SPHERES 16TH ISS Test Session - DRAFT

Version 0.1, 2009/09/02

Abstract

The SPHERES Test Session 16 occurred on 2009-June-26, operated by astronaut Michael Barrat. This session was a return to operations after a period of more than 7 months without operations and operated by a new crew member. Issues arose in the setup of beacons. Some issues arose when setting up the beacon and loading the satellites. Post-operations analysis showed that two beacons were wrongly entered into the GUI which affected the performance of the global estimation. The Fluid Slosh tests were the only tests that were successfully run, due to operational issues, and so the only ones that were able to meet their objectives. The Fluid Slosh tests verified the major principal axis of the SPHERES and observed nutation for both tests. The use of video as the sole source of rotation rate was found not to allow for full nutation characterization. Also, the effect of atmospheric drag was observed when the SPHERE was rotating without control and needs to be considered for physical system tests.

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1 Test Session Objectives

Date, basis of the objectives (based on continuing some part of past sessions, which are new threads, etc). Explain any "operational" goals.

The session included the following research topics:

(a) Operations

i. *Objectives*

(b) Docking

i. *Objectives*

(c) Formation Flight

i. *Objectives*

(d) Common

i. *Objectives*

(e) Guest Scientists? (if applicable)

i. *Objectives*

To achieve these goals the session test plan was divided into 3 groups:

- Group A: Fluid Slosh
  - *Obtain data on the nutation of the SPHERE spinning in the X-axis*
  - *Demonstrate SPHERE spinning at higher rotation rates and obtain control data for fluid slosh tests*
- Group B: Reconfiguration
  - *Test reconfigurable estimation based on current mass properties*
  - *Demonstrate the elements of autonomous assembly maneuvers*
- Group C: Communication FDIR
  - *Test a communication transmitter/receiver failure detection and isolation scheme*
  - *Demonstrate communication failure recovery techniques in a circular formation flying mission using cyclic pursuit or reconfiguring global trajectories*

2 Timeline Summary

Operational delays took a significant portion of the total test session time. There were four operationally successful tests run over the 80 minutes in following the beginning of the testing. However, two of those were Quick Checkout runs, so there were only two science tests successfully run. Table 2.1below shows a summary of the tests run during this session.

Table 2.1. Test Summary

Program	Test	Description	Start time	Interval
Fluid Slosh	T1	Quick Checkout	12:28:17	04:58
	T2	Fluid Slosh - X Nutation	12:33:15	01:17
	T2	Fluid Slosh - X Nutation	12:34:32	08:47
	T2	Fluid Slosh - X Nutation	12:43:19	00:19
	T2	Fluid Slosh - X Nutation	12:43:38	11:36
	T2	Fluid Slosh - X Nutation	12:55:14	11:53

	T3	Fluid Slosh - Rotation Rate High	13:07:07	33:18
Reconfiguration	T1	Quick Checkout	13:40:25	03:41
	T4	Joint Maneuvering w/ Reconfig Est.	13:44:06	05:07
# of test runs attempted	9	*End Time*	*13:49:13*	

3 Operations

During the beacons setup, the astronaut placed beacons 4 and 5 in the opposite corners of the volume wall. This was identified as a likely mistake due to the images presented in the procedures. In the procedures, the suggested locations are presented in two pictures from different perspectives. In the image for placing beacons 1,2 and 3, the picture is from aft to forward, whereas for the placement of beacons 4 and 5 is taken from forward to aft. The MIT team recognized the misplacement when the astronaut called down the locations and instructed switching to the correct locations.

3.1 Problem entering beacons into GUI

When the astronaut tried to enter the beacons location into the GUI, the error message: “Beacon too close to existing beacon placement” appeared in the GUI. This error was caused probably because either the setup of beacons from the previous session was in conflict with the current one, or because the astronaut was probably incorrectly entering the information.

The astronaut was instructed to make all beacons unconfirmed and enter them again one at a time. This procedure worked to prevent the error to show up again, and the team focused attention in the correct placement of beacons 4 and 5.

3.2 Communications Transmitter

When following the setup procedure, the astronaut recognized a problem with the communication with the satellites. The astronaut called down the GUI not recognizing one of the SPHERES. Although the SPHERE was on, the GUI did not show the green signal. MIT operations recommended verifying the connections to the computer. The astronaut switched the USB connection to a new one and the problem was solved. It is believed that either the connection to the USB was loose or the lower USB port on the SCS is faulty. The problem however was not repeatable on the ground.

3.3 Post Test session analysis of beacon locations

From analysis of the test data, misplacement of one of the beacons was detected. It had been properly placed in the test volume, but incorrectly entered into the wrong wall GUI. This error caused problems with the metrology.

3.4 Consumables Consumption

3.4.1 Batteries

- Blue Satellite: PSI02250J in (new, saved as “used”), PSI02260J (new, saved as “used”)
- Orange Satellite: PSI02252J (new, saved as “used”), PSI02256J (new, saved as “used”)

3.4.2 Tanks

- Blue Satellite: PSI01054J In new, PSI01099J Out Empty.
- Orange Satellite: PSI01104J In new, PSI01014J Out Empty.

4 Results Analysis

4.1 Program 251 Fluid Slosh

The objectives of this program include verifying the X-axis as the major principal axis of inertia and demonstrating the ability of the SPHERE to spin above the sensor limit and gather control data relating to fluid slosh. The tests were to also capture the nutation of the SPHERE. All tests above the group success line were run and achieved their objectives. No tests in this group need to be rerun.

4.1.1 P251, Test 2 Fluid Slosh - X Nutation

The results of Fluid Slosh – X Nutation demonstrate the ability of the SPHERE to spin stably about the X-axis and detectable nutation in the off-spin axes.

There were three runs of this test. The first two were not valid, as the estimator didn't converge properly in the first test and SPHERE ran out of CO2 gas in the second test. The third run of the test provided clear data up until 232 seconds into the test, when the SPHERE bumped into the deck of the ISS.

The format of the test is as following: the estimator converges, the SPHERE holds position and a specified attitude, the SPHERE rotates about the X-axis up to 1.14 rad/s, and then the satellite drifts for 200 seconds. An open loop thrust resulting in slight kick in spin about the +Y-axis was originally planned prior to the drift, but due to a coding error, this occurred in the +X-axis instead. Since this transient thrust was intended to ensure nutation in the off-spin axes, which occurs anyways, it is actually better that it did not occur.

As seen in Figure 4.1, the X rotation rate drops from 1.14 to 1.06 rad/s over the course of the drift, prior to bumping the wall. During this time, the amplitudes of the Y and Z rotation rates also decrease some. By calculating the magnitude of the angular momentum vector (Figure 4.2), it is possible to see that it is also decreasing over time almost linearly. This implies that there is a constant external torque on the system.

This torque is environmental, since the control system is turned off during the drift. It is assumed to be due to atmospheric drag, since the air pressure and composition in the ISS is maintained to be the same as at sea level on Earth. The decline in angular momentum is seen in all previous tests where the SPHERE rotates without control. However, the slope of the decline is lower when rotating about the Z-axis compared to the rotating about the X- and Y-axes. This is expected, since rotating about the tank symmetry axis would not induce as much drag.

Energy dissipation can be detected by a decline in the rotational kinetic energy, as the angular momentum vector moves within the body towards the major principal axis (i.e. lower energy state) changing in magnitude. However, since the magnitude of the angular momentum vector is decreasing, it will be necessary to separate that effect out. There is still a residual sine wave present within the angular momentum magnitude that needs to be filtered out by finding the proper inertia ratio of the principal axes before this can happen; otherwise, the direction of the angular momentum vector cannot be accurately calculated.

Due to the tank being changed immediately before the test began, we have very good knowledge of the fluid in the tank. It was ~68% full. The liquid CO2 is the only mass in the system that is of a measurable quantity that has the flexibility of movement.

The test conclusively demonstrated that the X-axis is the major axis of the SPHERE. The CAD inertia model provided gives the Y-axis as the major axis, the X-axis as the intermediate axis, and the Z axis as the minor axis of inertia. The instability of the Y-axis when a SPHERE with no additional mass spins about that axis was demonstrated in Test Session 14b P236 T8. The physical ground inertia model switches the order of the X and Y axes such that X is the major axis and Y is the minor axis. However, the difference between the X and Y axes is not too great, in that the additional inertia of the battery pack does not result the Y-axis becoming the major axis of inertia. The stability of spin about the Y-axis with the battery pack has been demonstrated in test from Test Sessions 13, 14b and 16. So the physical inertia model can still be improved upon. An inertia model from testing on the ISS is currently being developed from data from Test Sessions 13, 14b, and 16 with the nutation frequency calculation based on the inertia of the object and its rotation rate about a single axis.

Table 4.1 Principle Moments of Inertia for SPHERE (wet) (kg m^2 10^{-2})

Model	Configuration	Ixx	Iyy	Izz
CAD	SPHERE	2.29	2.42	2.14
	SPHERE + Battery	2.3	2.74	2.46
Physical	SPHERE	2.57	2.25	2.03
	SPHERE + Battery	2.61	2.51	2.35

The frequency of the nutation is ~0.031 +/- 0.01 rad/s, seen in the rotation rates of all three axes. In nutation frequency calculation, the nutation frequency is proportional to the spin rate and constant calculated based on the inertia matrix. It does decrease with the principal axis rotation rate, as expected. Since this is the only test that spins about the X-axis, the results will be used to develop the ISS inertia model and therefore cannot be predicted.

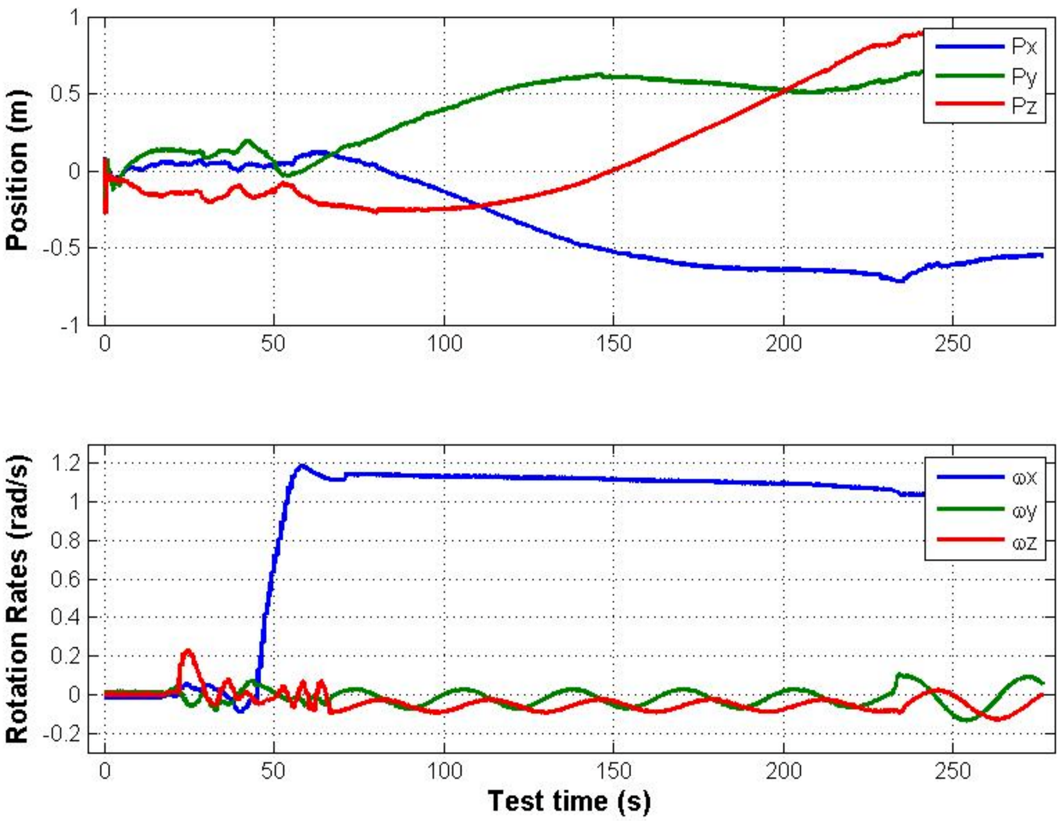


Figure 4.1 TS16 P251 T2-3 Fluid Slosh: SPHERE Only, X Rotation – Position and Rotation Rates

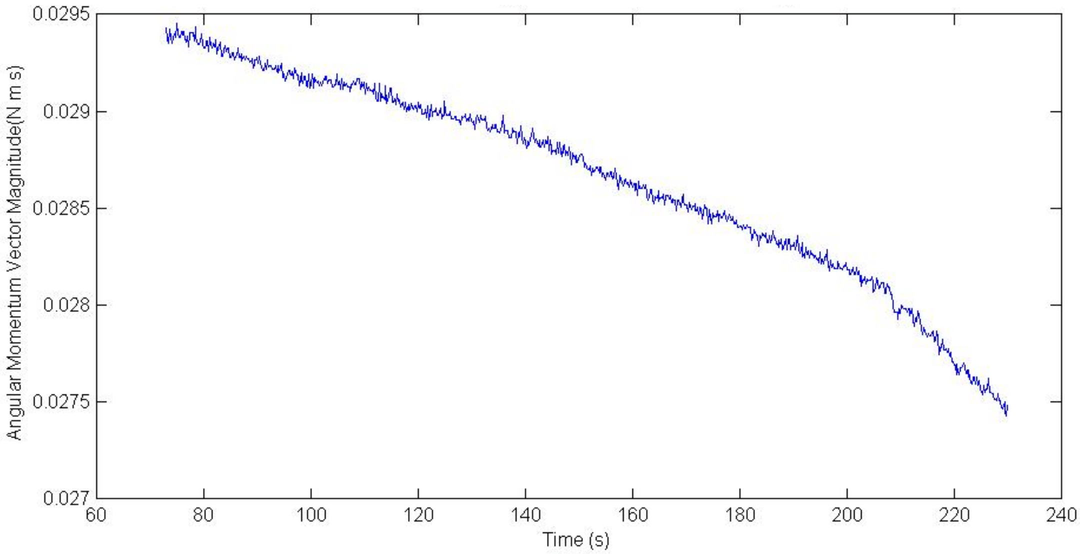


Figure 4.2 TS16 P251 T2-3 Fluid Slosh: SPHERE Only, X Rotation - Total Angular Momentum for Drift Only

4.1.2 P251, Test 3 Fluid Slosh - Rotation Rate High

The results of Fluid Slosh – Rotation Rate High demonstrate the ability of the SPHERE to spin about the Y-axis with a battery pack at above sensor rotation rates and detectable nutation in the off-spin axes.

The format of the test is as following: the estimator converges, the SPHERE holds position and a specified attitude, the SPHERE rotates about the +Y-axis up to 1.4 rad/s via closed loop control, the SPHERE rotates up to 5.2 rad/s via open loop thrusting and then the satellite drifts for 200 seconds.

The Y rotation rate was calculated from video, as it exceeds the sensor limit of 1.44 rad/s. This was possible since the +Y face of the SPHERE pointed at the camera. The tank end and the battery pack attached stuck out in the –Z and -X directions and were used as markers to determine when a rotation had been completed. From 43 to 74 seconds, the frequency low enough that the frames per quarter rotations could be used to measure the frequency. From 74 to 181 seconds, the frames per whole rotation were used to measure the frequency. Following 181 seconds, there was a loss of video signal. Upon receipt of the video recorded on the ISS, the rotation rate for the remainder of the test can be measured.

The frame rate on the video was approximately 13 Hz; all rotations had a minimum of 10 frames. The video was transmitted from the ISS and then relayed in the lab at MIT and recorded on VHS. The video had a jump just prior to the start of the test, and it is possible other, less noticeable jumps occurred throughout the test. There are several issues with the observed Y-axis rotation rate that will hopefully be cleared up with receipt of the ISS video. One is whether the cause for the spikes in rotation rate from 80 to 110 seconds is due to variances in video frame length or the actual rotation rate of the SPHERE, which would be unexpected. The other issue is in matching the sensor rotation rate. From 60-70 seconds, the video calculates the Y-axis rotation as ranging between 1.27-1.36 rad/s. During this time, telemetry has the Y-axis rotation range between 1.39-1.4 rad/s.

As seen in Figure 4.4, the Y rotation rate drops from 5.5 to 5.0 rad/s over the course of the drift (120 to 180 seconds). During this time, the amplitudes of the Y and Z rotation rates also decrease slightly. This is the same effect caused by atmospheric drag mentioned in 4.1.1 P251, Test 2 Fluid Slosh - X Nutation.

In observing nutation frequency and growth/decay, it is preferable to observe as many nutation cycles as possible (i.e. 20 or more). Since the nutation frequency is proportional to the spin rate, this can be accomplished by increasing either the spin rate and/or increasing the time period in which the data is recorded. However, both have issues within the SPHERES system. Increasing the spin rate, as in this case, decreases the accuracy of the knowledge of the spin rate and also how the spin rate varies throughout the test. This gives few data points for changes in the angular momentum vector in reference to the SPHERE frame, which it vital in tracking the body's nutation. However, increasing the time period of the drift doesn't increase the number of nutation cycles if the SPHERE hits a wall during the drift, making all data following the bump useless.

The nutation frequency of the SPHERE is 0.074 +/- 0.01 rad/s for this test. The fill fraction for the CO_2 is ~65%. Further nutation data can be gathered following refinement of the Y-axis rotation rate.

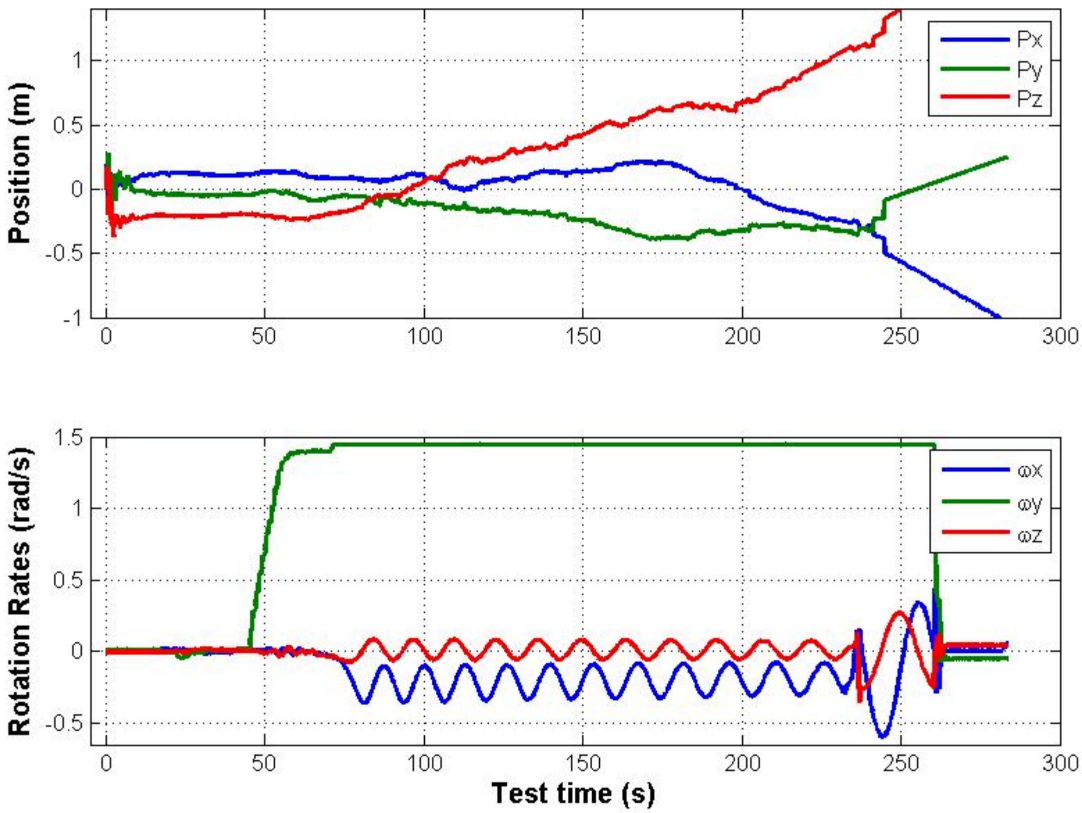


Figure 4.3 TS16 P251 T3 Fluid Slosh: SPHERE + Battery Pack, Y Rotation – Position and Rotation Rates

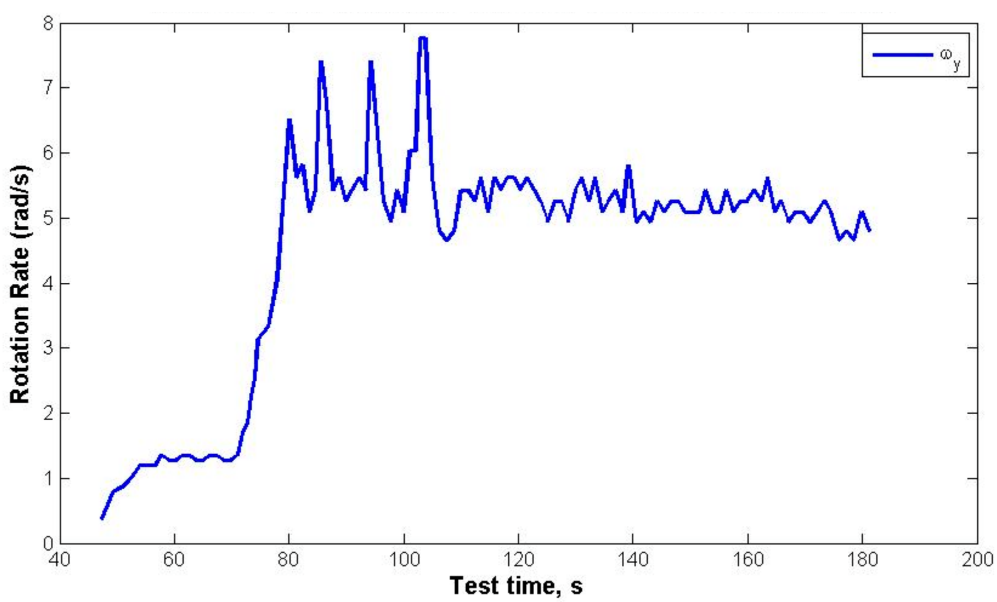


Figure 4.4 TS16 P251 T3 Fluid Slosh: SPHERE + Battery Pack, Y Rotation – Y-axis Rotation Rate

4.2 Program 254 Reconfiguration

There was a single attempt of the Joint Maneuvering with Reconfiguration Estimation test, which was interrupted by a satellite reset. No other tests were attempted and all tests will need to be run in the future.

4.2.1 P254, Test 4 Joint Maneuvering w/ Reconfig Est

T4 joint maneuvering did not complete successfully due to a satellite reset on the Primary satellite. The Primary satellite reset at test time = 58s. Up until this point, as seen in Figure 4.5, it appears as though the estimator converged and it was properly approaching the target position. However, after Primary reset, Secondary kept firing the thruster commands last sent by Primary. This caused the joined satellites to go unstable. It is not known what caused the satellite reset.

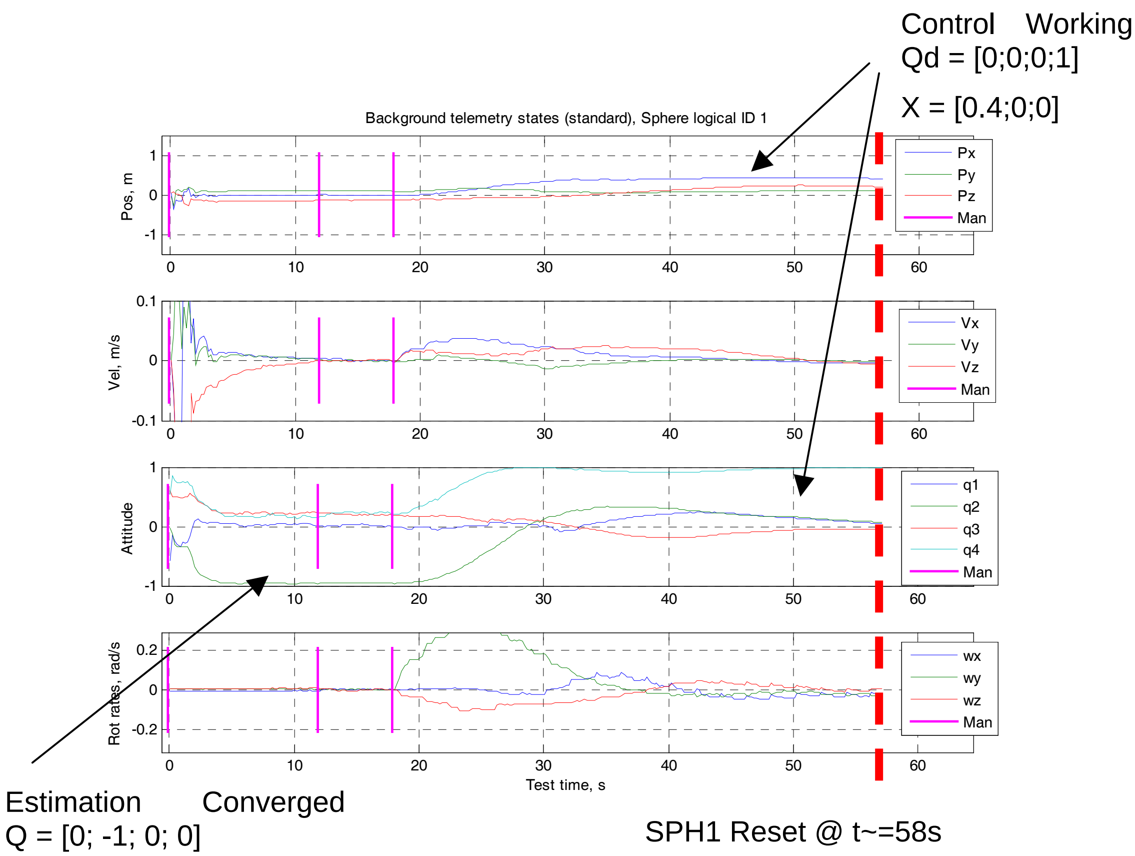


Figure 4.5 Primary satellite states vs time

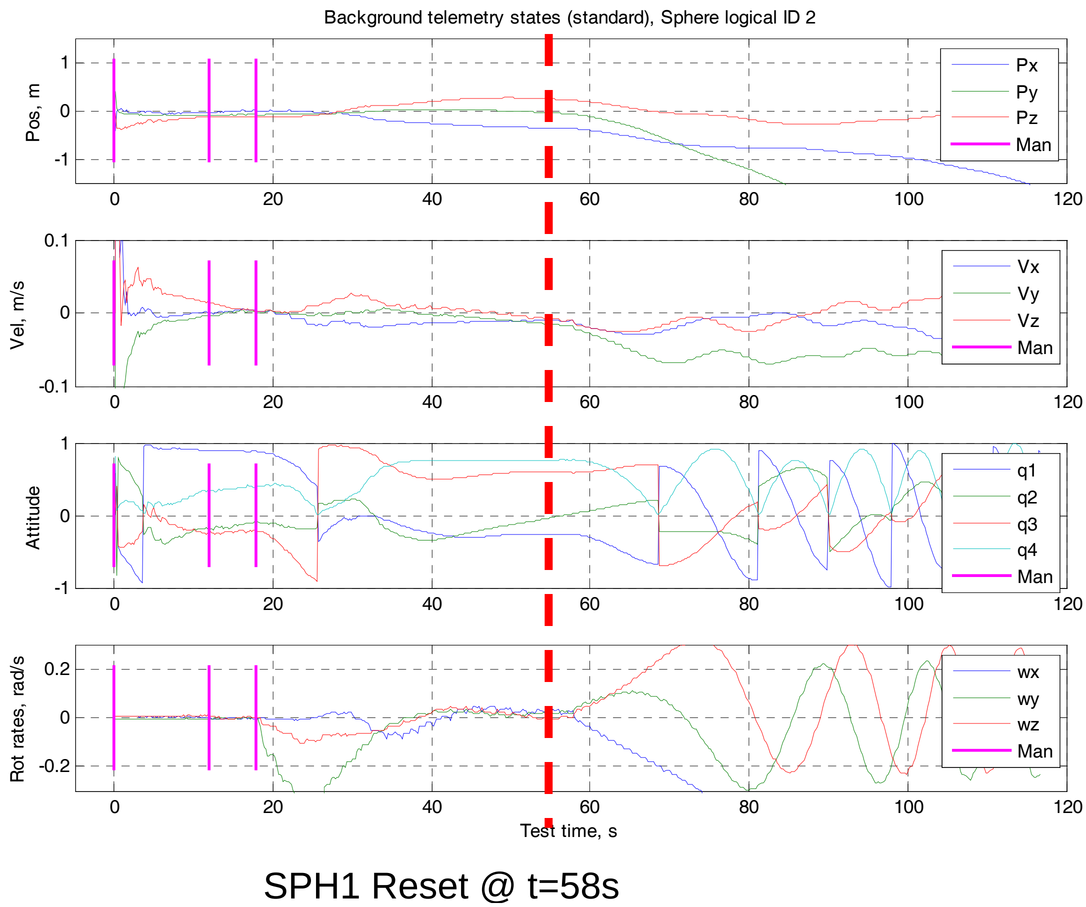
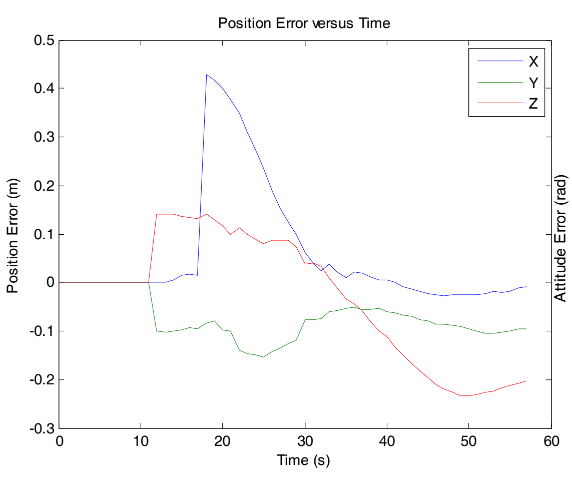
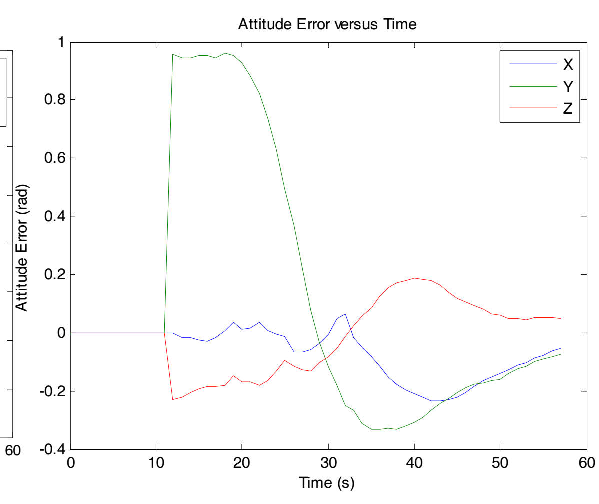


Figure 4.6 Secondary satellite states vs time



(a) Position error



(b) Attitude error

Figure 4.7 Error vs Time

5 Conclusions

The Fluid Slosh – X Nutation was able to conclusively determine that the X-axis is the major principal axis of rotation. However, the inertia ratio of this SPHERE at the fill fraction and rotation direction of this test is still being determined. Once determined, it will be possible to calculate if this test observed energy dissipation due to fluid slosh. The Fluid Slosh - Rotation Rate High demonstrated that the SPHERE can stably rotate above the sensor limit. However, unless the video to be received from the ISS is show to be of sufficiently high fidelity, nutation will not be able to be fully characterized if operating outside the sensor limits.

6 Lessons learned

Operations:

The procedures should be changed to allow an easier understanding of the suggested beacon setup. In general the procedures and the HTML instruction should take into account the astronauts point of view which is new to SPHERES and does not necessarily have all the information for the correct setup unless the instructions are clear.

It should be taken into accounts that there seems to be a faulty USB connection in one of the SSC and that the GUI could recognize this problem again in the future and the astronaut should be asked to switch to another USB port on the SCS.

Science:

When running physical model test, be sure to take into account all possible forces acting on the body. The atmospheric drag was not originally accounted for in determining the forces necessary to spin the SPHERE up via open loop thrust to a rotation rate above what was the sensors were capable of measuring. Inside the ISS is not the same as being in the vacuum of space.

7 Future Actions

7.1 Revision of the procedures

Following the issues detected in the test session, a revision to the procedures will be issued. In this revision the procedures regarding the beacon setup will be improved with more accurate and easy to understand images.

7.2 Revision of issues with the GUI

The issues with the GUI not detection the faulty USB connection are to be further investigated. Additionally, the process of placement of beacons and repositioning of beacons will be reviewed for any new version of the GUI in a way that make it a more intuitive process and reduced delays unconfirming and reconfirming the beacons.

8 SPHERES Team

The SPHERES team members who played a direct role in the preparation, operation, and data analysis part of Test Session 16 are identified in Table 8.1. This group is in addition to the support of the SPHERES sponsor at JSC, the DoD Space Test Program.

Table 8.1. SPHERES Team Members for TS16

Principal Investigator		
Prof. David W Miller	ScD '88	
Lead Scientist		
Dr. Alvar Saenz Otero	PhD '05	
MIT Graduate Students		
Caley Burke	Masters Student	Fluid Slosh
Swati Mohan	PhD Candidate	Reconfiguration
Dan Kwon	PhD' 09	Operations
Jaime Ramirez	PhD Candidate	Operations
Christopher Mandy	Masters Student	Operations
Christopher Pong	Masters Student	Operations
Jacob Katz	PhD Candidate	Operations
Martin Azkarate	Visiting Student	Operations
MIT Undergraduate Students		
David Sternberg	Class of 2012	Operations
Aurora Flight Sciences		
John Merk	Program Manager	

9 Revision History

Date	Version	Notes	Released by
2009/09/02	0.1	Initial draft	caley
2009/12/05	0.2	Released as draft, not complete	alvarso
NOT AUTO	1.0	Initial release (MUST be reviewed before release)	<username>