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Optimal Propellant Maneuver Flight Demonstrations on ISS

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This paper presents results for the flight demonstrations of Optimal Propellant Maneuver (OPM) on August 1, 2012. The OPM was used to complete two docking maneuvers of the International Space Station (ISS) using only 19.9 kg of propellant, saving 93% compared to using ISS flight software. The savings were achieved by commanding the ISS to follow a pre-planned attitude trajectory which was optimized to take advantage of naturally occurring environmental torques and available control authority from the jets. The trajectory was obtained by solving an optimal control problem. The flight implementation did not require any modifications to flight software. This approach is applicable to any spacecraft controlled with thrusters.

I. Introduction

IN this paper, first ever flight demonstrations of Optimal Propellant Maneuver (OPM), a method of propulsive rotational state transition for spacecraft controlled using thrusters, is presented for the International Space Station (ISS). On August 1, 2012, two ISS reorientations of about 180deg each were performed using OPMs. These maneuvers were in preparation for the same-day launch and rendezvous of a Progress vehicle, also a first for ISS visiting vehicles. The first maneuver used 9.7 kg of propellant, whereas the second used 10.2 kg. Identical maneuvers performed without using OPMs would have used approximately 151.1kg and 150.9kg respectively.

The OPM method is to use a pre-planned attitude command trajectory to accomplish a rotational state transition. The trajectory is designed to take advantage of the complete nonlinear system dynamics. The trajectory choice directly influences the cost of the maneuver, in this case, propellant. For example, while an eigenaxis maneuver is kinematically the shortest path between two orientations, following that path requires overcoming the nonlinear system dynamics, thereby increasing the cost of the maneuver. The eigenaxis path is used for ISS maneuvers using thrusters. By considering a longer angular path, the path dependence of the system dynamics can be exploited to reduce the cost.

The benefits of OPM for the ISS include not only reduced lifetime propellant use, but also reduced loads, erosion, and contamination from thrusters due to fewer firings. Another advantage of the OPM is that it does not require ISS flight software modifications since it is a set of commands tailored to the specific attitude control architecture.

The OPM takes advantage of the existing ISS control system architecture for propulsive rotation called USTO control mode[1]. USTO was originally developed to provide ISS Orbiter stack attitude control capability for a contingency tile-repair scenario, where the Orbiter is maneuvered using its robotic manipulator relative to the ISS. Since 2005 USTO has been used for nominal ISS operations.

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Previous work on minimum propellant spacecraft rotations has utilized bang-off-bang profiles[2] designed based on simplifying assumptions such as rest-to-rest maneuvers, inertially symmetric spacecraft, and no disturbance torques[3]. A three-pulse algorithm with reduced propellant usage has also been developed for axisymmetric spacecraft with non-zero initial rates[4]. Recent computational advances have allowed the solution of increasingly complex optimization problems. Consequently, the minimum fuel problem can be solved with fewer simplifying assumptions. By incorporating the full nonlinear dynamics, disturbance torques, and a varying control profile, the OPM trajectory can be shaped to complete the rotation as efficiently as possible.

OPM is similar to the Zero-Propellant Maneuver (ZPM), which commanded the CMGs to complete the maneuver while simultaneously performing momentum dumping. The first ZPM flight demonstration on November 5, 2006 rotated the ISS 90 degrees[5]. On March 3, 2007, a second ZPM demonstration rotated the ISS 180 degrees without using propellant[6]. To avoid CMG saturation, ZPM generally requires longer maneuver times. With OPM, the maneuver times can be made significantly shorter, depending on the propellant budget, thus allowing fewer restrictions on ISS operations and requiring less ISS thermal analysis. Another advantage of OPM compared to ZPM is that the ISS thrusters have much more control authority than the CMGs and thus can better handle discrepancies between predicted and on-orbit initial conditions, mass properties, and environment.

This paper presents the OPM method within the context of two specific ISS docking maneuvers. The ISS 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 ISS flight software and operations will be presented. The flight operational maneuver is described and OPM trajectory is verified in high fidelity simulation. Flight results are then presented.

II. Problem Formulation and Solution Technique

A rotational state transition, e.g. attitude, rate and angular momentum, 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 satisfying the system dynamics and any constraints on the system. For the ISS, the system dynamics include Euler, gravity gradient and aerodynamic torques, articulating appendages, attitude kinematics, and the 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 jet torques. 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 LVLH frame. It should be noted that in general the maneuver trajectory is a function of the particular ISS configuration mass properties as well as the specific combination of rotary joint motions (e.g. solar arrays).

The details of this nonlinear, constrained optimal control problem are similar to that described in Ref. 7. The optimal control problem is solved using the software package DIDO[8].

III. Operational Implementation

To implement the OPM, the ground-developed trajectory commands are uploaded to the ISS. The Attitude Determination and Control Officer (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. Since the C&C MDM command buffer is limited to 900 slots, the OPM is allocated 110 slots and is composed of 55 commands.

Since the OPM 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. 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, more propellant may be used to initialize the rotational states.

IV. Flight Demonstration Description & Predicted Performance

The first OPM operational demonstration was prior to docking of Progress (48P) to ISS, and involved a maneuver from +X-axis in Velocity Vector (+XVV) to –X-axis in Velocity Vector (–XVV) flight attitude. The ISS GN&C would be in +XVV momentum management, then transition to USTO control to perform the maneuver and then transition into the –XVV momentum manager. The initial and final Local Vertical Local Horizontal (LVLH) attitude targets were $\begin{bmatrix}-6 & 0.2 & 0.6\end{bmatrix}$ degrees and $\begin{bmatrix}175 & 0.8 & 0.6\end{bmatrix}$ degrees (YPR order and sequence) respectively.

The initial CMG momentum in LVLH frame was $\begin{bmatrix}0 & 0 & -1000\end{bmatrix}$ft-lbf-s and the final momentum target was $\begin{bmatrix}500 & 0 & 1000\end{bmatrix}$ft-lbf-s (RPY order). The maneuver duration was 5500s, with 55 uniformly spaced attitude/rate command pairs (updated every 100s). The expected ISS altitude was 224 nautical miles and the expected solar beta angle was 52deg. The atmosphere parameters were based on predicted NOAA[9] environmental conditions of F10.7=120 (solar radio noise flux) and Ap=5 (geomagnetic index). The rotary joint operations were assumed to be as follows:

- Port Solar Array Rotary Joint (SARJ): Fixed at 270°
- Starboard SARJ: Fixed at 90°
- P4,P6,S4,S6 Beta Joints: Autotrack
- Port & Starboard Thermal Radiator Rotary Joints (TRRJs): Fixed at 45°

The second OPM demonstration was scheduled after Progress 48P had docked to ISS and involved a maneuver from –XVV to +XVV flight attitude. The ISS GN&C would be in +XVV momentum management, then transition to USTO control to perform the maneuver and then transition into the –XVV momentum manager. The initial and final Local Vertical Local Horizontal (LVLH) attitude targets were $\begin{bmatrix}175 & -0.3 & 0.6\end{bmatrix}$degrees and $\begin{bmatrix}-6 & -0.8 & 0.6\end{bmatrix}$degrees (YPR order and sequence) respectively. The initial CMG momentum in LVLH frame was $\begin{bmatrix}1000 & 0 & 1000\end{bmatrix}$ft-lbf-s and the final momentum target was $\begin{bmatrix}500 & 0 & -500\end{bmatrix}$ft-lbf-s (RPY order). The maneuver duration was 5500s, with 55 uniformly spaced attitude/rate command pairs (updated every 100s). The expected ISS altitude was 224 nautical miles and the expected solar beta angle was 56deg. The atmosphere parameters were based on predicted NOAA[9] environmental conditions of F10.7=120 (solar radio noise flux) and Ap=5 (geomagnetic index). The rotary joint operations were assumed to be as follows:

- Port Solar Array Rotary Joint (SARJ): Fixed at 270°
- Starboard SARJ: Fixed at 90°
- P4,P6,S4,S6 Beta Joints: Autotrack
- Port & Starboard Thermal Radiator Rotary Joints (TRRJs): Fixed at 45°

To assess the robustness of the OPM, Monte-Carlo simulations were performed using the high-fidelity Space Station Multi-Rigid Body Simulation (SSMRBS)[10] for various parameter uncertainties. A single variable was perturbed at a time to identify sensitivity to individual error sources. Results for initial state and inertia perturbations are given in Figure 1, which shows propellant consumed for the OPM for 500 samples. It is seen that the OPM can tolerate a wide range of errors, but completing the maneuver with large perturbations without redesigning the optimal trajectory costs more propellant. Figure 2 shows similar results for the second OPM.

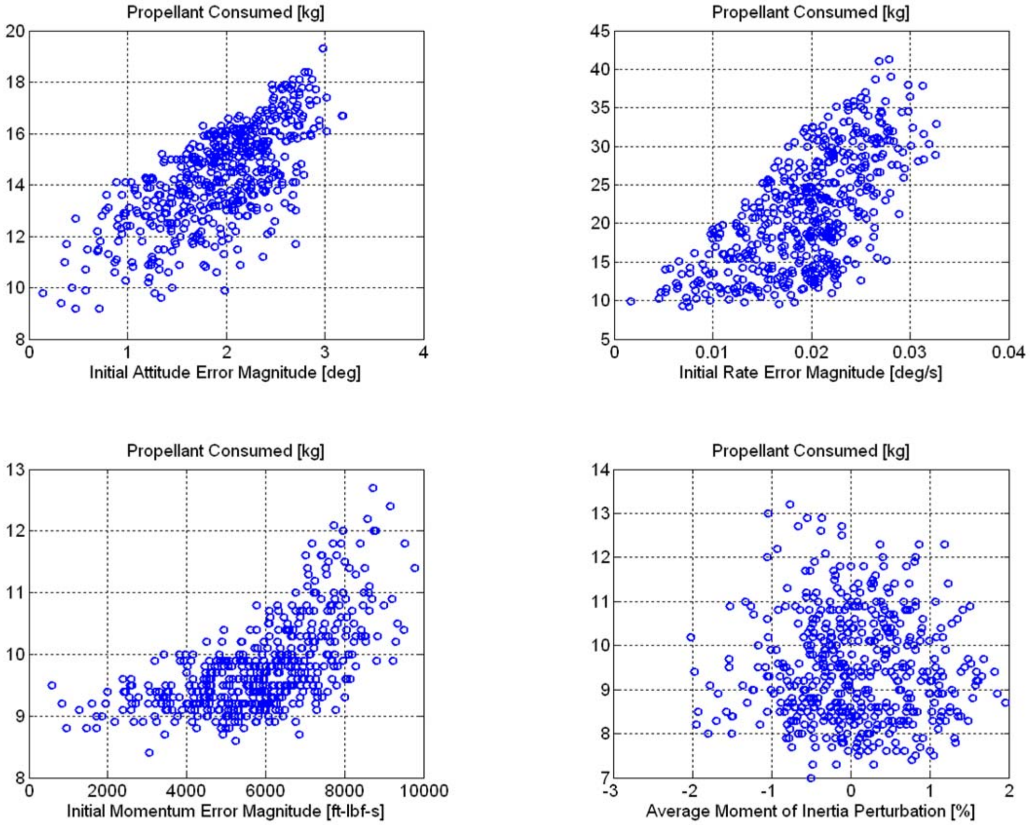

Figure 1. OPM1 robust performance.

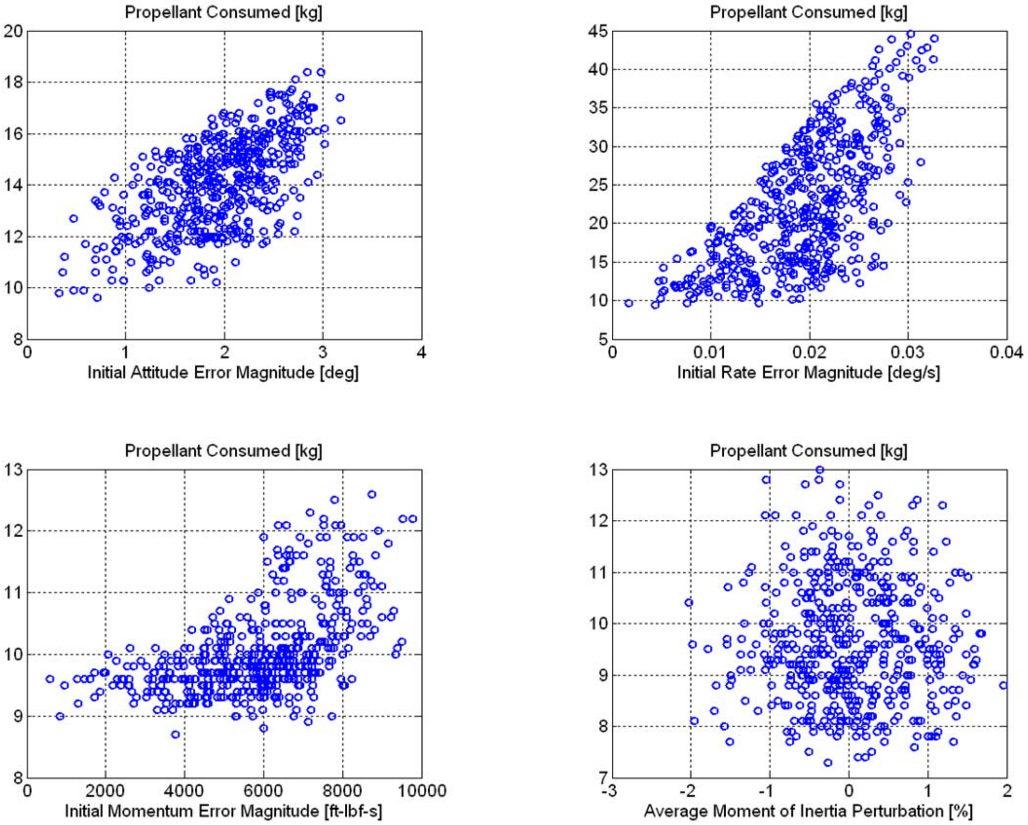

Figure 2. OPM2 robust performance.

The robustness of OPM to mass properties is advantageous in the presence of ISS visiting vehicle schedule uncertainties since a single OPM can be used for multiple configurations. Figure 3 shows the expected visiting vehicles for the OPM flight demonstration, including the 48P Progress docked at the DC1 port. Since HTV3 was to be berthed days before the first OPM demonstration, we considered the impact of using the unmodified OPM to maneuver the ISS without HTV berthed. Figure 4 and Figure 5 show the OPM is robust to the absence or presence of HTV as well as the Progress at DC1.

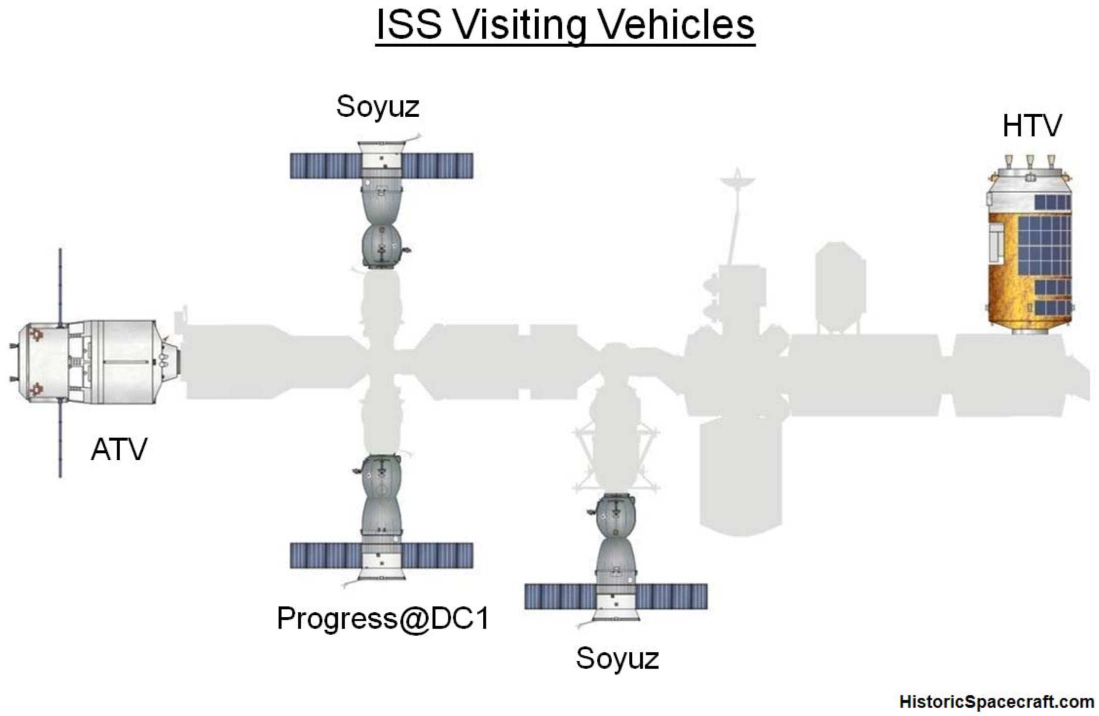

Figure 3. ISS visiting vehicles.

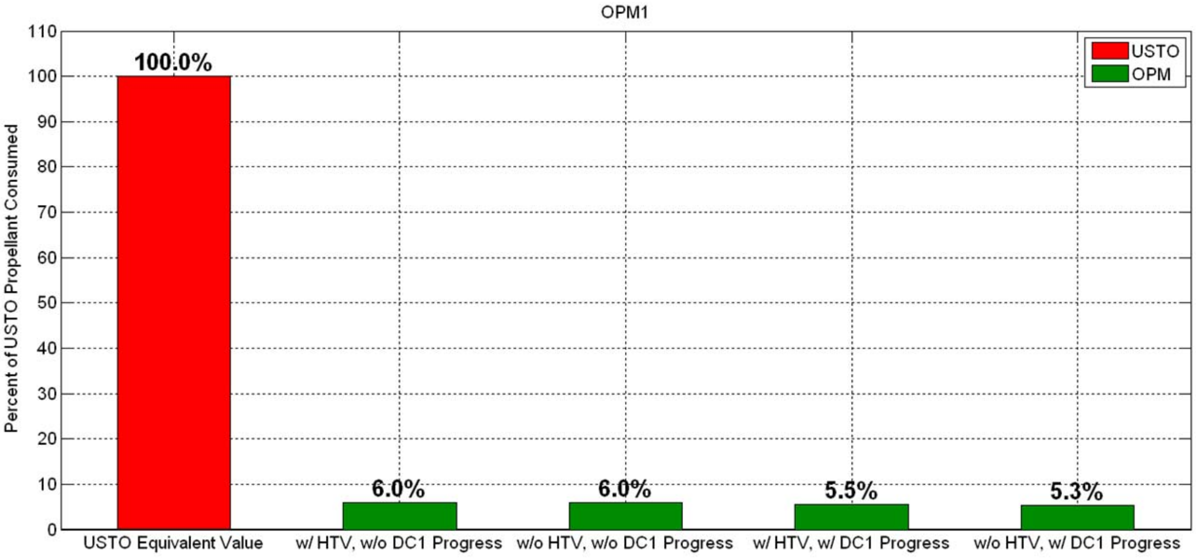

Figure 4. OPM1 robust performance to visiting vehicle uncertainty.

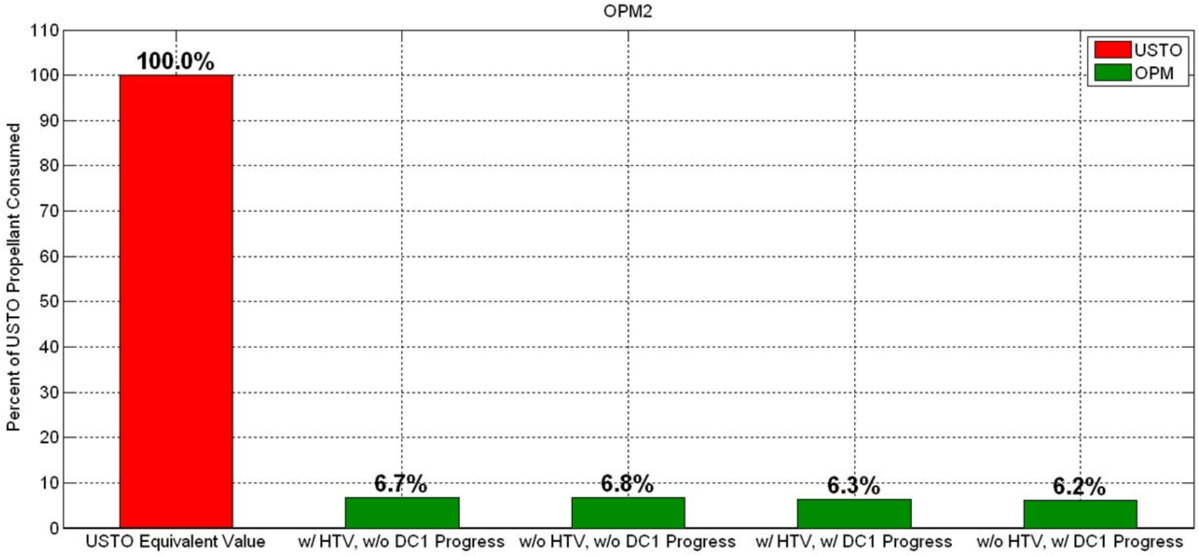

Figure 5. OPM2 robust performance to visiting vehicle uncertainty.

V. Flight Results

The OPM flight tests took place on August 1, 2012 and surrounded the launch and docking of the 48P Progress vehicle. The first OPM began at GMT 214:11:55 and ended at GMT 214:13:25, rotating the ISS 180deg in preparation for 48P docking. Then 48P launched at GMT 214:19:35, successfully executing a new fast rendezvous technique to dock to ISS at GMT 215:01:18. The second OPM was then initiated at GMT 215:04:15, and ended at GMT 215:05:45, putting the ISS back in an orientation suitable for long-term attitude hold with momentum manager. Both OPMs completed successfully and used 9.7kg and 10.2kg respectively. The Mission Evaluation Room (MER) console views of the first OPM are shown in Figure 6Figure 8. Figure 6 shows the ISS actual attitude and the commands, while Figure 7 shows the total CMG momentum magnitude, the total CMG momentum vector, and momentum as a percent of total CMG capacity. Figure 8 shows the estimated propellant consumption immediately after maneuver completion. The propellant consumption values quoted earlier are based on finalized estimates from processed telemetry. Similarly, Figure 9Figure 11 show the attitude, CMG momentum, and propellant for the second OPM.

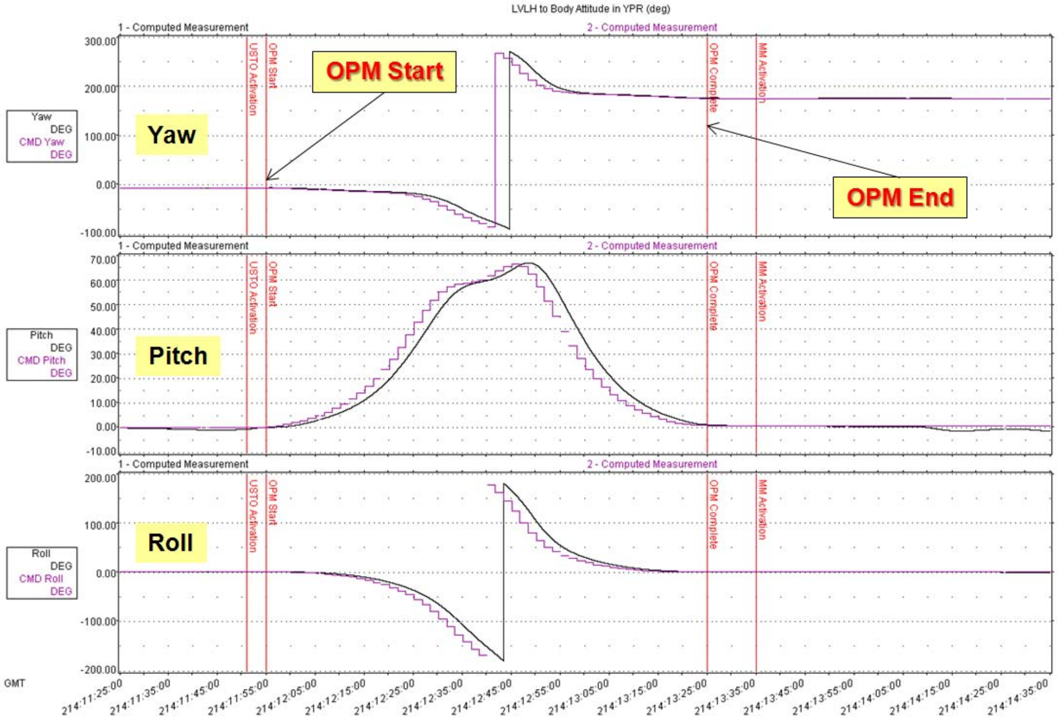

Figure 6. OPM1 flight commanded and actual attitude.

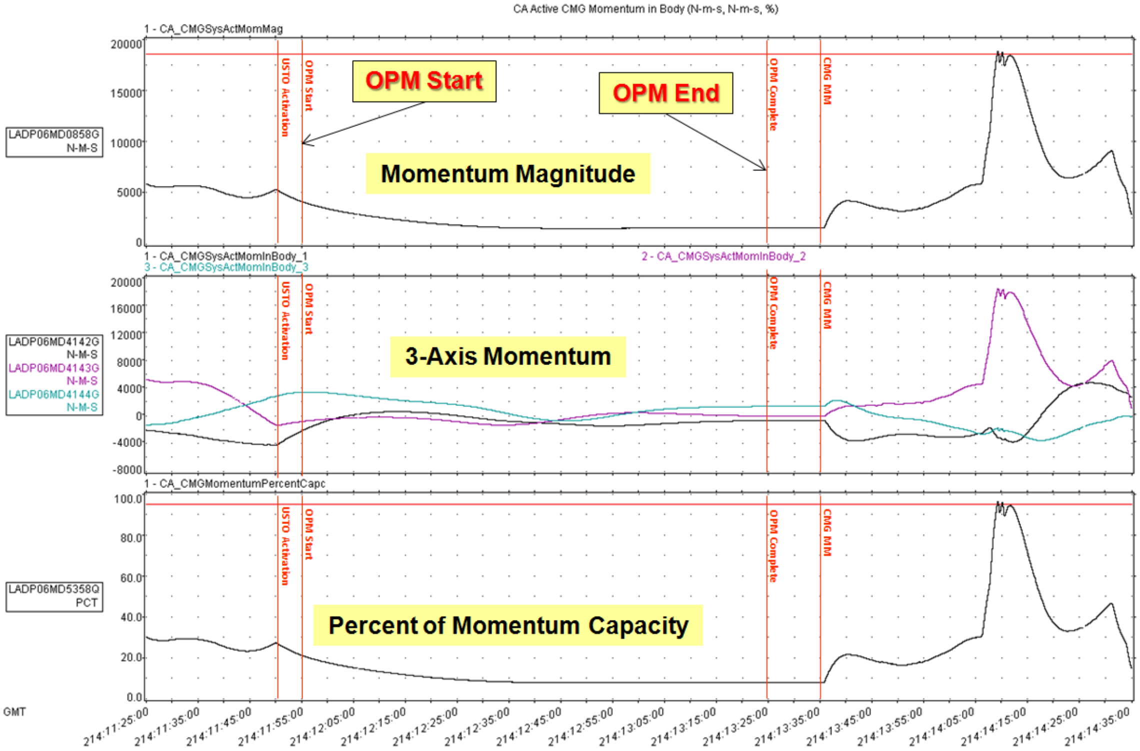

Figure 7. OPM1 flight total CMG momentum.

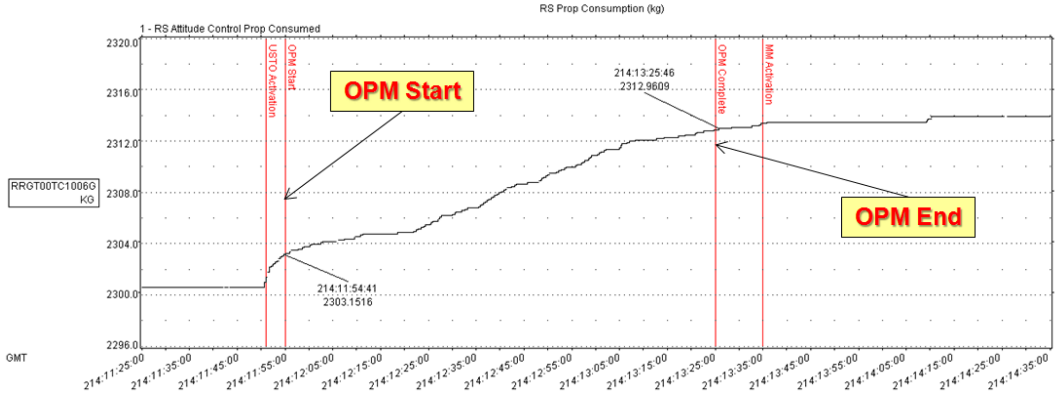

Figure 8. OPM1 estimated flight propellant consumption.

VI. USTO Comparison

For comparison, the identical maneuvers from the demonstrations were simulated with USTO without using OPM. Flight data from the demonstrations were used to set the initial conditions. The attitude and propellant consumption are shown in Figure 12 for the first OPM, and Figure 13 for the second OPM. It is seen that the identical maneuver using USTO consumes 150kg.

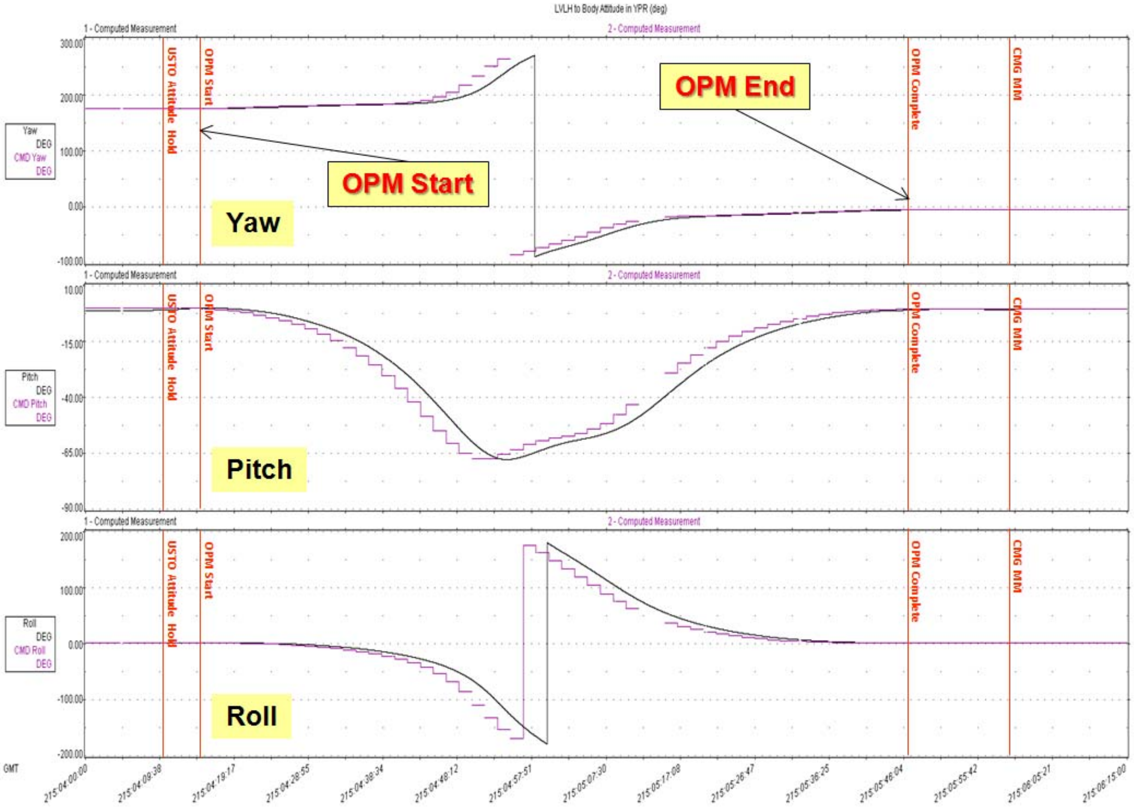

Figure 9. OPM2 flight commanded and actual attitude.

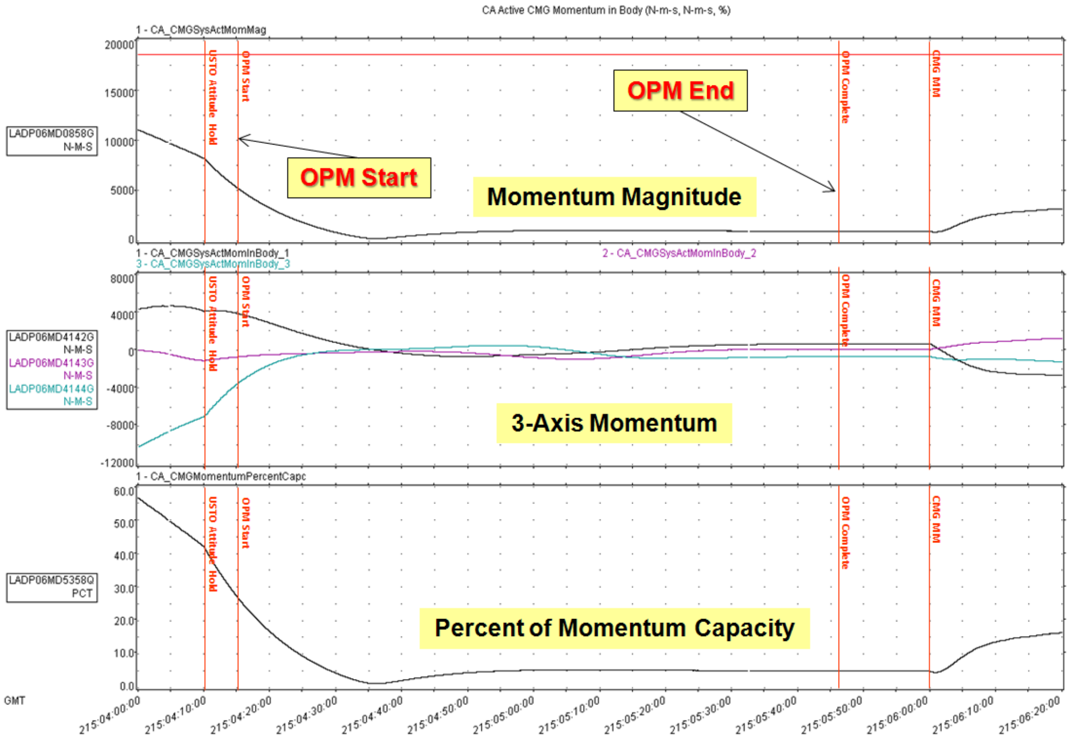

Figure 10. OPM2 flight total CMG momentum.

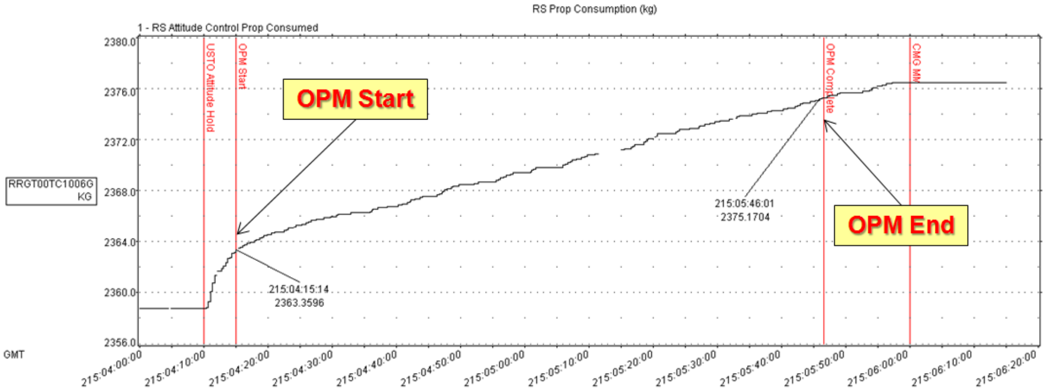

Figure 11. OPM2 estimated flight propellant consumption.

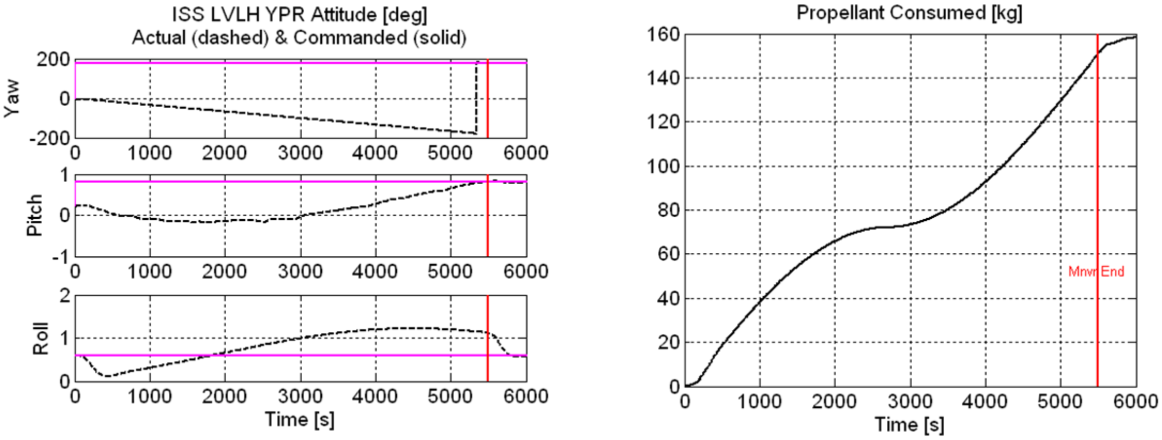

Figure 12. Simulated USTO performance for identical maneuver as OPM1.

VII. Conclusions

This paper presented the results of the first ever flight demonstration of the Optimal Propellant Maneuver (OPM). On August 1, 2012, OPM was successfully used to complete two ISS docking maneuvers which saved 93% propellant compared to standard methods. Additionally, OPM was designed to not require any flight software modifications, which was achieved by only uploading time-tagged commands. It also reduces ISS structural loads compared to typical ISS rotations using thruster control. This OPM was historic at several levels. From an economic perspective, the amount of propellant saved was approximately 280kg for an estimated value of over $9M. Feedback implementation is also possible, however, to implement it would require modifications to the ISS flight software. Moreover, the OPM flight tests established that "low-cost" rotational state transition using thrusters could be executed while satisfying system constraints, much like the ZPM flight tests established for momentum actuators. Thus the OPM and ZPM concepts can be applied to any spacecraft controlled using thrusters or momentum actuators respectively.

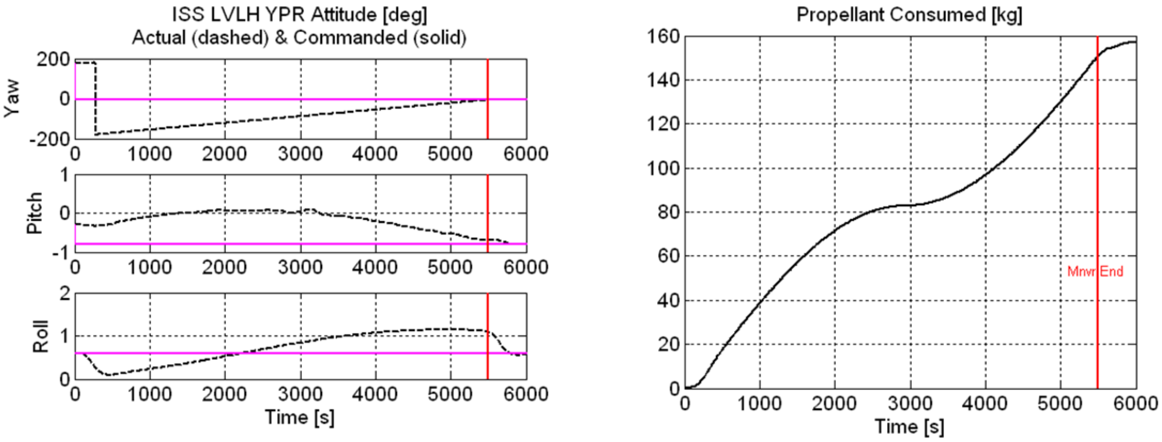

Figure 13. Simulated USTO performance for identical maneuver as OPM2.

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