EXCHANGE OF STANDARIZED FLIGHT DYNAMICS DATA

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ABSTRACT

Spacecraft operations require the knowledge of the vehicle trajectory and attitude and also that of other spacecraft or natural bodies. This knowledge is normally provided by the Flight Dynamics teams of the different space organizations and, as very often spacecraft operations involve more than one organization, this information needs to be exchanged between Agencies. This is why the Navigation Working Group within the CCSDS (Consultative Committee for Space Data Systems) has been instituted with the task of establishing standards for the exchange of Flight Dynamics data. This exchange encompasses trajectory data, attitude data, and tracking data. The Navigation Working Group includes regular members and observers representing the participating Space Agencies. Currently the group includes representatives from CNES, DLR, ESA, NASA and JAXA. This Working Group meets twice per year in order to devise standardized language, methods, and formats for the description and exchange of Navigation data. Early versions of some of these standards have been used to support mutual tracking of ESA and NASA interplanetary spacecraft, especially during the arrival of the 2003 missions to Mars. This paper provides a summary of the activities carried out by the group, briefly outlines the current and envisioned standards, describes the tests and operational activities that have been performed using the standards, and lists and discusses the lessons learned from these activities.

1. THE CCSDS NAVIGATION WORKING GROUP

The Consultative Committee for Space Data Systems (CCSDS) is established as a forum for international cooperation in the development of data handling techniques supporting space research [1]. The work of the CCSDS is organized in Areas covering closely related subjects related to a particular technical discipline, with Working Groups chartered to produce specific standards. The CCSDS Navigation Working Group is part of the Mission Operations and Information Management Area and its charter is to provide a discipline-oriented forum for detailed discussions and development of technical flight dynamics standards. The Navigation Working Group is currently chaired by Felipe Flores-Amaya (NASA/GSFC) and is supported by representatives from CNES, DLR, ESA, JAXA, JPL and NASA. Each CCSDS Working Group is tasked to generate specific standards, and the standards assigned to the Navigation Working Group are:

1. Development of a Recommendation for the agency-to-agency exchange of orbit (trajectory) data. Deliverable: Orbit Data Messages CCSDS Recommendation.

2. Development of a Recommendation for the agency-to-agency exchange of tracking data. Deliverable: Tracking Data Message CCSDS Recommendation.

3. Development of a Recommendation for the agency-to-agency exchange of spacecraft attitude data. Deliverable: Attitude Data Message CCSDS Recommendation.

A recommendation starts as a Concept Paper, and when it reaches an appropriate level of completeness and maturity and has been reviewed it can be elevated to the "White Book" status, a proposed standard [2]. When the recommendation is found to be useful and mature, then it can be promoted to "Red Book" status, a draft standard. Finally, after the standard has been validated and tested and it has passed a formal review, it can then be approved as a "Blue Book", a recommended standard.

The three CCSDS recommendations described in this paper are being developed with the following principles in mind:

- Maximum commonality between recommendations: the way the documents are organized; the notation in which parameters are specified; the format used to represent numbers.

- Clear definition of units.

- Ease of transition to a common XML specification.

- Flexibility to include additional information, such comments and optional parameters.

- Identification of those items that cannot or should not be standardized, so they can be addressed in an Interface Control Document (ICD). Each document contains an Appendix, not formally part of the recommendation, that lists which items shall be addressed in an ICD.

The CCSDS Navigation Working Group documents address the format and content of the navigation data to be exchanged. They do not discuss the method of transmission of these messages. There are other groups within the CCSDS that make recommendations on service management, real-time and file transfers, transmission protocols, and data security. The navigation messages should be able to use these or any other means of transmission.

2. THE ORBIT DATA MESSAGES CCSDS RECOMMENDATION

The Orbit Data Messages (ODM) CCSDS Recommendation was the first standard that the Navigation Working Group started developing. It intends to be the baseline for trajectory representation in data exchange applications that are cross-supported between Agencies of the CCSDS [3].

The first thing that the group did was to develop a set of requirements that the new standard should fulfil. The requirements were divided between primary and heritage. The primary requirements included that the standard must be defined so the messages can be stored and used by computers, that a standard is provided that does not require high fidelity dynamic modelling or the integration of the trajectory, and that the messages are unambiguous, with time, units, and reference frames and systems clearly identified by the standard or in the message. The heritage requirements were developed to ensure a smooth transition between currently used trajectory formats and the new standard, and to make the use of the new standard independent of the use of a particular software set. Additionally the CCSDS management demanded that the standard should also be specified so it could be implemented using the Extensible Markup Language (XML) [4].

The group developed a recommendation that includes two different types of messages, the Orbit Parameters Message, a single state vector at a given time that represents the trajectory of the spacecraft, and the Orbit Ephemeris Message, a history of state vectors that can be interpolated to obtain the trajectory of the spacecraft at other times. The group decided to specify the messages as ASCII, so they could be easily readable and to facilitate the transition to XML. The thinking was that if the messages were too big, they could always be compressed, using easily available algorithms and programs, before they are transmitted. Binary formats have been used in the past for trajectory interchange, when bandwidth, computer memory and disk space were scarce, but have been shown to be difficult to inspect, and sometimes dependent on the computer architecture that was used to generate them.

The ODM is, at time that this paper is written, in the process of being approved for release as a Blue Book. DLR/GSOC and CNES have selected the ODM as their standard interface for future cross-support, and it is expected that it will also be adopted for future exchanges between JPL and ESA, and possibly JPL and JAXA, and JPL and GSFC.

2.1 Orbit Parameters Message

An Orbit Parameters Message (OPM) specifies the position and velocity of a single object at a specified epoch. This message is suited to inter-agency exchanges that involve automated and/or human interaction, and do not require high-fidelity dynamic modeling. The OPM requires the use of a propagation technique to determine the position and velocity at times different from the specified epoch, leading to a higher level of effort for software implementation than for the Orbit Ephemeris Message. The OPM is fully self-contained; no additional information is required. The standard also allows for modeling of any number of maneuvers (as both finite and instantaneous events) and simple modeling of solar radiation pressure and atmospheric drag. The attributes of this code also make it suitable for applications such as exchanges by FAX or voice, or applications where the message is to be frequently interpreted by humans.

The OPM starts with a header and metadata, followed by optional comments and then by the data. The header identifies the format, when the file was created, and who created it. The metadata identifies the object for which the trajectory is being provided, and the reference frame and time system used in the data. The data section contains the time, the Cartesian state vector, an optional Keplerian state, spacecraft parameters such as mass and drag and solar radiation pressure areas and coefficients, and, optionally, maneuvers. The data is specified in the "keyword = value" notation (KVN), with only one value per line. The recommendation specifies what the units shall be for numeric values, the format of time values, and what are the recommended values for the character fields. Figure 1 shows an example of a very simple OPM. The OPM message has been successfully tested with exchanges between DLR/GSOC and ESA/ESOC, and between JPL and GSFC.

2.2 Orbit Ephemeris Message

An Orbit Ephemeris Message (OEM) contains a set of time-tagged state vectors (Cartesian vectors providing position and velocity) that represent the trajectory of an object. The user of the OEM must have means of interpolating across these state vectors to obtain the state at an arbitrary time contained within the span of the ephemeris. The OEM is more suited to inter-agency exchanges that involve automated interaction (e.g., computer-to-computer communication where frequent, fast automated time interpretation and processing is required), and/or require higher fidelity or higher precision dynamic modeling than is possible with the OPM. The OEM allows for dynamic modeling of any gravitational and non-gravitational perturbations. The drawback of using OEMs is that the file size can be very large, especially for files with a long time span in a very dynamical environment, or when the time step chosen is small.

As for the OPM, the OEM starts with a header and metadata, followed by optional comments and then by the data. The header is similar to that of an OPM, and the metadata has similar parameters to that in an OPM, and additional parameters that specify the applicability and recommended method of interpolation. In an OEM the data section contains a set of ephemeris data lines, with the time, position and velocity of the object. Figure 2 shows an example of a very small OEM.

An earlier non-standard version of the OEM, the Ephermeris Parameter Message (EPM), was used, and it is still being used, waiting for the final approval of the OEM, for cross support between ESOC and JPL. ESA's Mars Express and Rosettta are being successfully tracked by NASA's DSN antennas using EPMs and JPL has also delivered EPMs to ESOC for tests and contingency support for MER, MGS, Mars Odyssey, Cassini, Ulysses, and SOHO. EPMs were also used to compare Ulysses and Mars Express trajectory solutions generated by ESOC and JPL. These interchanges not only helped to refine the ODM recommendation, like with the inclusion of parameters for interpolation method and usability interval, but also validated the feasibility of the basic ODM concept, including the use of the ASCII format. The files were compressed before transmission, using a widely available compression program; the size of a typical file with more than 30,000 ephemeris records was about 3.8 Mbytes, or 1.3 Mbytes when compressed. If the same information had been stored using a double precision binary representation the size of the resulting file would have been about 1.7 Mbytes. One issue that was identified during the exchange, but that cannot be forced by a standard recommendation, is that the precision of the file always should be commensurate with its accuracy and its expected use, especially for predictions. Using very precise models for predictions, and a lot of ephemeris records to follow the expected dynamics, is not really necessary when the prediction is going to be affected by errors in the models for things such as atmospheric density or propulsive spacecraft events. In addition, if the files are just going to be used to schedule antenna time, that is not going to require knowing the position of the spacecraft within millimeters; kilometer accuracy would suffice.

3. THE ATTITUDE DATA MESSAGES CCSDS RECOMMENDATION

The Attitude Data Message (ADM) is the equivalent of the ODM for attitude data. The ADM is being developed in parallel with the ODM and the Working Group is making sure that both recommendations are as close as possible to each other, in order to ease the implementation of both, encourage reuse of basic elements, and facilitate the transition to a shared XML implementation. The ADM also contains two message formats, the Attitude Parameters Message, with an instantaneous attitude state and optional attitude maneuvers, and the Attitude Ephemeris Message, with a history representation of the attitude of the object. The ADM is currently in "White Book" status.

3.1 Attitude Parameters Message

An Attitude Parameter Message (APM) is an ASCII description of the attitude, orientation, and angular velocity of a single object at a given time in a given reference frame. This message is suited to inter-agency exchanges that involve automated and/or human interaction, and do not require high-fidelity dynamic modeling. The APM may require the use of a propagation technique to determine the attitude orientation and angular velocity at times different from the specified epoch, depending on the reference frame and representation that is selected.

As with the OPM, the APM starts with a header and metadata, followed by optional comments and then by the data. The header identifies the format, when the file was created and who created it. The metadata identifies the object for which the attitude is being provided and the reference frame and time system used in the data. In the data section the APM requires the attitude state to always be represented by a quaternion, but it also allows for other optional information and representations: quaternion rates, Euler angles and their rates, angular momentum direction for spin-stabilized objects, moments of inertia, and attitude maneuvers. As for the APM the information is specified in the KVN format, with one value per line. The recommendation specifies what the units shall be for numeric values, the format of time values, and what are the recommended values for the character fields.

3.2 Attitude Ephemeris Message

The Attitude Ephemeris Message (AEM) is the attitude equivalent of the OEM, and in its data block or blocks it lists time-tagged attitude states. Again, like with the APM, the quaternion is always required, but users can also provide quaternion rates and Euler angles.

4. THE TRACKING DATA MESSAGE CCSDS RECOMMENDATION

The Tracking Data Message (TDM) CCSDS Recommendation specifies a standard message format for use in exchanging spacecraft tracking data between space Agencies. Such exchanges are used for distributing tracking data output from interagency cross supports in which spacecraft missions managed by one agency are tracked from a ground station managed by a second agency. Additionally, the ability to transfer tracking data between space agencies facilitates the allocation of tracking sessions to alternate antenna resources and increases the ability of space agencies to tolerate availability issues with their primary antennas.

The development of the Tracking Data Message (TDM) is the most recent endeavour of the CCSDS Navigation Working Group. The TDM is still a “White Book” and is in the process of being completed to include the most widely used tracking data types. It is intended that the TDM will support at least the following types:

- Ground-based radio metric types: uplink frequencies, range, Doppler, antenna angles, and interferometric types.

- Spacecraft-to-spacecraft Doppler and range.

- Ground and spacecraft optical measurements.

- Ancillary information needed to calculate the measurement residuals, such us meteorological data, media delays, and clock parameters.

The TDM will be significantly different from the ODM and ADM, with only one type of message, but many different kinds of fields possible in the data section. The TDM is being developed using the KVN format, in order to ease the transition to XML.

The tracking data in a TDM should as free as possible from the particulars of the tracking equipment that was used. Data should represent a real physical parameter, and not the derived quantity that may be measured by the equipment, and it should be corrected for instrumental biases and delays. The participants in the tracking exchange also need to decide which other corrections are going to be performed on the data, including media calibrations, clock biases and transponder delays.

5. TRANSITION TO XML

During the long gestation of the ODM it was realized that the KVN format was very limited and that it was not well suited to cover all possible needs of the Navigation Messages. The Extensible Markup Language is a much better form of specifying ASCII-based data, with at least the following advantages over standard text for this kind of application:

- It allows for the definition of the data message in a machine-readable format. This format can then be referred to in the data file and it can be used to verify that the data is compliant with the format. There are widely-available programs to both specify formats, called schemas in XML, to assist with the processing of XML data, and to automatically verify that the data messages comply with the schema. Each participant in a data exchange can independently verify that the message is compliant. This simplifies the development and validation of the software used to write data in the right format.

- It defines standards for time formats and numerical values.

- It allows for the nesting of data, so it is clear which metadata corresponds to which data.

- It allows for the specification of default and alternative attributes, such as units.

- It allows for compulsory and optional elements and attributes.

- It allows for range checking and specification of lists of allowed values.

- It allows for sharing elements between different specifications.

The few drawbacks of using XML for this application are:

- Some values can be specified as either attributes or child elements, so there is always an argument on whether to use one way or the other.

- Tags are always duplicated, with the opening tag and the corresponding ending tag making files bigger.

- There are not many Flight Dynamics specialists that are skilled in XML.

The Navigation Working Group is currently in the process of developing a common XML specification for all the navigation messages. This will also allow for navigation messages to be embedded in other messages, such us those used for service management.

6. CONCLUSION

The Navigation Working Group of the CCSDS is in the process of developing messages recommendations that will facilitate the exchange of navigation data between Space Agencies and, consequently, their cooperation and cross-support. We hope that this work will be useful to the international Flight Dynamics community and we encourage those that are interested to participate in the CCSDS activities, and to consider its recommendations for use.

7. ACKNOLEDGEMENTS

The CCSDS Navigation Working Group would like to acknowledge the contributions of all former members of the group, and all the people, from both Space Agencies and Industry, that have contributed to the work of the Group. In particular we would especially like to acknowledge the efforts of Chuck Acton (JPL), the first editor of the ODM and a very important contributor to the success of the Group.

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References

1. *Consultative Committee for Space Data Systems,* http://www.ccsds.org.

2. *Restructured Organization and Processes for the Consultative Committee for Space Data Systems*, CCSDS A02.1-Y-2.

3. *Orbit Data Messages*, CCSDS 502.0-R-3.5.

4. *Extensible Markup Language*, http://www.w3.org/XML

```
CCSDS_OPM_VERS = 1.0
CREATION_DATE = 2000-06-03T05:33:00
ORIGINATOR = GSOC

OBJECT_NAME = EUTELSAT W4
OBJECT_ID = 2000-028A
CENTER_NAME = EARTH
REF_FRAME = TOD
TIME_SYSTEM = UTC

COMMENT  Current intermediate orbit IO2

COMMENT State Vector

EPOCH = 2006-06-03T00:00:00.000
X =   6655.9942 [KM]
Y = -40218.5751 [KM]
Z =    -82.9177 [KM]
X_DOT =  3.11548208 [KM/S]
Y_DOT =  0.47042605 [KM/S]
Z_DOT = -0.00101495 [KM/S]

COMMENT Spacecraft parameters

MASS = 1913.000 [KG]
SOLAR_RAD_AREA = 10.000 [M**2]
SOLAR_RAD_COEFF = 1.300
DRAG_AREA =      10.000 [M**2]
DRAG_COEFF =      2.300
```

Fig. 1. OPM example

```
CCSDS_OEM_VERS = 1.0
CREATION_DATE  = 2005-05-07T15:32:32
ORIGINATOR = NASA/JPL

META_START
OBJECT_NAME    = MARS ORBITER
OBJECT_ID      = 2005-999A
CENTER_NAME    = MARS BARYCENTER
REF_FRAME      = EME2000
TIME_SYSTEM    = TDB
START_TIME        = 2005-05-07T13:10:51.946
USABLE_START_TIME = 2005-05-07T13:10:51.946
USABLE_STOP_TIME  = 2005-05-07T13:11:21.772
STOP_TIME         = 2005-05-07T13:11:21.772
INTERPOLATION = Hermite
INTERPOLATION_DEGREE = 11
META_STOP

COMMENT To be used for instrument planning only

2005-05-07T13:10:51.946000    319.431707   6790.818947   2014.707980   -1.203543   -0.873390   -2.253507
2005-05-07T13:10:54.928600    315.841850   6788.210340   2007.985592   -1.203657   -0.875827   -2.254229
2005-05-07T13:10:57.911200    312.251655   6785.594458   2001.261054   -1.203769   -0.878268   -2.254949
2005-05-07T13:11:00.893800    308.661126   6782.971289   1994.534369   -1.203881   -0.880713   -2.255669
2005-05-07T13:11:03.876400    305.070267   6780.340824   1987.805538   -1.203991   -0.883162   -2.256387
2005-05-07T13:11:06.859000    301.479080   6777.703049   1981.074567   -1.204100   -0.885614   -2.257105
2005-05-07T13:11:09.841600    297.887569   6775.057954   1974.341457   -1.204208   -0.888070   -2.257821
2005-05-07T13:11:12.824200    294.295737   6772.405527   1967.606212   -1.204316   -0.890530   -2.258537
2005-05-07T13:11:15.806800    290.703588   6769.745758   1960.868835   -1.204421   -0.892994   -2.259251
2005-05-07T13:11:18.789400    287.111123   6767.078634   1954.129329   -1.204526   -0.895462   -2.259964
2005-05-07T13:11:21.772000    283.518348   6764.404144   1947.387698   -1.204630   -0.897933   -2.260676
```

Fig. 2. OEM example