D-SAT Simplified Magnetic Attitude Control

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Abstract

Dosimeter Satellite (D-SAT) is an ATSB in-house build nano-satellite platform that supports the operations of a dosimeter payload. D-SAT’s orbit is targeted at a nominal altitude of 750km and 60° inclination. The dosimeter is designed to collect the radiation dosage in a Near Equatorial Orbit (NEqO). The design philosophy of D-SAT is to ‘Keep it Simple’, weighing only 14kg and 230 x 230 x 290mm in size. This paper describes the trade study and simulations carried out to evaluate the attitude stability achievable during acquisition and housekeeping phases, using either permanent magnets or magnetic-torques as actuators and magnetometers as dedicated attitude sensors. An alternative to attitude observations without sensors and the B-Dot algorithm coupled to a B-field rate observation algorithm to achieve 3-axis spin rate control to any desired rate are also described.

Keywords: Permanent Magnet, Magnetometer, Magnetic-Torque Coils, B-Dot algorithm

I. Introduction

The space environment near the Earth’s equator has yet to be fully understood and characterized. This is because previous and current simulated space environment models in this region have not been verified by actual data. ATSB has embarked on an in-house nano-satellite development program to provide a platform to meet the need for collecting space environmental data near the equator while maintaining a ‘Keep it Simple (KIS)’ approach for satellite platform design and development. The initial space environment data to be collected is the radiation dosage received by a satellite while operating in a near equatorial orbit. This forms the primary objective of the nano-satellite, that is, “To characterize the radiation dosage for an near equatorial orbit”. This is achieved by using 6 dosimeters. Three dosimeters are covered with a 3mm thick shield while the rest are exposed to space. All dosimeters are placed on the same face of the satellite.

The Dosimeter Satellite (D-SAT) platform was allocated 20kg in mass and not to exceed an envelope of 300 x 300 x 300 mm³. As there are no pointing requirements for the dosimeters, the attitude control requirements of D-SAT are open. To take advantage of this, the secondary objective is set, “To provide an open platform for different attitude control algorithm testing”. To keep within the budget mass, dimensions, power and KIS approach of the satellite, either permanent magnets or magnetic torque coils with a magnetometer attitude control scheme were considered. Previous operational satellites using permanent magnets were Quake-Sat [1] and the MicroSats, PACSAT, DOVE and LUDSAT [2]. WEBERSAT was the only Microsat with a pre-biased magnetometer and permanent magnets for attitude control. Other operational satellites of this class used magnetometers with magnetic torque coils or torque rods. D-SAT is unique as it is the first nano-satellite to be operated in an equatorial orbit region, shown in Figure 1, as compared to others that operate in highly inclined orbits. Since D-SAT’s velocity vector will be nearly perpendicular to the Geomagnetic field vector as shown, selection of the best magnetic attitude actuation is critical.

This paper describes the trade studies and simulations of the two different magnetic attitude control schemes. Attitude and rate observations are also discussed.

II. Earth Geomagnetic Field for NEqO

The Earth Geo-magnetic field of D-SAT in the Earth Centered Inertial frame for a near equatorial orbit at 750km altitude and 60° inclination is simulated using an IGRF model to the 4th order with year 2000 coefficients. Rotating the field to the Orbit Coordinate System (OCS), the resultant magnetic field vector directed to the satellite is given in Figure 3. The
schematic in Figure 4 explains actuation using magnetic means for D-SAT’s orbit will be limited to the roll – yaw plane, that is pitch control will be minimum or non at all due to the alignment of the pitch axis with the resultant Earth Geomagnetic Field.

Figure 1: D-SAT Ground Track for 60 inclination at 750km altitude

Figure 2: D-SAT Groundtrack overlay on The Earth's Geomagnetic Field Contour

Figure 3: Earth Geomagnetic Field components in OCS for D-SAT's orbit over a 24 hour period (14 Orbits) in NEqO

Figure 4: Simplified relation of D-SAT's pitch axis(Y body control axis) and the Earth's Geomagnetic Field Lines

III. Trade Study

Previous satellites have shown that the tip-off rate after separation from their launch platforms can range from 15°/s to 2°/s on the roll axis. D-SAT is required to detumble to the lowest rate possible on all axes during the acquisition phase, to achieve a stabilize platform. The two proposed attitude control schemes for both phases are discussed qualitatively.

Permanent magnets are favored for nano-satellites due to the zero power requirements and natural continuous self alignment, or ‘locking’ of the magnet’s dipole axis to the Geomagnetic field, resulting in passive stabilization in two axes. Hysterisis rods and nutation dampers are often installed to reduce the spin rates of the satellite in the third axes. Such a scheme for D-SAT saves on power consumption and meets the KIS concept without the need of an onboard control algorithm. However, the drawback is that no other control algorithms can be implemented, thus the secondary objective cannot be met.

Magnetic Torques on the other hand, will allow different control algorithms to be implemented when uploaded to the satellite. This scheme, as expected, consumes power and requires a 3-axis magnetometer to produce data for the algorithm to generate the required torque commands.

Section IV and V highlights the modeling and simulation implemented to verify the trade-off study.
IV. Modeling

The structural design of D-SAT consist of 4 tray assemblies housing the electronics, five solar panel backplanes and adaptor ring plane as shown in Figure 5. The total CBE mass of D-SAT is 14.62kg with the moments of inertia:

\[
\begin{align*}
I_{xx} &= 0.2025 \text{kgm}^2 \\
I_{yy} &= 0.2024 \text{kgm}^2 \\
I_{zz} &= 0.1969 \text{kgm}^2 \\
I_{xy} &= 0.0003 \text{kgm}^2 \\
I_{xz} &= -0.0006 \text{kgm}^2 \\
I_{yz} &= -0.0002 \text{kgm}^2
\end{align*}
\]

![Figure 5: Simplified mechanical configuration of D-SAT without any Attitude Control System](image)

The torque generated by magnetic actuation is:

\[
\begin{bmatrix}
T_x_{-CS} \\
T_y_{-CS} \\
T_z_{-CS}
\end{bmatrix} = 
\begin{bmatrix}
0 & M_z & -M_y \\
-M_z & 0 & M_x \\
M_y & -M_x & 0
\end{bmatrix}
\begin{bmatrix}
b_{y_{-OCS}} \\
b_{y_{-OCS}} \\
b_{z_{-OCS}}
\end{bmatrix}
\]

(1)

Where \( T_{i,-BC} \) = Torque along the \( i \) axis in Control Coordinate System (CS) (Nm), \( M_i \) = Magnetic Dipole Moment in the \( i \) axis (Am²), and \( b_{i_{-OCS}} \) = Earth Geomagnetic Field in OCS (Tesla). The torque magnitude and direction is determined by the Magnetic Dipole Moment and that actuation along one axis will generate torque along two orthogonal axes in opposing vectors. A back of the envelope calculation using Euler’s equation and equation (1) shows that for an initial roll of 50/s, the required dipole to reduce the angular roll rate to zero in 1 orbit (5940 sec) for an average Earth Geomagnetic field of 2.0 x 10^6 Tesla is about 1.5 Am².

The permanent magnet dipoles were modeled using the following equation for permanent magnets, magnetized in a single direction [3].

\[
M_i = \frac{B_i V}{\mu_0}
\]

(2)

Where, \( M_i \) = Magnetic dipole moment along the \( i \) axis (Am²), \( B_i \) = Magnetic material residue inductance (T) and \( \mu_0 \) = Magnetic permeability constant in SI (1.26x10⁻⁶ H/m). For practical purposes eight commercially available cast AlNiCo 8He permanent magnets[4], with the volume of 6.35 x 6.35 x 20.00 mm³ shortened length wise, were selected due to their high resistance to demagnetization. The eight magnets were evenly distributed along the Z- Body Axis (Pitch axis) of D-SAT as shown in Figure 6. The total dipole is 4.73Am². This is 3 times more than required, but the number of magnets is necessary to maintain the even mass distribution on all axes.

![Figure 6: Mechanical configuration of Permanent Magnet ACS Scheme](image)

The magnetic torque coils were modeled using the equation for current carrying loops in a magnetic field

\[
M_i = INAm\hat{n}
\]

(3)

Where, \( M_i \) = Magnetic dipole moment along the \( i \) axis (Am²), \( I \) = Current (A), \( N \) = Number of coil turns, \( A \) = Cross sectional area of the coil, \( \mu \) = Magnetic permeability of the core material (Dimensionless in EMU) and \( \hat{n} \) is the unit vector perpendicular to the cross section of the coil. The proposed design is to incorporate 6 coreless frames wound with commercially available enameled copper wire of size AWG30 [5]. Each axis is mounted with a pair of coils. The supplied current is regulated at 50 mA, resulting in 798 wounds for each coil for a 12 V line. The maximum dipole generated by each coil is 1.83 Am². The coils are switched on and off according to the torque commands, and since current is regulated, no magnitude dipole scaling is available.

The baseline control algorithm for the Magnetic Torques and Magnetometers ACS scheme is a B-Dot algorithm:

\[
M_{i\text{-BC}} = -KB - m_{\text{const}}
\]

(4)
Where: \( M_{ic} \) = Command control dipole along the \( i \) axis, \( K \) = Gain constant, \( \dot{B} \) = Rate of change of the measured geomagnetic field and \( m_{bias} \) is the bias moment. The tuned gain was 100 and the tuned bias moment was 50 along the Y CS only to compensate for the orbit rate.

![Mechanical configuration with Magnetic Torque Coils ACS Scheme](image)

Figure 7: Mechanical configuration with Magnetic Torque Coils ACS Scheme, only the X Body Axis coils are shown

The simulation was evaluated in the acquisition and housekeeping phases for both the permanent magnet and magnetic torque ACS schemes. The models were created in Matlab & Simulink\textsuperscript{TM}. The satellite orbit was propagated using the SGP4 propagation model. Euler’s equation of motion for rigid bodies was integrated and attitude kinematics was represented in quaternions. A 10\textsuperscript{th} order IGRF 2000 model was used to calculate the Earth Geomagnetic Field and a 4\textsuperscript{th} order IGRF 2000 model was used to generate the magnetometer reading. The gravitational, magnetic and solar pressure disturbance torques were dynamically modeled.

For the Magnetic Torque Coil ACS Scheme, only the Y Control Axis (Pitch) was activated based on the magnetic torque command with a 10\% duty cycle, i.e. 2 second repeated actuation for every 20 seconds lag.

The initial conditions for the simulation were set as follows: Roll-tip off rate was 5\(^{\circ}\)/s for the acquisition phase and the initial body angular rate conditions during the housekeeping mode were 10\(^{\circ}\)/s for the roll axis only. Disturbance torques were not included in the acquisition phase simulation.

V. Analysis of Simulation Results

It can be seen from Figure 8 and Figure 9 that the permanent magnets increases the body angular rates rather than lowering the rates before the first orbit. But once the total dipole of D-SAT ‘locked’ into the Earth Geomagnetic Field, the body angular rates for all axes reduced to about 10\(^{\circ}\)/s. The magnetic torque coils on the other hand were highly damped and achieves stability 3 orbits less than the permanent magnets. However the body angular rates achievable were not less than 10\(^{\circ}\)/s for the roll and pitch axis.

Since there exist an uncertainty for the body angular rates in the first few minutes after separation from the launcher for the Permanent Magnet actuators and the body angular rates are similar for both ACS schemes once stability is achieved, it was proposed that the Magnetic Torque ACS scheme was baseline for D-SAT.

![Comparison of total angular momentum for Permanent Magnet actuation and Magnetic Torque with B-Dot control actuation during acquisition phase](image)

Figure 8: Comparison of total angular momentum for Permanent Magnet actuation and Magnetic Torque with B-Dot control actuation during acquisition phase

![Comparison of body angular rates for both Attitude Control Schemes during acquisition phase for 14 Orbits](image)

Figure 9: Comparison of body angular rates for both Attitude Control Schemes during acquisition phase for 14 Orbits

Following on this selection, the controllability of just actuating along the pitch axis via the B-Dot algorithm command was evaluated for the housekeeping phase. In other words, the same control algorithm was maintained throughout the change of phases. Figure 10 clearly indicates that over the period of 24 hours, i.e. 14 orbits, the total angular momentum was maintained and the body angular rates achievable for all axes were about 10\(^{\circ}\)/s.
In summary the Magnetic Torque actuation scheme with B-Dot control for the pitch axis was adequate to stabilize D-SAT in the NEqO orbit from separation to housekeeping operations. Having six torque coils provides the flexibility for future control algorithms requiring more than one coil actuation.

VI. Attitude and Rate Observations

In order to change the body angular rates, the current B-Dot algorithm can be inverted, i.e. using a positive control gain, $+K$, to spin-up the desired axes following the cross product of equation (1). The actual body angular rate is needed to determine whether the desired body angular rate is achieved. Since the ACS scheme has only one 3-axis magnetometer that does not provide rate observations, the only method to determine body angular rates is by estimation. Several methodologies have been reviewed, proposed by Psiaki [6] and Bar-Itzack [7]. The estimation models used the following Earth Geomagnetic Field kinematic model:

$$A \cdot \dot{b}_m = \dot{b} + \omega \otimes b$$

(5)

Where $A =$ Attitude matrix, $b_m =$ IGRF model in the orbit frame, $b =$ magnetometer measurements in body coordinates and $\omega =$ body angular rates. Thus the propagation of the IGRF model must be included in the control algorithm.

One of the most common estimation algorithms to predict the state of the satellite is the Extended Kalman Filter (EKF). Both the attitude in quaternion representation and body angular rate information can be estimated for on-board and ground purposes. The proposed EKF has a measurement sensitivity matrix generated from the magnetometer readings only, and the conceptual design coupled to the inverted B-Dot algorithm is given in Figure 12.

An alternative to observing the attitude of D-SAT is to use the solar panel current measurements mounted on the 5 sides of D-SAT as shown in Figure 13. The incidence angle, measured from the solar panel normal, for at least two panels can be calculated, as the current from the solar cells changes almost instantaneously as a function of the sun angle on the solar panel. This is the same method used by the Microsats and as reported by White, a crude estimation can be done above 15° from the panel surface of the rotation rate with respect to the sun. The incidence angle is given as:

$$\theta = 90 - ar \cos(I / I_{\text{max}})$$

(6)

Where $\theta =$ Incidence angle, $I =$ actual current of panel generated, $I_{\text{max}} =$ Maximum current achievable by panel determined by ground calibration. The solar panel readings can be incorporated into the sensitivity matrix to improve the estimation of the states of the satellite.
The estimated angular rates will allow future control algorithms that requires this information can be implemented, and thus satisfying the secondary objective of D-SAT. However, the KIS concept would be violated as the complexity of the algorithm increases with the inclusion of the EKF and the addition of an IGRF propagation model. Both the EKF scheme and the attitude measurement from solar panels have yet to be modeled and analyzed.

![Diagram of D-SAT](image)

**Figure 13:** Current Mechanical Configuration of D-SAT

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**VII. Conclusion**

The analysis of the Permanent Magnet and Magnetic Torques Coils justifies the latter as the preferred attitude determination and control scheme for D-SAT. The B-Dot algorithm actuating the pitch coil is the best ‘Keep it Simple’ ACS scheme from separation to housekeeping operations. The control algorithms will reside in the Onboard Microprocessor, and is designed for interrupts from the Ground Control Station. Future control algorithms such as an EKF for body angular rate estimation coupled to an inverted B-Dot for ‘spin-up’s can be uploaded during the lifetime of the satellite. A simple attitude observation using solar panels was discussed. The EKF and solar panel attitude observation algorithms have yet to be analyzed for feasible inclusion.

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