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Attitude Determination With Magnetometers for Gun-Launched Munitions

by Michael J. Wilson

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14. ABSTRACT

Recent advances in digital signal processors (DSPs) and low cost sensing technology provide the capability for on-board attitude (orientation) determination for gun-launched projectiles. A complete, real-time solution for all three Euler angles (azimuth, elevation, and roll) that describes a projectile's attitude is presented, which uses magnetometers and angular rate sensors processed by a DSP. Unlike attitude estimation systems that rely exclusively on costly rate gyroscopes, magnetometers are used to stabilize drift errors. The proposed system fulfills the requirements of passive sensing, high-g survivability, small size, low cost, and low power.

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1. Introduction

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 (*1*). 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.

2. Coordinate Systems and Parameters

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.

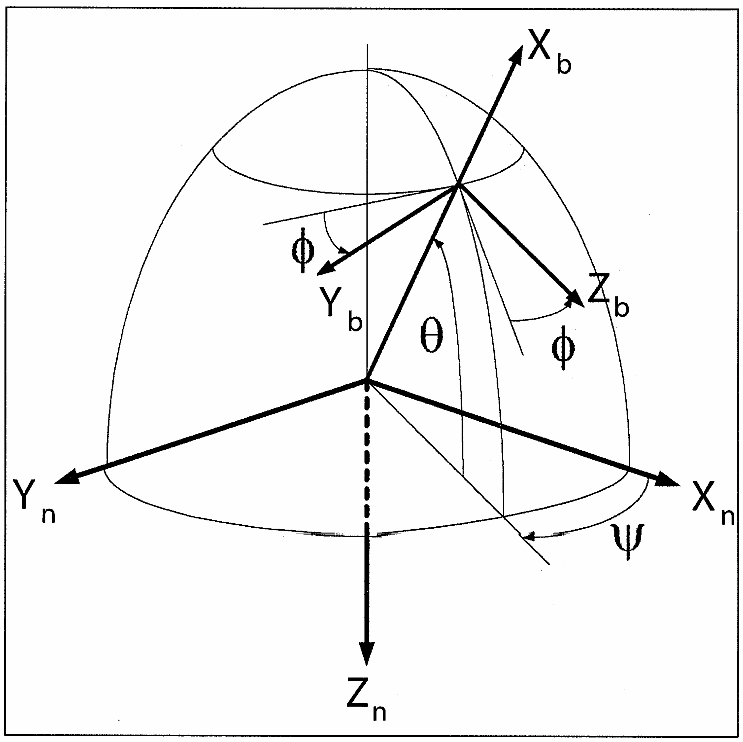

Figure 1. Euler sequence.

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 $\psi_{n\to b}$. The system is then rotated about the new Y axis through an elevation angle $\theta_{n\to b}$. Finally, the system is rotated about the new X axis through a roll angle $\phi_{n\to b}$. The two systems are related by a DCM, $C\left(\vec{\alpha}_{n\to b}\right)$, parameterized by the three Euler angles, $\vec{\alpha}_{n\to b} = \left(\psi_{n\to b}, \theta_{n\to b}, \phi_{n\to b}\right)^T$. The form for the DCM is

$$C(\vec{\alpha}) = \begin{bmatrix} \cos(\psi)\cos(\theta) & \sin(\psi)\cos(\theta) & -\sin(\theta) \\ \begin{pmatrix} \cos(\psi)\sin(\theta)\sin(\phi) \\ -\sin(\psi)\cos(\phi) \end{pmatrix} & \begin{pmatrix} \sin(\psi)\sin(\theta)\sin(\phi) \\ +\cos(\psi)\cos(\phi) \end{pmatrix} & \cos(\theta)\sin(\phi) \\ \begin{pmatrix} \cos(\psi)\sin(\theta)\cos(\phi) \\ +\sin(\psi)\sin(\phi) \end{pmatrix} & \begin{pmatrix} \sin(\psi)\sin(\theta)\cos(\phi) \\ -\cos(\psi)\sin(\phi) \end{pmatrix} & \cos(\theta)\cos(\phi) \end{bmatrix}. \tag{1}$$

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.

3. Flight Parameter Solution

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

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

in which $C(\vec{\alpha})$ is given by equation 1. Equation 2 represents three simultaneous equations involving $\psi_{n\to b}$, $\theta_{n\to b}$, and $\phi_{n\to b}$. 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 $C(\vec{\alpha}_{n\to m})$ be the DCM that transforms from the navigation frame to $\{X_m, Y_m, Z_m\}$, and let $C(\vec{\alpha}_{m\to b})$ be the DCM that transforms from $\{X_m, Y_m, Z_m\}$ to the body frame where $\vec{\alpha}_{m\to b} = (\psi_{m\to b}, \theta_{m\to b}, \phi_{m\to b})^T$. Now since

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

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

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

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

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

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

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

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

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

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

Magnetometers alone cannot provide a complete attitude solution since $\psi_{m\to b}$ 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

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

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

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

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

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

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

$$C(\vec{\alpha}_{n\to b}) = C(\vec{\alpha}_{m\to b})\,C(\vec{\alpha}_{n\to s}) \tag{12}$$

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 ϕ_s cannot be determined, ψ_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

$$\theta_{m\to b}(t) = \arcsin\left[-H_{b,x}(t)\right] \tag{13}$$

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

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

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

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

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

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)[1]. 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.

[1]Expected SNRs are 60 dB.

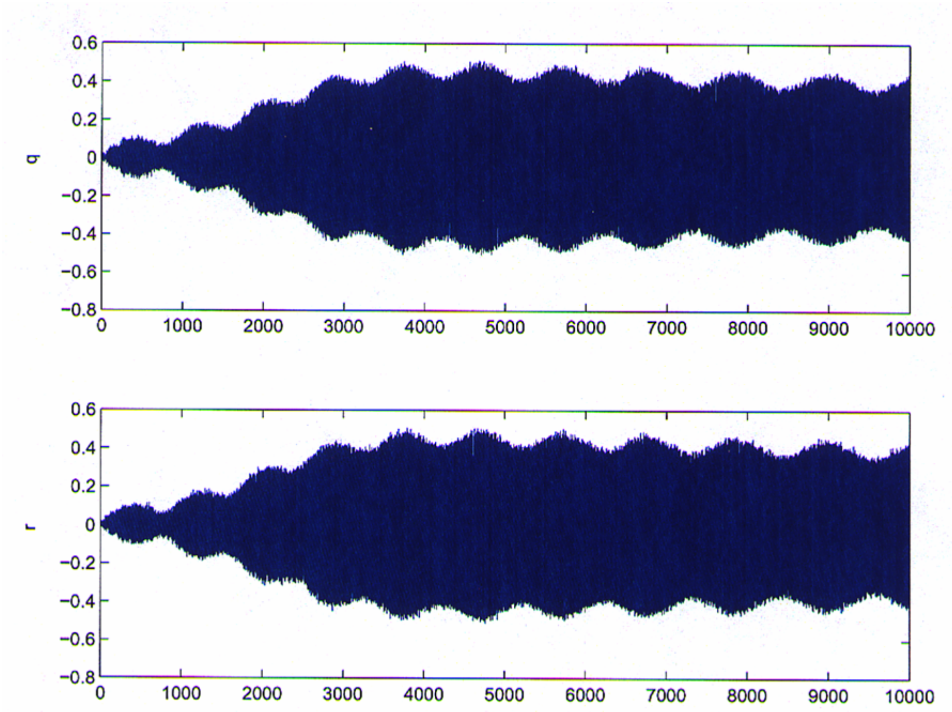

Figure 2. *q* and *r* for M483 simulation.

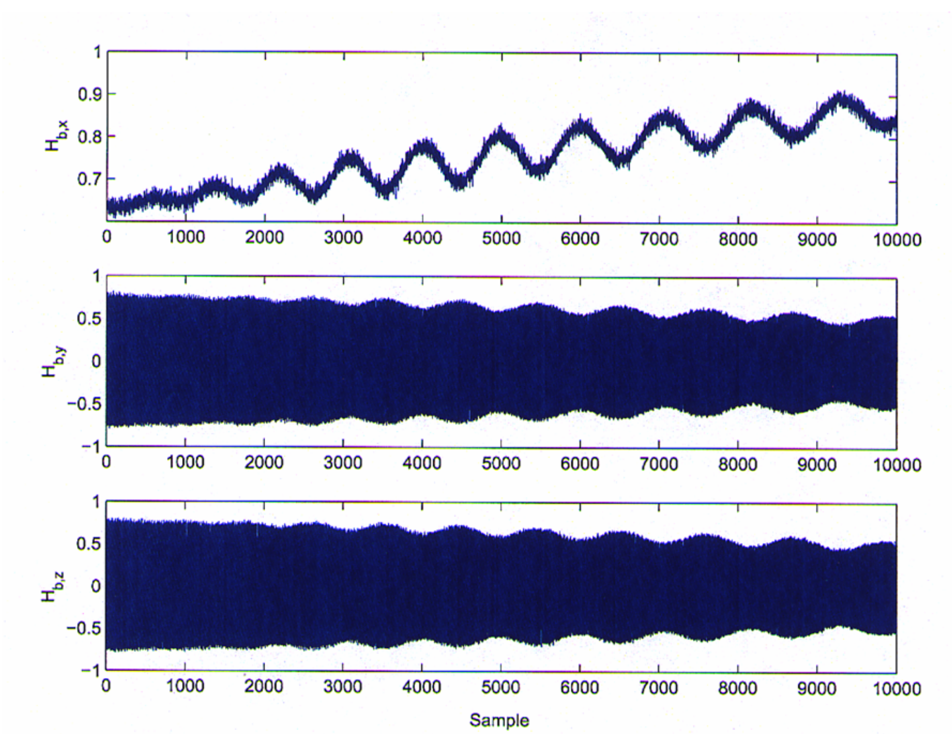

Figure 3. Magnetometer output for M483 simulation.

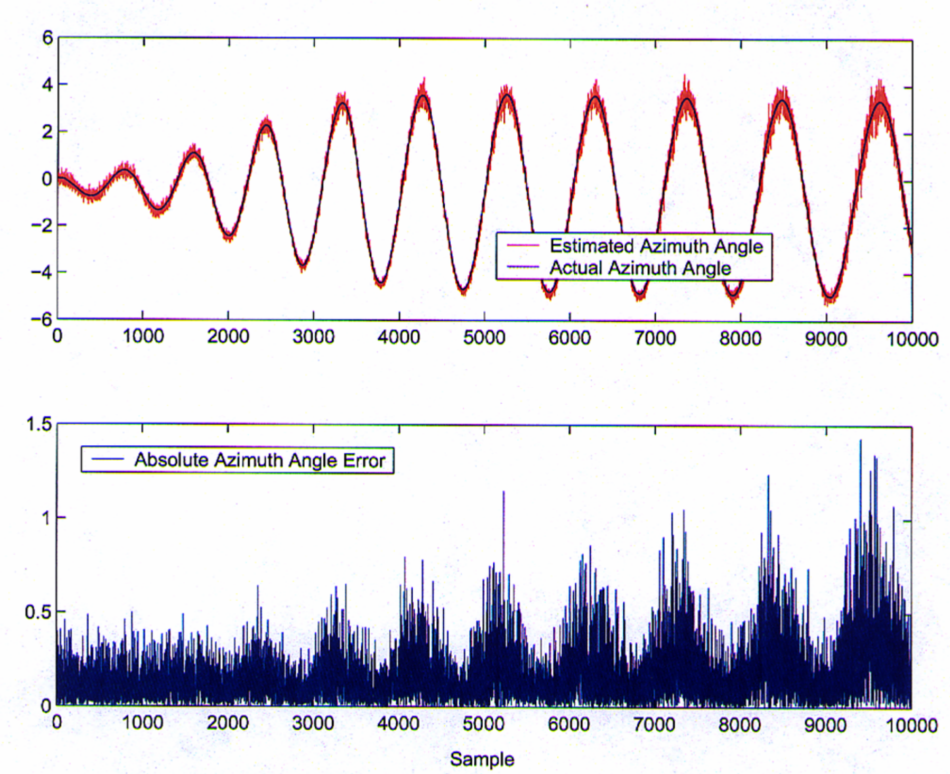

Figure 4. Azimuth angle (ψ) for M483 simulation.

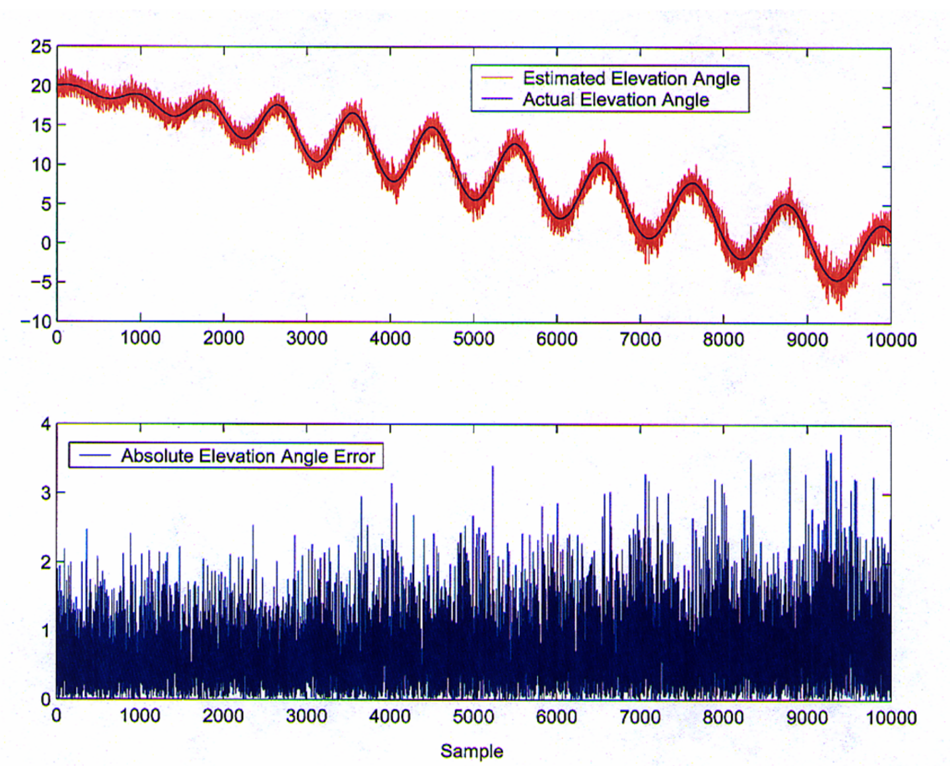

Figure 5. Elevation angle (θ) for M483 simulation.

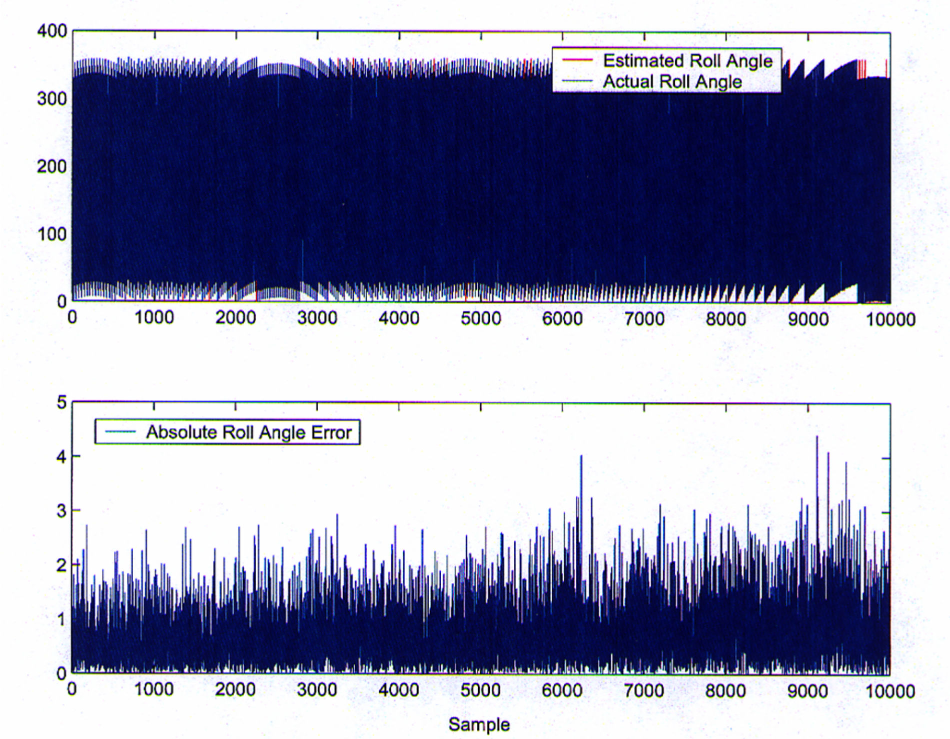

Figure 6. Roll angle (ϕ) for M483 simulation.

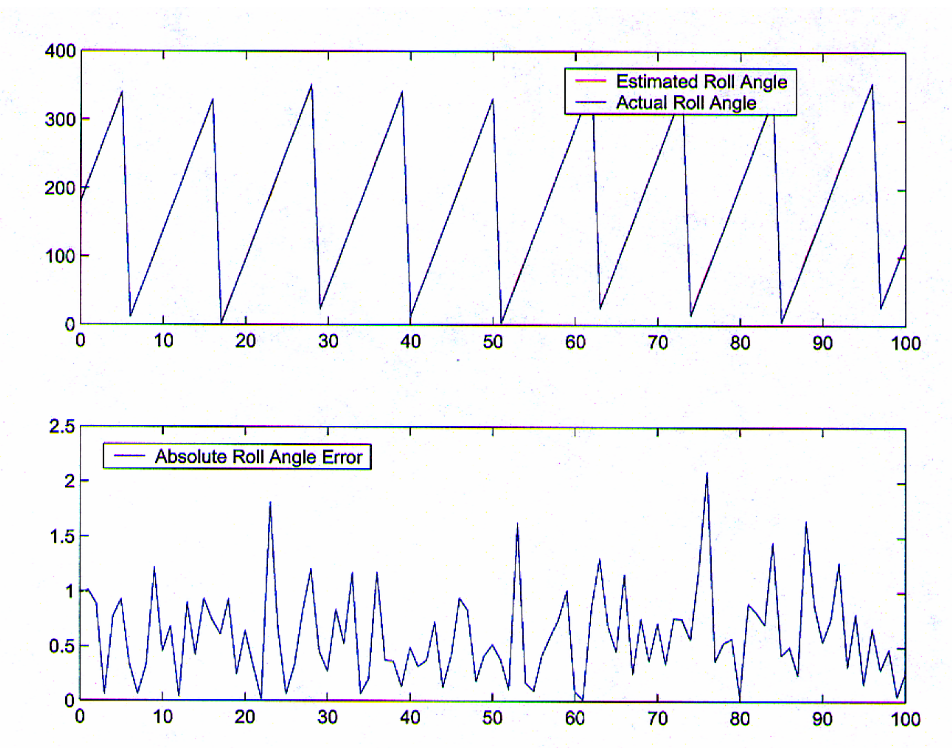

Figure 7. Roll angle (ϕ), first 100 samples.

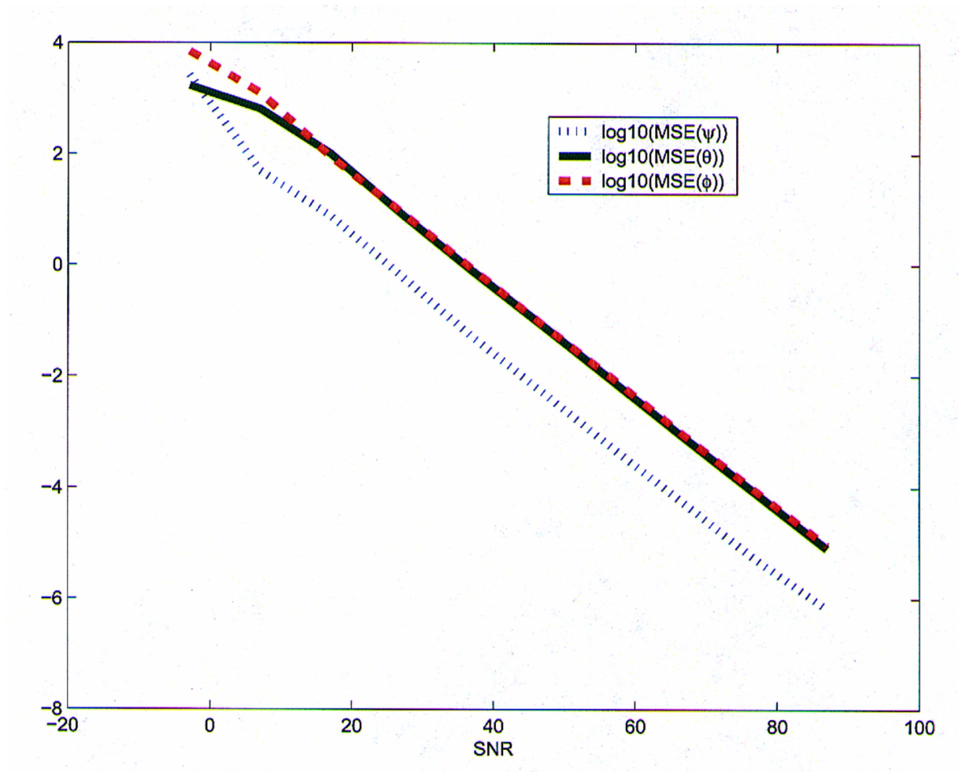

Figure 8. Mean square error for Euler angles.

5. Conclusion

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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