UTIAS SFL RESEARCH

...Big Performance, Smaller Satellites

FIBER OPTIC GYRO-BASED ATTITUDE DETERMINATION FOR HIGH-PERFORMANCE TARGET TRACKING

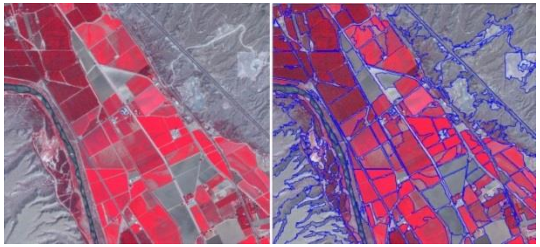
Elias F. Solorzano
University of Toronto (Space Flight Laboratory)
Toronto, ON (Canada)

August 10th, 2016
30th AIAA/USU Conference on Small Satellites

Research Motivation

- Earth observation (EO) market opportunities

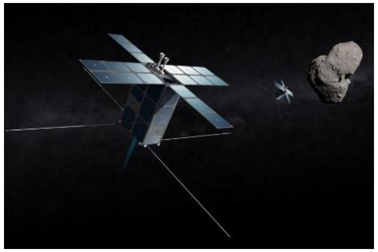
Agriculture
- Precision Farming
- Crop Health & Production



Environmental
- Monitor Carbon Emissions
- Forestry Operations

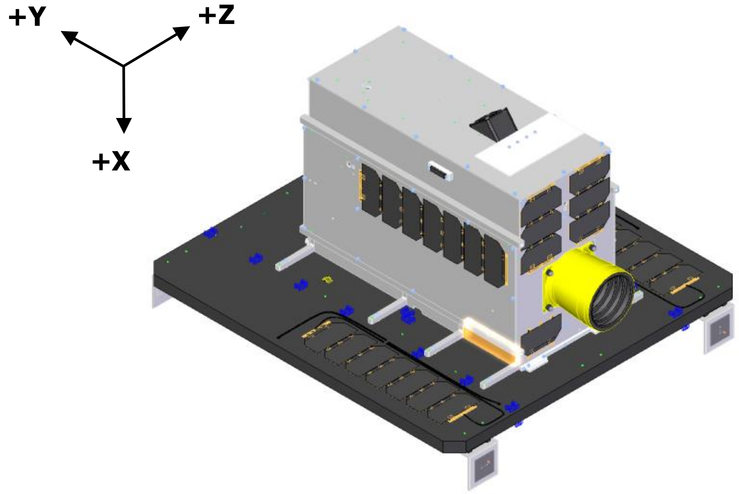
Humanitarian Aid
- Disaster Response
- Crisis Management

- Applications beyond LEO
  - Asteroid mining
  - Planetary exploration



SFL-Built Target Tracking Platforms

- The **N**ext-Generation **E**arth **M**onitoring and **O**bservation (NEMO) bus is developed specifically for ground-target tracking applications.
- The standard NEMO-bus structure is used for EO-specific missions such as NEMO-AM and GHGSat-D.

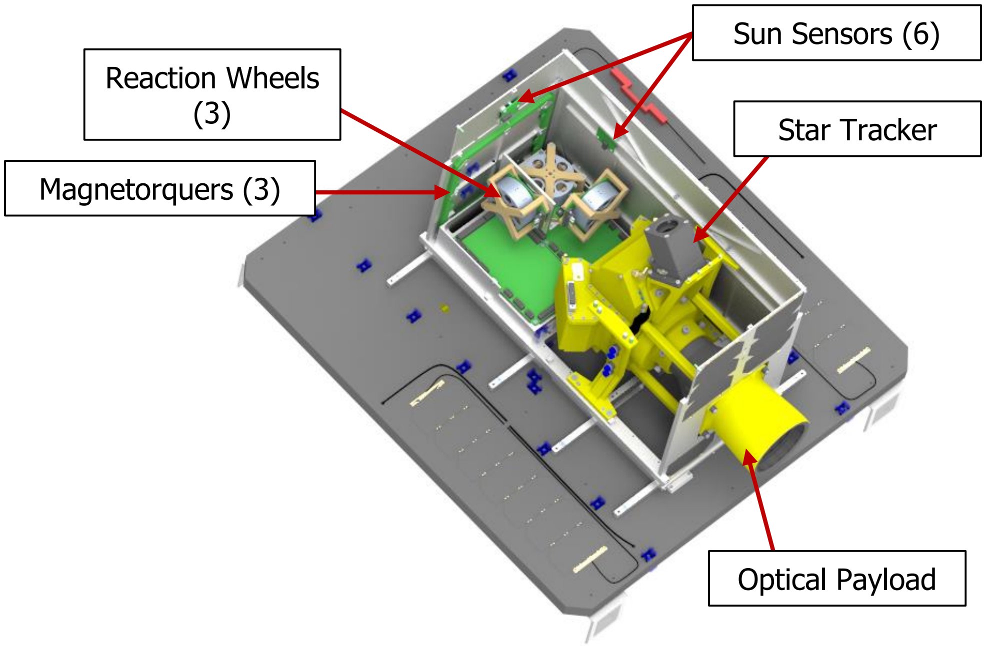


SFL's standard NEMO-class spacecraft

GHGSat-D being launched on-board a PSLV rocket on June 2016 (credit: ISRO)

NEMO Bus: System Overview

- Suitable for autonomous observations of selected ground targets.
- Peak tracking control error constrained below **0.3°** on target-tracking mode.



Specification	Nominal Value
Dimensions	20 x 20 x 40 cm
Max. Weight	15 kg
Peak Power @20°C	80 W
Payload Capacity	9 kg
ACS Stability	~ 2° [1]
	~ 60″ [2]

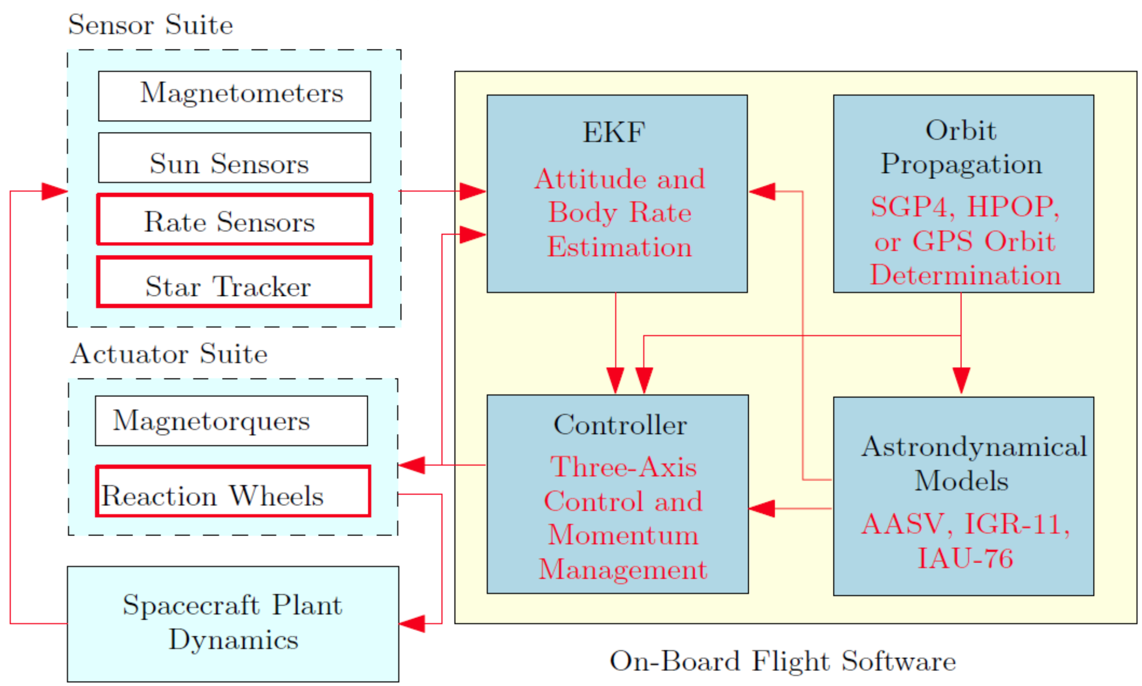
[1] Using MAG, FSS, and RWs
[2] With Star Tracker

- ACS design satisfies the requirements of current EO missions.
- Future missions may require superior pointing performance.

UTIAS SFL RESEARCH

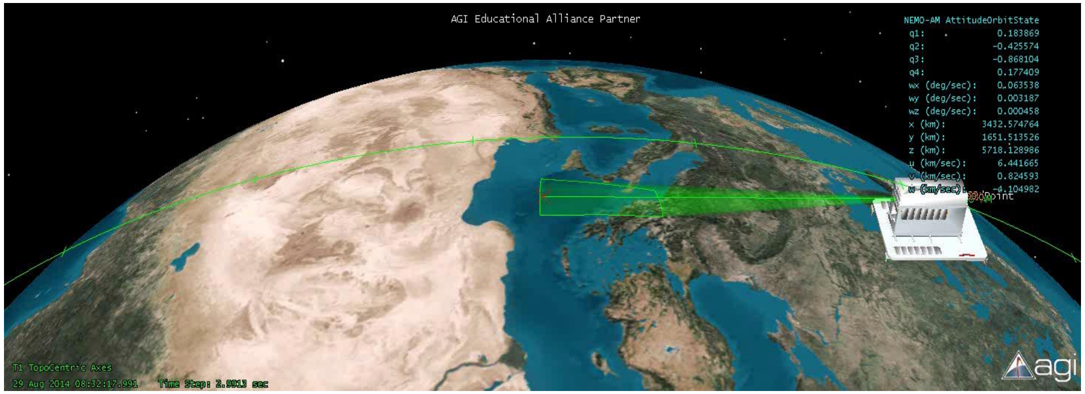
NEMO Bus: ADCS Architecture

- Orbit and attitude determination EKF and controller run at 1Hz.
- PID three-axis controller based on quaternion and rate feedback.
- Control modes:
  - Inertial Pointing
  - Align & Constrain
  - ECEF-frame Target Tracking
- Other features:
  - Gyroscopic torque cancellation.



Terrestrial Target Tracking Overview

- Spacecraft is commanded to maintain line-of-sight (LoS) with specific ground target.
- Only star tracker measurements (sampled at 1Hz) are used to determine satellite's attitude during the slew maneuver.
  - May not be sufficient for future missions requiring pointing performance better than 0.3° (2-σ).
  - High-grade fiber-optic gyro (FOG) measurements can be used to augment the star tracker.



STK-generated animation of a NEMO-class satellite in target tracking

Fiber Optic Gyros (FOGs)

- High-grade miniaturized FOGs are suitable for high-rate target-tracking maneuvers.
  - High bandwidth
  - Low noise parameters (e.g. angular random walk, bias drift, etc.).
  - Commercially accessible
- ST is augmented using FOG measurements at high cadence (≥2Hz), allowing for more frequent control torque commands.
- Can compensate for the attitude error drift caused by invalid star tracker measurements.

The Challenge

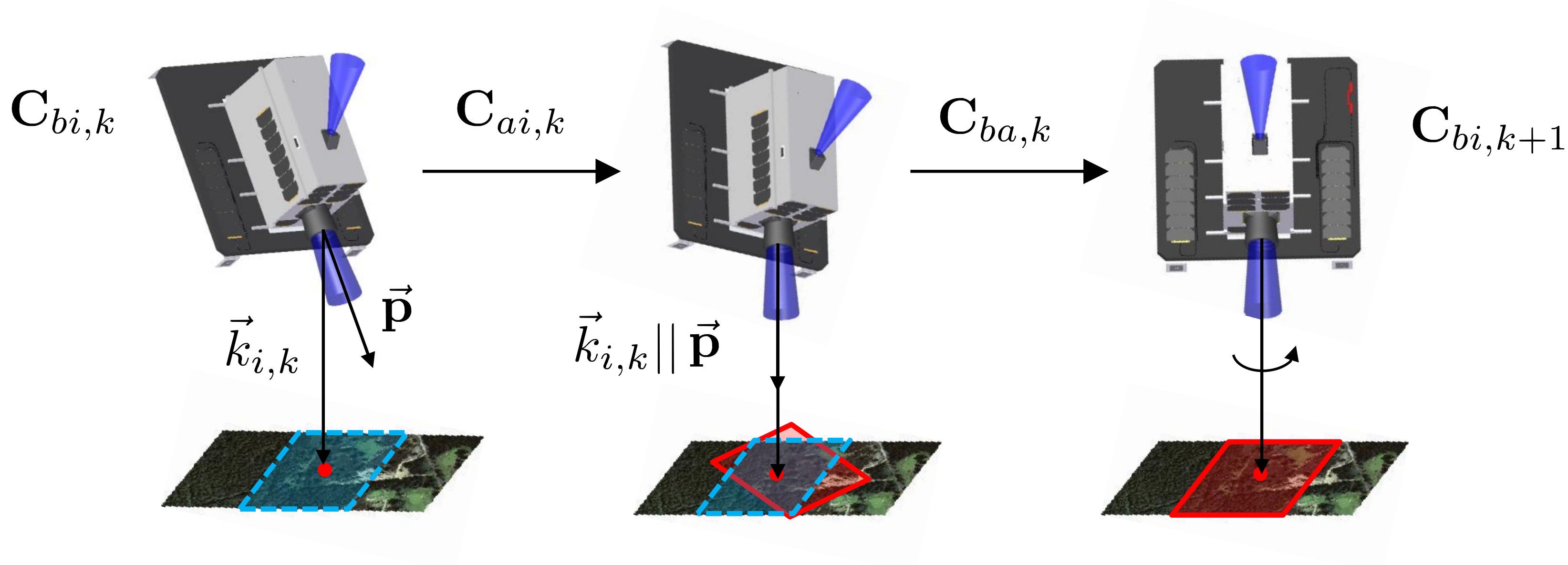
To design a technology that improves the current pointing performance of SFL's terrestrial target tracking spacecraft by allowing the ACS subsystem to run at frequencies above 1Hz.

Proposed Solution:

- To implement a combination of star tracker and high-grade FOG running at high cadence.
- Modify our existing attitude determination algorithms to account for additional gyro states.

GUIDANCE & NAVIGATION

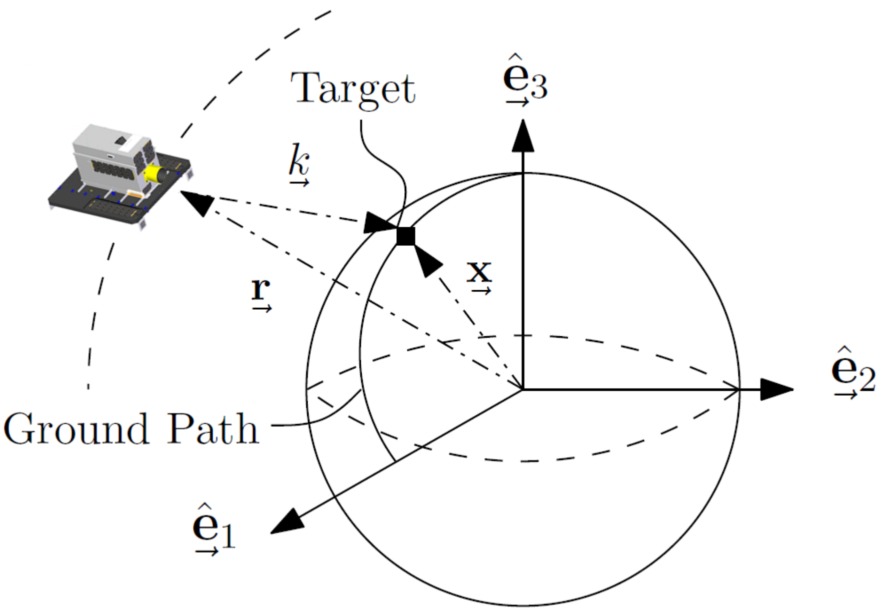
Trajectory Construction: Slew Maneuver



Initial orientation → Payload boresight alignment → Imaging Constraint

Trajectory Construction: Orbital Parameters

- Position and Velocity at t_k and t_{k+1} are obtained in the ECEF and converted into ECI coordinates to be used in the navigation model.



Pointing Geometry as Observed in a non-rotating ECEF Frame

$\underset{\rightarrow}{\mathbf{x}}$: Target Position Vector

$\underset{\rightarrow}{\mathbf{r}}$: Satellite Position Vector

$\underset{\rightarrow}{k}$: Satellite-To-Target Vector

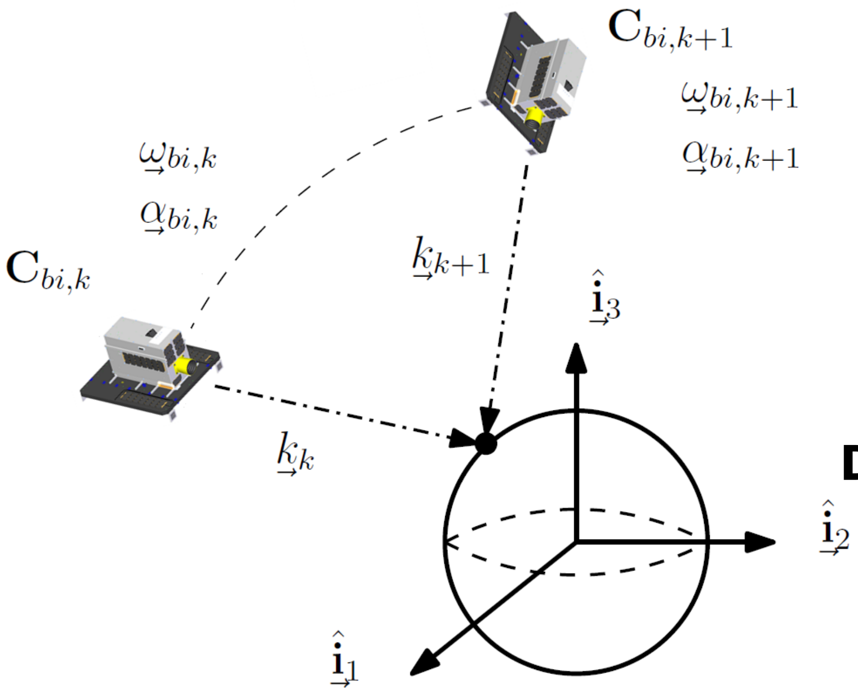
$$k_{e,k} = \mathbf{x}_e - \mathbf{r}_{e,k}$$

$$k_{i,k} = \mathbf{C}_{ie,k}(\mathbf{x}_e - \mathbf{r}_{e,k})$$

$$k_{i,k+1} = \mathbf{C}_{ie,k+1}(\mathbf{x}_e - \mathbf{r}_{e,k+1})$$

Trajectory Construction: Desired Attitude and Rates

- Desired attitude, body rates and angular accelerations can be constructed based on position and velocity.



Target Tracking Trajectory at Discrete Timesteps

Inertial-To-Body Attitude:

$$\mathbf{C}_{bi,k} = \mathbf{C}_{ba,k}\mathbf{C}_{ai,k}$$

Desired Angular Rate:

$$\underset{\rightarrow}{\omega}_{bi,k+1} = \underset{\rightarrow}{\omega}_{ba,k} + \underset{\rightarrow}{\omega}_{ai,k}$$

Desired Angular Acceleration:

$$\underset{\rightarrow}{\alpha}_{bi,k+1} = \underset{\rightarrow}{\alpha}_{ba,k} + \underset{\rightarrow}{\alpha}_{ai,k}$$

ATTITUDE DETERMINATION

Attitude Determination: Overview

State Vector

Original: $\mathbf{x} = [\boldsymbol{\omega}_{bi}^T \quad \mathbf{q}_{bi}^T]^T$

To: $\mathbf{x} = [\boldsymbol{\omega}_{bi}^T \quad \mathbf{q}_{bi}^T \quad \boldsymbol{s}_g^T \quad \boldsymbol{b}_g^T]^T$

where,

$\boldsymbol{\omega}_{bi} \in \mathbb{R}^3$: spacecraft body rate

$\mathbf{q}_{bi} \in \mathbb{R}^4$: attitude quaternion

$\boldsymbol{s}_g \in \mathbb{R}^3$: gyro scale factor

$\boldsymbol{b}_g \in \mathbb{R}^3$: gyro bias

Measurements

Interoceptive:

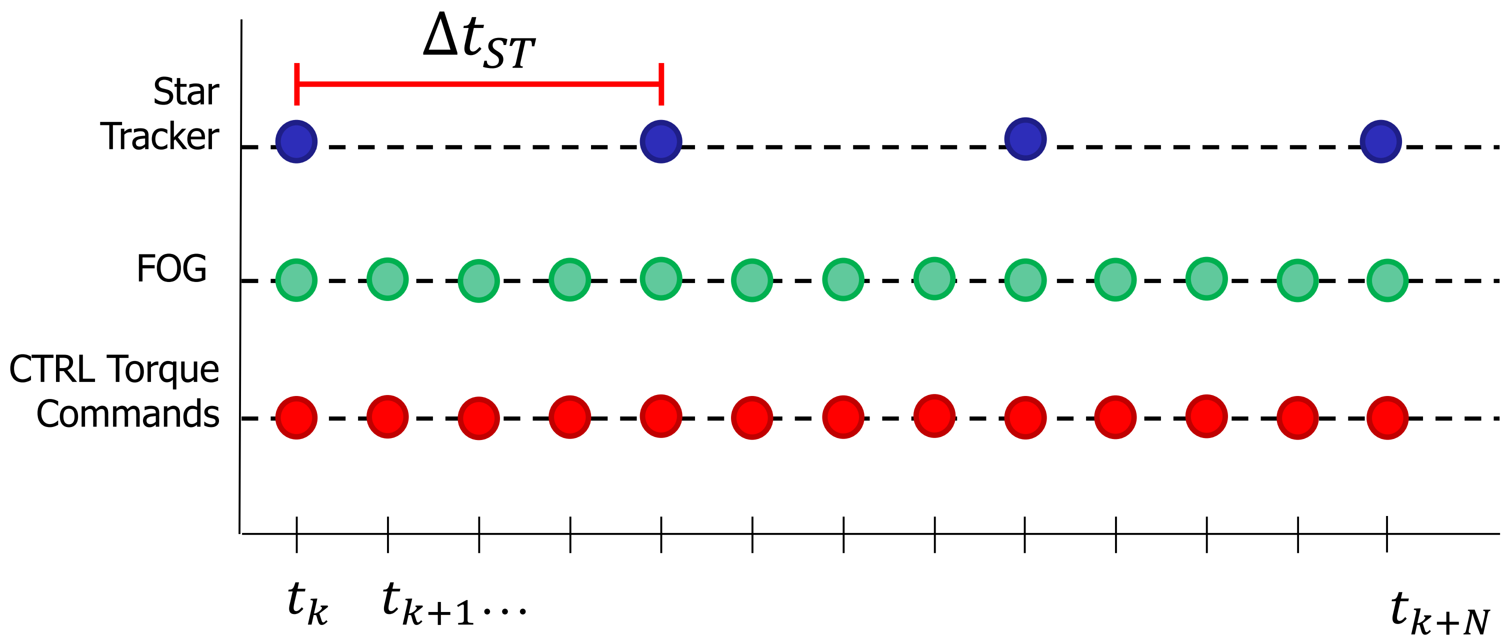
- Reaction Wheel Torques
- Environmental Disturbances

Exteroceptive:

- Star Tracker Quaternions
- FOG Angular Rates

Note: Measurement vector changes size depending on which sensors are reporting values (star tracker, FOG, or both)

Attitude Determination: State Propagation



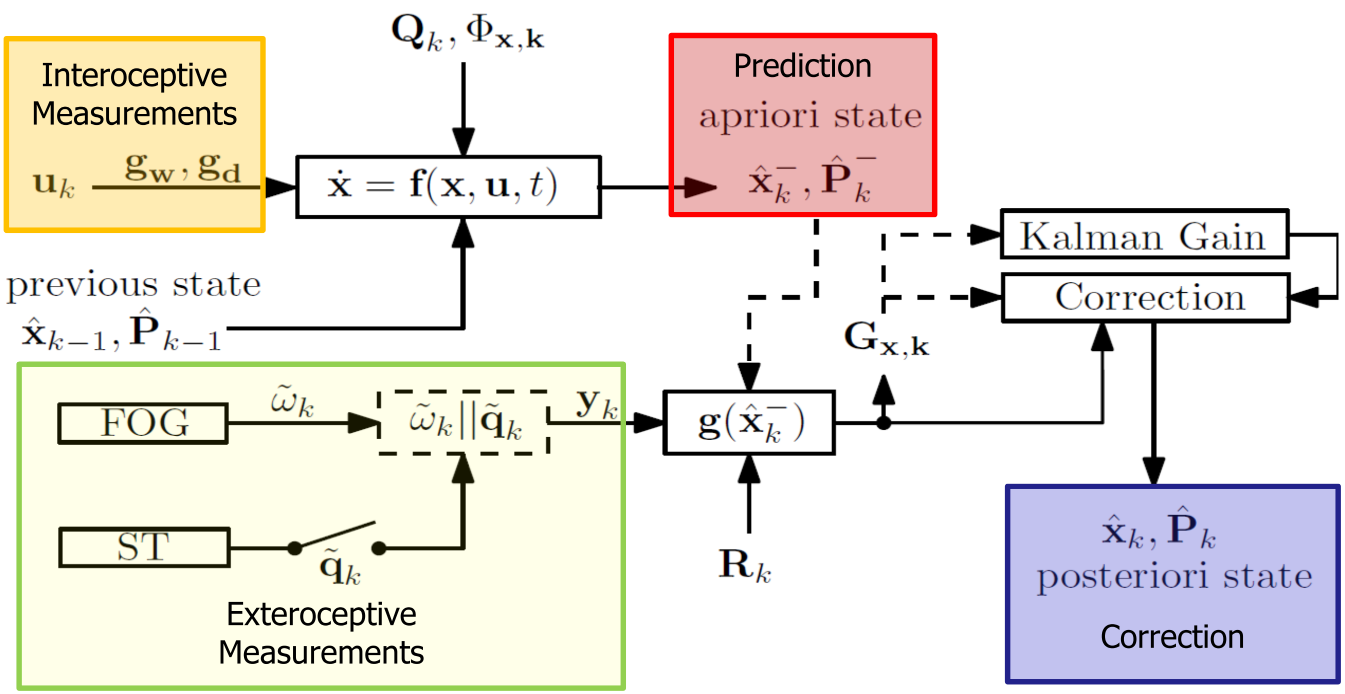
State Propagation using FOG only

Filter Initialization (ST + FOG)

Notation:

Δt_{ST} : Star Tracker Exposure Time
t_k : Simulation Time

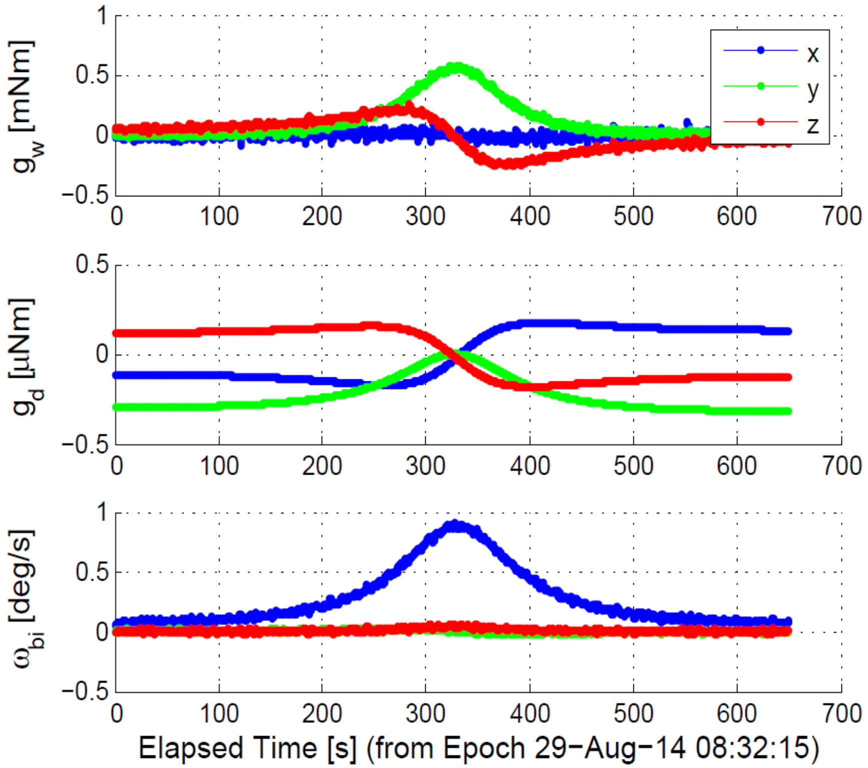
Attitude Determination: EKF Architecture



TERRESTRIAL TARGET TRACKING SIMULATIONS

Target Tracking Simulation: Overview

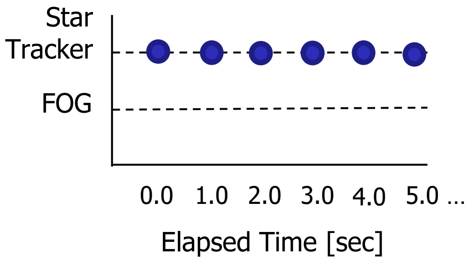
- 500km sun-synchronous orbit
- Total duration is 650 seconds
- Epoch: 29-August-2014 [08:32:15 UTC]
- Peak angular velocity of ~0.8°/s directly overhead%
- Control torques, disturbances and true body attitude/rates generated using SFL's high-fidelity simulator.
- Torques are used as interoceptive measurements in the EKF.
- True attitude/rates are perturbed with noise in sensor models to simulate exteroceptive measurements.



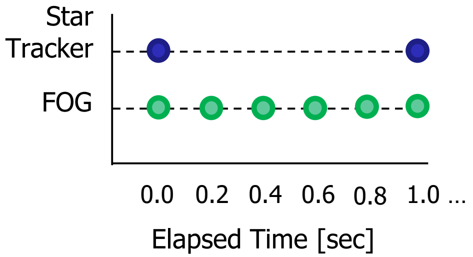
Top to Bottom: Reaction wheel torques, disturbances, and body rates.

Attitude Determination Cases

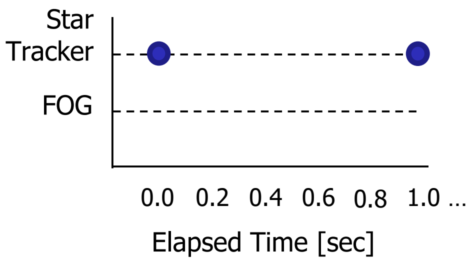
- **Case 1:** Simulation runs at 1Hz, single star tracker sampling at 1 Hz (current method used in orbit).



- **Case 2:** Sensor fusion using FS-EKF, simulation runs at 5Hz, star tracker at 1Hz, and fiber optic gyro (FOG) at 5Hz.



- **Case 3:** Simulation runs at 5Hz, and star tracker at 1Hz (open loop approach). No FOGs.

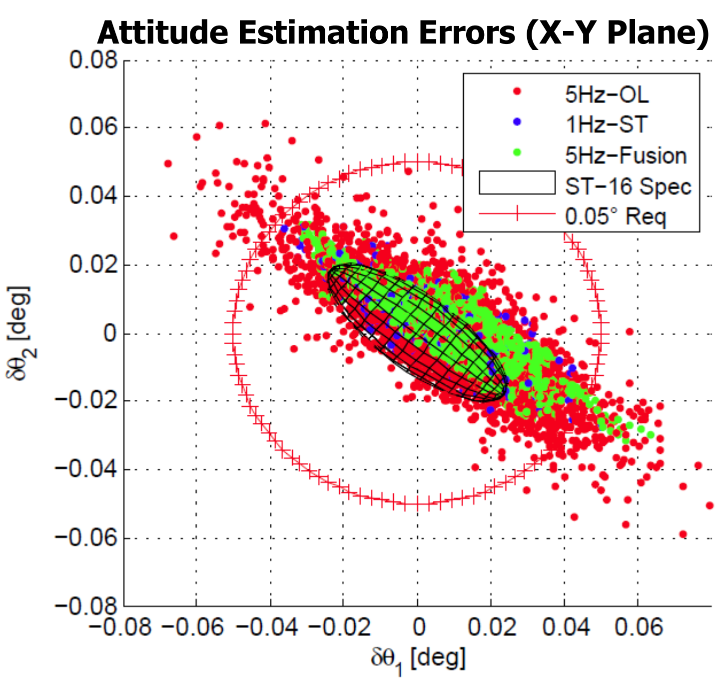


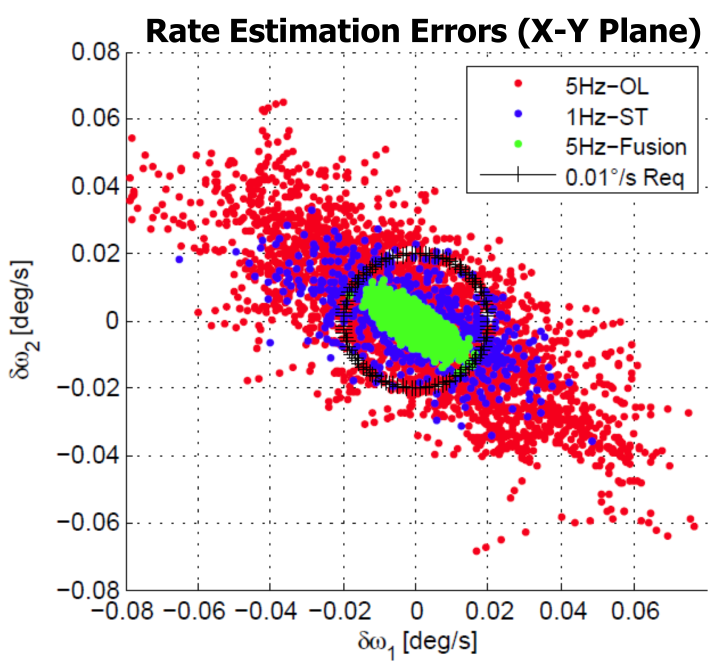
Attitude Determination: Preliminary Results

- Rate estimation errors using FS-EKF are within the 0.01°/s req. circle 100% of the time.
- Slightly better attitude estimates. Overall fusion approach offers better attitude estimates than ST-only solution.
- 5Hz star tracker-only open loop solution resulted in the worst estimation out of all cases.

RMS Attitude & Rate Estimation Errors (over 650 seconds)

Error Type	RMS Attitude Error [°]			RMS Rate Error [°/s]		
	$\delta\theta_x$	$\delta\theta_y$	$\delta\theta_z$	$\delta\omega_x$	$\delta\omega_y$	$\delta\omega_z$
1Hz-ST	0.016	0.010	0.004	0.017	0.011	0.009
FS-EKF	0.016	0.010	0.002	0.005	0.004	0.002
5Hz-OL	0.002	0.022	0.006	0.027	0.021	0.011





Conclusion & Future Work

- A fiber optic gyro-based attitude estimation scheme has been proposed to allow the controller on-board NEMO-class target tracking satellites to command torques at ≥2Hz to improve pointing performance.

Future work: The modified Kalman filter (FS-EKF) will be implemented in the loop with the controller to demonstrate that the control pointing accuracy can be reduced substantially and bounded well below 0.3° (2-σ).