Report Concerning Space Data System Standards

NAVIGATION DATA MESSAGES OVERVIEW

INFORMATIONAL REPORT

CCSDS 500.2-G-3

GREEN BOOK

March 2023

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Email: secretariat@mailman.ccsds.org

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

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 interagency 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. Reference [17] is a registry of technical definitions of navigation standard time systems, coordinate frames, and element sets.

For the purposes of this document, orbit, attitude, maneuver, tracking data, conjunction assessment information, pointing, and re-entry data 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 network 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 document's purpose and scope, applicability, structure, and references.

Section 2 provides a brief overview of the spacecraft navigation processes as well as the definition of key terms relevant to this process.

Section 3 provides foundational information regarding the navigation data message exchange architecture.

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.

Annex A provides a listing of abbreviations and acronyms.

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.

[2] Bob Schutz, Byron Tapley, and George Born. *Statistical Orbit Determination*. Burlington, Massachusetts: Academic Press, 2004.

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

[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.

[6] *Attitude Data Messages*. Issue 2. Recommendation for Space Data System Standards (Blue Book), CCSDS 504.0-B-2. Washington, D.C.: CCSDS, forthcoming.

[7] *Orbit Data Messages*. Issue 3. Recommendation for Space Data System Standards (Blue Book), CCSDS 502.0-B-3. Washington, D.C.: CCSDS, forthcoming.

[8] *Tracking Data Message*. Issue 2. Recommendation for Space Data System Standards (Blue Book), CCSDS 503.0-B-2. Washington, D.C.: CCSDS, June 2020.

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

[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 3. Recommendation for Space Data System Standards (Blue Book), CCSDS 505.0-B-3. Washington, D.C.: CCSDS, forthcoming.

[12] David A. Vallado. *Fundamentals of Astrodynamics and Applications*. 5th ed. Space Technology Library. El Segundo, CA: Microcosm Press, 2022.

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

[14] *Pointing Request Message*. Issue 1. Recommendation for Space Data System Standards (Blue Book), CCSDS 509.0-B-1. Washington, D.C.: CCSDS, February 2018.

[15] *Re-entry Data Message*. Issue 1. Recommendation for Space Data System Standards (Blue Book), CCSDS 508.1-B-1. Washington, D.C.: CCSDS, November 2019.

[16] *Navigation Events Message*. Under development.

[17] *Navigation Data—Definitions and Conventions*. Issue 4. Report Concerning Space Data System Standards (Green Book), CCSDS 500.0-G-4. Washington, D.C.: CCSDS, November 2019.

[18] "CCSDS Navigation Standards Normative Annexes." Space Assigned Numbers Authority. https://sanaregistry.org/r/navigation_standard_normative_annexes.

[19] "Navigation Data Messages XML Schema." Space Assigned Numbers Authority (SANA). https://sanaregistry.org/r/ndmxml.

[20] "Publications." The Consultative Committee for Space Data Systems. https://public.ccsds.org/Publications/default.aspx.

[21] *Cross Support Transfer Service—Tracking Data Service*. Issue 2. Recommendation for Space Data System Standards (Blue Book), CCSDS 922.2-B-2. Washington, D.C.: CCSDS, February 2023.

[22] *Fragmentation Data Message*. Under development.

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 their translational and rotational motion, respectively.

2.2.2 SPACECRAFT NAVIGATION TERMS AND DEFINITIONS

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:

property: An attribute or characteristic of an object or concept. In the context of this document, properties represent the physical attributes of the spacecraft, rovers, equipment, tracking stations, and relevant environment 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, and so on.

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 Recommended Standards as developed by the CCSDS Navigation Working Group.

participant: An entity that has the ability to acquire or broadcast navigation data. Possible participants can be arranged into three categories, as depicted in figure 2-1.
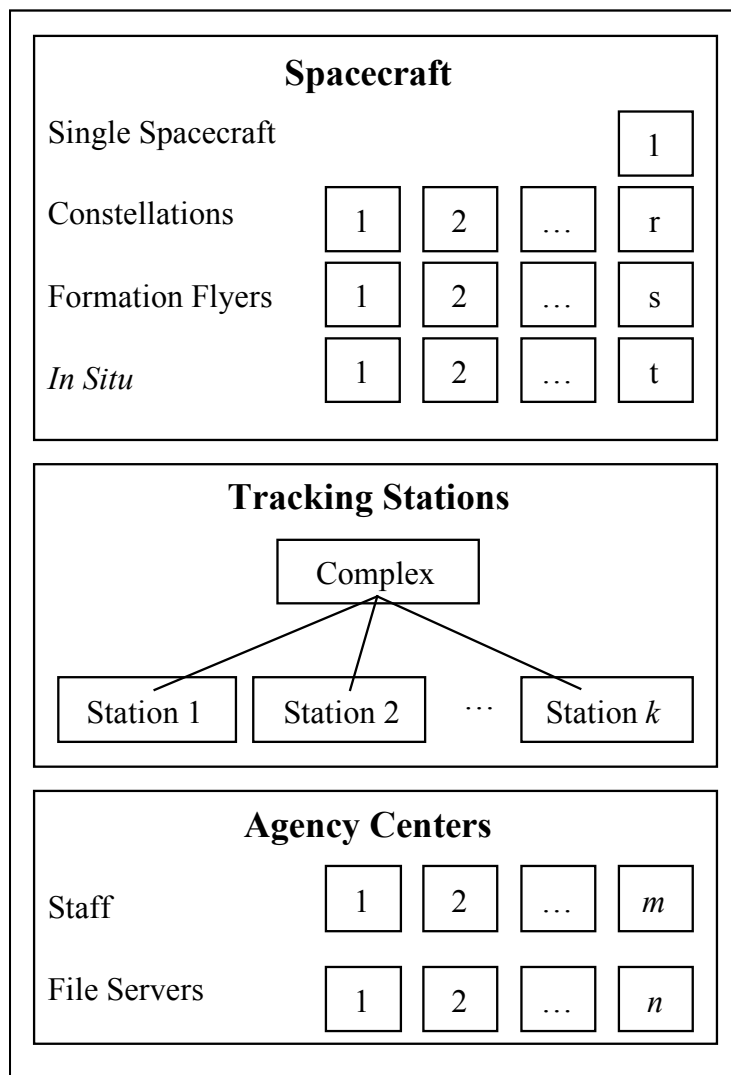
Figure 2-1: Participant Categories

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

ground stations and space networks: Participant types that enable 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 network of space-borne assets with a ground-based terminal. 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 a complex. Similarly, multiple space-borne assets in a network operated by a central entity are referred to as a fleet.

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 email or FTP) 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.

orbit: The translational motion of a spacecraft around a larger 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 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, for example, 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: The orientation and/or pointing of a spacecraft, defined by its rotation relative to a defined reference coordinate system. The preferred attitude representation depends on the stabilization mode of the spacecraft. For instance, 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: The study of the changes in the position of all orbiting bodies. In contrast, **attitude dynamics** deals with the changes in the orientation and pointing of the spacecraft.

flight dynamics: 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**: The processes within navigation to find the present and past positions and orientations of a spacecraft. 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 or representative 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 can also be used to predict future positions and orientations of the spacecraft.

guidance: The process of defining a path to move a spacecraft from one point to another or from one orientation to another.

control: The process to maintain a spacecraft within the prescribed path and attitude.

The above terms guidance, navigation, and control are commonly grouped together and abbreviated **GN&C**. The term GN&C is used to describe 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 or ground-based orbit and attitude determination and control.

The **Attitude Control System (ACS)**, or alternatively, the **Attitude Determination and Control System (ADCS)**, is part of GN&C and consists specifically of hardware and software for onboard attitude estimation and pointing control. 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. 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 2-2.
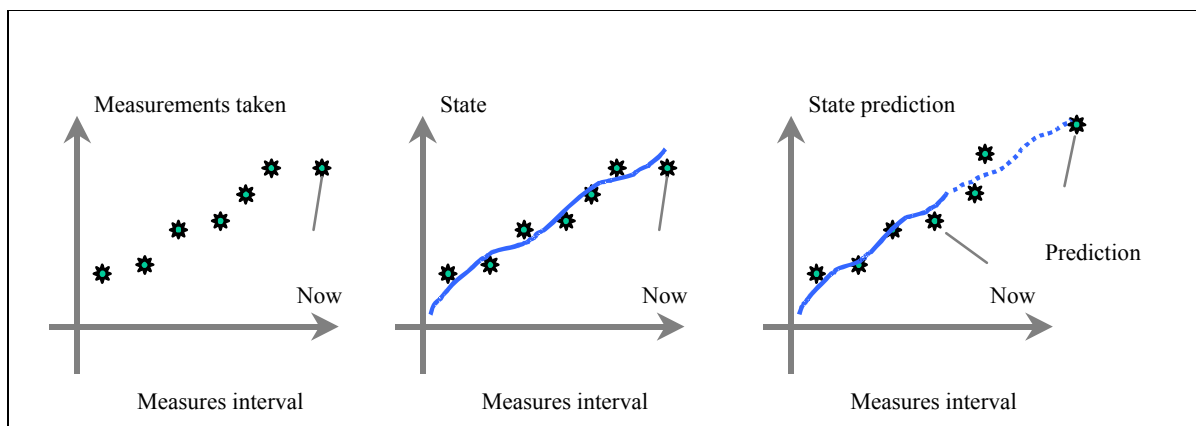

Figure 2-2: Navigation Estimation Process

Examples of the navigation data exchanged during orbit and attitude determination processes include tracking measurements or observations, orbit parameters, planned or conducted maneuvers, attitude parameters, and an ephemeris as 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.

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 a known point at different times or 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.

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) A dynamic model is fit to a set of measurements 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 to meet mission requirements and constraints or in the performance of debris avoidance. This process is called 'flight path control'.

        2) For attitudes: A maneuver is performed to modify the spacecraft attitude 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 NAVIGATION DATA AND NAVIGATION DATA MESSAGES

3.2.1 GENERAL

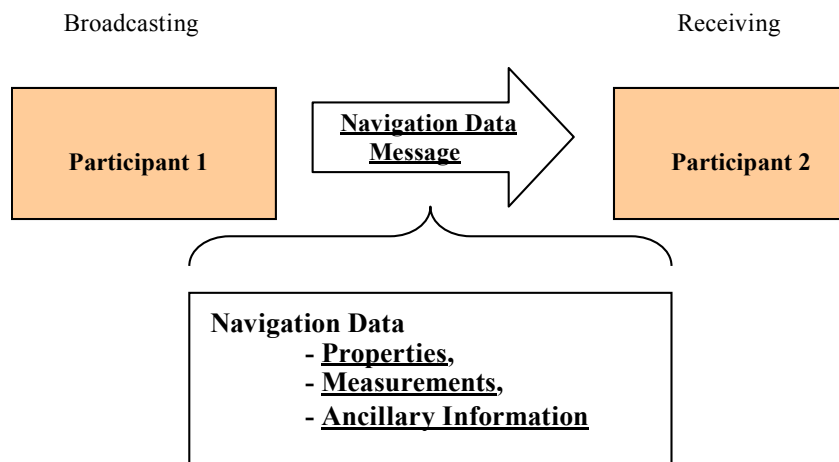Figure 3-1 describes the roles of navigation data versus navigation data messages.

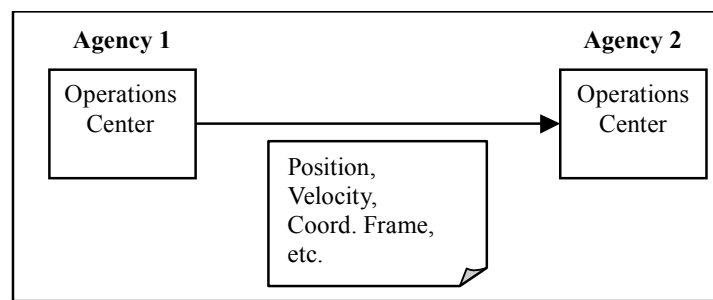**Figure 3-1: Navigation Data Message Exchange Definitions**

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. It should also be noted that spacecraft telemetry downlinked to the ground that contains navigation data is treated using CCSDS standards that are not in the flight dynamics domain. Section 4 introduces the current and proposed Recommended Standards for the exchange of navigation data. Agencies can benefit from utilizing 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 two non-spacecraft participants.

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

– **Flight-to-flight** exchanges are defined as the set of exchanges between two spacecraft participants.
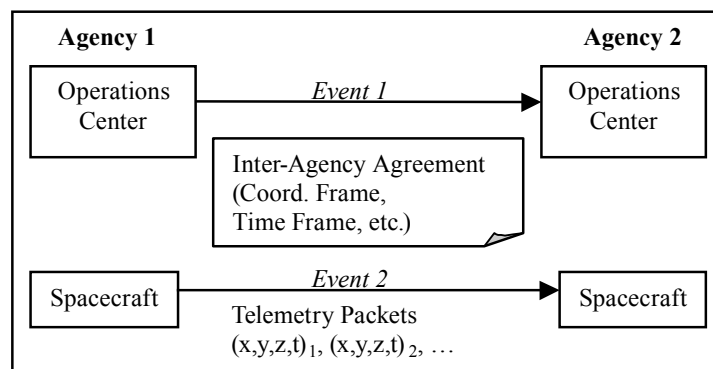
3.2.2 NAVIGATION DATA EXCHANGE CHARACTERISTICS

This subsection describes a framework for the exchange of messages between any two types of participants (see 2.2.2 and figure 2-1). It is not possible to describe every potential navigation session in detail, but navigation sessions generally have the following three general characteristics:

a) **Navigation sessions may be divided so as to accommodate constraints on data rates or availability of relevant information**. For example, for launch support of a spacecraft, state vectors (see references [17], [12], and [3]) could be exchanged between operations centers of two agencies. This exchange may be digital or through sharing of an image of the data. 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, and so on, 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 3-2.

(a) Spacecraft state vectors between agencies

(b) Spacecraft relative position information between spacecraft

Figure 3-2: Examples of Navigation Sessions

b) **Navigation data messages may utilize a shorthand of a CCSDS Recommended Standard to convey ancillary information**. The shorthand developed in each case should be unambiguous, flexible, and extensible. For example, in the case described in part (a) of figure 3-2, 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].)

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 format: (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 3-3).
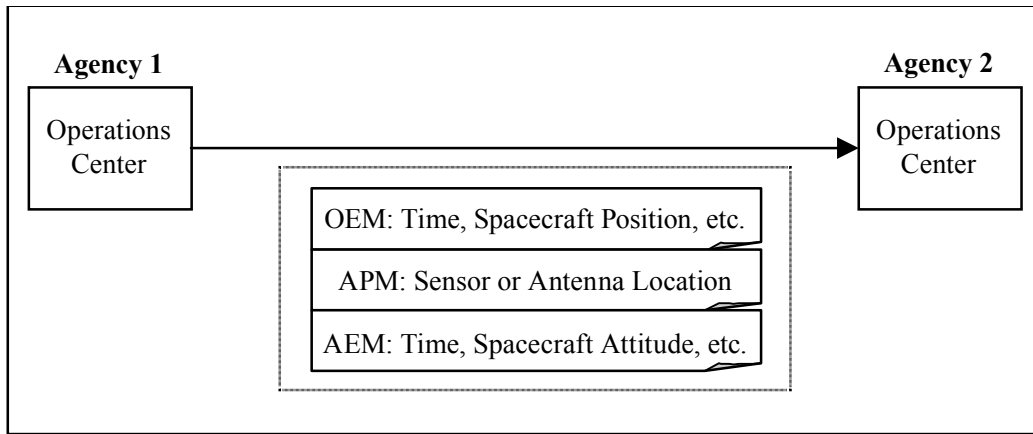
Figure 3-3: Navigation Session Using Multiple CCSDS Recommended Standards

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 six published standards for the exchange of spacecraft navigation data: Attitude Data Message (ADM), Orbit Data Message (ODM), Tracking Data Message (TDM), Conjunction Data Message (CDM), Pointing Request Message (PRM), and Re-Entry Data Message (RDM). An overview of these standards is provided in the subsequent subsections. The details of the ADM, ODM, TDM, CDM, PRM, and RDM are specified in references [6], [7], [8], [13], [14], and [15], 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 additional navigation data standards being developed and envisioned to fulfill and facilitate the execution and implementation of other navigation functions. Such standards under development are: Navigation Events Message (NEM, reference [16]) and Fragmentation Data Message (FDM, reference [[22]]), which will provide a standard framework for the exchange of orbit and attitude events and a standard message format for the exchange of fragmentation information, respectively.

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. 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 4.2.6:

–   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 or instrument at one or more times.

–   The CDM contains information that defines the relationship between the orbit states of different space objects at their time of closest approach.

–   The PRM contains information on the desired attitude state of an object at one or more future times.

–   The RDM contains information that describes the re-entry event of a space object.

–   The NEM provides a framework for the exchange of orbit, attitude, and related events.

The remainder of this document provides a more detailed overview of the CCSDS navigation standards that have either been published (see 4.2) or are under development (see 4.2.6).

4.2   PUBLISHED NAVIGATION DATA MESSAGES

4.2.1   TRACKING DATA MESSAGE

The TDM (reference [8])[1] 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 interagency exchange of the following tracking data types (see reference [17]):

–   ground- and space-based radio metric tracking data types:

   •   uplink and downlink (transmitted/received) frequencies,

   •   range,

   •   Delta Differential One-way Ranging (Delta-DOR),

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[1] At time of publication the TDM is undergoing revision as a result of mandatory CCSDS five-year review.

- range rate,

- differenced range,

- Doppler (one-way, two-way, three-way, and four-way),

- differenced Doppler,

- antenna angles,

- interferometric types,

- optical data;

  – 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 that qualify the data section keywords and provide supplementary information that is necessary to interpret the data. For any given TDM data type, the metadata keywords fall into three categories: required metadata, situation-specific required metadata, and completely optional metadata. There are relatively few metadata keywords that are required for every TDM; as in general, there are only a small number of the metadata keywords that are meaningful across every data type. One of the most important metadata keywords, required in all TDMs, are the keywords that represent the participants (spacecraft, antennas, etc.) involved in a tracking data session. 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 interagency 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, and so on. While most agencies are transferring TDMs using a file-based transfer protocol, another CCSDS Working Group, the Cross Support Transfer Services (CSTS) Working Group, has developed a standard for real-time transfer of radiometric tracking data that will use the TDM as the data format [21].

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 the Deep Space Network (DSN) for multiple European Space Agency (ESA) spacecraft (e.g., Mars Express, Venus Express, ROSETTA) and for the Indian Space Research Organization (ISRO) Mars Orbiter Mission. The TDM has also been used for tracking data exchanges between Goddard Space Flight Center (GSFC) and Johnson Spaceflight Center for the Orion Exploration Flight Test-1 (EFT-1), and between ESA and China for the Chang-E-2 mission and with Russia for the Phobos-Grunt 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 four messages that serve different purposes: the Orbit Parameter Message (OPM), the Orbit Mean-Elements Message (OMM), the Orbit Ephemeris Message (OEM), and the Orbit Comprehensive Message (OCM). 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 a particular instant; 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. One feature of the OMM is that 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 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).

An OCM specifies position and velocity of either a single object or an en masse parent/child deployment scenario stemming from a single object. The OCM aggregates and extends OPM, OEM, and OMM content in a single comprehensive hybrid message (file) and includes the following additional capabilities:

– optional Earth Orientation (UT1 and UTC) at a nearby (relevant) reference epoch;

– optional Leap second specification;

– optional area cross-sections for drag, SRP perturbations modeling;

– optional spacecraft dimensions and orientation information for collision probability estimation;

– optional orbit states (specified using one or more of Cartesian and orbit elements and reference frames) for a single or parent object at either a single epoch or as a time history (ephemeris);

− optional covariance matrix of selectable/arbitrary order for a single or parent object at either a single epoch or as a time history (ephemeris) that reflects the uncertainty of the orbit solution or simulation used to obtain the nominal states in the orbit state(s);

− optional covariance content options (e.g., Cartesian 3x3, 6x6, 7x7, or any combination of order, reference frame and orbit elements);

− optional maneuver specification (impulsive or finite burn);

− optional perturbations model specification;

− optional orbit determination data and metrics.

A 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, uncertainties of the mean Keplerian elements in the OMM, and uncertainties of the orbit solution for a single or parent object in the OCM.

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), or alternately as an OCM, where a parent/child object association is applicable.

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 ESA for submission of spacecraft ephemeris to NASA's JPL for tracking of multiple ESA spacecraft (e.g., Mars Express, Venus Express, ROSETTA) by the 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 fur Luft-und Raumfahrt (DLR), Centre National d'Etudes Spatiales (CNES), and ESOC, and is used frequently for external support. The ODMs have also been implemented and used to support projects within NASA GSFC. For instance, OEMs are used for owner/operator ephemerides in conjunction assessment by the NASA GSFC by Conjunction Assessment Risk Analysis (CARA), by the Combined Space Operations Center (CSpOC), by the Space Data Association, and in the Magnetospheric Multiscale Mission (MMS) for definitive and predictive products for mission operations and science. OEMs are also in use within NASA Johnson Space Center for the delivery of International Space Station (ISS) trajectories to GSFC and Orion spacecraft ephemerides to GSFC and JPL. Numerous other implementations are likely to exist given the popularity and flexibility of the OEM.

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. 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 three message formats for use in transferring spacecraft attitude information between space agencies: the Attitude Parameter Message (APM), the Attitude Ephemeris Message (AEM), and the Attitude Comprehensive Message (ACM). All 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 needs to have, therefore, angular velocity data or 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, and so on.

The ACM specifies the attitude state of a single object at multiple epochs, contained within a specified time range. The ACM aggregates and extends the APM and AEM content in a single hybrid message. The ACM simultaneously emphasizes flexibility and message conciseness by offering extensive optional standardized content while minimizing mandatory content.

The APM allows for modeling of any number of finite maneuvers; 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, AEM, or ACM 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, AEM, or ACM 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 GSFC and 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 Conjunction Assessment (CA) results and spacecraft owners and operators. CA is the process of predicting conjunction events by comparing observations and orbit determination solutions for more than one space object. The CA results provide information associated with the closest point of approach or local minimum in the difference between the position components of two space object trajectories at their Time of Closest Approach (TCA). 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 is transmitted to the owner/operator of a spacecraft or the group that performs the conjunction assessment analysis.

CA considerations when assessing the conjunction risk include the trajectory geometry, collision probability and variability, 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.

In summary, the CDM is the final product of CA results and is intended to provide spacecraft owner/operators with sufficient 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), 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 CSpOC has fully implemented the CDM in operations. It is their primary means of notifying an operator of a conjunction assessment. They are also used at NASA JSC in support of Human Spaceflight operations and at GSFC for the support of CARA operations.

The CDM is currently undergoing revision as a result of the mandatory CCSDS five-year review, but it would be premature to provide details.

4.2.5   POINTING REQUEST MESSAGE

The PRM (reference [14]) provides 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 desire to point the spacecraft and describe their needs 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 in 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 text representations of 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, for example, Tracking and Data Relay Satellite System (TDRSS). Text representations of 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.

4.2.6   RE-ENTRY DATA MESSAGE

The RDM (reference [15]) specifies a standard message format to be used in the exchange of spacecraft re-entry information between Space Situational Awareness (SSA) or Space Surveillance and Tracking (SST) data providers, satellite owners/operators, and other parties. These messages are used to inform spacecraft owners/operators of predicted re-entries, warn

civil protection agencies about potential ground impacts, or, conversely, to inform SSA/SST providers of the prediction.

The RDM is applicable to SST activities, spacecraft operations, and other 'ground'-based activities (e.g., civil protection, civil and military aviation) in which re-entering space objects are a concern. It contains the specifications for re-entry prediction information exchange between originators of re-entry data and recipients. Re-entry data includes remaining orbital lifetime, start and end of the re-entry and impact windows, impact location, and object physical properties.

The RDM is suitable for both manual and automated interaction, and for machine-to-machine interfaces for high data volume. The RDM is self-contained, but it can be paired with other Navigation Data Messages to enhance its functionality. For example, an RDM could be paired with several OPMs to exchange state vectors at critical epochs (last orbit determination, current, re-entry, etc.) or with one OEM to give the trajectory for (most of) the re-entry. The presence of user defined keywords allows other information to be exchanged after being specified in an ICD; ICDs are not necessary for most RDM exchanges, but are expected in some cases (especially if ODMs are to be exchanged for object position).

4.3 NAVIGATION DATA MESSAGES IN DEVELOPMENT

4.3.1 NAVIGATION EVENTS MESSAGE

The NEM (reference [16]) is foreseen to provide a method of exchanging a sequence of navigation related orbital events for a spacecraft or mission. These messages would enable the capability to handle exchanges of information not currently handled by CCSDS standard messages for the classical data types of orbit, attitude, and other measurements. Orbital events (and more precisely, predicted orbital events) constitute a major data type used in control centers for operations and science planning. Orbital events describe when, and possibly how, certain situations related to one or more satellites occur.

Examples of typical events are:

  – when, generally, some geometric condition is met (in relation to onboard sensors, celestial bodies, possibly other satellites, etc.);

  – when certain orbit parameters have some specific value (e.g., a satellite crosses the Equator).

NOTE – The CCSDS Blue Book *Cross Support Service Management—Communications Planning Information Format* (CCSDS 902.2-B-1) specifies standard formats for use in transferring communications-planning information related to ground stations and/or relay satellites between space agencies and commercial or governmental spacecraft operators. The NEM will not duplicate these events.

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.

Figure 4-1 below shows a high-level exchange scenario of OEMs and CDMs in an end-to-end CA process. As seen in the figure, two OEMs are used to determine a conjunction, one OEM per object. If there is a high probability of collision, a CDM is 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 OEM and CDM exchanges are essential for CA.
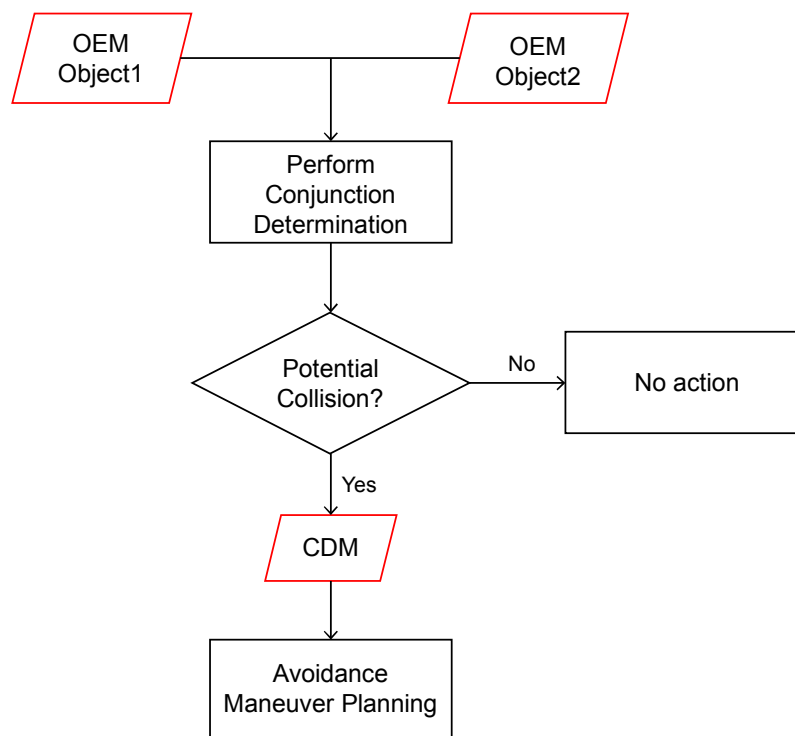
Figure 4-1: Use Case Example

Two other navigation processes that require exchanges of 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 (e.g., GNSS receiver), while 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 as input for orbit determination, and ODMs and ADMs as the generated output of these two processes, respectively.

NOTE – 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.
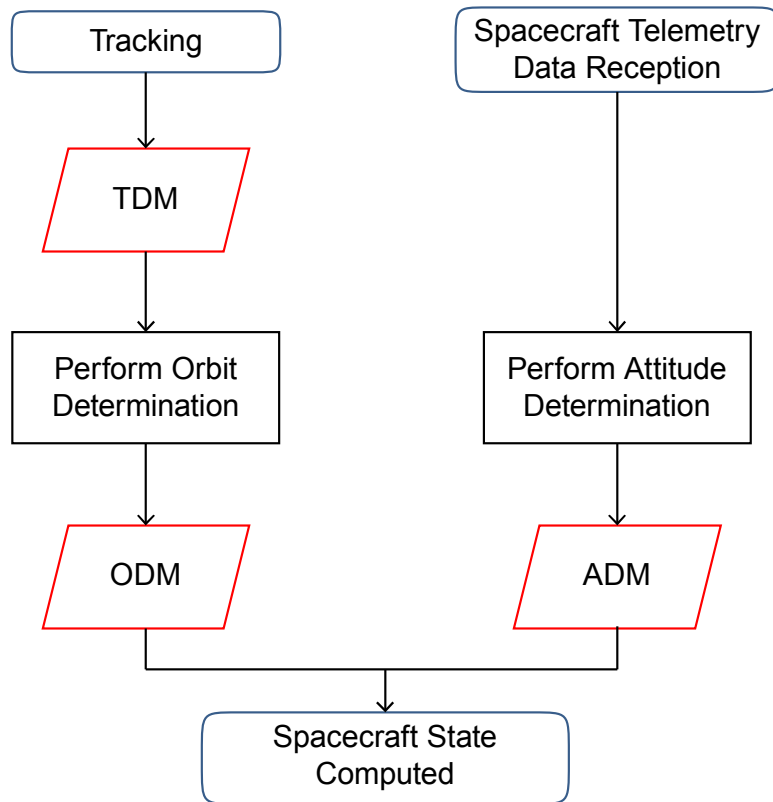
Figure 4-2: TDM, ODM, and ADM Use Case Example

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, an exchange of a PRM is the catalyst for spacecraft orbit and attitude maneuver planning, execution, and reconstruction. 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.
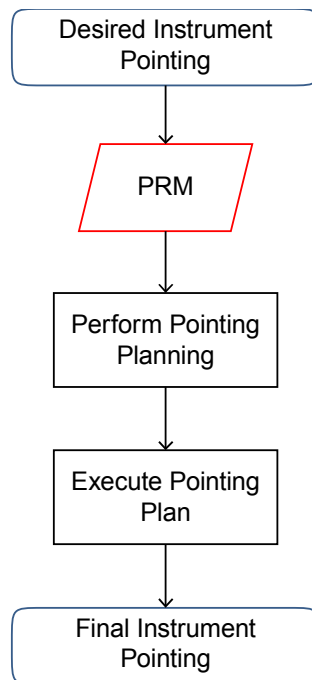
Figure 4-3: PRM Use Case Example

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 document tags that specify how to organize the content. NDM tags in the XML format are usually identical to the keywords used in the KVN format.

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]. It should also be noted that the PRM is implemented using a set of XML templates, rather than as an XML message that can be validated via the XML schema.

XML schemas for all of the CCSDS Navigation Data Messages are available on the CCSDS SANA registry https://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 is 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 is used in the NDMs. Reference [19] provides a listing of current time systems and reference frames used in navigation processes and messages.

ANNEX A

ABBREVIATIONS AND ACRONYMS

ACS	attitude control system
ACM	Attitude Comprehensive Message
ADCS	attitude determination and control system
ADM	Attitude Data Message
AEM	Attitude Ephemeris Message
AOS	acquisition of signal
APM	Attitude Parameter Message
ASCII	American Standard Code for Information Interchange
CA	Conjunction Assessment
CARA	Conjunction Assessment Risk Analysis
CCSDS	Consultative Committee for Space Data Systems
CDM	Conjunction Data Message
CNES	Centre National d'Etudes Spatiales
CSpOC	Combined Space Operations Center
CSTS	Cross Support Transfer Services
DLR	Deutsches Zentrum fur Luft-und Raumfahrt
DOR	differential one-way ranging
DSN	Deep Space Network
EFT-1	Exploration Flight Test-1
ESA	European Space Agency
ESOC	European Space Operations Centre
FDM	Fragmentation Data Message

FTP	File Transfer Protocol
GN&C	Guidance, Navigation, and Control
GNSS	Global Navigation Satellite System
GSFC	Goddard Space Flight Center
ICD	interface control document
ID	identification
IRU	inertial reference unit
ISRO	Indian Space Research Organization
ISS	International Space Station
JAXA	Japan Aerospace Exploration Agency
JPL	Jet Propulsion Laboratory
JSC	Johnson Space Center
KVN	keyword value notation
LOS	loss of signal
MMS	Magnetospheric Multiscale Mission
NASA	National Aeronautics and Space Administration
NDM	Navigation Data Message
NEM	Navigation Event Message
NORAD	North American Aerospace Defense Command
OCM	Orbit Comprehensive Message
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
RDM	Re-Entry Data Message
SANA	Space Assigned Numbers Authority
SFTP	Secure File Transfer Protocol
SI	International System of Units
SSA	space situational awareness
SST	space surveillance and tracking
TCA	time of closest approach
TDM	Tracking Data Message
TDRSS	Tracking and Data Relay Satellite System
TLE	two-line elements
UT1	Universal Time
UTC	Coordinated Universal Time
WRMS	weighted root-mean square
XML	Extensible Markup Language