# An Attitude Control System and Commissioning Results of the SNAP-1 Nanosatellite

WH Steyn , Y Hashida and V Lappas
Surrey Space Centre
University of Surrey
Guildford, Surrey GU2 5XH
United Kingdom

Abstract. SNAP-1 is a low-cost nanosatellite build by Surrey Satellite Technology Ltd. (SSTL), it is amongst other objectives a technology demonstrator for 3-axis stabilisation and orbit control for a future constellation of small satellites during formation flying. The satellite uses a single miniature Y-momentum wheel, 3-axis magnetorquer rods and a single butane gas thruster to ensure a nominal nadir-pointing attitude with full pitch control and in-track delta-V manoeuvrability. The magnetorquer rods do momentum maintenance and nutation damping of the Y-wheel. The primary attitude sensor used, is a miniature 3-axis fluxgate magnetometer. Precise orbital knowledge will be obtained using a small single antenna GPS receiver supported by an on-board orbit estimator. This paper describes the various attitude control modes required to support: 1) a narrow and three wide angle CMOS cameras during pointing and tracking of targets, 2) the propulsion thruster during orbit manoeuvres, 3) the initial attitude acquisition phase and 4) a safe mode backup controller. The specific attitude controllers and estimators used during these modes are explained. Simulation and in-orbit commissioning results will be presented to evaluate the performance and design objectives.

Introduction

The SNAP-1 (Surrey Nanosatellite Applications Platform) is a flexible commercial nanosatellite platform aimed at providing access to space at a cost an order of magnitude less even than Surrey's low cost microsatellite missions. The in-orbit mass of the satellite is only 6.5 kg. The satellite was launched from the Plesetsk Cosmodrome on a
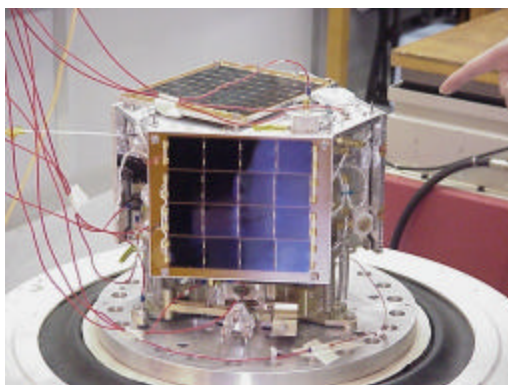
Figure 1: SNAP-1

Cosmos launcher, in a low earth 704 km sun-synchronous, circular orbit with the Tsinghua-1 microsatellite in the 28th of June this year. The main objectives from the ADCS point of view are to demonstrate 3-axis stabilisation on a nanosatellite platform (miniaturisation), to 3-axis stabilise the CMOS cameras for nominal nadir viewing and to support the propulsion system during formation flying.

The attitude and rate parameters of SNAP-1 are determined by measurement of the geomagnetic field vector in the body frame and comparing it with a modelled vector of the geomagnetic field (IGRF model) in the orbit reference frame. These vector pairs are then fed into an extended Kalman filter to extract the full attitude and rate estimates for use in the momentum wheel and magnetorquer attitude controllers. Additional attitude information can be obtained from the wide-angle CMOS cameras when pointed towards the earth's horizon. As attitude actuators, the 3-axis magnetorquer rods and the Y-momentum wheel are used to stabilise and point the cameras and thruster. The torque-rods are used during the initial attitude acquisition phase to damp the body angular rates and to align and regulate the satellite's Y-spin axis along the orbit normal. Next the momentum wheel is used to absorb the Y-spin body momentum and to 3-axis stabilise the attitude at zero roll and yaw angles while controlling the pitch angle to any desired pointing reference. The torque-rods are now used to damp any nutational motion in roll and yaw and to manage the wheel momentum at a fixed reference value. The two

basic control modes supported by SNAP-1's

- Attitude Acquisition: After separation from the launch vehicle or when stabilisation is lost due to large external disturbances e.g. during thruster firings or when the ADCS software stops executing for a while due to OBC outages. The torque-rods are used to dump the angular momentum in the body X- and Z-axes and to control the Y-axis angular rate at a reference value. The result of this will be to inertially align the body Y-axis to the orbit normal with the satellite in a Y-Thomson attitude. The detumbling controller will be supported by a robust angular rate Kalman filter which uses only the magnetometer measurements to

ADCS system are the following:

estimate the orbit referenced body rates.

- 3-Axis Stabilisation: The Y-wheel will be used the give the satellite inertial stiffness in the orbit normal direction (zero roll and yaw). By varying the wheel speed the pitch angle can be controlled to point the cameras and thruster within the orbital plane. An extended Kalman filter using the magnetometer and camera measurements will be used for attitude/rate estimation.

Table 1 lists the ADCS components used by SNAP-1 and their relevant specifications.

Table 1: ADCS Sensor and Actuator Specifications

	Magnetometer	**GPS**	**Torqrod**	**Momentum wheel**	**ADCS Module**
Manufacturer	Billingsley	SSTL	SSTL	SSTL	SSTL
Quantity	1	1	3	1	1
Type	Fluxgate	Mitel Chipset	Nickel-alloy core	Brushless DC Motor	C515 CAN µController
Range	±60 µTesla	12-Channel 1-Antennae	±0.122 Am^2	0-5000 rpm 0-0.01 Nms	-
Resolution/ Accuracy	±60 nT	< 15 meter	10 msec min. pulse	±5 rpm	-
Mass (gram)	117	43	36 each	80	300
Size (mm)	35x32x83	95x50x8	125xΦ5	40xΦ47	168x122x20
Power (mW)	150	1700	100	100-500	250

Attitude Acquisition

After separation from the Cosmos launch vehicle, the satellite can be tumbling at an unknown rate. Although a 5^0/s rate was expected, in-orbit results showed an initial 30^0/s tumbling rate. A simple B-dot[1] rate damping controller requiring only Y-axis magnetic moment is used. This controller will reduce the X and Z-axis angular rates and align the spacecraft Y-axis to the orbit normal without the explicit need of attitude or rate information. In this controller, the magnetic field vector is measured at regular intervals and the M_y magnetorquers is fired for short periods at the correct polarity, depending on the angular rate of the magnetic field vector:

$$M_y = K_d \, \dot{\boldsymbol{b}} \quad , \quad \boldsymbol{b} = \arccos\left(\frac{B_y}{\|\mathbf{B}\|}\right) \qquad (1)$$

with K_d a constant gain parameter.

The next step will be to control the Y-axis rate of the satellite's body to a certain reference value. This brings the satellite to a Y-Thomson mode of stabilization[2]. This is done by using a X-axis magnetic moment. The magnetorquer pulse duration and polarity depends on the angular rate error and the polarity of the Z-axis component of the magnetic field vector:

$$M_x = K_s \left(\boldsymbol{w}_{yo} - \boldsymbol{w}_{yo-ref} \right) \mathrm{sgn}\left(B_z \right) \qquad (2)$$

with K_s a constant gain parameter, $\boldsymbol{w}_{yo}$ the orbit referenced angular rate of the satellite's body can be estimated from be estimated from a simple pitch filter or a Kalman rate filter. The Kalman type rate filter is used to determine all the angular body rates from magnetometer measurements only. Details on this filter are explained in detail in reference 3. The advantages of this estimator are: 1) no orbit propagator and hence no IGRF computation is required, 2) the filtering algorithm is very simple

and has low computational demand, 3) it is robust against modelling errors and it does not diverge. The main disadvantage is that rate estimation errors similar in size to the orbit angular rate w_o (mean motion) will occur. This filter has been used as a standard in previous SSC/SSTL missions such as UOSAT-12[4] and in the Cerise microsatellite[5], which lost its gravity gradient boom due a collision with space debris.

The pitch filter is reasonably accurate once the satellite is in a pure Y-Thomson spin (i.e. small roll and yaw assumption). This filter will determine both the orbit referenced pitch angle q and rate $\dot{q}$ ($\approx w_{yo}$) using the magnetometer measurements and the modelled IGRF[3] geomagnetic field vector. The filter is based on a double integrator model of the decoupled pitch axis of the spacecraft's dynamics:

$$\ddot{q} = N_y / I_{yy} \qquad (3)$$

with N_y the total torque applied and I_{yy} the moment of inertia (MOI) around the spacecraft Y-axis. The discrete state space model for a sampling period of Δt can then be written as:

$$\begin{bmatrix} q(k+1) \\ \dot{q}(k+1) \end{bmatrix} = \begin{bmatrix} 1 & \Delta t \\ 0 & 1 \end{bmatrix} \begin{bmatrix} q(k) \\ \dot{q}(k) \end{bmatrix} + \begin{bmatrix} \Delta t^2 / 2 I_{yy} \\ \Delta t / I_{yy} \end{bmatrix} N_y(k) \qquad (4)$$

The measurement equation assuming a pure Y-spin:

$$q = \tan^{-1} \left\{ \frac{-b_x b_{zo} + b_z b_{xo}}{b_x b_{xo} + b_z b_{zo}} \right\} \qquad (5)$$

The b_{io} and b_i terms are normalised modelled (orbit referenced) and measured geomagnetic field vector components, as only the direction of the vectors is important. Equations (4) and (5) are then used in a discrete second order state to determine the filtered pitch angle and rate values.

3-Axis Stabilisation

After the satellite has been fully detumbled and brought to the reference Y-Thomson state, a Y-axis momentum wheel is used to absorb the body momentum and stabilise the satellite into a fixed nadir pointing attitude (zero roll, pitch and yaw). The first phase of this manoeuvre is to ramp the Y-wheel momentum (speed) to close to the initial body momentum. This will slow down the Y-axis body rate. When the target wheel speed is reached, it is kept constant and the satellite body allowed to drift towards its nadir pointing attitude. When the pitch angle (estimated by the pitch filter) becomes less than ± 20° from nadir a closed loop PD-type wheel pitch attitude controller is enabled:

$$N_{wy} = K_d \dot{q} + K_p \left(q - q_{ref} \right) \quad \text{and} \quad \left| N_{wy} \right| \le N_{w\_max}$$

$$w_{wy} = \int N_{wy}\, dt / J_{wheel} \qquad \text{and} \qquad \left| w_{wy} \right| \le w_{w\_max}$$

$$(6)$$

where K_p and K_d are the PD controller gains, N_{wy} and N_{w_max} are the Y-wheel required and maximum torque values, w_{wy} and w_{w_max} are the Y-wheel reference and maximum speed values, and J_{wheel} is the wheel MOI.

The reference pitch angle q_{ref} is zero for the nadir pointing case, but can be any angle in the Y-axis stabilised mode. To maintain the wheel momentum at a certain reference level and to damp any nutation in roll and yaw, a magnetorquer cross-product[6] control law is utilised:

$$\mathbf{M} = \frac{\mathbf{e} \times \mathbf{B}}{\|\mathbf{B}\|} \qquad (7)$$

with,

$$\mathbf{e} = \begin{bmatrix} K_x \mathbf{w}_{xo} \\ K_y \left(h_{wy} - h_{wy-ref} \right) \\ K_z \mathbf{w}_{zo} \end{bmatrix} \qquad (8)$$

K_i is the controller gain constants, w_{io} is the orbit reference angular rates and h_{wy} and h_{wy-ref} is the Y-wheel angular momentum measurement and reference values. The orbit reference angular rates in Eq. (8) are obtained from a full state (attitude and rate) Extended Kalman filter (EKF) for improved accuracy above the Rate Kalman filter mentioned previously. This filter takes measurement vectors (in the body frame) from the magnetometer and cameras (applied as earth horizon sensors) and by combining them with corresponding modelled vectors (in a reference frame), estimates the attitude and angular rate values of the satellite. The 7-element discrete state vector to be estimated, is defined as:

$$\mathbf{x}(k) = \begin{bmatrix} \boldsymbol{\omega}_B^{I\,T}(k) & \mathbf{q}^T(k) \end{bmatrix}^T \qquad (9)$$

with $\boldsymbol{\omega}_B^I$ the inertial referenced angular rate vector and $\mathbf{q}$ the orbit referenced quaternion vector. The innovation used in the EKF is the vector difference between the measured body referenced vector and a modelled orbit

referenced vector, transformed to the body frame by the estimated attitude transformation matrix:

$$\mathbf{e}(k) = \mathbf{v}_{meas}(k) - \mathbf{A}\left[\hat{\mathbf{q}}(k)\right]\mathbf{v}_{orb}(k) \quad (10)$$

where,

$$\mathbf{v}_{meas}(k) = \mathbf{B}_{meas}(k)\big/\left\|\mathbf{B}_{meas}(k)\right\|$$

$$\mathbf{v}_{orb}(k) = \mathbf{B}_{orb}(k)\big/\left\|\mathbf{B}_{orb}(k)\right\|$$

for the magnetometer measurement and IGRF modelled vectors[3].

The same method is applied for all the attitude sensors, to supply a measurement and modelled vector pair to the filter when a valid sensor output is received. Depending on the sensor type, various measurement noise covariance values are used in the Kalman filter to put different weight factors on the less accurate (magnetometer) and the more accurate (earth sensor) innovations.

Figure 2 shows the simulation performance of the B-dot controller, Rate Kalman filter and Pitch filter during the initial detumbling period. The initial orbit referenced angular rate vector is $\mathbf{w}_B^O = \begin{bmatrix} 5 & 0 & -2 \end{bmatrix}^T$ °/s. The rate damping controller of Eq.(1) and the Rate Kalman filter are enabled after one orbit (6000 seconds. One orbit later (12000 seconds) the Y-spin controller of Eq.(2) is started. The Y-axis body rate is controlled towards -2 °/s. The target rate is reached within 1 orbit, during which the Pitch filter is also enabled for improved Y-rate estimation.

At the start of the 3th orbit (18000 seconds) the Y-wheel is ramp to a momentum of -0.0021 Nms (-1000 rpm) using an open-loop strategy. The Y-body rate is slowed from -2.0 °/s to +0.1 °/s as the satellite's body momentum is absorbed by the wheel. After 1000 seconds the wheel reached its target of -1000 rpm and the speed is kept constant to allow the pitch angle to drift towards the nadir direction. During the 3th orbit the spin damping controller of Eq.(1) is activated to damp any nutation motion. When the pitch angle is within 20° from nadir, the Pitch wheel controller of Eq.(6) and the Cross-product wheel momentum controller of Eqs.(7,8) are enabled. Within a few minutes the pitch angle of the satellite is zeroed and the satellite is now Y-momentum wheel stabilised.
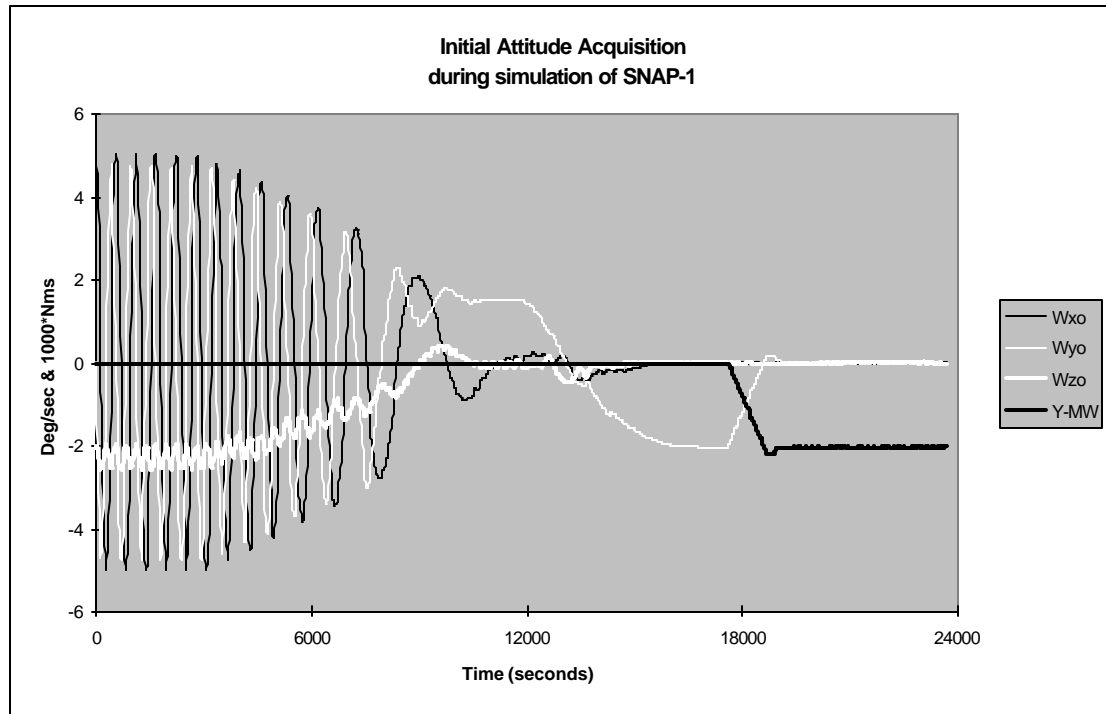

Figure 2: Simulation result of the initial attitude acquisition phase

In-Orbit Commissioning

Since OBC software was not ready initially, the microcontroller in the ADCS module (see Table 1) was used to perform the initial attitude acquisition. The following functions were implemented to assist the commissioning:

- Simplified B-dot detumbling controller, using the Y-torquer rod
- Simplified Y-rate spin-up/spin-down open loop controller, using the X and Z torquer rods
- Robust rate Kalman filter
- Circular buffers for whole orbit data sampling e.g. magnetometer, torquer rod commands, Y-wheel speed/current, estimated X/Y/Z angular rates

SNAP-1 was launched from the Plesetsk Cosmodrome on the 28th of June 2000 together with the SSTL built Tsinghua-1 microsatellite. The initial telemetry indicated a rapid random tumbling motion of about 5 rpm (30 deg/sec). The next day (29th) the magnetometer readings confirmed that SNAP-1 was tumbling with a 26 deg/sec rate, which can be seen in Figure 3. On the 30th, the sampling period was reduced to 3 second units and a magnetorquer rate damping controller, using the new SSTL designed magnetorquer rods, was enabled. Within about one day the initial high tumbling motion was completely damped in the X and Z axes and a low Y-rate of 2 rotations per orbit reached. A surprising result was that the space pointing facet (-Z) of SNAP was now tracking the B-field vector almost perfectly. Figure 4 shows this compass mode tracking evidence from magnetometer readings. The reason for this phenomena can be explained by an internal small magnetic moment in the Z-axis direction. This residual moment is caused by the harness which forms a current loop in the X/Y-plane. The compass mode not only gives SNAP a low Y-rate but also a known attitude. The slow Y-Thomson spin ensures a good down link during ground station passes and a positive power budget. The next step during commissioning was to test the momentum wheel. On the 5th of July, the Y-momentum wheel was commanded to a 500 rpm speed. Figure 5 indicates the momentum exchange with the satellite's body when the magnetometer measurements starts to change rapidly. Conservation of momentum should give SNAP a Y-tumbling rate of 1.46 deg/sec with the wheel running at 500 rpm. This value was confirmed by the estimated Kalman filter value, which can be seen in Figure 6. Figure 7 shows the momentum wheel current (torque) for the 500 rpm speed reference. Interesting to note the fluctuation of the current mainly due to the MW bearing friction. Initially the wheel bearings are cold (higher friction) and more current is needed to overcome friction. Then the bearings heat themselves and the current drop to values below 40 mA. Later, during eclipse, the current increased slightly above 40 mA due to a colder temperature experienced at the wheel.
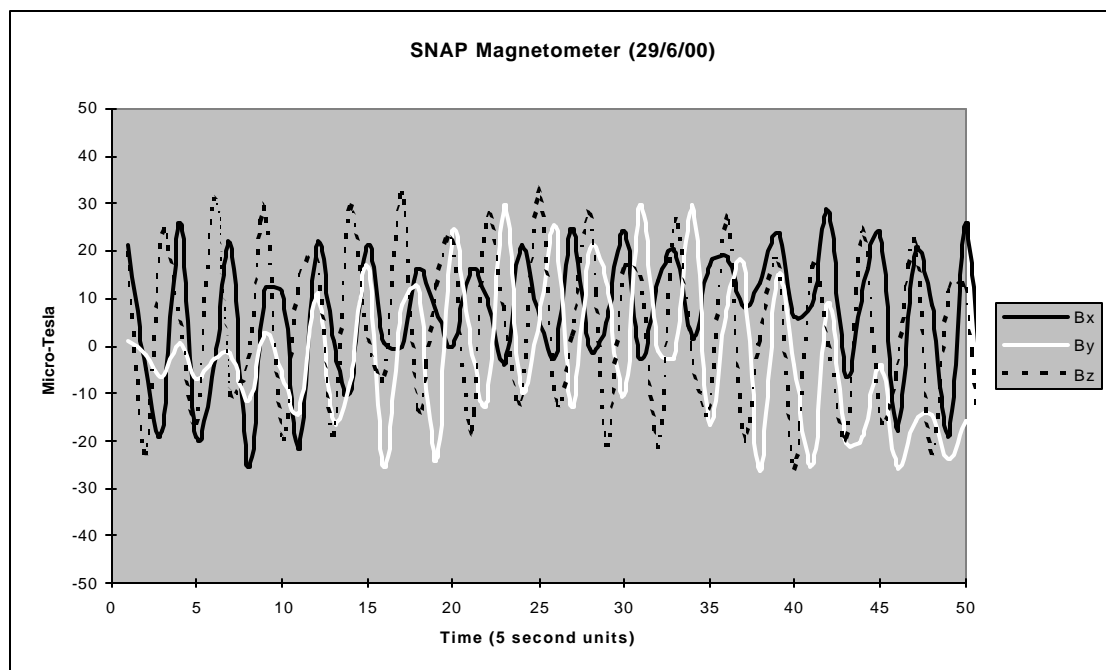

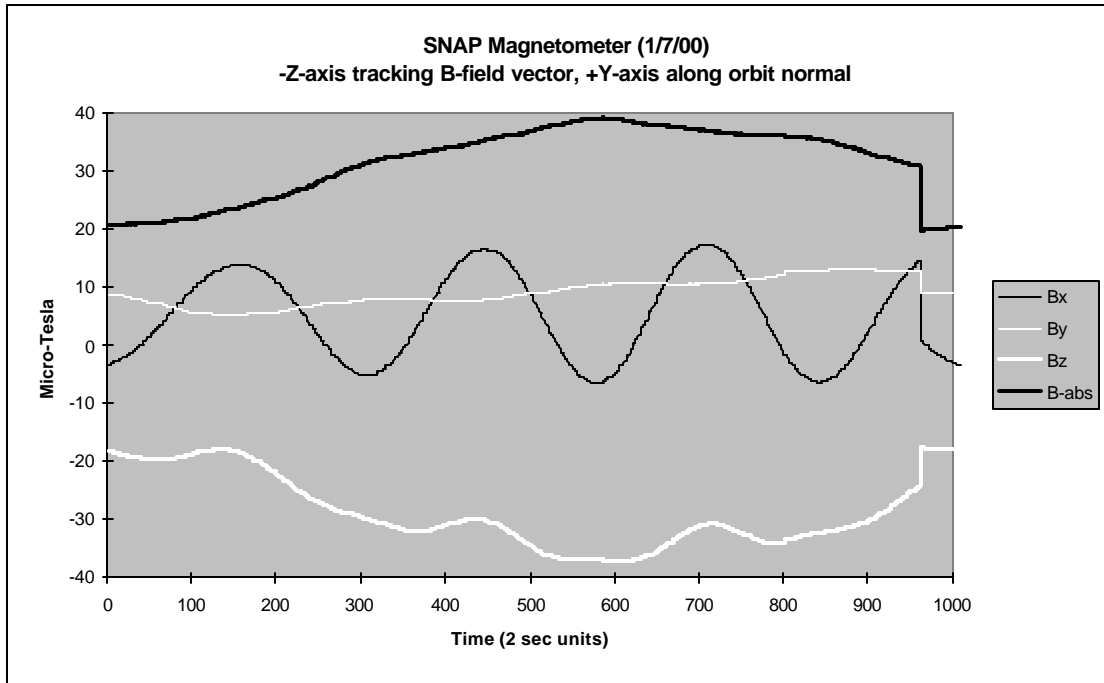**Figure 3: Initial magnetometer evidence of SNAP's high tumbling rate**

SNAP Magnetometer (1/7/00)
-Z-axis tracking B-field vector, +Y-axis along orbit normal

Figure 4: SNAP in Y-Thomson and locked onto B-field vector (Compass mode)

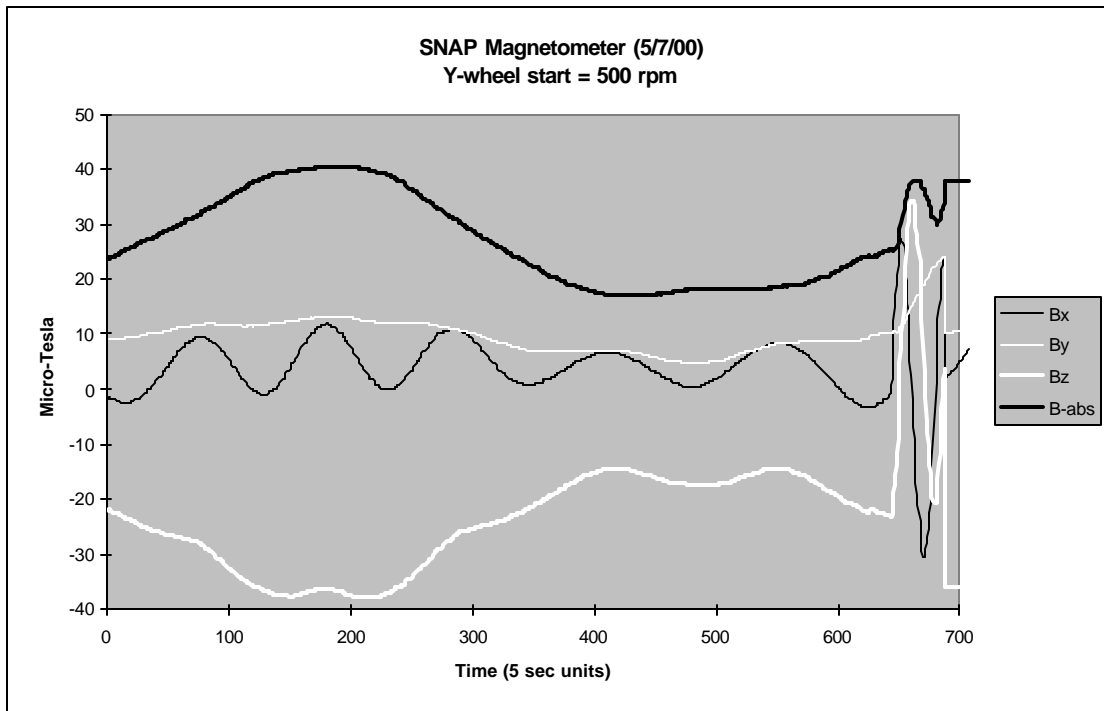**SNAP Magnetometer (5/7/00)**
Y-wheel start = 500 rpm

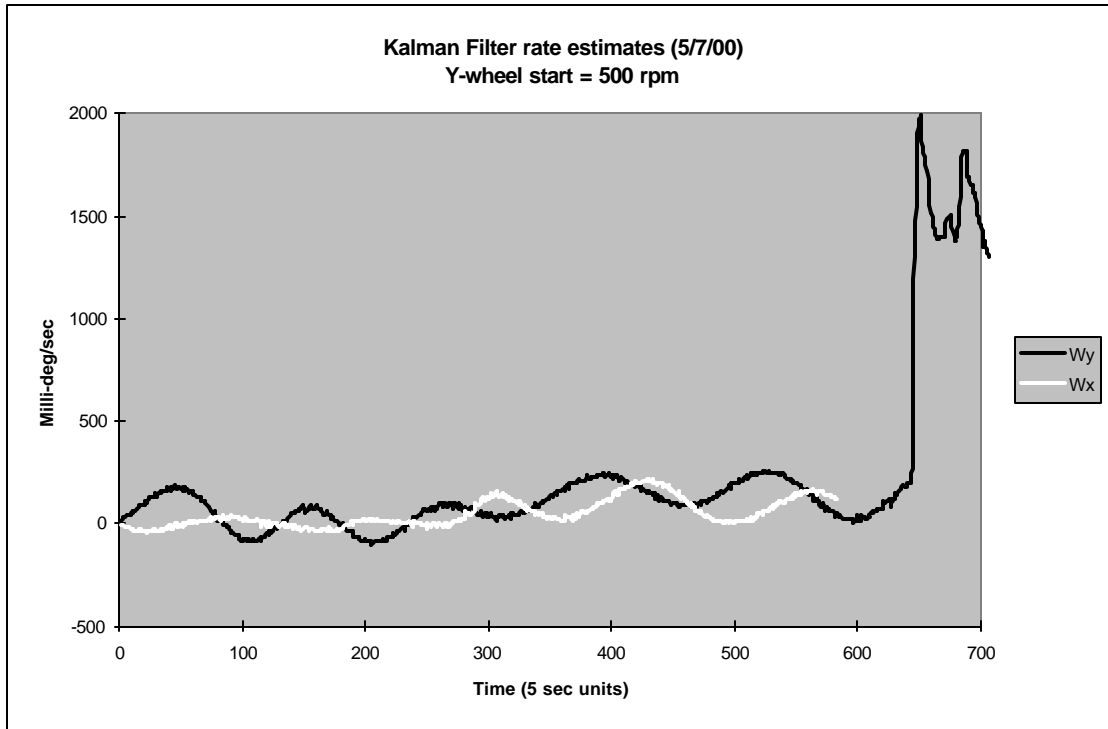**Figure 5: Magnetometer indicating Y-wheel disturbance**

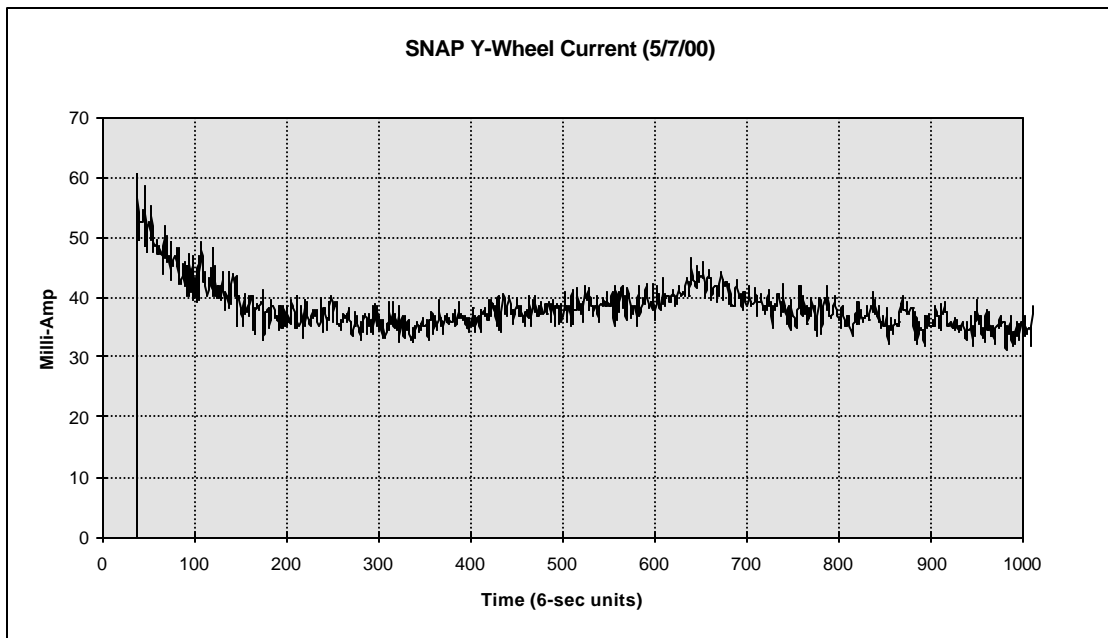**Figure 6: Kalman rate estimates indicating Y-wheel disturbance**

Figure 7: Y-Wheel current at 500 rpm indicating bearing friction variation

Conclusion

At the writing of this paper SNAP-1 was only one week in-orbit. The ADCS system has not been fully commissioned yet, but the initial results show good performance from all the ADCS sensors and actuators.

SNAP has been detumbled into a slow Y-Thomson attitude with the Z-axis locked onto the magnetic field vector. The next ADCS step will be to implement the full ADCS task on the OBC. This will enable us to bring the satellite into a 3-axis stabilisation attitude with the Y-momentum wheel. Further results will be presented during the conference.

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