The Evolution of the CCSDS Orbit Data Messages

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The Consultative Committee for Space Data Systems (CCSDS) Orbit Data Messages (ODM) is undoubtedly the most successful and widely infused international standard developed by the CCSDS Navigation Working Group (NavWG). In 2004, the first version of the ODM was published after a development period of several years; before this, there was no CCSDS or ISO standard for the representation of a spacecraft trajectory. This paper will describe in detail the evolution of the CCSDS ODM through its several versions past, present, and future; its infusion into spacecraft operations in many if not most of the Earth's major space agencies; and some of the growing number of applications in which it is being utilized.

I. Introduction

THE Consultative Committee for Space Data Systems (CCSDS) was established in 1982 to foster international cooperation in the development of standards for data communication and data exchange supporting space research [1]. The CCSDS represents the technical branch of the International Organization for Standardization (ISO) Technical Committee 20, Subcommittee 13 (TC20/SC13). The work of the CCSDS is organized into six Areas and further subdivided into over twenty Working Groups [2]. The CCSDS Navigation Working Group (NavWG) is part of the Mission Operations and Information Management Services (MOIMS) Area and its charter is to provide "a discipline-oriented forum for detailed discussions and development of technical flight dynamics standards (orbit/trajectory, attitude, tracking, maneuver, pointing, orbital events, conjunction assessment, etc.)" [3]. The NavWG includes regular membership representing seven of the eleven CCSDS member Space Agencies. As of this writing, the group includes representatives from the Centre National d'Etudes Spatiales (CNES, France), the Deutsches Zentrum für Luft- und Raumfahrt (DLR, Germany), the European Space Agency (ESA, European Union), the Japan Aerospace Exploration Agency (JAXA, Japan), the National Aeronautics and Space Administration (NASA, USA), the Russian Federal Space Agency (RFSA, Russia), and the UK Space Agency (UKSA, United Kingdom). There is also observer representation from the Electronics and Telecommunications Research Institute (ETRI, South Korea) and a liaison relationship with the ISO Technical Committee 20, Subcommittee 14 (ISO TC20/SC14)[3] . The NavWG meets twice per year for face-to-face meetings to conduct its standards development work, and meets approximately monthly via telecon to discuss special topics, get status on action items, review schedules, etc. Starting in 2004, the progress of the NavWG has been regularly presented at various conferences, including the International Symposium on Space Flight Dynamics (ISSFD) [4-5,7-8] and SpaceOps [6], in order to keep space flight dynamics practitioners informed regarding recent developments in standardized data exchange formats.

Given that spacecraft operations require knowledge of the spacecraft trajectory, and the fact that space missions increasingly involve more than a single organization, trajectory information frequently needs to be exchanged between organizations. The CCSDS was reminded of the importance of standardizing such data exchanges after learning of a satellite operator's failed attempt [9] to exchange data in compatible formats prior to a relatively high-risk GEO satellite transit due to a lack of data exchange standardization that used a common format, reference frame, timing system and element sets. The CCSDS Orbit Data Messages (ODM) was developed specifically for this data exchange process. The ODM provides a means of exchanging information on spacecraft trajectories in an international standard format that is easily read, easily processed, and does not require software produced by any other space

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agency/operator. The ODM is undoubtedly the most successful and widely infused international standard developed by the NavWG. This paper will describe in detail the evolution of the ODM through its several versions, its infusion into spacecraft operations in many if not most of the Earth's major space agencies, and some of the growing number of applications in which it is being utilized.

II. Basics of the CCSDS Standardization Process and the CCSDS Spectrum

In brief, CCSDS standards proceed through several progressively more mature levels: Concept Paper, Proposed Standard, Draft Standard, and finally Recommended Standard, a process defined in detail in Ref. [10]. Concept Papers and Proposed Standards are documents internal to a designated CCSDS Working Group; and the Draft Standard is made available for external review and commentary by the world wide technical community. Recommended Standards are suitable for implementation in operations by virtue of the fact that in order to achieve the Recommended Standard status "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]. The Recommended Standards are available without charge on the CCSDS website "Publications" link [11] and are available through ISO.

Historically, the CCSDS printed paper copies of documents with colored covers: Proposed Standards had white covers, Draft Standards had red covers, and Recommended Standards had blue covers; these three levels in the hierarchy became known as "White Book", "Red Book", and "Blue Book" respectively. Usage of these terms continues, though printed copies of CCSDS documents are no longer produced in the digital age. Though not specifically relevant to this paper, other colors in the CCSDS spectrum include "Green Books" (Technical Reports), "Yellow Books" (Reports, Records, and Normative Procedures of the CCSDS), and "Silver Books" (Historical Documents) [10].

III. Orbit Data Messages "Version 0"

The first Blue Book developed by the predecessor of the NavWG (the "CCSDS Panel P1J") was called "Radio Metric and Orbit Data" [12]. Published in 1987, it consisted of a total of 15 pages, seven of which can be considered CCSDS boilerplate (cover, table of contents, various front matter sections). Two pages deal with orbital elements, one page describes the reference system, two pages discuss tracking data, there is a two-page appendix, and there is one page for a few references. There is no mention of attitude/orientation or maneuvers. It is not known how this document was used in practice given that no member of the Panel P1J at the time is still in the NavWG. Interestingly, though the stated purpose of the document was "to establish common recommendations for adequately exchanging data involved in orbit computation" [12], no format for the data is specified. Important attributes such as required content, applicable units, a few constants and conversions, etc., were provided, but the format was entirely unspecified. Notably, there are no "shall" statements in the document (i.e., engineering-speak for "no requirements"); there are numerous "should" statements. It does however seem that this simple document informed the later development of the Orbit Data Messages Version 1 and another NavWG standard, the Tracking Data Message. Between April and October 2003, the CCSDS was reorganized; during this reorganization Panel P1J became the "Navigation Working Group", with charter essentially unchanged. The "Radio Metric and Orbit Data" standard was finally retired from the CCSDS active documents and given "Silver Book" status in November of 2003, as the ODM Version 1 was nearing completion.

IV. Orbit Data Messages Version 1

The ODM Version 1 (hereafter, "ODMV1") [13] was the first standard published by the "new" NavWG. Work on the ODMV1 commenced in the late 1990's. It was under development for several years, during which three formal CCSDS Agency Reviews of the document were conducted (June 2001, June 2002, November 2003) before it finally became a CCSDS Blue Book in September 2004. Prior to the publication of the ODMV1, there was no ISO international standard for the representation of a spacecraft trajectory. The ODMV1 had two data messages: the "Orbit Parameter Message" (OPM) and the "Orbit Ephemeris Message" (OEM). Primary requirements for the messages in the ODMV1 included a digital implementation that could be processed and stored via computer, and that the applicable object, time system, units, and reference frames were unambiguous and clearly identified. Other requirements provided that they did not require high fidelity dynamic modelling or the integration of the trajectory. The ODMV1 detailed the keywords allowed in the message, the allowable format of the data lines, the syntax allowed for text keywords, the units for numeric values, the format of time values, and recommended values for the character fields.

The OPM and OEM shared a common structure: a Header Section, a Metadata Section, and a Data Section; in these structural components, there were a mixture of required parameters and optional parameters. The Header Section provided basic identification information (message type, version number, creation date, message originator), the

Metadata Section provided information that does not change relative to the data and described the forthcoming data (i.e., "data about data" such as object identification, reference frame(s), time system, etc.). For the OEM, the Metadata Section also contained information regarding data start/stop times and parameters useful for interpolating between ephemeris states and covariances. The Data Section provided the actual trajectory data.

The OPM Data Section contained a single Cartesian state vector at a single instant in time that had to be propagated by the recipient to determine an arbitrary state. The OPM adopted the specification of the position and velocity of an object as the mandatory parameterization of an orbit. Optional components of the Data Section included osculating Keplerian elements of the orbit and the spacecraft parameters necessary for simple modeling of solar radiation pressure and atmospheric drag. The OPM also allowed for modeling of any number of maneuvers (as both finite and instantaneous events). OPMs were typically relatively short messages of low complexity and relatively low fidelity in the ODMV1.

The OEM Data Section consisted of a series of Cartesian state vectors that specified the position and velocity of a single object at an arbitrary number of epochs contained within a specified time range, a time sequenced series of states that in principle modeled all forces acting upon the spacecraft; it had to be interpolated by the recipient to determine an arbitrary state within the span of the ephemeris. The OEM was designed for exchanges that require higher fidelity or higher precision dynamic modeling than is possible with the OPM. Originally, these early prototype messages were known as "EPM"s (Ephemeris Parameter Message); however, after the concept for the Attitude Ephemeris Message was introduced in the NavWG, the "EPM" was rechristened as "Orbit Ephemeris Message" in October 2003. Even several years later one will occasionally come across old documentation that refers to the OPM and EPM as being the two message types in the ODM. The OEM allowed for dynamic modeling of any number of gravitational and non-gravitational accelerations, but did not specify them in the file; the effects were "built-in" to the states. In the ODMV1, the state vectors provided only position and velocity information (epoch, x, y, z, x', y', z'); no acceleration data was provided. A minimum OEM was required to have at least one Metadata Section and one Data Section, however, multiple occurrences of a Metadata Section followed by an ephemeris Data Section could be used if so desired. OEMs could be relatively large messages of moderate complexity in the ODMV1, particularly if the number of states was large and the inter-state delta-T was small.

As the ODMV1 was nearing publication, at the Spring 2004 meetings of the NavWG in Montreal, there was an agreement among attendees that the ODMV1 document design would be the model for future standards developed by the group (other standards were already in progress), and successive standards would be consistent with it. This agreement set the mold for most of what happened in the NavWG for several years, and there is still a major influence from the "ODMV1 Style", with features such as a Header section, a Metadata Section, and a Data Section; use of ASCII, a common format used in all computing architectures [14]; tables of mandatory and optional "keyword = value" (KVN) keywords with invariant order; one keyword/value pair per line; common numerical formats; clear definition of units that are ideally part of the International System (SI) of Units (either SI base units, SI derived units, or units outside the SI that are accepted for use with the SI) [15]. In the ODMV1, comments were allowed anywhere in the message, even though they were very likely to be processed by computers, rendering comments marginally useful in a large file such as an OEM. The "ODMV1 Style" also encouraged the use of Interface Control Documents (ICDs) jointly developed by exchange participants to capture special information and points of procedure that might not have been formally part of the standard. The ODMV1 standard addressed the format and content of the trajectory data to be exchanged, but did not discuss the method of transmission of these messages. Exchange partners were able to specify in the ICD provisions for the exchange mechanism, transmission protocol, security, message compression, etc.

The primary use case for the ODMV1 was to provide a trajectory representation to be used by missions cross-supported between Agencies of the CCSDS. The OPM was particularly useful for target states during launch scenarios and the OEM was well suited for applications that generate pointing and/or frequency predicts for tracking. One potential drawback of using OEMs was that files which spanned a long period of time or had a small delta-T between states could be quite large; this size could be compounded by the ASCII formatted files (as opposed to the size of a binary). One mitigating factor was that OEMs primarily planned for scheduling antenna time do not generally require very small delta-T.

Early versions of the ODM standard were used to support mutual tracking of ESA and NASA interplanetary spacecraft, especially during the arrival of the 2003 missions to Mars. An earlier prototype version of the OEM, the Ephemeris Parameter Message (EPM), was used, and it was still being used, waiting for the final approval of the OEM, for cross support between the ESA/European Space Operations Center (ESOC) and the NASA/Jet Propulsion Laboratory (JPL). ESA's Mars Express and ROSETTA were successfully tracked by NASA's Deep Space Network (DSN) antennas using EPMs, and JPL delivered EPMs to the ESA/ESOC for tests and contingency support for MER, MGS, Mars Odyssey, Cassini, Ulysses, and SOHO. The use of these prototypes in live operations helped to refine the

ODMV1 recommendation, and validated the feasibility of the basic ODM concept. Currently the OEMV1 is still used in regular operations at ESA/ESOC and NASA/JPL/DSN. JAXA also has the ability to produce OEMs. In industry software, the Satellite Tool Kit (STK) developed and marketed by Analytical Graphics Incorporated (AGI) can also output an OEMV1.

In January 2006, the ODMV1 was accepted by ISO as ISO-22644:2006, the first ISO international standard for the representation of an orbit. The ODMV1 standard consisted of a total of 43 pages including cover and all "boilerplate" sections, with 3 annexes.

V. Orbit Data Messages Version 2

Relatively soon after the ODMV1 was finalized, it became apparent that a somewhat parallel effort was underway in the ISO TC20/SC14 that could have resulted in a duplicate ISO standard for the representation of a trajectory. The SC14 was apparently unaware of the existence of the CCSDS ODMV1, and in fact had some trajectory use cases in addition to those that were used in developing the CCSDS standard. In the spirit of collaboration and consensus, SC13 and SC14 committed to work together on a modification to the existing ODMV1 standard that would accommodate the augmented set of requirements; as a result of this collaboration, a revision to the ODM (hereafter "ODMV2") [16] commenced in mid-2005.

In the ODMV2, a number of important changes were introduced. There are two categories of differences between the ODMV1 and the ODMV2. Some changes affected the content of one or more of the message formats, and some changes only affected the document. For the purposes of this paper, the changes that affected the content of the messages are of principal importance. The following lists the new and changed features in the ODMV2 relative to the ODMV1:

- A third message type was added to the two messages already in the ODMV1. This message, called the "Orbit Mean-Elements Message" (OMM) allowed a straightforward conversion from an ODM orbital state to a North American Aerospace Defense Command (NORAD) Two Line Elements (TLE) set and from a TLE to an ODM orbital state. The TLE had over the years become the "de facto" standard for the representation of mean orbital elements despite some well-documented deficiencies [17]. The OMM Data Section contains a single orbital state based on mean Keplerian elements at a specified epoch; in order to derive an arbitrary state, the OMM state must be propagated by the recipient using an orbit propagator that is consistent with the models used to develop the orbit data. It has provided a way for TLE users to transform the information in a TLE into an international standard format in a style that is consistent with that of the OPM and OEM. The OMM Metadata Section provides a keyword which allows the user to specify which of several possible mean element theories applies to the data (e.g., the Draper Semi-Analytic Satellite Theory (DSST)), thus indicating to the user the proper method for propagating the elements. Unlike for TLEs, there are no field limitations on the values in the OMM other than those presented by standard double precision numbers. The OMM has been infused into the USSTRATCOM "Space-Track" web page (see https://www.space-track.org/#/catalog) [18]. Here one can see TLEs and the associated OMMs right alongside each other.
- A 6x6, lower triangular form position/velocity covariance matrix which reflects the uncertainty of the mean Keplerian elements was also included in the OMM definition in order to facilitate conjunction assessment and the calculation of a collision probability using TLE's. In principle, we do not know precisely where a satellite might be within an ellipsoid defined by the covariance matrix. Adding covariance matrices was one of the key new requirements that emerged from the collaboration with SC14.
- The 6x6 covariance matrix construct was also added to the ODMV2 OPM and OEM as a set of optional parameters (lack of information regarding the trajectory uncertainties was acknowledged by the NavWG as having been a technical oversight in the ODMV1). This provided a way for producers of these files to provide the uncertainties associated with the state(s) and a physical connection between measurements and state variables. An OPM may contain a single covariance matrix; an OEM may support one or more covariance matrices.
- Optional acceleration components were added to the position/velocity state vectors provided in the OEM format. It has been noted that fewer ephemeris points, and thus less disk space for storing an ephemeris, may be required if accelerations are included in the state vector [19]. However, not all navigation software can process the accelerations as input, so these components were not made mandatory.
- The option to use the Julian Date in formatting of epochs and other time fields was withdrawn. as this format is described in neither the CCSDS Time Code Formats [20] nor the ISO 8601 standard "Data elements and interchange formats — Information interchange — Representation of dates and times" [21].
- The ODMV1 requirement to put the object identifying parameter in SPACEWARN format was changed from a requirement ("shall") to a recommendation ("should") based on operational uses of the OEM which did not enforce

the requirement. (Note that object identifiers in SPACEWARN are not currently being updated, so in the forthcoming ODMV3 a new authoritative source for the object identifiers will be recommended.)

- The fields in the "Spacecraft Parameters" block of the OPM were changed from mandatory to optional parameters since there were some applications that did not require them.
- A block of optional "User Defined Parameters" that had been included in the initial version of the OMM was added to the OPM. This has been one of the more controversial new features in the ODMV2 from the standpoint of the NavWG. This feature can allow users to add information that they consider to be mission-essential, but which is not codified in the standard. Another way in which this could have been accommodated would have been to use COMMENTs, however, it has been viewed as dangerous to specify in COMMENTs information meant to be used in operations. The use of User Defined Parameters necessitates an ICD to explain usage; it also implies a requirement for custom software development in order to utilize the non-standard information. Accordingly, user defined parameters were recommended to be used as sparingly as possible.
- A keyword to allow specification of the reference frame epoch was added to accommodate cases where the reference frame epoch is not intrinsic to the reference frame definition.
- The relationship between successive blocks of ephemeris data was clarified for interpolation purposes.
- A "Checklist ICD" consisting of candidate comment statements was added that was intended to facilitate the exchange of important information between partners when a formal ICD is neither required, desired, nor feasible. Extensive comments in an ODM were recommended in cases where there is insufficient time to negotiate an ICD.
- The maximum line width for the OPM message was changed to 254 to be consistent with other NavWG standards.
- The case rules for text value fields were constrained to be only all uppercase or all lowercase (no mixed case values).
- Some restrictions were imposed on the placement of comment statements in order to allow easy conversion of ODMs from KVN format to XML format or vice versa.

In some cases, a user may wish to create an orbit message that is compliant with the ODMV2 and is also compatible with the ODMV1. Because of the way the ODMV2 was designed, it is possible to "upgrade" to ODMV2 by observing a few simple conventions that will minimize the necessity to modify existing ODMV1 application code. For example, if use of the new ODMV2 keywords and data structures is avoided by agreement in an ICD, then very little modification of existing application code will be necessary because no new mandatory keywords were added in the ODMV2; there were some changes from mandatory to optional in ODMV2, but as long as those keywords are present in an ODMV2 message processed by an ODMV1 program, there will be no issue. One exception is that because the OMM was introduced in ODMV2, there is no ODMV1 compatible OMM.

One of the primary "new" applications of the ODMV2 was related to space situational awareness due to the capability for enhanced analysis of collision avoidance, enhanced orbital debris tracking, and enhanced knowledge of uncertainties of the state vectors and states in the ephemeris. Pairs of space object trajectories can be analyzed to determine whether or not there are any close approaches/potential collisions of the objects within the shared span of the ephemerides. Currently there are several organizations using the ODMV2 (OEMs with covariance matrices in particular) for conjunction assessment, including NASA's Conjunction Assessment Risk Analysis (CARA) operation for Earth orbiters [22], AGI's Commercial Space Operations Center (ComSpOC) for Earth orbiters [23], and NASA's Multimission Automated Deepspace Conjunction Assessment Process (MADCAP) for Moon and Mars orbiters [24]. As the world's space agencies put more and more spacecraft into orbit at the Earth, Moon, and Mars, there will be an increasing need to exchange ephemeris data on a regular basis. Because of the traits of an ODM (international standard format, easily read, easily processed, etc.), the ODMV2 represents a good candidate for such data exchanges.

The ODMV2 was published in 2009. Responsibility for this second issue of the ODM was jointly shared by the SC13 and SC14; the formal arrangement involved development of the document by the SC13, but having the standard appear in the formal Work Programme of the SC14. ISO 26900:2012 was approved in July 2012, and ISO 22644:2006 was retired. The ODMV2 document consists of a total of 73 pages including cover and all boilerplate sections, with 7 annexes.

VI. The ODM in XML Format

In 2002, the CCSDS Management Council (CMC) directed the predecessor of the NavWG (Panel P1J) to use "PVL, or preferably XML in the CCSDS 502.0-R-2 Orbit Data Messages"[4]. The Extensible Markup Language (XML) [25] has some advantages over KVN for encoding ASCII data in that it allows for the definition of the data message in a machine-readable format that can be checked against a model (called a "schema") to verify that the data is

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[4] CMC-R-2002-10-009 Resolution, provided by Thomas Gannett, CCSDS Lead Editor, CCSDS Secretariat.

compliant with the model. There are widely-available software tools that can edit XML and check XML messages against the schemas to automatically determine whether or not the data messages comply with the standard (e.g., verification of time string formats, verification of numerical value formats, presence of correct units, range checking and allowed values for certain keywords). XML also allows the sharing of common message structures across different message types. Each participant in a data exchange can independently verify that a given message is compliant with the schema. Some disadvantages of using XML for encoding the ODMs are that two markup tags (i.e., keywords) are required for each value (opening/closing), which increases the file size; and, as with KVN, logic flow cannot be enforced. Additionally, some flight dynamics practitioners have expressed opposition to the exclusive use of XML for representation of navigation data in the ODM and future standards.

Based on the 2002 direction from the CMC, the NavWG was essentially obligated to produce XML formatting for the messages in the ODM. However, XML formatting of the OPM and OEM was not developed in time for the ODMV1 (or ODMV2) publication. In December 2010 the "Navigation Data Messages XML Specification" Blue Book (NDM/XML) [26] was published; development of this standard largely proceeded concurrently with the development of the ODMV2. The NDM/XML provided XML schemas for the OPM, OEM, and the then new OMM, as well as schemas for all other NavWG standards, along with instructions for how to code instantiations of these messages. As part of its CCSDS-required five-year review process, the NDM/XML is as of this writing being revised and much of its content is being moved to the associated standard documents as they are updated. This will avoid having to update the NDM/XML standard each time a new or updated Blue Book is published. The CCSDS Conjunction Data Message (CDM) document [27] was the first standard to implement this new direction, and all new/updated NavWG standards (including the ODM) will follow. Thus, the NavWG plans to continue providing both the KVN and XML representations of the orbit data messages (OPM, OMM, OEM). An agency can elect whether to provide the KVN or the XML version, or both, as meets their requirements with respect to exchange partners.

One key concept that was incorporated in the NDM/XML standard was the concept of a "combined instantiation". In such an XML message, orbit data messages could be combined as applicable with instantiations of other NavWG standards that described attitudes, tracking data, and conjunctions. A variant (and extension) of this concept will be leveraged in the ODM of the future described later in this paper.

VII. Orbit Data Messages Version 3

CCSDS operating procedures require a review of each standard every five years [10]. The review process has one of three possible outcomes: reconfirm the standard, retire it, or revise it. In the case of the ODMV2's periodic review in 2014, there was a decision to revise the document given that additional new use cases for the trajectory representation had emerged. Therefore, late in 2014, the NavWG embarked on an updated version of the ODM (hereafter, "ODMV3"). The new use cases in large part emerged as a result of the maturation of space object conjunction assessment processing and large-scale ephemeris exchange by such providers as ESA's Space Astronomy Center (ESA/ESAC), the ComSpOC, and the Space Data Association (SDA). The new use cases have resulted in the addition of another new message to the ODM, called the "Orbit Comprehensive Message" (OCM). As its name implies, the OCM represents a substantial expansion of the types of data available to describe the spacecraft trajectory than is available in the OEM, including more extensive covariance matrices, state transition matrices, maneuver information, perturbation information, etc. The OCM aggregates and extends much of the content of the three existing constituent messages in the ODM into a single hybrid message, and adds the ability to describe force models, orbit determination method used, and other information. In particular, the OCM will allow the exchange of more detailed information describing translational maneuvers than can be conveyed in the simpler Orbit Parameter Message (OPM). The 2004 ODMV1 model, with a few exceptions, has generally been observed by NavWG standards; though over time it has increasingly shown signs of strain. The addition of several new constructs and an emphasis on file compactness have resulted in a more complex style for the OCM that represents a significant departure from the 2004 ODMV1 model. And as noted previously, the ODMV3 will incorporate XML formatting material that is now treated separately in the NDM/XML standard [26].

The versions of the OPM, OMM, and OEM are essentially unchanged in the ODMV3, which should be of interest to current users of the ODMV2 from the standpoint of minimizing software changes, though some users might need to make software changes to accommodate the larger number of time systems and reference frames planned for inclusion in the ODMV3.

The ODMV3 is still in development; as of this writing the draft is becoming quite mature. The NavWG hopes to have this version of the ODM available sometime in late 2019/early 2020. Yet to go are final drafts (4 to 6 months), document processing by the CCSDS Editor (2 to 3 months), an Agency Review and resolution of comments (3 to 6

months), two prototypes (approximately 6 to 8 months), and internal polls to approve publication of the standard (2 to 3 months).

The most recent ODMV3 draft [28] consists of over 140 pages including cover and all boilerplate sections, with 12 annexes, continuing the growth of the ODM.

VIII.   The ODM and the Space Assigned Numbers Authority

The purpose of the CCSDS Space Assigned Numbers Authority (SANA) is to provide a single, CCSDS-wide, central location to register "a variety of standards-related information, such as protocol identifiers, agencies, service and data providers, XML schema, a glossary of terms, and other information that is used across CCSDS" [29]. The SANA Registry did not exist at the time the ODMV1 and ODMV2 were developed; however, the NDM/XML schemas (including the schemas for the OPM, OMM, and OEM) were the first approved registry on the SANA in February 2011. The NavWG is currently working to migrate the values for ODM keywords related to time system, reference frames, components of orbital elements sets and covariances, orbit centers, attitude parameters, etc. to SANA Registries from static document annexes that are infrequently updated. In the process of doing this, a number of time systems, reference frames, orbital element sets, etc. have been added as acceptable values for associated keywords. This work is currently in progress and will be unveiled in the ODMV3, or possibly earlier in conjunction with the publication of a different NavWG standard (several are in development or are in the process of being updated).

IX.   Orbit Data Messages "Version Future"

Two important objectives of CCSDS international standards are interoperability and cross-support, which makes consistency in data exchange standards essential. Still, maintaining consistency from one standard to another can be challenging. Additionally, as can be seen from the history to date of the ODM, new use cases have been arising on a fairly regular basis, some of which could require modifications to the standard.

For example, because spacecraft navigation depends on knowledge of the position/velocity of the spacecraft over time, the concept of "state" and related data items is ubiquitous. Accordingly, it permeates the NavWG standards. For example, a new NavWG standard currently in development called the Re-Entry Data Message (RDM) inherits many data items from the CDM standard, which inherits many data items from the ODM. This is not necessarily a problem if done in a manner that is consistent; however, at times various small inconsistencies have crept in, even though the NavWG endeavors to avoid duplication and achieve consistency.

Around the same time that the NavWG embarked upon the development of the ODMV3, struggles with the need to duplicate data structures without introducing inconsistency led to the informally proposed notion of a "universal, modular message". At the time, this casually-voiced notion seemed entirely wishful thinking, but as the ODMV3 has evolved and broken several of the constraints of the ODMV1 model, the "universal, modular message" concept seemed much more plausible. In this construct, users can combine one or more standardized message blocks within a single composite message, tailored to achieve specific mission needs. Within the NavWG, the concept is currently called the "NDM/KVN" (Navigation Data Messages KVN) in contrast to the NDM/XML standard), though it has had several names during the conceptual phase.

The NDM/KVN is in concept similar to the NDM/XML standard in that it allows a fusion of various pre-existing NavWG standards, though it is expected that the building block granularity will be smaller in the NDM/KVN than it is in the NDM/XML. It does represent a rather complete break with most of the ODMV1 2004 conventions. The NDM/KVN will present its own challenges, for example, accommodating past use cases while providing the flexibility to incorporate standard structures relating to a variety of flight dynamics scenarios including orbit, attitude, conjunctions, tracking, etc. The NDM/KVN may present conversion challenges to those agencies which currently process ODMs. To some extent the NavWG has been heading in this direction for a while, given the concept of the "combined instantiation" that was incorporated in the NDM/XML specifications document. One potential drawback to the NDM/KVN idea is that it may require an accompanying explanatory ICD, and the CCSDS Engineering Steering Group (CESG) has recently been discouraging reliance upon ICDs. The concept of this modular message is still in its early formative stages, but its feasibility continues to increase.

X.   Conclusion

This paper has described in detail the evolution of the CCSDS ODM, its infusion into cross-supported and interoperable spacecraft operations in many if not most of the Earth's major space agencies, and some of the growing number of applications in which it is being utilized. To date, the ODM has been one of the most successful and most broadly infused of the standards developed by the NavWG. Over time, it has evolved from a "non-message" (ODM "Version 0"); to a relatively short, simple standard with two messages (ODMV1); to a more complex standard with

three messages (ODMV2) and XML instantiations (NDM/XML); and is currently growing into a much more complex and richly featured standard spread across four messages with varying applications (ODMV3). As the CCSDS NavWG continues its transition to the "Navigation Data Message of the Future", it is conceivable that the ODM itself could cease to exist as a separate document, replaced by a compendium message framework that captures a broad set of navigation and flight dynamics constructs in a flexible, "building block" style. This will represent a partial return to the style of the original ODM "Version 0", in which there were no specified formats and little or no specified ordering for the data. Over the years, as the Orbit Data Messages international standard has matured, it has encompassed an increasingly broad number of use cases. It is now the primary standard for spacecraft trajectory exchange in interoperable, cross-supported space flight dynamics operations.

XI. Acknowledgments

XII. References

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