Dynamics and Control Design for the Drag-free CubeSat

Anh N. Nguyen, Seong Hyeon Hong, John W. Conklin

University of Florida

Saps Buchman, Eric Hultgrin, Andreas Zoellner

Stanford University

Carlo Zanoni

University of Trento

UF
- Drag-free attitude and Control system
- Mission operations
- Communications & Power system

S
- Drag-free sensor
- Systems Engineering

AMES RESEARCH CENTER
- Assembly, Integration, & Test
- S/C bus manager
- Operations & Ground system

Overview

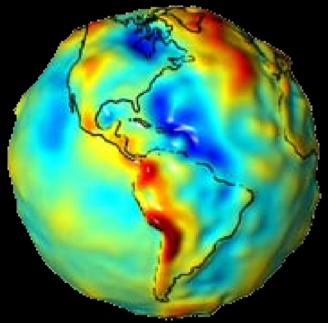
- Concept and Applications
- CubeSat Design
- Drag Modeling
- Drag-Free Control & Simulation

Concept

- Spacecraft follows a pure geodesic
  - Utilizes a gravitational reference sensor (GRS) shielded from all external forces
  - TRIAD (1972), Gravity Probe B (2004), GOCE (2009)
- Key Technologies: Formation flying, precision optical sensing, propulsion and orbit determination
- Future Impact: Low cost, strategic Earth Observing constellations

Applications

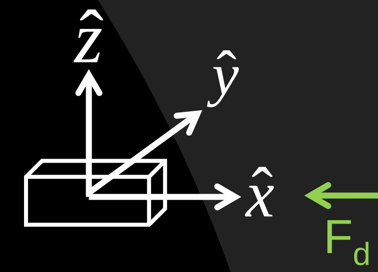
- Autonomous, fuel efficient orbit maintenance
- Precision real-time navigation
- Earth geodesy/aeronomy
- Earth observation



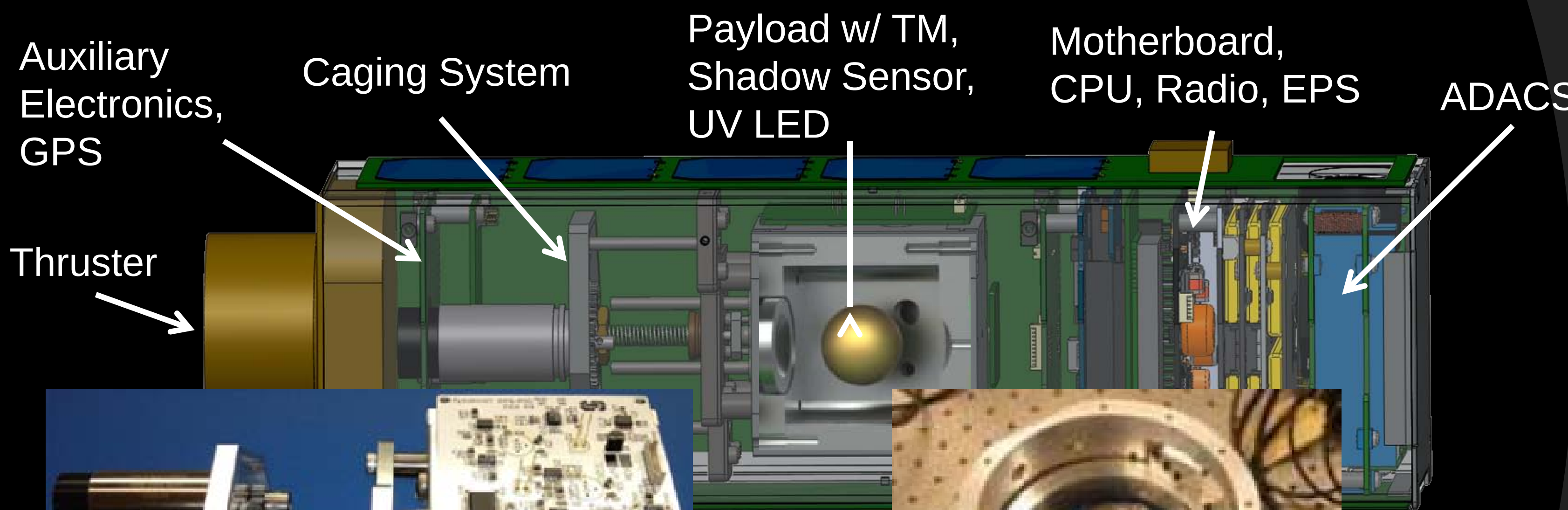
Earth gravity anomaly
from GRACE

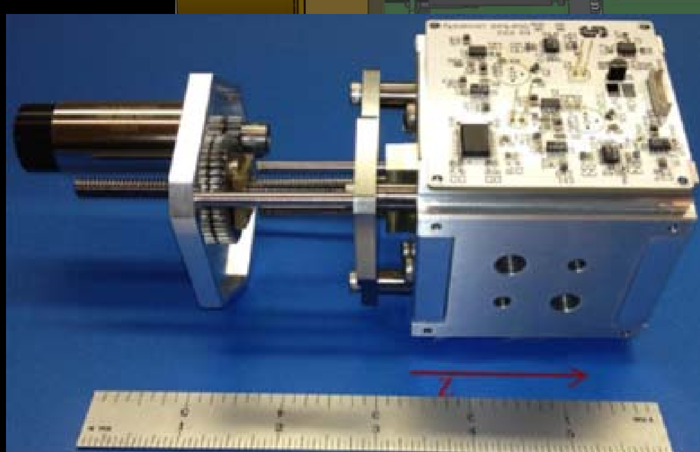
- UF team evaluating geoid height sensitivity of pairs of drag-free nano-satellites

Design

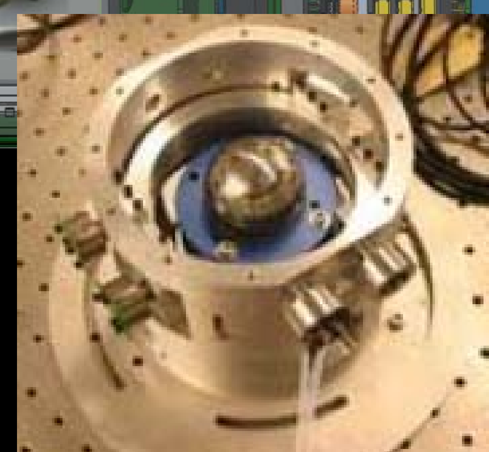


Performance goal: $\sim 10^{-12}$ m/sec^2 / $\sqrt{\text{Hz}}$



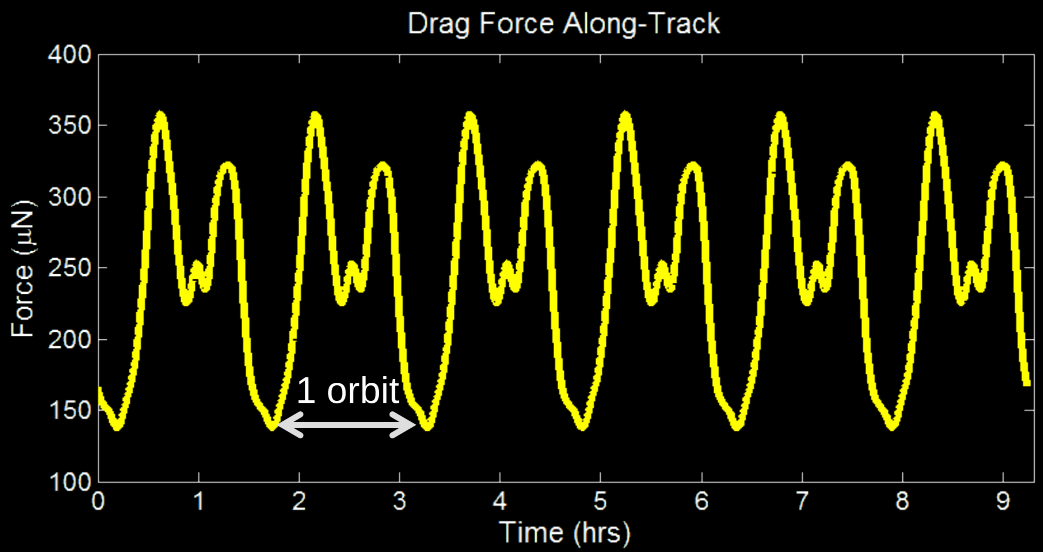


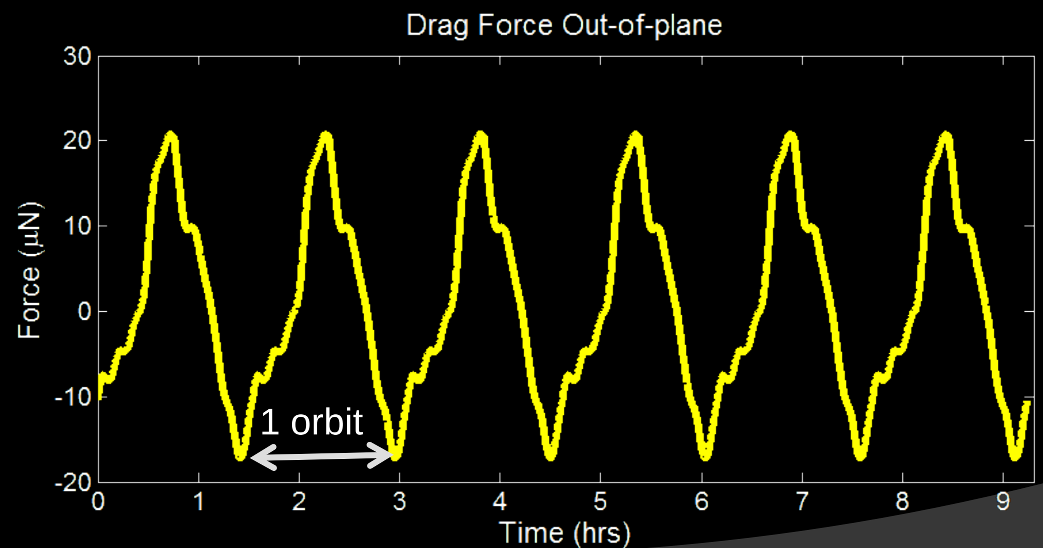
Caging System



Test Mass with DOSS

Total Atmospheric Drag





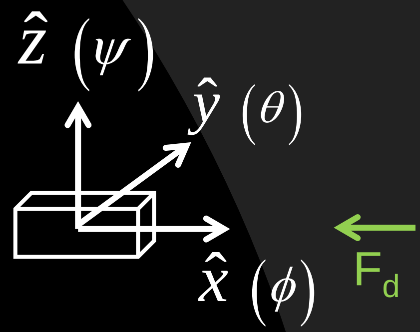
Drag Acceleration:

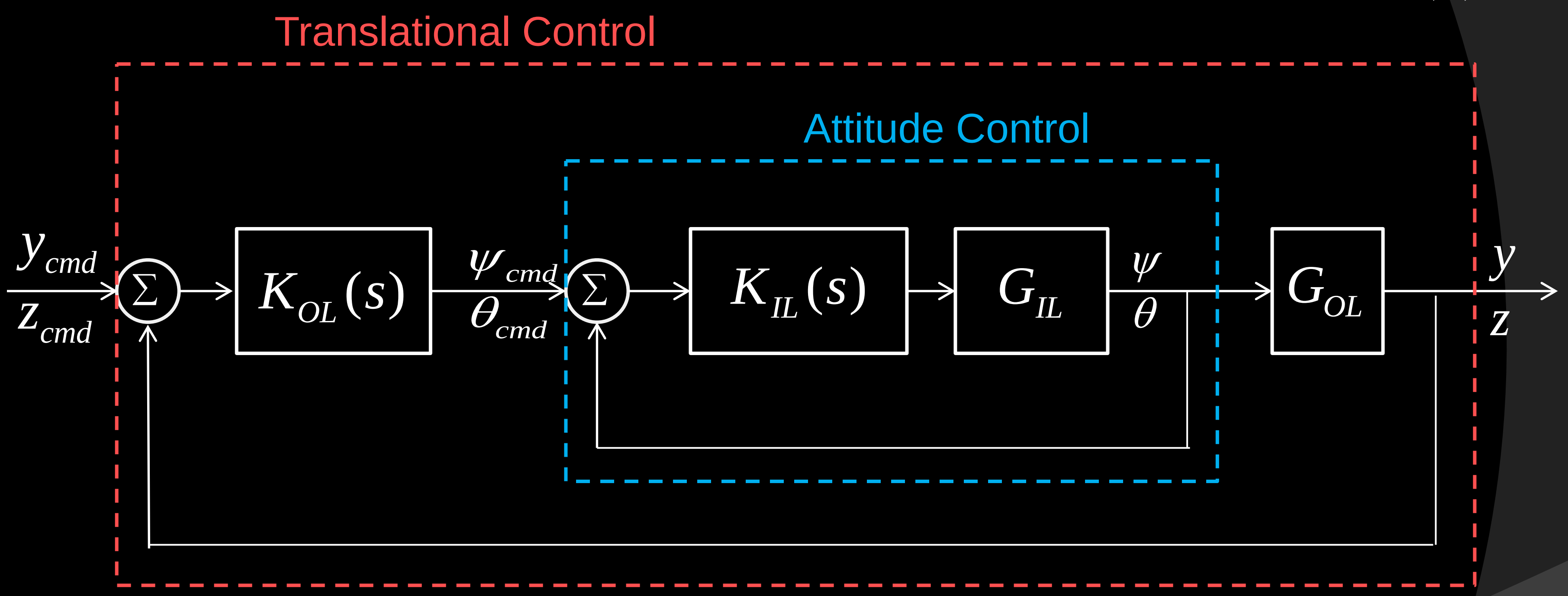
$$\vec{a}_{drag} = \frac{1}{2} C_d \frac{A}{m} \rho v_r \overrightarrow{v_r}$$

- 400km Circular Polar Orbit
- Drag Coefficient of 3
- Density: Mass Spectrometer and Incoherent Scatter Radar (MSIS-E-90) Model
- Velocity: Angular rotation of Earth and Horizontal Winds Model (HWM07)

10% Difference

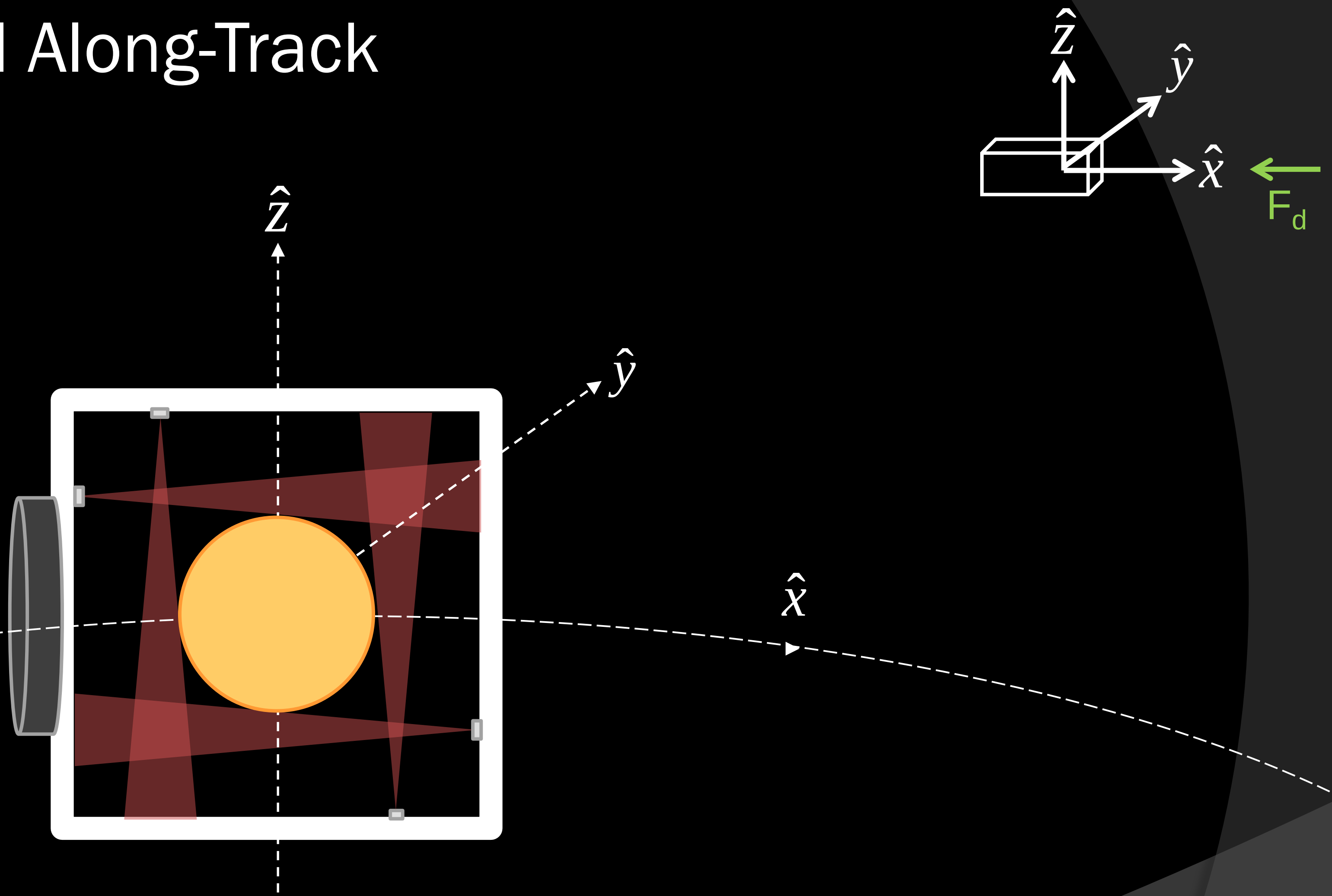
Drag-free Control



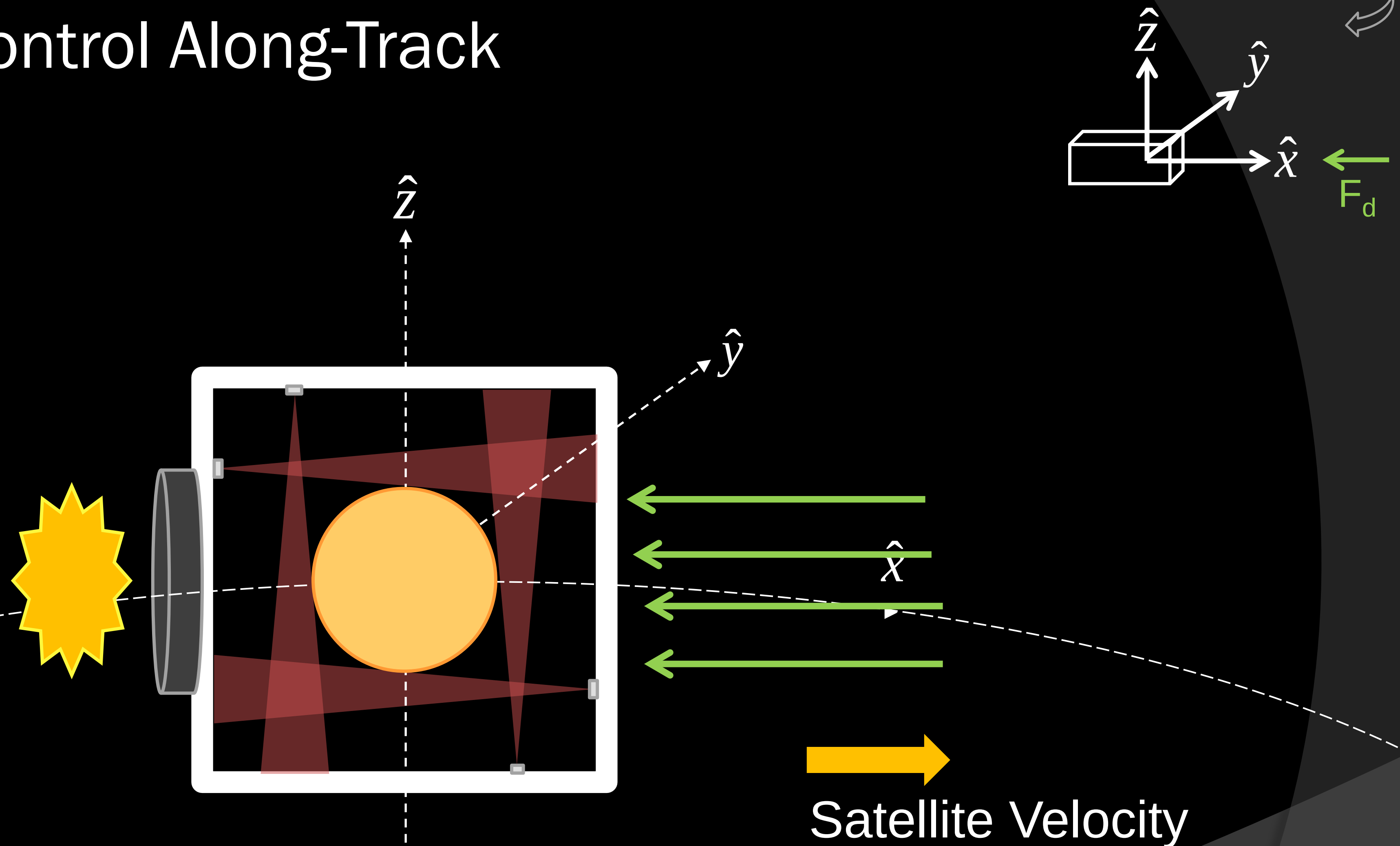


- Faster inner attitude control loop
- Slower outer translational control loop

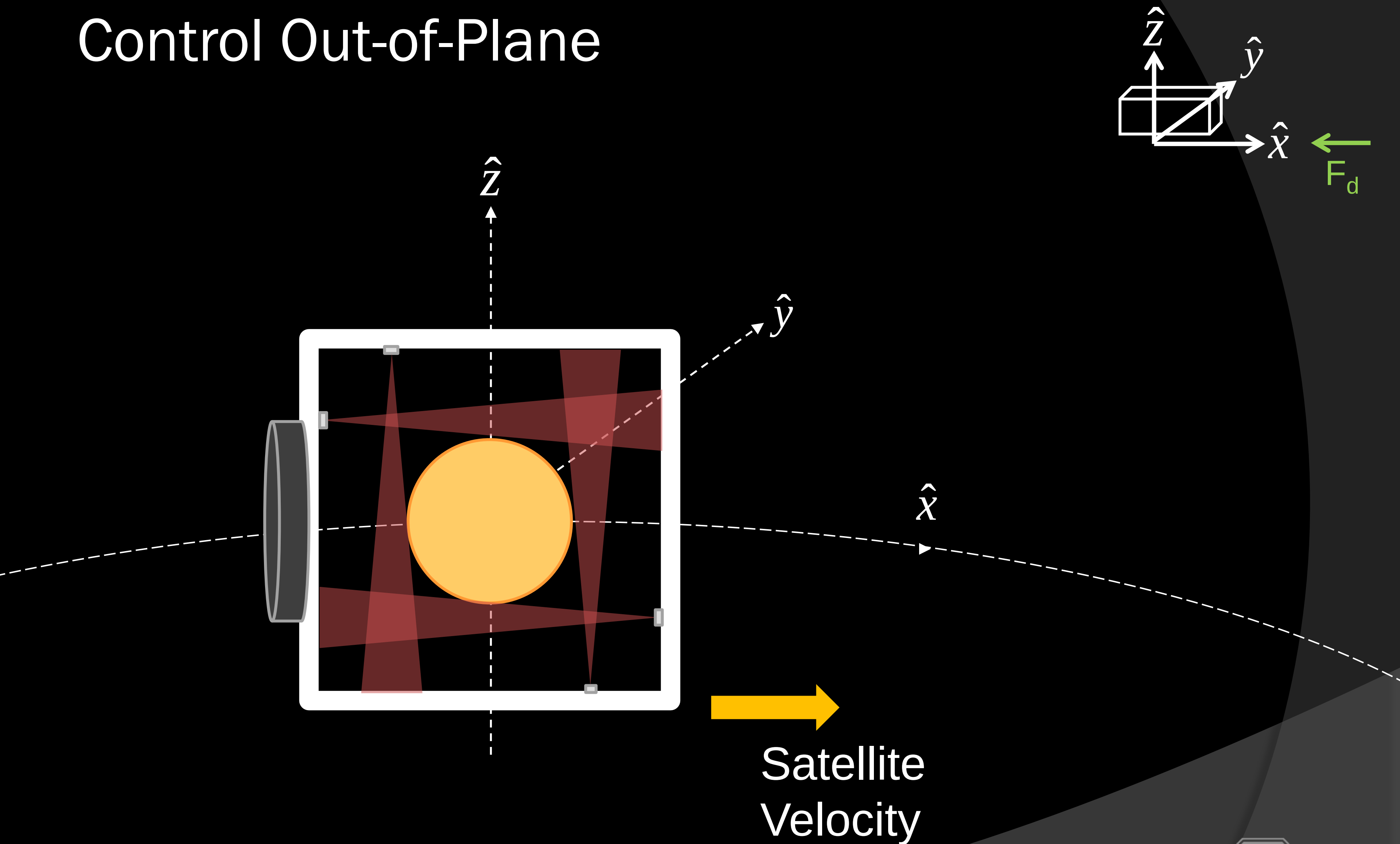
Control Along-Track



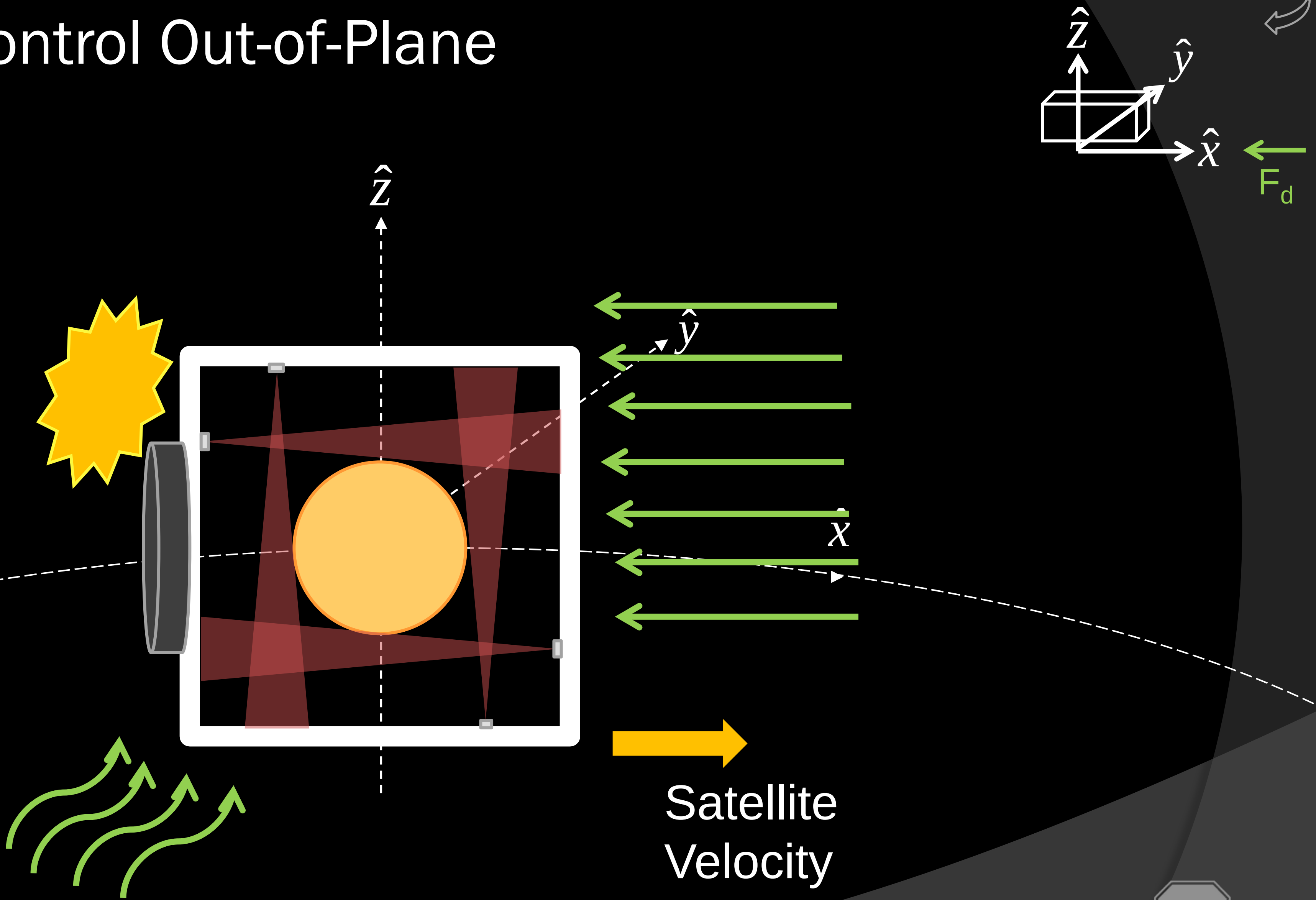
Control Along-Track

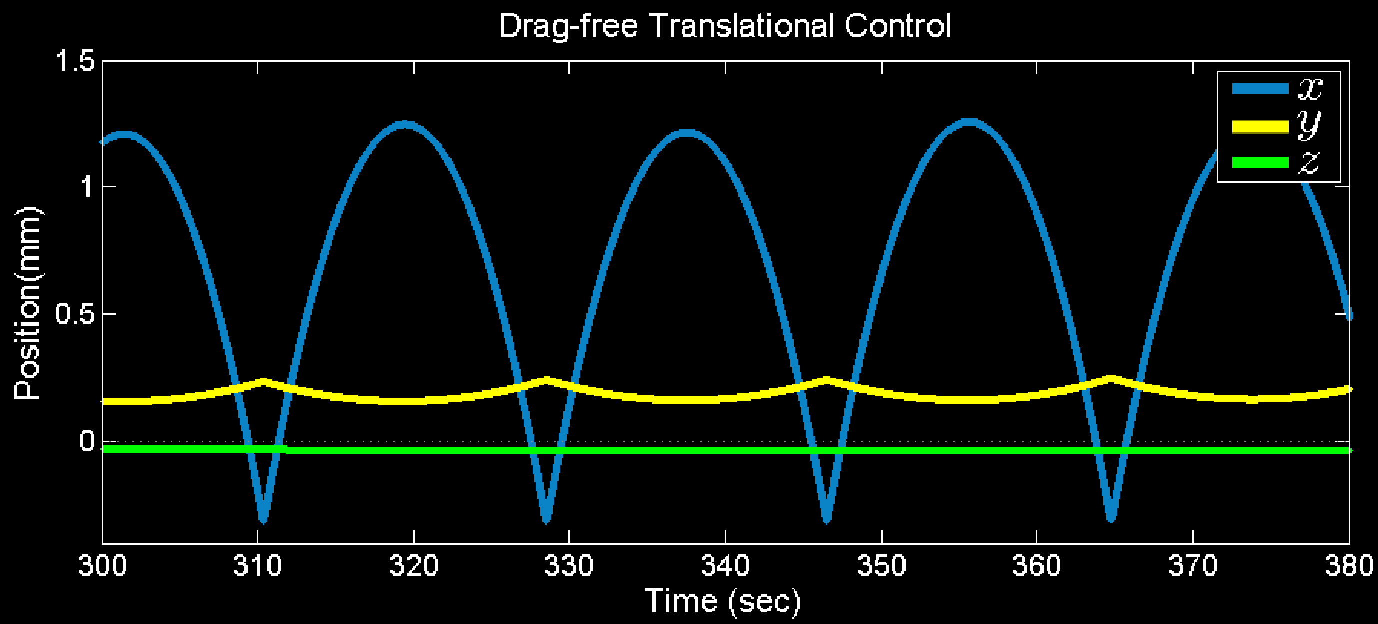


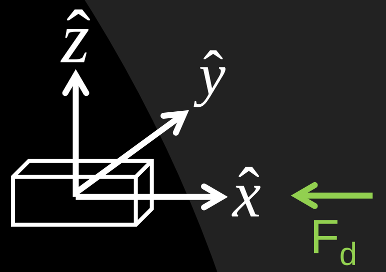
Control Out-of-Plane

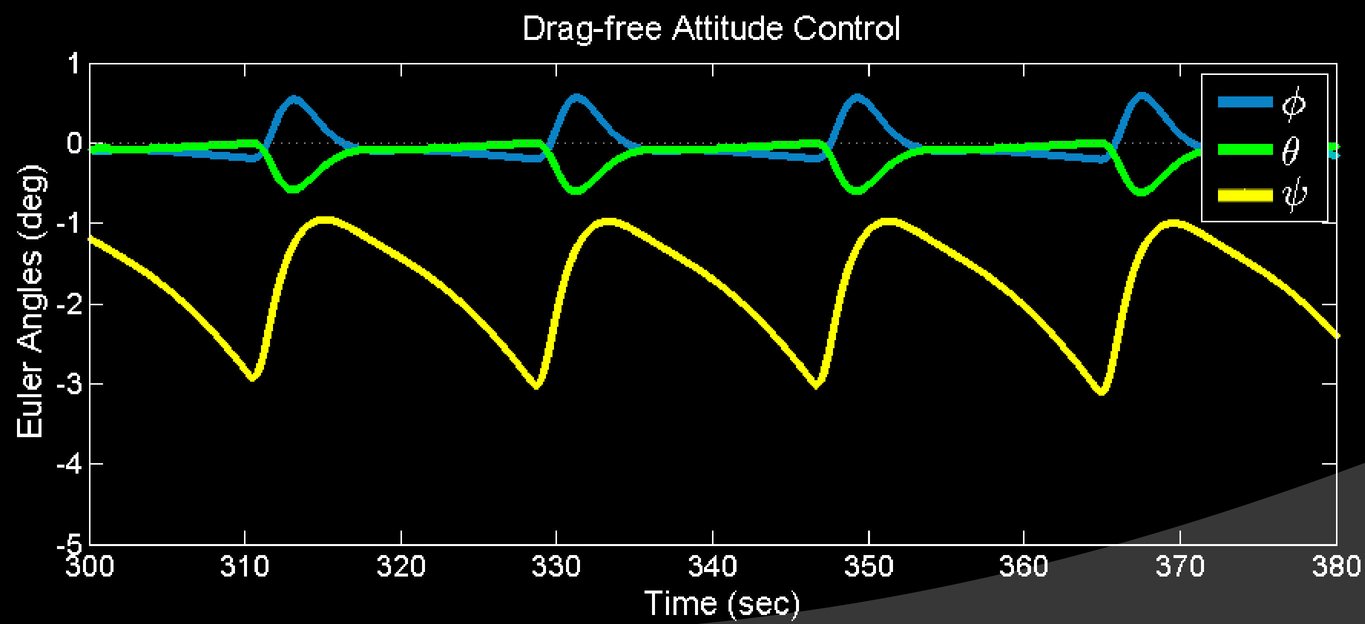


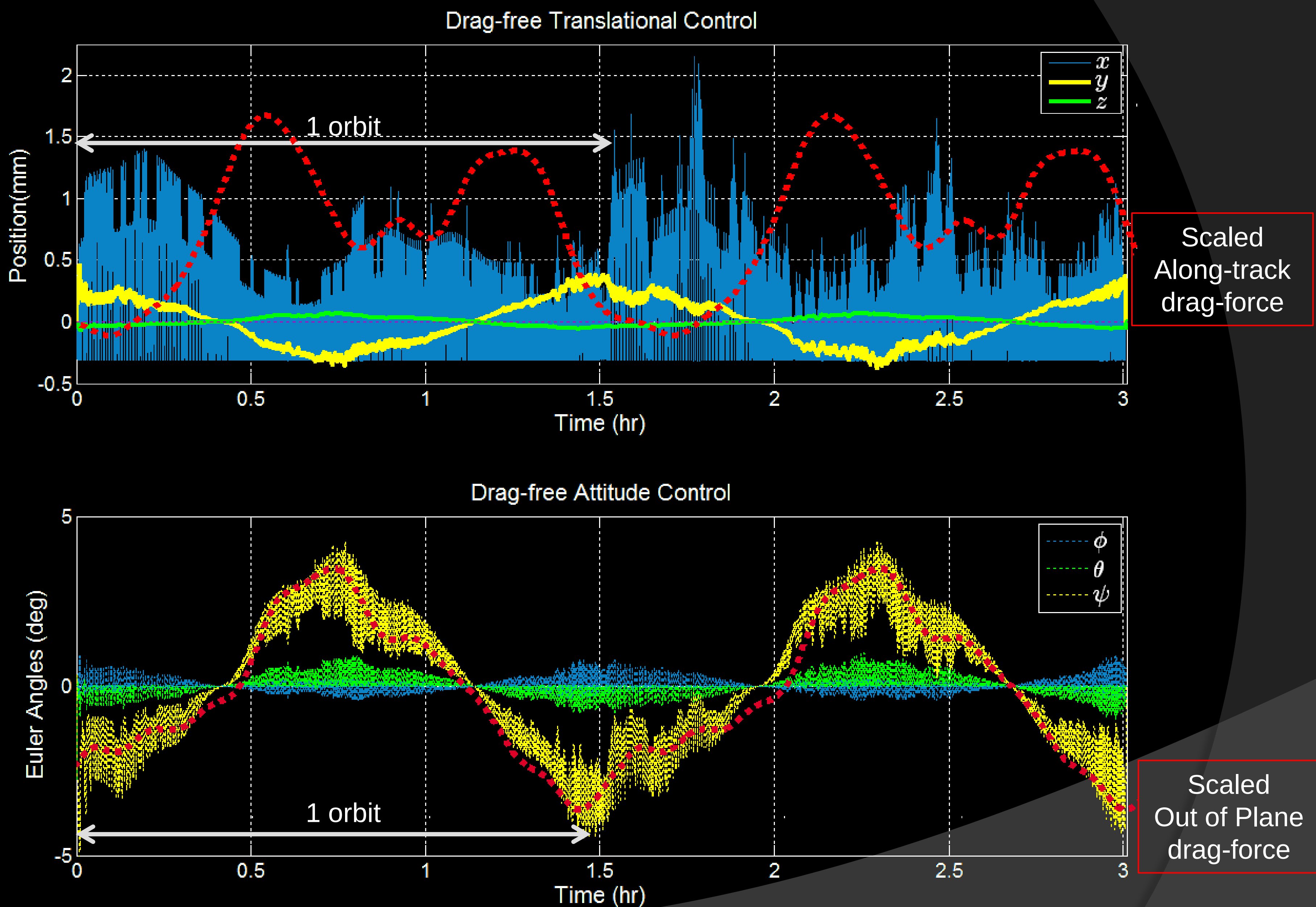
Control Out-of-Plane




Drag-free Translational Control
Position(mm)
Time (sec)
x
y
z
1.5
1
0.5
0
300
310
320
330
340
350
360
370
380


$\hat{z}$
$\hat{y}$
$\hat{x}$
F_d


Drag-free Attitude Control
Euler Angles (deg)
Time (sec)
ϕ
θ
ψ
1
0
-1
-2
-3
-4
-5
300
310
320
330
340
350
360
370
380


Drag-free Translational Control
Position(mm)
Time (hr)
1 orbit
x
y
z
Scaled
Along-track
drag-force
Drag-free Attitude Control
Euler Angles (deg)
Time (hr)
1 orbit
ϕ
θ
ψ
Scaled
Out of Plane
drag-force

Future Steps

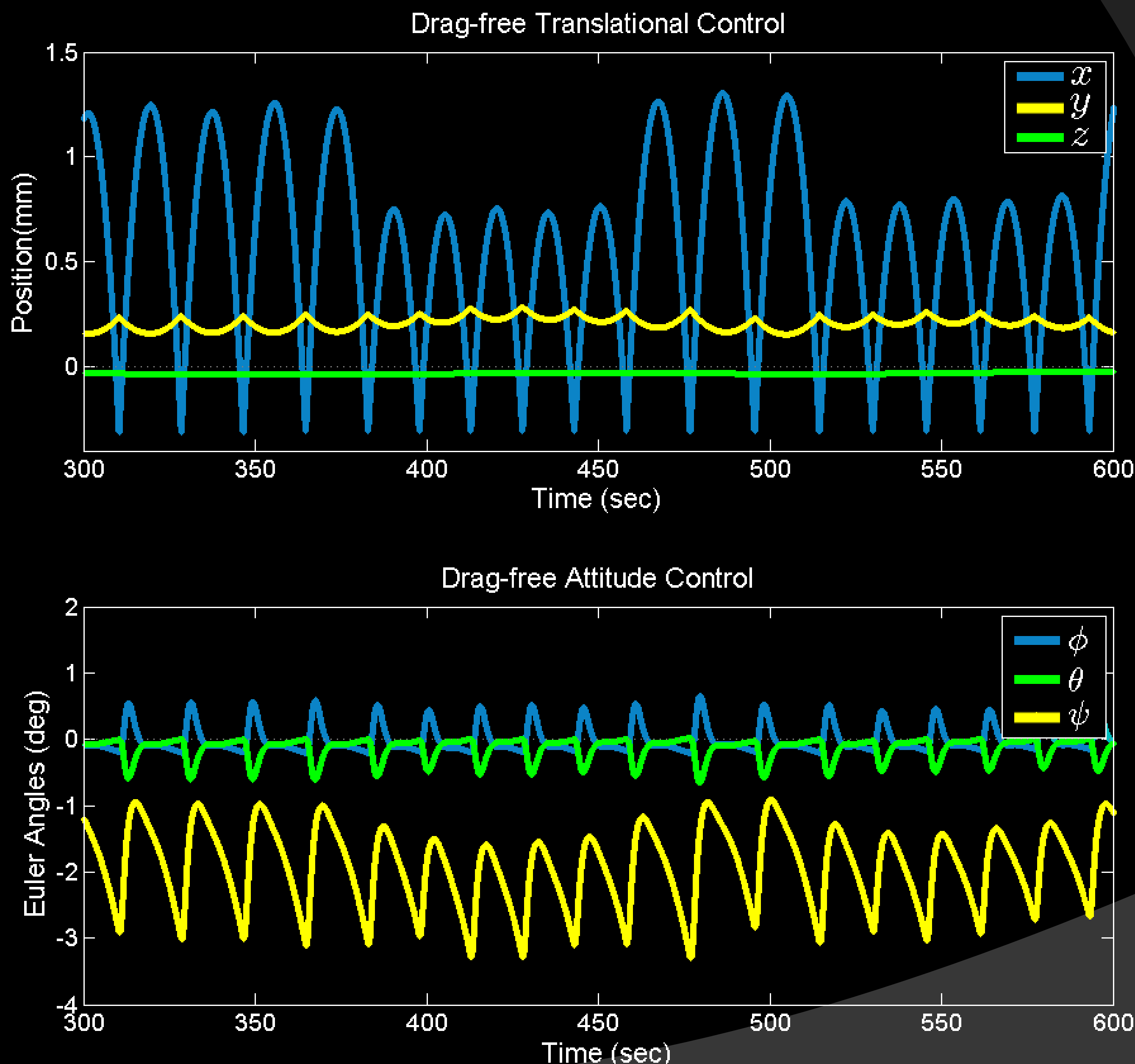
- Implement Kalman Filter
- Stabilize over broad range of conditions
- Incorporate residual non-gravitational pertubations on TM (thermal, magnetic, etc…)

Mission Timeline

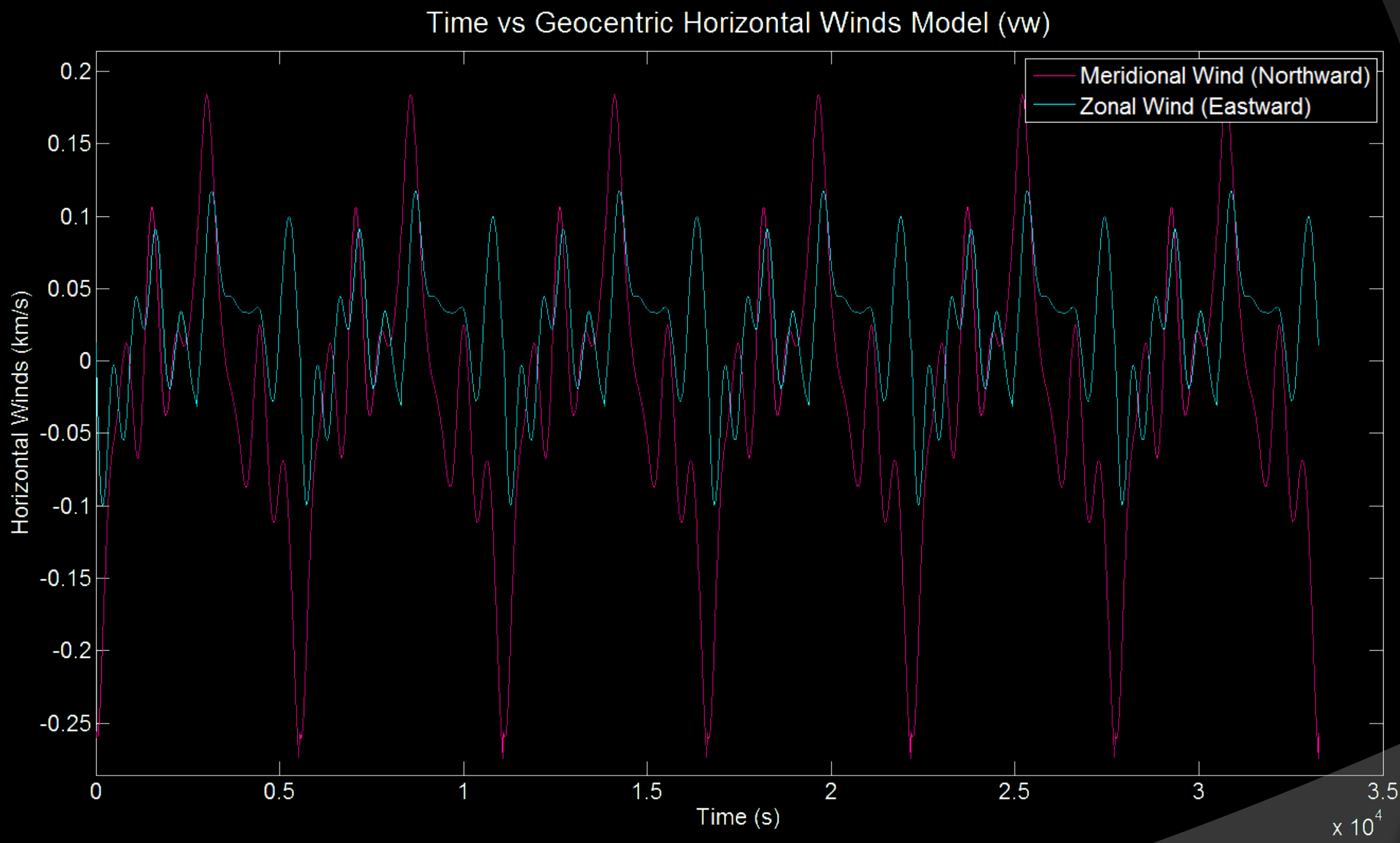
- Preliminary DOSS satellite selected for ELaNa, earliest launch Fall 2013
- Drag-free CubeSat ready by late 2015

Questions

Backup Slides

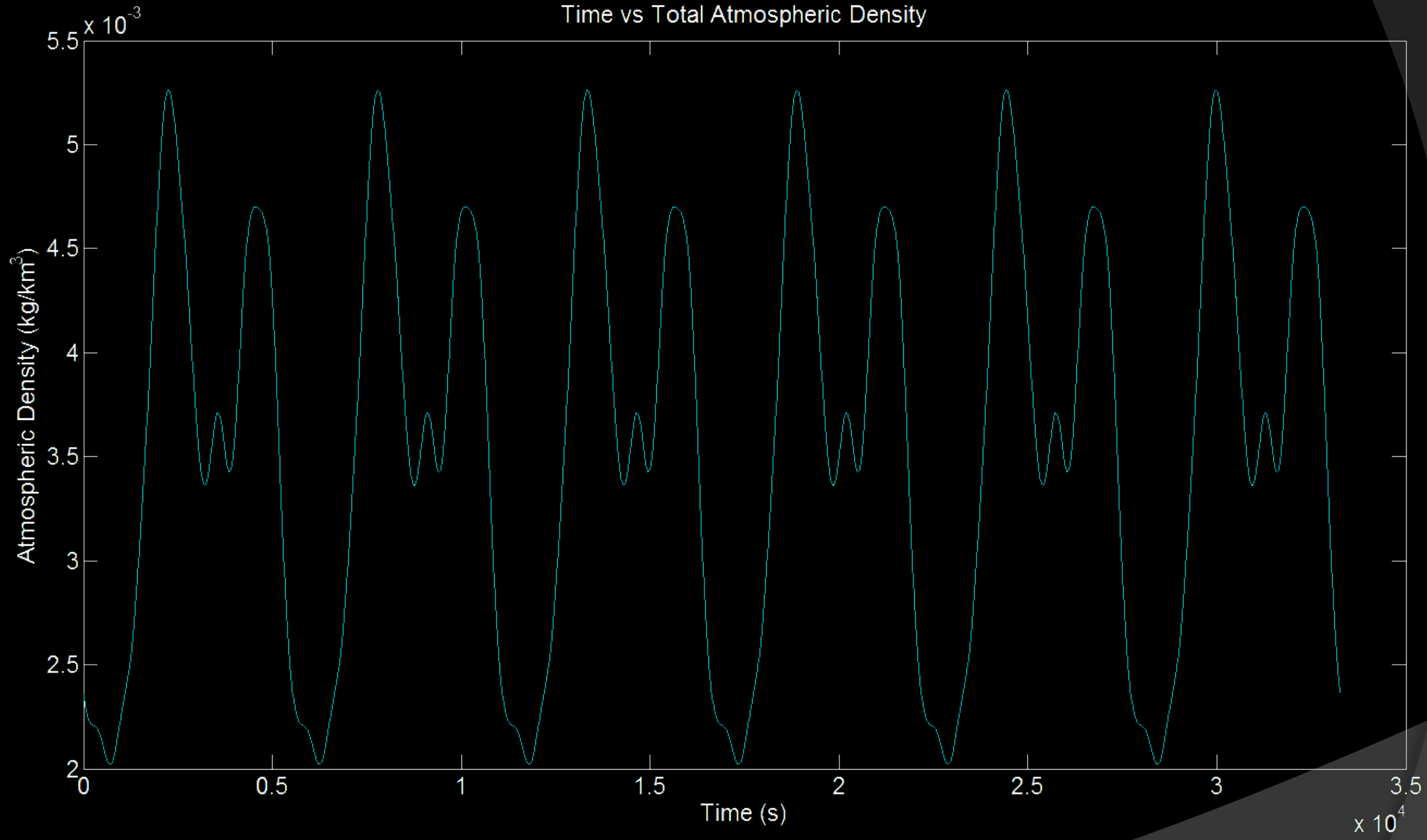

Drag-free Translational Control
Position(mm)
1.5
1
0.5
0
300
350
400
450
500
550
600
Time (sec)
x
y
z
Drag-free Attitude Control
Euler Angles (deg)
2
1
0
-1
-2
-3
-4
300
350
400
450
500
550
600
Time (sec)
ϕ
θ
ψ

HWM07



Based on extensive new ground-based and space- based wind measurements, including height profiles from NASA-UARS/WINDII, NASA-UARS/HRDI, measurements from ground-based optical and radar instruments obtained from the NSF-CEDAR database, and lower atmospheric NCEP data

MSIS



Considered superior than the upstanding Jacchia density models

- Assimilates total mass density values determined from drag on satellites and other space objects while retaining the traditional mass spectrometer and radar databases

Rotational Dynamics

$$T = \dot{h}_I = \dot{h}_B + \omega \times h$$

Then solve the equation for $\ddot{\phi}, \ddot{\theta}, \ddot{\psi}$

$$0 = \dot{h}_B + \omega \times h - T$$

Where,

$$T = T_{command} - T_{disturbance}$$

$$\dot{h}_B = \begin{bmatrix} I_x \dot{\omega}_x \\ I_y \dot{\omega}_y \\ I_z \dot{\omega}_z \end{bmatrix} \qquad I = \begin{bmatrix} I_x \\ I_y \\ I_z \end{bmatrix} = \frac{m}{12} \begin{bmatrix} (l_y{}^2 \cdot l_z{}^2) \\ (l_x{}^2 \cdot l_z{}^2) \\ (l_x{}^2 \cdot l_y{}^2) \end{bmatrix}$$

$$\omega = \begin{bmatrix} \omega_x \\ \omega_y \\ \omega_z \end{bmatrix} = \begin{bmatrix} \dot{\phi} - \dot{\psi} sin(\theta) \\ \dot{\theta} cos(\phi) + \dot{\psi} cos(\theta) sin(\phi) \\ \dot{\psi} cos(\theta) cos(\phi) - \dot{\theta} sin(\phi) \end{bmatrix}$$

$$\dot{\omega} = \begin{bmatrix} \dot{\omega}_x \\ \dot{\omega}_y \\ \dot{\omega}_z \end{bmatrix} = \begin{bmatrix} \ddot{\phi} - \dot{\psi} cos(\theta) + \ddot{\psi} sin(\theta) \\ \ddot{\theta} cos(\phi) - \dot{\theta} sin(\phi) + \ddot{\psi} cos(\theta) sin(\phi) - \dot{\psi} sin(\theta) sin(\phi) + \dot{\psi} cos(\theta) cos(\phi) \\ -\ddot{\theta} \sin(\phi) - \dot{\theta} \cos(\phi) + \ddot{\psi} cos(\theta) \cos(\phi) - \dot{\psi} \sin(\theta) \cos(\phi) - \dot{\psi} \cos(\theta) \sin(\phi) \end{bmatrix}$$

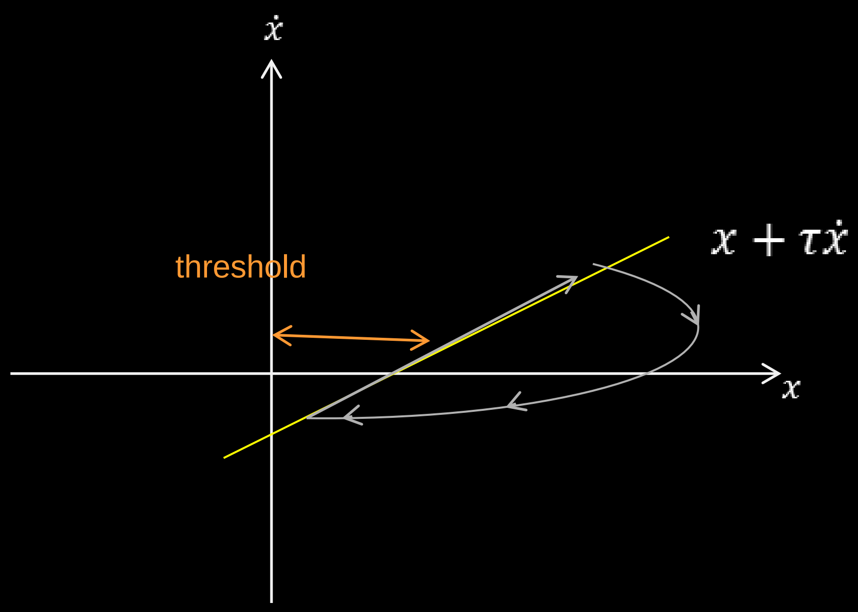
Translational Dynamics

$$F = ma$$

Then solve the equation for $\ddot{x}, \ddot{y}, \ddot{z}$

$$a = \begin{bmatrix} \ddot{x} \\ \ddot{y} \\ \ddot{z} \end{bmatrix} = \frac{1}{m} \begin{bmatrix} F_x \\ F_y \\ F_z \end{bmatrix}$$

Translational Dynamics



Switching Based on X

$$k\tau = \frac{|\dot{x}|}{2U_{max}}$$

$$U_{max} = \frac{T_{max}}{I}$$

Thrust Forces in x, y, z

$$F_{cx} = F_T \cos(\theta)\cos(\psi)$$

$$F_{cy} = F_T \cos(\theta)\sin(\psi)$$

$$F_{cz} = F_T \sin(-\theta)$$

F_T Thrust Force = 25 mN = 0.025 N

k Slope Gain = 5

Threshold = 300 um = -3E-4 km