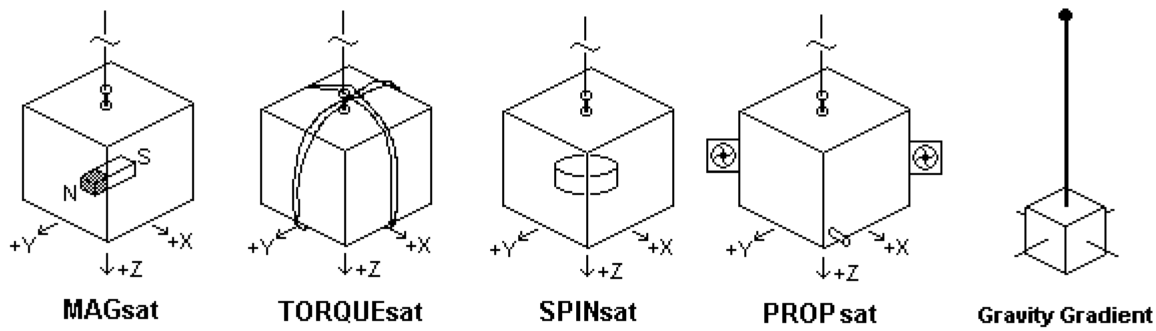
EA-467 ATTITUDE CONTROL LAB (rev g) Fall 2008

Introduction: This is the third/final part of the Attitude Dynamics and Control series. The first portion computed and then measured the spacecraft's moment of inertia. The second lab demonstrated three methods for attitude estimation. This lab will use the LABsats to demonstrate as much about attitude control that we can achieve in the lab, in air and in a 1 G environment. By hanging the LABsats on a string, we can show the principles involved in 4 out of 5 of the attitude control methods shown below.



Lab Coordinate Frame: The room coordinate frame is designated as North-East-Down (NED), and is shown below. The LABSat XYZ coordinate frame is also shown. The NED frame is represented under each LABsat by the turntable and compass rose we used in the Estimation Lab. The LABsats are suspended on a string for minimum reaction torque. In all parts of this lab, we will ignore the damping torque, and only consider the string torque as the disturbance.

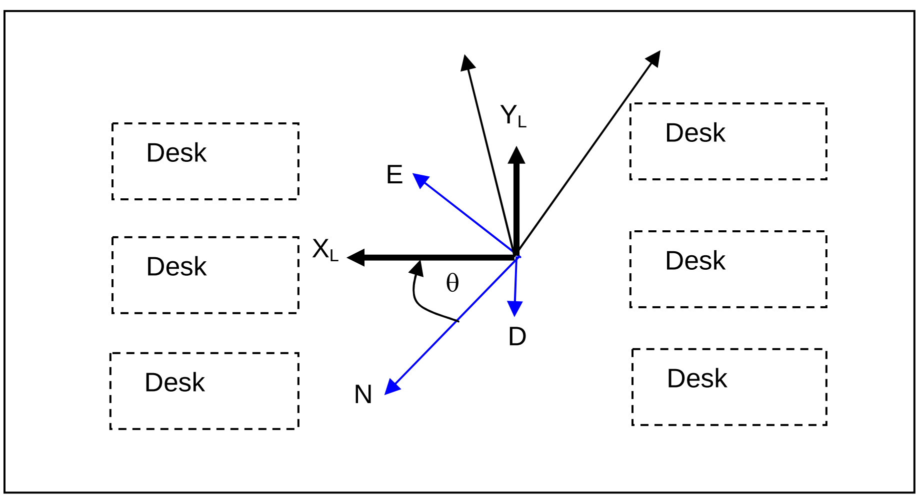
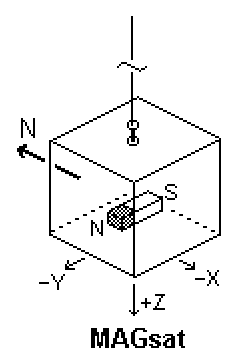


Figure 1. LABsat Coordinate Definitions

Part A: MAGsat Passive Magnetic Stabilization:



This experiment uses passive magnetic stabilization to keep one axis of the satellite aligned with the Earth's magnetic field.

1) Each of the LABsats has a pair of passive-magnetic-brackets on the top tray that are oriented orthogonally on the -X and -Y faces. Hang your LABsat on a string and help it to stabilize to the string's neutral point. Place the compass rose under the LABsat and align the disk to Geographic North (311 degrees on the cal point.

2) Adjust the copper hanging-loop on the top of the satellite so that the neutral direction of the LABsat coordinate frame is aligned with the NED frame (+X

pointing to geographic North). Hold the LABsat steady, being careful not to induce any other torques. Place a permanent magnet on the -Y face of your LABsat with the white North-seeking magnet pole west. Hold the LABsat still until you are ready to record data.

3) *Gently* release your satellite and observe the movement of the –Y face towards North. With one person watching the clock and recording, the other should sound out when the LABsat pointer passes 10, 30, 60, 90, 120, 150 and 170. Repeat 3 times to gain confidence in your data.

Post Lab: As you have seen in EA364, the equations of motion for the LABsat are:

$$I_B \dot{\underline{\omega}}_B + \underline{\omega}_B \times I_B \underline{\omega}_B = \underline{T}_{mag} + \underline{T}_{string} = \underline{M}_B \times \underline{B}_B + \underline{T}_{string} \tag{1}$$

Where $\underline{M}_B$ is the magnetic dipole of the magnet, in the body frame, and $\underline{T}_{string}$ is the torque from the string. I_B is the LABsat inertia matrix. The magnetic field vector is transformed from the NED frame to the body frame as:

$$\begin{bmatrix} B_{x,B} \\ B_{y,B} \\ B_{z,B} \end{bmatrix} = C_{B,NED}\underline{B}_{NED} = \begin{bmatrix} \cos(\theta) & \sin(\theta) & 0 \\ -\sin(\theta) & \cos(\theta) & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} B_{x,NED} \\ B_{y,NED} \\ B_{z,NED} \end{bmatrix} \tag{2}$$

where $C_{B,NED}$ is the direction cosine matrix, transforming from the NED frame to the body frame. $\underline{B}_{NED}$ was provided in the estimation lab and θ is the direction of rotation around the Z body axis.

We are only viewing angular velocity in the vertical, or Z body direction. The magnetic moment is along the –Y body direction ($\underline{M}^T = [0 \quad -M \quad 0]$), and the string torque only acts in the Z body direction ($\underline{T}_{string}{}^T = [0 \quad 0 \quad -k\theta]$). The above equation then simplifies to:

$$I_z\ddot{\theta} + k\theta = M(B_{x,NED}\cos(\theta) + B_{y,NED}\sin(\theta)) \tag{3}$$

Or, if the angle, θ, is small (and ignoring the product of $B_{y,NED}$ and the small angle θ)

$$\ddot{\theta} + \frac{k}{I_z}\theta = \frac{M}{I_z}B_{x,NED} \tag{4}$$

The solution to this simplified equation is: $\theta(t) = \frac{MB_{x,NED}}{k}(1 - \cos(\sqrt{\frac{k}{I_z}}t))$ (5)

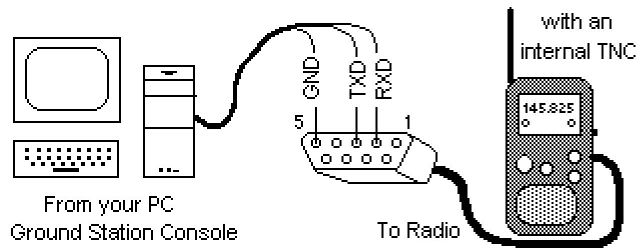
a) Using your first measurement of θ (less than 20 degrees) and the time, estimate M. Using the value of M, use the ODE solver in Matlab to provide the solution for equation (3). Plot the estimated θ and your measured θ to see if they compare. To use the ODE solver, it is easier if you combine the solution for θ and $\dot{\theta}$ into a single derivative expression.

$$\dot{\underline{x}} = \underline{f}(\underline{x}) \qquad \text{where } \underline{x} = \begin{bmatrix} \theta \\ \dot{\theta} \end{bmatrix} \quad \text{and } \underline{f} = \begin{bmatrix} x_2 \\ -\frac{k}{I_z}x_1 + \frac{M}{I_z}(B_{x,NED}\cos(x_1) + B_{y,NED}\sin(x_1)) \end{bmatrix}$$

b) PCSAT-1 has a permanent magnet along its Z axis. Its orbit is nearly polar and 100 minutes. How many rotations in attitude will occur for each orbit of the spacecraft?____ How long will each side face the sun per orbit?___________

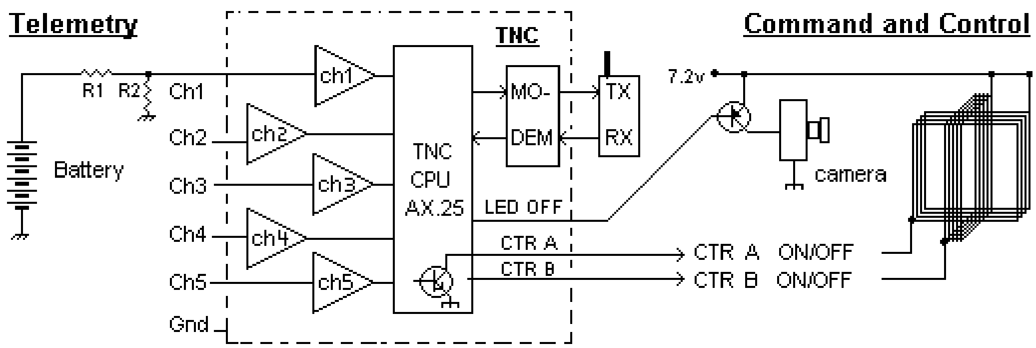
c) If PCSAT-1 had an antenna aligned with its Z axis, and with this stabilization method, approximately what attitude (polarization) will an observer on the ground at the equator see of PCSAT when it crosses the equator? _____

ADCS Spacecraft Command/Control: As before, the LABsat's communicate to your Ground Station on one of the two shared VHF or UHF TDMA channels as in the Telemetry Lab. Each workstation using Hyperterm connects to a ground station Kenwood TH-D7 data transceiver via the RS-232 serial port as shown to the right. Connect your serial port GND to pin 5, TXD to pin 3, and RXD to pin 2.



As you recall, the password protected command system has three ON/OFF commands. The CTR A and CTR B commands can close a circuit of up to 200 mA and LEDS ON/OFF can provide a logic level output. You will use CTR A and CTR B for momentum wheel control or to energize an X or Y magnetic coil or thruster in these experiments. You can use L ON to turn **on** your SPYsat Lens (camera), but be sure to use L OFF to turn it back **off** when not in use to save power. *Watch your battery voltage on telemetry channel 1. Stop if your voltage falls below 6.5 volts (65).*

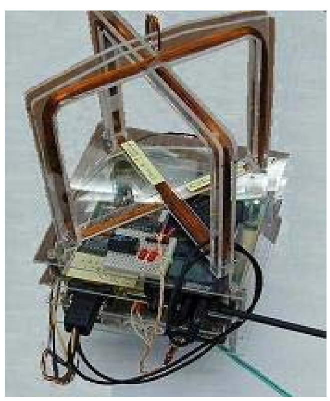
To establish the command link to the spacecraft, you will logon via the password protected command link. To do this, at the ground station "cmd:" prompt, type C COMAND-n for your LABsat-n.



The LABsat responds with three lines of 6 digits that you must match from your "secret" password string ("gonavy"). Select one line and respond with the matching character for the given digits. For example, "g" is for 1, "o" is for 2, etc… Type these 6 characters followed by the ENTER key and if successful, you will get the spacecraft's "prompt:". From the prompt you can send the CTR A/B ON/OFF or pulse commands. In addition, shortcuts CTR ON will turn both on, and CTR OFF will turn both off.

Use these commands to control the momentum wheel in SPINsat and torqueing coils in TORQUEsat. But there are significant delays in the exchange of data and ack's (like the internet or other packet-network), so precise timing is not possible with this command system. Anticipate a second or more delays.

Part B: TORQUEsat Torquing Coils: (we have 2 of these):



TORQUEsat has two orthogonal 20 ohm coils wound from 100 turns of #30 wire operated from the 8 volt bus. Calculate the current in the coil when energized. _______ Measure the area of the coils. Hang the TORQUEsat on the string and using the half-period, compute the I_z moment of inertia. ______

These two coils may be individually activated using the commands CTR A ON or CTR B ON. The North seeking pole of the coils is marked on the satellite and has an LED to indicate when that coil is energized. Maximum torque is achieved when the coil is pulsed or energized when its vector is orthogonal to the magnetic field. These torques are very small, so watch carefully.

1) Let the satellite stabilize as in Part A, such that the perpendicular to one of the coils is 90 degrees from North (the positive direction is the side of the coils with the LED).

2) Send CTR A ON or CTR B ON to energize the proper coil. Measure how long it takes to travel 90 degrees.

3) At this point, observe the orientation of the other coil with respect to the Earth's magnetic field. If it can be used to further torque the spacecraft in the same direction, send the commands to turn it on and the other coil off. OR if the other coil is not optimally oriented, then simply turn off the first coil and let the counter torque of the string carry it back past its original orientation to a point where the other coil can be effective.

4) Try to spin up the spacecraft by alternating the pulsing of the coils. (Just for observation here, don't need to record angles.)

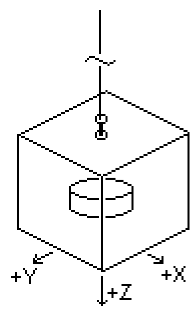
5) Once the LABsat is spinning, try to pulse the coils on and off to damp the rotation to zero.

Post Lab:

a) Calculate the magnetic moment for each set of coils (look up the formula for the magnetic dipole of a current loop). For comparison with the permanent magnet moment you calculated in Part-A, scale this TORQUEsat moment by the ratio of the two satellite's I_z moments of inertia. How do they compare? _____ How long did it take to reach 90 degrees?_____ Is that faster or slower than in Part A?_____

b) What magnetic control law is used to establish a spin rate about a given axis? ______ What magnetic control law is used to damp a rate? ______ What instrument would you need to add to the LABsat in order to calculate the magnetic moment for the two magnetic control laws? _____

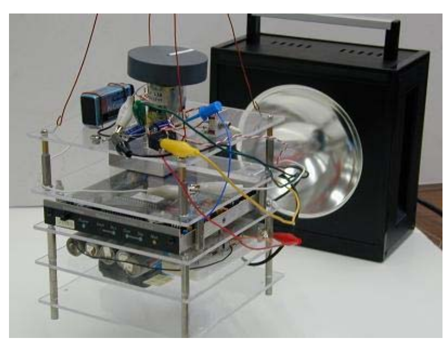
Part C: SPINsat Momentum Wheel: **(We have 3 of these)**



SPINsat

In this experiment, your LABsat motor will act as a small momentum wheel. The motor is connected so that CTR A *N* will pulse the motor counterclockwise and CTR B *N* will pulse the motor clockwise where *N* is in 100's of milliseconds. You have additional full ON/OFF commands. For example, CTR A ON will run the motor indefinitely CCW and CTR A OFF followed by CTR B ON will rotate it CW.

Lab Procedure: Let the spacecraft achieve equilibrium at rest. Using your compass rose, determine your initial angle θ. Your measured angle will be relative to this starting angle. Prepare to record θ and time.



1) Logon and send CTR A ON to spin the motor. This will provide an impulsive torque to the motor, and cause a CCW spin of the wheel. Measure how long it takes the LABsat to cross 45 degrees. What direction is the spacecraft moving with respect to the NED coordinate frame?

2) Shut the wheel off and let the LABsat return to equilibrium. Turn on the Sun lamp.

3) Now you can make small attitude adjustments with the CTR A *N* and CTR B *N* pulse commands. These timed pulses can re-orient the LABsat in small increments independent of command system latency. Test your skill by using these commands to orient your satellite first to point at the Sun lamp, and then to a star at the front of the lab as seen in your camera and maintain that position. Record your observations on how well this worked and include in your lab report.

Post Lab: Estimate the motor torque in 1) using the same equations of motion, adding in the wheel momentum $\underline{h}_w$:

$$I_B \underline{\dot{\omega}}_B + \underline{\dot{h}}_w + \underline{\omega}_B \times (I_B \underline{\omega}_B + \underline{h}_w) = \underline{T}_{string} \tag{6}$$

Again, we are only considering angular velocity in the +Z direction, and the wheel is spinning in the +Z direction ($\underline{\dot{h}}_w^{\,T} = \begin{bmatrix} 0 & 0 & \dot{h}_w \end{bmatrix}$). Recall that the differential equation for the wheel momentum is

$$\dot{h}_w = T_m - I_{wheel}\dot{\omega}_z = T_m - I_{wheel}\ddot{\theta} \tag{7}$$

Substituting equation (7) into equation (6) gives the equation for the Z direction

$$(I_z - I_{wheel})\ddot{\theta} + k\theta = -T_m \tag{8}$$

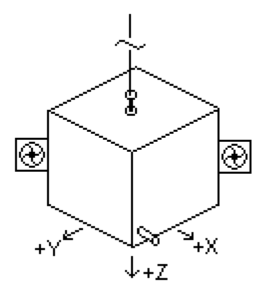
If T_m is treated as an impulse, the solution for θ(t) is

$$\theta(t) = -\frac{T_m}{k}\left(\sin\left(\sqrt{\frac{k}{(I_z - I_{wheel})}}\,t\right)\right)$$

Using your measurement of θ (make sure you subtract your initial θ from your data), determine the motor torque, T_m.

In each part of this lab we ignored another disturbance torque. What torque did we ignore and how would this affect your solutions to the differential equations (answer this qualitatively, don't solve the equations)? _____

Part D: PROPsat Thrusters: (We have 1 of these)



PROP sat

In this experiment, two thrusters have been added to the labsat, one to rotate CW using the CTR A commands and the other to rotate CCW using the CTR B commands. Of course there is no air in space, but the thrust from these fans is comparable to cold-gas thrusters on actual spacecraft (excepting the string forces, of course). This exercise is not quantitative but is more for operational experience than anything else. Let the spacecraft achieve equilibrium at rest. Using your CTR A and B commands see if you can uses pulses for fine camera positioning control. Or use ON and OFF commands for greater movement. **Do NOT over-spin this experiment!**

Lab Procedure:

1) Remotely log into the LABsat command system using your ground station. Use the Lens (L ON) command to activate the camera. **(Remember to turn it off when done with the L OFF command).**

2) Use the CTR A *N* and CTR B *N* commands (N between 1 and 20) for fine movement control of your attitude as seen in your ground station video monitor. You can use the CTR (A/B) ON/OFF commands for longer "burns".

Lab Report (Final one for the semester):

Write one lab report covering the 3 different parts of the ADCS lab. Follow the format provided at the beginning of the semester. **<u>Proofread</u>** the report before you turn it in, to avoid losing points due to grammar, spelling, and formatting mistakes. Write as a TEAM, not as individual/disjoint sections.