

INFUSION OF CCSDS FLIGHT DYNAMICS STANDARDS IN THE NASA AMMOS GROUND SYSTEM SOFTWARE

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Abstract: *The Consultative Committee for Space Data Systems (CCSDS) has developed a large number of space data related international standards that have been used by hundreds of space missions. Several flight dynamics related standards have been published by the CCSDS Navigation Working Group since 2004, and several more are currently in development. Some of these flight dynamics standards have been implemented in the NASA Advanced Multimission Operations System (AMMOS) ground system software. NASA's AMMOS software provides most of the functions needed to support the design, implementation, and operation of a Mission Operations System (MOS), including the focus of this paper, mission design/navigation. AMMOS is based on a simple idea: build the core elements of an MOS that are common to multiple missions once rather than having individual missions duplicate the effort, then adapt the core elements to account for the specific needs of individual missions. The AMMOS program provides substantial funding support for Mission Design and Navigation (MDN) software that is utilized across all space mission phases, from preliminary design through mission disposal. The AMMOS has been discussed frequently in a wide variety of Space Ops papers, but never previously at ISSFD. The AMMOS is a mature "system of systems" that has existed since the late 1980's, but it is continuously evolving and being improved. The evolution of the AMMOS is guided by a set of nine key architecture principles, among which are several that directly apply to the infusion of international standards. The AMMOS system primarily supports NASA's deep space and astrophysics missions, however, the AMMOS/MDN software has been utilized in support of many international missions as well. This paper discusses how the CCSDS flight dynamics standards have been implemented in the AMMOS/MDN software, and how they facilitate the provision of a multimission, multiagency operations environment. Primary ISSFD areas of interest addressed will be application of international standards in the areas of flight dynamics operations (principally tracking and orbit determination).*

Keywords: *International Standards, Flight Dynamics Operations, Tracking, Orbit Determination*

1. Introduction

The Consultative Committee for Space Data Systems (CCSDS) is a consortium of the world's major space agencies that since its creation in 1982 has developed a large number of space data related international standards that have been used by hundreds of space missions [1]. A component of this body of international standards is several standards in the area of flight dynamics developed by the CCSDS Navigation Working Group; several other standards are currently in various stages of development. Some of the CCSDS flight dynamics standards have been implemented into NASA's Advanced Multimission Operations System (AMMOS) ground system software [2]. The AMMOS system provides most of the functions needed to support the

design, implementation, and operation of a Mission Operations System (MOS), including functions that are the focus of this paper, mission design and navigation.

This paper will discuss how the CCSDS flight dynamics standards have been implemented in the AMMOS Mission Design and Navigation (MDN) software, and how they facilitate the provision of a multimission, multiagency operations environment. Provided will be a brief overview of the CCSDS and the standards developed by its Navigation Working Group, the NASA/AMMOS ground data system and its MDN software, the infusion of the CCSDS flight dynamics standards into the AMMOS/MDN software, and a brief history the usage of these standards in flight operations. Potential opportunities for further future infusion are also introduced.

2. CCSDS and the Navigation Working Group

The CCSDS is affiliated with the International Organization for Standardization (ISO) via the ISO Technical Committee 20, Subcommittee 13. Its mission is to develop communications and data systems standards for space flight. CCSDS has developed a large number of space data related international standards that have been used in some way by an ever growing number of space missions since its creation in 1982 (approximately 750 as of this writing); this number is growing all the time [3]. A component of this body of international standards is several standards in the area of flight dynamics developed by the CCSDS Navigation Working Group. The CCSDS Navigation Working Group is organized in the Mission Operations and Information Management Services Area, one of six areas into which the CCSDS is organized [4].

Specifically, the CCSDS Navigation Working Group is chartered to provide "development of technical flight dynamics standards (orbit/trajectory, attitude, tracking, maneuver, pointing, orbital events, etc.)", with the goal of increased possibility of flight dynamics interoperability [5]. Since 2004, several standards have been published in these areas: the Orbit Data Messages (ODM, 2004, 2009), Tracking Data Message (TDM, 2007), Attitude Data Messages (ADM, 2008), Conjunction Data Message (CDM, 2013), and Navigation Data Messages XML Specification (NDM/XML, 2010). Several other standards are currently in various stages of development. The development, history, and features of these standards have been featured in three previous ISSFD papers ([6], [7], [8]). Some of these flight dynamics standards have been implemented into NASA's Advanced Multimission Operations System (AMMOS) ground system software [2]. The CCSDS Standards Development Process is fully described in [9], so it will not be discussed in detail here. Full details on the ODM, TDM, ADM, CDM, and NDM/XML are specified in references [10], [11], [12], [13], and [14] respectively. Very brief descriptions of these CCSDS flight dynamics standards are:

- The ODM contains information that defines the orbit state of a spacecraft at one or more times. An instantiation of the ODM may be one of the following three messages that serve different purposes: the Orbit Parameter Message (OPM) specifies a single orbital state at epoch in Cartesian position/velocity coordinates or osculating Keplerian elements; the Orbit Mean-Elements Message (OMM) specifies a single orbital state at epoch in mean Keplerian elements; the Orbit Ephemeris Message (OEM) specifies Cartesian state vectors at any number of epochs within a time range.

- The TDM contains tracking data that can be used to determine the orbital state of a spacecraft.
- The ADM contains information that defines the attitude state of a spacecraft at one or more times. An instantiation of the ADM may be one of the following two messages that serve different purposes: the Attitude Parameter Message (APM) specifies a single attitude state at epoch; the Attitude Ephemeris Message (AEM) specifies the attitude state at any number of epochs within a time range.
- The CDM contains information that defines the relationship between the orbit states of two different space objects at their time of closest approach. The CDM is the final expression of the results of conjunction assessment processes and is intended to provide spacecraft operators with information they can use to assess the risk of collision and design collision avoidance maneuvers if necessary.
- The NDM/XML provides instructions for how to create XML formatted instantiations of the CCSDS flight dynamics standards. The primary format discussed in the various standards is a Keyword=Value Notation (KVN) format. As such, it is a supplement to the other standards.

3. The NASA Advanced Multimission Operations System (AMMOS)

NASA's AMMOS provides most of the functions needed to support the design, implementation, and operation of a Mission Operations System (MOS), consisting of multimission tools and services for the activities of mission planning, observation planning, sequencing, command generation/transmission, telemetry processing/display, data archive, spacecraft health/performance monitoring, instrument data processing, and the focus of this paper, mission design/navigation [2]. AMMOS is based on a simple idea: build the core elements of an MOS that are common to multiple missions once rather than having individual missions duplicate the effort, then adapt the core elements to account for the specific needs of individual missions. The foundation of common multimission tools and services enables mission customers to operate at a lower total cost to NASA, with comparable or higher reliability and performance and lower risk, than would be the case if these customers developed their own unique tools and services. The AMMOS program provides substantial funding for the development and maintenance of the MDN software that is utilized in preliminary mission design, launch analysis, navigation planning, tracking data planning, trajectory design/optimization, orbit determination, optical navigation, maneuver design/reconstruction, entry/descent/landing analysis and design, and real time event monitoring. The AMMOS has been discussed frequently in a wide variety of Space Ops papers [e.g., 15], but never previously at ISSFD.

While the AMMOS is a mature "system of systems" that has existed since the late 1980's, it is continuously evolving and being improved. Accordingly, since 2004, the use of CCSDS standards in the AMMOS/MDN software has been increasing. The evolution of AMMOS is guided by a set of nine key architecture principles formulated by the AMMOS Program Office [16]. Among these AMMOS architectural principles are several that directly apply to the infusion of international standards:

- Use of Common Services: By their very nature, international standards imply a significant degree of exploitation of commonality that is central to the AMMOS concept.

- **Customer Focus:** Space operations organizations that are customers of the AMMOS are nearly always focused on cost reduction wherever it is possible, and standards have a history of reducing non-recurring engineering costs.
- **Learn from Experience:** The content of international standards is informed by the experience of those involved in their development.
- **Interoperability:** One of the main purposes of standardization is to promote between cooperating organizations.

The integrated AMMOS system primarily supports NASA's deep space and astrophysics missions, however, the AMMOS/MDN software has been utilized in support of many international missions as well. These missions include ESA's Mars Express and ROSETTA; JAXA's SELENE, Hayabusa-1, Hayabusa-2, and Planet-C; and ISRO's Chandrayaan-1 and Mars Orbiter Mission. Part of what makes such support possible in an efficient manner is the infusion of CCSDS international standards into the AMMOS/MDN software and partner agency software.

4. The AMMOS Mission Design and Navigation (MDN) Software

The AMMOS/MDN software is broadly organized into several main code sets: Legacy Navigation Software, Legacy Mission Analysis Software, Optical Navigation, SPICE, and Monte/Masar. Very brief descriptions follow below.

The Legacy Navigation Software consists primarily of the Orbit Determination Program and assorted utilities, as well as the dynamical and observational models required for precise navigation to deep space destinations. The primary purpose of this software is determining the flight path of a spacecraft using multiple tracking data types from multiple tracking stations (primarily, the Deep Space Network). This software set is no longer used in operations and is no longer being actively updated; it has been functionally replaced by the Monte software set (see below).

Legacy Mission Analysis Software consists of various optimizing codes and search tools used to design and optimize spacecraft trajectories subject to a wide variety of mission goals and constraints. This software set still sees usage in analysis, but is no longer being actively updated; it has been functionally replaced by the Masar software set (see below).

Optical Navigation Software consists of software used to specify camera design, optical image parameters, and pointing; perform conversion of images into navigation observables as a supplement to radiometric observables; perform determination of small-body surfaces and dynamic characteristics based on optical images; and utilize surface landmarks in navigation.

SPICE consists of a large library of portable, extensively documented, multimission software APIs (subroutines) available in several languages [17]. These APIs can be incorporated into user programs to read SPICE files of various sorts (spacecraft and natural body ephemerides; body size, shape, and other characteristics; spacecraft and instrument orientation; instrument descriptions; reference frames; spacecraft clocks; leap seconds history; mission events). The SPICE APIs are then used to calculate observation geometry parameters such as range, latitude/longitude, and lighting angles, either for predicted events or past events. A geometric

event finder subsystem can be used to find times when certain geometric conditions occur. NOTE: SPICE is only partially funded by the AMMOS program.

Monte/Masar is the next generation software set for navigation and mission design. It has replaced and extended the functionality of the Legacy Navigation and Legacy Mission Analysis software sets in a system engineered, more readily maintainable environment. "Monte" is actually an acronym that stands for the "Mission Operations and Navigation Toolkit Environment" and its focus is primarily on spacecraft navigation. "Masar" is similar to Monte in that it is built on the same architectural model and there is extensive re-use of software infrastructure, but it focuses primarily on mission design functionality. "Masar" is also an acronym of sorts ("Mission Analysis Software ARchitecture"); not coincidentally it can be interpreted as meaning "trajectory" in Arabic.

5. CCSDS Navigation Standards Infusion into the AMMOS/MDN Software

As stated in "Principle 3 of Standardization" in [18] "The mere publication of a standard is of little value unless it can be implemented. Implementation may necessitate sacrifices by the few for the benefit of the many." (It should be noted that, aside from implementation, this same principle applies to standards development as well.)

In general, international standards are highly desirable in the exchange of navigation data to facilitate technical communications between agencies. As interagency partnering in mission operations becomes more widespread, the standardization of flight dynamics data formats increases in importance to facilitate interoperability. In missions where mission design and/or navigation functions for a mission of one agency are performed by another agency, standard formats can improve responsiveness, reduce costs, and expedite operations.

5.1. Operations Usage: The Orbit Data Messages (ODM)

The OEM [10] (one of the ODM formats) was the first of the CCSDS flight dynamics standards to be implemented in the AMMOS software. The OEM is the format used by the European Space Agency (ESA) for submission of spacecraft ephemerides to NASA's Jet Propulsion Laboratory (JPL) for tracking of multiple ESA spacecraft (e.g. Mars Express, Venus Express, ROSETTA) by the Deep Space Network (DSN) [19]. OEMs are also delivered to navigation teams at JPL, necessitating the ability to read them. Initially OEMs were converted to SPICE Spacecraft & Planetary Kernel (SPK) files via a SPICE utility "OEM2SPK"; the Monte software has also been enhanced to read the XML format of the OEM. 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) and conjunction assessment at Mars. JPL navigation team SPK files were originally converted to OEM files via a SPICE utility "SPK2OEM"; the Monte software has also been enhanced to write the KVN format of the OEM. Additionally, the Japan Aerospace Exploration Agency (JAXA) has used the OEM for DSN tracking of the SELENE and Hayabusa-2 spacecraft and navigation operations of Hayabusa-2. JPL navigation teams provide OEMs to the Indian Space Research Organization (ISRO) in support of the Mars Orbiter Mission. OEMs are produced by Monte for use by NASA's Conjunction Assessment Risk Analysis (CARA) processing for missions that either operate in or pass through the Earth orbital environment during a flyby (e.g., SMAP, Juno).

5.2. Operations Usage: The Tracking Data Message (TDM)

Monte/Masar can read a TDM instantiation created by either the DSN or several other tracking networks (notably ISRO, ESA/ESOC). The DSN produces TDMs as one of its standard tracking data output formats for providing ESA/ESOC the tracking data from multiple ESA spacecraft (e.g. Mars Express, ROSETTA). The Monte implementation of the TDM can both read and write TDMs that are compatible with the DSN's interface document [20]. For most cases at NASA/JPL, the DSN is the writer of choice for TDMs; however, certain international missions for which NASA/JPL's navigation services have been engaged prefer to receive their tracking data from the DSN with troposphere and ionosphere calibrations already applied to the data rather than having to apply these calibrations themselves. For these customers, the JPL navigation team reads DSN radiometric data and DSN media calibration data, applies the calibrations to the tracking data, and produces a TDM containing the calibrated tracking data that is provided to the customer. For example, JPL/MDNAV provides this calibrated tracking data TDM for the Indian Space Research Organization (ISRO) for the Mars Orbiter Mission.

5.3. Operations Usage: The Attitude Data Messages (ADM)

The ADM [12] is not currently used in operations by the AMMOS/MDN software; however, the SPICE team recently coded utilities in support of ESA's ExoMars mission that convert a SPICE "C-kernel" to an AEM, or convert an AEM to a SPICE "C-kernel". These limited functionality utilities (AEM quaternions only) were only recently prepared and have not yet been used in operations.

5.4. Operations Usage: The Conjunction Data Message (CDM)

The CDM [13] is not currently used in operations by the AMMOS/MDN software. However, recall that the CCSDS standardization process requires two prototypes prior to approving a standard. As one of those prototypes, the Multimission Automated Deepspace Conjunction Assessment Process (MADCAP) utility used for conjunction assessment at Mars and the Moon [21] was updated to produce a prototype CDM as an output option during the prototyping phase of the CDM [22]. Pending the availability of funding and customer interest, this standard format could relatively easily be formally added to the operations version of MADCAP.

5.5. Infusion Summary

Table 1 below summarizes the current level of infusion of the various CCSDS flight dynamics standards into the AMMOS/MDN software. A notation of "Read" means that the software set can ingest and process an instantiation of the standard. A notation of "Write" means that the software can produce an instantiation of the standard. A notation of "None" suggests an opportunity for expansion of the standards infusion level for software sets that are being actively updated. Note that the column marked "Other" includes both software outside the main AMMOS/MDN software sets and Non-AMMOS software with which the AMMOS/MDN software regularly interfaces.

Table 1. Infusion Matrix

AMMOS S/W→ CCSDS Standard ↓	Legacy Nav, Legacy MAS	Optical Navigation	Monte/Masar	SPICE	Other
ADM/AEM	None	None	None	Read/Write	None
ADM/APM	None	None	None	None	None
CDM	None	None	None	None	Write (prototype in MADCAP)
ODM/OEM	Read via Converters (OEM=>SPK =>NIO)	None	Read XML, Write KVN	Read (OEM2SPK), Write (SPK2OEM)	Read (DSN uses OEM2SPK)
ODM/OMM	None	None	None	None	None
ODM/OPM	None	None	Read	None	None
TDM	None	None	Read/Write	None	Write (DSN)

5.6. Future Infusions: Navigation Data Messages in Development

As noted in Section 2, there are several standards currently in development within the CCSDS Navigation WG. These are obviously not yet ready for operations implementation. However, as soon as the standards take rough form it can be beneficial to commence the prototyping process required by the CCSDS standardization process. The following standards are nearing the point where prototyping would be desirable and/or required: the Pointing Request Message (PRM) and the Navigation Hardware Message (NHM). Another set of messages, the Spacecraft Maneuver Messages (SMM), is fairly early in the process and is not quite ready for prototyping treatment.

- The PRM will provide a common and standardized format for the exchange of pointing requests between a requestor (e.g., a principal investigator) and spacecraft operators.
- The NHM will contain hardware information from onboard telemetry (e.g., accelerometers, GPS receivers, thrusters) that could be used to determine both the spacecraft attitude and orbit state. It will also contain information that could be used for spacecraft maneuver reconstruction.
- The SMM will contain information on the transformation from one state (attitude or orbit) to another via maneuvers. The exchange of maneuver data between organizations is critical for the planning, calibration, and reconstruction of spacecraft maneuvers.

Also under consideration is a standard framework for the exchange of orbit and attitude events; this standard is tentatively named the “Event Messages (EVM).” As these efforts are still underway, some in the very early stages, it remains to be seen how much they will be infused into the AMMOS/MDN software. Given the emphasis of SPICE on observation geometry, it seems possible that the PRM might find an implementation there, at least on the back end to analyze the request with respect to mission constraints and objectives. The NHM could be used in navigation software processing of "small forces files". The SMM could conceivably replace a number of proprietary maneuver interface files. The EVM could conceivably provide an

interface between the AMMOS/MDN software and the AMMOS sequencing software. Given the CCSDS requirement for two interoperable prototype implementations in a relevant operations environment (real or simulated) before approving a standard, it seems conceivable that some of the standards in development below will have prototypes developed by NASA/JPL in the AMMOS/MDN software. Historically (e.g., OEM2SPK), these prototypes can evolve into operations implementations.

6. Conclusion

As may be inferred from the above discussion of operations infusions, the implementation of CCSDS flight dynamics related standards in the AMMOS/MDN software has been somewhat uneven. Of the CCSDS flight dynamics standards, the OEM and TDM have been the most thoroughly infused and most utilized standards. This is primarily due to the realities of funding constraints on several levels, and lack of mission drivers. However, with the available funding and a prioritization of requirements a reasonably effective coverage of the major CCSDS flight dynamics standards has been achieved, and there are promising opportunities for future infusion of some of the flight dynamics standards under development.

7. Acknowledgements

This work was carried out at the Jet Propulsion Laboratory, California Institute of Technology, Pasadena, California, under contract to the National Aeronautics and Space Administration.

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