Dynamics and Control Design for the Drag-free Small Satellite

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ABSTRACT

A drag-free spacecraft utilizes a Gravitational Reference Sensor (GRS) to shield an internal free-floating test mass (TM) from both external disturbances and disturbances caused by the spacecraft itself. It measures the position of the spacecraft with respect to the TM and a feedback control system commands thrusters at the aft to maintain that position. In principle, the TM is then completely freed from non-gravitational disturbances so that it and its "tender" spacecraft follow a pure geodesic. This technology can be applied to a broad range of applications including but not limited to, Gravitational waves.

MOTIVATION

Drag-free space systems provide autonomous precision orbit determination, more accurately map the static and time varying components of the Earth's mass distribution, and aid our understanding of the fundamental force of gravity. The performance in *Table 1* is measured by the residual of acceleration of the test mass.

	Category	Application	Performance ($m\ s^{-2}\ Hz^{-1/2}$)	Metrology (m)
✔	Navigation	Autonomous, fuel efficient orbit maintenance	$\leq 10^{-10}$, near zero freq.	$\leq$ 10 absolute
		Precision real-time on-board navigation	$\leq 10^{-10}$, near zero freq.	$\leq$ 10 absolute
✔	Earth Science	Aeronomy	$\leq 10^{-10}$, 10^{-2} to 1 Hz	1 absolute
		Geodesy	10^{-10}, 10^{-2} to 1 Hz	10^{-6} differential
		Future Earth Geodesy	$\leq 10^{-12}$, 10^{-2} to 1 Hz	$\leq 10^{-9}$ differential
✔	Fundamental Physics	Equivalence Principle Tests	$\leq 10^{-10}$, 10^{-2} to 1 Hz	$\leq 10^{-10}$ differential
		Tests of General Relativity	$\leq 10^{-10}$, near zero freq.	$\leq$ 1 absolute
	Astrophysics	Gravitational Waves	3×10^{-15}, 10^{-4} to 1 Hz	$\leq 10^{-11}$ differential

Table 1: Drag-free Applications

The following single thruster configuration and control design requires only one thruster to oppose drag force, minimizing amount of fuel required for the system.

KEY TECHNOLOGIES

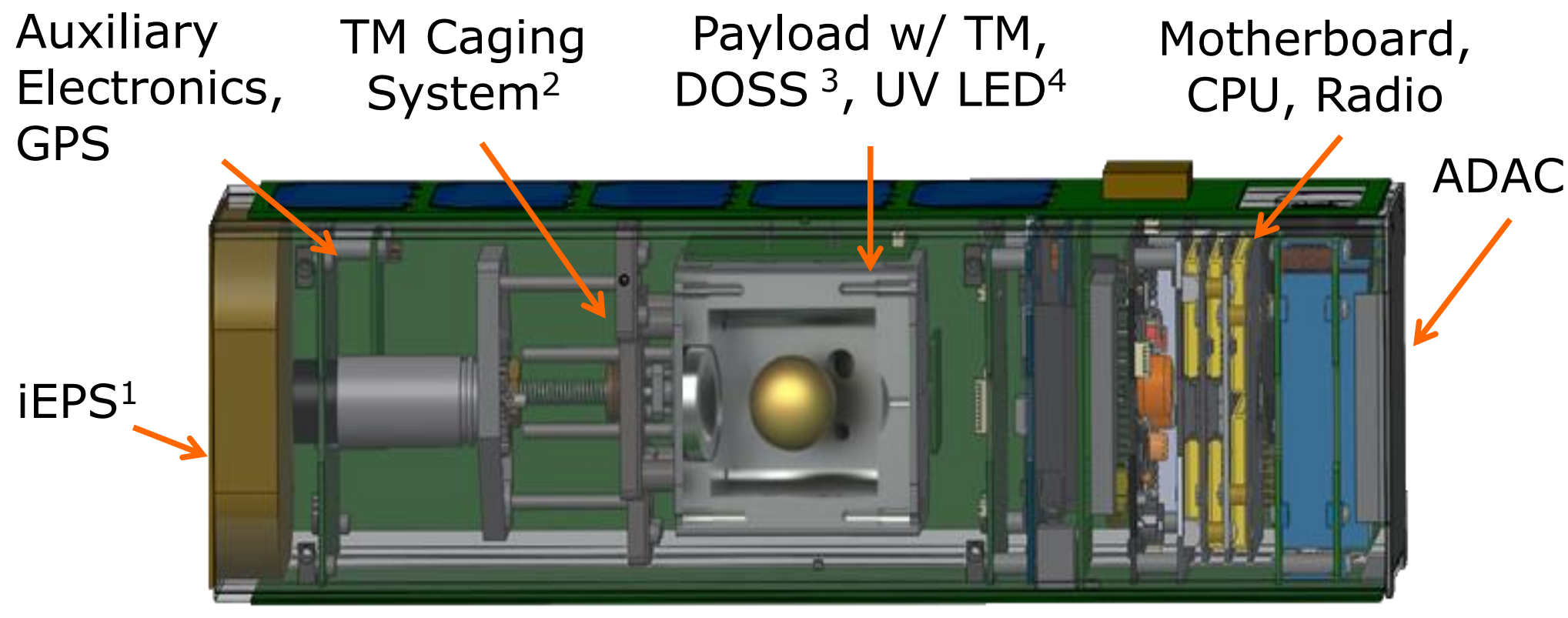


Fig: 1: Drag-free small satellite Candidate design

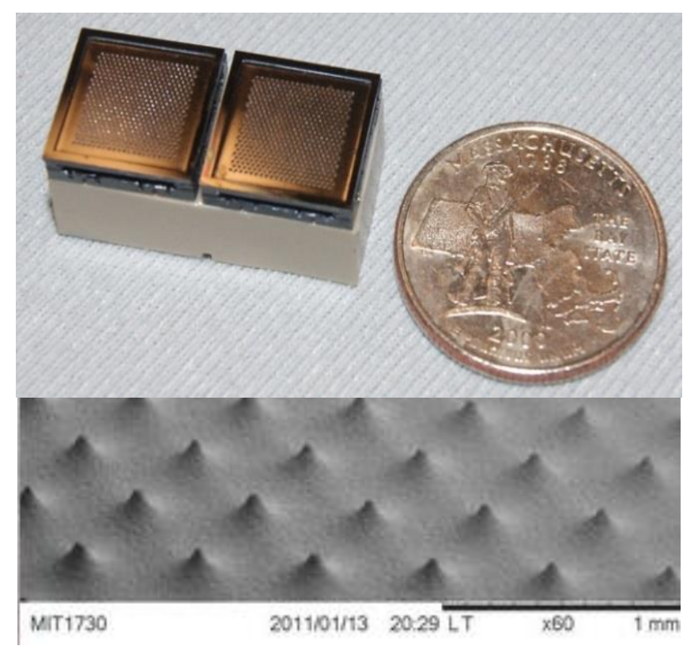


Fig. 2: iEPS

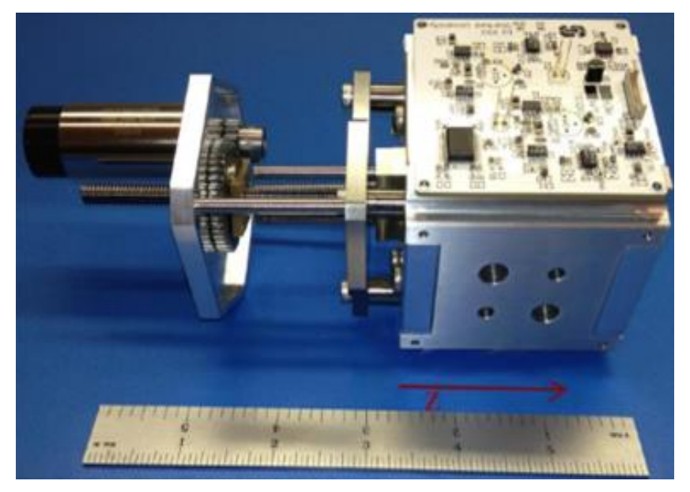


Fig. 3: Test mass caging system

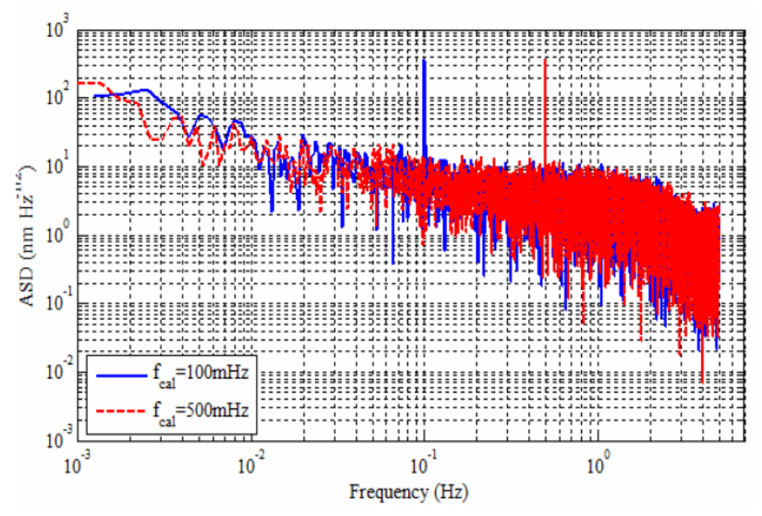


Fig. 4: Flight-like DOSS Noise

1. ion Electrospray Propulsion System (iEPS)
- Based on the electrostatic extraction and acceleration of positive and negative ions from an ionic liquid; developed by Massachusetts Institute of Technology
  - Assumed Min. thrust bit: ~12 μN
  - Assumed Max. thrust bit: ~480 μN
  - Assumed Noise: ~12 μN

2. Test Mass Caging System
- Prevents damage to the sphere during launch and releases the sphere after arrival of the satellite on orbit; developed by Stanford University

3. Differential Optical Shadow Sensor (DOSS)
- LED sensing system that measures the position of the test mass relative to the housing; developed by Stanford University
- Noise: ~10 nm-Hz

4. UV LED Charge Control
- Utilizes ultra-violet LEDs to minimize charge build-up on test-mass; developed by University of Florida

5. Attitude and Control System (ADACS)
- Measures attitude of the outer satellite; commercially developed
- Assumed Max. torque: ~0.6 nM-m
- Assumed Noise: ~0.18°

SIMULATION

To determine the stability and performance of the drag-free control system, a 4kg 3U nano-satellite candidate was simulated with a circular polar orbit at 400km and is summarized by the block diagram below.

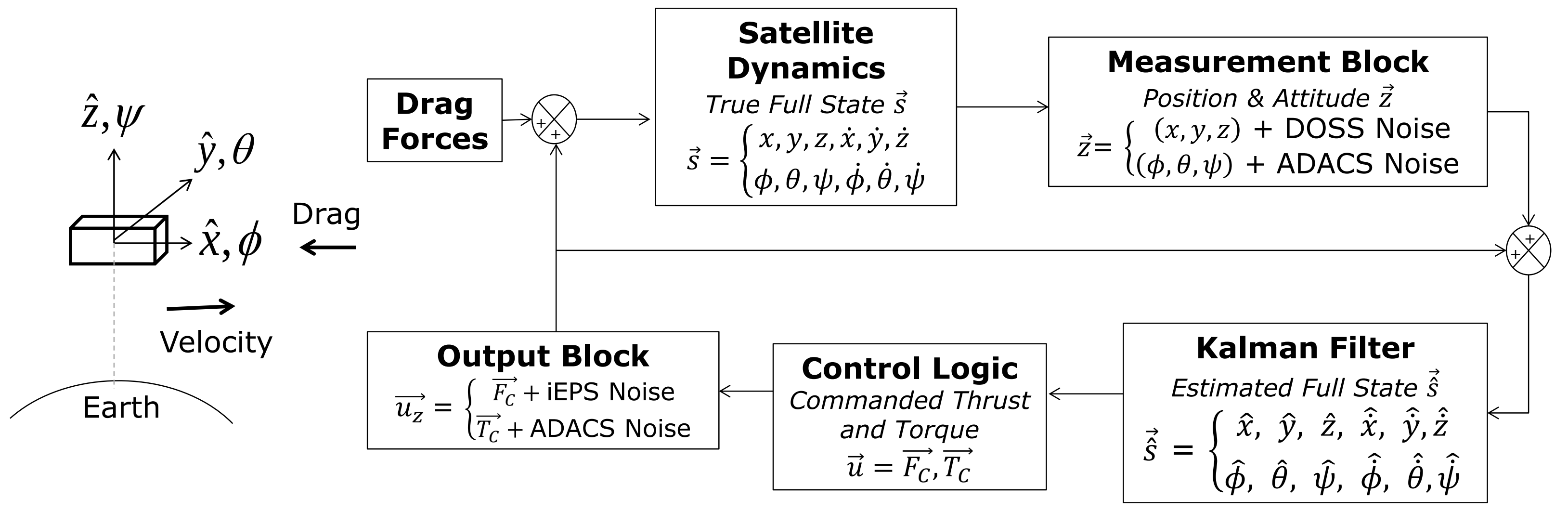


Fig. 5: Simulation Block Diagram

DRAG FORCE MODELING

In order do the simulation, the following drag forces were modeled and compared to STK10 (AGI Satellite Tool Kit). For completeness of the estimated model, the drag forces from the horizontal winds and Earth radiation pressure were included while they were not available in STK10. The noted differences in the second plot are due to a factor of 2 difference in the atmospheric densities.

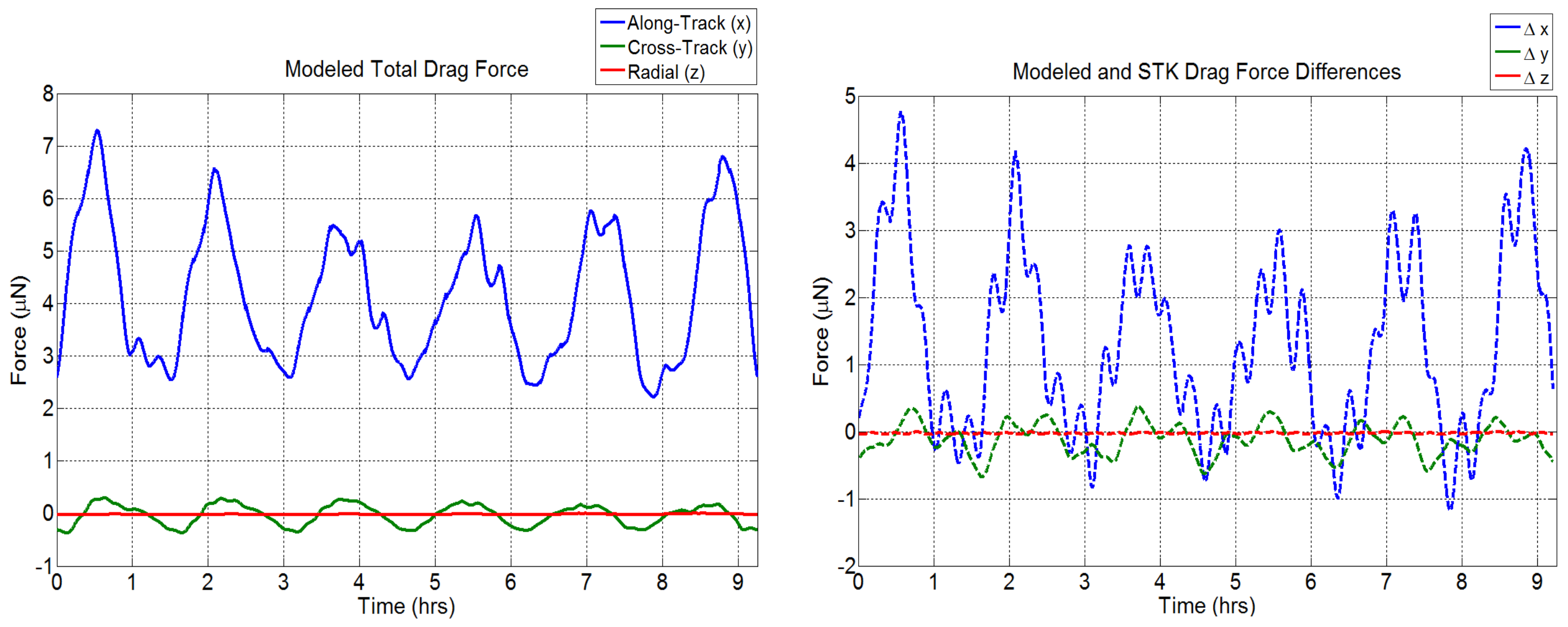


Fig. 6: Modeled Drag Forces and STK Comparison

Atmospheric Drag:
- US Naval Research Laboratory MSISE-00 Model for density †‡
- NASA HWM07 Model for Horizontal winds †

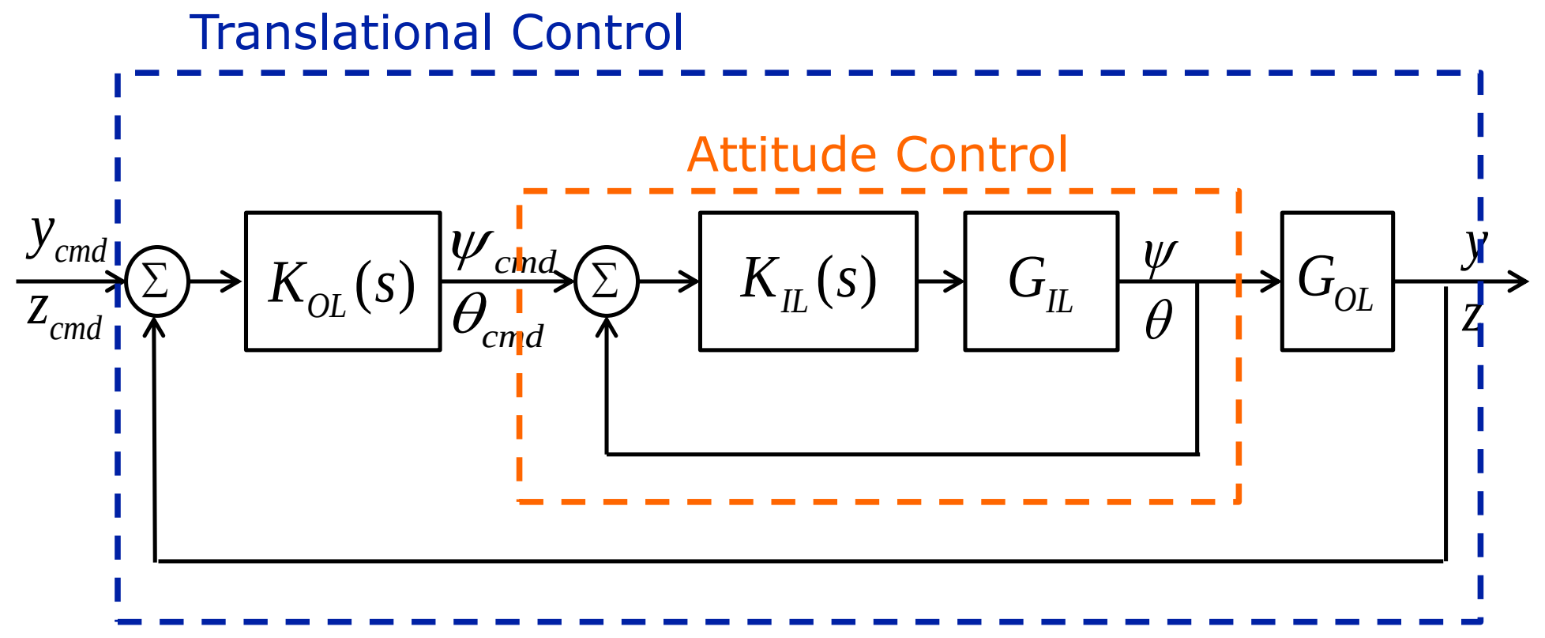
Solar Radiation Pressure:
- Solar panels on all sides of nano-satellite with reflectance $(\varepsilon = 0.21)$ and emittance of $(1 - \varepsilon = 0.79)$ †‡

Earth Radiation Pressure:
- NASA TOMS Ozone and Albedo †

† Applied to Modeled Drag Force
‡ Applied to STK Drag Force

DRAG-FREE ATTITUDE AND CONTROL SYSTEM

- The Drag-free attitude and control system (DFACS) is a feed-back control system that utilizes a fast inner attitude control loop (ϕ, θ, ψ) nested in a slower translational control loop (x, y, z)
- The y-direction is coupled with the ψ yaw angle and the z-direction is coupled with the θ direction
- The x-direction and ϕ roll angle are decoupled from the rest of the system



K_{IL}, K_{OL} : Control logic
G_{IL}, G_{OL} : Dynamic transfer function

Fig. 7: DFACS Block Diagram

RESULTS

The dominant drag forces act in the negative x-direction of the satellite causing it to spin about the body z-axis. Therefore, the largest displacements can be seen in the y-direction and associated coupled yaw angle ψ.

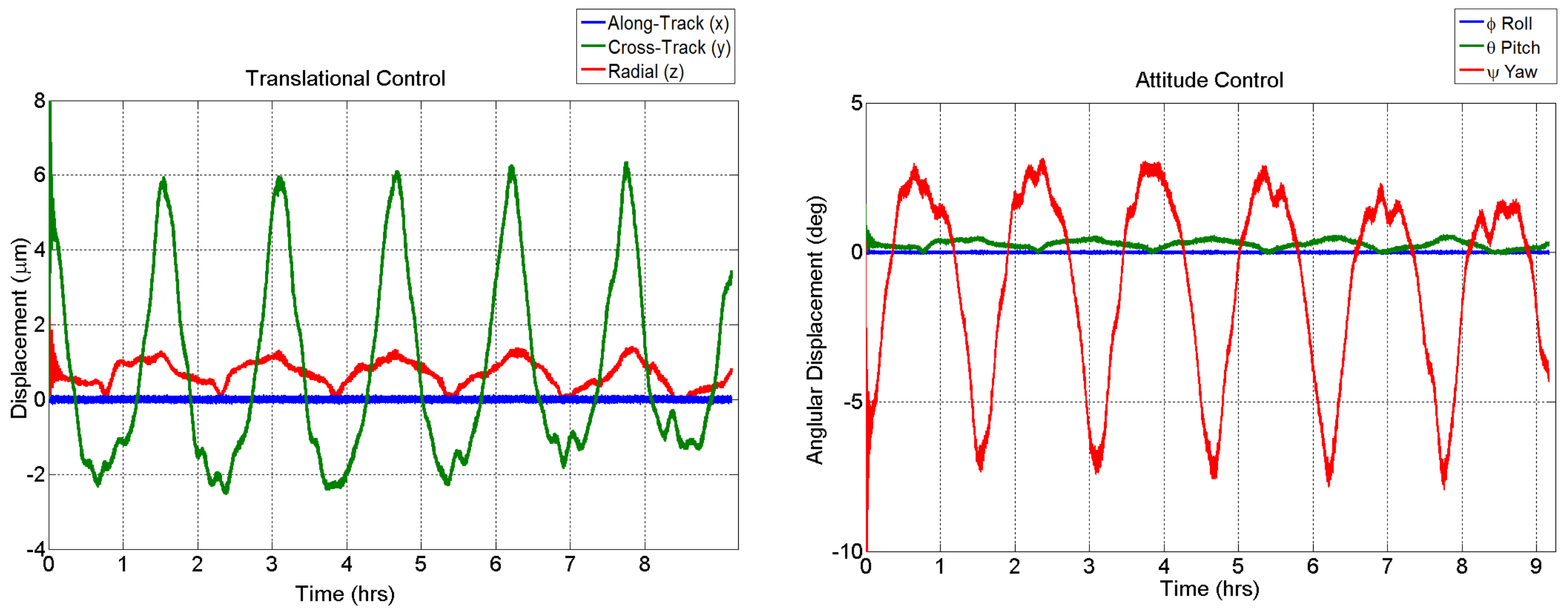


Fig. 8: Flight Characteristics

Stable ✔
- Drag-free attitude control system proved to be stable and feasible on-orbit

Drag force approximations ✔
- Unknown drag forces and atmospheric densities can be recovered from the DOSS measurements and optional on-board mass spectrometers
- Higher sampling rates can produce more precise results at the cost of processing speed and power

Fuel Efficiency
- Single thruster configuration only allows fuel to be expended to counteract the drag-forces on-orbit
- Approximate navigation error of 30%-50% and fuel consumption reduction of 50% compared to a satellite compensated after three weeks at 350km

HARDWARE IN THE LOOP SIMULATION

Small satellite ADACS limitations predominantly lie within the processor selection. The feasibility of the Texas Instruments single core DSP ARM 9 is evaluated for the following criteria:

Speed
- Must be fast enough to compute required calculations at every sampling period (notably the Kalman Filtering and Control Logic)

Accuracy ✔
- Floating-point precision
- Current errors ~10^{-26}

Space Qualification✔
- From manufacturer

Fig. 9: TI TMS320C6748

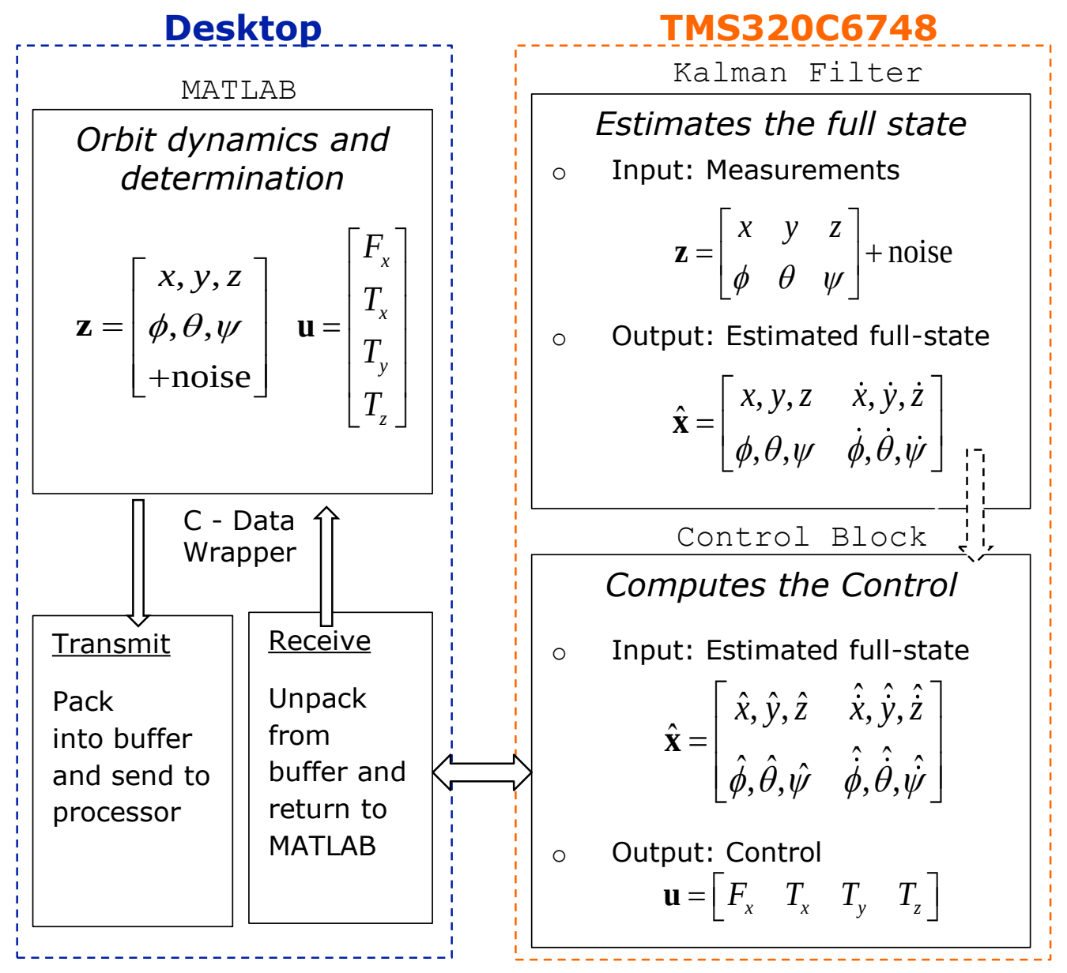


Fig. 10: HIL Setup

FUTURE WORK

- Compare performance between a small cubic GRS and the Stanford spherical GRS
- Fuel reduction studies and navigation errors at different small satellite heights
- Compare performance between a commercial reaction wheel system and a custom control moment gyro based attitude control system

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