The Consultative Committee for Space Data Systems

ATTITUDE DATA MESSAGE

PROTOTYPING TEST PLAN/REPORT

FINAL REPORT

1-April-2008

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1. Introduction

This document provides a description of the prototype testing of the CCSDS Attitude Data Message (ADM), CCSDS 504.0-R-1.8 (reference [2]). The ADM is part of the technical program of the CCSDS Navigation Working Group. The ADM document completed a CCSDS Agency Review in March 2006, with nine revisions following this initial review; this process is described in reference [1].

The first sections of this document describe the Test Plan for the prototyping activity; the last sections of the document provide a Test Report of the realized plan. This plan has been prepared by the members of the CCSDS Navigation Working Group who are coordinating the prototyping for their respective agencies, specifically:

Jacques Foliard (CNES)
John M. Van Eepoel (NASA/GSFC)

Note that in applicable places the prototyping includes results based on modifications to the ADM document provided via the Agency Review Item Discrepancy (RID) process (see reference [3]), available internally through the Navigation Working Group. Changes based on the ongoing working group activity were also incorporated as applicable, and as documented in reference [3].

2. Blue Book Promotion Criteria

The CCSDS Procedures Manual states that for a Recommendation to become a Blue Book, the standard must be tested in an operational manner. The following requirements for an implementation exercise were excerpted from reference [1]:

> "At least two independent and interoperable prototypes or implementations must have been developed and demonstrated in an operationally relevant environment, either real or simulated."

It is the intent of this document to outline the Navigation Working Group's approach to meeting this requirement for the ADM.

3. Summary Conclusion

ADM Prototypes were developed at two CCSDS member agencies: CNES, and NASA. The ADM contains two message types, the Attitude Parameter Message (APM), and the Attitude Ephemeris Message (AEM). Two tests were completed for each message type encompassing the basic elements to specify the attitudes of satellites in orbit and of a mock satellite where the attitude was determined through simulation. The tests of the APM required extrapolation techniques to produce predicted attitude data, which had positive comparison results in both tests. The tests of the AEM required interpolation techniques to produce attitude data, which also had positive comparison results in both tests. Based on these positive test results in a simulated operational environment, the ADM prototyping effort successfully addresses the Blue Book promotion criteria. It is thus proposed to approve the Attitude Data Message as a CCSDS Recommended Standard.

4. Attitude Data Message (ADM) Testing Goals

The testing of the ADM will be broken down in to two sections, one for the APM and one for the AEM. The goal of the testing is to not exercise all of the optional fields and parameterizations of each message, but to test the basic functionality of the message and its exchange between agencies. While all of the fields of each message are not a part of this testing, this does not imply that they are not needed for other types of attitude data exchanges. As this testing is only intended to show "proof of concept", the testing goals described here achieve this end.

4.1 Attitude Parameter Message Test Goals

The tests of the APM will exercise the following elements of the message:

- Quaternions
- Euler Angles (includes repeated axis rotation)
- Euler Rates
- Maneuver torques
- Spacecraft inertias
- Reference frames

The test will not exercise the following optional elements of the message:

- Quaternion rates
- Spin Parameters

4.2 Attitude Ephemeris Message Test Goals

The tests of the AEM will exercise the following elements of the message:

- Quaternions
- Euler angles
- Euler rates
- Reference frames
- Specification of OEM filename and provide an associated OEM

The tests will not exercise the following optional elements of the message:

- Quaternion rates
- Spin Parameters
- Repeated Euler axis

The tests described in Section 5 and Section 6 of this plan will be conducted in order to meet the CCSDS requirements. The typical use of attitude in operations is in comparing two attitudes and determining their difference, and the tests of the APM and AEM reflect this operational use. In Section 7 and Section 8, the results of the testing are presented.

5. Test Plan Overview

The testing goals outlined above required prototype implementations in order to carry out the testing of the ADM. Two CCSDS member agencies represented in the CCSDS MOIMS Navigation Working Group volunteered for this task: CNES and NASA/GSFC, with JAXA as an observer to the testing. The following table outlines the tests, the approach to the exchange of attitude data and the current status of the tests.

Test #	Attitude Message	Agencies, Direction	Data Types	Schedule	%Complete
1	APM	CNES » NASA/GSFC	Quaternions Euler rates (repeated axis) Reference frames	March 2008	100%
2	APM	CNES » NASA/GSFC	Quaternions Euler rates (repeated axis) Reference frames Maneuver	March 2008	100%
3	AEM	NASA/GSFC » CNES	Quaternions Euler rates Reference frames	October 2007	100%
4	AEM	NASA/GSFC » CNES	Euler angles Euler rates Reference frames	October 2007	100%

6. Test Plan Details

6.1 Test Case #1: APM / CNES » NASA/GSFC

In this test, CNES will develop an APM message for a simulated low-earth orbiting spacecraft. The message will contain the appropriate header information, as well as reference frame information, the obligatory quaternion data, and optional Euler angle rate data. For this test, the Euler rate data given was specified using a repeated axis rotation.

To validate the utility of the APM message, the attitude and Euler rate data will be used to determine the attitude at a time different than the specified epoch, and the result compared to the CNES simulated data.

Expected Result
It is anticipated that the attitude determined using the quaternion and Euler rate data will compare to the expected attitude of the CNES simulation to within the extrapolation technique and the accuracy of the initial data input. NASA/GSFC will compare the APM delivered by CNES and report the results to CNES at the CCSDS Working Group meetings to be held in Washington, DC 10-March-2008 to 15-March-2008.

6.2 Test Case #2: APM w/ Maneuver / CNES » NASA/GSFC

In this test, CNES will develop an APM message for a simulated low-earth orbiting spacecraft. The message will contain the appropriate header information, as well as reference frame information, the obligatory quaternion data, optional Euler angle and rate data, and optional maneuver data. For this test, the Euler rate data given was specified using a repeated axis rotation. Additionally, for the maneuver, it is necessary to specify the inertias of the object, and so the message will provide the optional spacecraft inertias.

To validate the utility of the APM message, the attitude and maneuver data will be used to determine the attitude at a time different than the specified epoch, and the result compared to the CNES simulated data.

Expected Result
It is anticipated that the attitude determined using the quaternion and Euler rate data will compare to the expected attitude of the CNES simulation to within the extrapolation technique and the accuracy of the initial data input. NASA/GSFC will process the APM delivered by CNES and report the results to CNES at the CCSDS Working Group meetings to be held in Washington, DC 10-March-2008 to 15-March-2008.

6.3 Test Case #3: AEM Quaternion / NASA/GSFC » CNES

In this test, NASA/GSFC will develop an AEM message for a simulated low-earth orbiting spacecraft. The message will contain the appropriate header information, reference frame and time system specification, and specify the AEM data lines as

QUATERNION/RATE, implying that quaternion data and Euler rate data will be given in the data section of the message. In specifying that Euler rate data are provided in the message, an Euler rotation sequence will also be provided in the message metadata.

To validate the utility of the AEM message, CNES will process the attitude data, interpolating to points other than those specified in the data section of the AEM message, and the result compared to the NASA/GSFC simulated data.

Expected Results
It is anticipated that the attitude interpolation will compare to the simulated data to within the accuracy of the interpolation technique and the initial data input. CNES will generate the interpolated data from the AEM provided by NASA/GSFC, and the results of the comparison will be reported by NASA/GSFC at the CCSDS Working Group meetings to be held in Washington, DC 10-March-2008 to 15-March-2008.

6.4 Test Case #4: AEM Euler Angle / NASA/GSFC » CNES

In this test, NASA/GSFC will develop an AEM message for a low-earth orbiting spacecraft using a local orbital frame. The AEM message will contain the appropriate header information, reference frame and time system specification information, and specify the AEM data lines as EULER_ANGLE/RATE, implying that Euler angle and Euler rate data will be given in the data section of the message. In specifying the Euler angle data, a local orbital reference frame will be given, which denotes that the Euler angle data given is an error angle to the local orbital reference frame. Thus, to determine the local orbital reference frame, an Orbit Ephemeris Message (OEM) will also be provided, and the name of the associated message placed in a COMMENT line in the AEM provided by NASA/GSFC.

To validate the utility of the AEM message, CNES will process the attitude and orbit data, and provide data that properly interprets the attitude information given and determines the corresponding quaternion data for the same attitude. The result will be compared to the original NASA/GSFC data.

Expected Results
It is anticipated that the attitude result generated by CNES will compare to the original data to within the accuracy of the interpolation technique and the initial data input. CNES will generate the quaternion data to be compared to the original data from NASA/GSFC, and the results will be reported by NASA/GSFC at the CCSDS Working Group meetings to be held in Washington, DC 10-March-2008 to 15-March-2008.

7. Test Report Overview

Engineers at CNES and NASA/GSFC will prepare the comparison data as detailed in Section 6, and also file test reports for each test using the Test Data Sheet provided in this section.

The Test Report Details will be found in Section 8 of this document. A summarization of the test process and the recommendation of the Navigation Working Group may be found in Section 2 of the report. The report will be posted to the Navigation Working Group Common Working Environment (CWE) on the CCSDS web page at http://cwe.ccsds.org. The report will be submitted to the CCSDS Engineering Steering Group (CESG) and CCSDS Management Council (CMC), along with results of the Agency Reviews. At that time, a formal request will be submitted to the CMC for progression of the ADM to CCSDS Blue Book status.

The next page contains a format for the test data sheets that will be used to report the results of individual tests.

SAMPLE

Attitude Data Message Prototype Test Data Sheet

Version 1.0

1	Report Date:	
2	Program Under Test:	Attitude Data Message (ADM) Prototype
3	Agency Responsible for Prototype:	
4	Prototype Version # (if applicable):	
5	Test Engineer:	
6	Agencies Participating in this Test Case:	
7	Test Case Number:	
8	Spacecraft:	
9	Attitude Data Types:	
10	Attitude Data Date/Time Range:	
11	Variances from Expected Results:	
12	Results (Pass, Partial Pass, Fail):	
13	Results Reviewed / Approved By:	
14	Comments:	

8. Test Report Details

8.1 Test Case #1: APM / CNES » NASA/GSFC

Attitude Data Message Prototype Test Data Sheet

Version 1.0

1	Report Date:	2008/3/8
2	Program Under Test:	Attitude Data Message (ADM) Prototype
3	Agency Responsible for Prototype:	APM generation: CNES APM processing: NASA/GSFC
4	Prototype Version # (if applicable):	n.a., CNES prototype based on ADM Red Book 1.7
5	Test Engineer:	Jacques Foliard
6	Agencies Participating in this Test Case:	CNES/GSFC
7	Test Case Number:	1
8	Spacecraft:	simulated
9	Attitude Data Types:	Quaternion, Euler rates
10	Attitude Data Date/Time Range:	2007-10-01T00:02:00.000
11	Variances from Expected Results:	A comparison of the results is anticipated to yield less than +/- 1E-3 degrees (1 milli-degree) in the rotation magnitude to the simulated result.
12	Results (Pass, Partial Pass, Fail):	Pass
13	Results Reviewed / Approved By:	Jacques Foliard
14	Comments:	Only a single message was originally provided that contained the data for Test Case #1 and #2. NASA/GSFC split up the message to create this test case.

Table 1 : ADM Test 1 – Attitude Comparison Results

Parameter	Initial Condition (CNES)	Extrapolated Result (NASA/GSFC)	True Result (CNES)
EPOCH	2007-10-01T00:02:00	2007-10-01T00:02:01	2007-10-01T00:02:01
Q_FRAME_A	SC_BODY	SC_BODY	SC_BODY
Q_FRAME_B	J2000	J2000	J2000
Q_DIR	A2B	A2B	A2B
QC	0.422157	0.4214547	0.42146
Q1	-0.005068	0.0423818	0.04238
Q2	0.906506	0.9055285	0.90553
Q3	0.002360	0.0244507	0.02445
EULER_FRAME_A	SC_BODY	SC_BODY	SC_BODY
EULER_FRAME_B	J2000	J2000	J2000

EULER_DIR	A2B	A2B	A2B
EULER_ROT_SEQ	313	313	313
RATE_FRAME	EULER_FRAME_A	EULER_FRAME_A	EULER_FRAME_A
Z_RATE	0.0	0.0	0.0
X_RATE	0.0	0.0	0.0
Z_RATE	6.0	6.0	6.0

The comparison between the NASA/GSFC extrapolated result and the CNES simulated (true) value is quite small. The quaternion values, when compared, have an error of only [0.00004 0.00047 0.00024] degrees for the three axes, and the Euler rate difference is within machine precision.

The angular error for this case is less than 0.1 % of the rotation angle (0.6 degree) over the time step simulated. This error being much smaller than even the simulated subtended angle leads to the conclusion of the success of this test, and giving it a passing mark.

8.2 Test Case #2: APM w/ Maneuver / CNES » NASA/GSFC

Attitude Data Message Prototype Test Data Sheet

Version 1.0

1	Report Date:	2008/3/8
2	Program Under Test:	Attitude Data Message (ADM) Prototype
3	Agency Responsible for Prototype:	APM generation: CNES APM processing: NASA/GSFC
4	Prototype Version # (if applicable):	n.a., CNES prototype based on ADM Red Book 1.7
5	Test Engineer:	Jacques Foliard
6	Agencies Participating in this Test Case:	CNES/GSFC
7	Test Case Number:	2
8	Spacecraft:	simulated
9	Attitude Data Types:	Quaternion, Euler rates, Inertias, Maneuver
10	Attitude Data Date/Time Range:	2007-10-01T00:02:00.000
11	Variances from Expected Results:	A comparison of the results is anticipated to yield less than 2.0% error in the propagated attitude.
12	Results (Pass, Partial Pass, Fail):	Pass
13	Results Reviewed / Approved By:	Jacques Foliard
14	Comments:	Only a single message was originally provided that contained the data for Test Case #1 and #2. NASA/GSFC split up the message to create this test case.

Table 2 : ADM Test 2 – Attitude Comparison Results

Parameter	Initial Condition (CNES)	Extrapolated Result (NASA/GSFC)	True Result (CNES)
EPOCH	2007-10-01T00:02:00	2007-10-01T00:02:02	2007-10-01T00:02:02
Q_FRAME_A	SC_BODY	SC_BODY	SC_BODY
Q_FRAME_B	J2000	J2000	J2000
Q_DIR	A2B	A2B	A2B
QC	0.422157	0.41260	0.41350
Q1	-0.005068	0.09551	0.09495
Q2	0.906506	0.90524	0.90486
Q3	0.002360	0.03423	0.03520
EULER_FRAME_A	SC_BODY	SC_BODY	SC_BODY
EULER_FRAME_B	J2000	J2000	J2000
EULER_DIR	A2B	A2B	A2B
EULER_ROT_SEQ	313	313	313
RATE_FRAME	EULER_FRAME_A	EULER_FRAME_A	EULER_FRAME_A

Z_RATE	0.0	1.29576	1.28211
X_RATE	0.0	1.16843	1.07200
Z_RATE	6.0	6.00000	6.00001

In addition to these parameters, the APM developed by CNES also contained the optional inertia and maneuver logical blocks. Those blocks had the following values:

```
COMMENT           Spacecraft Parameters
I11         = 300.   [kg*m**2]
I22         = 300.   [kg*m**2]
I33         = 2400.   [kg*m**2]
I12         =  0. [kg*m**2]
I13         =  0.      [kg*m**2]
I23         =  0.     [kg*m**2]

COMMENT           Data follows for 1 planned maneuver.
COMMENT           attitude maneuver for: SATELI_TEST_MAN
COMMENT           Impulsive, torque direction fixed in body frame
MAN_EPOCH_START = 2007-10-01T00:02.00.000
MAN_DURATION    = 2        [S]
MAN_REF_FRAME   = SC_BODY
MAN_TOR_1       = 5.    [N*m]
MAN_TOR_2       = 0.    [N*m]
MAN_TOR_3       = 0.    [N*m]
```

In comparing the NASA/GSFC extrapolated result to the true simulation data provided by CNES, the quaternions have an angular difference of [0.139 0.098 0.012] degrees, and the Euler rates have a difference of [0.0137 0.0964 0.0000] deg/s. While errors of this size may seem large, in reality they are not. The method used to extrapolate the attitude was a simple 4th order Runge-Kutta integrator, integrating equations of motion for a rigid body over a two second time period, using a 0.002 step increment.

Based on these results, the utility of the APM quaternions, Euler angles and optional inertia and maneuver parameters can be used to determine the attitude at times different than that given in the original message. The angular difference in attitude is within 1.5% of the final attitude rate, which is well within the realm of integration error and an acceptable error for this test. As such, the test was deemed successful and given a passing mark.

8.3 Test Case #3: AEM Quaternion / NASA/GSFC » CNES

Attitude Data Message Prototype Test Data Sheet
Version 1.0

1	Report Date:	2008/3/8
2	Program Under Test:	Attitude Data Message (ADM) Prototype
3	Agency Responsible for Prototype:	AEM generation: NASA/GSFC AEM processing: CNES
4	Prototype Version # (if applicable):	n.a., NASA/GSFC prototype based on ADM Red Book 1.7
5	Test Engineer:	John M. Van Eepoel
6	Agencies Participating in this Test Case:	CNES/GSFC
7	Test Case Number:	3
8	Spacecraft:	simulated
9	Attitude Data Types:	Quaternion, Euler rates,
10	Attitude Data Date/Time Range:	2006-01-01T00:00:00.0 2006-01-01T00:03:19.0
11	Variances from Expected Results:	A comparison of the results is anticipated to yield less than +/- 1E-10 degrees in error to the simulated result.
12	Results (Pass, Partial Pass, Fail):	Pass
13	Results Reviewed / Approved By:	John Van Eepoel
14	Comments:	The comparison generated values close to machine precision and the accuracy of the interpolation algorithm used to obtain the interpolated quaternion data.

The AEM returned by CNES with interpolated data was compared to NASA/GSFC data, and the mean error and standard deviation are reported in Table 3.

Table 3 : ADM Test 3 – AEM Error Statistics

Statistic / Axis	X	Y	Z
Angle Error Mean	-4.37326e-17	1.13307e-16	-1.59314e-33
Angle Error Standard Dev.	1.89839e-15	9.03946e-16	1.51033e-32
Rate Error Mean	0.00000e+00	0.00000e+00	0.00000e+00
Rate Error Standard Dev.	0.00000e+00	0.00000e+00	0.00000e+00

Plots of the comparison were also generated, but are only shown for the angle errors as the rate errors lie very close to the zero line, as demonstrated by the mean and standard deviations of the errors. From these comparison results, this test of AEM quaternions and Euler rates is successful.

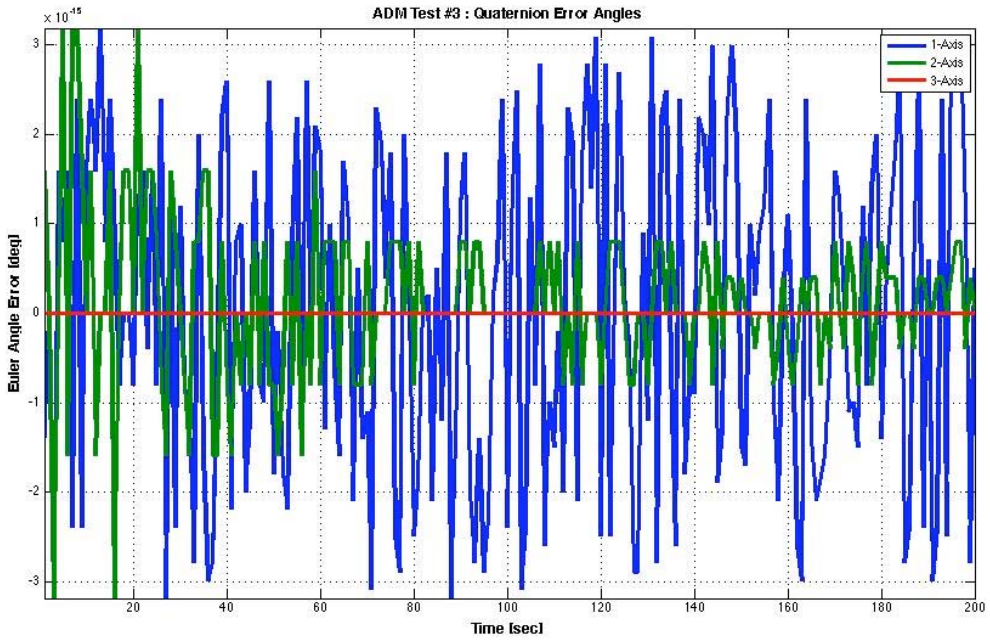

Figure 1 : ADM Test 3 - Angle Errors

The errors presented here are very nearly zero for the angle, and almost identically zero for the rate error. The interpolation technique employed by CNES used the data provided to interpolate to other times, but constrained the interpolated result to go through the points provided in the data. As such, the data compared is within machine precision for the angle, and, since rate errors are typically an order of magnitude less than angular errors, they simply show as identically zero.

8.4 Test Case #4: AEM Euler Angles / NASA/GSFC » CNES

Attitude Data Message Prototype Test Data Sheet

Version 1.0

1	Report Date:	2008/3/8
2	Program Under Test:	Attitude Data Message (ADM) Prototype
3	Agency Responsible for Prototype:	AEM generation: NASA/GSFC AEM processing: CNES
4	Prototype Version # (if applicable):	n.a., NASA/GSFC prototype based on ADM Red Book 1.7
5	Test Engineer:	John M. Van Eepoel
6	Agencies Participating in this Test Case:	CNES/GSFC
7	Test Case Number:	4
8	Spacecraft:	TRMM
9	Attitude Data Types:	Euler angles and rates, Local Orbital Reference frame
10	Attitude Data Date/Time Range:	2003-03-04T12:00:00.0 2003-03-04T12:03:20.0
11	Variances from Expected Results:	A comparison of the results is anticipated to yield less than +/- 1E-3 degrees in error to the simulated result.
12	Results (Pass, Partial Pass, Fail):	Pass
13	Results Reviewed / Approved By:	John Van Eepoel
14	Comments:	This was a very complicated test involving the transfer of not only an AEM, but also a corresponding OEM.

The AEM file returned by CNES was compared to the original data by NASA/GSFC, and the following error statistics were generated, shown in Table 4.

Table 4 : ADM Test 4 – AEM Error Statistics

Statistic / Axis	X	Y	Z
Angle Error Mean	0.00000e+00	0.00000e+00	0.00000e+00
Angle Error Standard Dev.	0.00000e+00	0.00000e+00	0.00000e+00
Rate Error Mean	0.00000e+00	1.18725e-04	0.00000e+00
Rate Error Standard Dev.	0.00000e+00	1.51355e-06	0.00000e+00

The table shows that comparison of the Euler angles shows exact comparison between the interpolated data and the original data. There is some discrepancy in the Y-axis Euler rates, and a plot of this is shown below in Figure 2.

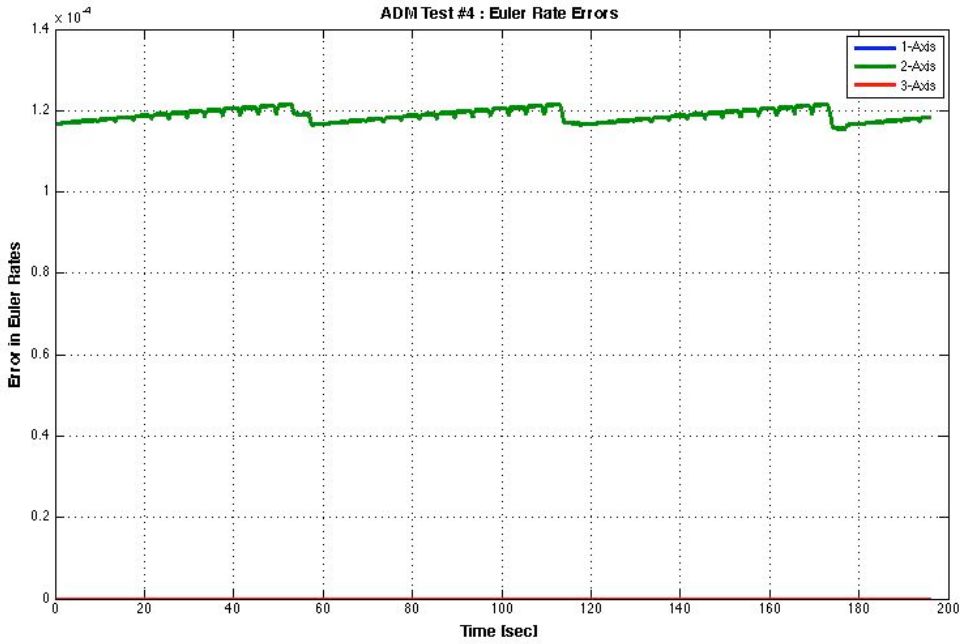

Figure 2 : ADM Test 4 - Euler Rate Errors

The variation in the 2-axis can be attributed to errors in the orbit points provided and the need to interpolate these points to the same time as the attitude data, which is at a finer granularity than the orbit data provided in the OEM. Therefore, it does not imply errors in the use of the AEM, but rather limitations in the data provided, which can be easily corrected by providing the orbit information at additional times or interpolating the given data to the attitude time points.

The same comment from Test #3 regarding the interpolated data and the resulting identically zero error results applies to this test as well (see p. 15).

The results from this test indicate a successful comparison of the two data sets, implying successful interpretation of the original AEM delivered to CNES from NASA/GSFC, and successful interpretation of the AEM sent to NASA/GSFC from CNES. The final conclusion is to give this test a passing mark.

9. References

[1] *Procedures Manual for the Consultative Committee for Space Data Systems*. CCSDS A00.0-Y-9. Yellow Book. Issue 9. Washington, D.C.: CCSDS, November 2003.

[2] Attitude Data Message, CCSDS 504.0-R-1.8, Red Book, January 2008.

[3] Attitude Data Message, CCSDS 504.0-R-1.9, Red Book, March 2008.

10. Acronyms

ADM	Attitude Data Message
AEM	Attitude Ephemeris Message
APM	Attitude Parameter Message
CCSDS	Consultative Committee for Space Data Systems
CESG	CCSDS Engineering Steering Group
CMC	CCSDS Management Council
CNES	Centre National d'Etudes Spatial
CWE	Common Working Environment
NASA	National Aeronautics and Space Administration
GSFC	Goddard Space Flight Center
ODM	Orbit Data Message
OEM	Orbit Ephemeris Message
RID	Review Item Discrepancy