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**Attitude Determination With Magnetometers  
for Gun-Launched Munitions**

**by Michael J. Wilson**

**ARL-TR-3209**

**August 2004**

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## **Attitude Determination With Magnetometers for Gun-Launched Munitions**

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## 1. Introduction

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Recent advances in digital signal processor (DSP) technology provide the capability for low cost, real-time processing of navigation sensors. Attitude determination is a critical element of a guidance, navigation, and control (GN&C) system, which can be implemented with DSPs. The requirements for GN&C systems on board gun-launched munitions exclude many traditional attitude determination systems. Such systems typically use rate gyroscopes that are high cost and not well suited to munitions with high spin rates. This report proposes an attitude determination system that employs magnetometers and angular rate sensors with a DSP to provide a complete solution for all three Euler angles that describe the attitude of a projectile. The proposed system fulfills the requirements of passive sensing, high-g survivability, small size, low cost, and low power.

Magnetometers have been used to estimate partial attitude information through the post-processing of flight data (*I*). The proposed system is designed to operate in real time and provide a full attitude solution. It uses three magnetometers aligned within the projectile so that the first is aligned with the spin axis and the other two are aligned orthogonally to the first and to each other. Each sensor output is proportional to the component of the magnetic field in the direction of the sensitive axis of the sensor. The magnetometer triad therefore resolves the earth-fixed magnetic field vector in the projectile- or body-fixed coordinate system defined by the magnetometers' orientations. This naturally leads to a vector-matching algorithm to estimate the Euler angles.

The problem of solving for the direction cosine matrix (DCM) by matching two or more non-zero, non-collinear vectors in multiple coordinate frames was first published by Wabha in 1965 (2). (Two vector matches are required for a complete attitude solution.) Since then, several methods have been proposed to solve the vector-matching problem (for examples, see references (3, 4, 5)). Santoni and Bolotti devised an attitude determination system using magnetometers and solar panels (6). These approaches were created for satellite applications when two or more vectors were known in the navigation and body frames. Psiaki (7) and Michalareas et al. (8) have spacecraft attitude determination systems that use only magnetometers. However, the filters used in these systems do not apply to projectiles. The proposed algorithm is different from all these because of a coordinate system transformation that allows angular rate sensors to naturally assist the attitude determination while keeping the system heavily dependent on magnetometers. This algorithm is therefore suitable for gun-launched munition applications, for which multiple vector matching is not readily available.

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## 2. Coordinate Systems and Parameters

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Many coordinate systems exist for describing projectile motion (9). All parameters of interest considered here are resolved in an earth-fixed Cartesian reference frame  $\{X_n, Y_n, Z_n\}$ . This system is usually chosen to be the north, east, down system: the  $X_n$  axis points northward in a local plane tangential to the earth's surface. Likewise, the  $Y_n$  axis points eastward. The right-handed system is completed with the  $Z_n$  axis pointing toward the center of the earth. The subscript  $n$  will denote this navigation frame  $\{X_n, Y_n, Z_n\}$ . Let  $\{X_b, Y_b, Z_b\}$  be a body-fixed Cartesian system with the  $X_b$  axis along the body's axis of symmetry or spin axis pointed in the direction of motion and the  $Y_b$  and  $Z_b$  oriented to complete the orthogonal right-handed system. The subscript  $b$  will denote this frame. Figure 1 shows both coordinate systems and the Euler angle relations between them.

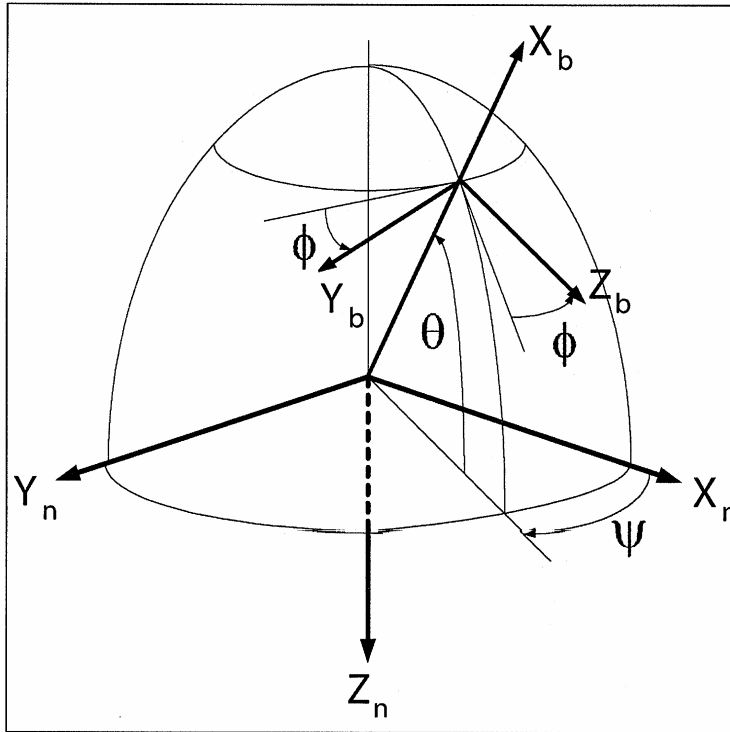


Figure 1. Euler sequence.

The transformation between the navigation frame and the body frame is now demonstrated. The navigation frame is first rotated about the  $Z_n$  axis through an azimuth angle  $\psi_{n \rightarrow b}$ . The system is then rotated about the new  $Y$  axis through an elevation angle  $\theta_{n \rightarrow b}$ . Finally, the system is rotated about the new  $X$  axis through a roll angle  $\phi_{n \rightarrow b}$ . The two systems are related by a DCM,  $C(\vec{\alpha}_{n \rightarrow b})$ , parameterized by the three Euler angles,  $\vec{\alpha}_{n \rightarrow b} = (\psi_{n \rightarrow b}, \theta_{n \rightarrow b}, \phi_{n \rightarrow b})^T$ . The form for the DCM is

$$C(\vec{\alpha}) = \begin{bmatrix} \cos(\psi)\cos(\theta) & \sin(\psi)\cos(\theta) & -\sin(\theta) \\ \left( \begin{array}{c} \cos(\psi)\sin(\theta)\sin(\phi) \\ -\sin(\psi)\cos(\phi) \end{array} \right) \left( \begin{array}{c} \sin(\psi)\sin(\theta)\sin(\phi) \\ +\cos(\psi)\cos(\phi) \end{array} \right) \cos(\theta)\sin(\phi) \\ \left( \begin{array}{c} \cos(\psi)\sin(\theta)\cos(\phi) \\ +\sin(\psi)\sin(\phi) \end{array} \right) \left( \begin{array}{c} \sin(\psi)\sin(\theta)\cos(\phi) \\ -\cos(\psi)\sin(\phi) \end{array} \right) \cos(\theta)\cos(\phi) \end{bmatrix}. \quad (1)$$

Let the angular velocity vector of the projectile-fixed system with respect to the earth-fixed system be denoted as  $\vec{\Omega}_b = (p, q, r)^T$ , in which  $p$  is the angular velocity of the  $Y_b$  and  $Z_b$  axes about the  $X_b$  axis;  $q$  is the angular velocity of the  $Z_b$  and  $X_b$  axes about the  $Y_b$  axis;  $r$  is the angular velocity of the  $X_b$  and  $Y_b$  axes about the  $Z_b$  axis.

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### 3. Flight Parameter Solution

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The algorithm to estimate the Euler angles that relate the body frame to the navigation frame is considered to use vector matching. A direct approach is considered, based on a transformation to an intermediate coordinate system. With magnetometer values and knowledge of the local magnetic field, the magnetic field vector can be matched in the earth- and body-fixed systems. The angular rate sensors are then used to determine the ambiguity that results from only one vector match.

Let  $\vec{H}_n$  and  $\vec{H}_b$  be the earth's magnetic field vector resolved in the navigation and body frames, respectively. The vectors are related by

$$\vec{H}_b = C(\vec{\alpha}_{n \rightarrow b}) \vec{H}_n \quad (2)$$

in which  $C(\vec{\alpha})$  is given by equation 1. Equation 2 represents three simultaneous equations involving  $\psi_{n \rightarrow b}$ ,  $\theta_{n \rightarrow b}$ , and  $\phi_{n \rightarrow b}$ . To simplify the solution, an intermediate coordinate system is introduced as in (10) that separates variables.

Let  $\{X_m, Y_m, Z_m\}$  be an earth-fixed Cartesian coordinate system so that the  $Z_m$  axis is in the direction of  $\vec{H}_n$ .  $\{X_m, Y_m, Z_m\}$  will be referred to as the magnetic coordinate system, and the subscript  $m$  will denote this frame. Let  $C(\vec{\alpha}_{n \rightarrow m})$  be the DCM that transforms from the navigation frame to  $\{X_m, Y_m, Z_m\}$ , and let  $C(\vec{\alpha}_{m \rightarrow b})$  be the DCM that transforms from  $\{X_m, Y_m, Z_m\}$  to the body frame where  $\vec{\alpha}_{m \rightarrow b} = (\psi_{m \rightarrow b}, \theta_{m \rightarrow b}, \phi_{m \rightarrow b})^T$ . Now since

$$\psi_{m \rightarrow b}(t) = \psi_{m \rightarrow b,0} + \int_{\tau=0}^t \frac{q(t) \sin[\phi_{m \rightarrow b}(t)] + r(t) \cos[\phi_{m \rightarrow b}(t)]}{\cos[\theta_{m \rightarrow b}(t)]} dt. \quad \vec{H}_m = (0, 0, 1)^T \quad (3)$$

by definition, using  $C(\vec{\alpha}_{m \rightarrow b})$  to transform  $\vec{H}_m$  into the body-fixed system results in the following three equations:

$$\vec{H}_{b,x} = -\sin(\theta_{m \rightarrow b}) \quad (4)$$

$$\vec{H}_{b,y} = \cos(\theta_{m \rightarrow b}) \sin(\phi_{m \rightarrow b}) \quad (5)$$

$$\vec{H}_{b,z} = \cos(\theta_{m \rightarrow b}) \cos(\phi_{m \rightarrow b}) \quad (6)$$

Since  $\vec{H}_b$  is known from the magnetometer sensor values,  $\theta_{m \rightarrow b}$  can be solved for as

$$\theta_{m \rightarrow b} = \arcsin(-H_{b,x}) \quad (7)$$

in which  $\arcsin(\bullet)$  is defined on the range  $\left(-\frac{\pi}{2}, \frac{\pi}{2}\right)$ . can then be solved for as

$$\phi_{m \rightarrow b} = \arctan\left(\frac{H_{b,y}}{H_{b,z}}\right) \quad (8)$$

in which  $\arctan(\bullet)$  is the four-quadrant arctan function.

Magnetometers alone cannot provide a complete attitude solution since  $\psi_{m \rightarrow b}$  cannot be determined. Angular rate sensors effectively provide measurements of the angular rates  $q$  and  $r$ . The angular rate vector,  $\vec{\Omega}_b = (p, q, r)^T$ , is related to the Euler rate vector,  $\dot{\vec{\alpha}}_m = (\dot{\phi}_m, \dot{\theta}_m, \dot{\psi}_m)^T$ , through the transformation

$$\dot{\vec{\alpha}} = \begin{bmatrix} 1 & \sin(\phi) \tan(\theta) & \cos(\phi) \tan(\theta) \\ 0 & \cos(\phi) & -\sin(\phi) \\ 0 & \frac{\sin(\phi)}{\cos(\theta)} & \frac{\cos(\phi)}{\cos(\theta)} \end{bmatrix} \vec{\Omega}_b. \quad (9)$$

The temporal derivative of  $\psi_{m \rightarrow b}$  is then

$$\dot{\psi}_{m \rightarrow b}(t) = \frac{q(t) \sin[\phi_{m \rightarrow b}(t)] + r(t) \cos[\phi_{m \rightarrow b}(t)]}{\cos[\theta_{m \rightarrow b}(t)]}. \quad (10)$$

We can then obtain  $\psi_{m \rightarrow b}$  by integrating  $\dot{\psi}_{m \rightarrow b}(t)$  with knowledge of the initial condition,  $\psi_{m \rightarrow b,0}$ :

$$\psi_{m \rightarrow b}(t) = \psi_{m \rightarrow b,0} + \int_{\tau=0}^t \dot{\psi}_{m \rightarrow b}(t) dt. \quad (11)$$

$C(\vec{\alpha}_{n \rightarrow b})$  can now be calculated with

$$C(\vec{\alpha}_{n \rightarrow b}) = C(\vec{\alpha}_{m \rightarrow b})C(\vec{\alpha}_{n \rightarrow s}) \quad (12)$$

### 3.1 Singular Points

Equation 8 is unreliable when  $H_{b,y}$  and  $H_{b,z}$  are both close to zero. This corresponds to singular points in the Euler angle attitude description when the spin axis of the projectile is in the direction of the earth's magnetic field or the opposite direction. Since  $\phi_s$  cannot be determined,  $\psi_s$  is also undefined. In many cases, this is not an issue since the projectile may never point in the singular direction throughout its flight. However, if this is not the case, the angular rate sensor output may be integrated to revise the last known stable solution until the magnetometer solution is again stable. Another rate sensor to determine spin rate would be required.

### 3.2 Algorithm Summary and DSP Implementation

Obtain  $\vec{H}_n$  from a magnetic model for the coordinates of the launch. Also obtain the initial azimuth in the magnetic coordinate system,  $\psi_{m,0}$ .

For each new set of sensor values, calculate  $\theta_m(t)$  and  $\phi_m(t)$  from the magnetometer values,  $\vec{H}_b$ , as

$$\theta_{m \rightarrow b}(t) = \arcsin[-H_{b,x}(t)] \quad (13)$$

$$\phi_{m \rightarrow b}(t) = \arctan\left[\frac{H_{b,y}(t)}{H_{b,z}(t)}\right]. \quad (14)$$

Then calculate the  $\psi_m(t)$  revision using the angular rate sensors as

$$\psi_{m \rightarrow b}(t) = \psi_{m \rightarrow b,0} + \int_{\tau=0}^t \frac{q(t) \sin[\phi_{m \rightarrow b}(t)] + r(t) \cos[\phi_{m \rightarrow b}(t)]}{\cos[\theta_{m \rightarrow b}(t)]} dt. \quad (15)$$

Form  $C(\vec{\alpha}_{m \rightarrow b})$  and use

$$C(\vec{\alpha}_{n \rightarrow b}) = C(\vec{\alpha}_{m \rightarrow b})C(\vec{\alpha}_{n \rightarrow s}) \quad (16)$$

to obtain the full attitude solution.

The above set of equations has been designed so that they are easily implemented in real time on a DSP. Each of the sensor's values is sampled in time at an appropriate rate. The elevation and roll angles and the derivative of the azimuth angle only depend on the current sensor samples and are therefore straightforward to implement. At each new sample point, the derivative of the azimuth angle times the sampling period is added to the previous azimuth angle. It is then possible to transform into any navigation frame.

## 4. Performance

Simulations were conducted with equations 13 through 16 on simulated flight data to evaluate performance. A 10-second flight on an M483 round was generated via CONTRAJ (control trajectory simulation) (11) with a gun elevation of 20 degrees and an initial muzzle velocity of 274 meters per second. From the generated flight data, the sensor values (magnetometers and rate sensors) were derived. Additive white Gaussian noise was then added to the sensor values at various noise powers. The proposed algorithm was then run to generate estimates of the Euler angles. Figure 2 plots the angular rates throughout the flight as measured by the sensors at a 37-dB signal-to-noise ratio (SNR)<sup>1</sup>. Likewise, figure 3 plots the magnetometer output at the same SNR.

The orthogonality of the spin axis to the earth's magnetic field is demonstrated in the first graph of figure 3, which is effectively the inner product between the two vectors. The algorithm works best when the two vectors are orthogonal. This simulation demonstrates the performance of the algorithm when this is not the case.

Figures 4 through 7 plot the actual and estimated Euler angles and the corresponding error throughout the flight. Figure 8 shows the performance of the algorithm for this simulation by plotting the mean square error of the Euler angles as a function of the SNR.

<sup>1</sup>Expected SNRs are 60 dB.

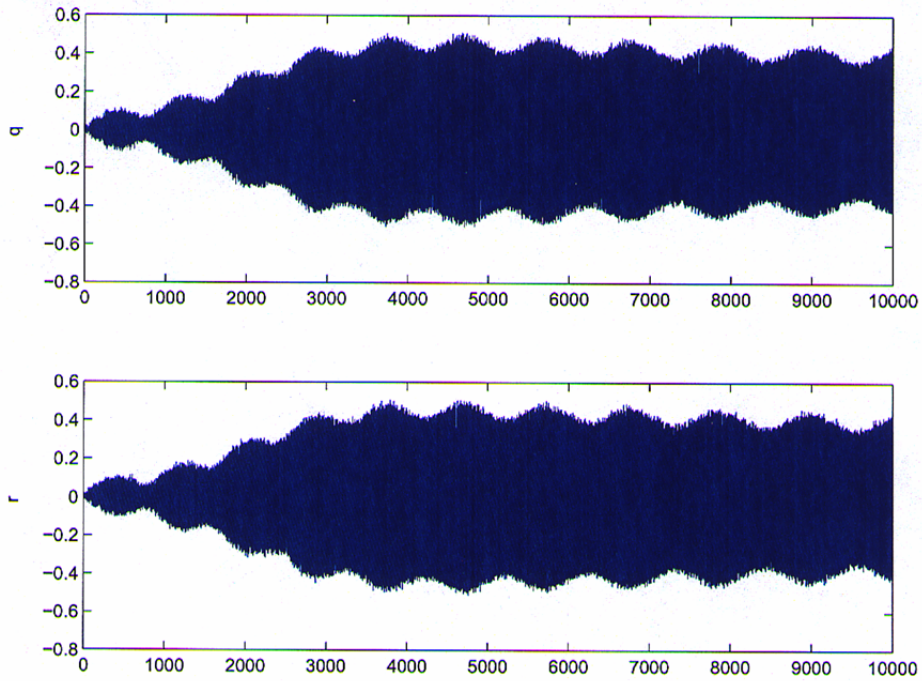


Figure 2.  $q$  and  $r$  for M483 simulation.

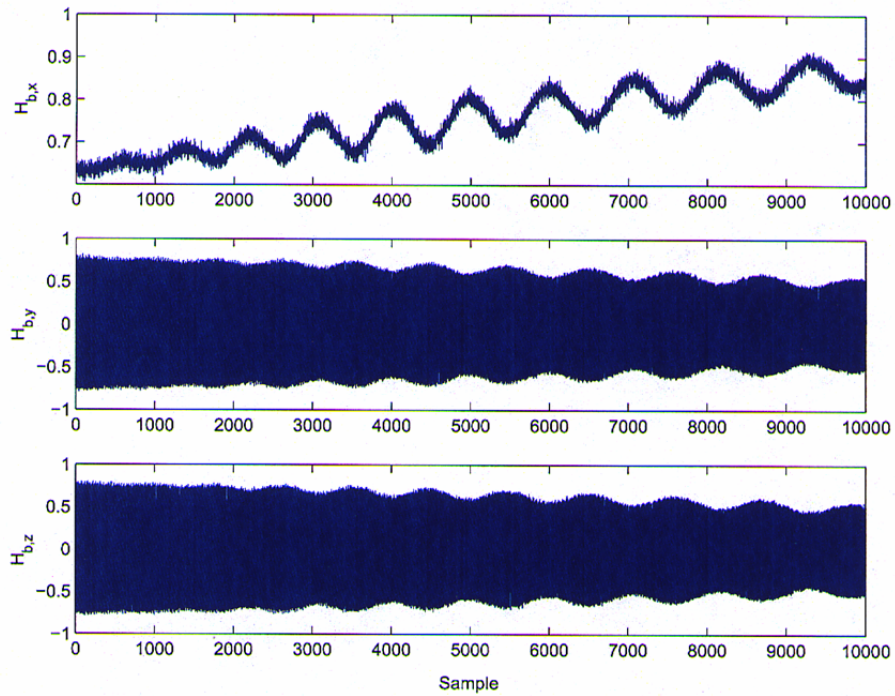


Figure 3. Magnetometer output for M483 simulation.

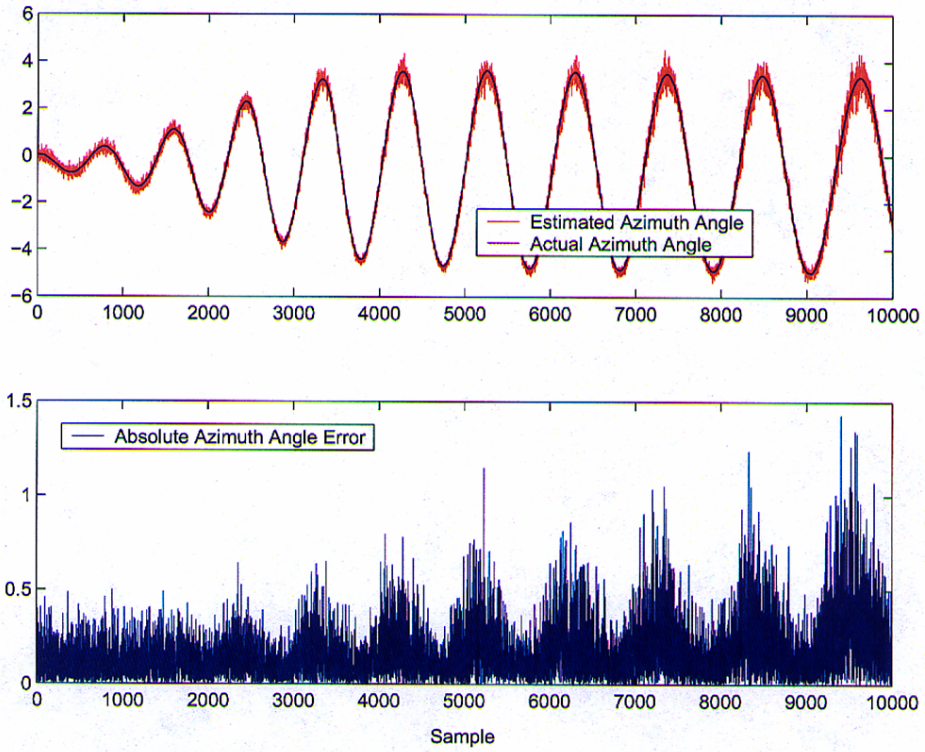


Figure 4. Azimuth angle ( $\psi$ ) for M483 simulation.

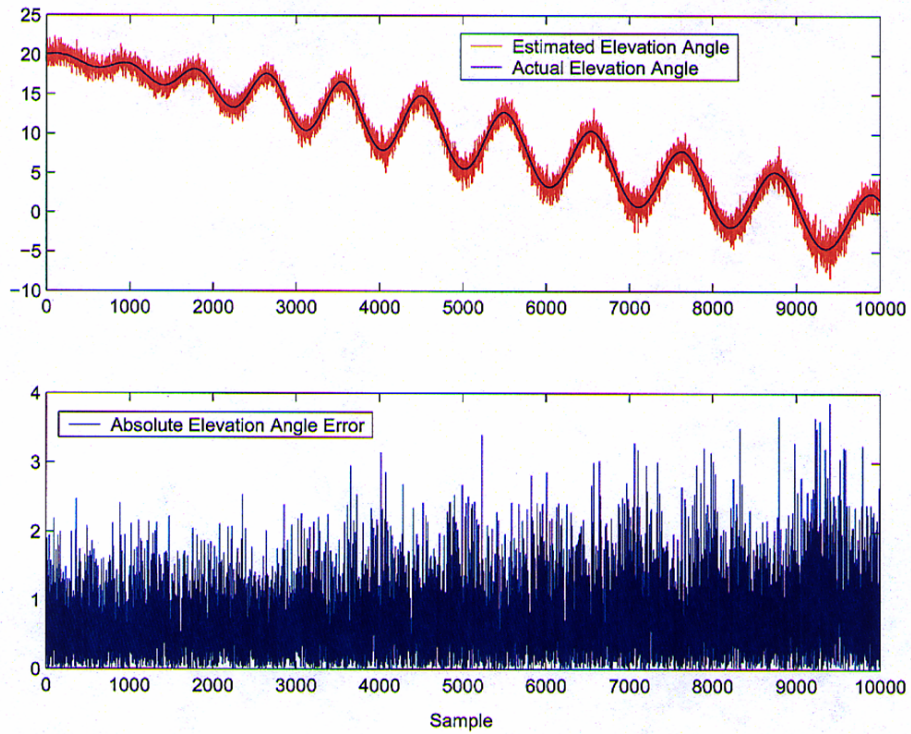


Figure 5. Elevation angle ( $\theta$ ) for M483 simulation.

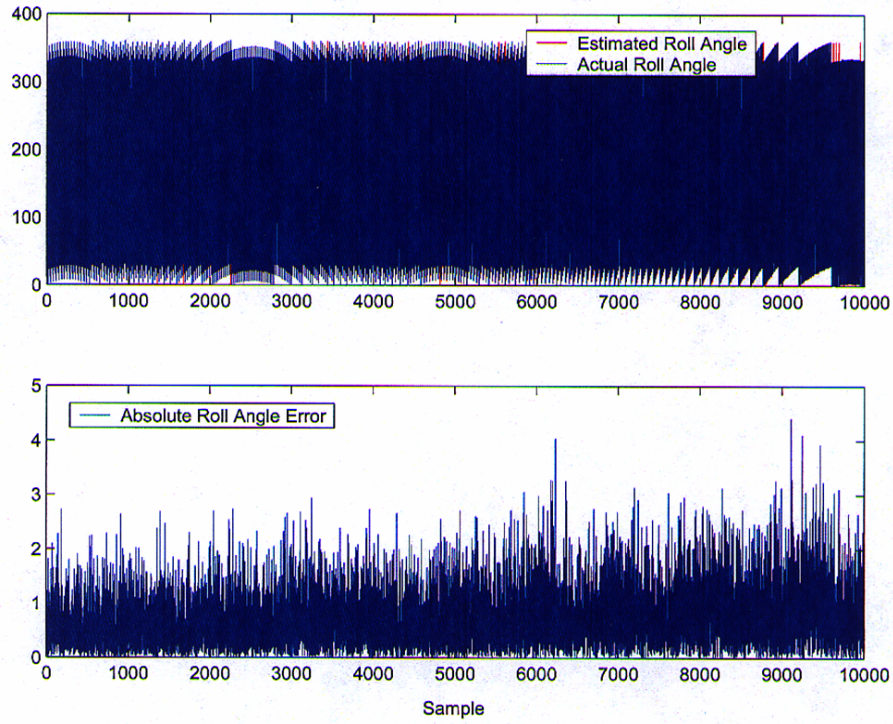


Figure 6. Roll angle ( $\phi$ ) for M483 simulation.

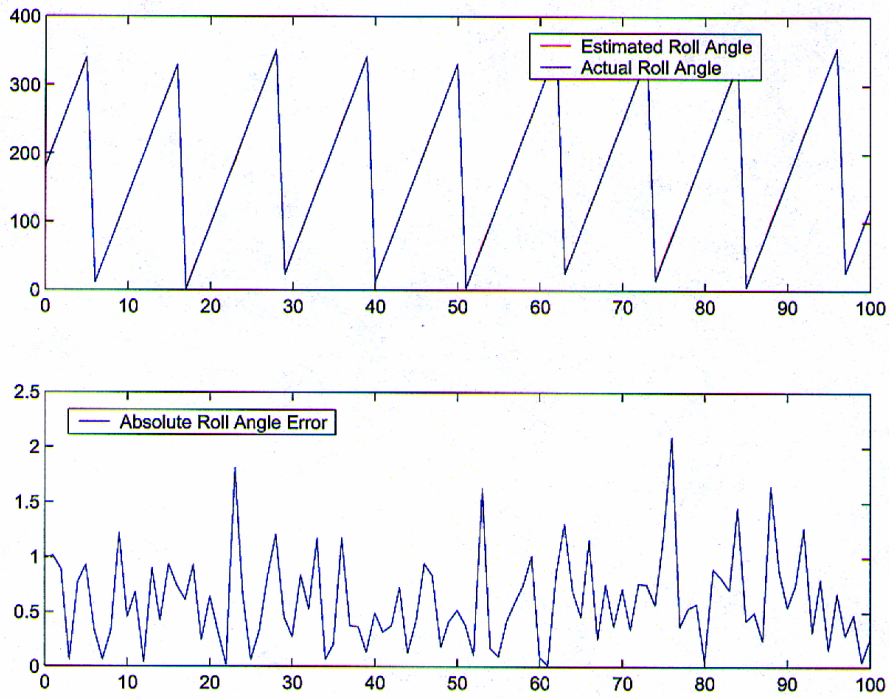


Figure 7. Roll angle ( $\phi$ ), first 100 samples.

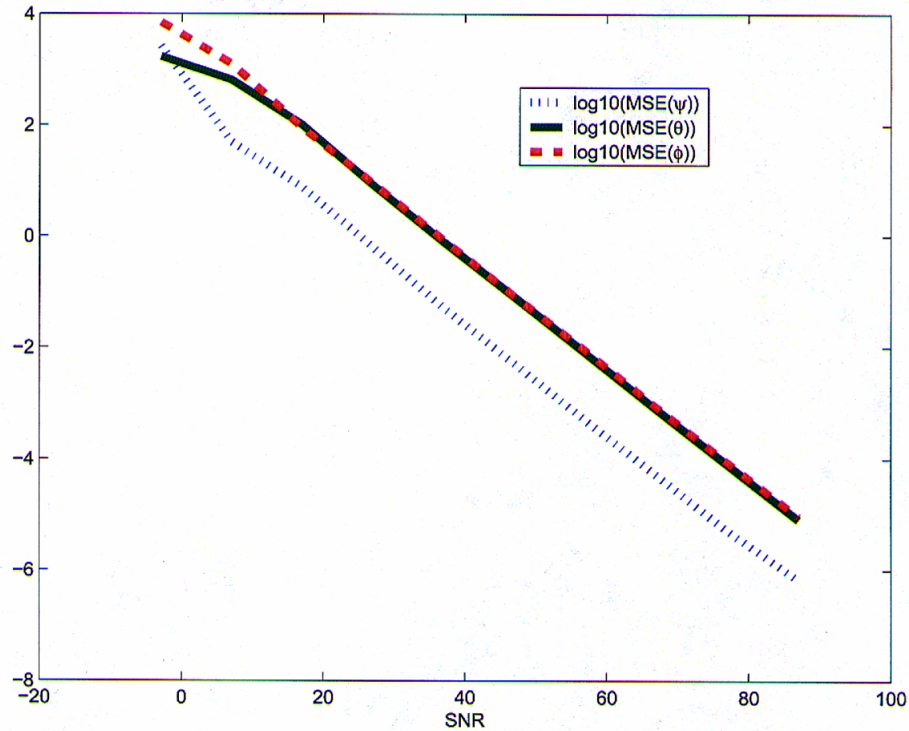


Figure 8. Mean square error for Euler angles.

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## 5. Conclusion

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The proposed algorithms have been demonstrated to be successful in determining a full attitude solution. The example given shows the performance in a low SNR environment for a high arc trajectory munition. Flat fire munitions would provide even better performance since the spin axis would stay more orthogonal to the earth's magnetic field. Programs such as the Defense Advanced Research Projects Agency's SCORPION (self-correcting projectile for infantry operations) can use the proposed system for attitude determination since only magnetometers and rate sensors are required.

The algorithm has been implemented on a DSP with low cost, high-g qualified magnetometers and angular rate sensors in a configuration similar to a diagnostic fuze (12). The system satisfies the design requirements for gun-launched munitions and can provide attitude for various projectile dynamics.

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A MOLINA  
PICATINNY ARSENAL NJ 07806-5000

1 CDR US ARMY TACOM ARDEC  
ATTN SFAE SDR SW IW B  
D AHMAD  
BLDG 151  
PICATINNY ARSENAL NJ 07806-5000

1 CDR US ARMY TACOM ARDEC  
ATTN SFAE AMO CAS EX  
C GRASSANO  
BLDG 171A  
PICATINNY ARSENAL NJ 07806-5000

1 CDR US ARMY TACOM ARDEC  
ATTN SFAE AMO MAS SMC  
R KOWALSKI  
PICATINNY ARSENAL NJ 07806-5000

1 CDR US ARMY TACOM ARDEC  
ATTN SFAE AMO MAS LC  
D COLLETT  
BLDG 354  
PICATINNY ARSENAL NJ 07806-5000

4 PRODUCT MANAGER FOR MORTARS  
ATTN SFAE AMO CAS MS G BISHOP  
J TERHUNE P BURKE D SUPER  
BLDG 162 SOUTH  
PICATINNY ARSENAL NJ 07806-5000

3 CDR US ARMY TACOM ARDEC  
ATTN SFAE AMO CAS R KIEBLER  
M MORATZ A HERRERA  
BLDG 162 SOUTH  
PICATINNY ARSENAL NJ 07806-5000

1 PROD MGR FOR JOINT LW 155-MM HOW  
ATTN SFAE GCS JLW J SHIELDS  
BLDG 151  
PICATINNY ARSENAL NJ 07806-5000

NO. OF  
COPIES ORGANIZATION

1 DIR M109A6 PALADIN/M992A2 FAASV  
ATTN PEO GROUND COMBAT SYSTEMS  
K HURBAN  
BLDG 171 NORTH  
PICATINNY ARSENAL NJ 07806-5000

3 US ARMY OPERATIONAL TEST CMD  
ATTN CSTE OTC CC M HAYNES  
J KOLLER K HENDERSON  
91012 STATION AVE  
FORT HOOD TX 76544-5068

5 CDR NAVAL SURF WARFARE CTR  
ATTN G22 R GAMACHE  
G32 ELLIS G32 M BOTTASS  
G33 J FRAYSSE G33 T TSCHIRN  
17320 DAHLGREN ROAD  
DAHLGREN VA 22448-5100

6 CDR NAVAL SURF WARFARE CTR  
ATTN G34 M TILL G34 H WENDT  
G34 M HAMILTON S POMEROY  
G34 S CHAPPELL G34 H MALIN  
17320 DAHLGREN ROAD  
DAHLGREN VA 22448-5100

3 CDR NAVAL SURF WARFARE CTR  
ATTN G34 J LEONARD G34 W WORRELL  
G34 M ENGEL  
17320 DAHLGREN ROAD  
DAHLGREN VA 22448-5100

4 CDR NAVAL SURF WARFARE CTR  
ATTN G61 E LARACH G61 M KELLY  
G61 A EVANS G5 D HAGEN  
17320 DAHLGREN ROAD  
DAHLGREN VA 22448-5100

1 CDR OFC OF NAVAL RSCH  
ATTN CODE 333 P MORRISSON  
800 N QUINCY ST RM 507  
ARLINGTON VA 22217-5660

1 DIR NAVAL AIR SYSTEMS CMD  
TEST ARTICLE PREP DEP  
ATTN CODE 5 4 R FAULSTICH  
BLDG 1492 UNIT 1  
47758 RANCH RD  
PATUXENT RIVER MD 20670-1456

1 CDR NAWC WEAPONS DIV  
ATTN CODE 543200E G BORGEN  
BLDG 311  
POINT MUGU CA 93042-5000

NO. OF  
COPIES ORGANIZATION

1 CDR NAVSEA  
ATTN CODE 6024 M SIMMS  
BLDG 2940W  
CRANE IN 47522

1 CDR NAVAL AIR WARFARE CTR  
WEAPONS DIVISION  
ATTN CODE C3904 S MEYERS  
CHINA LAKE CA 93555-6100

2 PROGRAM MANAGER ITTS  
PEO-STRI  
ATTN AMSTI EL D SCHNEIDER  
C GOODWIN  
12350 RESEARCH PKWY  
ORLANDO FL 32826-3276

1 CDR US ARMY  
YUMA PROVING GROUND  
ATTN CSTE DTC YP YT ED M LAUSS  
YPG AZ 85365-9498

2 CDR US ARMY  
YUMA PROVING GROUND  
ATTN CSTE DTC YP MT EW D HO  
I GOODE  
YPG AZ 85365-9498

1 CDR US ARMY  
YUMA PROVING GROUND  
ATTN CSTE DTC YP YT GC EV  
B AYNES  
YPG AZ 85365-9498

1 CDR US ARMY  
YUMA PROVING GROUND  
ATTN STEYP TD ATO A HART  
YPG AZ 85365-9106

2 CDR US ARMY RDEC  
ATTN AMSRD AMR SG SD P JENKINS  
AMSRD AMR SG SP P RUFFIN  
BLDG 5400  
REDSTONE ARSENAL AL 35898-5247

3 CDR US ARMY RDEC  
ATTN AMSRD AMR SG NC V LEFEVRE  
S BURGETT C ROBERTS  
BLDG 5400  
REDSTONE ARSENAL AL 35898-5247

NO. OF  
COPIES ORGANIZATION

2 CDR US ARMY RDEC  
ATTN AMSRD AMR WS P ASHLEY  
AMSRD AMR WS DP B ROBERTSON  
BLDG 7804  
REDSTONE ARSENAL AL 35898-5247

1 CDR US ARMY RDEC  
ATTN AMSRD AMR AS AC  
G HUTCHESON  
BLDG 5400  
REDSTONE ARSENAL AL 35898-5247

2 DIR US ARMY RTTC  
ATTN STERT TE F TD R EPPS  
ATTN CSTE DTC RT F TD (B 7855)  
S HAATAJA  
REDSTONE ARSENAL AL 35898-8052

1 CDR US ARMY RDEC  
ATTN AMSRD AMR WS ID T HUDSON  
BLDG 5400  
REDSTONE ARSENAL AL 35898-5247

1 CDR WEST DESERT TEST CENTER  
US ARMY DUGWAY PROVING GND  
ATTN CSTE DTC DP WD MU T  
M BULLETT  
DUGWAY UT 84022-5000

1 CDR AFRL/MNMF  
ATTN S ROBERSON  
306 W EGLIN BLVD STE 219  
EGLIN AFB FL 32542-6810

1 DARPA/MTO  
ATTN C NGUYEN  
3701 N FAIRFAX DRIVE  
ARLINGTON VA 22203-1714

1 OSD DOT&E R&R  
ATTN W ATTERBURY  
1700 DEFENSE PENTAGON  
WASHINGTON DC 20301-1700

2 OSD DOT&E  
CTEIP PROGRAM OFFICE  
ATTN J TEDESCHI D HINTON  
4850 MARK CENTER DRIVE  
ALEXANDRIA VA 22311

2 IDA SCIENCE AND TECH DIV  
ATTN H LAST K WALZL  
4850 MARK CENTER DRIVE  
ALEXANDRIA VA 22311-1882

NO. OF  
COPIES ORGANIZATION

1 ARROW TECH ASSOCIATES  
ATTN W HATHAWAY  
1233 SHELburnE RD STE 8  
SOUTH BURLINGTON VT 05403

1 CAMBER CORP  
ATTN W CHIUSANO  
200 VALLEY RD SUITE 403  
MOUNT ARLINGTON NJ 07856

5 ALLIANT TECHSYSTEMS  
ATTN A GAUZENS J MILLS  
B LINDBLOOM E KOSCO  
D JACKSON  
PO BOX 4648  
CLEARWATER FL 33758-4648

2 ALLIANT TECHSYSTEMS  
ATTN C CANDLAND R DOHRN  
5050 LINCOLN DR  
MINNEAPOLIS MN 55436-1097

2 ALLIANT TECHSYSTEMS  
ATTN G PICKUS F HARRISON  
4700 NATHAN LANE NORTH  
PLYMOUTH MN 55442

7 ALLIANT TECHSYSTEMS  
ALLEGANY BALLISTICS LAB  
ATTN S OWENS C FRITZ J CONDON B NYGA  
J PARRILL M WHITE S MCCLINTOCK  
MAIL STOP WV01-08 BLDG 300 RM 180  
210 STATE ROUTE 956  
ROCKET CENTER WV 26726-3548

2 SAIC  
ATTN J DISHON G PHILLIPS  
16701 W BERNARDO DR  
SAN DIEGO CA 92127

3 SAIC  
ATTN J GLISH J NORTHRUP  
G WILLENBRING  
8500 NORMANDEALE LAKE BLVD  
SUITE 1610  
BLOOMINGTON MN 55437-3828

1 SAIC  
ATTN M PALMER  
1410 SPRING HILL RD STE 400  
MCLEAN VA 22102

NO. OF  
COPIES ORGANIZATION

1 SAIC  
ATTN D HALL  
1150 FIRST AVE SUITE 400  
KING OF PRUSSIA PA 19406

2 ROCKWELL COLLINS  
ATTN M JOHNSON R MINOR  
350 COLLINS RD NE  
CEDAR RAPIDS IA 52498

2 JOHNS HOPKINS UNIV  
APPLIED PHYSICS LABORATORY  
ATTN W D'AMICO K FOWLER  
1110 JOHNS HOPKINS RD  
LAUREL MD 20723-6099

5 CHLS STARK DRAPER LAB  
ATTN J CONNELLY J SITOMER  
R POLUTCHKO T EASTERLY  
A KOUREPENIS  
555 TECHNOLOGY SQUARE  
CAMBRIDGE MA 02139-3563

2 ECIII LLC  
ATTN R GIVEN J SWAIN  
BLDG 2023E  
YPG AZ 85365

2 LOCKHEED MARTIN  
ATTN MP-562 S BISHOP  
MP-951 A WINDON  
5600 SAND LAKE RD  
ORLANDO FL 32819

1 LOCKHEED/MARTIN-SANDERS  
ATTN M CARLSON  
NCA1-2078 95 CANAL ST  
NASHUA NH 03061-0868

1 KAMAN AEROSPACE CORP  
RAYMOND ENGINEERING OPERATIONS  
ATTN D SPENCER  
217 SMITH ST  
MIDDLETOWN CT 06457-9990

2 RAYTHEON MISSILE SYSTEMS  
ATTN B PETERSON P VO  
MS12-4  
PO BOX 11337  
TUSCON AZ 85734-1337

NO. OF  
COPIES ORGANIZATION

- 2 RAYTHEON MISSILE SYSTEMS  
ATTN R GOURLEY D STREETER  
MS11-10  
PO BOX 11337  
TUSCON AZ 85734-1337
- 2 CUSTOM ANALYTICAL ENG SYSTEMS  
ATTN A ALEXANDER S ADAMS  
13000 TENSOR LANE NE  
FLINTSTONE MD 21530
- 9 UNITED DEFENSE LP  
ATTN C BIES T BLUMER B CITRO  
B ENGEL M HAFTON T MELODY  
S MILLER D MIERHOFFER J RUPERT  
4800 EAST RIVER RD MS380  
MINNEAPOLIS MN 55421-1498
- 1 ALION SCIENCE  
ATTN P KISATSKY  
12 PEACE RD  
RANDOLPH NJ 07861
- 1 PM MANEUVER AMMO SYS DIRECT FIRE  
ATTN SFAE AMO D J RICE  
PICATINNY ARSENAL NJ 07806-5000
- 1 PM CLOSE COMBAT SYSTEMS  
ATTN SFAE AMO MCD J C SUTTON  
PICATINNY ARSENAL NJ 07806-5000
- 1 PM COMBAT AMMO SYS INDIRECT FIRE  
ATTN SFAE AMO CAS N H SLEDGE JR  
BLDG 171  
PICATINNY ARSENAL NJ 07806-5000
- 1 PM MORTAR SYSTEMS  
ATTN SFAE AMO CAS MS A C KIRNES  
BLDG 162 SOUTH  
PICATINNY ARSENAL NJ 07806-5000
- 1 PM EXCALIBUR  
ATTN J K WILSON  
PICATINNY ARSENAL NJ 07806-5000
- 1 PM TMDE  
ATTN SFAE CSS ME T R B PAUL  
BLDG 5300 RM 5436  
REDSTONE ARSENAL AL 35898
- 1 PM NLOS CANNON/MORTAR  
ATTN SFAE GCS FCS NL J V DAY  
4800 E RIVER ROAD  
MINNEAPOLIS MN 55421

NO. OF  
COPIES ORGANIZATION

- 1 PM PRECISION GUIDED MUNITIONS  
ATTN SFAE MSL ML PGM S H LEE JR  
REDSTONE ARSENAL AL 35898-5700  
  
ABERDEEN PROVING GROUND
- 1 DIRECTOR  
US ARMY RSCH LABORATORY  
ATTN AMSRD ARL CI OK (TECH LIB)  
BLDG 4600
- 4 CDR US ARMY TACOM ARDEC  
ATTN AMSRD AAR AEF T  
R LIESKE J MATTS  
F MIRABELLE J WHITESIDE  
BLDG 120
- 1 CDR ABERDEEN TEST CENTER  
ATTN CSTE DTC AT TC M ZWIEBEL  
BLDG 400
- 2 CDR ABERDEEN TEST CENTER  
ATTN CSTE DTC AT FC S T GARCIA  
CSTE DTC AT CO J WALLACE  
BLDG 400
- 2 CDR ABERDEEN TEST CENTER  
ATTN CSTE DTC AT TD B K MCMULLEN  
CSTE DTC AT SL B D DAWSON  
BLDG 359
- 2 CDR ABERDEEN TEST CENTER  
ATTN CSTE DTC AT FC L R SCHNELL  
J DAMIANO  
BLDG 400
- 1 CDR ABERDEEN TEST CENTER  
ATTN CSTE DTC AT TD S WALTON  
BLDG 359
- 1 CDR USAEC  
ATTN CSTE AEC SVE B D SCOTT  
BLDG 4120
- 3 DIR USARL  
ATTN AMSRD ARL WM T ROSENBERGER  
AMSRD ARL WM B T KOGLER  
AMSRD ARL WM SG B RINGERS  
BLDG 4600
- 3 DIR USARL  
ATTN AMSRD ARL WM BD M NUSCA  
J COLBURN T COFFEE  
BLDG 390

NO. OF  
COPIES ORGANIZATION

- 18 DIR USARL  
ATTN AMSRD ARL WM BA D LYON  
J CONDON B DAVIS (5)  
T HARKINS D HEPNER  
G KATULKA M WILSON  
P MULLER P PEREGINO  
A THOMPSON T BROWN  
R HALL B PATTON  
M CHILDERS  
BLDG 4600
- 6 DIR USARL  
ATTN AMSRD ARL WM BC P PLOSTINS  
B GUIDOS P WEINACHT  
M BUNDY J NEWILL  
J GARNER  
BLDG 390
- 2 DIR USARL  
ATTN AMSRD ARL WM BF  
S WILKERSON H EDGE  
BLDG 390
- 2 DIR USARL  
ATTN AMSRD ARL WM MB  
J BENDER W DRYSDALE  
BLDG 390
- 6 DIR USARL  
ATTN AMSRD ARL WM T B BURNS  
ATTN AMSRD ARL WM TC R COATES  
R MUDD B SORENSEN  
R SUMMERS R PHILLABAUM  
BLDG 309