ZERO PROPELLANT MANEUVER[TM] FLIGHT RESULTS FOR 180° ISS ROTATION

Nazareth Bedrossian[1], Sagar Bhatt[2]
The Charles Stark Draper Laboratory, Inc., Houston, TX 77058

Mike Lammers[3], Louis Nguyen[4]
NASA Johnson Space Center, Houston, TX, 77058

This paper presents results for the Zero Propellant Maneuver (ZPM)[TM] attitude control concept flight demonstration. On March 3, 2007, a ZPM was used to reorient the International Space Station 180 degrees without using any propellant. The identical reorientation performed with thrusters would have burned 110lbs of propellant. The ZPM was a pre-planned trajectory used to command the CMG attitude hold controller to perform the maneuver between specified initial and final states while maintaining the CMGs within their operational limits. The trajectory was obtained from a PseudoSpectral solution to a new optimal attitude control problem. The flight test established the breakthrough capability to simultaneously perform a large angle attitude maneuver and momentum desaturation without the need to use thrusters. The flight implementation did not require any modifications to flight software. This approach is applicable to any spacecraft that are controlled by momentum storage devices.

I. Introduction

IN this paper, the Zero Propellant Maneuver (ZPM)[TM] attitude control concept is described and results are presented for the flight demonstration on March 3, 2007, when the International Space Station (ISS) was rotated by 180 degrees without using any propellant. With the ZPM, non-propulsive rotational state transition for spacecraft controlled by momentum storage devices can be accomplished. In this context, the rotational state includes attitude, angular rate and momentum. A rotational state transition can be either a maneuver between prescribed states and/or an attitude maneuver used to desaturate the momentum actuators.

The general ZPM concept is based on developing a special attitude trajectory to accomplish the desired rotational state transition. The trajectory is shaped in a manner that takes advantage of the nonlinear system dynamics to reduce or eliminate the "cost" of the maneuver. For example, an eigenaxis maneuver is kinematically the shortest path between two orientations. For the attitude controller system to follow the eigenaxis, the nonlinear system dynamics must be overcome, thereby increasing the "cost" of the maneuver. By considering a kinematically longer path and increasing the time to perform the maneuver, path dependence of system dynamics can be exploited to lower the "cost". This allows spacecraft that use momentum storage devices for attitude control, such as the ISS, to perform large angle attitude maneuvers by commanding their maneuver logic.

Normally, ISS large angle attitude maneuvers are performed using thrusters. The maneuvers are typically between torque equilibrium attitudes (TEAs), i.e., attitudes that can be held by the Control Moment Gyroscopes (CMGs) attitude control system without momentum saturation. A Momentum Manager (MM) controller is used for long term attitude hold at these equilibrium orientations[1]. For short term attitude hold and maneuvers, a PID attitude

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[1] Group Leader, Manned Space Systems
[2] Member of Technical Staff II, Manned Space Systems
[3] Attitude Determination and Control Officer, Mission Operations Directorate
[4] Deputy Manager, Space Station GN&C Systems, Engineering Directorate

hold controller with an eigenaxis maneuver logic is used. However, the CMGs have limited torque and momentum capacity. Commanding a large angle maneuver using the existing attitude control flight software would cause the CMGs to rapidly reach their capacity limits, i.e., saturate. To regain control authority, thrusters would then be used for momentum desaturation. Due to CMG lifetime issues, momentum desaturation using thrusters is currently prohibited. For the ISS, the benefits of a ZPM include reduced lifetime propellant use and reduced constraints on solar array operations due to loads, erosion and contamination from thrusters. Another advantage of the ZPM is that it does not require ISS flight software modifications since it is a set of attitude and rate commands tailored to the specific attitude control architecture. More importantly, ZPM provides the only means by which to rotate the ISS in case thruster control capability is lost.

Previous related work can be traced back to the Skylab program where gravity gradient torque was used for momentum control. During the night portion of the orbit, gravity gradient torques produced by two-axis attitude maneuvers were successfully used to desaturate momentum accumulated during the daylight portion of the orbit.[2,3] Other applications of using gravity gradient to desaturate CMG momentum have been proposed in Ref. 4-5. The common thread in these approaches appears to be the use of small angle approximation in the gravity gradient torque model in order to compute the momentum dumping maneuver. An approach for optimizing the attitude command sequence to the ISS CMG attitude hold controller in order to minimize fuel use that includes nonlinear system dynamics was proposed in Ref. 6. In this work, an ISS 90 degree yaw maneuver using a simplified model of the vehicle dynamics and environment (including Euler and gravity gradient, but no aerodynamics) was performed without using propellant, however, the CMGs were saturated at the end of the maneuver.

The ZPM attitude control concept was developed by Draper Laboratory over the previous decade. Its origins can be traced back to the mid 90's when the first author proposed this approach during the development of a general Centralized Momentum Management concept[7] for spacecraft that utilize various momentum exchange devices such as CMGs, reaction wheels, thrusters, ion propulsion, etc.. The goal was to improve performance (increase satellite life) by trading-off between satellite "degrees-of-freedom" (e.g. performance or control variables) and incorporating "look-ahead" in decision making. To achieve the trade-off and "look-ahead" capability, a general optimal control problem framework was proposed. With such an approach, no simplifying assumptions such as small angular excursions are necessary and disturbance terms such as Euler or aerodynamic torques do not have to be neglected. In the late 90's, the first application of this "planning" approach was to pose and solve the problem of performing a CMG maneuver between specified attitudes while avoiding momentum saturation during Orbiter-mated-to-ISS robotic payload operations[8]. This was the first demonstration of the ZPM concept to utilize prediction of environmental dynamics, including time-varying dynamics due to payload motion, in performing a rotational maneuver using CMGs while avoiding saturation during the maneuver and minimizing the final momentum magnitude. In the early 00's, the ZPM concept was used to establish the capability for general three-axis momentum desaturation without the need to use thrusters[9]. By maneuvering an Orbiter-mated-to-ISS along a ZPM attitude trajectory, it was shown for the first time that large amounts of momentum can be unloaded. The general full rotational state transition problem was then solved and flight demonstrated by rotating the ISS 90 degrees[10-11] on November 5, 2006. With this flight test, the breakthrough capability to simultaneously perform an attitude maneuver and CMG momentum desaturation without the use of thrusters was established.

This paper reviews the ZPM attitude control concept within the context of a specific 180 degree Space Station maneuver. The Station environmental dynamics, control systems, and operational modes are introduced, and a suitable optimal control problem solved. Specific constraints imposed on the control problem due to Station flight software and operations will be presented. The flight operational maneuver is described and ZPM trajectory is verified in high fidelity simulation. Flight results are then presented with detailed comparison between predicted and actual results.

II. Problem Formulation & Solution Technique

A rotational state transition can be planned to minimize a user specified "cost" by posing and solving an optimal control problem (OCP) for a specified maneuver time. The OCP in this context is to transition the spacecraft from an initial to a final rotational state while satisfying the system dynamics and maintaining the CMGs within their capability. For the ISS, the system dynamics include Euler, gravity gradient and aerodynamic torques, articulating appendages, attitude kinematics, and the ISS CMG attitude hold controller dynamics.

The constraints for the OCP include the attitude, rate, and momentum states at the beginning and end of the maneuver, as well as peak CMG momentum and torque magnitudes and peak CMG gimbal rates. Additional constraints such as maximum angular excursions in each axis can also be specified. The degrees of freedom are the commanded vehicle attitude and rate history with respect to the Local Vertical Local Horizontal (LVLH) reference

frame. It should be noted that the maneuver trajectory is a function of the particular ISS configuration mass properties as well as the specific combination of rotary joint motions.

The complete details of this nonlinear, constrained optimal control problem are described in Ref. 10. In general, solving optimal control problems has been considered difficult;[12] however, in recent years, advances in PseudoSpectral (PS) methods[13-14] have allowed for the efficient and rapid solution of optimal control problems governed by arbitrary nonlinear dynamical systems. PS methods differ from other techniques in several different ways. Because they are based on discretizing the problem by way of Lagrange interpolating polynomials over Gaussian nodes, they offer spectral accuracy (i.e., a faster convergence rate than any given polynomial rate) which provides the efficiency required for flight applications. In contrast, prior methods typically offer only order four convergence.[12] Furthermore, PS methods offer a simple way to check the optimality of the solution by way of the Covector Mapping Principle.[13] This concept is particularly important in solving a complex problem like the ZPM because it facilitates quick and efficient ways to validate the feasibility and optimality of the solution. These ideas were used by the first and second authors to solve and validate the ZPM optimal control problem[10] using the 2003a version of the software package DIDO,[15] which implements the Legendre PS method in an object-oriented framework under MATLAB®.[16] DIDO uses a spectral algorithm in conjunction with SNOPT,[17] an active-set sequential quadratic programming solver, to generate fast ZPM solutions.

III. Operational Implementation

The ZPM process usually starts about a month before the flight date, L-30days. First, the relevant data about the specific ISS configuration and maneuver definition are collected. For convenience and subsystem coordination, orbit noon was selected as the location in orbit at which to start the ZPM. Once an initial trajectory is developed, it is verified in simulation. In the next phase, robustness of the trajectory to parameter uncertainties is analyzed. At L-21days, the trajectory is sent to Attitude Determination and Control Officer (ADCO) for ISS communication coverage analysis during the ZPM. It is also sent to other subsystems such as thermal and power for evaluation. A final verification is performed at L-7days based on updates to environmental conditions and orbit parameters from the Trajectory OPerations Officer (TOPO) and any changes which may require a revision to the trajectory. The final trajectory is delivered to Mission Control Center (MCC) three days before flight.

To implement the ZPM, the ground-developed trajectory commands are uploaded to the ISS. The ADCO receives this data from the Mission Evaluation Room (MER) GN&C Team and uses it as input to a software tool which builds a GMT time-tagged command pair sequence for uplink to the Command and Control computer (C&C MDM) prior to the maneuver execution time. This implies that the ZPM commands are hardwired to start at the specified GMT times only. As the C&C MDM command buffer is limited to 200 slots, the non-propulsive maneuver is allocated 160 slots and is composed of 80 command pairs (attitude and rate). Since the ISS attitude hold controller uses an eigenaxis maneuver logic, the rate command is a scalar maneuver rate required to transition from one attitude command to the next in the specified time. The attitude and rate command cannot be issued at the same time with the current flight software and must be separated by a minimum of 1sec. The rate command is issued first. The ISS GN&C system begins in momentum management in one reference frame, and transitions to a CMG attitude hold controller with desaturation inhibited to perform the maneuver. After the maneuver is completed, the GN&C transitions into the momentum manager in the final reference frame. The command timing sequence tailored for the specific ISS ZPM flight demonstration is shown in Figure 1. A partial listing of the ZPM attitude and rate command files for the flight demonstration are shown in Figure 2.

As the non-propulsive maneuver is a feedforward open loop trajectory that is a function of initial states and ISS dynamics, its performance depends on how accurately these are known, e.g. mass properties, center of pressure, aerodynamic drag force, etc. Robustness analysis is performed to identify the range of uncertainty in these parameters for which the maneuver can still be completed without the use of thrusters. If the flight conditions are outside this uncertainty range, the trajectory needs to be redesigned or thrusters can be used to initialize the rotational states at the desired values in order to start the maneuver. Similarly, when handing-off from the maneuver to momentum manager there will also be discrepancies in the rotational states from their target values. If these discrepancies are outside the robustness bounds of momentum manager startup, thrusters can be used to initialize the rotational states.
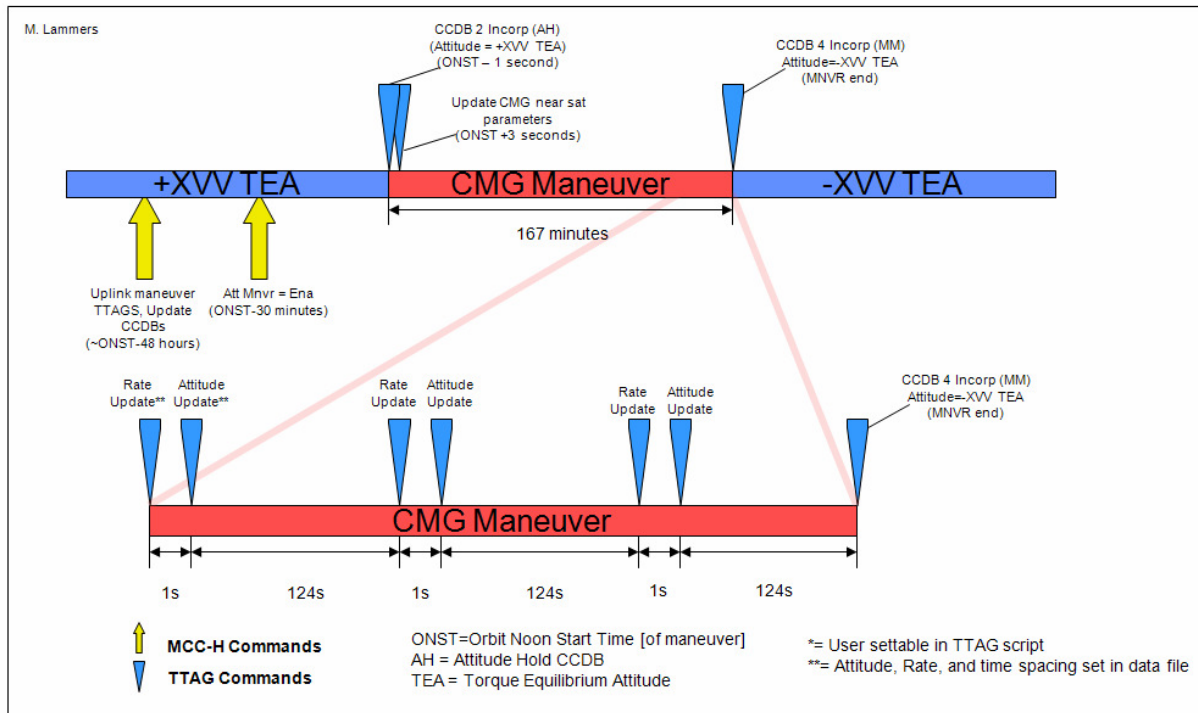
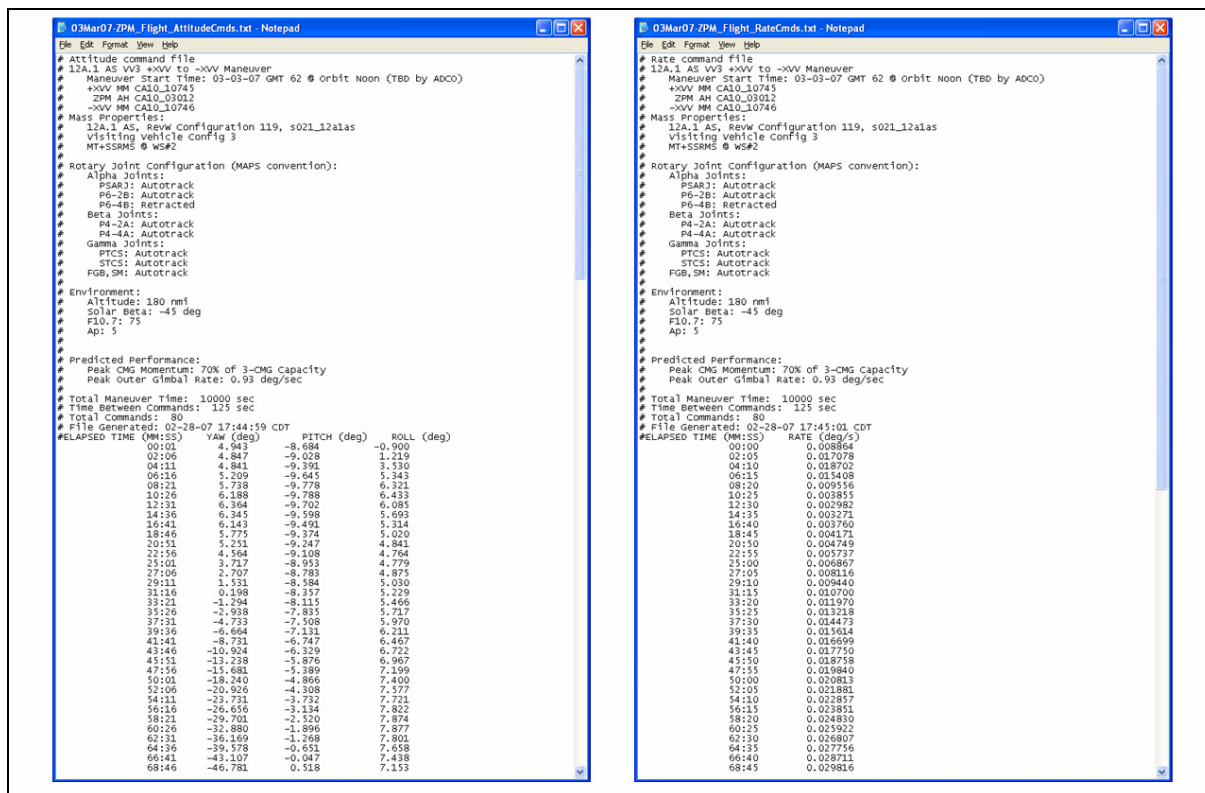**Figure 1. ZPM command timing sequence for ISS ZPM flight demonstration.**


Figure 2. ZPM command files.

IV. Flight Demonstration Description & Predicted Performance

The ZPM operation was designed for ISS Stage 12A.1 and involved a maneuver from X-axis in Velocity Vector (+XVV) to -X-axis in Velocity Vector (-XVV) flight attitude using only 3 CMGs. The ISS Stage 12A.1 mass properties are given in Table 1. The ISS GN&C would be in +XVV momentum management, then transition to CMG attitude hold control to perform the maneuver and then transition into the -XVV momentum manager. The initial and final LVLH attitude targets were $\begin{bmatrix} 5 & -8.5 & -2 \end{bmatrix}$ degrees and $\begin{bmatrix} -175 & -8 & -2 \end{bmatrix}$ degrees (YPR order and sequence) respectively. The initial and final angular rates were the rates needed to maintain the initial and final LVLH attitudes respectively (i.e., zero rates with respect to LVLH). The initial CMG momentum in the ISS Body frame was $\begin{bmatrix} 1275 & -100 & -625 \end{bmatrix}$ ft-lbf-sec and the final momentum target was $\begin{bmatrix} -3200 & 300 & 400 \end{bmatrix}$ ft-lbf-sec (RPY order). The momentum targets were obtained from the momentum manager design specifications. The maneuver duration was 10000sec, with 80 uniformly spaced attitude/rate command pairs (updated every 125sec). The maneuver was assumed to start at orbit noon. The expected ISS altitude was 180nm and the expected solar beta angle was -45deg. The atmosphere parameters were based on predicted NOAA[18] environmental conditions of F10.7=75 (solar flux) and Ap=5 (geomagnetic index). The rotary joint operations (see Figure 3) were assumed as:

- Port Solar Array Rotary Joint (SARJ): Autotrack (The SARJ assembly constitutes ~7% of the ISS mass.)
- P4, P6, Russian FGB & SM Solar Photo Voltaic Arrays (PVAs): Autotrack
- Thermal Radiator Rotary Joints (TRRJs): Autotrack

Table 1. ISS Stage 12A.1 Mass Properties.

Mass [lbs]	465,873		
Inertia [slug-ft^2]	19,886,842	2,530,940	3,039,659
	2,530,940	27,966,826	-729,378
	3,039,659	-729,378	40,507,299
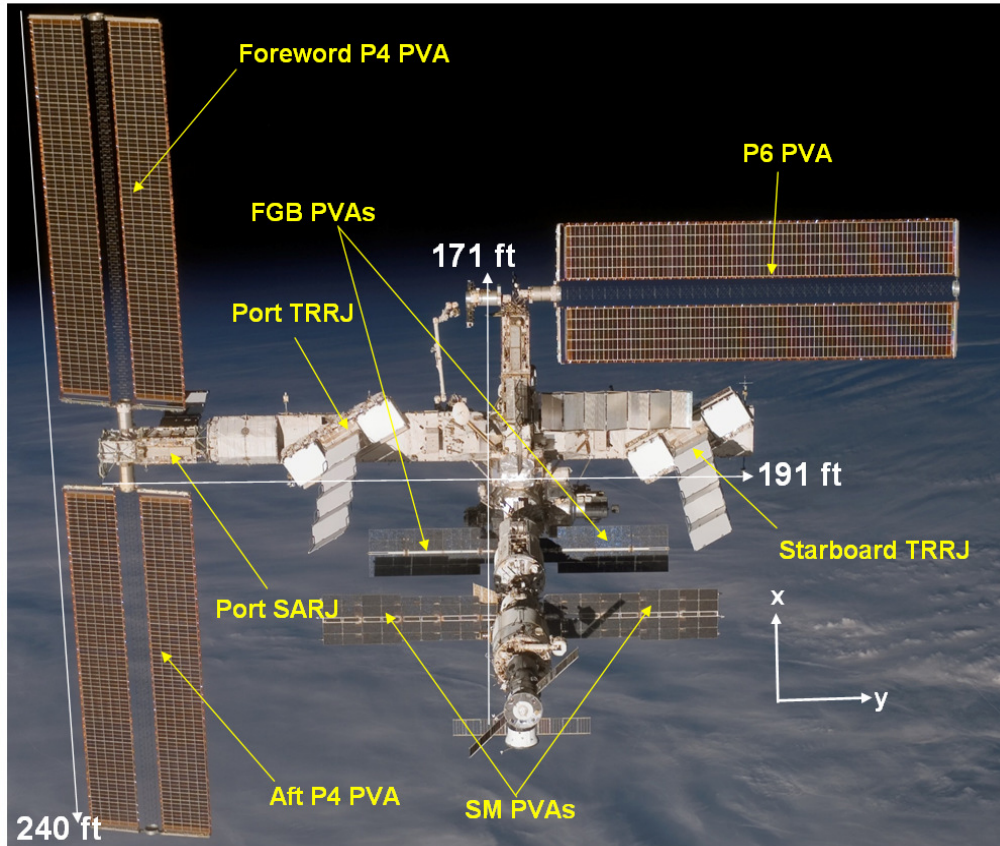
Figure 3. International Space Station Stage 12A.1 components.

A. Nominal Performance

The ZPM was tested and verified in non-realtime simulation. The ISS vehicle response to the sequence of attitude/rate commands was verified using the high-fidelity Space Station Multi-Rigid Body Simulation (SSMRBS).[19] A performance summary of the maneuver is shown in Figure 4, where the simulation results are compared to the DIDO optimal solution. The attitude and rate profiles agree very well, however, there are differences in the CMG momentum profile. This is expected as the fidelity in the dynamical models of the simulation and the optimization are not the same. The peak momentum in simulation is 70% of capacity while it was 62% for the optimal solution. For comparison, the result of commanding an eigenaxis trajectory for the same maneuver time (10000sec) is shown in Figure 5. In this case, the CMGs saturate very quickly, resulting in loss of attitude control.
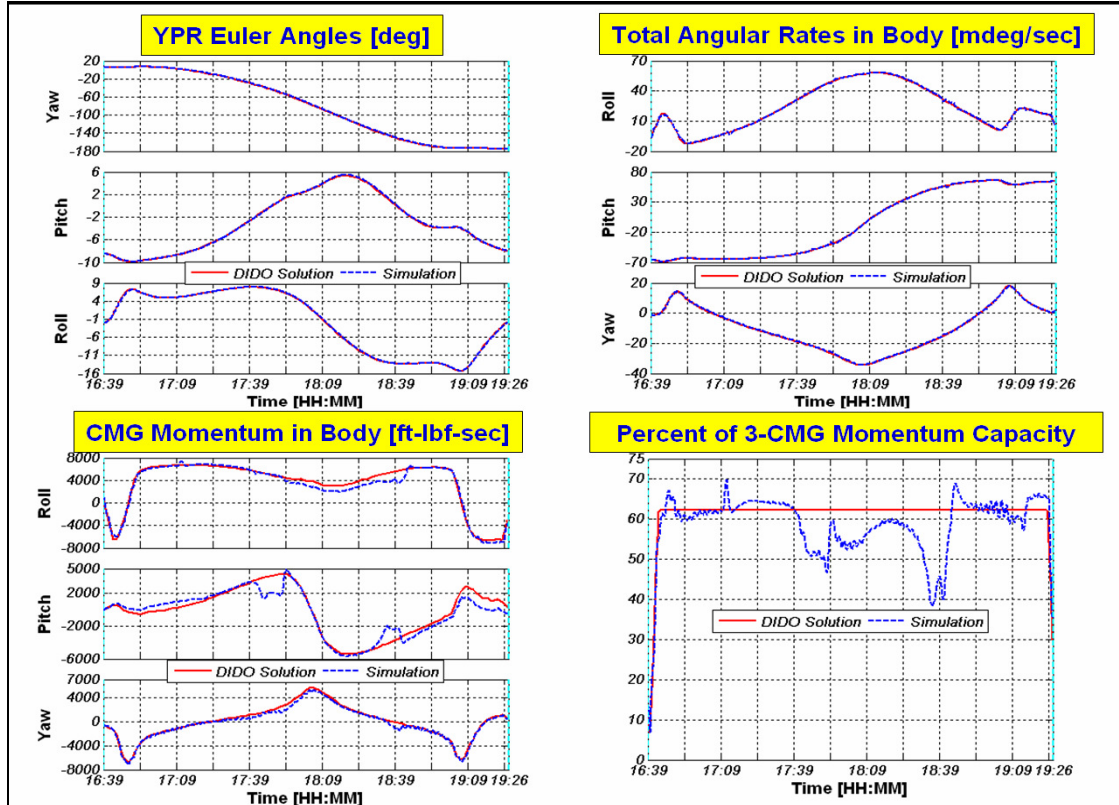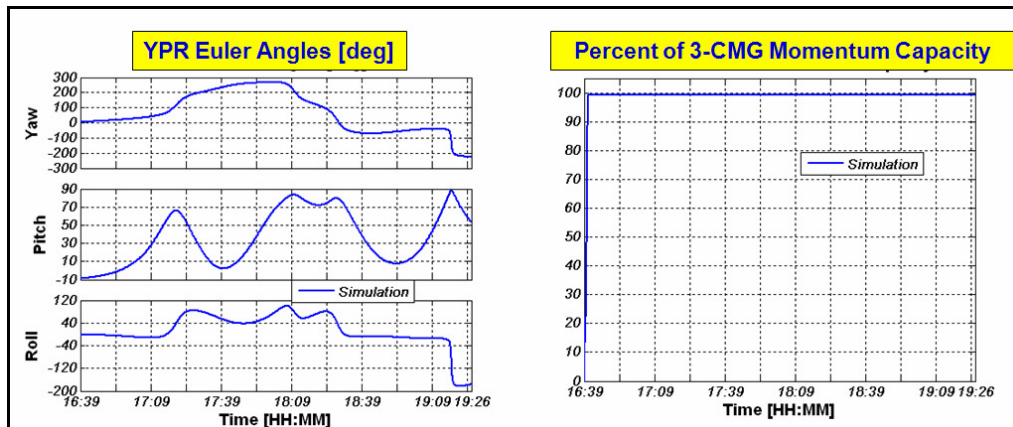

Figure 4. ZPM predicted performance.

Figure 5. Eigenaxis performance.

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B. Robust Performance

To assess the robustness of the ZPM, Monte-Carlo simulations were performed using SSMRBS for various parameter uncertainties. A single variable was perturbed at a time to identify sensitivity to individual error sources. Results for initial state perturbations as well as altitude are given in Figure 6, which shows percentage of total CMG capacity reached during the ZPM for 100 samples. Thus 100% of capacity indicates saturation. It is seen that the ZPM can tolerate initial error magnitudes of at least 2deg in attitude, 5mdeg/sec in rate, and 3000ft-lbf-sec in momentum. Also, the ZPM is relatively insensitive to altitude (180nm is nominal).
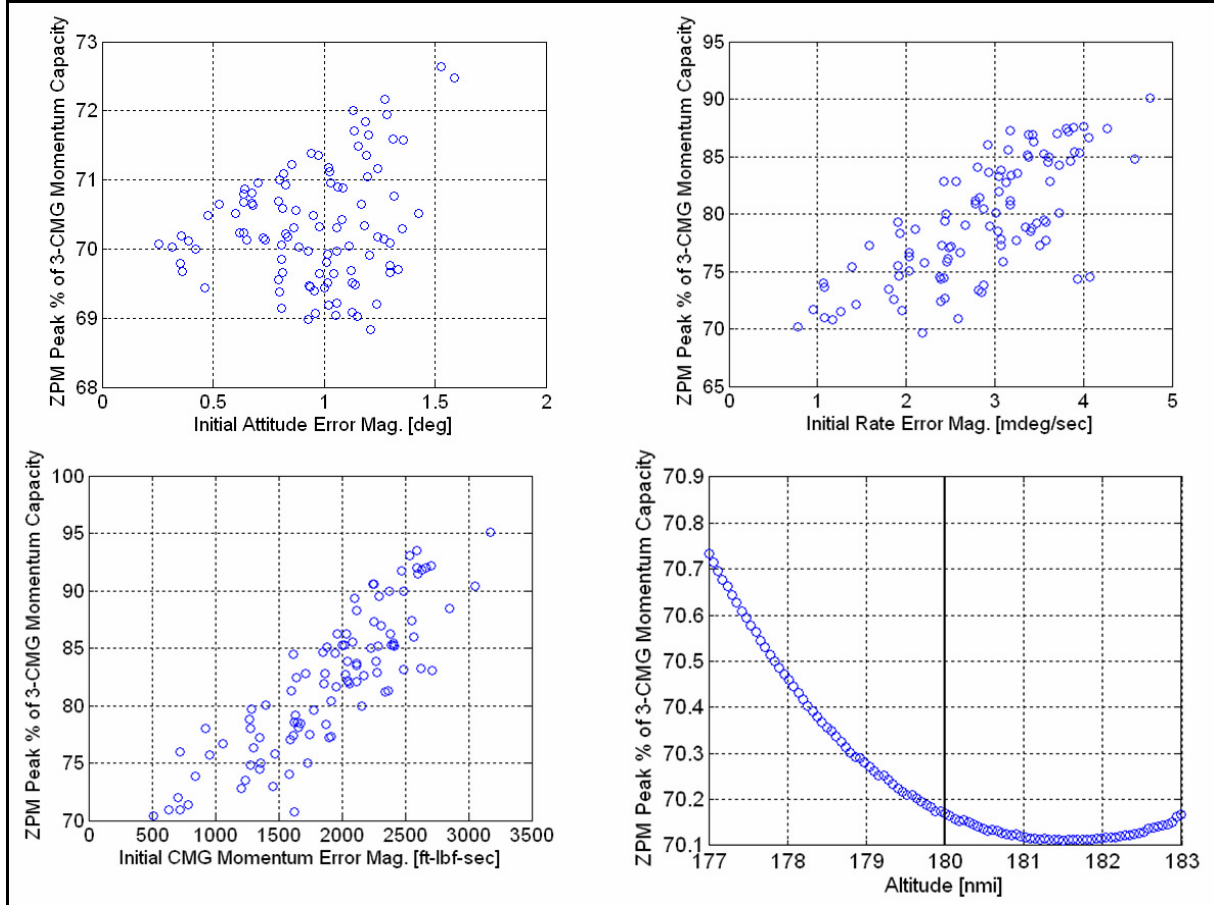

Figure 6. ZPM robust performance.

V. Flight Results

The flight took place on March 3, 2007. The transition to ZPM from +XVV momentum manager occurred at GMT 062:16:39:16 which was orbit noon, while transition to -XVV momentum manager occurred at GMT 062:19:25:56. The ZPM completed successfully and no propellant was used. The Mission Evaluation Room (MER) console views of the ZPM are shown in Figure 7Figure 9. Figure 7 shows the ISS actual attitude and the commands, Figure 8 shows the momentum which does not exceed 76% of capacity, and Figure 9 shows the CMG gimbal rates which are less than 0.91deg/sec.

While the flight attitude matches design, there are differences in CMG momentum. These differences are attributed to simulation fidelity and mass property uncertainty, and rotary joint operation. For example, Figure 10 shows a large difference in the flight TRRJ behavior from the pre-flight assumptions.
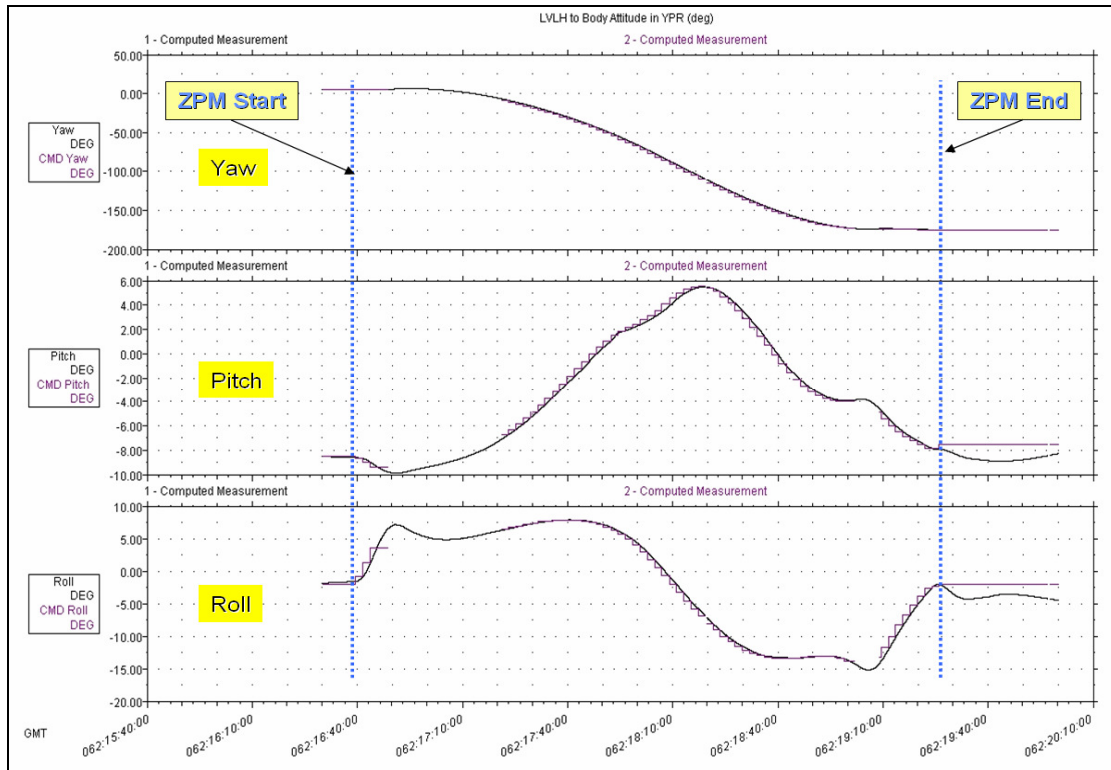
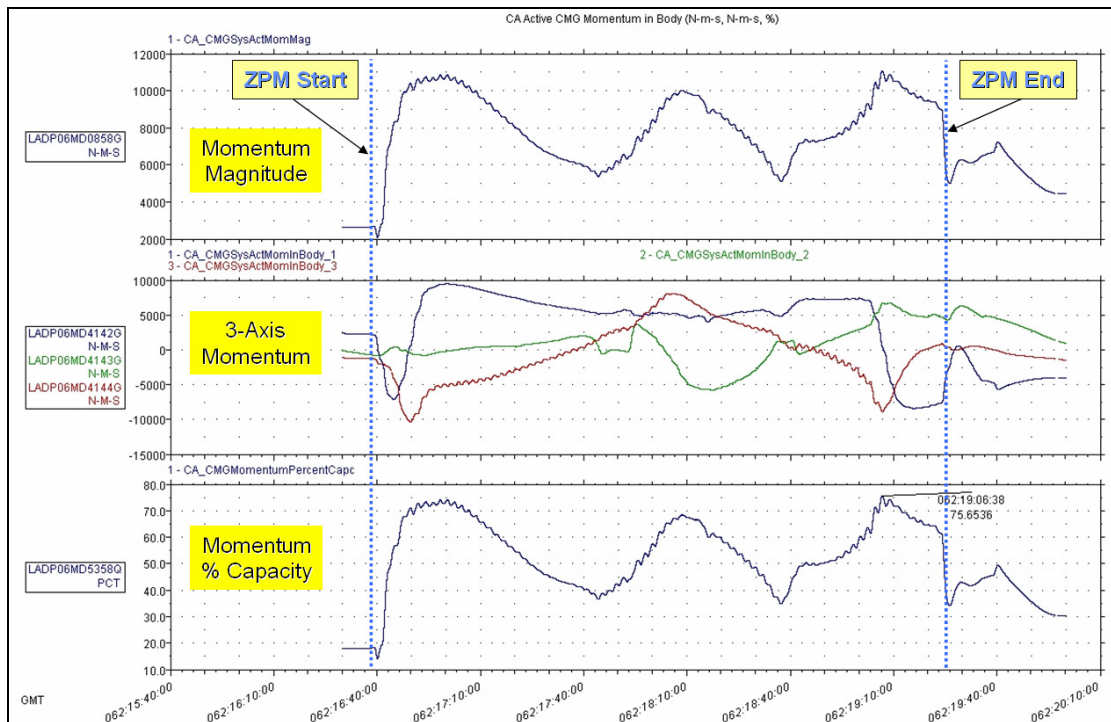**Figure 7. ZPM Flight commanded and actual attitude.**

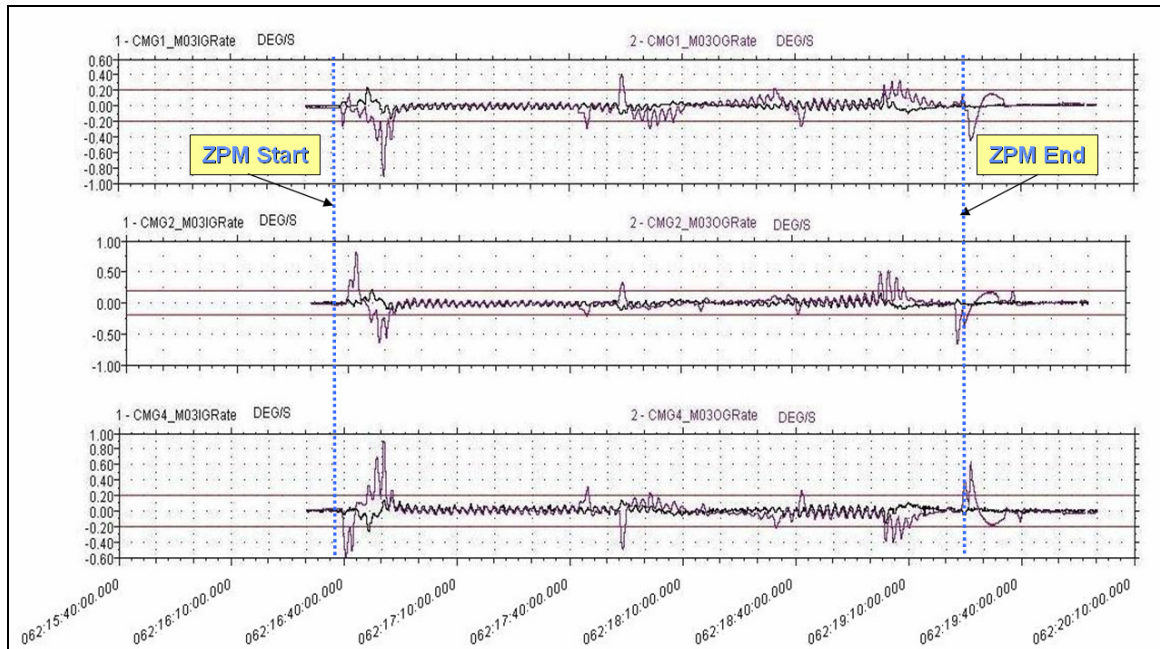**Figure 8. ZPM Flight CMG momentum.**

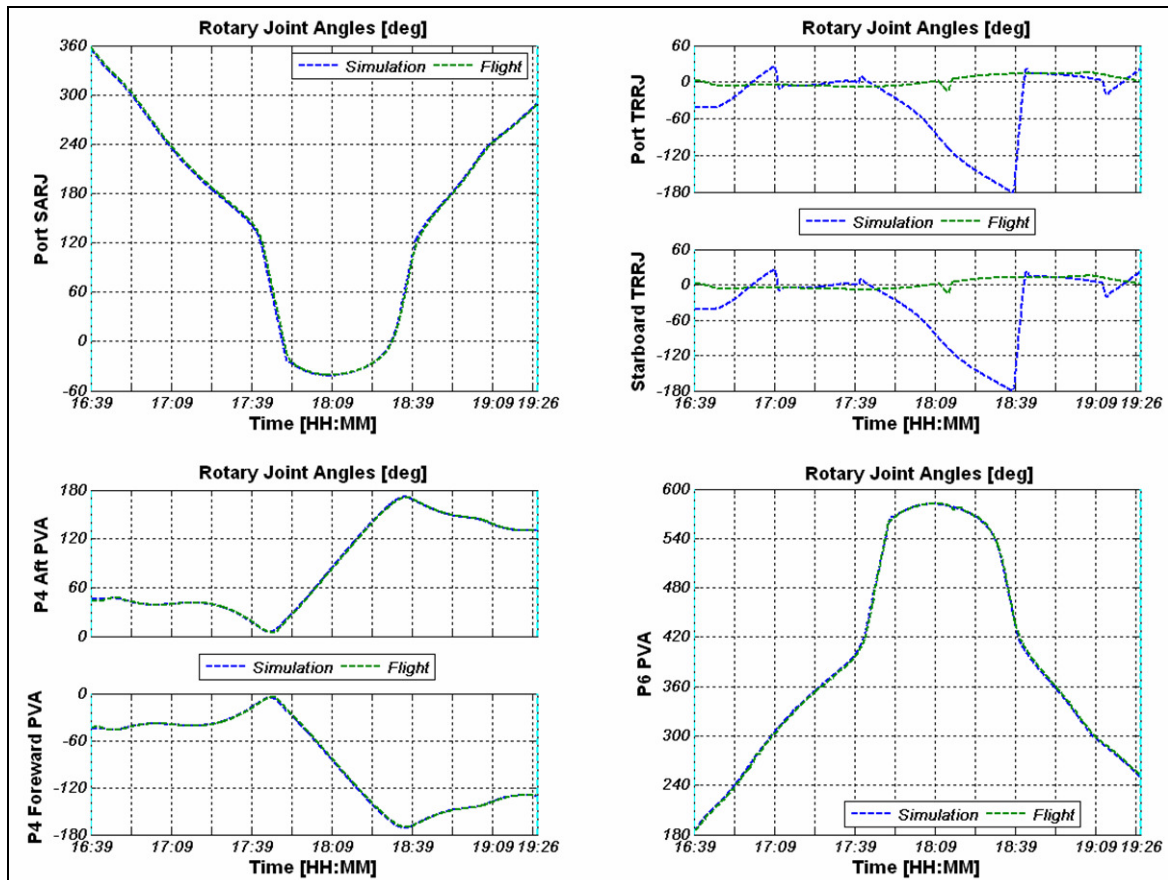**Figure 9. ZPM Flight CMG gimbal rates.**

Figure 10. ZPM rotary joint performance comparison.

VI. Conclusions

This paper presented the results for the Zero Propellant Maneuver (ZPM) [TM] attitude control concept flight demonstration of a 180 degree International Space Station rotation on March 3, 2007 without using propellant. The ZPM was designed to not require any flight software modifications, which was achieved by only uploading time-tagged commands. It also provides the only means to perform ISS rotations if thruster control is unavailable. This ZPM was historic at several levels. While the ZPM did not use any propellant, the identical maneuver performed with thrusters on January 2, 2007 consumed 110lbs of propellant with an estimated cost of $1M. The ZPM also made history from a mathematical perspective as it was the first ever use in flight of PseudoSpectral (PS) optimal control theory in a feedforward guidance mode. Feedback implementation is also possible, however, to implement it would require modifications to the ISS flight software. Moreover, the flight test established that the ZPM concept can be used to execute a large angle attitude maneuver and momentum desaturation at the same time without the need to use thrusters. This concept can be applied to any spacecraft controlled by momentum storage devices.

Acknowledgments

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