

Passive Roll Stabilization of the Near Earth Asteroid Scout Solar Sail Mission

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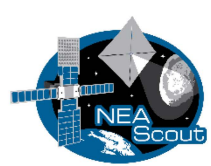




Overview

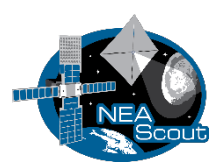


- **The Near Earth Asteroid (NEA) Scout mission is a solar sail mission in a 6U form factor.**
 - Mission objective is to provide science information on a NEA within 1AU of Earth and demonstrate solar sail technology.
 - Secondary payload on Artemis I – the maiden launch of SLS and Orion.
- **Main propulsion system is a solar sail which makes the ADCS much more susceptible to solar radiation pressure torques (SRPs) than traditional chemical propulsion systems.**
 - Only 1.3kg of cold gas propellant loaded on spacecraft. >50% devoted to an initial Trajectory Correction Maneuver (TCM). Remainder is devoted to momentum management.
- **Major contribution of this work is the demonstration that the “roll” (i.e., the rotation about the thrust axis) for a large variety of solar sail shapes is *locally stable in the sense of Lyapunov* for certain Solar Incidence Angles (SIAs).**
 - When including possible sources of damping, like internal friction or nutation dampers, the roll axis becomes *locally asymptotically stable*.
 - For certain mission concepts, only *two-axis stabilization of the solar sail* may be required. The “roll” axis may be passively controlled.



NEA Scout Concept of Operations





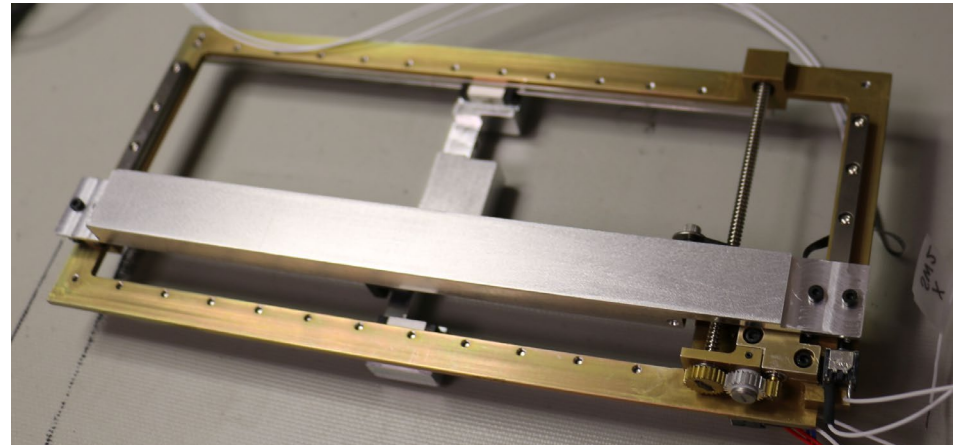
NEA Scout Background



- ❑ **2.5 year mission to image and obtain science data of a NEA within 1AU of earth.**
- ❑ **NEA Scout will deploy an 84.9m² solar sail from a ~2U (20x10x10mm) volume.**
 - 10 micron thick polymer with a reflective coating.
 - Material produced by Nexolve.
- ❑ **Uses a cold gas reaction control systems for initial trajectory correction maneuver and momentum management.**
 - R236-fa propellant → 40s ISP
 - 1.3kg of propellant onboard spacecraft.
 - 2 axial and 4 canted RCS thrusters.
- ❑ **ADCS sensors and effectors:**
 - BCT Thin Slice Star Tracker
 - 3x BCT Coarse Sun Sensors
 - 4x BCT 15mN-m-s Reaction Wheels
 - Sensoror STIM300 MEMS IMU
- ❑ **Adjustable Mass Translator (AMT) translates ~40% of spacecraft mass in sail plane.**
 - X: -80mm to 30mm, Y: +/-34mm
 - Used to manage moment and center center of mass with sail center of pressure.



NEA Scout full-size solar sail deployment at Nexolve in Huntsville, AL



Adjustable Mass Translator (AMT) engineering design unit

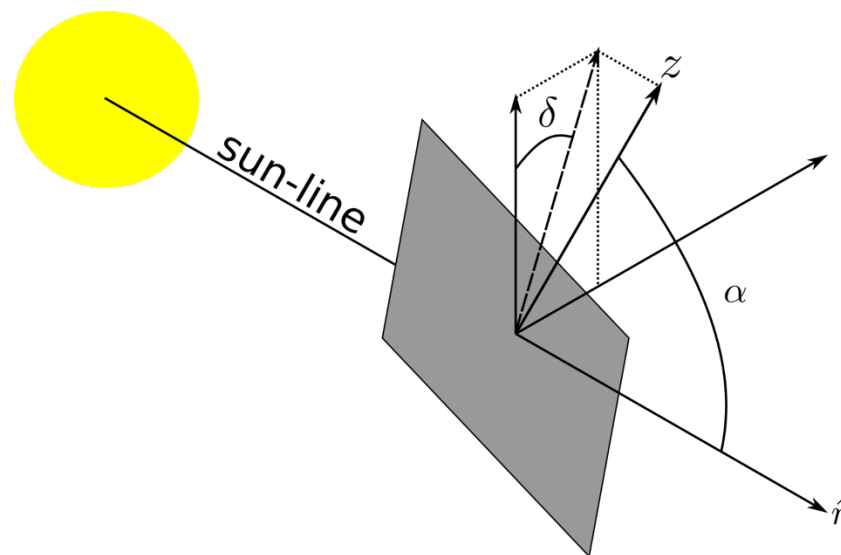
□ **Solar sails operate off the momentum exchange between photons and a reflective sail.**

- Although a photon is mass-less, it does have a very small amount of momentum proportional to its frequency ν .
- From Plank's law: $E = h\nu$
- From special relativity: $E^2 = m_0^2 c^4 + p^2 c^2$
 $\Rightarrow E = pc$ for $m_0 = 0$
- Combining the above,

$$p = \frac{h\nu}{c}$$

□ **The combined solar flux on the sail produces a pressure distribution on the sail.**

- Much like a wind sail, there will be a center of pressure on the sail. The offset between the center of pressure on the center of mass of the spacecraft will create a torque the ADCS must constantly overcome.



□ **Solar sail convention defines rotations relative to the sun-line.**

- α : **Solar incident angle (SIA)**. Angle formed between sail normal and the sun-line.
- δ : **Clock angle**. Extrinsic rotation of the sail normal about the sun-line.
- ψ : **Roll angle**. Rotation about the sail normal.

□ **Combining the clock, SIA, and roll angles produce a 3-2-3 rotation from an arbitrary solar frame.**

- Neglecting parasitic flexible body dynamics from the sail and momentum contribution from the reaction wheels, a simple 3DOF equation of motion can be constructed:

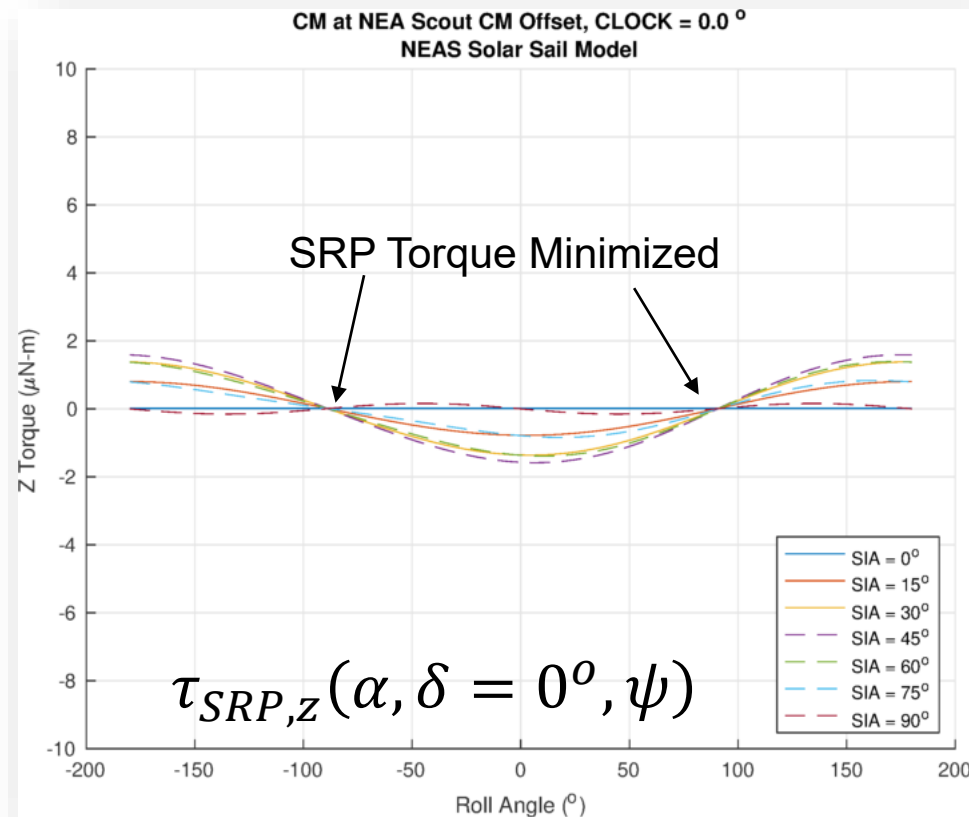
$$I\dot{\omega} + \omega^\times I\omega = \tau_{ctrl} + \tau_{dist}$$

- where $\tau_{ctrl} \in \mathbb{R}^3$ are the control torques and $\tau_{dist} \in \mathbb{R}^3$ are the disturbance torques.
- For a non-spinning solar sail, the three axes can be decoupled. In deep space, the dominant disturbance torque will be SRP.
 - Negligible gyroscopic torques. Diagonal terms of inertia matrix dominant over off-diagonal.

$$I_{zz}\ddot{\psi} = \tau_{ctrl,z} + \tau_{SRP,z}(\alpha, \delta, \psi)$$

- Dynamics of the “roll” axis (z-axis) become a function of the orientation of the sail w.r.t. the sun-line and the control torques.
- NASA Langley Research Center produced a high-fidelity mesh of the NEA Scout solar sail, including the effects of thermal deformations.
- SRP thrust can be calculated on each polygon of the sail mesh, and then cross-product with CM can be summed to calculate total SRP torques on spacecraft.

NEA Scout SRP torques about the Z-axis for multiple solar incidence angles



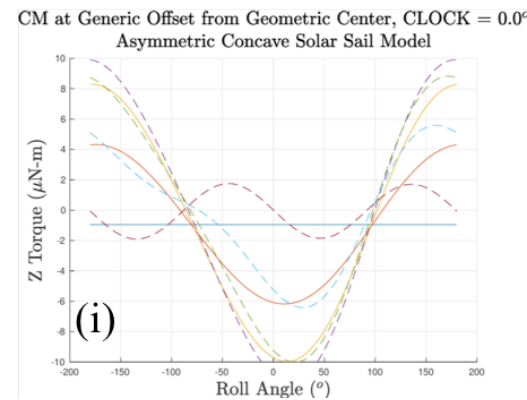
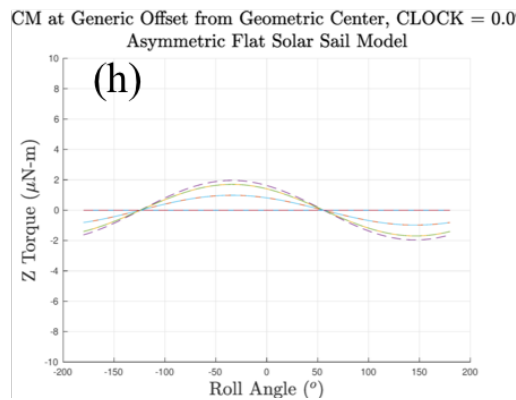
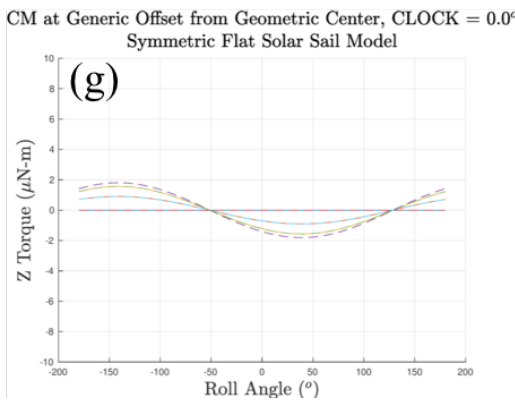
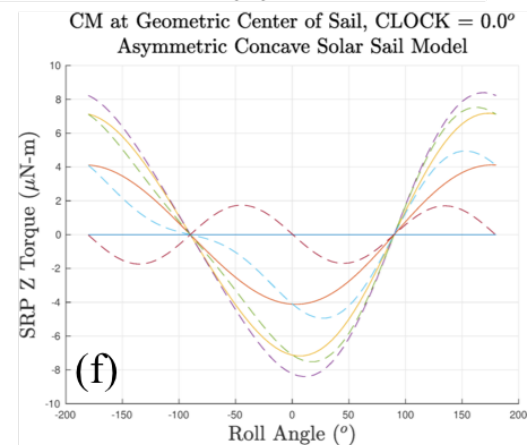
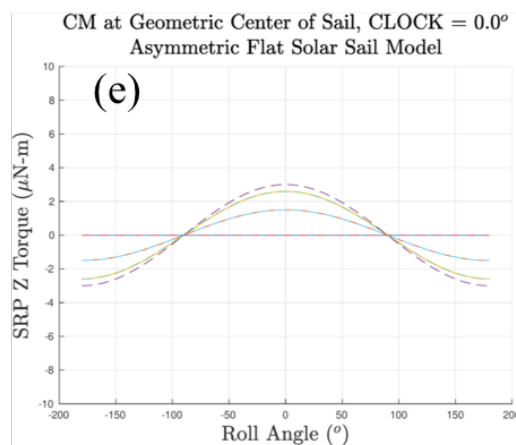
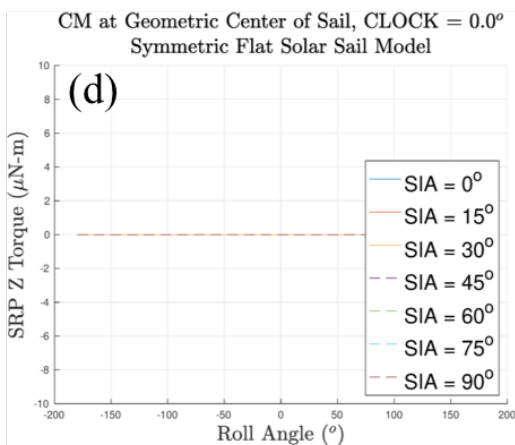
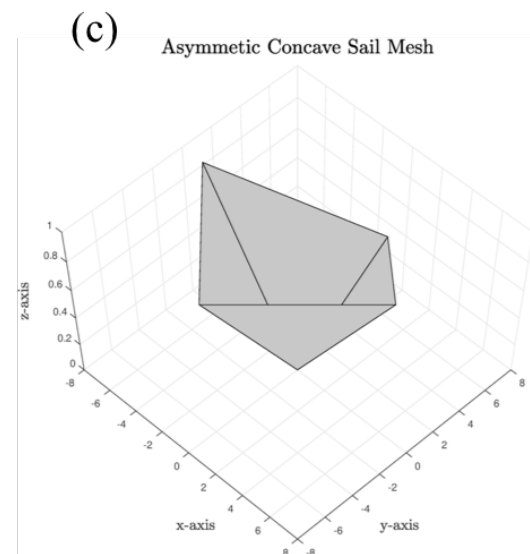
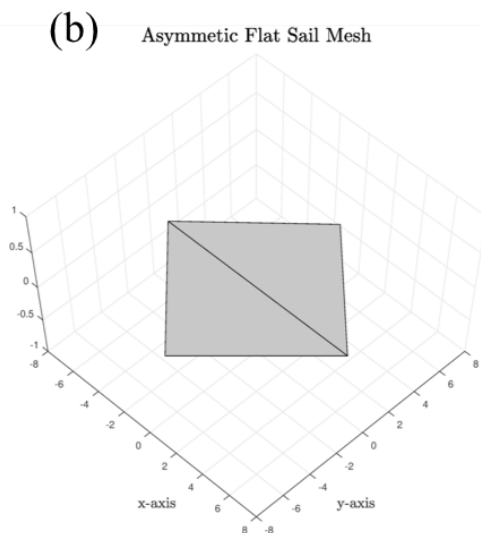
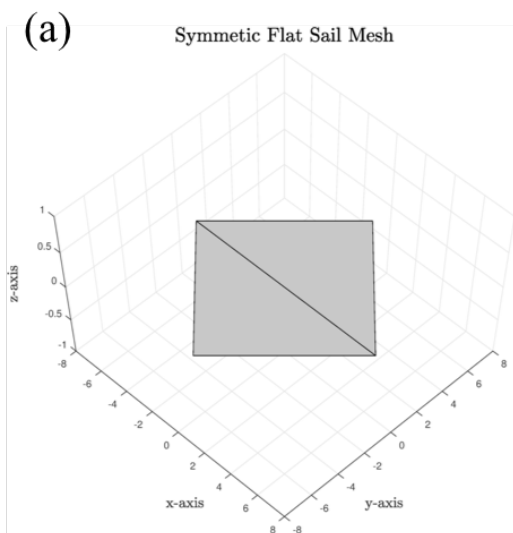


Sail Shape

CM @ Center of Geometric Center

Ideal Flat Plate

CM Offset from Geometric Center



Lyapunov Stability Analysis

- A Lyapunov stability analysis can be conducted on the roll-only system in the homogenous case (i.e. $\tau_{ctrl,z} = 0$).
- Define $g(x) = -\tau_{SRP}(\alpha, \delta, \psi - \psi_0)$ such that $g(0) = 0$.
- By inspection of the SRP torques on the previous chart, it is apparent that $g(x)$ is locally Lipchitz over a domain $D = (a, b)$ about $x = 0$. The following condition holds:

$$xg(x) > 0 \quad \forall x \neq 0 \text{ and } x \in (a, b)$$

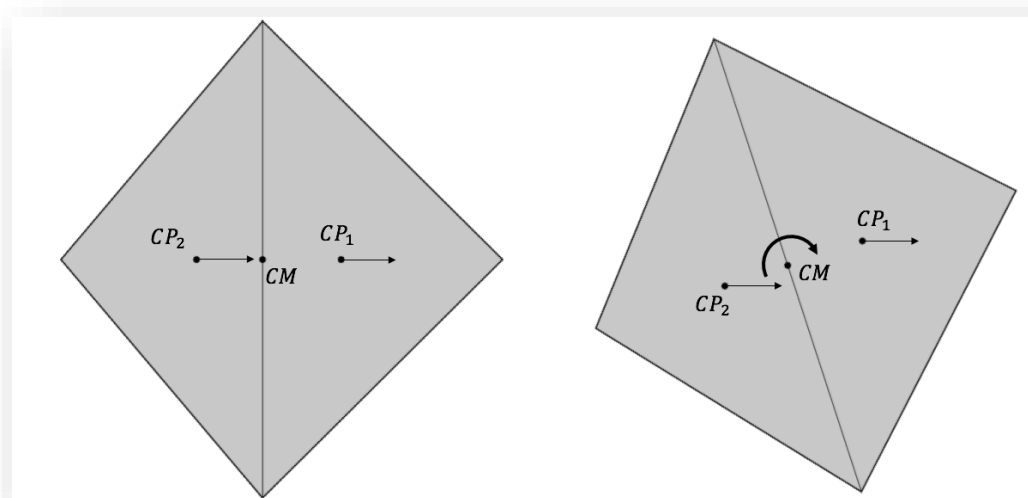
- This is a classical nonlinear dynamics problem that can be readily solved. A positive definite Lyapunov function is defined as:

$$V(x) = \int_0^x g(y) dy + \frac{1}{2} \dot{x}^2$$

- Taking the time derivative above proves the local stability *in the sense of Lyapunov* of the system.

$$\boxed{\dot{V}(x) = g(x)\dot{x} - g(x)\dot{x} = 0 \quad \forall x \in D}$$

- It is important to note that no energy dissipation mechanism is modeled. Thus, *local asymptotic stability* cannot be proven. The system will enter a limit-cycle oscillation.
- However, if other sources of damping are modeled, such as internal friction within the sail, or added in the design, like nutation dampers, then *local asymptotic stability* can be guaranteed.



- An alternative method to guarantee local asymptotic stability is to design a *rate damping* controller.
 - Assumes spacecraft has a way of effecting the “roll” axis. NEA Scout has four RW in a rectangular pyramid configuration.

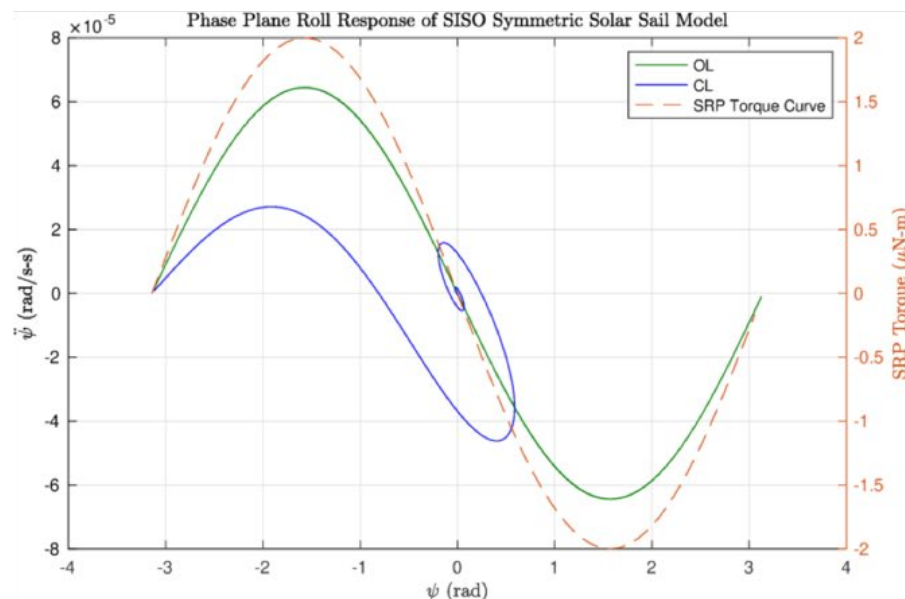
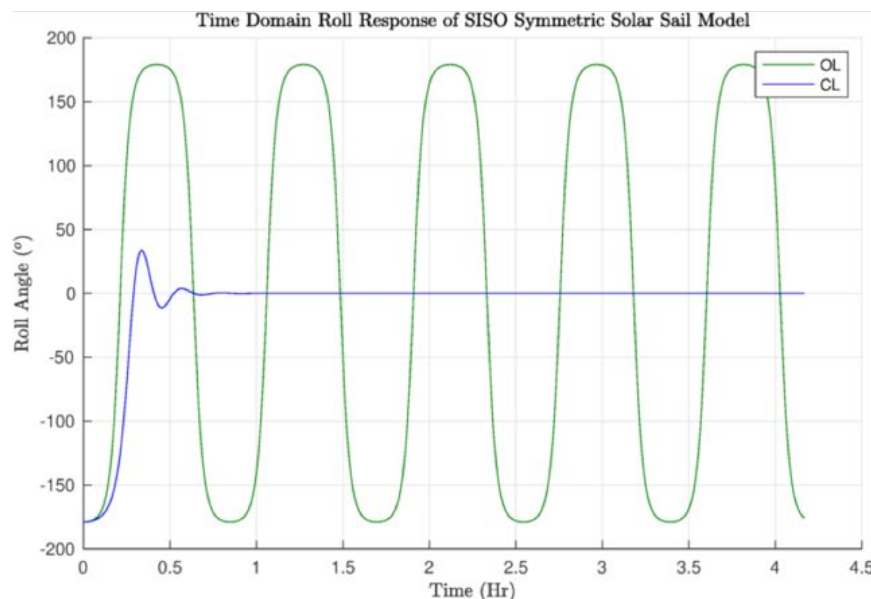
- Linearizing the roll-axis system, a derivative controller can be designed,

$$I_{zz}\ddot{x} = -k_d\dot{x} - g(x) \approx -k_d\dot{x} - Ax$$

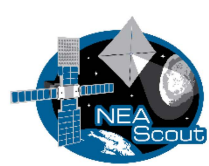
- Taking a Laplace transform, the desired closed loop damping and break frequency can be designed to:

$$X(s) = \frac{1}{I_{zz}} \frac{1}{s^2 + k_d/I_{zz}s + A/I_{zz}} = K \frac{\omega_n^2}{s^2 + 2\zeta\omega_n s + \omega_n^2}$$

- Although the active roll damping controller is part of the ADCS flight software, it is not enabled by default. There is still sufficient propellant margin on NEA Scout to achieve full three-axis control throughout its 2.5 year mission.



Left: Time domain response of the homogenous case (green) and rate damped (blue) system. Right: Phase plane of the the homogenous case (green) and rate damped (blue) system



Conclusion, Remarks, and Forward Work



- **For the NEA Scout solar sail, and other solar sails where the flat plate sail is a valid approximation, the SRP torques about the thrust axis produce multiple equilibrium points, where at least one is guaranteed to be a stable equilibrium.**
 - A simplified roll axis equation for a deep-space solar sail spacecraft was shown to be locally asymptotically stable in the sense of Lyapunov (i.e., will develop a limit cycle) for an uncontrolled response.
 - If a source of damping is added, such as internal friction or the addition of a derivative controller, the system becomes locally asymptotically stable.
- **This opens the possibility of only requiring only two axis control for some solar sail missions concepts, or like NEA Scout, the “roll” axis can be tuned to minimize the resultant SRP torques.**
- **Possible avenues for further investigation:**
 - Further analysis to determine if the internal friction of the solar sail is a feasible source of damping for a two axis-stabilized solar sail.
 - Solar sail material is easily deformable → Large amount of energy is dissipated in deformation of solar sail thin membrane.
 - Characterization of the NEA Scout solar sail “roll” torque in orbit.
 - Validation of the active rate damping controller.
 - Roll will not affect the direction of the thrust vector in the inertial frame for a sail that closely approximates a flat sail. However, for a badly deformed sail, the thrust vector will change direction dependent on the roll angle.