Standardizing Navigation Data: A Status Update

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This paper presents the work of the Navigation Working Group of the Consultative Committee for Space Data Systems (CCSDS) on development of standards addressing the transfer of orbit, attitude and tracking data for space objects. Much progress has been made since the initial presentation of the standards in 2004, including the progression of the orbit data standard to an accepted standard, and the near completion of the attitude and tracking data standards. The orbit, attitude and tracking standards attempt to address predominant parameterizations for their respective data, and create a message format that enables communication of the data across space agencies and other entities. The messages detailed in each standard are built upon a *keyword = value* paradigm, where a fixed list of keywords is provided in the standard where users specify information about their data, and also use keywords to encapsulate their data. The paper presents a primer on the CCSDS standardization process to put in context the state of the message standards, and the parameterizations supported in each standard, then shows examples of these standards for orbit, attitude and tracking data. Finalization of the standards is expected by the end of calendar year 2007.

Introduction

The development of standards, most particularly in space mission operations, has been an ongoing area of international cooperation between space agencies in recent years. The Consultative Committee for Space Data Systems (CCSDS) represents the technical branch of the International Standards Organization (ISO) Technical Committee 20, Subcommittee 13, and works to develop standards targeting spacecraft mission operations, intra-spacecraft, and spacecraft to ground communications, to name a few. A group within the organization of CCSDS is the Mission Operations and Information Management Services Area (MOIMS), which addresses standards in mission operations, information exchange formats, and spacecraft monitoring and control standards, among others. For further information on the mission of the CCSDS and the technical organization, please see the web pages at http://www.ccsds.org.

The MOIMS area is broken into what are known as Working Groups (WG), and one of those working groups is the Navigation Working Group. This group has worked to address the standardization of spacecraft navigation data by developing three standards: an orbit message, attitude message, and a tracking data message. Each standard has been developed to communicate the necessary data elements in a compact format that is readable to the human eye and also readable by computers, which enables the input of navigation data to be automated in a mission operations situation. The navigation standards take advantage of international standards currently in place as well, such as the specification of a standard alphabet (ISO/IEC 8859-1: 1998) [6], and a standard representation of numerical values based on IEEE Standard 754-1985 [7].

The three standards, Orbit Data Message (ODM) [1], Attitude Data Message (ADM) [2], and the Tracking Data Message (TDM) [3], will be detailed in the following sections. The approach to the development of each standard will be presented, along with relevant keywords and examples on using the standard. Also discussed will be the operationally relevant environment for such a standard. Status updates will discuss the substantial work that has been accomplished since 2004 when these standards were first discussed at the International Symposium on Space Flight Dynamics (ISSFD) [9]. What will not be discussed, but are still a large part of the use of these standards, are the Navigation Green Book [4] and the XML Specification [5]. The Navigation Green Book gives a primer on the use of the data contained in these messages, to demonstrate how to interpret the data, and to show how one would use the data to derive other relevant information. Work on this document continues and a final version will be published in 2008. The XML Specification is a standard that will detail how to format the ODM, ADM, and TDM (collectively called the Navigation Data Messages (NDM)) using the XML parsing language, and will be finalized in 2008 as well.

Primer on the CCSDS Standardization Process

The CCSDS Standardization Process is defined in detail in [10]. In brief, standards proceed through the following levels:

- CCSDS Concept Paper: discusses the concept of standardization in a designated area. In order to progress, the CCSDS Engineering Steering Group (CESG) must endorse the concept and assign it to a Working Group.
- CCSDS Proposed Standard ("White Book"): expands on the Concept Paper. The White Book is developed by the chartered Working Group. In order to progress, the document must be reasonably mature and ready for formal review outside the Working Group.
- CCSDS Draft Standard ("Red Book"): a formal release by the CCSDS Secretariat. The Red Book is made available on its web site for what is termed the "Agency Review". In order to progress, the Working Group is obligated to consider and formally respond to comments submitted by reviewers, a process which usually requires some degree of change in the document. Depending on the magnitude of the changes, one or more additional Agency Reviews may be required. Another condition for progressing is that "at least two independent and interoperable prototypes or implementations must have been developed and demonstrated in an operationally relevant environment, either real or simulated" [10]. Such prototyping establishes the viability of the concept.
- CCSDS Recommended Standard ("Blue Book"): Once the CESG is satisfied that the Agency Review and prototyping requirements have been met, the document becomes a Recommended Standard. A Blue Book is subject to review and potential revision after 5 years, or sooner if conditions warrant. The CCSDS Recommended Standards are suitable for infusion into space operations, which can be one of the most complex yet rewarding aspects of the standardization process. CCSDS Blue Books also enter the ISO voting process at an advanced level (Final Draft International Standard).

At each level of the process, the document becomes more mature and more formal. There are some subtleties and technicalities to the process, but the above fairly well represents the fundamentals. CCSDS documents that have gone all the way through the CCSDS Standardization Process are available without charge at http://public.ccsds.org/publications/default.aspx. Furthermore, the CCSDS Working Groups are encouraged to work in the open and all working standards are in the public domain. Thus it is possible for interested parties to observe the progress of CCSDS Navigation Working Group White Book and Red Book drafts for [1], [2], [3], and [5], and the draft for the Green Book [4], at http://cwe.ccsds.org/moims/docs/MOIMS-NAV/Draft%20Documents/.

Common Navigation Information

The structure of the Navigation Data Messages relies on a key design feature - the *keyword = value* paradigm. In order for the standard to then be useful in an operational environment, the set of keywords must be fixed. The keywords are used to navigate through a message and for the end user to ferret out the bits of information for their application. There are keywords in the NDM messages that are allowed particular values, while others are used to denote the data being transferred. Many of the keywords with particular values enable the user to interpret the data in the message correctly and unambiguously.

While the NDMs each address significantly different information at their core, there is much in common with the suite of messages. Each message's information relies on the specification of time and coordinate frames. These particular elements of the messages will be discussed in this section. In addition to these common technical elements, there is much in common in terms of ancillary information regarding the specification of the genesis of a particular message. Information such as a message version number, a field for the agency creating the message, a date the message was created, vehicle naming, and comments have all been standardized across the Navigation Data Messages.

All NDMs contain a section in the message known as the header. Contained in this section are items such as message version number, the date and time the message was created, and the agency originating the message. Following the header is the metadata section, whose contents vary between the NDMs, but each contains keywords for the time system, and the reference frame(s) being employed in the message. Considering the number of different time systems in existence, NDMs rely on [11] to standardize the format of the date and time. The standard does not attempt to explain the myriad time systems, but rather provide a means to specify the time system used in a message. It is up to the user to understand the time system in a given message. The Navigation WG has included several allowed values for time systems, which include many of the current time systems in use (UTC, TAI, GPS, TDB, TT, etc.). The standard also allows for the use of any future time system as long as the agencies exchanging messages specify the different key word values in an Interface Control Document (ICD).

Turning to the specification of coordinate frames, these have been addressed by introducing various key words in each of the three messages that are used to communicate reference frame information. For instance, in the Orbit Data Message, the key word REF_FRAME is used. However, for the Attitude Data Message, the specification of attitude requires two reference frames to specify the rotation, typically an inertial reference frame and a body-fixed reference frame. The keyword for one of the reference frames in the rotation is provided by the keyword *_FRAME_A, where * is replaced by a prefix pertinent to the type of data. Similarly, the other half of the reference frame specification is provided by *_FRAME_B. The values for many inertial reference frames and some local orbital reference frames have been standardized in the NDM messages. However, the exchange of NDMs can be enhanced with additional features and other keyword values through an ICD. The NDMs currently support many of the Earth-centered and orbital reference frames (EME2000, ITRF, LVLH, RTN, etc.), and also the International Celestial Reference Frame (ICRF).

The definition for each of the values of these keywords is or will be covered in the Navigation Green Book, [4]. The Green Book is not an approved standard, but rather a technical handbook that will provide fundamental concepts of the navigation process, address the definitions of certain keyword values and demonstrate the use of the information contained in the NDMs. However, since it is not an approved standards document, it is not required to adhere to the same strict rules of review as a standard, and as such the information contained in it is *caveat emptor*.

The NDM messages also address format and detail a standard approach to formatting in each message. NDMs use ASCII [6], a common format used in all computing architectures, as the basis for the message format. Thus there is a reasonably high probability that any given agency can process an ASCII-based NDM. There is also no requirement on any agency to use software provided by another agency. While some tracking data users may wish to contract with each other to provide software, it is not a requirement of the standard. Finally, insofar as possible, all of the NDMs use units that are part of the International System of Units (SI Units); units are either SI base units, SI derived units, or units outside the SI that are accepted for use with the SI. There are a small number of specific cases where units that are more widely used in the navigation community are specified, but every effort has been made to minimize these departures from the SI [12].

Orbit Data Message

The specification of the orbit of an object is normally achieved, in high fidelity applications, by specifying the position and velocity of the object in a given reference frame at a given epoch. Many other parameterizations of the orbit exist that use quantities giving more insight into the motion of the object, such as mean elements, orbital elements, etc. However, the specification of the position and velocity is unambiguous, and as such, the ODM adopted the specification of the position and velocity of an object as the obligatory parameterization of an orbit, and all other values are optional.

The ODM is divided into two separate messages, the Orbit Parameter Message (OPM) and the Orbit Ephemeris Message (OEM). The OPM is intended to specify the orbit of the object at a single instant in time, and allows for the specification of Cartesian coordinates and Keplerian elements in the message, as well as orbit maneuver information, solar radiation information and aerodynamic drag information. The OEM is intended to specify the orbital state at multiple epochs in a single message. These two messages constitute the standard for specifying orbital state information. The ODM also details not only the keywords allowed in the message, but information on the allowable format of the data lines and syntax allowed for text keywords and comments.

Orbit Parameter Message (OPM)

The OPM specifies keywords, in addition to the time and reference frame keywords, to specify the orbital state of an object at a single designated epoch. Generation of the orbital state is not the intent of the standard, or of this paper, but only the clear, concise and compact specification of the orbital state. The message is divided into a header, a metadata, and finally a data section to specify not only the orbital state, but also parameters that enable the appropriate interpretation of the orbital state by the end user. The information contained in the metadata section is summarized in Table 1.

Table 1: Metadata Section of an OPM

Keyword	Description	Example Values
OBJECT_NAME OBJECT_ID	Keywords provided to describe the object	MYSAT 2015-004b
CENTER_NAME	Keyword to specify the center of the reference frame	earth MARS
REF_FRAME	Keyword to specify the reference frame that the orbital	J2000

	state is given	EME2000
TIME_SYSTEM	The time system used to interpret epoch information	UTC TAI

After the metadata section, there are keywords specified that allow for the specification of the orbital state. In the case of position and velocity, the keywords provided are X, Y, Z, X_DOT, Y_DOT, Z_DOT. These keywords are mandatory in every OPM. The units associated with the position and velocity information are kilometers (km) and kilometers per second (km/s), respectively. There are also keywords provided to specify Keplerian elements, and those are SEMI_MAJOR_AXIS, ECCENTRICITY, INCLINATION, RA_OF_ASC_NODE, ARG_OF_PERICENTER, TRUE_ANOMALY, MEAN_ANOMALY, and GM, which are all self-explanatory. Note that only either true anomaly or mean anomaly needs to be specified for a complete parameterization of the orbital state. The specification of the Keplerian elements is optional.

Additional keywords are provided to enable the user to propagate the provided orbital state to a time different than the given epoch. A quantity necessary for this purpose is the mass of the object, specified using the keyword MASS. To determine the effect of solar radiation pressure, the user would need the area normal to the Sun vector (SOLAR_RAD_AREA), and the solar radiation coefficient (SOLAR_RAD_COEFF). Similarly, to predict the aerodynamic drag effect on the orbital state, the user would need the area normal to the velocity vector (DRAG_AREA) and the drag coefficient (DRAG_COEFF). The specification of these keywords is obligatory and must be provided in every OPM. Normally orbital states are produced from a curve fit to tracking data measurements, and these parameters are necessary to properly propagate the orbital state determined in this manner.

In addition to the orbital state parameterization, keywords are provided in the OPM to specify orbital maneuvers. The maneuver is parameterized using the epoch of the maneuver, the duration of the maneuver, the mass expelled during the maneuver, the reference frame applicable to the maneuver, and finally the delta velocity being applied in the given reference frame. The keywords provided for this purpose are MAN_EPOCH_IGNITION, MAN_DURATION, MAN_DELTA_MASS, MAN_REF_FRAME, MAN_DV_1, MAN_DV_2, MAN_DV_3, respectively. Unlike the object parameters, maneuver parameters are optional. An example OPM is provided in Figure 1, which specifies the maneuver duration as zero seconds, implying an impulsive maneuver.

Figure 1: Example OPM specifying a Maneuver

```
CCSDS_OPM_VERS        = 1.0
CREATION_DATE         = 2013-08-29T14:56:34
ORIGINATOR            = JAXA
OBJECT_NAME           = THISSAT
OBJECT_ID             = 2012-003b
CENTER_NAME           = EARTH
REF_FRAME             = ITRF-97
TIME_SYSTEM           = UTC

EPOCH                 = 2013-08-29T13:35:45.688
X                     = 6503.514000
Y                     = 1239.647000
Z                     = -717.490000
X_DOT                 = -0.873160
Y_DOT                 =  8.740420
Z_DOT                 = -4.191076
MASS                  = 3000.0000
SOLAR_RAD_AREA        = 18.770000
SOLAR_RAD_COEFF       = 1.000000
DRAG_AREA             = 18.770000
```

```
DRAG_COEFF            = 2.50000

COMMENT Impulsive maneuver, duration set to 0 seconds
MAN_EPOCH_IGNITION    = 2013-08-29T13:41:32.544
MAN_DURATION          = 0.00
MAN_DELTA_MASS        = -1.469       [KG]
MAN_REF_FRAME         = RTN
MAN_DV_1              = 0.001015
MAN_DV_2              = -0.001873
MAN_DV_3              = 0.000000
```

Orbit Ephemeris Message (OEM)

An OEM is intended to specify the orbital history of an object and allow for high fidelity interpolation between epochs specified in the OEM. The OEM is also divided into a header, metadata and data sections, similar to the OPM. The OEM is quite different in that it provides a sequence of data in a compact form. As such, more information is relayed in the metadata. In addition to the keywords provided in the OPM, the OEM allows for the specification of a start and stop time (START_TIME, STOP_TIME), and the specification of a sub-block of the data that is useful using the keywords USEABLE_START_TIME and USEABLE_STOP_TIME. Finally, the message allows for the specification of an interpolation method to be used on the data with the keyword INTERPOLATION_METHOD and INTERPOLATION_DEGREE. These keywords, along with the keywords provided in Table 1 for the OPM, constitute the metadata section for an OEM. The data section of the message has a single format to specify the orbital state at various epochs. The data lines are formatted in the order of the epoch, the x, y and z components of position and the x, y, and z components of velocity of the object. The limits on the formatting of the data lines and the syntax of the OEM message are provided in [1]. An example OEM is provided in Figure 2.

Figure 2: Example OEM

```
CCSDS_OEM_VERS = 1.0
CREATION_DATE         = 2015-09-20T18:32:45
ORIGINATOR            = NASA/JPL
META_START
OBJECT_NAME           = MARS MYSAT
OBJECT_ID             = 2014-045b
CENTER_NAME           = MARS BARYCENTER
REF_FRAME             = EME2000
TIME_SYSTEM           = UTC
START_TIME            = 2015-09-20T13:34:32.544
STOP_TIME             = 2015-09-20T13:58:45.944
META_STOP

2015-09-20T13:34:32.544 2789.619 -280.045 -1746.755 4.73372 -2.49586 -1.04195
. . .
2015-09-20T13:58:45.944 -3881.024 563.959 -682.773 -3.28827 -3.66735 1.63861
```

Note that the ODM has been assimilated into the operations environments of several of the CCSDS Member Agencies. The OEM is the format used by European Space Agency (ESA) for submission of spacecraft ephemerides to NASA's Jet Propulsion Lab (NASA/JPL) for tracking of multiple ESA spacecraft (Mars Express, Venus Express, ROSETTA) by the Deep Space Network (DSN). The OEM has also been used to deliver trajectories to ESOC for possible contingency tracking (e.g. Mars missions, SOHO). Additionally, The Japan Aerospace Exploration Agency may use the OEM for DSN tracking of the SELENE spacecraft. The OPM has been implemented at the DSN, NASA/JPL Navigation, Deutsches Zentrum fur Luft-und Raumfahrt (DLR), Centre National d'Etudes Spatiales (CNES), and European Space Operations Centre (ESOC), and is used frequently for external support. Finally, while this paper does not discuss the XML specification of the Navigation Data Messages, it is worth noting that the forthcoming CCSDS Service Management Recommended Standard directly incorporates the XML representations of the OEM and OPM messages [5].

Currently the ODM is being extended via collaboration of the CCSDS (ISO TC20/SC13) with the other space-based ISO subcommittee (ISO TC20/SC14). These two subcommittees of the ISO Technical Committee 20 both cover space-related standardization, but serve different user communities. The ODM is the current international standard for the representation of an orbit (ISO 22644), and it is being extended to accommodate requirements raised by the TC20/SC14. In particular, these extensions include the addition of information regarding the uncertainty of orbit states (covariance matrix); addition of accelerations to the OEM state; more extensive documentation of the inputs to the development of the navigation solution; and a new message type that is based upon the NORAD Two Line Elements (TLE), which over the years has become the "de facto" standard for the representation of mean orbital elements.

Attitude Data Message

The definition of attitude is the orientation of one coordinate frame with respect to another. As it relates to a space object, Wertz [8] defines the attitude as "the orientation in space". The parameterization of the attitude can take many forms, but 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

In addition to these parameters, to propagate the attitude one would need the rotational rates of coordinate system 1 with respect to coordinate system 2, which can be expressed in either coordinate system. Depending on the particular parameterization of the attitude, additional information may be necessary to fully specify an unambiguous attitude. It is the goal of this standard to delineate a format and keywords that allow the exchange of attitude information in an unambiguous manner. This section will give a brief overview of the attitude parameterizations addressed with this standard, a handful of the keywords used to specify the attitude, give an example use of the standard, and conclude with the road ahead for the standard.

The ADM standard is divided into two messages, an Attitude Parameter Message (APM), and an Attitude Ephemeris Message (AEM). The APM is intended for specifying an attitude at a given instant in time, and if appropriate, specifying the attitude rates of the object at the same time for use in propagating the attitude. The AEM is intended to specify a list of attitude transformations at various times. Much is similar between the two messages because they both specify an attitude transformation, but the format of the message varies.

Attitude Parameter Message (APM)

The most widely used parameterizations of attitude are quaternions, Euler angles, and in the case of spinning spacecraft, spin parameters. Each parameterization requires specifying differing quantities, thus requiring a different set of keywords. Quaternions have gained wide use due to their lack of singularities in the evolution of the parameters, however Euler angles are a more intuitive quantity for engineering and analysis purposes. Due to the non-singular nature of quaternions, they were a natural choice as the obligatory specification of attitude in all APMs. All other parameterizations and keywords are optional. It is not the goal of this paper or the standard to discuss the merits of either representation, but rather to discuss how each parameterization is represented. For instruction on using an ADM for a particular purpose, the reader is directed to [2] and [4].

Quaternions are a compact representation of attitude requiring four numeric values to represent the attitude, the first three giving the orientation of the rotation vector, and the fourth giving the magnitude of the rotation. In addition to specifying the attitude, it may be necessary to specify the rate of attitude change, and this can be done by specifying values for the derivative of the quaternion. The keywords provided for specifying the attitude using quaternions are Q1, Q2, Q3 for the vector portion, and QC for the scalar value. The corresponding keywords for the derivative terms are Q1_DOT, Q2_DOT, Q3_DOT and QC_DOT. In addition to these keywords, the reference frame keywords provided are Q_FRAME_A, which could be used to specify the inertial frame (e.g. ITRF-2000, J2000), and Q_FRAME_B, which could specify the body-fixed frame. Q_FRAME_A and Q_FRAME_B have several allowed values by the standard that specify a reference frame, but require an ICD for the full understanding of the location of the reference frame. For instance, SC_BODY, DSS_x, TAM_x, where x is an integer from 0 to 9, are all allowed reference frame keyword values, but require an ICD to fully specify where on the spacecraft body this frame is located. The usefulness of this approach is that user systems can still process any APM message, but the interpretation of the information in the message may require additional knowledge. The standard does not preclude the specification of any reference frame using either Q_FRAME_A or Q_FRAME_B. For instance, a particular APM could specify a transformation from ITRF-2000 to J2000, or a transformation from SC_BODY to DSS_x. The final keyword necessary to fully specify the quaternion is the direction of the rotation. The keyword Q_DIR is provided and can have the values A2B or B2A. The keyword value A2B, given specifications of the reference frame given by Q_FRAME_A and the body frame given by Q_FRAME_B, will transform from Q_FRAME_A to Q_FRAME_B, and vice versa if Q_DIR has the value B2A. An example APM using quaternions is shown in Figure 3.

Figure 3: APM Example using Quaternions

```
CCSDS_APM_VERS         = 1.0
CREATION_DATE          = 2010-09-30T19:23:57
ORIGINATOR             = GSFC
OBJECT_NAME            = MYSAT
OBJECT_ID              = 2008-009A
CENTER_NAME            = EARTH
TIME_SYSTEM            = UTC

EPOCH                  = 2010-09-30T14:28:15.1172
Q_FRAME_A              = SC_BODY
Q_FRAME_B              = ITRF-97
Q_DIR                  = A2B
Q1                     = 0.00005
Q2                     = 0.87543
Q3                     = 0.40949
Q4                     = 0.25678
```

Euler angles are another parameterization of attitude that utilize angular values to express the attitude transformation, and a rotation sequence to apply the angles. The metadata necessary to interpret Euler angle data are shown in Table 2.

Table 2: Relevant Euler Angle Metadata

Keyword	Description	Value Examples
EULER_FRAME_A	Body-fixed, inertial or rotating reference frame	SC_BODY STARTRACKER

EULER_FRAME_B	Body-fixed, inertial or rotating reference frame	ICRF ITRF-97
EULER_ROT_SEQ	keyword for the sequence of rotation axes	123 321
EULER_DIR	direction of the Euler angle rotation, whether from EULER_B_FRAME to EULER_FRAME, or vice versa	A2B B2A
RATE_FRAME	If desired to specify Euler angle rates, this keyword is used to specify the reference frame used to express the Euler angle rates	EULER_FRAME_A EULER_FRAME_B

The final pieces of information necessary for the specification of Euler angles are the Euler angles themselves. The keywords provided for the specification of the Euler angles are X_ANGLE, Y_ANGLE and Z_ANGLE, denoting an X, Y and Z body axis rotation angle, respectively. The corresponding Euler angle rates are specified using the keywords X_RATE, Y_RATE, and Z_RATE denoting an X, Y and Z body rotation rate. Note that typically an attitude is specified using a quaternion and the Euler angle rates of the body with respect to an inertial frame, given in the body fixed frame. This parameterization of the attitude could be specified as in the example in Figure 4.

Figure 4: Example of Quaternions and Euler rates to Specify an Attitude Transformation

```
CCSDS_APM_VERS          = 1.0
CREATION_DATE           = 2012-01-21T19:23:57
ORIGINATOR              = GSFC
OBJECT_NAME             = YOURSAT
OBJECT_ID               = 2009-024B
CENTER_NAME             = MARS
TIME_SYSTEM             = UTC

EPOCH                   = 2012-01-21T19:21:49.3455
Q_FRAME_A               = SC_BODY
Q_FRAME_B               = J2000
Q_DIR                   = A2B
Q1                      = 0.03123
Q2                      = 0.78543
Q3                      = 0.39158
QC                      = 0.47832
COMMENT Euler rates of YOURSAT w.r.t. Mars J2000, given in the body
COMMENT frame
EULER_FRAME_A           = SC_BODY
EULER_FRAME_B           = J2000
EULER_ROT_SEQ           = 312
RATE_FRAME              = EULER_FRAME_A
ROLL_RATE               = 0.1045       [deg/s]
PITCH_RATE              = 0.03214      [deg/s]
YAW_RATE                = 0.02156      [deg/s]
```

The final specification of attitude in an APM is that of a spinning spacecraft using the specification of right ascension and declination of the spin axis, the phase of the spin and the angular velocity of the spinning vehicle to fully specify the spin attitude. In addition to this information, the spin attitude can be augmented by providing information about the nutation of the spin by specifying the nutation angle, nutation period and the nutation phase. This information will fully specify the orientation of the spin axis and enable the user to propagate the spin attitude.

In addition to the spin parameterization, the message must specify reference frame information similar to those specified in the quaternion and Euler angle sections. The keywords provided for the specification of attitude for a spinning satellite are summarized in Table 3.

Table 3: Keywords for the Attitude of a Spinning Satellite

Keyword	Description	Example Values or Units
SPIN_FRAME_A	Body-fixed, inertial or rotating reference frame	SC_BODY TAM_1
SPIN_FRAME_B	Body-fixed, inertial or rotating reference frame	ITRF-97 J2000
SPIN_DIR	Direction of spin rotation	B2SPIN SPIN2B
SPIN_ALPHA	Right ascension of the spin axis vector	deg
SPIN_DELTA	Declination of the spin axis vector	deg
SPIN_ANGLE	Phase of the satellite about the spin vector	deg
SPIN_ANGLE_VEL	Angular velocity of the satellite around spin axis	deg/s
NUTATION	Nutation angle of spin axis	deg
NUTATION_PER	Body nutation period of the spin axis	seconds
NUTATION_PHASE	Inertial nutation phase	deg

In addition to the specification of attitude using a quaternion, Euler angles, or spin parameters, an APM also allows for the specification of attitude maneuvers. The maneuvers are specified irrespective of the torque that generated the maneuver, but rather specify the torque itself. The keywords provided for a maneuver are the start time of the maneuver (MAN_EPOCH_START), the duration of the maneuver (MAN_DURATION), the reference frame for the maneuver (MAN_REF_FRAME), and finally the torques to apply for the maneuver, MAN_TOR_1, MAN_TOR_2, MAN_TOR_3. To properly interpret this information, other keywords are provided to specify the inertias of the object, but these do not necessarily need to be repeated for each maneuver.

Attitude Ephemeris Message (AEM)

The attitude ephemeris message takes much of this same information and attempts to compact it for delivering the attitude at multiple epochs in a single message. This compacting is achieved by specifying more information in the metadata that enables the unambiguous interpretation of the attitude data that follow. In addition to the standard header, the metadata for an AEM consists of the name of the object and its identification number (OBJECT_NAME and OBJECT_ID), the time system used to specify the epochs (TIME_SYSTEM), the reference frames, REF_FRAME_A and REF_FRAME_B, a keyword for the direction of the rotation (ATTITUDE_DIR), and the start and stop times of the attitude data (START_TIME, STOP_TIME).

In addition to these necessary parameters, the AEM achieves compactness by having an ATTITUDE_TYPE keyword that denotes the format of the lines of data that are in a message. There is no mandatory set of data that must be provided in an AEM, so the provider is free to specify attitude using any of several pre-defined parameterizations. The values for the ATTITUDE_TYPE keyword are summarized in Table 4.

Table 4: Values and Description for ATTITUDE_TYPE in an AEM

Keyword	Value	AEM Data Line
Quaternion Options		
QUATERNION_TYPE	FIRST	
ATTITUDE_TYPE	QUATERNION	Epoch, QC, Q1, Q2, Q3
	QUATERNION/DERIVATIVE	Epoch, QC, Q1, Q2, Q3, QC_DOT, Q1_DOT, Q2_DOT, Q3_DOT

	QUATERNION/RATE	Epoch, QC, Q1, Q2, Q3, X_RATE, Y_RATE, Z_RATE
Euler Angle Options		
ATTITUDE_TYPE	EULER_ANGLE	Epoch, X_ANGLE, Y_ANGLE, Z_ANGLE
	EULER_ANGLE/RATE	Epoch, X_ANGLE, Y_ANGLE, Z_ANGLE, X_RATE, Y_RATE, Z_RATE
Spin Axis Options		
ATTITUDE_TYPE	SPIN	Epoch, SPIN_ALPHA, SPIN_DELTA, SPIN_ANGLE, SPIN_ANGLE_VEL
	SPIN/NUTATION	Epoch, SPIN_ALPHA, SPIN_DELTA, SPIN_ANGLE, SPING_ANGLE_VEL, NUTATION, NUTATION_PER, NUTATION_PHASE

In the case of the 'Quaternion Options', there is a keyword QUATERNION_TYPE that allows the user to have the scalar value of the quaternion specified as the first or last element. The lines for the keyword QUATERNION_TYPE = LAST are not shown in Table 4. In addition, other keywords are provided to fully specify the interpretation of the attitude. There are also keywords to complete the specification of Euler angles and Euler rates using EULER_ROT_SEQ to specify the rotation sequence, and RATE_FRAME to specify the Euler rates frame. Figure 5 gives an example of an AEM using quaternions and Euler rates.

Figure 5: AEM example using Quaternions and Euler rates

```
CCSDS_AEM_VERS        = 1.0
CREATION_DATE         = 2012-11-04T17:22:31
ORIGINATOR            = NASA/JPL
META_START
OBJECT_NAME           = bigsat
OBJECT_ID             = 2010-001A
REF_FRAME_A           = EME2000
REF_FRAME_B           = SC_BODY
ATTITUDE_DIR          = A2B
TIME_SYSTEM           = UTC
START_TIME            = 2012-11-04T09:14:34.5633
STOP_TIME             = 2012-11-04T09:44:19.4533
ATTITUDE_TYPE         = QUATERNION/RATE
QUATERNION_TYPE       = FIRST
META_STOP
DATA_START
2012-11-04T09:14:34.5633 0.56748 0.03146 0.45689 0.68427 0.024 0.001 0.003
. . .
2012-11-04T09:44:19.4533 -0.84532 0.26974 -0.06532 0.45652 0.001 0.001 0.020
DATA_STOP
```

Recently, the ADM has gone through the CCSDS Agency Review, and prototypes are in development at CNES and NASA/GSFC. Upon completion of the implementation testing phase of the CCSDS Standardization Process, the Navigation Working Group plans to progress the ADM to a CCSDS Blue Book subsequent to the CCSDS Fall 2007 Meetings at Heppenheim, Germany, with the approval of the CESG.

Tracking Data Message

The Tracking Data Message (TDM) specifies a standard message format for use in exchanging spacecraft tracking data between tracking data users, primarily the world's space agencies. Such exchanges are used for distributing tracking data output from routine interagency cross-supports in which spacecraft missions managed by one agency are tracked from a tracking station managed by a second agency. The standardization of tracking data formats facilitates space agency allocation of tracking sessions to alternate tracking resources and international cooperation in the provision of tracking services.

The TDM standard is designed for the inter-agency exchange of tracking data types such as Doppler, transmitted/received frequencies, range, angles, Delta-DOR (Differenced One-Way Ranging), media correction, weather, etc. Part of the challenge associated with this range of data types has been arriving at a keyword set that is broad enough to meet all needs, but still retains the notion of economy and general applicability. Table 5 below lists the TDM Data Section keyword set that has been agreed upon.

Table 5: Summary Table of TDM Data Section Keywords

Keyword	Units	Notes
Signal Related Keywords		
CARRIER_POWER	dBW	Strength of radio signal, as received at ground
DOPPLER_INSTANTANEOUS	km/s	Instantaneous range rate of spacecraft
DOPPLER_INTEGRATED	km/s	Mean range rate of the spacecraft over the INTEGRATION_INTERVAL
PC_N0	dBHz	Carrier power to noise spectral density ratio
PR_N0	dBHz	Ranging power to noise spectral density ratio
RANGE	km, RU or s	Range measurements from ambiguous ranging systems, differenced range, skin radar, proximity radar, or similar radar
RECEIVE_FREQ	Hz	Measurements of the received frequency
TRANSMIT_FREQ_n (n = 1, 2, 3, 4, 5)	Hz	Measurements of a transmitted frequency
TRANSMIT_FREQ_RATE_n (n = 1, 2, 3, 4, 5)	Hz/s	Linear rate of change of the transmit frequency starting at the timetag
VLBI/Delta-DOR Related Keywords		
DOR	s	Used for the spacecraft observable in a Delta-DOR measurement.
VLBI_DELAY	s	Used for the quasar observable in a Delta-DOR measurement.
Angle Related Keywords		
ANGLE_1	deg	Azimuth, right ascension, or 'X' angle of the measurement, depending on the value of the ANGLE_TYPE keyword
ANGLE_2	deg	Elevation, declination, or 'Y' angle of the measurement, depending on the value of the ANGLE_TYPE keyword.
Time Related Keywords		

Keyword	Units	Notes
CLOCK_BIAS	s	Used to reflect clock offsets between 2 clocks (e.g., station clock and UTC).
CLOCK_DRIFT	s/s	Used to reflect clock drifts between 2 clocks (e.g., station clock and UTC).
Media Related Keywords		
STEC	TECU	Slant Total Electron Count
TROPO_DRY	m	Dry zenith delay through the troposphere
TROPO_WET	m	Wet zenith delay through the troposphere
Meteorological Related Keywords		
PRESSURE	hPa	Barometric pressure
RHUMIDITY	%	Relative humidity
TEMPERATURE	K	Temperature at the timetag

As noted earlier, each of the NDMs has a metadata section. For the TDM, the metadata section contains a large number of keywords that qualify the data section keywords and provide supplementary information that is necessary in order to interpret the data. There are a few metadata keywords that are required for every TDM, but in general there are only a very small number because most of the metadata keywords would be meaningless for several data types. For example, for the integrated Doppler data type, it is necessary to know the INTEGRATION_INTERVAL and the INTEGRATION_REF. The first of these is self-explanatory; the second provides the information as to whether the timetag on the data is the start, middle or end of the integration period. For some special applications, it is also necessary to know the TIMETAG_REF, i.e., is the timetag the transmit time or the receive time. In many cases this is somewhat obvious, but there are some applications in which data normally considered downlink data is tagged with the transmit time. But these three metadata keywords are not necessary to explain media calibration data or clock data. Other metadata keywords in the TDM include the START_TIME, STOP_TIME, the tracking MODE associated with the data, the signal PATH, TRANSMIT_BAND, RECEIVE_BAND, FREQ_OFFSET, RANGE_MODE, RANGE_MODULUS, RANGE_UNITS, ANGLE_TYPE, REFERENCE_FRAME, TRANSMIT_DELAY, RECEIVE_DELAY, DATA_QUALITY, and a set of CORRECTION_* keywords which apply to the various data types. One of the most important metadata keywords, required in all TDMs, is the set of PARTICIPANT_n keywords. These are used to identify the entities involved in the tracking session (spacecraft, antennas, quasars, etc.). For any given TDM data type, the metadata keywords fall into three categories: required metadata, situation-specific required metadata, and completely optional metadata.

Because of the large amount of data typically collected in a tracking pass, the TDM is suited to inter-agency exchanges from one computer to another (e.g., file transfer). It is acknowledged that the first version of the TDM may not apply to every single tracking session or data type; over the years engineers have developed many very creative ways to track their spacecraft. However, it is desired to focus on covering approximately the ‘95% level’ of tracking scenarios, and to expand the coverage in future versions as experience with the TDM is gained.

Based on the variety of data types, and the variety of tracking systems which exist in the various agencies, it is recommended that the TDM 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 of transferring data that will be supported, frequency of exchange, etc.

The TDM standard is applicable only to the message format and content, but not to its transmission. The method of transmitting of the message between exchange partners is beyond the scope of the standard, but 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. In general, the transmission mechanism must not place constraints on the technical data content of a TDM. While many of the agencies which plan to use the TDM are considering transferring file-based TDMs, another CCSDS Working Group, the Cross Support Transfer Services Working Group, is in the process of developing a standard for the real time transfer of radiometric tracking data that will use the TDM as the data format.

Completion of the TDM has been identified by the Interagency Operations Advisory Group (IOAG, http://www.ioag.org) as one of its top priorities. The IOAG is a consortium of the world's major space agencies that provides suggestions for interoperability standards and requirements to standards organizations (CCSDS, Space Frequency Coordination Group) and requirements organizations (Interagency Coordination Panel, Interagency Programs and Projects).

Recently, the TDM has gone through two CCSDS Agency Reviews, and prototypes are in development at DLR, ESA and NASA/JPL. Upon completion of the implementation testing phase of the CCSDS Standardization Process, the Navigation Working Group plans to progress the TDM to a CCSDS Blue Book subsequent to the CCSDS Fall 2007 Meetings at Heppenheim, Germany, with the approval of the CESG. The first operational use of the Tracking Data Message may come in late 2007 with the exchange of Delta-DOR data collected by ESA ground stations tracking NASA's Phoenix spacecraft.

Figures 6 and 7 are example TDMs drawn from the standard document. The first conveys transmitted frequencies, transmitted frequency rates, and received frequencies that can be used in a Doppler calculation. The second conveys integrated Doppler, range, and angle data in a single TDM. These represent only 2 examples of the kinds of tracking data that may be exchanged via the TDM. It is a very flexible data structure, which makes it prohibitive to show examples of all the ways in which a TDM can be formed within the confines of this paper. Interested readers are referred to Annex D of the TDM document [3], which contains a much larger set of examples of TDMs, encompassing the full range of data types which may be exchanged via the TDM.

Figure 6: TDM Example of Two-Way Frequency Data for Doppler Calculation

```
CCSDS_TDM_VERS=1.0
COMMENT TDM example created by yyyyy-nnnA Nav Team (NASA/JPL)
CREATION_DATE=2005-184T20:15:00
ORIGINATOR=NASA/JPL
META_START
TIME_SYSTEM=UTC
START_TIME=2005-184T11:12:23
STOP_TIME=2005-184T13:59:48.27
PARTICIPANT_1=DSS-55
PARTICIPANT_2=yyyy-nnnA
MODE=SEQUENTIAL
PATH=1,2,1
TIMETAG_REF=RECEIVE
INTEGRATION_INTERVAL=1.0
INTEGRATION_REF=MIDDLE
FREQ_OFFSET=0.0
META_STOP
DATA_START
TRANSMIT_FREQ_1=2005-184T11:12:23     7175173383.615373
TRANSMIT_FREQ_RATE_1=2005-184T11:12:23  0.40220
```

```
TRANSMIT_FREQ_1=2005-184T11:12:24     7175173384.017573
TRANSMIT_FREQ_RATE_1=2005-184T11:12:24  0.40220
. . .
TRANSMIT_FREQ_RATE_1=2005-184T11:12:36  0.40220
TRANSMIT_FREQ_1=2005-184T11:12:37     7175173389.246173
TRANSMIT_FREQ_RATE_1=2005-184T11:12:37  0.40220
TRANSMIT_FREQ_1=2005-184T11:12:38     7175173389.648373
RECEIVE_FREQ_1=2005-184T13:59:27.27  8429753135.986102
RECEIVE_FREQ_1=2005-184T13:59:28.27  8429749428.196568
. . .
RECEIVE_FREQ_1=2005-184T13:59:41.27  8429749420.204178
RECEIVE_FREQ_1=2005-184T13:59:42.27  8429749419.596043
DATA_STOP
```

Figure 7: TDM Example of Angles, Range and Doppler Combined in a Single TDM

```
CCSDS_TDM_VERS = 1.0
COMMENT  GEOSCX
CREATION_DATE = 2006-12-08T10:12:40.472
ORIGINATOR = GSOC

META_START
TIME_SYSTEM = UTC
START_TIME = 2005-12-15T00:00:02.000
STOP_TIME = 2005-12-18T23:59:42.000
PARTICIPANT_1 = WHM1
PARTICIPANT_2 = EW5
MODE = SEQUENTIAL
PATH = 1,2,1
INTEGRATION_INTERVAL =  10.0
INTEGRATION_REF = END
RANGE_MODULUS =   1.000000E+07
ANGLE_TYPE = AZEL
DATA_QUALITY = RAW
META_STOP

DATA_START
ANGLE_1               = 2005-12-15T00:00:02.000         57.691180
ANGLE_2               = 2005-12-15T00:00:02.000         37.052172
RANGE             = 2005-12-15T00:00:02.000   3.824634898E+04
DOPPLER_INTEGRATED    = 2005-12-15T00:00:02.000      -1.781311000
ANGLE_1               = 2005-12-15T00:00:12.000         57.680980
ANGLE_2               = 2005-12-15T00:00:12.000         37.064578
RANGE             = 2005-12-15T00:00:12.000   3.824629493E+04
DOPPLER_INTEGRATED    = 2005-12-15T00:00:12.000      -1.761957000
. . .
ANGLE_1               = 2005-12-18T23:59:32.000        219.206514
ANGLE_2               = 2005-12-18T23:59:32.000         27.411017
RANGE             = 2005-12-18T23:59:32.000   3.908802298E+04
DOPPLER_INTEGRATED    = 2005-12-18T23:59:32.000      -2.175859000
ANGLE_1               = 2005-12-18T23:59:42.000        219.226135
ANGLE_2               = 2005-12-18T23:59:42.000         27.367472
RANGE             = 2005-12-18T23:59:42.000   3.908801697E+04
DOPPLER_INTEGRATED    = 2005-12-18T23:59:42.000      -2.153102000
DATA_STOP
```

Conclusion

It is essential to develop standards to serve the purpose of easing communications and correct interpretation of data for future space missions within an agency and between agencies. In particular, interagency partnering in the operation of space missions is becoming more and more widespread; the development and use of international standards is essential to accommodating such partnering in an efficient fashion. The Navigation Data Messages detailed here have encapsulated the necessary information for processing of orbit, attitude and tracking data into a compact message that can be read by humans and computers. It is hopeful that the implementation of these standards into future systems is not overly burdensome, but moreover they are of a benefit to the agencies that use them and exchange them. The Navigation Data Messages presented here give a specification and unambiguous interpretation of orbit, attitude and tracking data as can be shown in the examples here, and those in [1], [2], and [3].

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