

~~2.3.2.6~~3.7 NAVIGATION HARDWARE MESSAGE (NHM)

The NHM (reference [16~~17~~]) will specify a standard message format for exchanging spacecraft hardware data that is used for navigation 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. Navigation hardware data is used for ground orbit and attitude determination, to monitor and analyze performance of the hardware, perform calibration of the hardware, as well as to validate the spacecraft navigation systems (GN&C/ACS) performance. Hardware data includes both raw data produced by the hardware and data that results from onboard processing of this raw data. Data from payload sensors is excluded unless it is to be used for navigation purposes.

~~2.3.2.7~~3.8 SPACECRAFT MANEUVER MESSAGE (SMM)

The SMM (reference [17~~18~~]) is foreseen to provide a spacecraft maneuver summary including information related to intentional changes to the spacecraft orbit and attitude states using actuators. The frequent 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 several 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.

~~2.3.2.8~~3.9 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. 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, the 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 ~~ASCII~~ KVN text files can be found in reference [11].

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.

~~2.3.2.9~~3.9.1 NAVIGATION DATA MESSAGE GENERIC STRUCTURE

There is a lot in common with 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. 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 [18~~19~~, 13], provides a brief description of current time systems and reference frames used in navigation processes and messages.

ANNEX A

GLOSSARY

This annex provides a glossary of spacecraft navigation terminology.

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

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

~~**Apoapsis:** 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.~~

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

Bias: A fixed-offset error ~~of~~ with respect to the 'true' value.

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

Doppler shift: 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.

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**~~**Navigation data message**: A particular arrangement of the navigation data whose structure and content are the subjects of CCSDS ~~flight dynamics~~Navigation Recommended Standards.

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

Orbit: The trajectory or path followed by a celestial body in space.

~~**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 message~~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. Range rate is determined by measuring the Doppler shift of the satellite beacon carrier.

~~**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.~~

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: Space or ~~G~~ground-based facility used to ~~monitor the location of~~ 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
~~ACS~~	~~Attitude Control System~~
CA	Conjunction Assessment
CCSDS	Consultative Committee for Space Data Systems
CDM	Conjunction Data Message
CNES	Centre National d'Etudes Spatiales
DLR	Deutsches Zentrum fur Luft-und Raumfahrt
DSN	Deep Space Network
ESA	European Space Agency
ESOC	European Space Operations Centre
FDC	Flight Dynamics Center
FTP	File Transfer Protocol
GLONASS	Global Navigation Satellite System
GNC (GN&C)	Guidance, Navigation and Control
GNS	Global Navigation System
GPS	Global Positioning System
GSFC	NASA Goddard Space Flight Center
ICD	Interface Control Document
JAXA	Japan Aerospace Exploration Agency

JPL	Jet Propulsion Laboratory
KVN	Keyword Value Notation
NASA	National Aeronautics and Space Administration
NAVSTAR	Navigation Satellite Timing and Ranging System
NDM	Navigation Data Message
NHM	Navigation Hardware Message
~~NASA~~	~~National Aeronautics and Space Administration~~
OC	Operations Center
ODM	Orbit Data Message
OEM	Orbit Ephemeris Message
OMM	Orbit Mean-Elements Message
OPM	Orbit Parameter Message
POC	Probability of ~~Collition~~Collision
PRM	Pointing Request Message
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
XML	Extensible Markup Language