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CCSDS

The Consultative Committee for Space Data Systems

Report Concerning Space Data System Standards

NAVIGATION DATA MESSAGES OVERVIEW

INFORMATIONAL REPORT

CCSDS 500.2-G-1

GREEN BOOK

December 2015



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FOREWORD

This CCSDS report, *Navigation Data Messages Overview*, contains background and explanatory material to supplement the CCSDS Recommended Standards for spacecraft navigation data. The document 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.

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CONTENTS

<u>Section</u>	<u>Page</u>
1 INTRODUCTION.....	1-1
1.1 PURPOSE AND SCOPE.....	1-1
1.2 APPLICABILITY.....	1-1
1.3 STRUCTURE OF THIS DOCUMENT.....	1-1
1.4 REFERENCES.....	1-2
2 SCOPE OF NAVIGATION.....	2-1
2.1 OVERVIEW.....	2-1
2.2 NAVIGATION.....	2-1
3 NAVIGATION DATA MESSAGE EXCHANGE FRAMEWORK.....	3-1
3.1 OVERVIEW.....	3-1
3.2 TERMS AND DEFINITIONS.....	3-1
3.3 NAVIGATION DATA AND NAVIGATION DATA MESSAGES.....	3-2
4 CCSDS NAVIGATION DATA MESSAGES.....	4-1
4.1 GENERAL.....	4-1
4.2 PUBLISHED NAVIGATION DATA MESSAGES.....	4-2
4.3 NAVIGATION DATA MESSAGES IN DEVELOPMENT.....	4-7
4.4 NAVIGATION DATA MESSAGES USE CASE EXAMPLES.....	4-10
4.5 NAVIGATION DATA MESSAGE FORMATS.....	4-15
ANNEX A GLOSSARY.....	A-1
ANNEX B ABBREVIATIONS AND ACRONYMS.....	B-1

Figure

2-1 Navigation Estimation Process.....	2-3
3-1 Participant Categories.....	3-1
3-2 Navigation Data Message Exchange Definitions.....	3-2
3-3 Examples of Navigation Sessions.....	3-4
3-4 Navigation Session Using Multiple CCSDS Recommended Standards.....	3-5
4-1 ODM and CDM Use Case Example.....	4-11
4-2 TDM, NHM, ODM, and ADM Use Case Example.....	4-12
4-3 PRM Use Case Example.....	4-13
4-4 SMM Use Case Example.....	4-14
4-5 SMM, ODM, and ADM Use Case Example.....	4-14

1 INTRODUCTION

1.1 PURPOSE AND SCOPE

Spacecraft navigation data is exchanged during cross support of space missions. The purpose 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. This document 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. Reference [17] 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 the 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 this document and reference [17] 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 THIS DOCUMENT

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

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.

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

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

Annexes A and B constitute a glossary of terms and a listing of acronyms, respectively.

1.4 REFERENCES

The following publications are referenced in this document. At the time of publication, the editions indicated were valid. All publications are subject to revision, and users of this document are encouraged to investigate the possibility of applying the most recent editions of the publications indicated below. The CCSDS Secretariat maintains a register of currently valid CCSDS publications.

- [1] *Organization and Processes for the Consultative Committee for Space Data Systems*. Issue 4. CCSDS Record (Yellow Book), CCSDS A02.1-Y-4. Washington, D.C.: CCSDS, April 2014.
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- [4] William G. Melbourne. "Navigation between the Planets." *Scientific American* 234, no. 6 (June 1976): 58–64, 68–74.
- [5] Catherine L. Thornton and James S. Border. *Radiometric Tracking Techniques for Deep-Space Navigation*. JPL Deep-Space Communications and Navigation Series. Joseph H. Yuen, Series Editor. Hoboken, N.J.: Wiley, 2003.
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- [7] *Orbit Data Messages*. Issue 2. Recommendation for Space Data System Standards (Blue Book), CCSDS 502.0-B-2. Washington, D.C.: CCSDS, November 2009.
- [8] *Tracking Data Message*. Issue 1. Recommendation for Space Data System Standards (Blue Book), CCSDS 503.0-B-1. Washington, D.C.: CCSDS, November 2007.

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- [10] David A. Vallado, et al. "Revisiting Spacetrack Report #3." In *Proceedings of the AIAA/AAS Astrodynamics Specialist Conference and Exhibit*. AIAA 2006-6753. Reston, Virginia: AIAA, 2006.
- [11] *XML Specification for Navigation Data Messages*. Issue 1. Recommendation for Space Data System Standards (Blue Book), CCSDS 505.0-B-1. Washington, D.C.: CCSDS, December 2010.
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- [14] *Pointing Request Message*. Under development.
- [15] *Navigation Hardware Message*. Under development.
- [16] *Spacecraft Maneuver Message*. Under development.
- [17] *Navigation Data—Definitions and Conventions*. Issue 3. Report Concerning Space Data System Standards (Green Book), CCSDS 500.0-G-3. Washington, D.C.: CCSDS, May 2010.
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2 SCOPE OF NAVIGATION

2.1 OVERVIEW

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** is 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 that terms relevant to this process be clearly defined. These terms are as follows:

Orbit is the translational motion of a spacecraft around a large central body, resulting from 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 references [17] and [12]. There are other types of orbits that are affected by the gravity pull of two larger masses, e.g., 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 axes in inertial space to the spacecraft body frame. (See references [17] and [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 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 discussion of guidance and control is outside of the scope of this Report.

2.2.3 SPACECRAFT NAVIGATION PROCESSES

In addition to orbit and attitude determination introduced in 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.

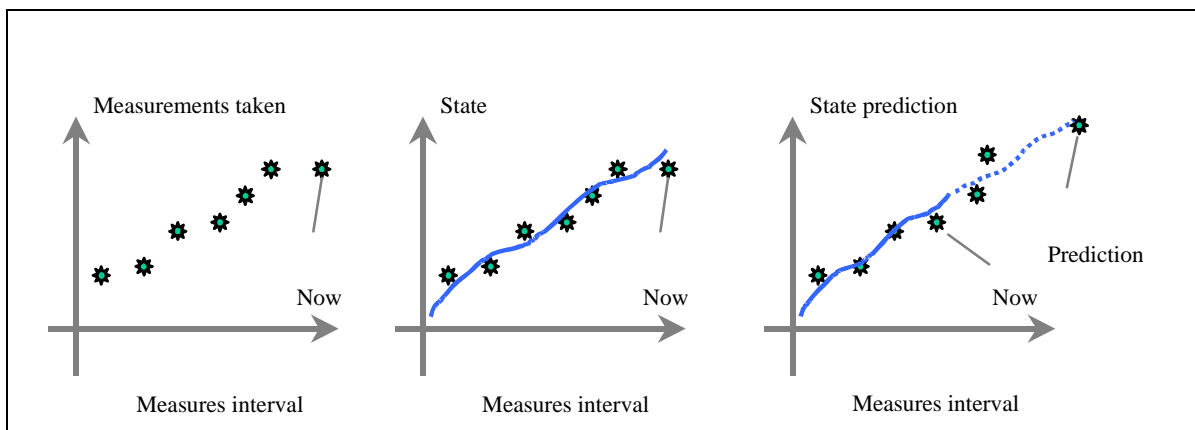


Figure 2-1: Navigation Estimation Process

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. 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.

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. The Orbit Data Message (4.2.2) and Conjunction Data Message (see 4.2.4) 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:

- a) A set of measurements is acquired.
- b) 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.
- c) The solution state may be used in the model to predict the future state.
- d) If necessary, the spacecraft state is altered at some future time:
 - 1) 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'.
 - 2) 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'.

3 NAVIGATION DATA MESSAGE EXCHANGE FRAMEWORK

3.1 OVERVIEW

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.

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 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 data messages. Possible participants can be arranged into three categories, as depicted in figure 3-1.

spacecraft: Participant type consisting of a single vehicle orbiting a celestial body or

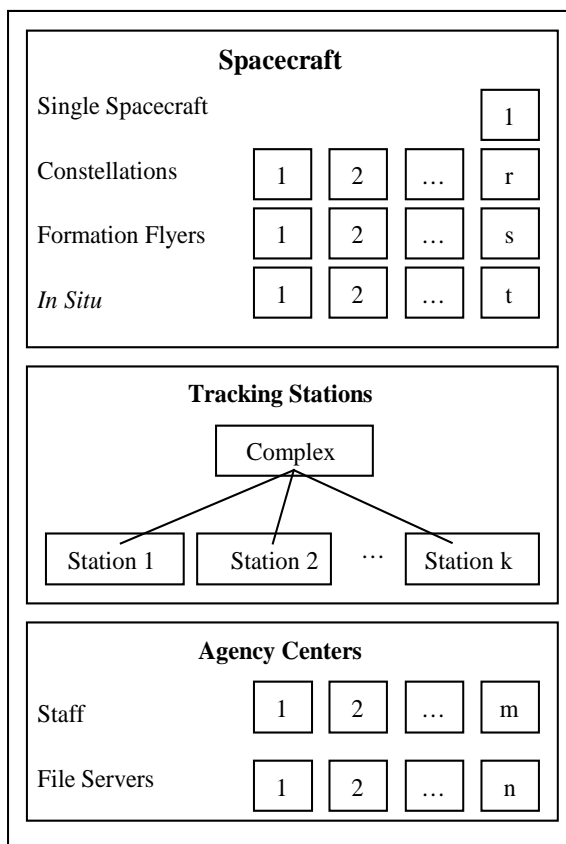


Figure 3-1: Participant Categories

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.

ground stations and space networks: Participant types that 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 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.

agency center: Participant type that 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

3.3.1 GENERAL

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

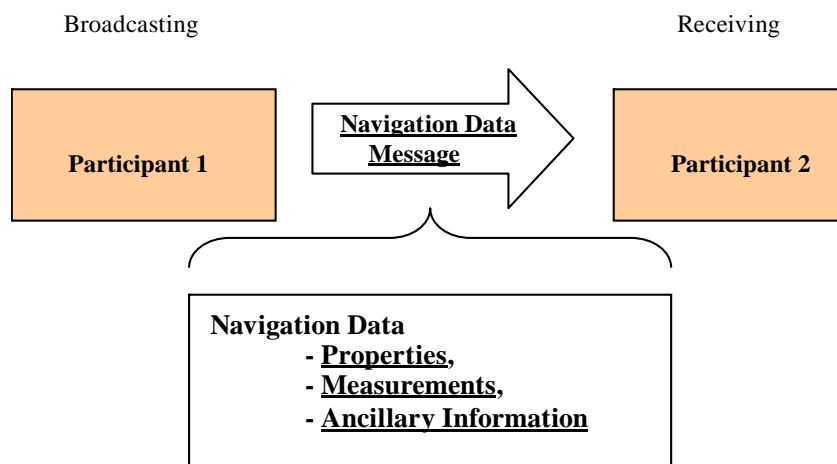


Figure 3-2: Navigation Data Message Exchange Definitions

Ideally, every navigation data message exchange will be covered by a CCSDS Recommended Standard related to flight dynamics. However, the completed CCSDS Recommended Standards cannot presently cover the entire range of exchanges. Section 4 introduces the current and proposed Recommended Standards for the exchange of navigation data. Agencies can benefit by promoting some of these formats at the present time. The following are the current exchange scenarios within the scope of CCSDS:

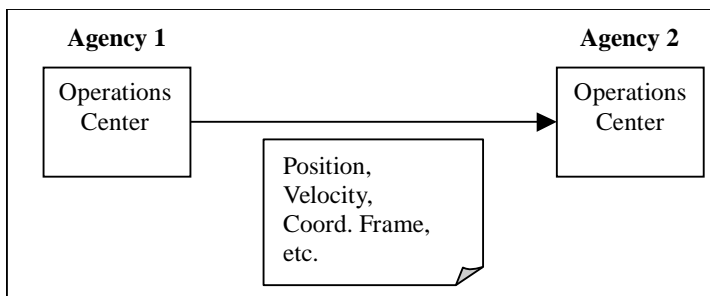
- **Ground-to-ground** exchanges are defined as the set of exchanges between any two non-spacecraft participants.
- **Ground-to-flight** and **flight-to-ground** exchanges are defined as the set of exchanges between any one spacecraft participant and a non-spacecraft participant.
- **Flight-to-flight**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

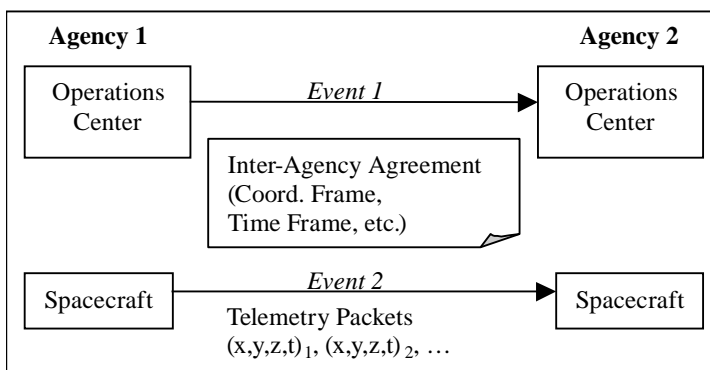
3.3.2 NAVIGATION DATA EXCHANGE CHARACTERISTICS

This subsection describes a framework for the exchange of messages between any two types of participants (see 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:

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 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

- a) **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 reference [17].)
- b) **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 comes from different Recommended Standards, the information itself can be sent at one time or in separate events (see figure 3-4).

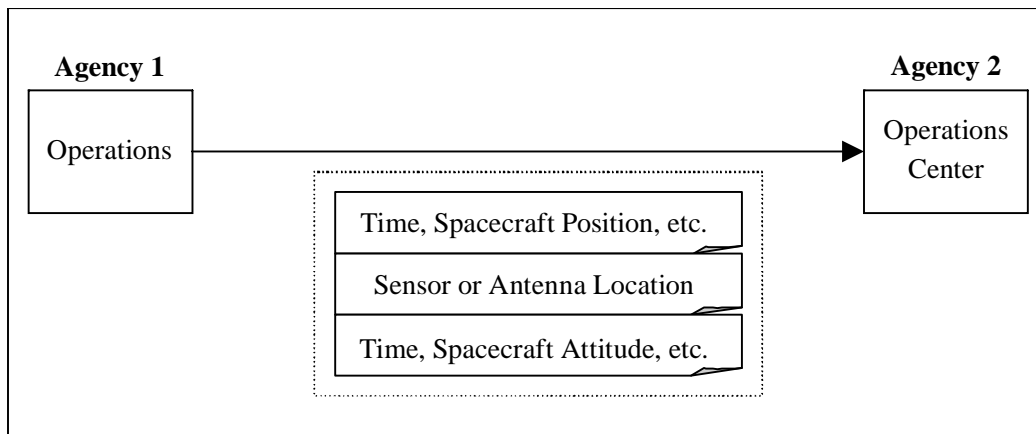


Figure 3-4: Navigation Session Using Multiple CCSDS Recommended Standards

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 described 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 is provided in the subsequent subsections. The details of the ADM, ODM, TDM, and CDM are specified in references [7], [8], and [13] respectively. The published standards are reviewed every five 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—reference [14]), Navigation Hardware Message (NHM—reference [15]), and Spacecraft Maneuver Message (SMM—reference [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 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 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 state 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 Web site (reference [20]). The following is a brief summary of all NDMs described in 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.

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

4.2 PUBLISHED NAVIGATION DATA MESSAGES

4.2.1 TRACKING DATA MESSAGE

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 a 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 reference [17]):

- ground-based radio metric tracking data types:
 - uplink and downlink (transmitted/received) frequencies;
 - range;
 - Delta Differential One-way Ranging) (Delta-DOR);
 - 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 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

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, commercial spacecraft operators, 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 a 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 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).

One 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 6×6 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.

If ephemeris information of multiple spacecraft is being exchanged, then multiple OPM, OMM, or OEM messages must be used (these could be packaged in a single file, if desired).

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 NASA/JPL Navigation, Deutsches Zentrum für 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, 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 five-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

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 need to 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 are being 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

The CDM (reference [13]) specifies a standard message format for exchanging spacecraft conjunction information between providers of 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. Within the overall CA processes, 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 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, Weighted Root-Mean Square (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

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 because of 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

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 facilitates 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

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 time of this Report, the SMM has been broken out into the Maneuver Planning Message (MPM), Maneuver Design Message (MDM), and Maneuver Analysis Message (MAM). The specific messages or data within the SMM are exchanged based on the phase of the overall maneuver concept as illustrated in figure 4-1.

4.4 NAVIGATION DATA MESSAGES USE CASE EXAMPLES

This subsection provides general examples of NDM use cases as input to and output from navigation processes. NDMs 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.

Although the use of ODMs and CDMs in the end-to-end CA and CARA processes was introduced in previous sections of this document, figure 4-1 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.

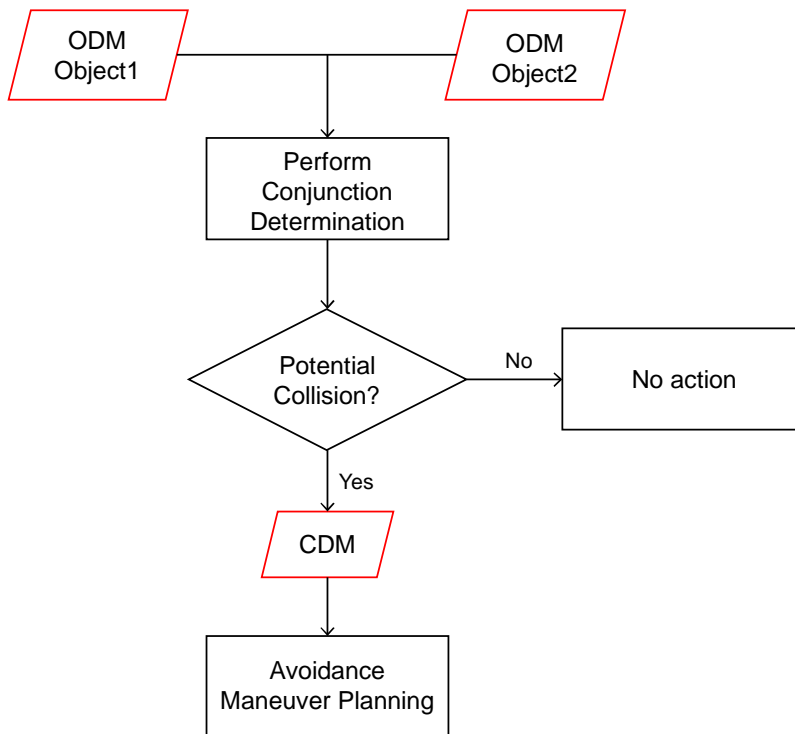


Figure 4-1: ODM and CDM Use Case Example

Two other navigation processes that require exchanges of multiple NDMs are orbit and attitude determination (see 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 necessary for attitude determination. ODMs and ADMs are the spacecraft orbit and attitude state solutions computed during the determination process. Figure 4-2 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.

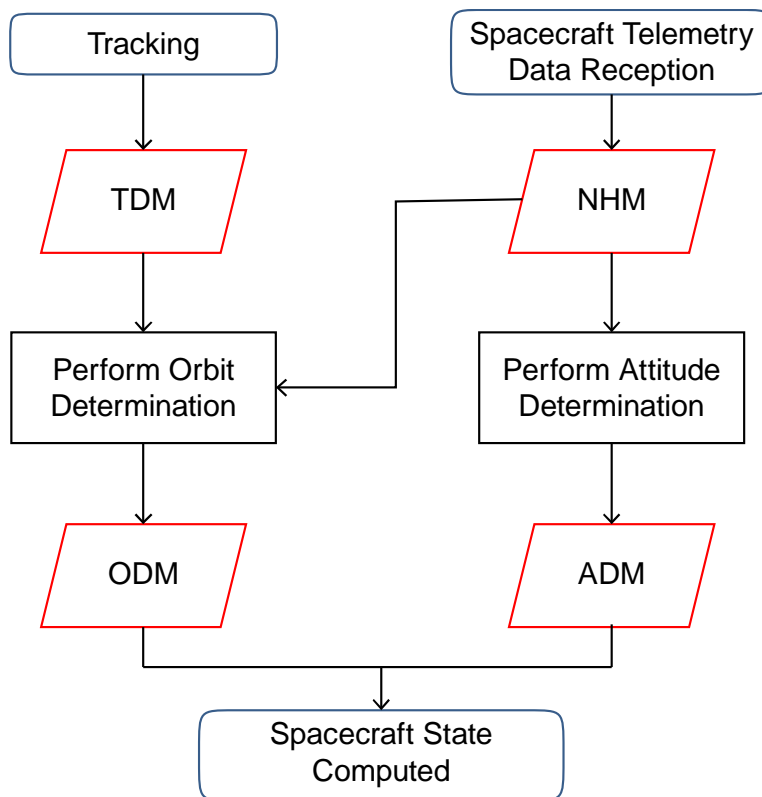


Figure 4-2: TDM, NHM, ODM, and ADM Use Case Example

As opposed to the previous use cases, which had to do with message exchanges primarily for attitude and orbit determination processes, as well as conjunction assessment, exchanges of other messages are required for spacecraft orbit and attitude maneuver planning, execution, and reconstruction. These messages are the PRM and SMM. The PRM may be used to request repointing the spacecraft to a different attitude, and for orientation changes of spacecraft articulated instruments or appendages. As seen in figure 4-3, the PRM is provided with the desired instrument pointing to the team that performs the maneuver planning and execution to achieve the final orientation.

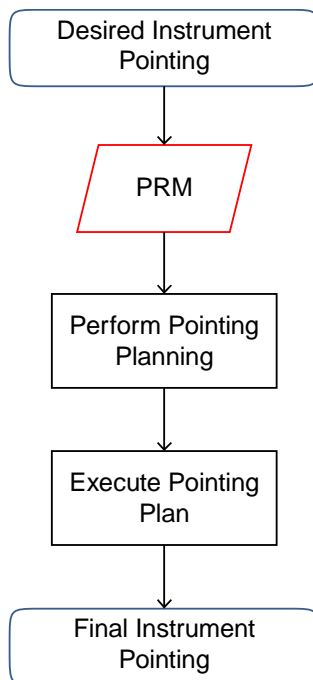


Figure 4-3: PRM Use Case Example

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 4-4). 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 4-5 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 MPM, MDM, and MAM are results obtained from the stages of maneuver planning, execution, and reconstruction.

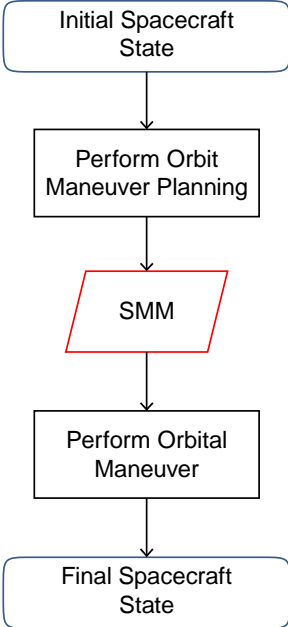


Figure 4-4: SMM Use Case Example

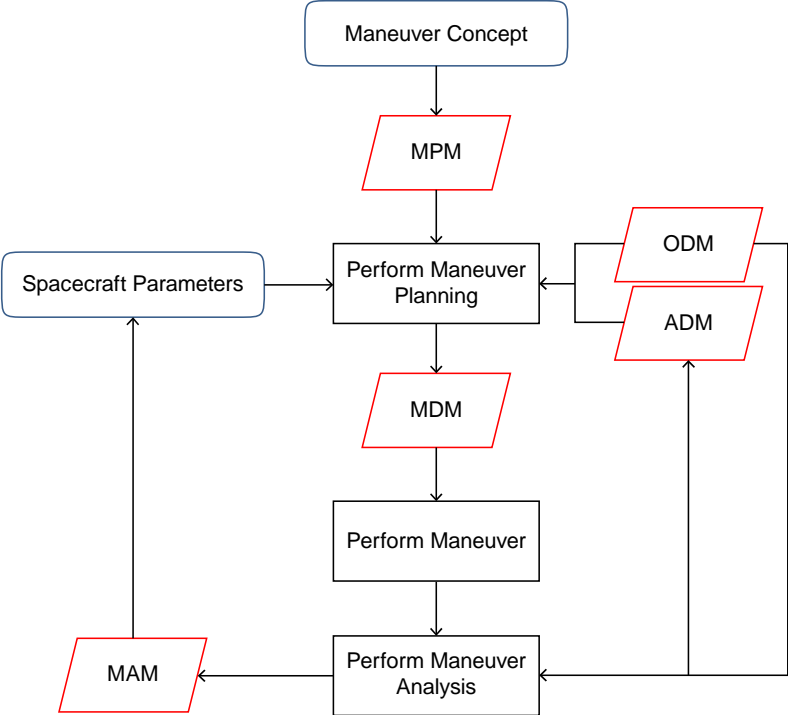


Figure 4-5: SMM, ODM, and ADM Use Case Example

4.5 NAVIGATION DATA MESSAGE FORMATS

4.5.1 GENERAL

The NDMs address the format and the approach for formatting each message. Currently, the NDMs use the Keyword Value Notation (KVN) and Extensible Markup Language (XML) 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 because of 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 CCSDS Navigation Data Messages are available on the CCSDS SANA registry <http://sanaregistry.org/r/ndmxml/ndmxml.html> (reference [19]).

4.5.2 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/data and two segment constructs. Each segment construct 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. Reference [17] 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, and monitoring telemetry, tracking, flight dynamics, and other engineering parameters (see also 3.2).

ancillary information: A data type used to interpret measurements and properties (see also 3.2).

attitude: Orientation of a given spacecraft reference frame with respect to another defined reference frame (see also 2.2.2).

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 (see also 2.2.2).

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, 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: 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 system, GNS: Navigation system that uses a constellation of spacecraft located around the globe to provide 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 (see also 2.2.2).

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

maneuver: 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 (see also 3.2).

navigation: The process used to find the present and imminent future position, orbit and orientation of a spacecraft using a series of measurements (see also 2.2.1). 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 (see also 3.2).

navigation data message: A particular arrangement of the navigation data whose structure and content are the subjects of CCSDS Recommended Standards for navigation (see also 3.2).

navigation session: The interchange of navigation data messages between participants for navigation purposes (see also 3.2).

orbit: The trajectory or path followed by a spacecraft and/or celestial body, typically a path around a central celestial body (see also 2.2.2).

participant: An entity that has the ability to acquire or broadcast navigation data messages (see also 3.2).

property: A data type that describes the physical characteristics of a participant (see also 3.2).

quality: Uncertainty information about a participant or a measurement.

quaternion: A four-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 because of 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 (see also 3.2).

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 für 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
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

CCSDS HISTORICAL DOCUMENT
CCSDS REPORT CONCERNING NAVIGATION DATA MESSAGES OVERVIEW

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
WRMS	Weighted Root-Mean Square
XML	Extensible Markup Language