Quick OPM / ZPM Calculation

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The goals of maneuver optimization

1. Maneuver is performed using thrusters (Optimal Propellant Maneuvers - OPM).

   To find a maneuver trajectory with minimal torques acting on the vehicle during the maneuver --> Minimal thruster firings (saves propellant, decreases structural loads and contamination, saves the service life of the thrusters).

   Variations : minimizing torques about a specific axis.

2. Maneuver is performed using Control Moment Gyroscopes (CMG) (Zero Propellant Maneuvers - ZPM).

   To find a maneuver trajectory where the peak of CMG momentum is minimal and is below the CMG saturation level.

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International Space Station (ISS) operations

For the ISS, yaw maneuvers are used most often. Optimization of these maneuvers is desired.

Background

- The first 180 deg. zero propellant yaw maneuver (ZPM) was created by Draper Laboratory (USA) and performed in 2006 on ISS. They were the first to prove that such maneuver is possible.

- ZPM was calculated on the ground since significant computer resources are needed for calculations.

- Complicated operation:
  - ~ 100-200 commands have to be sent onboard. Several days of planning.

- ZPMs were not used on ISS after demonstration in 2006 because of thermal concerns since ZPMs are rather slow (~ 3 hours).

- OPM are similar to ZPMs but faster (~ 1.5 hours). First OPM on ISS - in 2012. Propellant consumption for OPMs is low.

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Simplified maneuver optimization solution

The goal - to find a simplified optimization solution which does not require a lot of computer resources. In this case:

- ➢ The solution can be implemented using onboard software → maneuver execution can be automatic (simplify operations).

- The method is not solving the optimization problem (as Draper's method).

- The method is based on approximate solution of equation of motion → simple and fast.

Benefits of the Method

- **Fast calculations**
- **Easy to analyze the dependence from different parameters** (mass properties, maneuver duration, thruster configuration).
- **Can be implemented in the onboard s/w. Thus, ZPM/OPM can be completely automatic** (automatically adjusting to the changes of mass properties or maneuver duration). Eliminating preparations and analysis, potential command errors.
  - Can change maneuver duration to save prop in the specific circumstances.
- **Can obtain OPM profiles with decreased roll torques** (at the expense of yaw or pitch torques) (or decrease other torques) in case of a specific thruster configuration.

Model

- ISS is a rigid body
- The aerodynamic torques are not taken into account
  - Not very noticeable for OPM since the error is small
  - May have more significant effect on ZPM (since for current ISS configuration ZPMs are not far from CMG saturation level).

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ISS equation of rotation

- The ISS equation of rotation around its center of mass are described in yaw, pitch, and roll Euler angle sequence.
- For the pure yaw maneuver the roll and pitch angles are zero.
- For yaw maneuver optimization we consider the cases when the roll and pitch angles are small.

Formulating the problem

- The task is to perform a 180 degree yaw rotation minimizing the magnitudes of control torques.

  Designations:

  $$\alpha - \text{yaw angle},\ \ \beta - \text{pitch angle},\ \ \gamma - \text{roll angle}.$$

- The goal is to find $\alpha(t)$, $\beta(t)$, and $\gamma(t)$ which will bring the ISS from the initial to the final position with the minimized control torques (minimized thruster firings) or minimized increase of CMG momentum.

Yaw rate profile selection

- Yaw profile requirements:
  - The yaw profile should provide zero rate and acceleration at the start and the end of the maneuver.
  - For a yaw maneuver on CMGs, the yaw rate and acceleration should be low enough so that the yaw torque is as low as the CMGs are able to control.
  - For a maneuver on CMGs, it is necessary to avoid high accelerations spikes since the CMGs cannot handle high torques.
- To fulfill these requirements, a bell profile was selected. The parameters of this profile are obtained to satisfy the optimization criteria.

Pure yaw maneuver torques

- Pure yaw maneuver : roll and pitch angles remain zero.
- Consider a 180 deg. pure yaw maneuver. This maneuver is performed using thrusters.
- For such a maneuver the torques in roll (T_x) and pitch (T_y) can be written as:

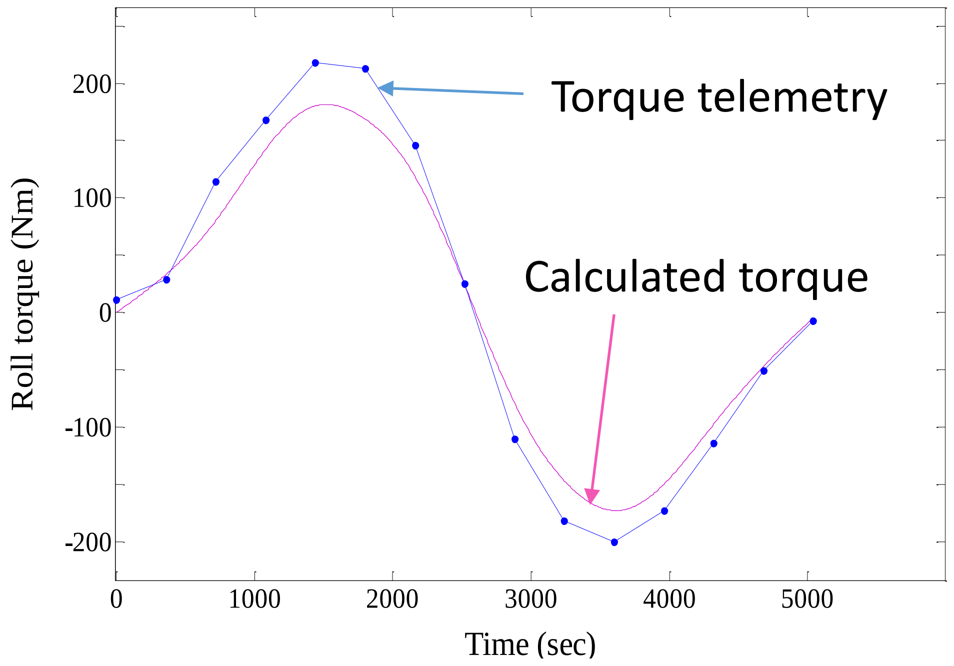
$$T_x = -(C - B + A)n\dot{\alpha}cos\alpha$$
$$T_y = (C + B - A)n\dot{\alpha}sin\alpha$$

where:
A, B, C - are the ISS principal moments of inertia, n - orbital rate, α – yaw angle.

- For the ISS mass properties and common maneuver durations (about 5400 sec.) these torques are large with respect to the CMG capabilities.

Pure yaw maneuver torques

Comparing flight roll torque telemetry (blue line) and calculated roll torque (red line).



Roll torque during a 180 deg. pure yaw maneuver.

- Torque is rather large - much more than the ISS CMGs can handle without desaturation.
- Goal of a maneuver optimization is to reduce these torques.
- Gravity torques can be used to solve the problem by compensating for these torques.
- This compensation is the essence of the suggested method.

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Maneuver optimization limitations

- The proposed maneuver optimization is not possible for all ranges of mass properties of any given space vehicle.

- The gravity torques have to be big enough to compensate for large torques. The gravity torques in case of a small angle approximation:

$$T_{gravity_x} = 3n^2\,(C - B)\gamma, \qquad T_{gravity_y} = 3n^2(C - A)\beta, \qquad T_{gravity_z} = 0$$

In the extreme case when $C = A$, or $C = B$ the proposed optimization is impossible.

- Simple computations can determine if the suggested maneuver optimization method is applicable for each specific vehicle. It is shown that it is applicable for the ISS.

First approximation solution

- In the range of the ISS mass properties, and in case of small pitch and roll angles, rates, and accelerations, the following simplified solution can be suggested as a first approximation for roll and pitch profiles:

$$\gamma_0 = \lambda\dot{\alpha}\, cos\alpha$$
$$\beta_0 = \mu\dot{\alpha}\, sin\alpha$$

where: $\lambda = -\frac{(C-B+A)}{4n(C-B)}$, $\mu = \frac{(C-A+B)}{4n(C-A)}$

- For the possible range of the ISS mass properties and for the commonly used range of the ISS maneuver rates, this very simple solution significantly reduces the roll and pitch torques.

Second approximation solution

$$\gamma = \lambda\dot{\alpha}\,cos\alpha\; + \lambda_1\ddot{\alpha}\dot{\alpha}\,sin\alpha + \lambda_2\,\ddot{\alpha}\,cos\alpha$$

$$\beta = \mu\dot{\alpha}\,sin\alpha + \mu_1\ddot{\alpha}\dot{\alpha}\,cos\alpha + \mu_2\,\ddot{\alpha}\,sin\alpha,$$ where:

$$\lambda = -\frac{(C-B+A)}{4n(C-B)}\;,\quad \mu = \frac{(C-A+B)}{4n(C-A)}$$

$$\lambda_1 = \frac{-3A\,\lambda - A\mu + (\,C-B-A)\mu}{4n^2\,(C-B)},\quad \mu_1 = \frac{-3A\,\lambda - A\mu + (\,C-B-A)\mu}{4n^2\,(C-A)}$$

$$\lambda_2 = \varepsilon_1\,\frac{A\,\lambda}{4n^2\,(C-B)},\quad \mu_2 = \varepsilon_2\,\frac{B\,\mu}{4n^2\,(C-A)}$$ ($\varepsilon_1 = 0.1$, $\varepsilon_2 = 0.6$, for example, for OPM).

- ε_1 and ε_2 values are obtained based on the selected optimization criteria.
- Equations for a more accurate solution can be found in [3].

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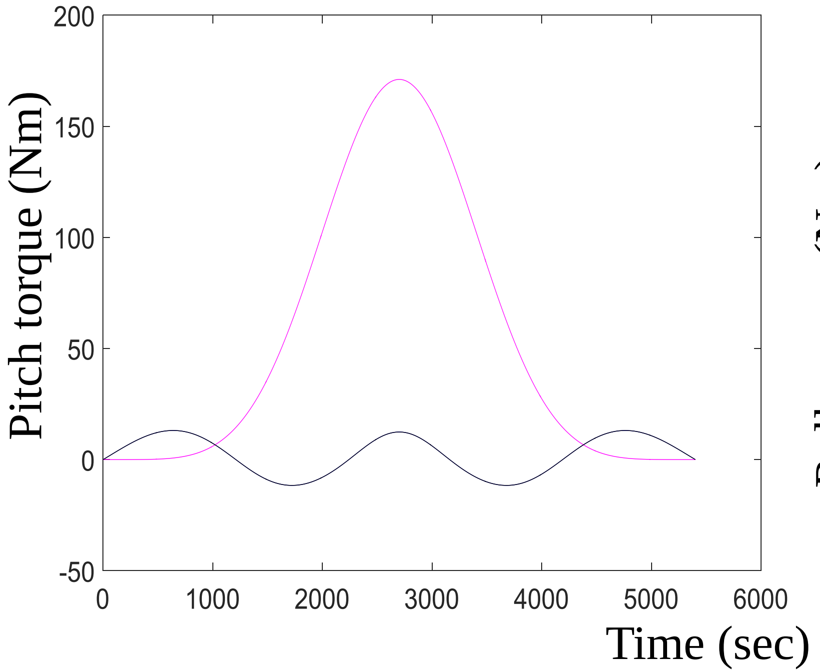
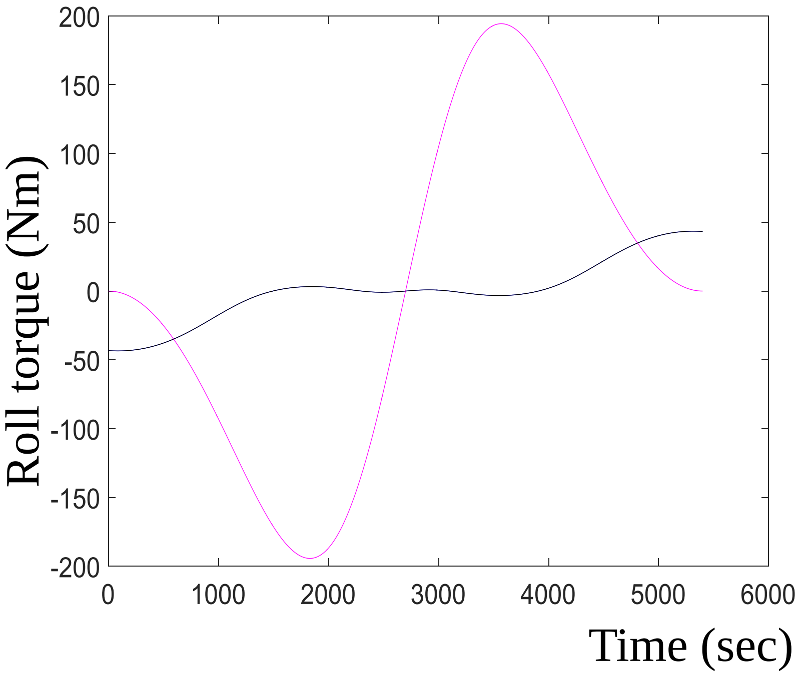
Torque reduction for optimized 5400 sec.180 deg. yaw maneuver

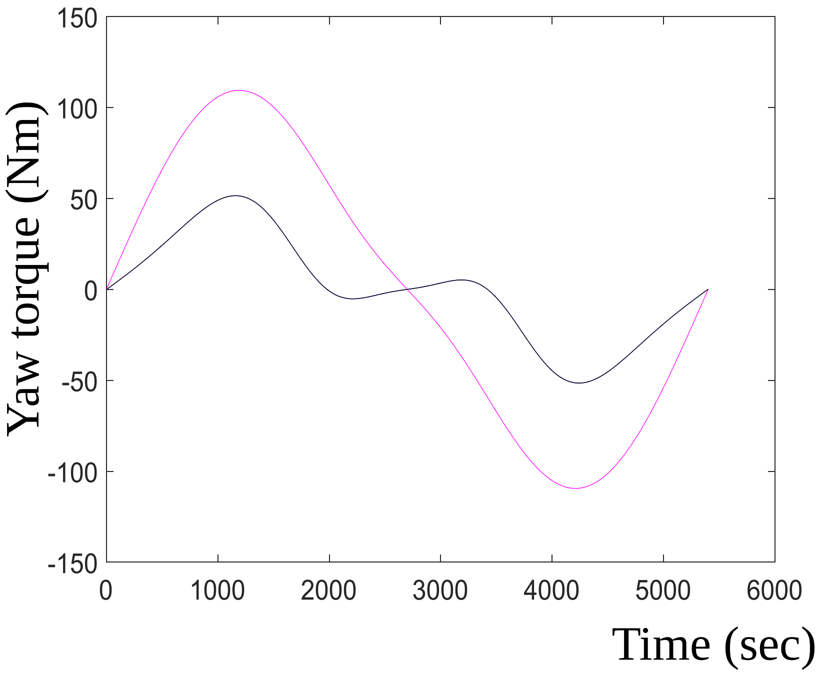
Legend: Red line –non optimized pure yaw maneuver
Black line – optimized maneuver



Pitch torque reduction.



Roll torque reduction.



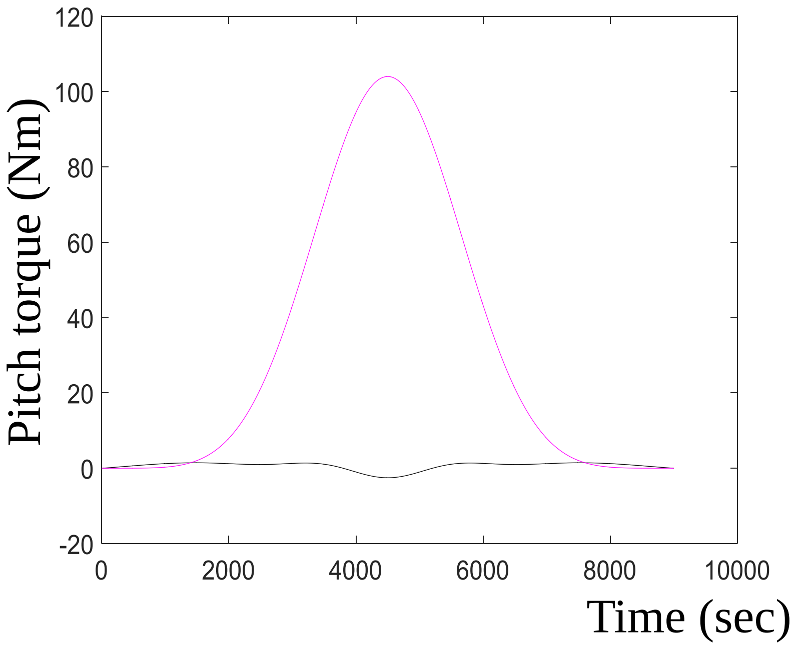
Yaw torque reduction.

Simulations showed that the proposed solution provides the maneuver performance similar to the existing computational solution.

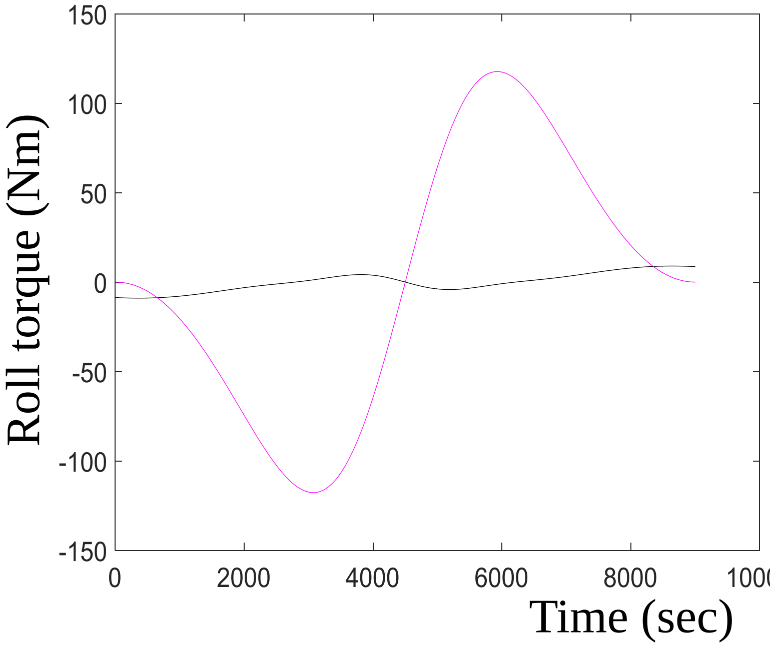
Torque reduction for optimized 9000 sec.180 deg. yaw maneuver

More significant torque reduction for longer maneuver.

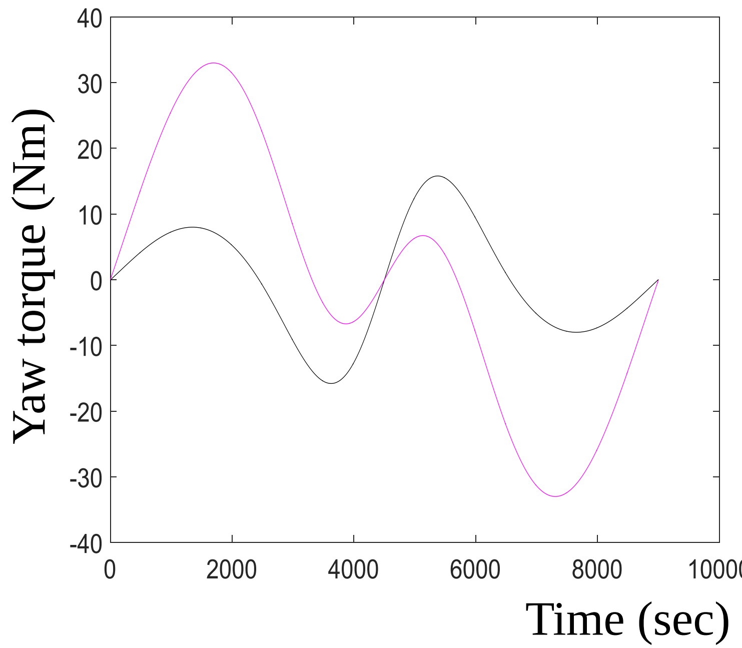
Legend:
Red line –non optimized pure yaw maneuver
Black line – optimized maneuver.



Pitch torque reduction.



Roll torque reduction.

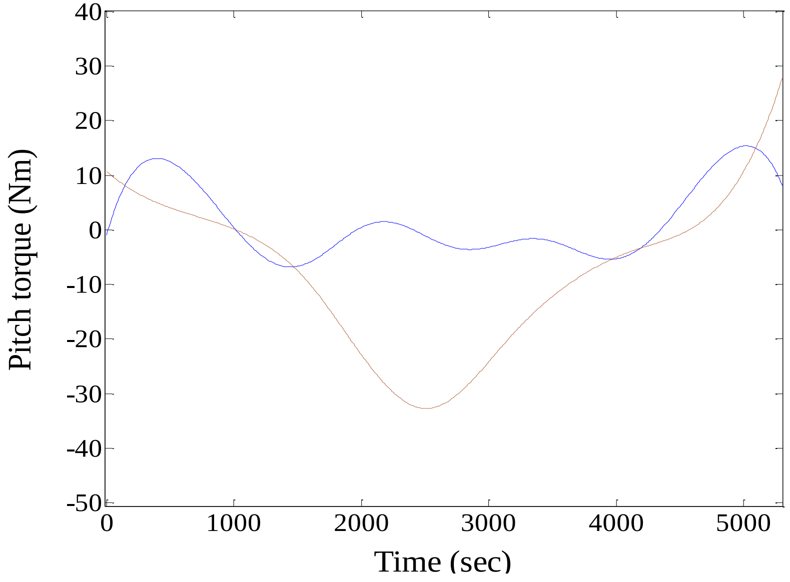


Yaw torque reduction.

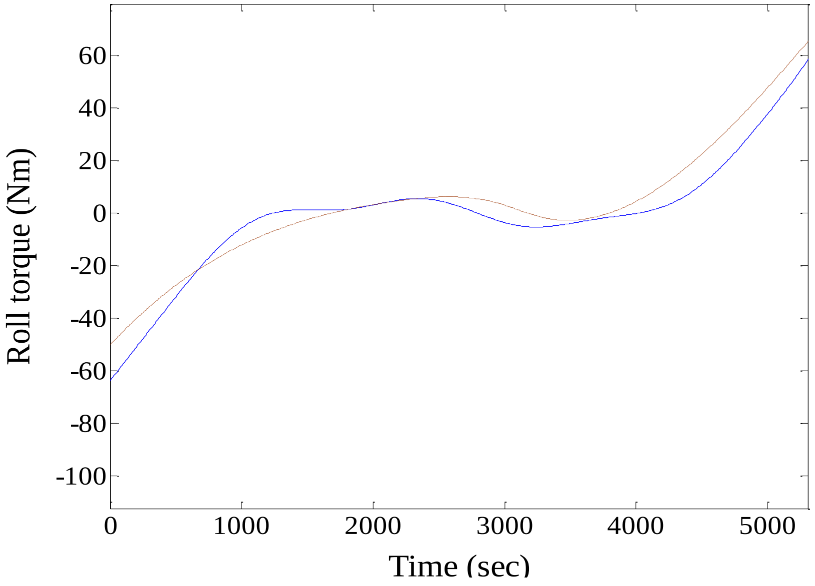
Torque reduction comparison with Draper OPM solution

Legend:
Blue line – analytical solution
Brown line – Draper Laboratory computational solution

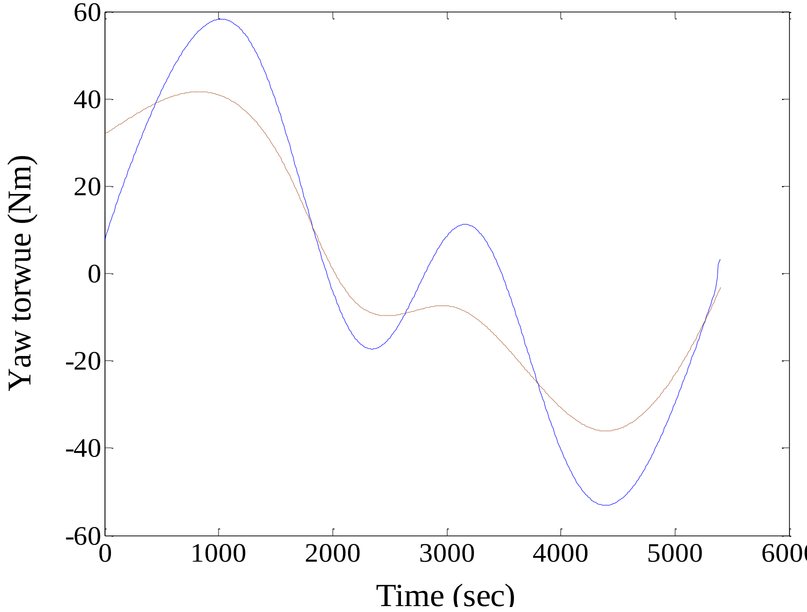
Maneuver duration = 5400 seconds.



Pitch torque comparison.



Roll torque comparison.

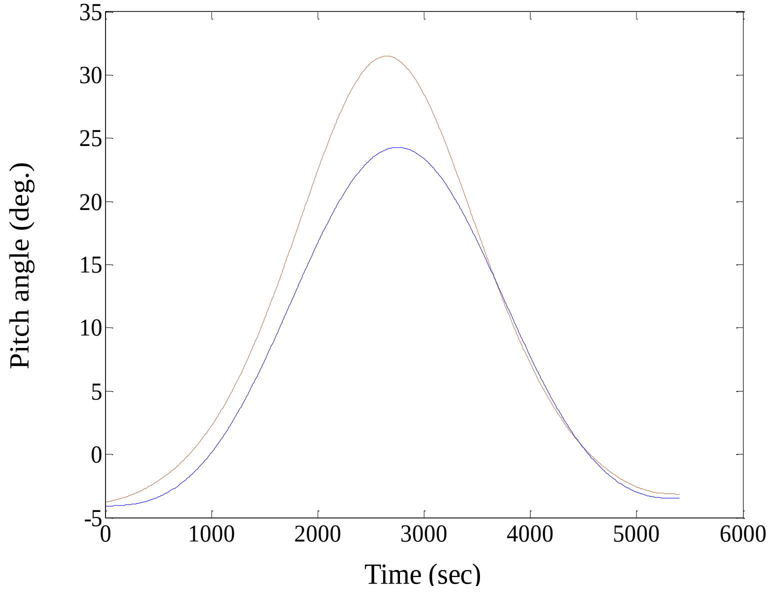


Yaw torque comparison.

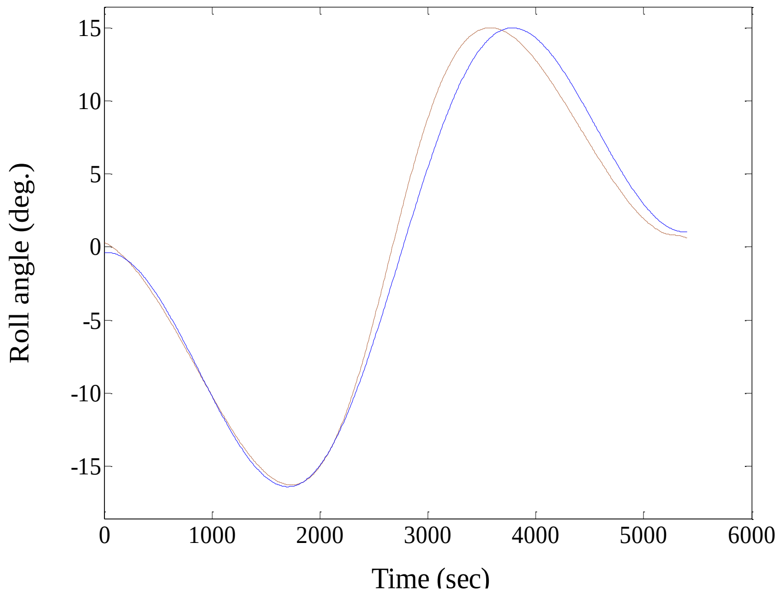
Pitch, roll and yaw profile comparison

Legend:
Blue line – analytical solution
Brown line – Draper Laboratory computational solution

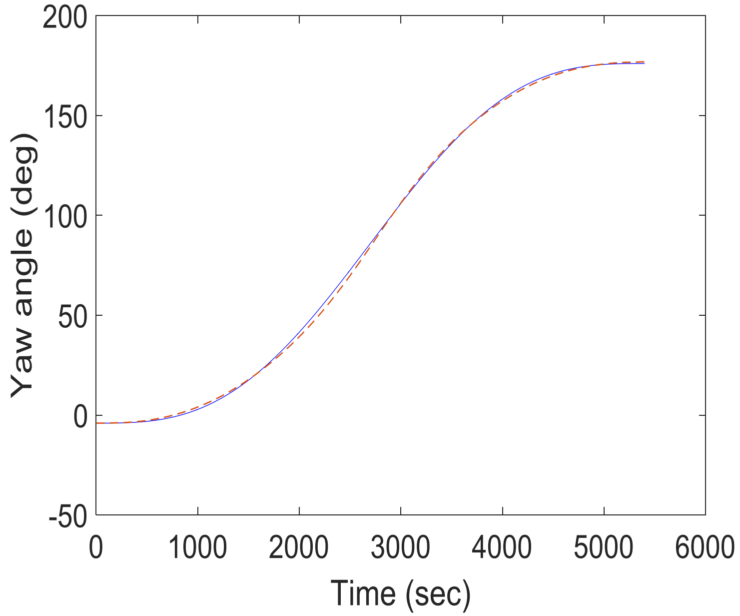
Maneuver duration 5400 seconds.



Pitch profile.



Roll profile.

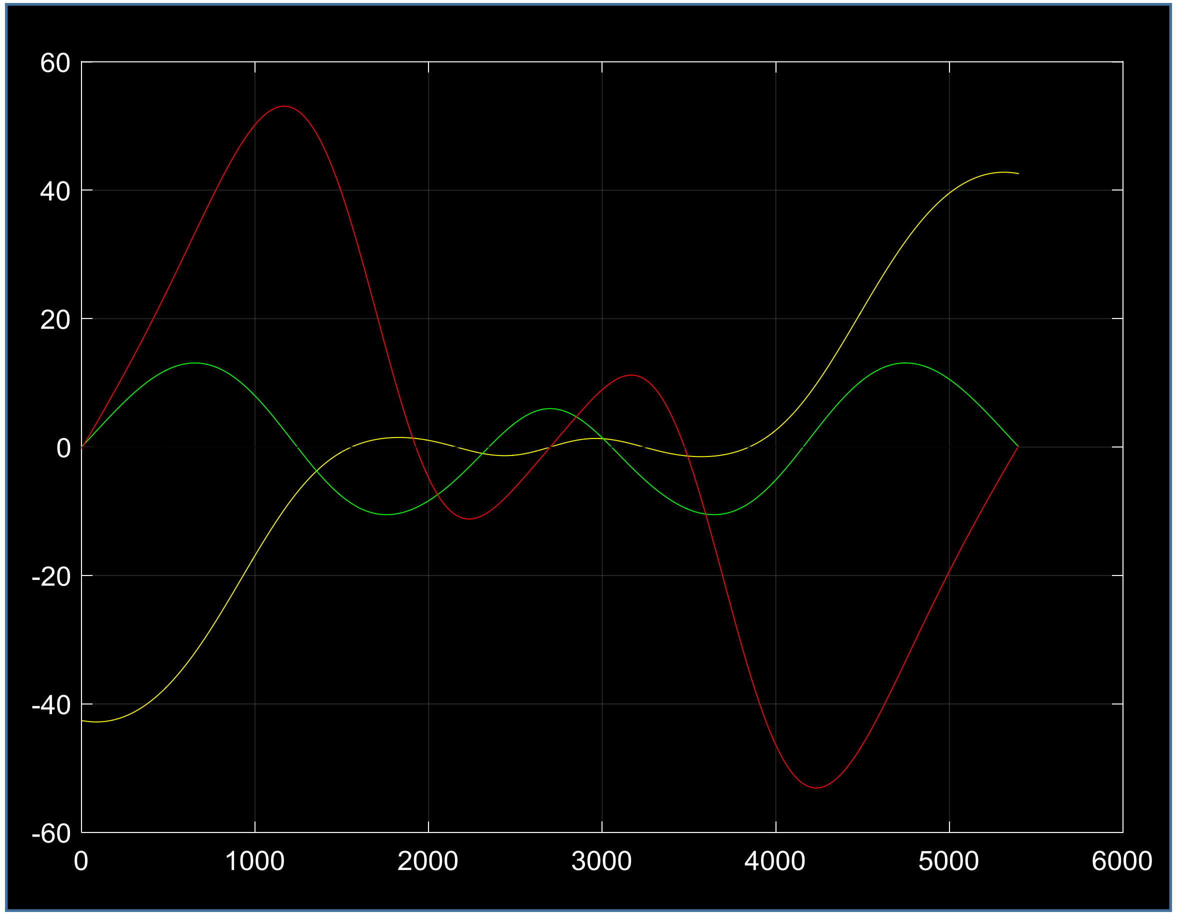


Yaw profile.

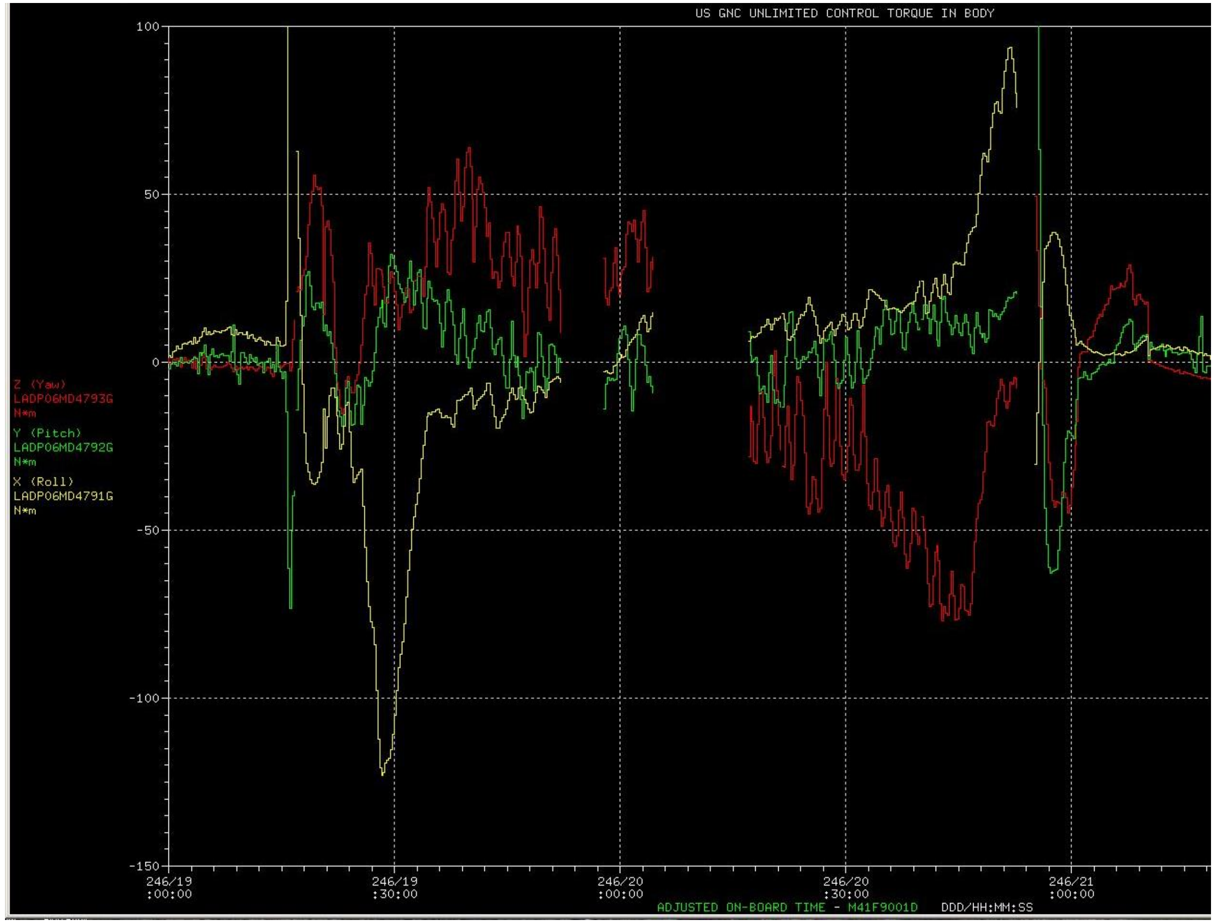
Torque comparison with flight data

OPM to -XVV.

Torques: Red – yaw, Yellow– roll, Green – pitch

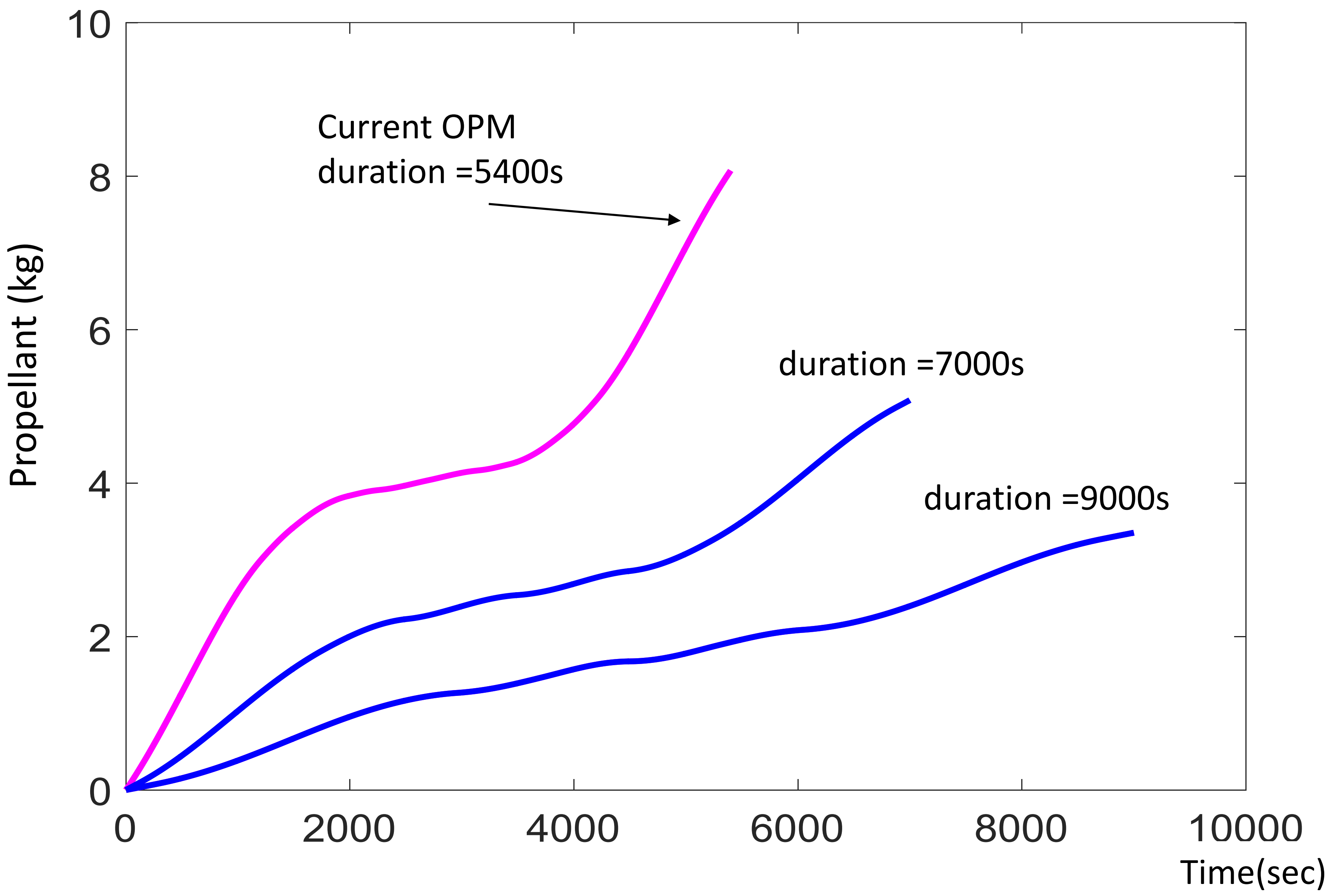


Calculated OPM



Flight data

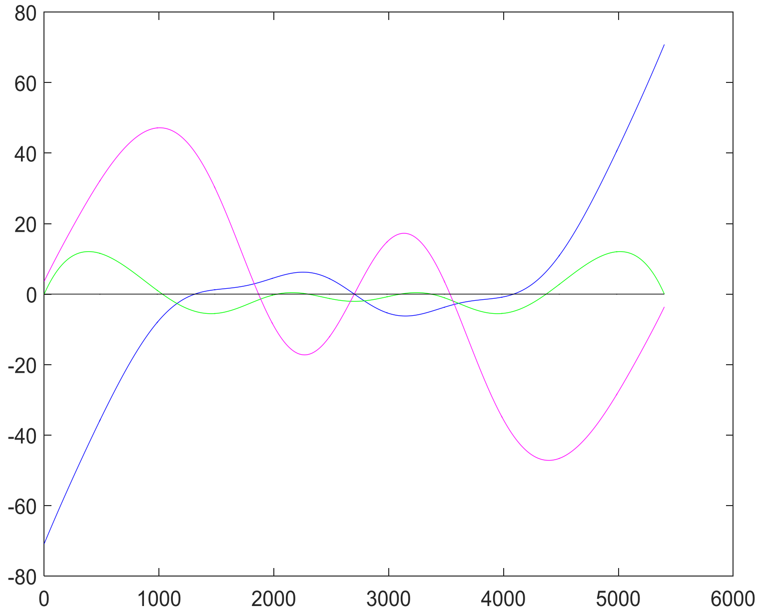
Variations of OPM duration - prop consumption estimations



Decreasing roll torque during OPM

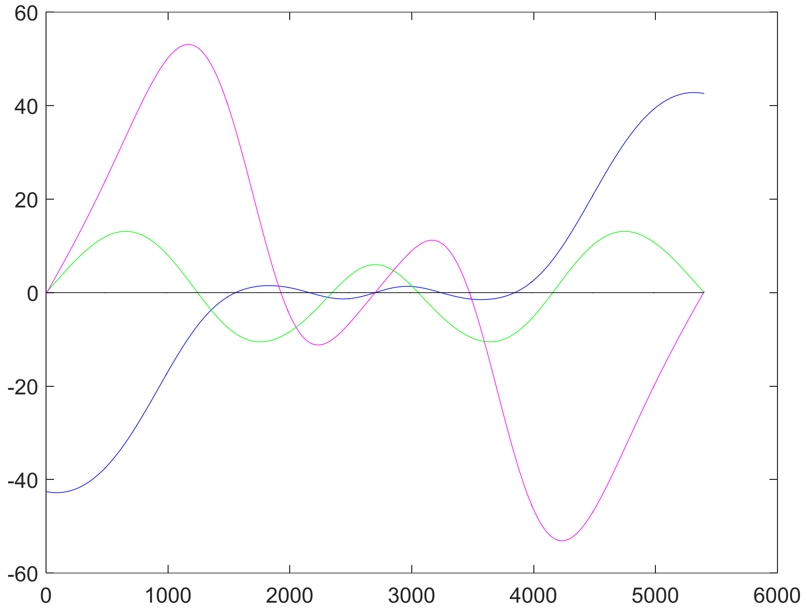
Torques: Red – yaw, Blue– roll, Green – pitch

Torque (Nm)



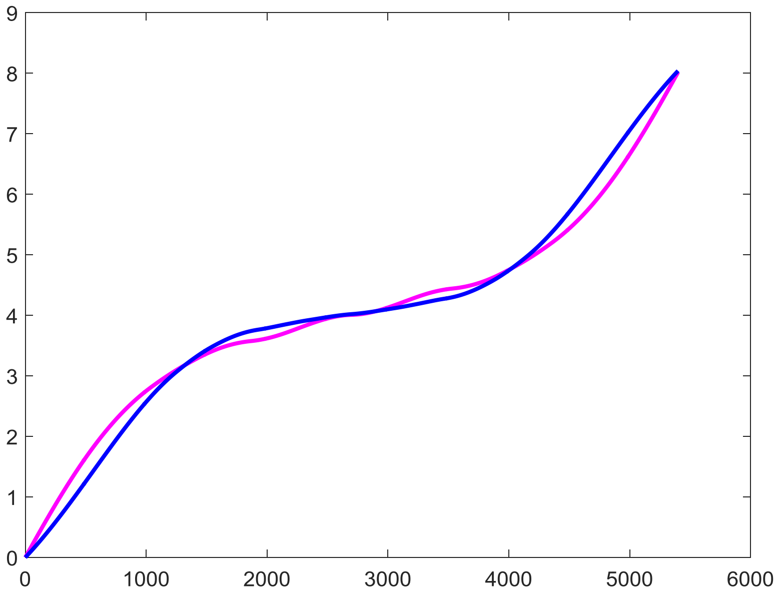
Roll torque increased,
pitch torque decreased

Torque (Nm)



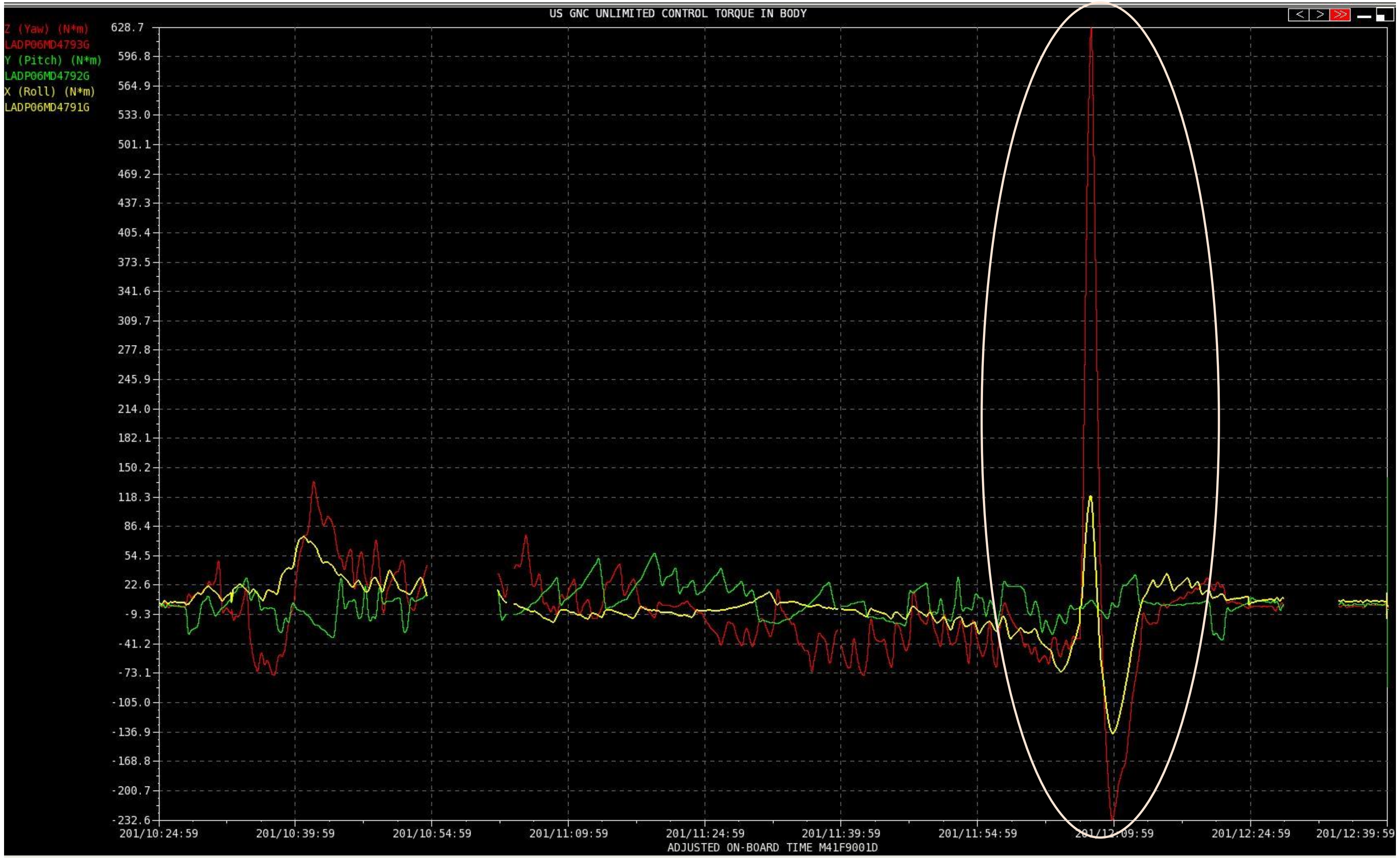
Roll torque decreased,
pitch torque increased

Prop (kg)



Total prop consumption
the same

“Trim maneuver”



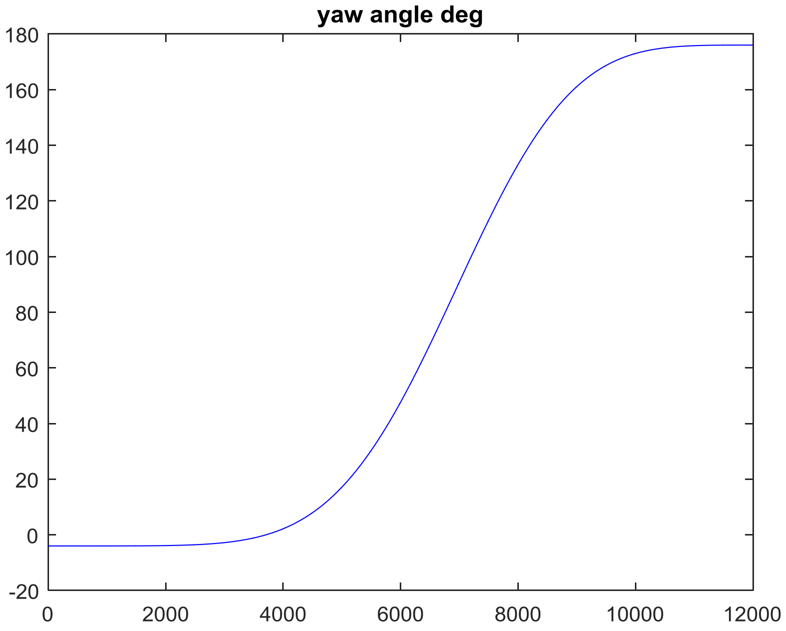
Prop saving by eliminating “Trim maneuvers” at the start /end of OPM

- Assuming the OPM is performed from TEA to TEA.
- In TEA, the ISS principal axes are aligned with LVLH 0,0,0, if aerodynamic torque is not taken into account.
- The OPM profile is calculated for the principle axes rotation.
- The position of body axes are then calculated with respect to principal axes for any specific mass properties.
- No need in trim maneuvers. When TEA changes, the OPM profile for the principal axis motion remains the same. Only position of the body axes with respect to the principal axes changes.

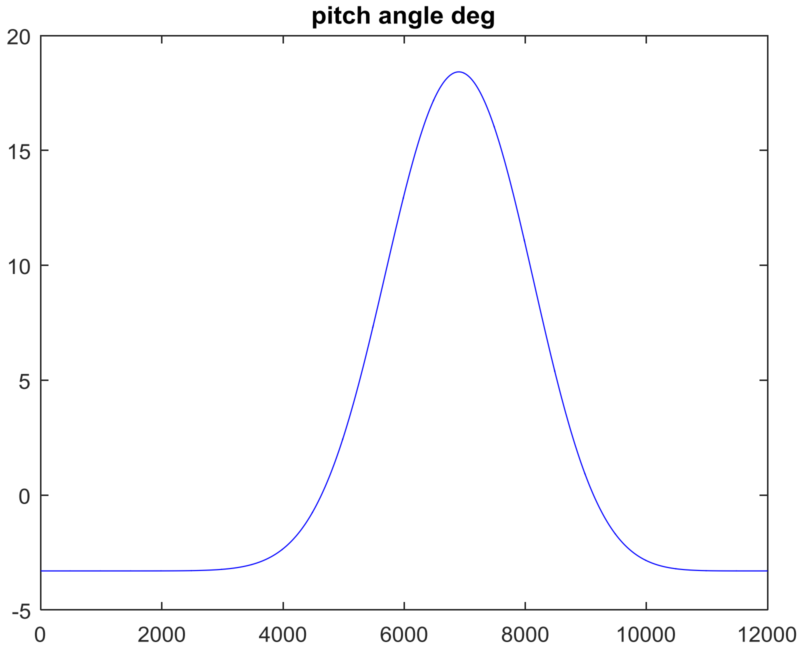
ZPM

ZPM calculations (ISS mass properties - year 2016)
+XVV to -XVV

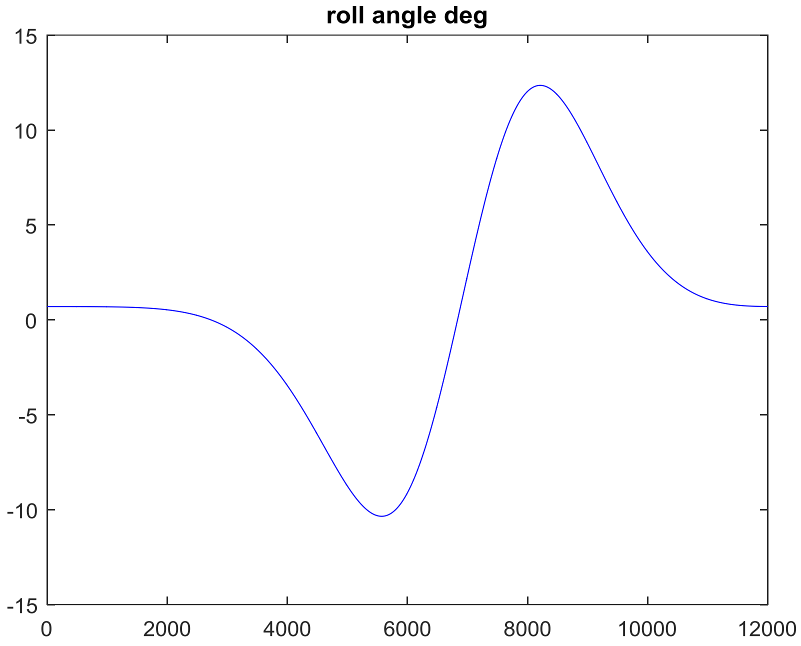
Maneuver duration = 12000 seconds.



Yaw angle

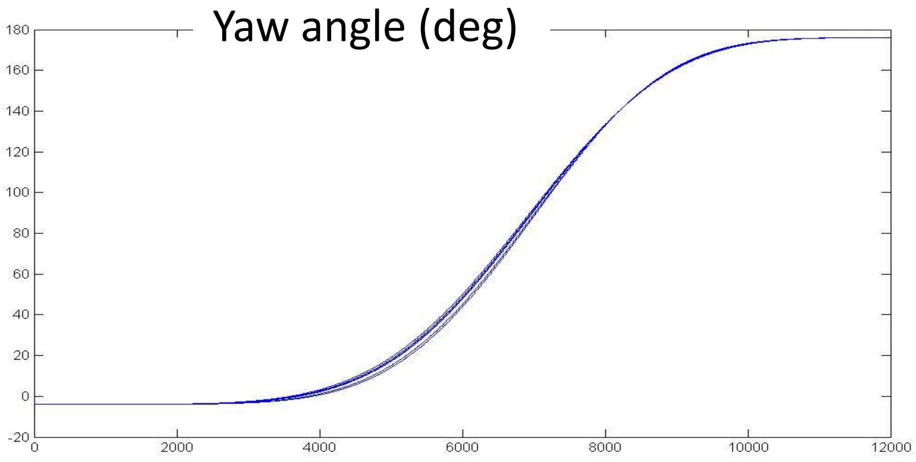


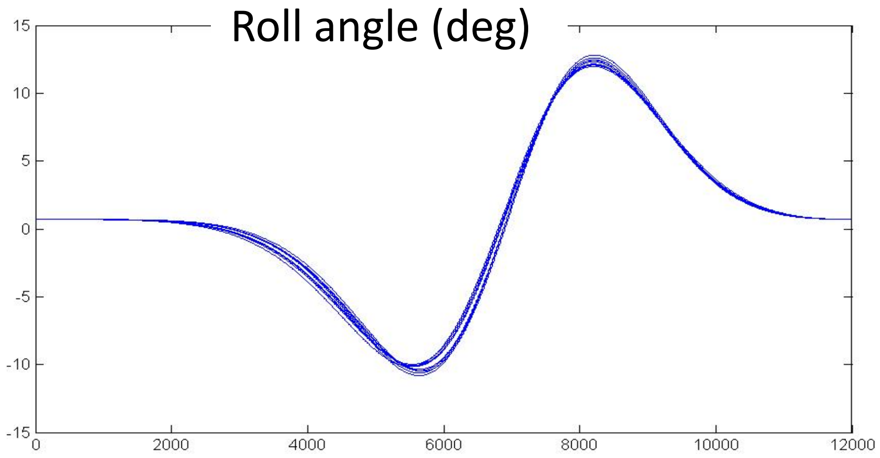
Pitch angle

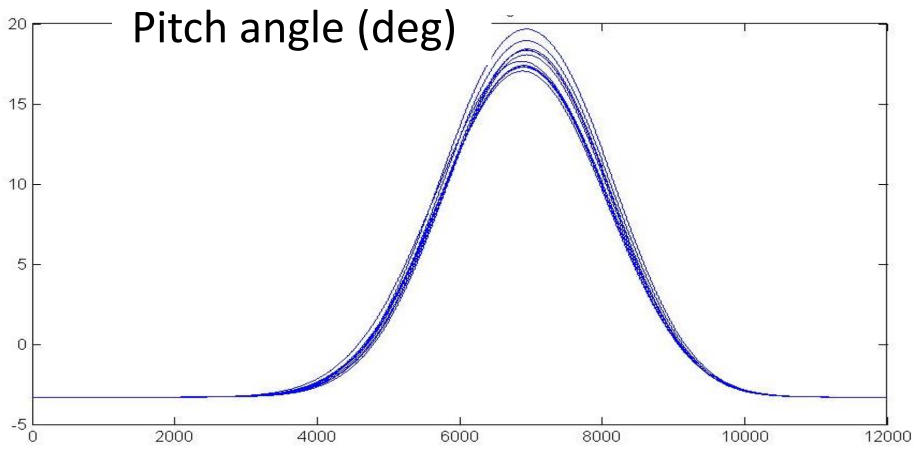


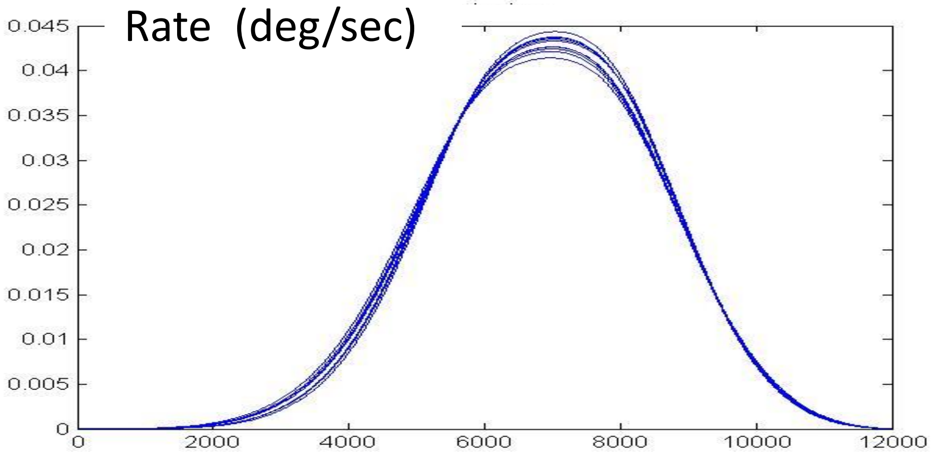
Roll angle

ZPM calculations
(ISS mass property variations - from HTV-5 berth to Jan. 2016)







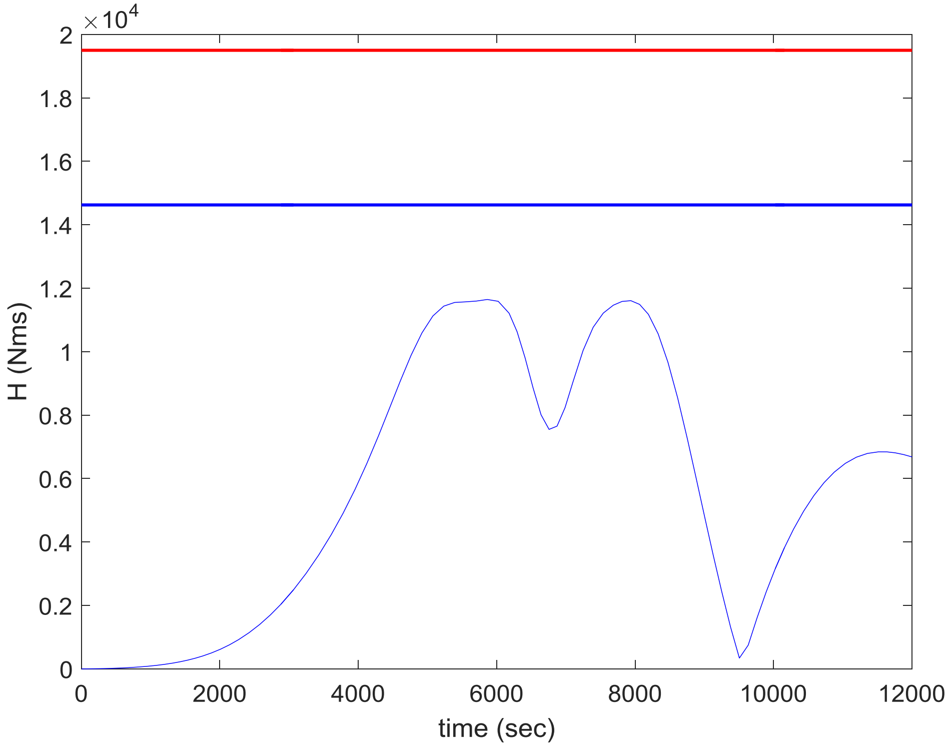


ZPM calculations (+XVV → –XVV) - CMG momentum (H)

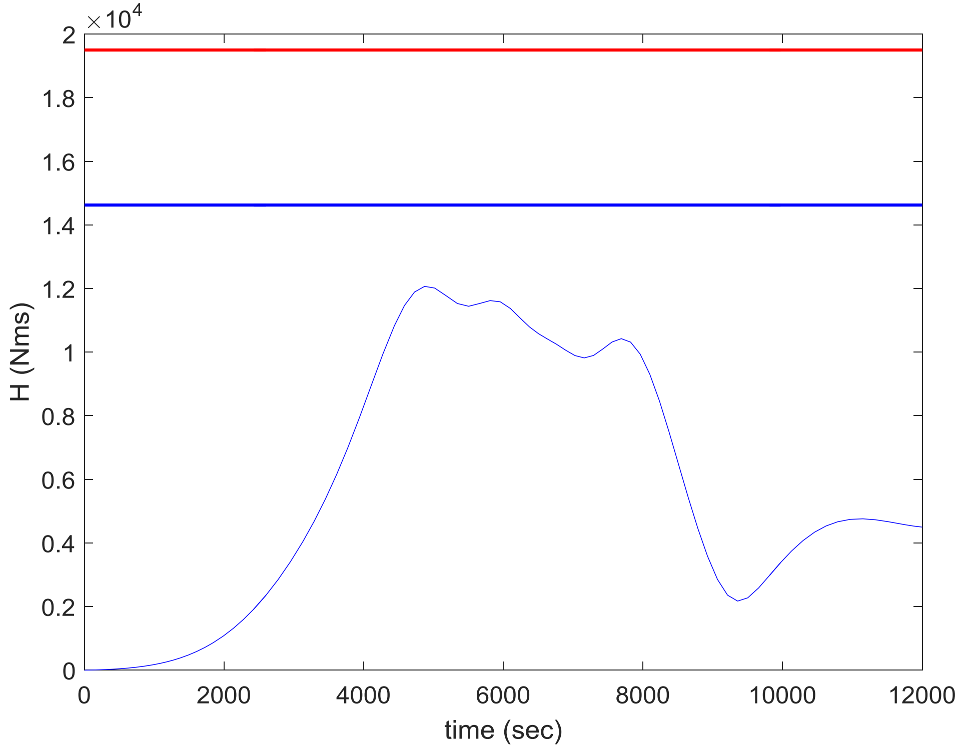
Maneuver duration = 12000 seconds

ISS mass properties - year 2016

CMG saturation level : H ~ 19500 Nms



Version 1.
Max H = 11610 Nms (~ 60%).



Version 2. (final momentum is less)
Max H = 12070 Nms (~ 61%).

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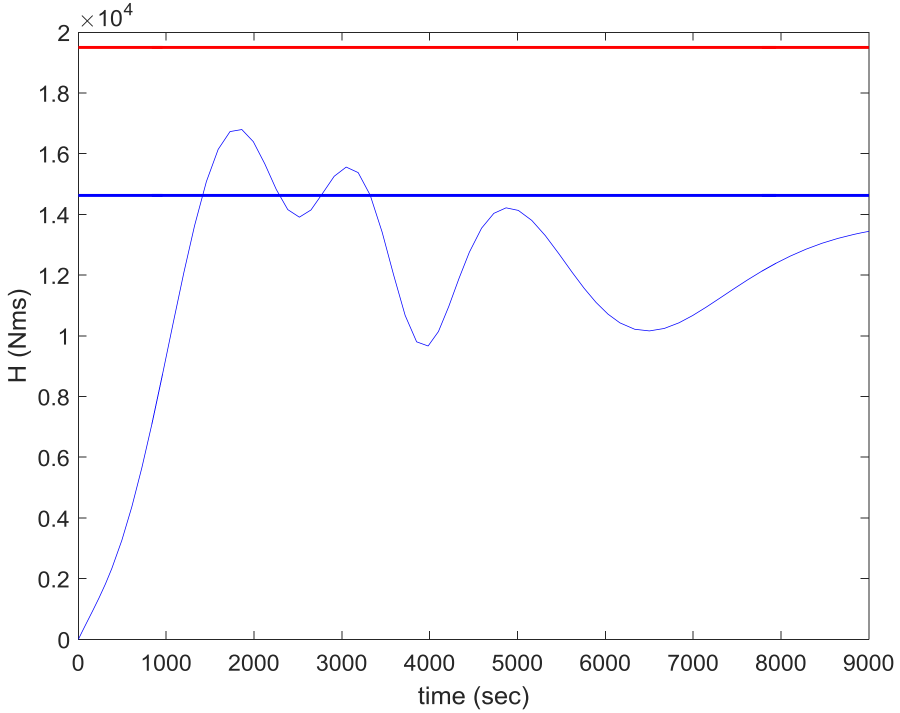
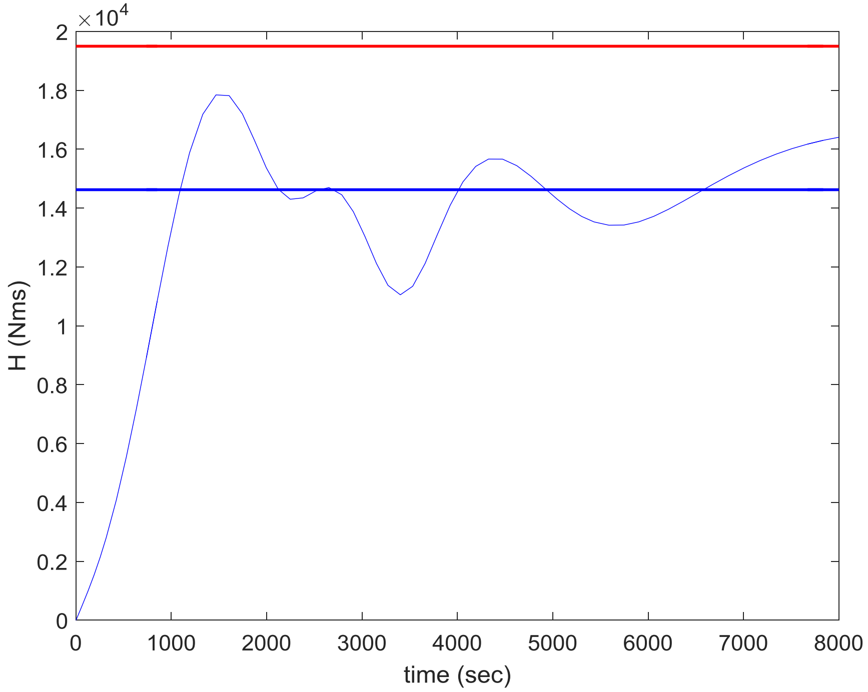
Variations of ZPM duration

CMG Momentum (H)



Maneuver duration = 9000 sec.



Maneuver duration = 8000 sec.

Conclusions

- An analytical solution for optimizing the ISS yaw attitude maneuvers was suggested.
- While approximate, the solution results agree with the existing computational solution obtained by Draper Laboratory.
- In contrast to the existing computational solution, the proposed analytical solution does not require extensive computer resources and, so, it can be implemented in the onboard software.
    - *Similar to existing maneuver options 0,1,2.*
    - *The attitude quaternion for each cycle can be calculated per the suggested equations*

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Conclusions (continue)

- As a result, the maneuver optimization can be automatic. The operations can be significantly easier and faster.

- The suggested method reduces the costs of maneuver preparation, eliminates command errors, and allows to quickly adjust to different changes and requirements.

- The maneuver can be performed without communication with the ground.

- The suggested method can be used not only for the ISS, but for other space vehicles as well.

References

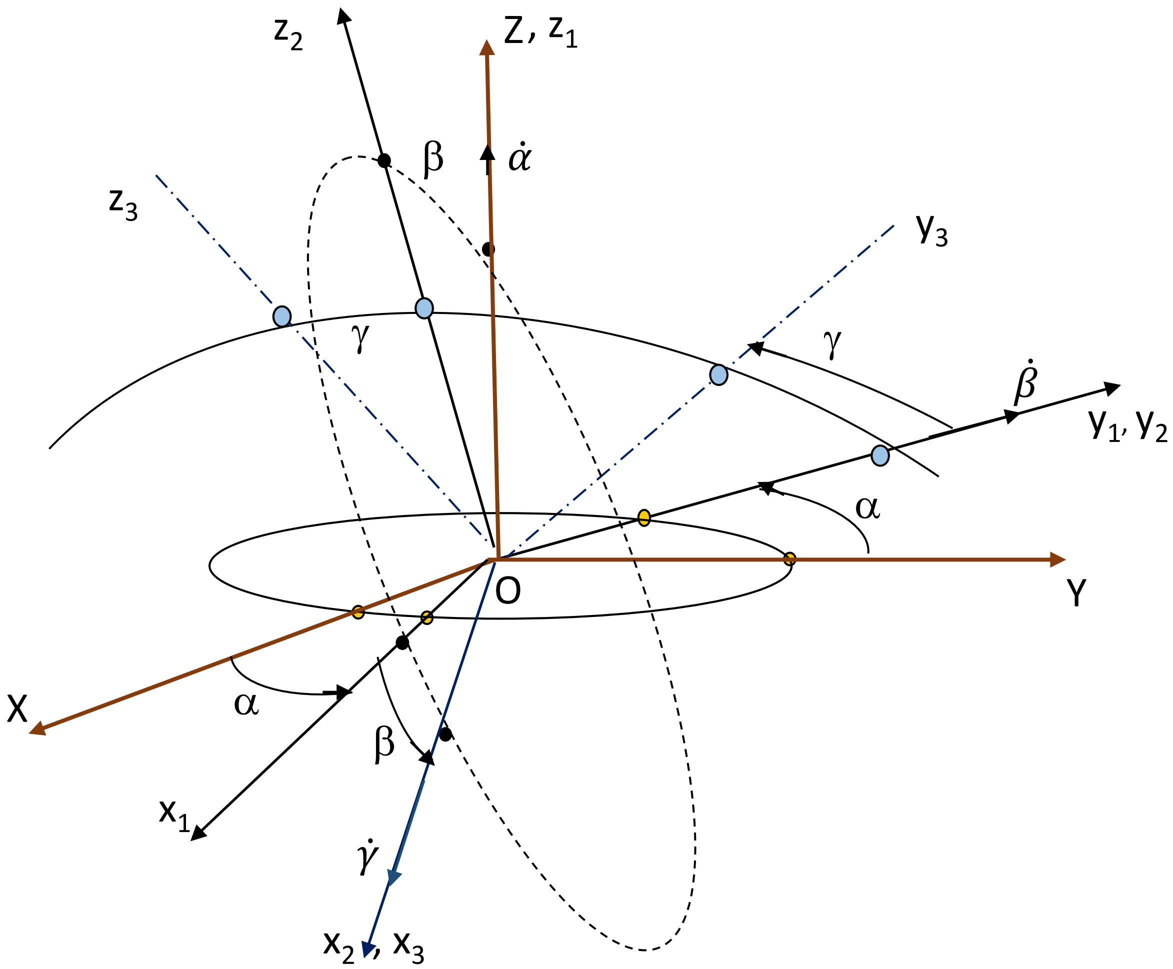
1. Bedrossian, N., Bhatt, S., Lammers, M., Nguyen, L., and Zhang, Y., “First Ever Flight Demonstration of Zero Propellant Maneuver Attitude Control Concept”, 2007 AIAA GN&C Conference, 20-23, August 2007, Hilton Head, SC, AIAA 2007-6734.

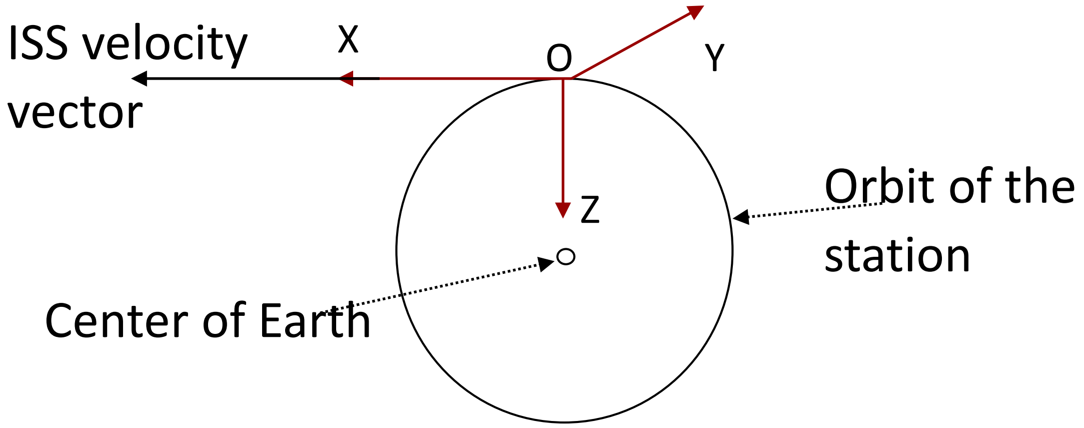
2. Sagar Bhatt, Nazareth Bedrossian, Kenneth Longacre, Louis Nguyen. “Optimal Propellant Maneuver Flight Demonstrations on ISS”, AIAA GN&C Conference, 2013. Boston, USA.

3. Tatiana Dobrinskaya, “An Analytical Solution For Yaw Maneuver Optimization On The International Space Station And Other Orbiting Space Vehicles”, International Astronautical Congress, October, 2015 (IAC-15-B6.1.2).

Back up slides

Euler angles (Yaw, Pitch, Roll)

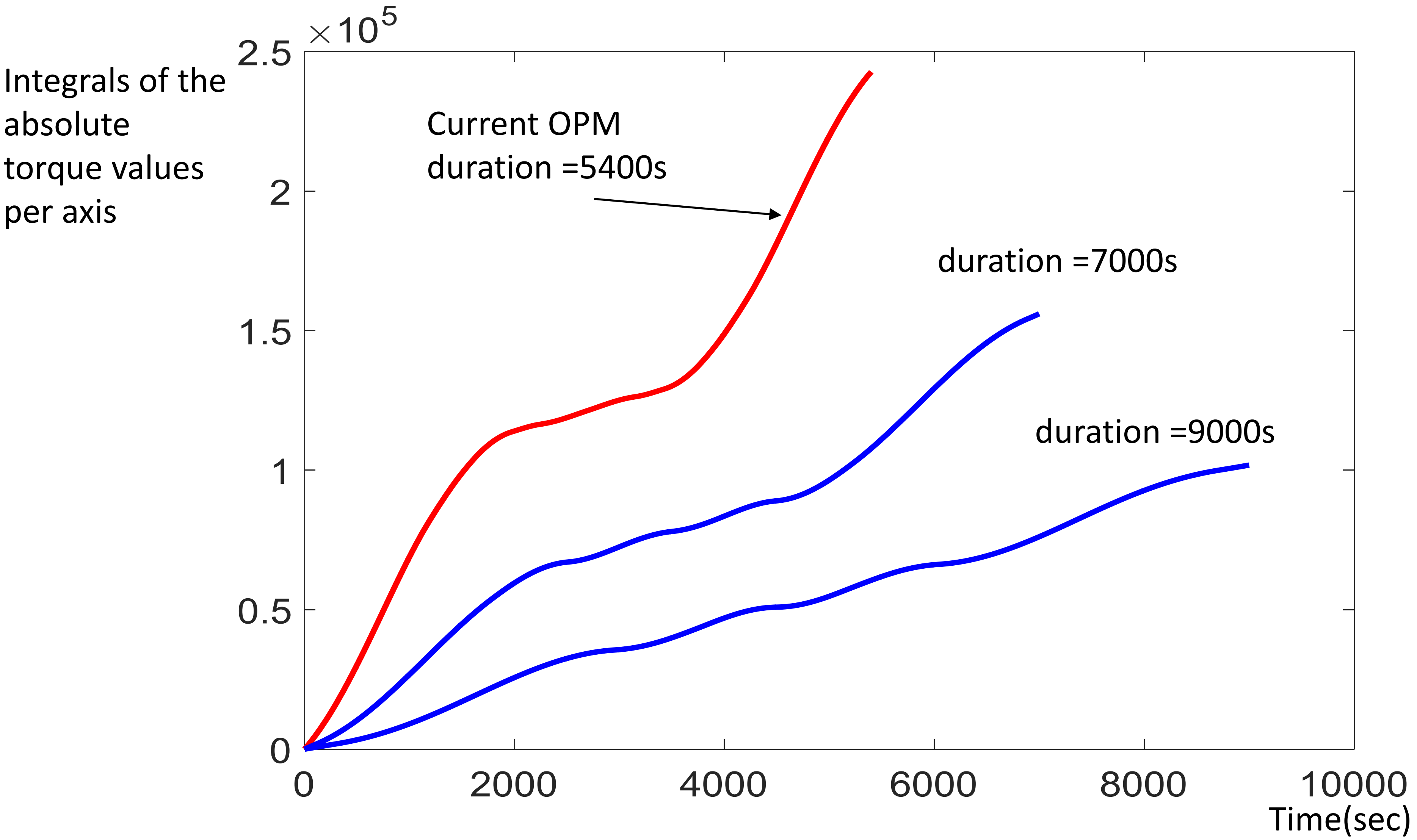




LVLH coordinate system

Euler angles: α – yaw angle, β – pitch angle, γ – roll angle.
Define position of a body coordinate system with respect to LVLH.

Variations of OPM duration



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