Attitude Determination and Control of ARKSAT-1

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Citation
ATTITUDE DETERMINATION
AND CONTROL OF ARKSAT-1

Undergraduate Honors Thesis

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ABSTRACT

ARKSAT-1 is a nanosatellite developed at the University of Arkansas as part of NASA’s CubeSat Launch Initiative (CSLI). The goal of ARKSAT-1 is to utilize an LED emitter paired with a ground-based tracking system to perform measurements of the composition of the atmosphere using spectroscopy. As part of its function, it is imperative that the satellite is able to control its orientation so that the emitter is aligned as closely as possible with the ground tracker. To do this, the attitude control system of ARKSAT-1 uses magnetic actuators to create a torque on the satellite by interacting with Earth’s magnetic field. Several variations of a B-Dot control algorithm were investigated for controlling the magnetic torquers based on magnetic field and angular velocity measurements as well as satellite position and magnetic field model data. The selected controllers were implemented in MATLAB and simulated to demonstrate their effectiveness for detumbling and pointing of the satellite.
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## DEFINITIONS

### Abbreviations

<table>
<thead>
<tr>
<th>Abbreviation</th>
<th>Description</th>
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<tbody>
<tr>
<td>ADCS</td>
<td>Attitude Determination and Control System</td>
</tr>
<tr>
<td>BCF</td>
<td>Body Coordinate Frame</td>
</tr>
<tr>
<td>CSLI</td>
<td>CubeSat Launch Initiative</td>
</tr>
<tr>
<td>ECI</td>
<td>Earth-Centered Inertial</td>
</tr>
<tr>
<td>ECEF</td>
<td>Earth-Centered Earth-Fixed</td>
</tr>
<tr>
<td>IGRF</td>
<td>International Geomagnetic Reference Field</td>
</tr>
<tr>
<td>ISS</td>
<td>International Space Station</td>
</tr>
<tr>
<td>LTP</td>
<td>Local Tangent Plane</td>
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<td>NED</td>
<td>North-East-Down</td>
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</table>
INTRODUCTION

Background

ARKSAT-1 is a 1U CubeSat designed at the University of Arkansas as part of NASA’s CubeSat Launch Initiative, which provides opportunities for small research satellites to be sent into space. ARKSAT-1 will be released into orbit from the International Space Station (ISS) following launch on the SpaceX 22 mission scheduled for March 12, 2021. The primary goal of ARKSAT-1 is to test a spectroscopy system consisting of a ground-based tracker and an emitter. The emitter consists of an LED light source aboard the satellite, which maintains alignment with the ground-based tracker. The tracker follows the emitter and takes spectral measurements of the light received. After this system is demonstrated aboard ARKSAT-1, the long-term goal is for it to be implemented as an emitter satellite and a receiver satellite working in tandem to orbit Earth or other bodies in the solar system and gather atmospheric composition data using spectroscopy (Sands et al., 2020).

As part of its primary goal, ARKSAT-1 must be able to reliably maintain accurate pointing alignment with its desired target. For this purpose, ARKSAT-1 is outfitted with magnetic torquers for actuation, in addition to a host of sensors including gyroscopes, accelerometers, and magnetometers. The function of the Attitude Determination and Control System (ADCS) is to take data from all available sensors and determine the appropriate outputs to control the actuators in a way that produces the desired attitude of the satellite. In addition to pointing, this includes detumbling of the satellite, as release from the ISS can cause high initial rates of rotation.
Objective

Develop, implement, and simulate attitude control algorithms to demonstrate their effectiveness for detumbling and pointing of the ARKSAT-1 satellite.
THEORY AND ANALYSIS

Magnetic Field Models

Various models exist for Earth’s magnetic field, including the WMM, EMM, and IGRF models. This work uses the International Geomagnetic Reference Field (IGRF) model, which represents Earth’s magnetic field \( \vec{B} \) as the gradient of a scalar potential \( V \) \( (\vec{B} = -\nabla V) \) which is approximated in spherical coordinates by the finite series

\[
V(r, \theta, \phi, t) = a \sum_{n=1}^{N} \sum_{m=1}^{n} \left( \frac{a}{r} \right)^{n+1} \left[ g_n^m(t) \cos(m\phi) + h_n^m(t) \sin(m\phi) \right] P_n^m(\cos(\theta))
\]

where \( a = 6371.2 \) km is the Earth’s mean surface radius and \( \theta \) and \( \phi \) represent geocentric latitude and east longitude (Thébault et al., 2015). The functions \( P_n^m(\cos(\theta)) \) are the Schmidt quasi-normalized associated Legendre functions of degree \( n \) and order \( m \). The coefficients \( g_n^m(t) \) and \( h_n^m(t) \) are updated every five years using global magnetic field data, and the variation over time is assumed to be linear between each five-year gap. The latest generation of the model is IGRF-13, which provides coefficients for 2020 and the expected variation for 2020-2025.

Coordinate Systems

To simplify the representation of quantities used in calculations, it is necessary to define a number of coordinate systems relevant to the geometries involved.
Earth-Centered Inertial (ECI)

The ECI coordinate frame has its origin centered at Earth’s center of mass, the x-axis aligning with the direction of the vernal equinox, the z-axis aligning with the direction of Earth’s rotation, and the y-axis following from the right-hand rule. Thus, the ECI frame is fixed in its orientation and follows the center of the Earth. The ECI is useful for defining the motion of objects orbiting the Earth, as it remains fixed in space while the Earth rotates.

Earth-Centered Earth-Fixed (ECEF)

The ECEF coordinate frame is similar to the ECI system, except its x-axis is defined to pass through Earth’s prime meridian at zero longitude, aligning the frame with the Earth’s surface as it rotates. This definition makes it useful for defining satellites’ positions relative to the Earth’s surface. The Earth Rotation Angle (ERA) is defined as the angle between the Terrestrial Intermediate Origin (TIO) and the Celestial Intermediate Origin (CIO), which can be approximated as the angle between the vernal equinox vector and the prime meridian, measured positively in the direction of Earth’s rotation (Petit and Luzum, 2010). The ERA in radians is linearly dependent on the UT1 time as given by the following equation, where \( t_{UT1} \) is the Julian UT1 date:

\[
ERA = 2\pi(0.7790572732640 + 1.00273781191135448(t_{UT1} - 2451545.0))
\]

Geocentric

When defining a satellite’s position relative to the Earth’s surface, it is often useful to use geocentric latitude and longitude. Here, latitude \( \phi \) is measured north from the equator, longitude
$\lambda$ is measured positive eastward from the prime meridian (or negative westward from the prime meridian), and altitude $h$ is measured in the radial direction from the Earth’s mean surface, $r_E = 6371.2$ km.

**Local Tangent Plane (LTP)**

The local tangent plane of a satellite or other object is centered at its position and oriented tangent to the surface of the Earth. One LTP system is the North-East-Down (NED) frame, which represents coordinates in the northward, eastward, and downward directions relative to the LTP, with the downward direction defined as normal to the LTP in the direction of the Earth’s surface. NED coordinates are useful for describing the magnetic field as given by the IGRF model.

**Body Coordinate Frame (BCF)**

The BCF system is centered on the center of mass of the satellite, with its axes defined relative to the positions of satellite hardware. For ARKSAT-1, the LED emitter is located on the -z-axis.
CONTROL ALGORITHMS

In order for the ADCS to properly control the attitude of the satellite, control algorithms must be employed. The purpose of a control algorithm is to systematically analyze the data collected from sensors and determine the appropriate outputs so that the actuators can be controlled in a way that produces the desired orientation. In general, there are two goals of the ADCS:

1. To achieve a specific rate of rotation of the satellite, for the purposes of spin-stabilization or detumbling
2. To achieve a specific orientation of the satellite relative to a reference frame such as the Earth, for the purposes of pointing at a specific target

For ARKSAT-1, the first required function of the ADCS is detumbling, or reducing the rate of rotation to as close to zero as possible. This ensures that the motion of the satellite is stabilized after its release into orbit from the ISS. The second function is nadir-pointing, ensuring that the -z-axis, which contains the LED emitter, is directed toward the center of the Earth as seen by the satellite. The third function is target-pointing, which directs the -z-axis to align with a particular location – in this case, the location of the ground tracker. This ensures the best possible visibility of the LED emitter from the ground.

Magnetic Torquers

A common means of actuation, and the one utilized by ARKSAT-1, is magnetic torquers. Generally, a magnetic torquer is a coiled wire through which a controlled current can be sent. For a rectangular coil with $N$ turns, the magnetic moment $\vec{\mu}$ generated is given by
\[ \vec{\mu} = A_{\text{coil}} \cdot I \cdot N \cdot \vec{n} \]  

(3)

where \( A_{\text{coil}} \) is the cross-sectional area of the coil, \( I \) is the current passing through the coil, and \( \vec{n} \) is the vector normal to the plane of the coil. A magnetic moment in a magnetic field produces a torque \( \vec{T} \) given by the equation

\[ \vec{T} = \vec{\mu} \times \vec{B} \]  

(4)

where \( \vec{B} \) is the local magnetic field vector. By adjusting the current sent through the magnetic torquers of ARKSAT-1, the torque acting on the satellite and thus its rate of rotation can be controlled along each of the three principal axes. It should be noted that if the axis of rotation is aligned with the magnetic field \( \vec{B} \), by Eq. (4), the torque produced will always be normal to the rotation of the satellite. This implies that, in general, the component of rotation of the satellite in the direction of the magnetic field cannot be controlled purely by magnetic actuation; the satellite is inherently under-actuated. For this reason, many satellites choose to use a secondary means of actuation to control the satellite’s rotation in the direction of the magnetic field, such as a reaction wheel.

**Detumbling Algorithms**

One common type of algorithm used for detumbling is B-Dot control laws. These laws make use of the fact that for a satellite with a high rate of rotation compared to its orbital period, the time rate of change of the magnetic field vector, \( \dot{\vec{B}} \), as observed by the satellite, is primarily
dependent on the rotation of the satellite. Thus, the measurement of \( \dot{\vec{B}} \) can be used to determine an appropriate response for the controller.

**Proportional B-Dot Controller**

The Proportional B-Dot Controller uses a magnetic moment that is proportional to the rate of change of the magnetic field vector:

\[
\vec{\mu} = -K \cdot \dot{\vec{B}} \tag{5}
\]

As the satellite rotates about some particular axis, \( \dot{\vec{B}} \) as observed by the satellite will be nearly perpendicular to the axis of rotation. By generating a magnetic moment proportional to and in the opposite direction of \( \dot{\vec{B}} \), the torque produced from Eq. (4) will always have some component opposing the rotation of the satellite, effectively damping its angular velocity.

**Bang-Bang B-Dot Controller**

Similar to the Proportional B-Dot Controller, the Bang-Bang B-Dot Controller uses a magnetic moment that is directly dependent on \( \dot{\vec{B}} \). However, the Bang-Bang Controller always uses the maximum output of the magnetic torquers to actively oppose the satellite’s rotation, as shown in Eq. (6).

\[
\vec{\mu} = -\mu_{max}\text{sign}\left(\dot{\vec{B}}\right) \tag{6}
\]
This approach is particularly effective for quickly reducing high angular velocities, but it can cause the satellite to rotate back and forth at low angular speeds, as the magnetic torquers constantly alternate direction at full strength – hence the “Bang-Bang” description.

**Follow B-Field Controller**

The Follow B-Field Controller aims to align the z-axis of the satellite with the magnetic field vector. The primary purpose of this algorithm is to allow satellites carrying a reaction wheel to align the axis of the wheel with the magnetic field vector so that the under-actuation of the magnetic torquers can be avoided. While ARKSAT-1 is not equipped with a reaction wheel, the algorithm was used for testing purposes. The control law is as follows:

$$\mathbf{\dot{\mu}} = \mu_{max} \cdot \begin{pmatrix} -\text{sign}(\dot{B}_x) \\ -\text{sign}(\dot{B}_y) \\ 1/2 \end{pmatrix}$$  \hspace{1cm} (7)

The magnetic torquer on the z-axis is continuously activated to bias the rotation of the satellite so that the z-axis is rotated toward the magnetic field vector. The Bang-Bang control law is used for the x- and y-axes to further stabilize the satellite.
Pointing Algorithms

COMPASS Controller

The COMPASS Controller, described by Reichel (2012), is designed to achieve three-axis stabilization and nadir-pointing using magnetic actuators. The goal is to compare the measured magnetic field $\vec{B}_{meas}$ with the expected magnetic field $\vec{B}_{exp}$ from a model such as the IGRF, using the error between the two to rotate the satellite so that the difference is reduced to zero. This effectively aligns the BCF with the reference frame of the magnetic field model, pointing the satellite toward nadir. The control law is given by

$$\tilde{\mu} = -K \cdot (\dot{\vec{B}}_{meas} - \dot{\vec{B}}_{exp}) + C \cdot (\vec{B}_{meas} - \vec{B}_{exp}) \quad (8)$$

where $K$ and $C$ are proportional gain constants. Additionally, a modified version of this control law was developed for ARKSAT-1 which rotates $\vec{B}_{exp}$ and $\dot{\vec{B}}_{exp}$ into the reference frame desired for pointing at a particular target, changing the goal of the controller from nadir-pointing to target-pointing. While this control law is designed for three-axis control, there is some concern that its accuracy is limited, since pure magnetic control is inherently under-actuated at a given moment in time.
TESTING PROCEDURE

In order to test the effects of the previously described control algorithms on ARKSAT-1, they were implemented into software and simulated using MATLAB. The procedure and data collected are described below.

MATLAB Implementation

To simulate the environment of the satellite, the most recently posted orbital elements of the ISS were used to simulate the position of the satellite and generate its ground track for an arbitrary time period. When compared to real-time ISS tracking, the ground track was found to be within approximately two degrees longitude and latitude (Figure 1). This data was then used to predict the Earth’s magnetic field from the IGRF model at the satellite location.
The magnetic field and satellite location data was then sent as inputs to the selected control algorithm, which produced the simulated output of the magnetic torquers for each axis. The dynamic response of the satellite was then calculated, taking into account the given initial conditions and satellite properties, as provided in Table 1. It should be noted that simulation properties were based on ideal scenarios (e.g., uniform mass distribution, principal axes aligned with BCF, etc.).

Table 1. Summary of ARKSAT-1 simulated properties

<table>
<thead>
<tr>
<th>Property</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Maximum magnetic torquer output</td>
<td>$\mu_{\text{max}}$ = 0.06 A · m²</td>
</tr>
<tr>
<td>Principal mass moments of inertia</td>
<td>$I_x = I_y = I_z = 3.33 \times 10^{-3}$ kg · m²</td>
</tr>
<tr>
<td>Magnetometer update rate</td>
<td>100 Hz</td>
</tr>
<tr>
<td>Controller update rate</td>
<td>50 Hz</td>
</tr>
</tbody>
</table>
Simulation Data and Results: Detumbling

For the detumbling scenario, each controller was simulated with an initial angular velocity of 10 deg/s about each of the x-, y-, and z-axes to represent a high rate of rotation upon release from the ISS. The controller was activated at $t = 30\;\text{min}$ to show the state of the system both before and after activation. Of note, brief discontinuities in the data appear such as near $t = 90\;\text{min}$ (Figures 2-a,c); this is likely due to the behavior of trigonometric functions as the longitude of the satellite changes from 180 deg to $-180\;\text{deg}$.

Proportional B-Dot Controller

For the Proportional B-Dot Controller, a proportional gain constant of $K = 30,000 \frac{\text{A}\cdot\text{m}^2\cdot\text{s}}{\text{T}}$ was used. This value demonstrated a high initial rate of decrease in the angular velocity (Figure 2-b) as well as a low residual angular velocity of less than 0.1 deg/s after $t = 150\;\text{min}$.

(a) Magnetic field measured from the satellite
(b) Angular velocity of the satellite – individual components and total magnitude

(c) Output magnetic moment and resultant angular acceleration of the satellite

Figure 2. Data from the Proportional B-Dot Controller simulated with

\[ \omega_i = 10 \text{ deg/s along each axis and } K = 30,000 \frac{\text{A-m}^2}{\text{s}} \]
**Bang-Bang B-Dot Controller**

The Bang-Bang B-Dot Controller, simulated under the same conditions as the Proportional B-Dot Controller, exhibited a somewhat higher initial rate of reduction of the angular velocity, but at the cost of a higher residual angular velocity of roughly 1 deg/s (Figure 3-b). Additionally, the satellite’s rotation appeared to stabilize around the y-axis, with the magnetic field remaining nearly constant along the x- and z-axes (Figure 3-a). The output magnetic moment demonstrates the expected behavior of alternating between the maximum magnetic moment in the positive and negative directions (Figure 3-c).

(a) Magnetic field measured from the satellite
(b) Angular velocity of the satellite – individual components and total magnitude

(c) Output magnetic moment and resultant angular acceleration of the satellite

Figure 3. Data from the Bang-Bang B-Dot Controller

simulated with $\omega_l = 10$ deg/s along each axis
Follow B-Field Controller

The Follow B-Field Controller was again simulated under the same conditions as the previous controllers. As expected, the rotation of the satellite aligned with the magnetic field along the z-axis (Figure 4-a), leaving a higher residual angular velocity than the previous controllers, close to 3 deg/s (Figure 4-b).

(a) Magnetic field measured from the satellite

(b) Angular velocity of the satellite – individual components and total magnitude
(c) Output magnetic moment and resultant angular acceleration of the satellite

Figure 4. Data from the Follow B-Field Controller

simulated with $\omega_i = 10$ deg/s along each axis

Simulation Data and Results: Pointing

To simulate the pointing controllers, it was assumed that the initial angular velocity would be comparable to the final angular velocity of the detumbling controllers, so it was chosen to be $\omega_i = 0.05$ deg/s along each axis. Each controller was again activated at $t = 30$ min.

COMPASS Controller

The COMPASS Controller was implemented according to Eq. (8), with the expected magnetic field calculated using the IGRF model. Proportional gain constants of $K = 30,000 \frac{A \cdot m^2 \cdot s}{T}$ and $C = 5,000 \frac{A \cdot m^2}{T}$ were used. Figure 5-a shows the magnetic field measured from the satellite compared to the expected magnetic field for a nadir-pointing satellite. The two plots match quite closely after $t = 120$ min, indicating successful nadir-pointing. As shown in
Figure 5-b, the angular velocity peaks initially as the controller forces the satellite toward nadir, then decreases back to the initial rate as pointing is achieved. Figure 5-c shows the longitude and latitude of the satellite’s pointing direction over time, as well as a plot of the pointing location for the entire time interval, all compared to the nadir position of the satellite. After the satellite’s initial motion toward the nadir-pointing position, most of the deviations appear to be caused by passing from 180 deg to −180 deg longitude.

(a) Magnetic field measured from the satellite compared to expected magnetic field for a nadir-pointing satellite

(b) Angular velocity of the satellite – individual components and total magnitude
(c) Longitude and latitude of the satellite’s pointing location over time compared to the satellite’s nadir position

Figure 5. Data from the COMPASS Controller with $K = 30,000 \frac{A \cdot m^2 \cdot s}{T}$ and $C = 5,000 \frac{A \cdot m^2}{T}$, simulated with $\omega_t = 0.05 \text{ deg/s}$ along each axis

**Modified COMPASS Controller**

The Modified COMPASS Controller was simulated with the same conditions as its nadir-pointing counterpart, with the target set to Fayetteville, AR, at 36.0625° N, 94.1575° W and an altitude of 427 m. The satellite’s attitude was quickly adjusted to align the measured magnetic field with the expected magnetic field for target-pointing, though the expected magnetic field exhibited oscillatory behavior for reasons which are unclear (Figure 6-a). Figure 6-c shows the satellite’s pointing location over time compared to the target location. While the satellite appears to miss the target entirely, this can be explained in part by the fact that for some periods of its orbit, the target is not within the satellite’s line of sight at all, but rather obscured from its view by the Earth. For this reason, the satellite’s secondary pointing location was calculated as the
intersection of the satellite’s pointing direction with the surface of the Earth opposite from the satellite’s position. This result is much more accurate, with the satellite’s pointing location passing and remaining near the target on multiple occasions (Figure 6-d).

(a) Magnetic field measured from the satellite compared to expected magnetic field for a target-pointing satellite

(b) Angular velocity of the satellite – individual components and total magnitude
(c) Longitude and latitude of the satellite’s pointing location over time compared to the target pointing position

(d) Longitude and latitude of the satellite’s secondary pointing location over time compared to the target pointing position

Figure 6. Data from the Modified COMPASS Controller with $K = 30,000 \frac{A \cdot m^2 \cdot s}{T}$

and $C = 5,000 \frac{A \cdot m^2}{T}$, simulated with $\omega_l = 0.05 \ deg/s$ along each axis
RESULTS AND DISCUSSION

From the simulation results, each of the detumbling algorithms was found to be successful in achieving its goal. Most notably, the Proportional B-Dot Controller with $K = 30,000 \frac{A \cdot m^2 \cdot s}{T}$ achieved a reduction of the satellite’s angular velocity from 10 deg/s to 1 deg/s along each axis in approximately 10 minutes with the residual total angular velocity reaching a minimum of 0.2 deg/s after 120 minutes. The Bang-Bang B-Dot Controller achieved the same reduction in angular velocity in just under 10 minutes with a minimum residual angular velocity of 0.9 deg/s after 120 minutes. While not anticipated to be utilized on ARKSAT-1 due to its lack of a reaction wheel, the Follow B-Field Controller successfully aligned the z-axis of the satellite with the magnetic field vector, reaching and maintaining an angular speed of 3.1 deg/s after 10 minutes. In summary, the Proportional B-Dot Controller demonstrated the best performance for minimizing the residual rotation rate of the satellite, while the Bang-Bang B-Dot Controller achieved a slightly faster initial reduction of angular velocity.

The simulation results indicate that the pointing algorithms were mostly successful, with some margin of error. Aside from errors caused by the implementation of the algorithm, the COMPASS Controller performed well, achieving near-nadir-pointing in approximately 30 minutes from an arbitrary initial angular velocity and pointing direction. After accounting for the visibility of the target from the satellite, the Modified COMPASS Controller also showed promising results, passing and remaining near the target on multiple occasions after roughly 15 minutes. While the modified controller was unable to maintain a consistent track on the target position, it is believed that with some further modification and investigation, the reliability and accuracy can be greatly improved.
Notable deviations from the expected results included the alignment of the satellite’s axis of rotation with the magnetic field produced by the Bang-Bang B-Dot Controller as well as the oscillation of the target magnetic field vector in the simulation of the Modified COMPASS Controller. Additional simulations as well as physical testing of ARKSAT-1 may be conducted in the future to further investigate these results. Additionally, errors caused by the implementation of the simulation in MATLAB should be investigated, such as the discontinuities in the measured magnetic field vector that appear to occur as the satellite passes through ±180 deg longitude. By further optimizing and reducing errors in the code used to perform the simulations, the accuracy of the results could be significantly improved.
CONCLUSIONS AND RECOMMENDATIONS

Conclusions

• Three types of B-Dot control algorithms were simulated using MATLAB and found to be successful in detumbling the satellite; in particular, all three algorithms reduced the angular velocity of the satellite from 10 deg/s to 1 deg/s along each axis within 10 minutes, with the Proportional B-Dot Controller achieving a minimum residual angular speed of 0.2 deg/s after 120 minutes.

• The COMPASS Controller along with a version modified for ARKSAT-1 were also simulated, and both showed promising performance for the applications of nadir- and target-pointing.

• Further investigation will include optimization of the simulations to improve accuracy of the results, in addition to both ground and in-orbit testing of the controllers onboard ARKSAT-1.

Recommendations

Physical Testing

While the simulation results presented here demonstrate the effectiveness of the control algorithms used, no simulation can perfectly replicate the actual environment of the satellite. For this reason, testing will be conducted once implementation of the ADCS onboard ARKSAT-1 is completed. This testing will include controlled ground-based testing of the controllers in addition to live testing of the effects of the controllers after release from the ISS.
Additional Control Algorithms

A vast array of control algorithms exist that utilize more complex control theory to perform very specific functions. In addition to investigating existing control algorithms, new ones could be developed to better achieve the desired functions for ARKSAT-1. For example, it is possible that a control algorithm could be designed to account for the predicted motion of the satellite and preemptively adjust the magnetic torquer outputs to improve pointing accuracy, rather than reacting only to the immediate satellite position and local magnetic field. Furthermore, if the ARKSAT series of satellites is intended to eventually work in pairs with one emitter and one receiver, the ADCS of each satellite must be able to locate the position of the other and perform attitude control maneuvers to maintain a target lock.
REFERENCES


