Realistic Operational Modeling for a Spin Stabilized CubeSat: Challenges and Anticipated Control Performance

❖Science
❖ Technology
❖ Applications
Bringing It All Together

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Abstract

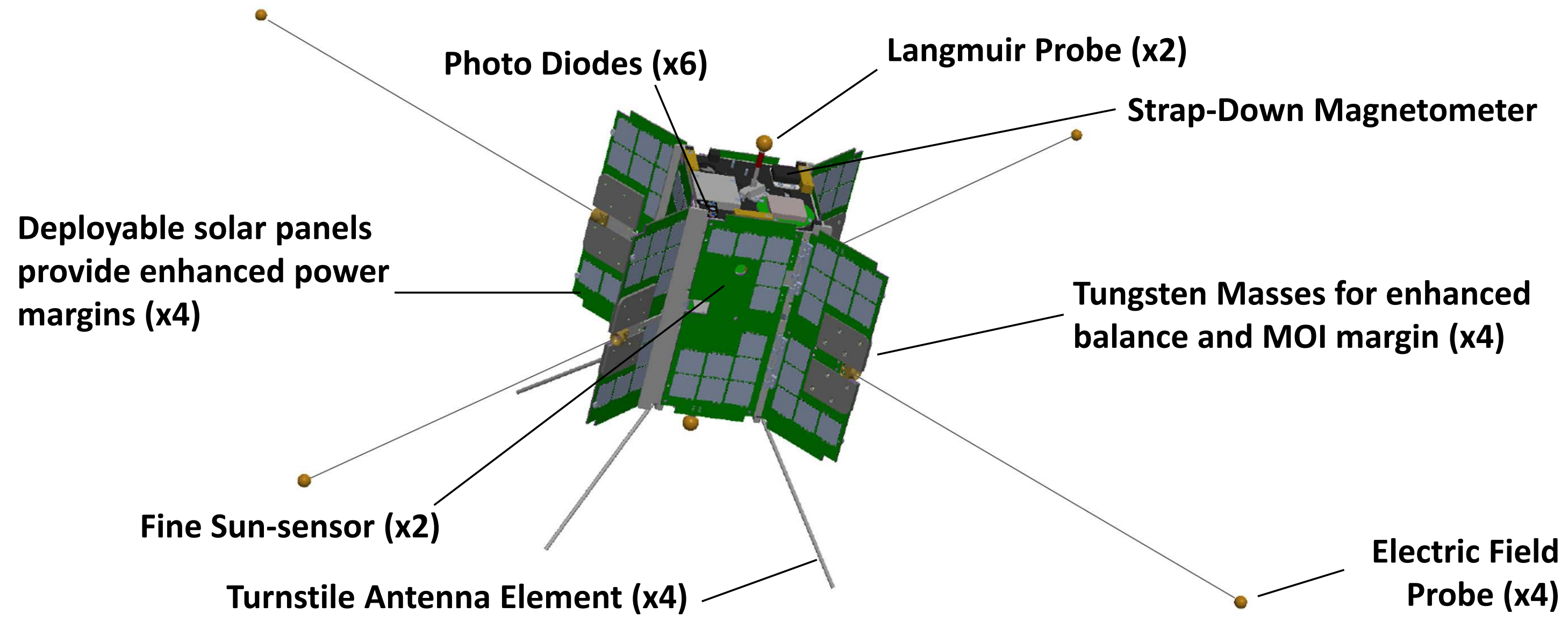
Recently, ASTRA LLC. has teamed with the Space Dynamics Laboratory of Utah State University to design a 1.5U CubeSat system for measuring electric fields. Such a system requires 2-axis control and relatively high spin-rates. The spacecraft is called the Double-probe Instrumentation for Measuring Electric-fields (DIME) SensorSat and is funded by the Air Force Research Laboratory SBIR program. In order to design and test control algorithms and verify requirements, ASTRA has developed a modeling-tool for a CubeSat 2-axis control system. First, a brief overview of the DIME SensorSat and attitude system is provided and the DIME attitude requirements are introduced. Next the operational attitude model is discussed followed by simulation results for the various operational phases of a spin-stabilized CubeSat. Finally, we present some anticipated challenges and related simulations for a spin-stabilized CubeSat.

Introduction

The 2-axis modeling tool presented here takes into account the use of noisy data, non-rigid hardware, realistic software implementation and computer hardware limitations, environmental torques, power system-attitude feedback, as well as a ground-segment operations and control simulator. The goal of the modeling is to demonstrate operational scenarios in which a CubeSat spinner is feasible given the power and hardware constraints. Throughout the poster, the DIME SensorSat is used as a representative design reference mission. The mission requirements and the satellite itself are described in the following two sections.

Double-probe Instrumentation for Measuring Electric–fields (DIME)

The DIME SensorSat (see Figure below) design incorporates lessons learned from DICE mission operations [Fish et al. Space Sci Rev, 2014]. The CubeSat is capable of deploying flexible electric field booms up to a distance of 10-m tip-to-tip. This is accomplished from the volume envelope of a 1.5U CubeSat, or 10x10x15cm. The satellite will measure AC and DC electric fields, ion densities, and magnetic fields to characterize the performance of the sensor in different plasma environments. The DIME SensorSat recently underwent a successful CDR and is currently being built at USU/SDL with assistance from ASTRA. Since DIME is a risk-reduction mission, we plan to deploy the wire booms to 3 meter (6 meter tip-to-tip) lengths which will require pre-deployment spin rates of 1.5Hz. The box below lists the actuators and sensors used on DIME along with their placement and relationship to the spacecraft body frame. Note that the z-axis is the direction of nominal spin. Below that are the DIME mission objectives.

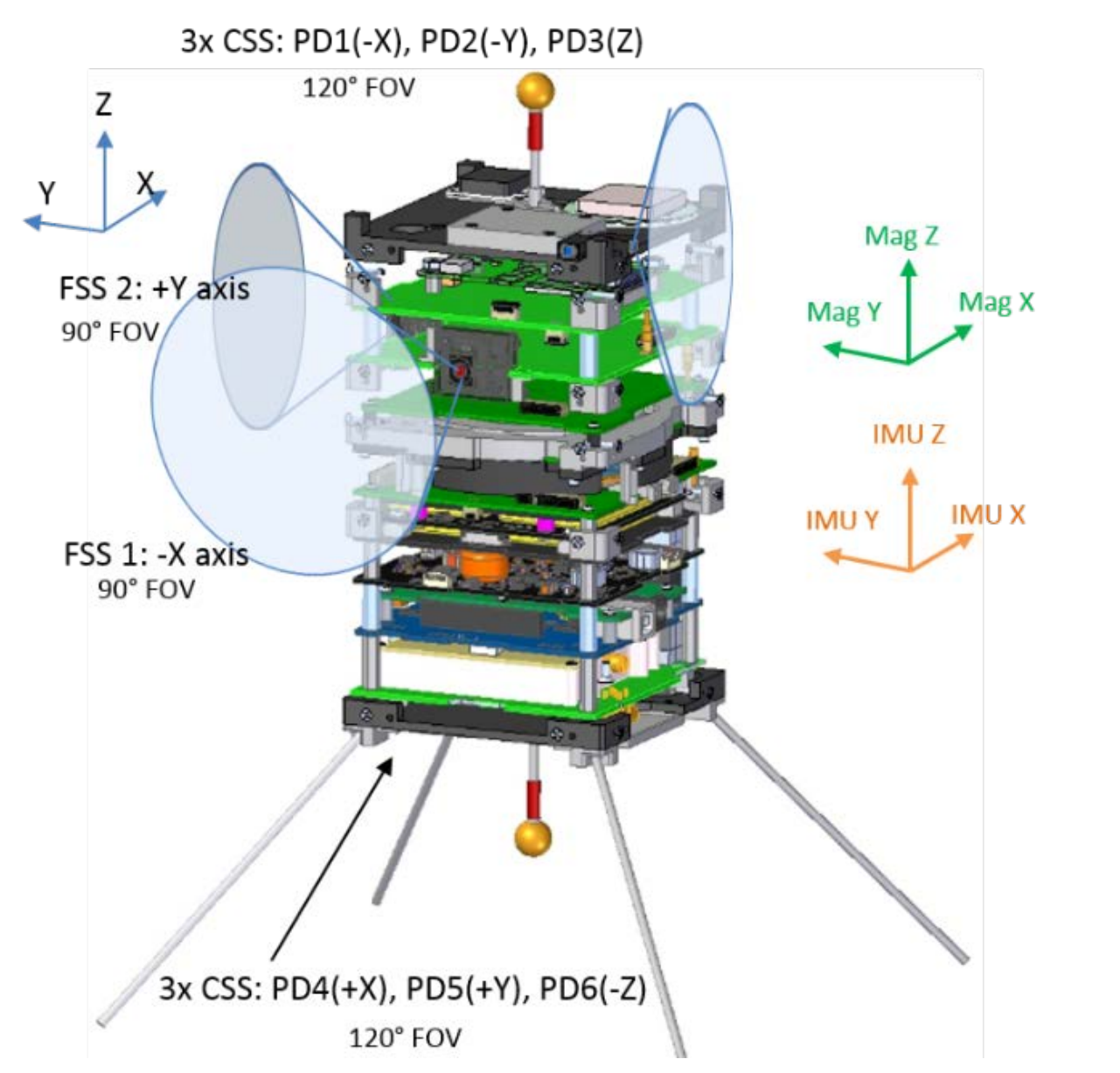


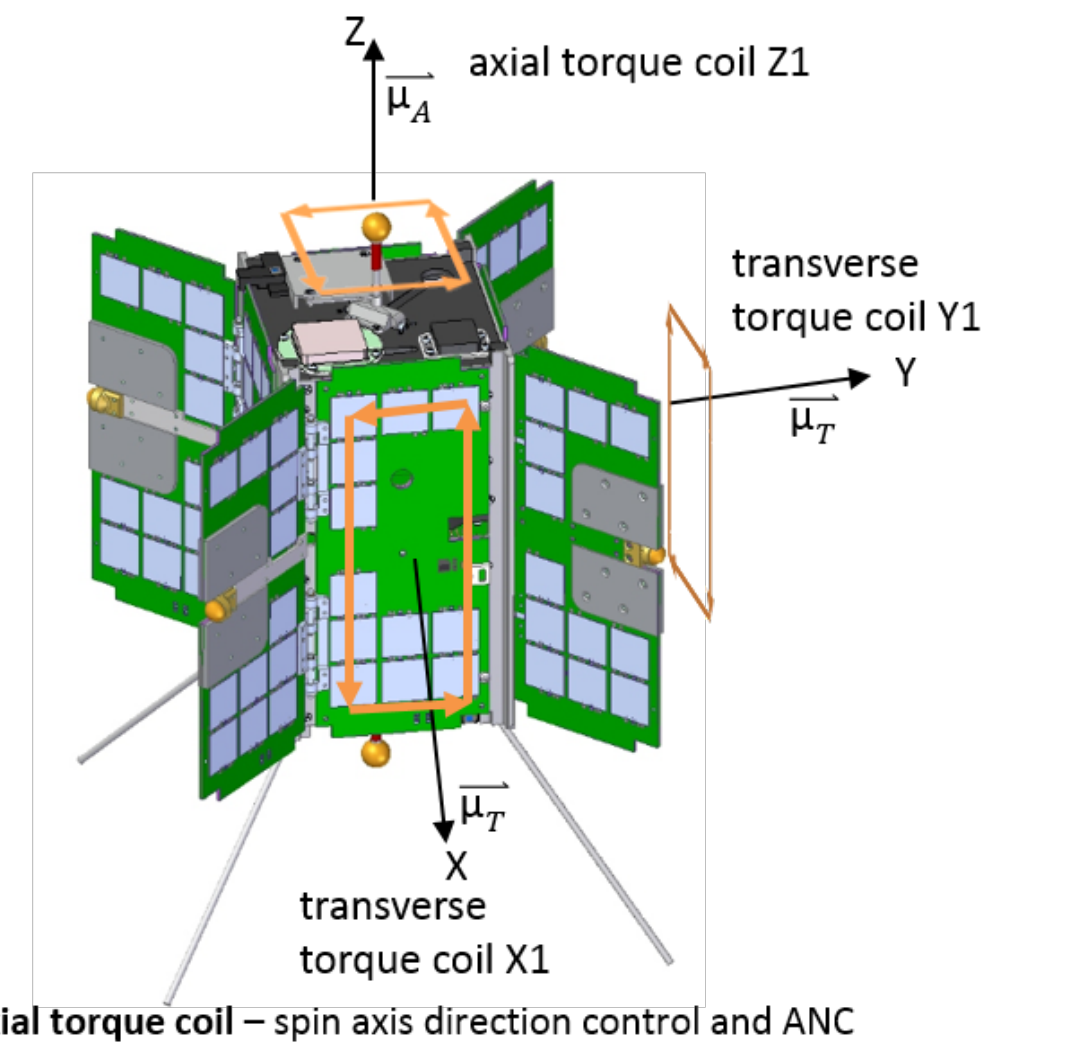
Subsystem Architecture: Major Axis Spinner

- Ultimate gyroscopic stability obtained through s/c spin and careful balance and design
- Deployable mass-trim (X-wings)
- Passive nutation damping from deployed booms
- 5x torque coils
  - – 4x redundant transverse torquers
  - – 1 axial torquer
- Open-Loop alignment
- Closed-loop spin rate control and nutation damping

Determination Architecture

- 2x sun-sensors (transverse direction) –*DICE Heritage*
- 6x photo-diodes provide rough attitude knowledge – *RAX Heritage*
- Solid-state IMU for
  - – nutation determination
  - – Spin rate knowledge during commissioning
  - – Nutation control algorithm inputs
- Magnetometer– *DICE Heritage*
- Ground determination software: Spin Axis Orientation, Z Spin Rate, Nutation Angle, Phase Angle





Axial torque coil – spin axis direction control and ANC

Transverse torque coils – spin rate control
Two for each direction:
1-Corresponds to the coil on the positive side of its respective axis,
2-Corresponds to the coil on the negative side of its respective axis

Primary Mission Objective for DIMEsat: Measure ionospheric electric-fields using a wire-boom double-probe on a spinning CubeSat platform.

Minimum Success Criteria:

a) Deploy E-field booms, verify deployment

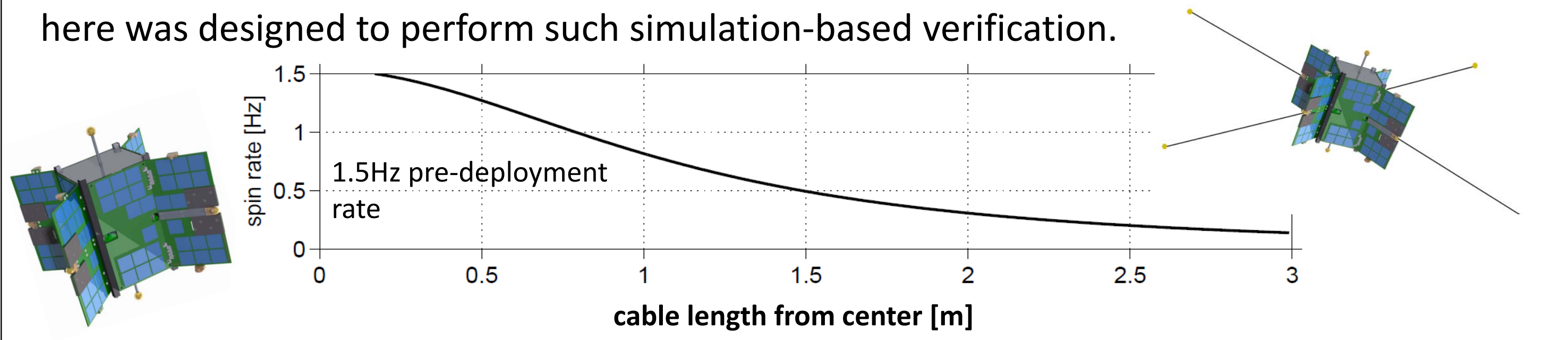
b) Collect on orbit and download 50,000 minutes of E-field data*

**over a 3 month period of time, we expect a much longer data collection period*

DIMEsat Spinning CubeSat Attitude Requirements

The objective of the DIME ADCS is to spin-up to rates between 1.0 Hz and 1.5 Hz and align to geodetic north. This flows directly from the mission objectives as well as from the boom-deployment simulation. The figure below shows a simulation of z-body rates during deployment of the long cable booms as well as the spacecraft before and during boom deployment. An initial rate of 1.5 Hz is required for 3-m boom lengths.

The table on the right summarizes the salient requirements for the DIME ADCS system. Note that several requirements are verified by simulation. The model presented here was designed to perform such simulation-based verification.



Parameter	Requirement			Spec.*	Verification	Margin**	Notes
Max spin rate	≥	1.10	Hz	3.00	Simulation	>100%	post-deployment rate of 0.09Hz, goal: 2.2Hz -> 0.18Hz
Rigid deployable first mode	≥	10.40	Hz	15.00	Analysis	44%	-> to structures
Alignment to geodetic north	≤	10.00	deg	3.00	Simulation	70%	
Post E-field-boom deployment spin rate	≥	0.05	Hz	0.19	Simulation	>100%	
Spin axis orientation and phase error	≤	0.45	deg	0.41	Sim. &Test	9%	knowledge requirements
Nutation angle knowledge	≤	0.05	deg	0.03	Sim. & Test	40%	spec at 1Hz. This flows to the IMU angulare rate error
Sensor sampling for onboard algorithms	≥	25	Hz	50	Test	100%	
Controller false detection rate	≤	20	%	5	Sim. & Test	75%	at rates between 0.5°/s to 3Hz
Telemetry rate	≥	8	Hz	10	Inspection	25%	
Largest MOI ratio	≥	1.20	V	1.21	Test	n/a	
Nutation (dynamic disturbances)	≤	0.1	deg	0.03	Sim.	70%	
CG offset (pre-deployment)	≤	3	mm	1	Test	67%	
Major axis offset to spacecraft Z	≤	1	deg	0.5	Test	50%	
Transverse torquer moment	≥	0.12	Am^2	0.150	Test	25%	
Axial torquer moment	≥	0.17	Am^2	0.179	Test	5%	

* Current Best Estimate
** Margin% = |[Requirement - Specification]|/|[Requirement]| * (100)

The Operational Attitude Model

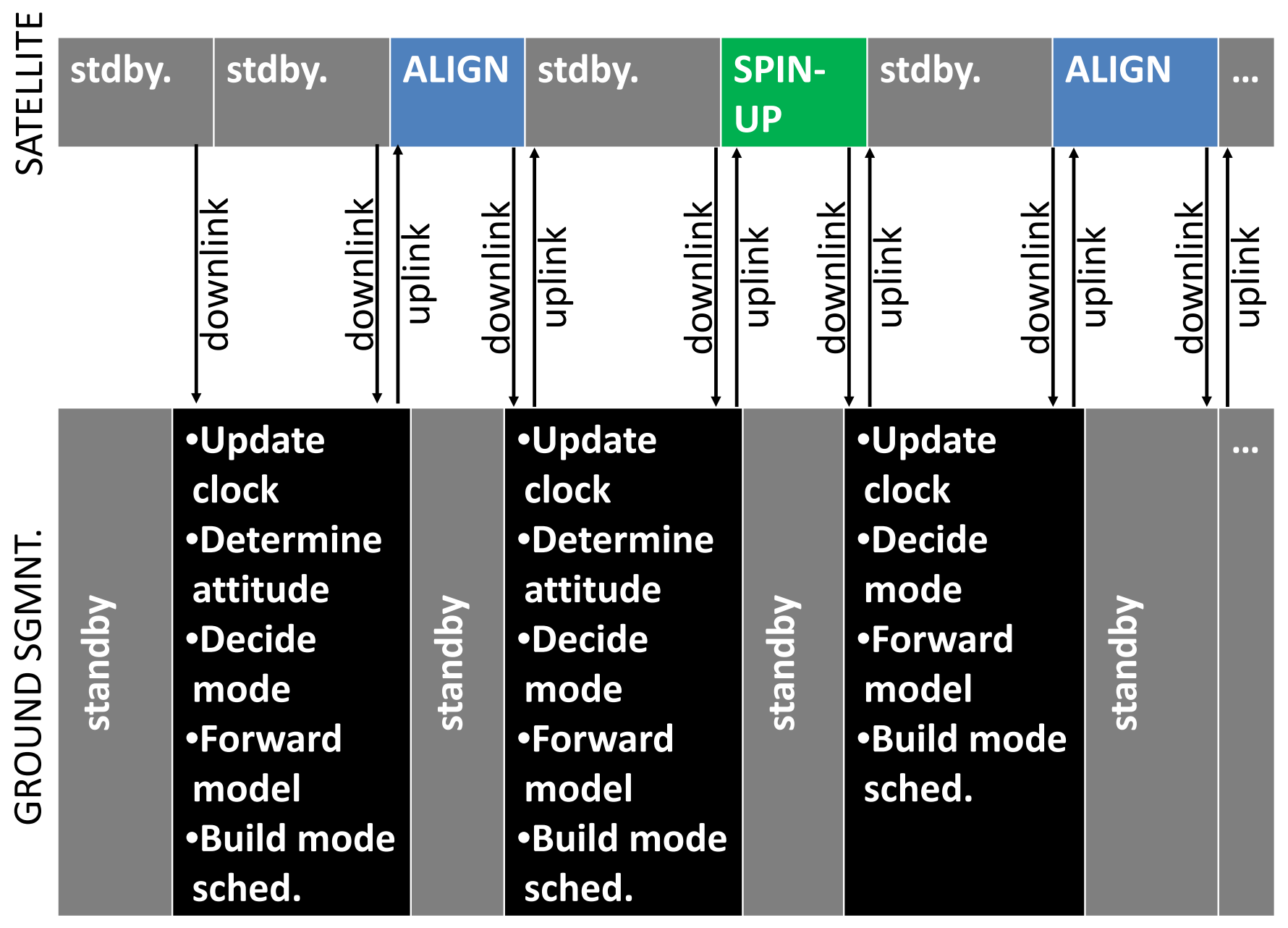
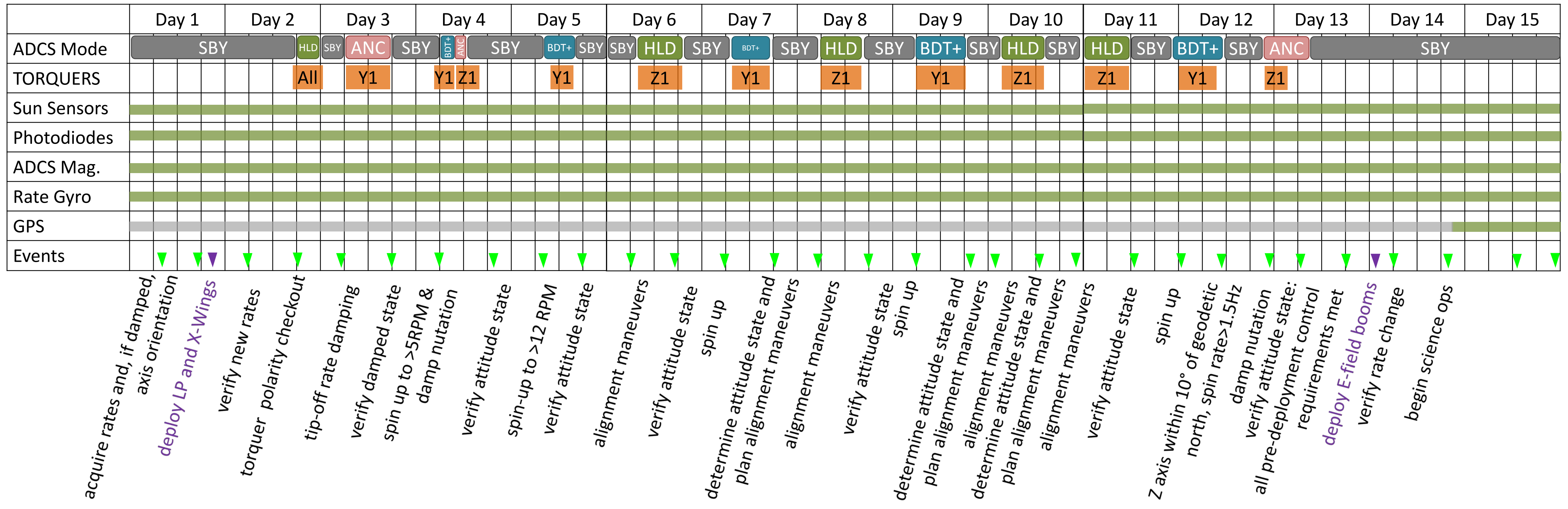


Figure 1: Quasi open-loop method. Ground operations and spacecraft control occur in series.

Figure 2 (below): Operational scenario for the DIME spacecraft. The spacecraft is in standby (grey boxes) during ground-control processing.



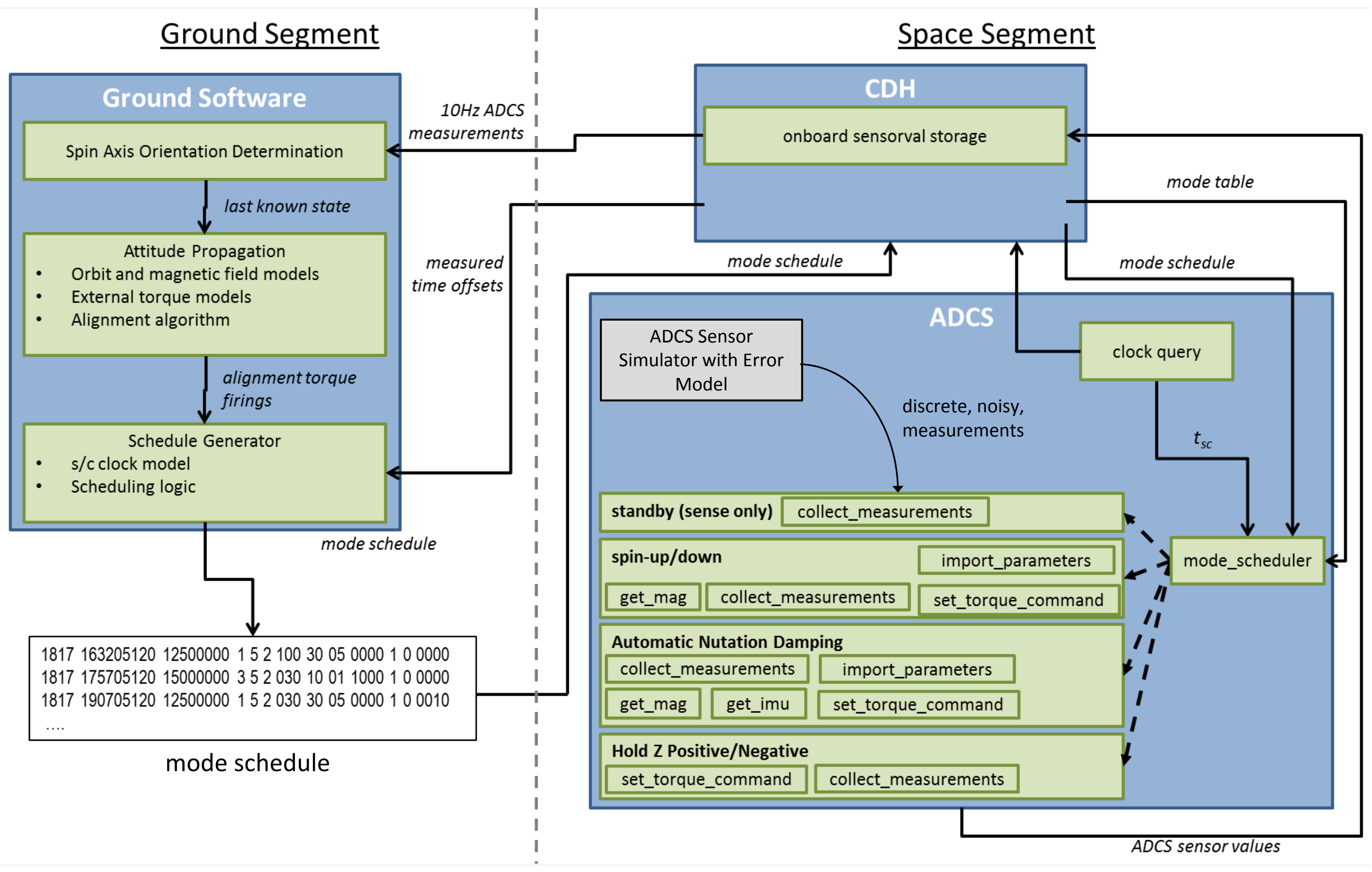


Figure 3: Our model couples the space-segment and ground-segment simulations. Noisy data is downlinked to the ground segment which simulates attitude determination and runs a forward model to determine control commands based on the results. The control commands are then passed to the spacecraft simulation during the next available pass.

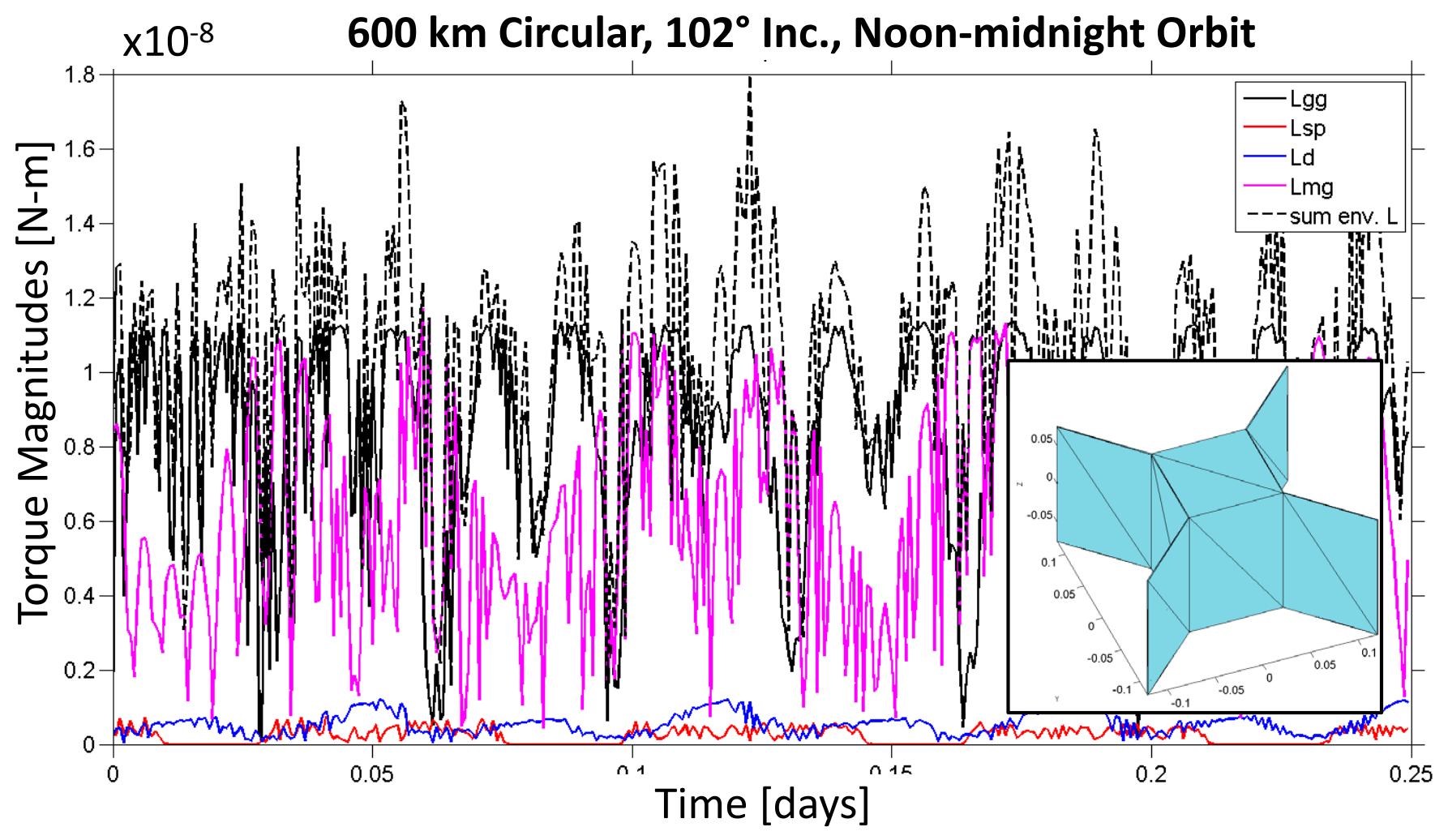


Figure 4: The model represents environmental torques including gravity gradient (Lgg), solar radiation pressure (Lsp), atmospheric drag (Ld), magnetic moment (Lmg), and eddy current (not shown). Lsp and Ld are modeled using a plate geometry like that shown in the lower right which can be imported from CAD software.

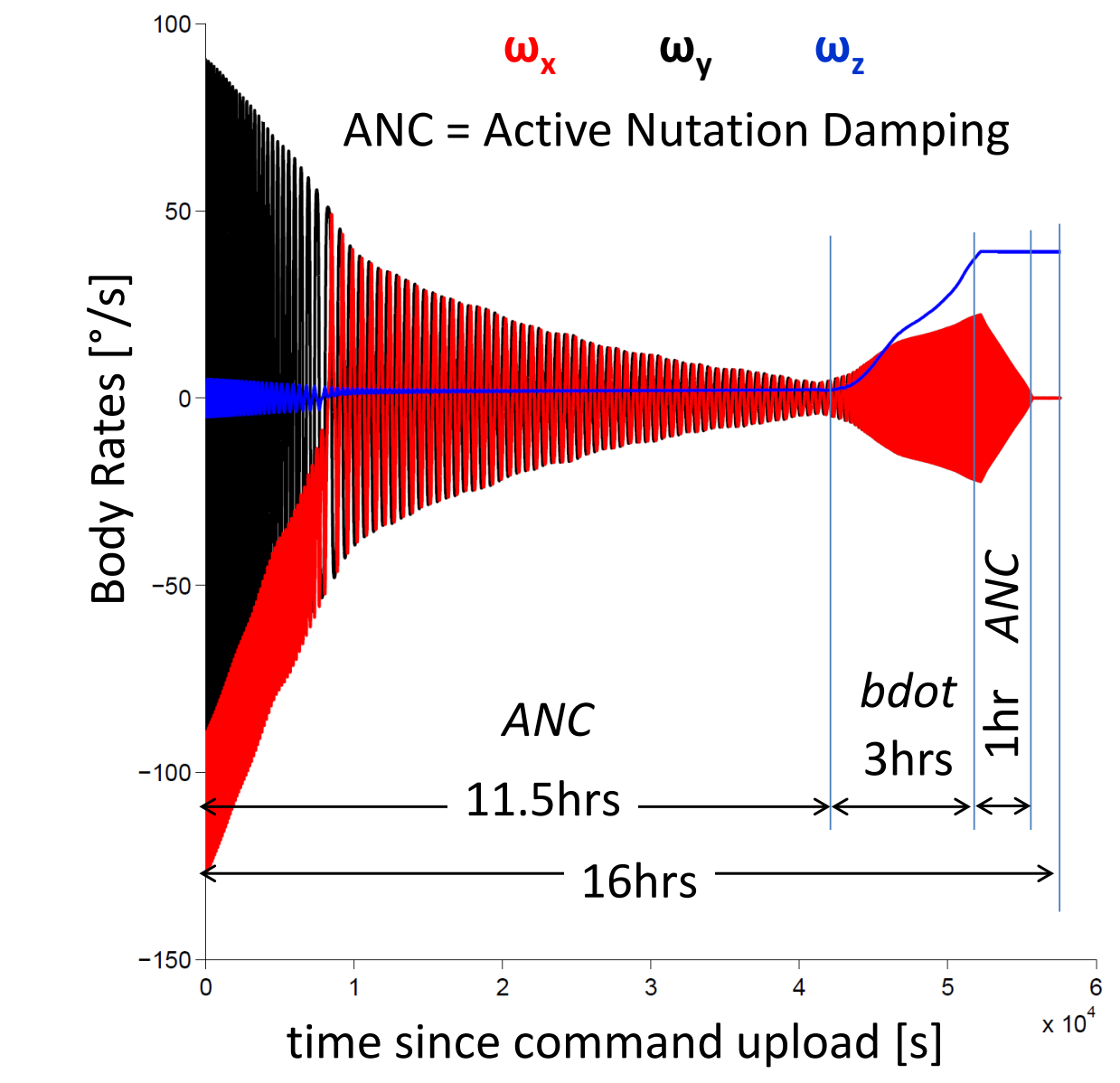


Figure 5: Initial tip-off rate damping and z-axis spin-up demonstrates commissioning and control authority.

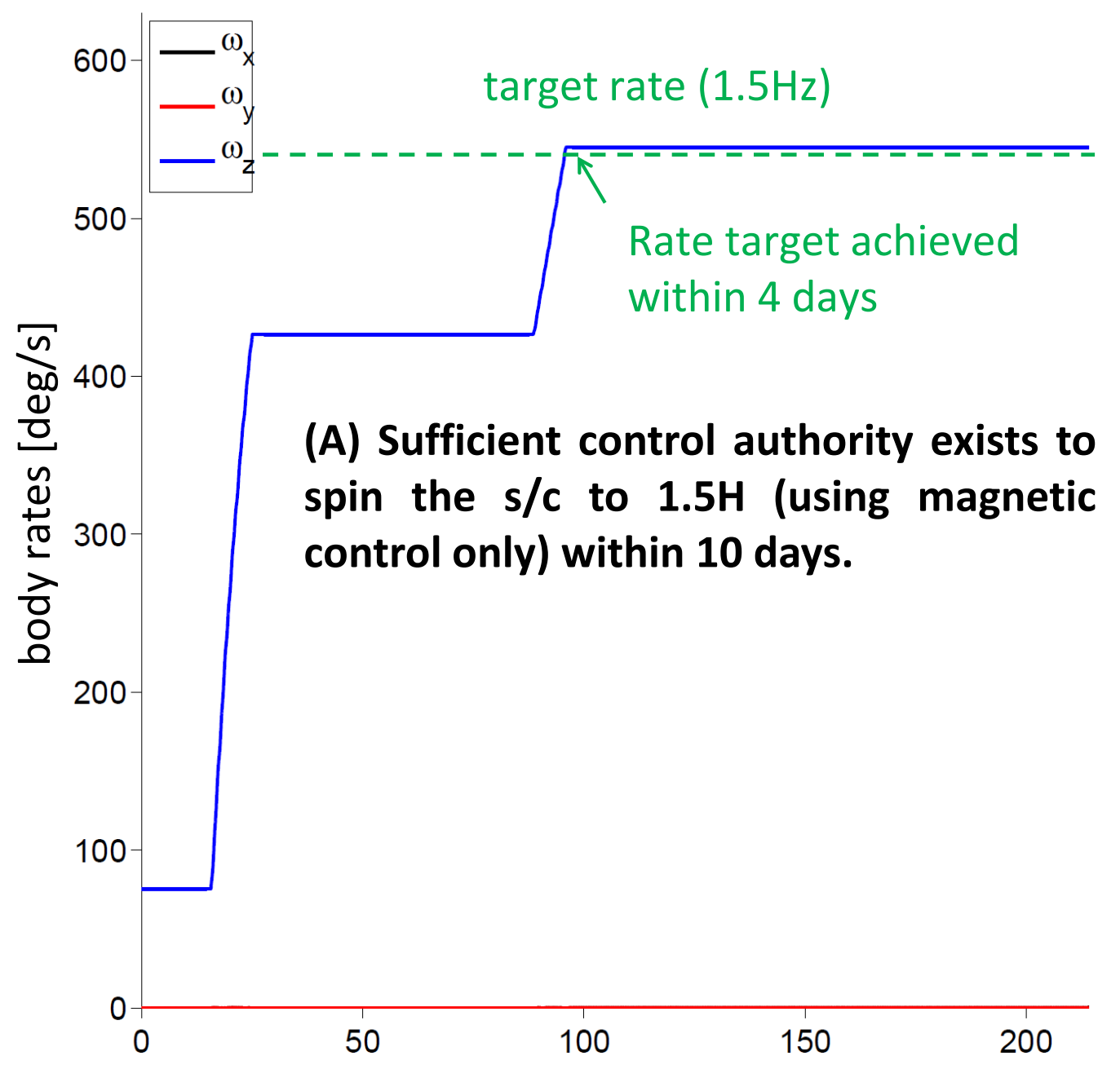
The ADCS model was designed to simulate control schemes wherein the ground system is in the loop. This is the case for the DIME “keep-it-simple” ADCS. The ground-in-the loop methodology is explained by Figure 1. Figure 2 shows an example implementation of this architecture for a 15 day commissioning phase. Figure 3 illustrates the operational attitude model design. Figure 4 shows environmental torque model outputs for a 600 km orbit. An example of simplified DIME geometry used to generate body torques is inset. Figure 5 demonstrates the results of initial de-tumble and z-axis spin up.

A sensor error model provides simulated measurements for the control algorithms. It includes stochastic error sources as well as systematic ones such as sensor-alignment uncertainties. This allows for the evaluation of post-processed attitude solutions.

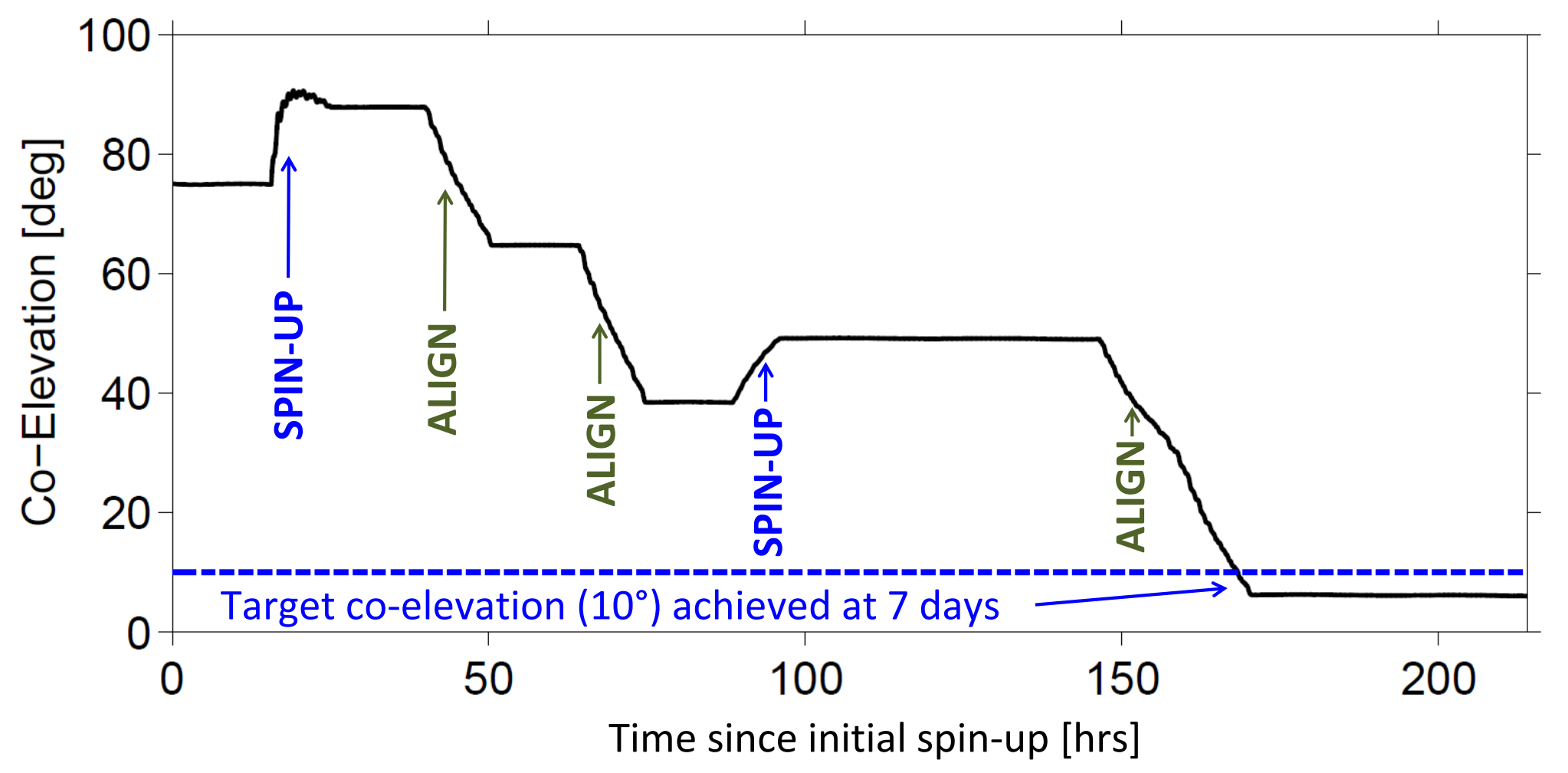
Ten-Day Simulation: Challenges and Performance Summary

Challenges for 2-axis, magnetic, ADCS operations on a CubeSat lead to complicated questions about performance. These questions can be evaluated using our model:

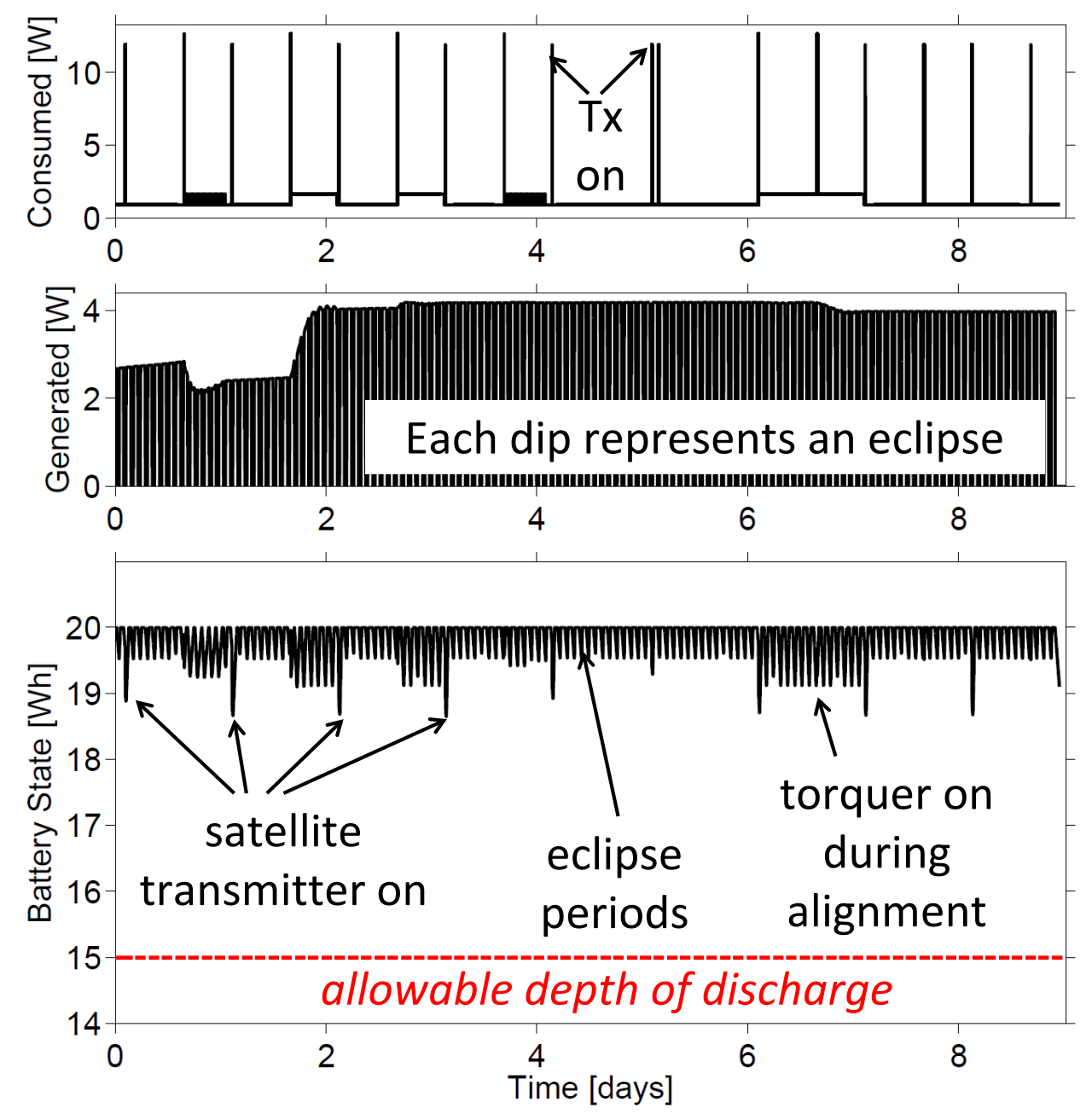
(A) Does the CubeSat have enough control authority to spin up to 1.5Hz?
(B) Is there sufficient authority and sensor-sampling to align within 10 degrees of geodetic north?
(C) Can the CubeSat power system support ADCS operations even though the angle to the sun may be changing?



(A) Sufficient control authority exists to spin the s/c to 1.5H (using magnetic control only) within 10 days.



(B) Given the environmental torques and increased inertial stiffness at higher rates, the spacecraft can still perform successful alignment maneuvers in open-loop mode. Note that co-elevation is the control error in this case. Control error increases during spin-up maneuvers because transverse torquers have a tendency to align the CubeSat spin perpendicular to the magnetic-field.



(C) Coupled power simulation indicates nominal depth of discharge through ADCS operations.

Conclusion

Realistic operational modeling of a spinning CubeSat and its ground-segment was presented. This modeling provides mission designers an effective tool for assessing the performance of open-loop control as well as ground and space system interactions. The tool has allowed us to demonstrate the feasibility of a low-cost and robust method of CubeSat attitude control using a 2-axis architecture.

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