ITEA Journal 2009; 30: 117–125

Addressing the Challenges of a Thruster-Based Precision Guided Mortar Munition With the Use of Embedded Telemetry Instrumentation

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This article describes advancements made with the use of embedded telemetry instrumentation with a digital signal processor and shows the large volume of information that is available during flight tests. Unique measurement capabilities and analytical techniques used to determine and understand the Precision Guided Mortar Munition flight behavior during the thruster-based guided maneuvers will be highlighted. Ways in which these data were used to make key decisions influencing the projectile's aerodynamic design and guidance, navigation, and control algorithms are discussed. These revisions resulted in a more stable airframe and more accurate maneuvers, as evidenced by several successful guide-to-hit demonstrations.

Key words: Mortar; munition; telemetry; aerodynamics; thruster.

The XM395 Precision Guided Mortar Munition (PGMM) is a multipurpose laser-guided 120-mm mortar round designed to defeat personnel under protective cover (behind earth or timber bunkers, behind masonry walls, or within lightly armored vehicles). The PGMM is being developed by the U.S. Army Office of the Product Manager for Mortar Systems (PM Mortars) for the U.S. Army Infantry Center (combat proponent). Alliant Techsystems (ATK, Plymouth, Minnesota) is the prime contractor. The U.S. Army Tank-Automotive and Armaments Command and the Armaments, Development, Research, and Engineering Center are providing technical support. The U.S. Army Research Laboratory (ARL) was tasked with developing an integral telemetry module (ITM) that fits within the round and can be used throughout the development, test, and evaluation process. The ITM provides an independent measure of truth for flight motion, structural characterization, and aerodynamic coefficient estimation from its on-board inertial sensors.

PGMM description

The PGMM is equipped with a semi-active laser (SAL) seeker to guide and maneuver to its intended target with the use of advanced guidance, navigation, and control (GNC) processors and a control thrust

Report Documentation Page

Form Approved
OMB No. 0704-0188

1. REPORT DATE **MAR 2009**	2. REPORT TYPE	3. DATES COVERED **00-00-2009 to 00-00-2009**
4. TITLE AND SUBTITLE **Addressing the Challenges of a Thruster-Based Precision Guided Mortar Munition With the Use of Embedded Telemetry Instrumentation**		5a. CONTRACT NUMBER 5b. GRANT NUMBER 5c. PROGRAM ELEMENT NUMBER
6. AUTHOR(S)		5d. PROJECT NUMBER 5e. TASK NUMBER 5f. WORK UNIT NUMBER
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) **U.S. Army Research Laboratory,Aberdeen Proving Ground,MD,21005**		8. PERFORMING ORGANIZATION REPORT NUMBER
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)		10. SPONSOR/MONITOR'S ACRONYM(S) 11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release; distribution unlimited

13. SUPPLEMENTARY NOTES

14. ABSTRACT

15. SUBJECT TERMS

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT **unclassified**	b. ABSTRACT **unclassified**	c. THIS PAGE **unclassified**	**Same as Report (SAR)**	**9**	

Standard Form 298 (Rev. 8-98)
Prescribed by ANSI Std Z39-18

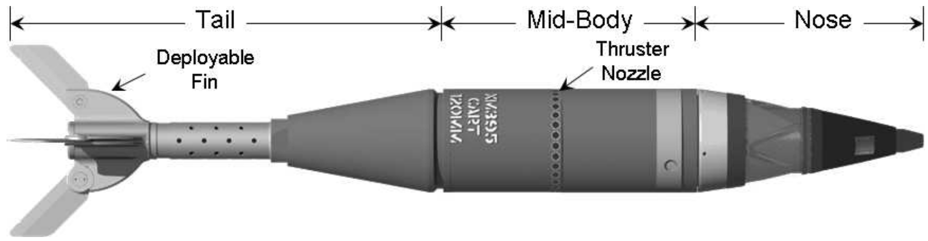

Figure 1. The XM395 Precision Guided Mortar Munition projectile flight configuration.

mechanism. The PGMM requires a human in the loop to designate the target and incorporates a blast fragmenting warhead with a variable delay fuze to provide high lethality against the intended target set. Designation is accomplished by any of the U.S. Department of Defense's laser designation devices (air, vehicle, or human transported). It will be compatible with all current and future 120-mm mortar systems. Its high accuracy will reduce collateral damage and decrease the logistics burden. After the fuze is programmed with time of flight, target type, and laser code of the day, it is fired much like any standard mortar cartridge via a five-zone charge system. The PGMM consists of three major assemblies (nose, mid-body, and tail) as shown in *Figure 1*.

Guided flight test program

Beginning in 2006, the PGMM program initiated a series of open-loop (preprogrammed) and closed loop (guide-to-hit) flight tests to characterize the projectile's performance and demonstrate its accuracy. During this guide-to-hit test campaign, the U.S. Army Office of the PM Mortars and ATK successfully demonstrated the world's first gun-launched, laser-guided mortar cartridge. One of the main contributors to its success was the timely, accurate, and thorough recording/transmission of in-flight performance information. This was made possible by the integration of a highly robust and reliable ITM. The ITM development was steered by a test and evaluation integrated product team providing inside knowledge of the schedule, technical issues, and test objectives.

ITM development and description

All flight-test rounds incorporated an ITM instrumentation system to collect and transmit on-board sensor and projectile mission data to a ground station for post-test analysis. The ITM (4.445 cm in diameter by 8.805 cm in length) provides an independent measure of truth for flight motion, structural characterization, and aerodynamic coefficient estimation from its on-board inertial sensors (see *Figure 2*). It also provides diagnostic information for ATK's on-board inertial sensors electronics unit, control thrust mechanism, warhead initiation module, SAL seeker, fuze function monitor, and flight thermal battery voltage monitor from the ITM's several input options (analog, digital, and low-speed and high-speed serial data). At the core of the ITM is a digital signal processor (DSP)–based telemetry system containing inertial sensor suite boards, a DSP encoder/formatter board, a transmitter board, and its own power supply. *Figure 3* shows the electrical block diagram of the ITM. The ITM's diagnostic functions for in-flight motion measurements are similar to those of other ARL telemetry systems (Davis et al., 2004; Wilson, Peregino, and Hall, 2006).

The ITM accommodates four channels of external analog input (0 to 5 volts direct current), 16 channels of external digital discrete input, and both low-speed and high-speed RS422 serial data input via two universal asynchronous receivers/transmitters. The asynchronous DSP encoder board enables reprogramming of the interfaces and telemetry frame format. The ITM has a 250-mW, S-band, phase-locked FM transmitter and uses a randomized non-return-to-zero-level (RNRZL-15) scheme. *Table 1* defines the various input and output of the ITM.

The ITM is installed into a portion of the warhead cavity located in the mid-body of the PGMM and

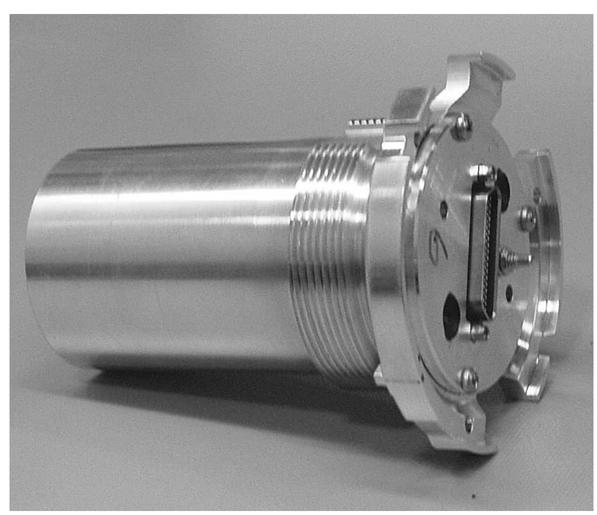

Figure 2. Integral telemetry module instrumentation package.

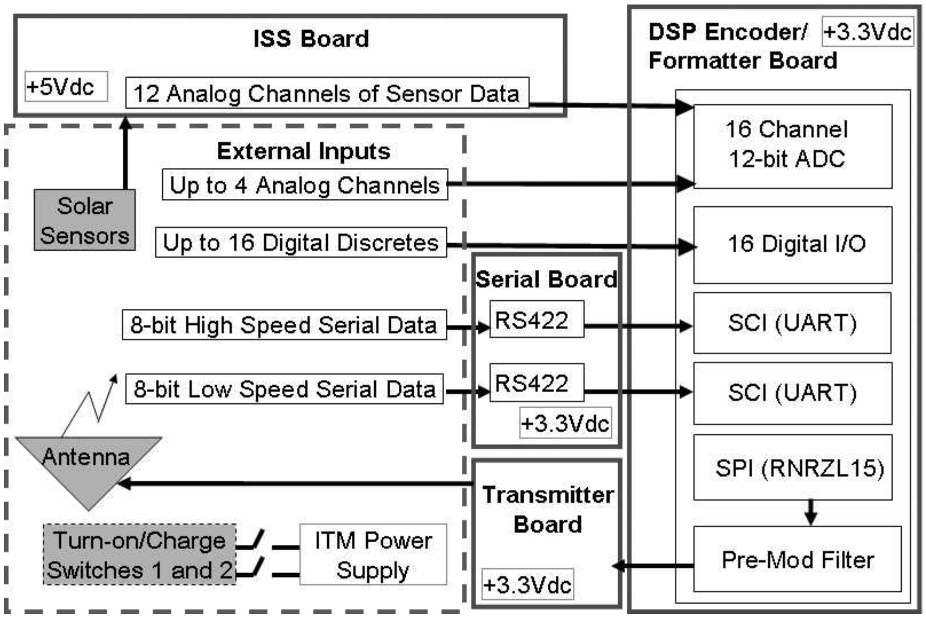

Figure 3. Integral telemetry module block diagram.

connects to a wrap-around antenna via a radio frequency (RF) connector. *Figure 4* shows the location of the ITM and associated PGMM subassemblies. A second connector enables an attachment to turn on switches, ARL solar likeness indicating transducer sensors, and various ATK input via a mating connector. The turn-on switches enable the ITM's batteries to be powered up externally. The ARL solar sensors are part of the inertial measurements and provide projectile roll rate and angular motion.

ITM data reduction

This section describes the data available from the flight tests, which demonstrate the extensive diagnostic capability of the ITM. The key aspects of each flight series were communicated with the ITM team to guide the output of quick-look data (available within minutes after a firing). This pretest planning was successful and enabled the PM Mortars to make quick, informed decisions about subsequent tests. Valuable test time and costs were saved because of this accurate, quick-look information.

All data are time stamped by the Inter-Range Instrumentation Group-B standard of time, and the time zero is referenced to the launch time. The data stream includes frame counter and subframe identifiers that verify any data losses. ITM battery voltage is monitored to ensure that it is above that required to power the ITM. Digital inputs from ATK hardware are monitored to determine the fuze status. ATK's

Table 1. Sensor, external analog, digital, and serial output

Measurement	Sampling	Range	Label
Solar field	16 KHz	0 to 5 V	Solarsonde
Axial acceleration along I	2 KHz	±50 g	Acc_I
Radial acceleration along J	2 KHz	±35 g	Acc_J
Radial acceleration along K	2 KHz	±35 g	Acc_K
Rate about I	2 KHz	±25 Hz	Acc_Ring
Magnetic field along I	2 KHz	±1.5 Gauss	Mag_I
Magnetic field along J	2 KHz	±1.5 Gauss	Mag_J
Magnetic field along K	2 KHz	±1.5 Gauss	Mag_K
Rate about J	2 KHz	±2000 deg/s	Rate_J
Rate about K	2 KHz	±2000 deg/s	Rate_K
Transmitter voltage	2 KHz	0 to 5 V	Bat_Mon
External analog inputs	2 KHz	0 to 5 V	ADC_R1 through ADC_R4
External digital inputs	2 KHz	0 to 3.3 V	Dig0 through Dig15
High-speed serial (HSS)	1.031 M	0 to 3.3 V	HSS
Low-speed serial (LSS)	38.4 K	0 to 3.3 V	LSS

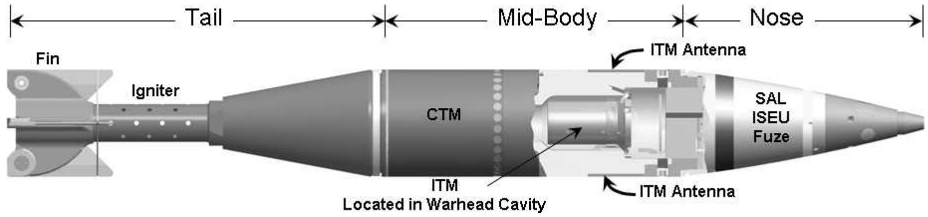

Figure 4. Precision Guided Mortar Munition guide-to-hit configuration with integral telemetry module parts located in the mid-body.

thermal battery voltage is monitored with one of the analog channels to verify that it is properly powered up. ATK's low-speed serial data, which contain the thruster commands (i.e., thruster number), and ATK's high-speed serial data, which contain the inertial sensors electronics unit and GNC solution output, are returned once they come online.

Several sensors within the ITM provide truth measurements. Accelerations (Acc_I, Acc_J, and Acc_K) from a triaxial constellation (I, J, and K body-fixed system) of low-g accelerometers are measured. Acc_I data provide axial acceleration data and detailed timing information during the drop, launch, and flight phases. Acc_J and Acc_K output provide radial acceleration during these phases, including detailed amplitude and timing information during thruster firings. All thrusters that were commanded by the control thrust mechanism can be verified by the low-speed serial data. Thruster firings can be observed in the accelerometer output. The accelerometer ring (Acc_Ring) is a constellation of accelerometers whose output is processed to obtain spin rate. Two rate sensors (Rate_J and Rate_K) provide a measurement of the body-fixed pitch and yaw angular rates. The root sum square (RSS) of Rate_J and Rate_K (RSS_Rate) gives the total angular rate. The processed solarsonde data provide roll rate (see *Figure 5*) and aspect angle relative to the sun. Similarly, the magnetometer output (Mag_I, Mag_J, and Mag_K) is processed to provide roll rate and aspect angle relative to the earth's magnetic field.

Additional ARL-developed processing can be used to determine the elevation and azimuth angles, namely, theta (θ) and psi (ψ). One technique requires two distinct planes of angular data (e.g., solar and magnetic) and transforms the motion in the earth-fixed system (Hepner and Harkins, 2001). Another technique integrates the pitch and yaw rate sensor data with respect to a known plane and then transforms these angles into the earth-fixed system. Theta and psi plots from this technique are shown in *Figures 6 and 7*. A θ versus ψ plot is shown for a short time interval covering one of the maneuver events (see *Figure 8*). Additional processing can be done to determine the body-fixed angles, alpha and beta.

Trajectory reconstruction and determining projectile aerodynamics

Additional processing can be done to fully reconstruct the trajectory and determine the aerodynamic coefficients. Both Extending Telemetry Reduction to Aerodynamic Coefficients and Trajectory Reconstruction (EXTRACTR) and TELA software packages have been used (Amoruso, 1996; Davis et al., 2005). Each combines telemetry data with radar data to fit the angular and positional data to a six-degrees-of-freedom equations-of-motion prediction of the test projectile trajectory. Telemetry data matched include rate sensors, solar and magnetometer aspect angles, roll rate, and accelerometer data. *Figure 9* illustrates a simulation match for one of the on-board rate sensors. This analysis has been done after each test to continually revise the aerodynamic database, enabling an accurate trajectory simulation of the projectile. *Figure 10* shows a revision of the aerodynamic database for pitching moment, $C_{M\alpha}$. The simulation is then used to perform trade studies, evaluate system performance, and aim the weapon during subsequent testing.

Thruster performance

The ITM's accelerometer measurements were used to evaluate the performance of the control thrusters. The accelerometers provided ample data to characterize the thruster firings, which typically lasted about

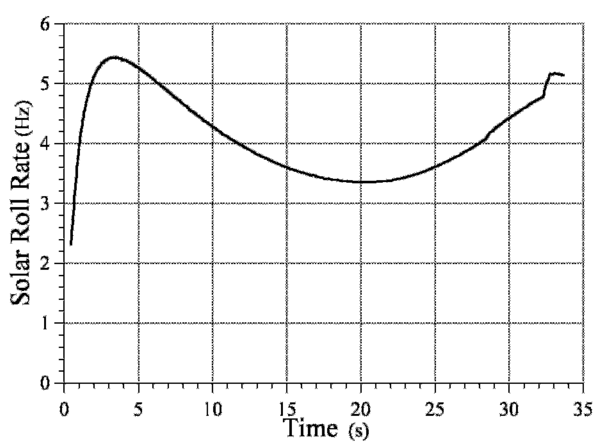

Figure 5. Solar roll rate versus time.

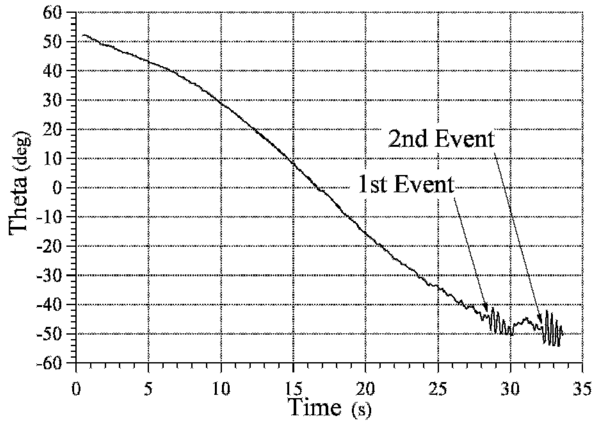

Figure 6. θ versus time.

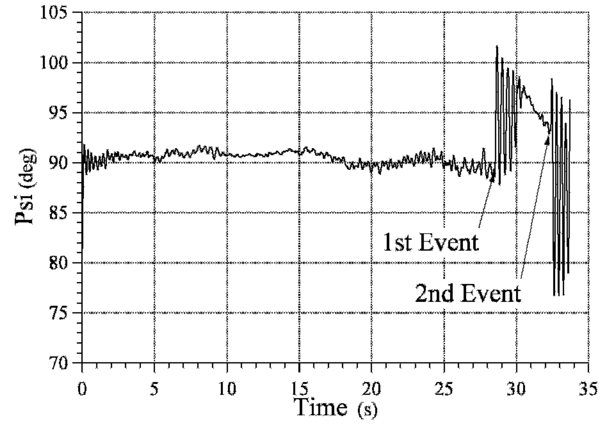

Figure 7. ψ versus time.

20 ms. We calculated the total acceleration of the body by taking the RSS of the lateral accelerations, as shown in *Figure 11* for a typical maneuver event in which six thrusters were fired in a group.

The accelerometer data clearly show the starting and ending time of each thruster firing. We converted the accelerations to forces by using the mass of the projectile and the total impulse applied to the projectile during each thruster firing (obtained by integrating the area under each curve). The thrust centroid (time to center of thrust) was also determined for each thruster firing. *Table 2* provides an example of the primary thruster data obtained or derived from the ITM, including thruster number, time of the thruster firing, and roll orientation of the initiated thruster nozzle relative to a reference frame (i.e., gravity, magnetic, or solar). The resulting body dynamics (roll, pitch, and yaw rate) at the thruster firing can also be measured. Precise knowledge of the impulse, thrust centroid, and projectile orientation is critically important for the projectile to accurately guide toward a target. The experimentally determined impulse and thrust centroid were used in the guidance algorithm for subsequent guide-to-hit shots.

Thrust angular alignment can also be determined with the use of ITM accelerometer data. Radial angular alignment is determined with the lateral acceleration components (Acc_J and Acc_K). The component impulse in the J and K directions can be calculated similarly to the method previously described to calculate the total impulse. Obtaining the J and K components of the impulse, one can then take the arctangent of the ratio of the impulses to determine the angular position of the impulse vector relative to the ITM. Relating this position to the known position of the thruster fired allows one to evaluate the radial alignment of the individual thruster. One can also obtain the axial thruster alignment in a similar manner. One can further obtain the axial alignment by taking the arctangent of the ratio of impulse in the I direction to the total impulse.

Jet interaction determination

When a lateral divert thruster is fired, the exhaust plume disturbs the flow field about the projectile. A high

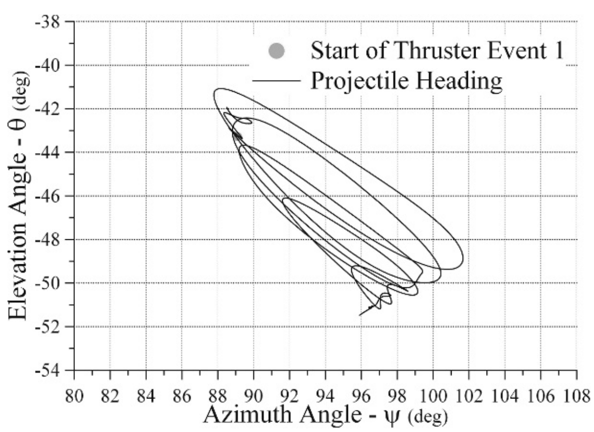

Figure 8. θ versus ψ after thruster Event 1.

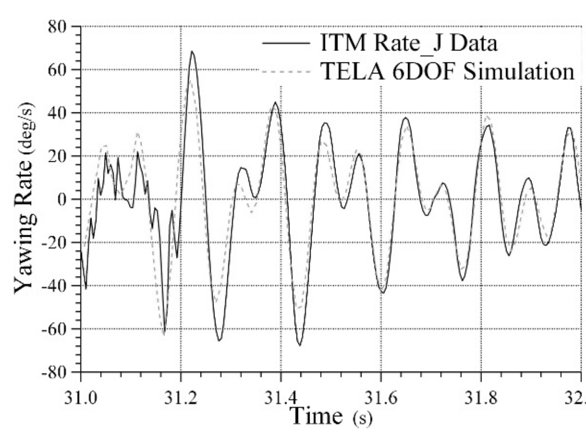

Figure 9. Trajectory reconstruction of rate data.

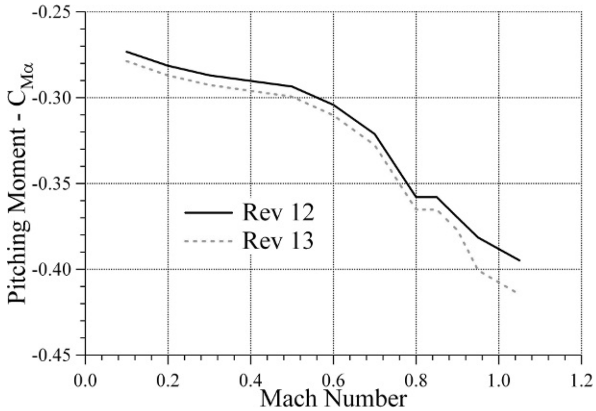

Figure 10. $C_{M\alpha}$ versus Mach.

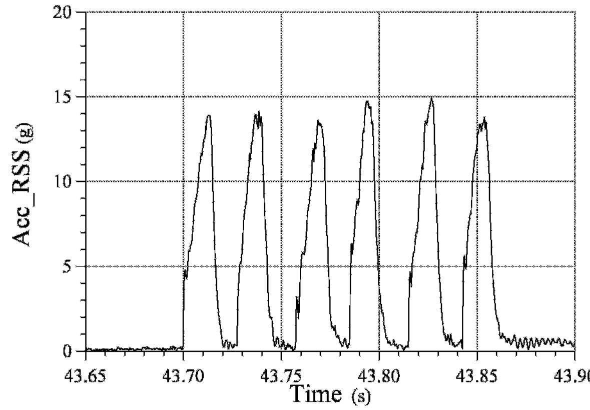

Figure 11. Root sum square of the lateral accelerations from thruster firings.

pressure region forms in front of the plume (where the free stream air slows as the plume is encountered), and a low pressure region is formed downstream from the jet. *Figure 12* shows the theoretical pressure field predicted by a computational fluid dynamics (CFD) code (Despirito, 2005). These pressures act asymmetrically on the body and are often referred to as the "jet interaction (JI)" effect. With the on-board measurements of thruster performance (from the accelerometers) and the angular response of the projectile (from the rate sensors), it is possible to estimate the JI.

To quantify the magnitude of the JI, an equation was derived to calculate the JI moment with known quantities for each shot and thruster event. The equation assumes that the angular rate measured by the on-board rate sensors is entirely attributable to two moments: the thrust force moment (from the nozzles not being located exactly at the center of gravity [c.g.]) and the JI moment. Additionally, it assumes that no aerodynamic forces or moments are contributing to the measured angular rates, and it treats each thruster event as one discrete event. If multiple diverters are fired in rapid succession and partially overlap, they are treated as a single event. The following equation defines the moment on the projectile attributable to JI:

$$M_{JI} = \left[I_Y * \dot{\varnothing} - I_T * X_T \right] / t \qquad (1)$$

where M_{JI} is the moment attributable to JI (about the c.g.), I_Y is the transverse moment of inertia, $\dot{\varnothing}$ is the peak angular rate measured after divert event, I_T is total impulse delivered by divert thrusters, X_T is the location of nozzle relative to c.g., and t is the burn time of thrust event.

One may obtain the peak angular rate for each event by calculating the RSS of the two rate sensors measurements and plotting it versus time (see *Figure 13*). This plot corresponds to the event shown in *Figure 11*. The peak rate observed after the divert event is then obtained manually off the plot. This is an example of a well-behaved rate versus time plot, where the peak is evident and the residual motion is as expected.

It is possible to determine a nozzle location that will, in theory, produce a moment equal in magnitude but in the opposite direction of that caused by the JI moment (referred to as the optimum thruster nozzle location, $X_{T,O}$). The following equation can be derived by setting the angular rate to zero in the above equation and solving for the location term:

$$X_{T,O} = - \left[M_{JI} * t \right] / I_T \qquad (2)$$

The optimum nozzle locations calculated with the methodology just given have been independently verified by a six-degrees-of-freedom trajectory simulation program. We do this by applying the measured thrust at the appropriate distance from the c.g. and

Table 2. Projectile thruster times and angles for the maneuver event

Thruster no.	Start time	End time	Burn time (ms)	Time to thrust centroid (ms)	Projectile roll orientation at thruster firing (deg)
1	43.6998	43.7195	19.7	10.42	322.29
2	43.7273	43.7460	18.7	9.18	329.11
3	43.7573	43.7780	20.7	10.65	316.18
4	43.7848	43.8035	18.7	8.67	321.78
5	43.8148	43.8335	18.7	9.63	327.45
6	43.8424	43.8615	19.1	9.20	321.12

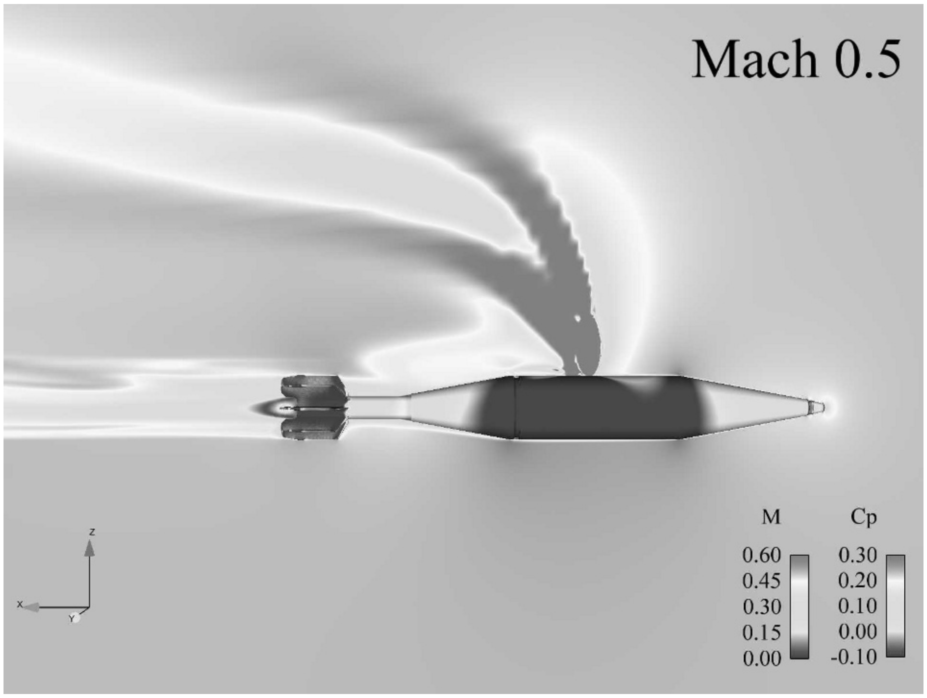

Figure 12. Simulated flow field during thruster firing.

verifying that the residual motion (angles, rates, etc.) matches the measured values. These results were very similar to those obtained from the CFD code.

Design iterations

During the development of the PGMM, there have been several changes in the projectile's exterior shape, fin type, and c.g. relative to the thruster location, as well as GNC algorithm changes. The thruster ring was originally located at the flight projectile's c.g., based on simulations of the early concept. During flight testing, it was found that the thrusters caused large yaw disturbances and the projectile had minimal yaw damping. CFD modeling helped determine that the large yaw

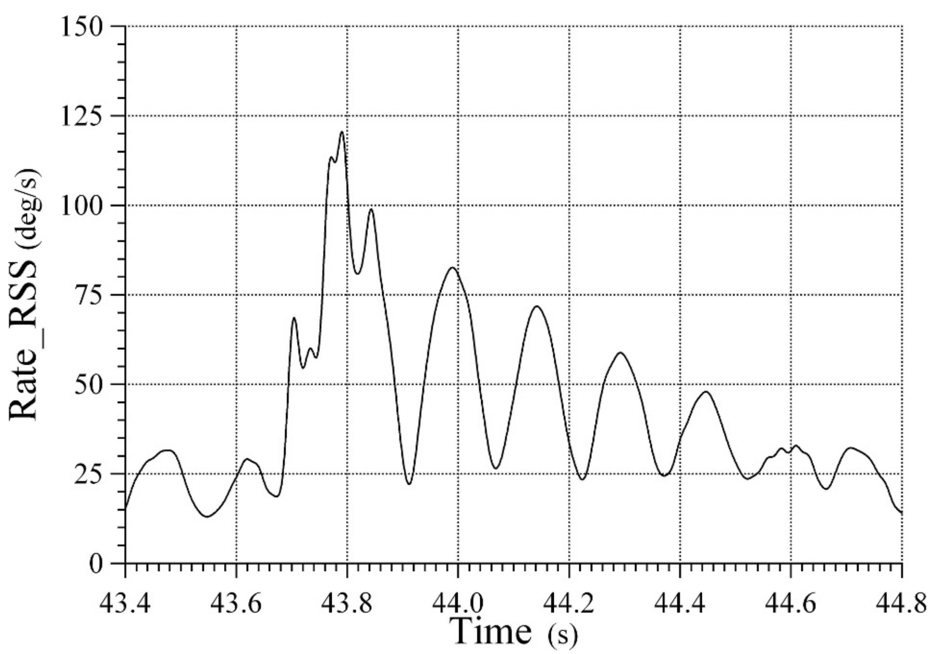

Figure 13. Root sum square of the angular rates from thruster firings.

disturbance was caused by JI. The data reduction methodology described in the previous section were used to identify an optimal thruster location relative to the projectile's c.g. The original fin design used subcaliber fixed fins. During the development, they were replaced by a super-caliber flip-back fin assembly shown in *Figure 1* for added stability and damping characteristics. Not only was the thruster design optimized for its desired impulse characteristics, but the time between successive thruster firings and the quantity of thruster firings required for a desired maneuver were determined from the numerous flight test data available.

Summary and conclusions

As of this report, the ITM has been successfully implemented on more than 30 PGMM flight tests. The ITMs have survived the high-g launch loads, transmitted clean/loss-free data to the ground, and provided a complete set of truth measurements and onboard diagnostics for each and every test. Quick-look data, available within minutes after the test, provided the necessary qualitative information to answer questions in the field regarding launch behavior, projectile stability in flight, proper thruster firing, and SAL acquisition. The data were made available to the test team, often before rounds had been marked for recovery by test ground personnel. This technical information, in concert with the photos and videos recorded by the test range, enabled the PM Mortars to make quick, informed decisions on subsequent test events. This reduced the cycle time for decision making from days to minutes, greatly reducing test costs and program schedule.

The processed data, available within days after the test, provided detailed quantitative information regarding the free-flight motion behavior (measurements of body orientation, yawing amplitude, and frequency), exact thruster timing (when the thrusters were commanded and when the body responded), and resulting projectile flight motion behavior after the thrusters were fired. This information was then used to determine airframe aerodynamics and to evaluate the GNC performance.

The telemetry system, data reduction, and processing techniques have provided a means to quickly, accurately, and fully understand what happened on board the projectile from launch through impact in multiple flight experiments. This information is not easily obtainable, if at all, from radar, video, or other ground-based instrumentation. The ITM data provided the necessary information leading to structural changes in the projectile's exterior shape, fin type, and c.g. relative to the thruster location, as well as GNC algorithm changes, which resulted in a more stable airframe and more accurate maneuvers, as evidenced by several successful guided-to-hit demonstrations. ❑

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Acknowledgments

The authors would like to thank all those individuals (too numerous to mention by name) at Project Manager for Combat Ammunition Systems (PM-CAS), U.S. Army Tank-Automotive and Armaments Command; Armaments, Development, Research, and Engineering Center; Alliant Techsystems (ATK); U.S. Army Research Laboratory; and their supporting staffs who participated on the Precision Guided Mortar Munition (PGMM) program and contributed to the various aspects of this article. The test and evaluation integrated product team members are thanked for their guidance and contributions during the integral telemetry module development and its success. LTC Andre Kirnes, LTC John Lewis, and Peter Burke, of the U.S. Army Office of the Product Manager for Mortar Systems, and Dave Rathe of ATK, are especially thanked for managing a successful PGMM program. Peter Burke and Gary Katulka are appreciated for technically reviewing this paper.