Development of a Telemetry-Enabled High–G Projectile Carrier

by David M. Grzybowski, Philip J. Peregino, and Bradford S. Davis

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Weapons and Materials Research Directorate, ARL

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14. ABSTRACT

The Guidance Technologies Branch (GTB) of the U.S. Army Research Laboratory (ARL) was contracted by Goodrich Sensors and Integrated Systems (GSIS) to assist them in conducting experimental evaluations of the survivability and performance of a developmental inertial measurement unit (IMU) in the high-g launch and flight environment of gun-launched projectiles. GTB's role, as outlined by the statement of work, was to provide carrier projectiles that would achieve prescribed dynamics and would house the GSIS IMU with a companion transmitter, an additional proven truth standard ARL sensor suite, and collection and transmission hardware for telemetering sensor data throughout planned flight experiments. GTB also performed the experimental design and provided field support to meet the evaluation criteria, satisfy data capture requirements, and obtain post-flight recovery of the test items.

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- Pete Jones, Dynamic Sciences Inc., fabricated the metal parts hardware
- Rex Hall, U.S. Army Research Laboratory (ARL), supported the antenna development
- Andy Brant, ARL, provided the Interior Ballistics of High Velocity Guns, Version 2 (IBHVG2) interior ballistics simulation
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1. Introduction

The Guidance Technologies Branch (GTB) of the U.S. Army Research Laboratory (ARL) was contracted by Goodrich Sensors and Integrated Systems (GSIS) to assist them in conducting experimental evaluations of the survivability and performance of a developmental inertial measurement unit (IMU) in the high-g launch and flight environment of gun-launched projectiles. GTB's role, as outlined by the statement of work, was to provide carrier projectiles that would achieve prescribed dynamics and would house the GSIS IMU with a companion transmitter, an additional proven truth standard ARL sensor suite, and collection and transmission hardware for telemetering sensor data throughout planned flight experiments. GTB also performed the experimental design and provided field support to meet the evaluation criteria, satisfy data capture requirements, and obtain post-flight recovery of the test items.

Technical efforts in multiple disciplines were necessary to successfully attain these goals. First, a projectile with desired aeroballistic performance and sufficient payload capacity needed to be identified or designed. Second, the GSIS and ARL sensors and transmitters needed to be electronically integrated and mechanically packaged within these carrier projectiles. Next, a telemetry system that included radio frequency (RF) combiner capability and four antennas was designed to accommodate multiple transmitter frequencies and provide reliable communications. Finally, interior ballistics computations, exterior ballistics computations, and data acquisition system characterizations were performed to define test range requirements for successful flight experiments. These efforts will be described in that order.

2. Carrier Projectile Selection

Three essential characteristics were required by GSIS for their flight experiments:

(1) Launch set back loads must be at least 17,000 g.

(2) The in-flight carrier spin rate must not exceed 4 Hz.

(3) Flight time must be at least 40 s.

Unspecified but nonetheless important characteristics that needed to be considered included set forward and high frequency balloting levels. These are typically 10–20% of the launch acceleration. Also, a reasonably stable flight greatly facilitates post-flight processing of resulting sensor data.

A number of large caliber projectile types were considered as potential options for the ballistic carrier but no inventory projectile/standard launcher combination exactly matched these specifications. Artillery projectiles were considered for their large internal volumes, but could not be used due to their high launch spin rates induced by tube rifling. Any methods to reduce that spin, such as using a slip band obturator, would have added excessive cost to the program. 120-mm mortar projectiles also have large internal cavities, but they too are launched from rifled tubes with spin rates too high for the given set of requirements. A 120-mm M831 target practice tank round was found to come closest to meeting the test requirements but several modifications were needed to meet the spin rate and launch acceleration criteria and to be able to carry all the GSIS and ARL sensor and telemetry system components. The 120-mm tank gun is a smooth bore tube that does not impart spin. Figure 1 shows a computer aided design (CAD) representation[*] of the inventory M831 tank round. Standard geometry and modified M831 rounds previously were used extensively at ARL as carriers for flight experiments with sensor, electronics, and telemetry hardware during the Hardened Subminiature Telemetry and Sensor System (HSTSS) Program (*1*, *2*).

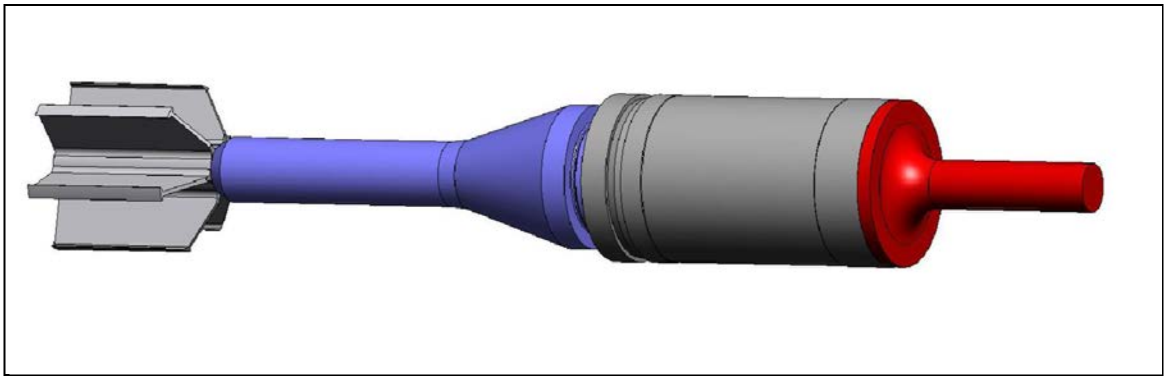

Figure 1. M831 120-mm tank round.

Using CAD models of all the structural and sensor/telemetry components, space requirements and achievable component layouts were determined. For our application, the spike nose (red in figure 1) was replaced by an ARL-designed ogival section to provide additional internal volume necessary to house all the required components. Within the ogive were included an ARL sensor suite, an ARL telemetry system, a Microwave Innovations tactical telemetry package, a dual radio frequency (RF) combiner board, and the ARL lithium polymer battery system. There also were design and space claims on and through the exterior surface of the ogive for 3 turn-on switches, 4 patch antennas with global positioning system (GPS) notch filters, and a 15-pin data interface connector. Additionally, space was allocated within the ogive for installation of onboard GPS hardware. In the initial phase of this program, this space housed a mass simulator of a GPS receiver. For the flight experiments covered in this report, GPS was included. The GSIS IMU was installed within the existing M831 midbody (gray in figure 1). The only

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[*] The Solid Works Design System was employed for all the solid modeling efforts in this program.

modification to the original cylindrical midbody was the addition of two 0.125 in diameter holes to allow for potting.

Figure 2 shows one of newly machined ogives prior to any hardware installation. The ogives were constructed out of stainless steel type-303 because this material has desirable electromagnetic, strength, and weight properties for this application. An ogive made from magnetizable materials such as carbon or tool steel likely would have caused the magnetometers within the ARL sensor suite to be saturated. Most often, we would use aluminum type 7075 T6 to avoid this problem, but the extra weight provided by the stainless steel was needed to get the desired projectile center of gravity. The ogival section was completed with the addition of a radome that will be described in section 3. The new forebody shape of the round had the added benefit of increasing the airframe's flight stability. The differences in external characteristics between the conventional M831 and the modified M831 high-g carrier projectile can be seen in figure 3.

Figure 2. Stainless steel ogive.

Modification of the afterbody was also necessary to meet GSIS requirements. The canted tail fins of the conventional M831 induce a spin rate of ~20–25 hertz. To achieve a spin rate below 4 hertz, the standard fins were replaced with redesigned fins having no cant angle. To gain flight stability, the new fins were made two inches longer than the originals. The T-tabs were carried over from the original fin design, but were made wider. The new fins were constructed out of aluminum type 7075 T6 and hard-coat anodized to prevent in bore thermal erosion during firing. The CAD model of the new fins and actual hardware are shown in figure 4.

Figure 3. M831 and modified M831 telemetry-enabled high-g carrier with cartridge cases.

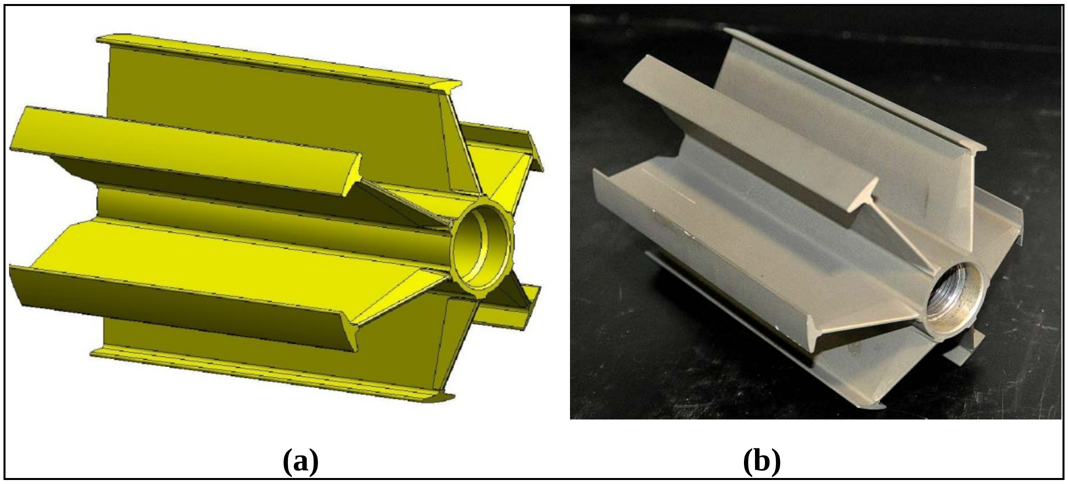

(a) **(b)**

Figure 4. Aluminum non-canted fin set (a) model (b) actual hardware.

3. Electronics, Integration, and Assembly

An ARL designed and assembled Inertial Sensor Suite (ISS) was chosen to obtain the data required to verify the operation of the GSIS IMU and was integrated into the ogive section of the modified M831. Various configurations of this ISS have been used in many prior flight experiments and have proven to survive under the high stresses of the gun launch environment and provide a measure of truth as described by Davis, et al. (*3, 4*). Fourteen channels of dynamics data are acquired from the sensors included within the ISS. These sensors and their supporting electronics along with power and signal conditioning electronics are on a three board stack. Figure 5 shows one of the ISS assemblies built during this effort.

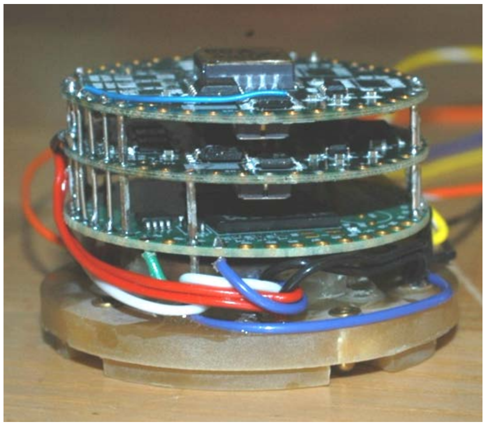


Figure 5. ARL Inertial Sensor Suite.

Table 1 lists the sensors included within the ISS. There are three accelerometers with low-g measurement ranges whose respective axes are oriented parallel to the principal axes of the projectile, i.e., one sensor axis parallel to the projectile spin axis and the other two sensor axes parallel to projectile radii such that the three axes are all mutually orthogonal. There are 5 high-g range accelerometers included with one oriented parallel to the spin axis and the remaining four in a single cross sectional plane and radially oriented 90° apart. A 3-axis magnetometer is included to provide orientation and rate data relative to the Earth’s magnetic field. Besides the previously mentioned accelerometers that are individually monitored, there are four additional accelerometers placed in a ring configuration about the spin axis whose output are combined onboard the projectile to measure centrifugal acceleration caused by projectile roll about the rotational axis. This measurement can easily be converted to roll rate. Finally, two angular rate sensors are included to measure pitching and yawing motions.

Table 1. ARL ISS components and ranges.

Sensor	Range ±	Part
Axial Accel (low-g accel)	50 G	Silicon Designs: 1221L-050
Axial Accel (high-g accel)	20 KG	Silicon Designs: 1222-20K
Radial Accel (low-g accel x2)	37 G	Analog Devices: AD22284
Radial Accel (high-g accel x4)	8 KG	Analog Devices: ADXSTC3-HG
Magnetometer (3-axis mag)	2 Gauss	Honeywell: HMC1053
AO_Sum Spin Ring (roll)	25 Hz	Analog Devices: AD22284
Rate Gyros (x2)(pitch/yaw)	2000 deg/s	Analog Devices: ADXRS300

Two other channels of data are obtained from ARL sensors. One channel gives the combined output from two optical sensors that provide angular measurements with respect to the sun. The other channel is output from a battery voltage monitor.

Precision installation of the components housed within the ogive section was accomplished by designing a rapid prototype skeleton fixture produced using a stereolithography apparatus (SLA), figure 6. Similarly produced mounting fixtures previously had been used by ARL during free flight testing and have survived gun launch of 25,000 g after potting. The SLA fixture allows for precise placement of components during the assembly process. Figure 7 shows where the ARL ISS and telemetry system (green), Microwave Innovations tactical telemetry package (yellow), lithium polymer batteries (red), and the GPS (blue) are located. After all the electronics were bench tested as a unit, the assembled instrumentation system was installed into the ogive and potted with Stycast encapsulation as shown in figure 8.

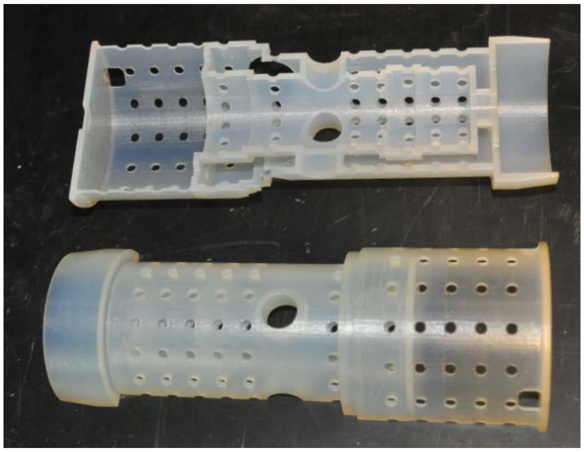


Figure 6. SLA instrumentation skeleton.

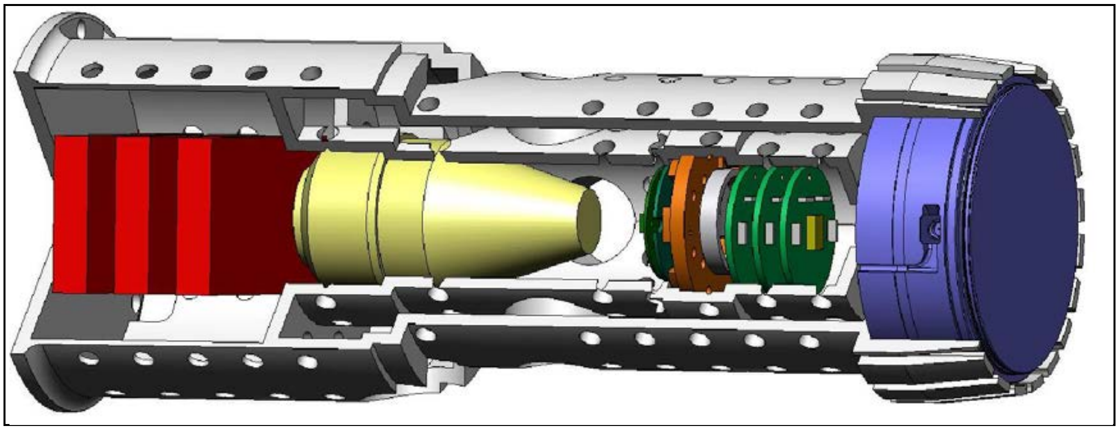


Figure 7. Assembled instrumentation system.

Figure 8. Instrumentation package being inserted into the ogive prior to potting.

The ogive shape was completed with the addition of a PolyEtherEther-Ketone (PEEK) nose cone and four Ultem 2300 plastic material antenna covers as shown in the CAD model in figure 9. PEEK was chosen for its combination of strength and heat resistance characteristics while offering RF transparency. Similarly, Ultem 2300 was chosen for the antenna covers because of thermal properties and RF transparency. Even though the antennas are located forward of the obturator and aerodynamic heating is concentrated at and near the projectile nose, the thermal protection offered by this material was deemed desirable to guard against potential in-bore blow-by heating and unanticipated in-flight heating of the patch antennas. Shown in figure 10, is a CAD representation of the GSIS sensor package. It consisted of two separate IMUs that were joined using aluminum alignment fixtures. These fixtures were designed to allow the proper clocking during the assembly process and also to provide the necessary space for the free flow of potting to completely encapsulate the IMU. Electrical connections between the two IMUs, the batteries, and the telemetry section were made via the ribbon cable seen in the figure.

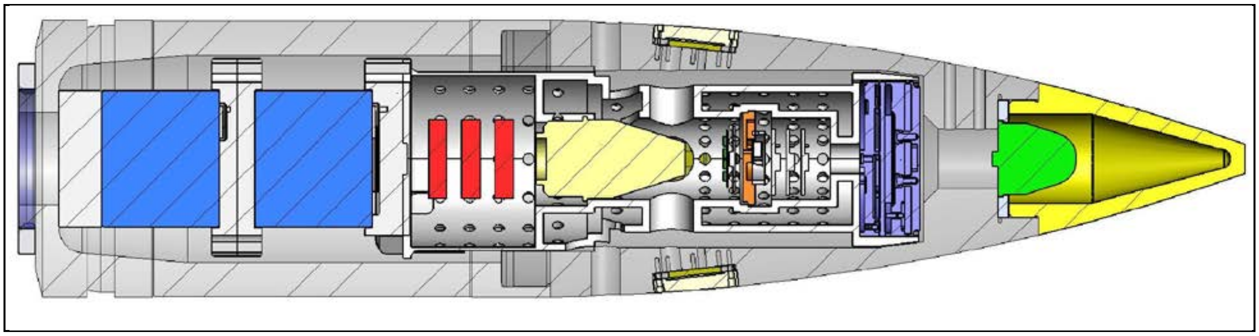


Figure 9. PEEK nose cone and Ultem 2300 antenna covers.

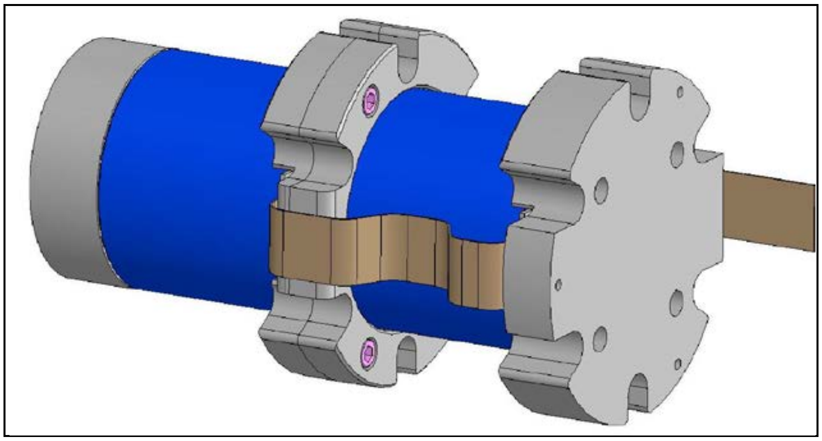


Figure 10. GSIS IMU.

4. RF Antenna Design

The antenna system was designed by ARL to provide capabilities beyond those typically required for test and evaluation (T&E) projectile experiments. To ensure a nearly uniform radiation pattern regardless of roll orientation, an array of four antennas was selected and mounted 90° apart on the exterior face of the ogive, as shown in figure 11. The antennas are Hardened HSTSS S-Band devices with integrated GPS notch filters, documented by Ryken (*5*).

These were chosen in anticipation of future efforts wherein a GPS receiver would be integrated into the modified M831. The use of a GPS notch filter allows the transmission of telemetry data without interfering with the reception of GPS signals.

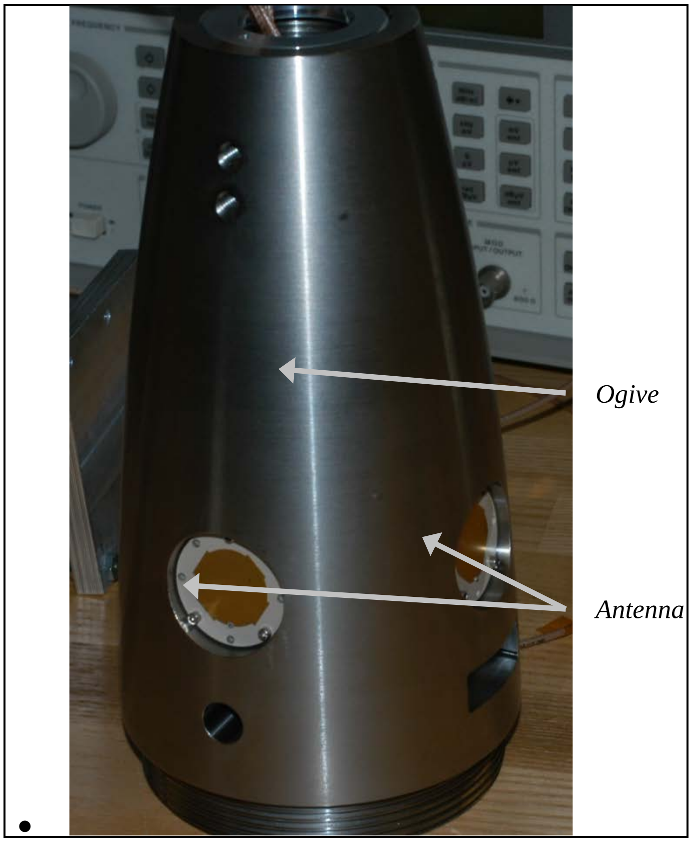


Figure 11. Antenna array.

The antenna system also needed to accommodate the transmission of output from the separate GSIS and ARL sensor systems. The frequencies of the two transmitters were chosen so that they were far enough apart that they would not interfere with each other, and so that they were close enough that one set of antennas could be tuned to efficiently transmit both frequencies. A RF combiner was designed and included in the antenna system to perform two functions; it had to merge the RF signals from both transmitters into one stream, and then split that stream into four separate antenna feeds. The basic block diagram of this combiner can be seen in figure 12. Two separate commercial components were acquired from Mini-Circuits (SP-2U+ and WP-4U+) to accomplish this, and a custom 0.800 in (20.31 mm) diameter circuit board was made to provide an interface. The combiner board alone can be seen in figure 13, the board with RF cabling attached in figure 14, and the board with attachments to the GSIS and ARL transmitters in figure 15.

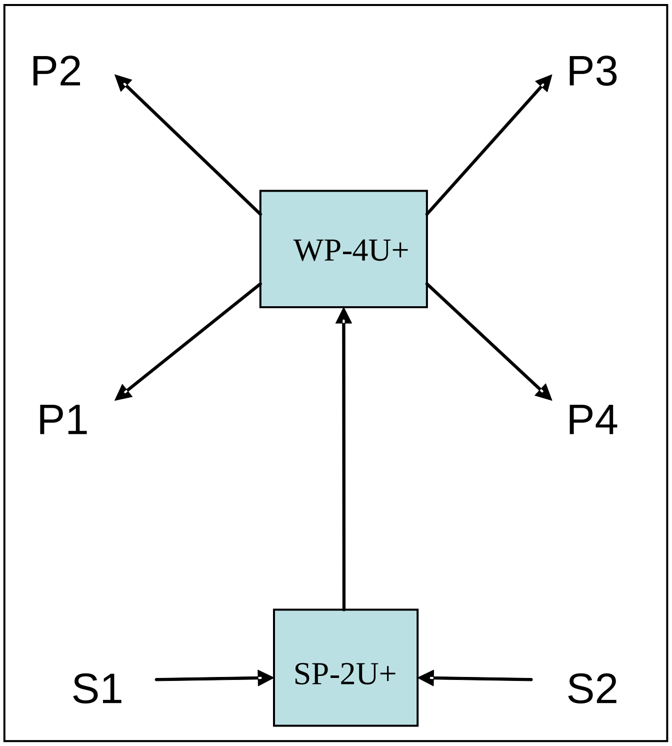


Figure 12. Combiner/splitter block diagram showing sources (S) and output ports (P).

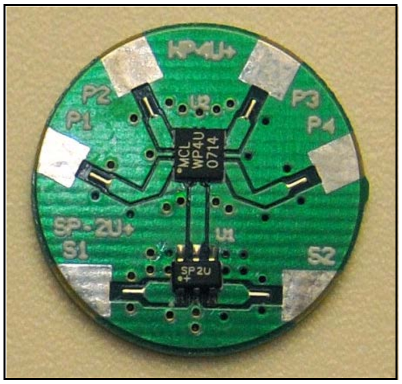


Figure 13. Combiner board.

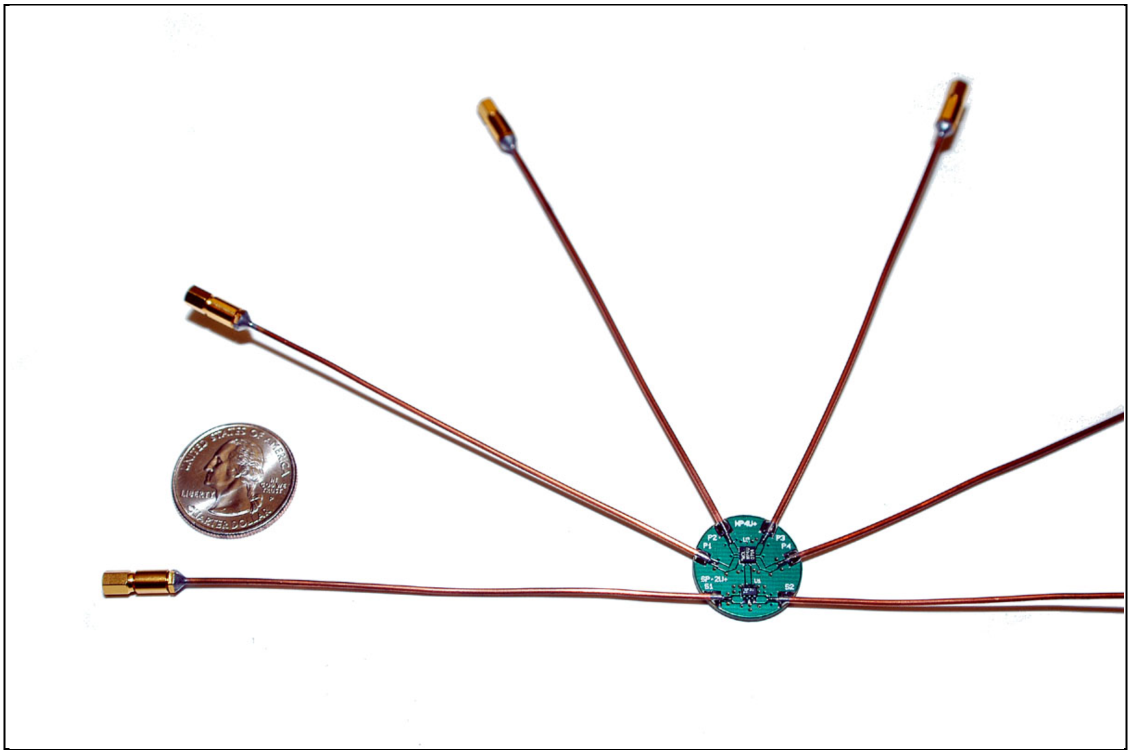


Figure 14. Combiner board with RF cables attached.

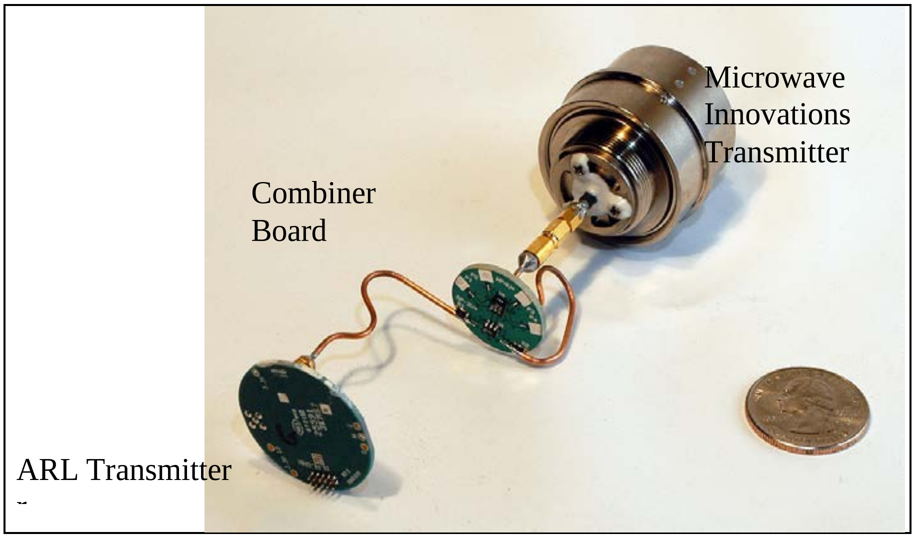
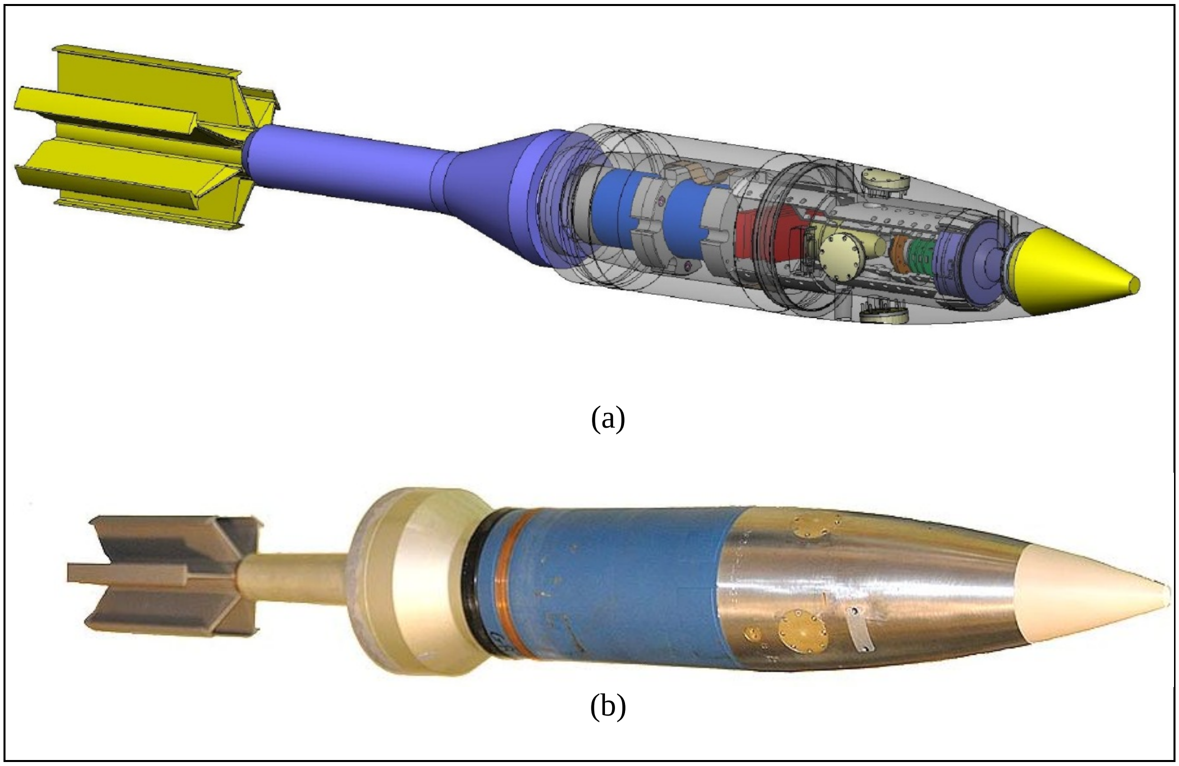


Figure 15. ARL transmitter, microwave innovations transmitter and combiner board.

Figure 16a shows the CAD model of the entire carrier round including payload and instrumentation. Figure 16b shows the final hardware prior to being installed in the cartridge case.



(a)

(b)

Figure 16. Modified M831 high-G carrier (a) CAD model (b) actual hardware.

5. Experiment Setup and Results

An estimate of the propellant charge weight required to achieve a 17,000 g in-bore loading of the modified M831 carrier was made using an ARL-developed simulation code called Interior Ballistics of High Velocity Guns, Version 2 (IBHVG2) (*6*). The output values from the simulation for the selected charge weight are seen in table 2.

Table 2. IBHVG2 calculations.

Output Values	At Pmax	At Muzzle
Time (ms)	6.807	13.483
Travel Distance (m)	0.4593	4.750
Velocity (m/s)	346.10	775.53
Acceleration (G)	17106	1949
Breech Pressure (MPa)	390.605	45.967
Mean Pressure (MPa)	377.649	44.442
Base Pressure (MPa)	352.240	41.452
Mean Temp (K)	2244	1380

A minimum of 40 s of flight time was required to capture sufficient telemetered data from the GSIS IMU and the ARL ISS. Select physical and aerodynamic properties of the standard M831 and the modified M831 high-g carrier are located in table 3. A trajectory model input file incorporating the effects of all the modifications to the standard M831 was created to estimate the flight performance of the high-g carrier projectiles. Using the 6° of freedom simulation program Projectile Design and Analysis System (PRODAS) (*7*), trajectories for various quadrant elevations (QEs) were modeled to predict time of flight, maximum range, and other variables as shown in table 4. As can be seen, flight time and QE are correlated. Due to limitations with the gun mount we chose 45° as the desired QE. However, after arriving at the test range, it was determined the breech would hit the vehicle during recoil if the available gun system was set up for a 45° launch. Therefore, the QE was reduced to 36° (645 mils) to eliminate this problem while still exceeding our minimum time-of-flight threshold.

Table 3. Select physical and aerodynamic properties.

—	M831	M831 Mod	Difference
Mass	13.6 kg	21.6 kg	8.0 kg
Length	851 mm	957 mm	106 mm
Diameter	119.7 mm	119.7 mm	0 mm
Center of Gravity Relative to Nose	358 mm	367 mm	9 mm
Center of Pressure Relative to Nose	600 mm	507 mm	–93 mm
Static Margin	2.03 cal	1.17 cal	–0.86 cal
Coefficient of Drag at Muzzle	0.621	0.364	–0.257

Table 4. PRODAS QE and range chart.

QE	QE	TOF	Range	Altitude	Azimuth
mils	°	s	m	m	m
100	5.6	13.6	6871	229	–7
200	11.2	23.5	9708	719	–10
300	16.9	31.9	11691	1357	–12
400	22.5	39.6	13222	2105	–14
500	28.1	46.9	14407	2940	–16
600	33.7	53.9	15272	3547	–19
700	39.4	60.5	15802	4810	–21
800	45.0	66.8	15963	5805	–23
900	50.6	72.7	15702	6810	–25
1000	56.2	78.1	14963	7793	–27
1100	61.9	83.0	13688	8720	–29
1200	67.5	87.3	11857	9552	–31

The experiment was conducted on 3–4 March, 2009 at Yuma Proving Ground (YPG), AZ. On both days M831A1s were fired as warmer rounds. Next, non-instrumented, modified M831s with similar ballistic properties to the test projectiles were fired to approximate the test rounds' trajectories for range instrumentation checkout and to aid spotting for eventual test item recovery. Finally, three modified M831 high-g carriers were fired.

The gun system used for this experiment consisted of a 120-mm tank tube mounted on a turretless chassis. This vehicle had to be positioned on an earthen ramp to achieve the 36° QE as seen in figure 17. The projectiles were loaded into the breech by the gun crew as seen in figure 18. Prior to loading, each round's electronics were turned on, the batteries were checked, and the telemetry systems were checked for signal acquisition.

Figure 17. Gun system setup at YPG.

Figure 18. Loading the modified M831 high-G telemetry carrier.

Test range instrumentation included a telemetry van responsible for collecting and recording the onboard sensor data. Multiple fixed and tracking antennas were used to ensure complete coverage throughout the trajectories. Tracking radar, flight follower video camera, and GPS tracking assets were also used during the test. Figure 19 shows some of the range instrumentation. The video provided early images during the flight to verify post-launch projectile structural integrity and flight stability, and to estimate spin rate using painted stripes on the ogive. This provided an independent check on the ARL sensor suite data for this portion of the flights. Figure 20 shows some selected images of one of the test rounds from the projectile flight follower video.

Figure 19. Range instrumentation.

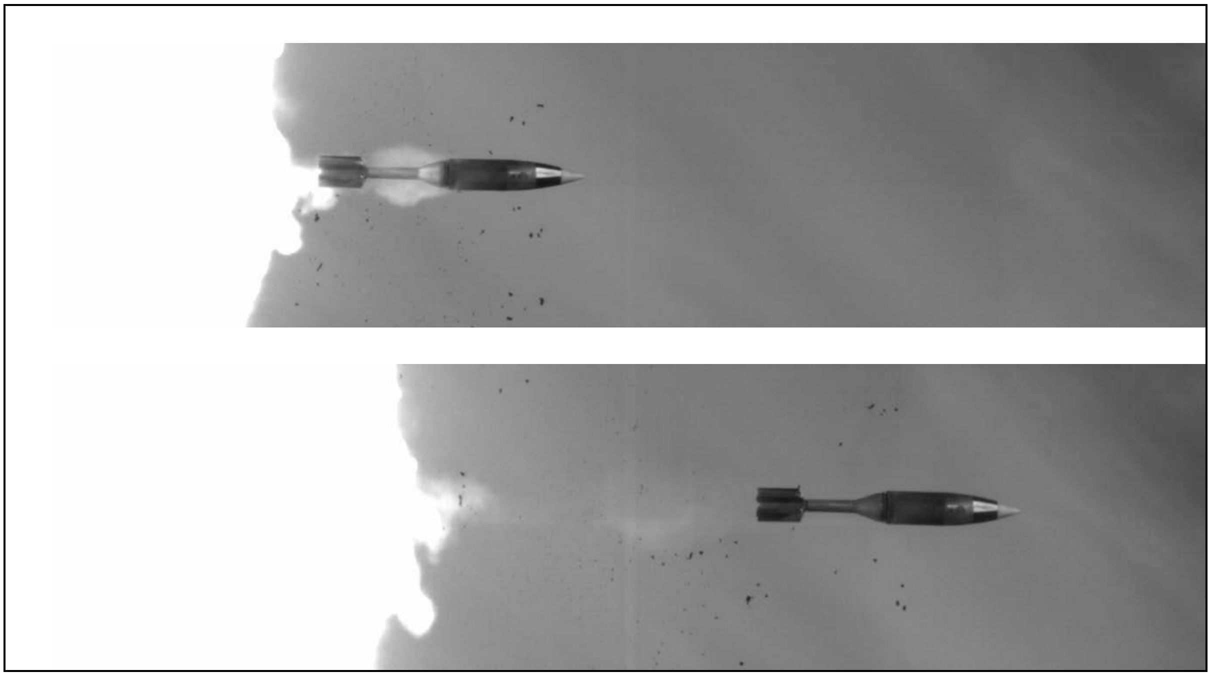


Figure 20. Select images of the high-G carrier projectile from the flight follower video.

The in-bore acceleration was measured to be ~24,000 g for all three shots which was about 41% higher than what was expected. Figure 21 shows ARL ISS high-g axial accelerometer output from one of the shots. The companion low-g axial accelerometer output are shown in figure 22. Figure 23 shows magnetometer data from one of the radial magnetometers. The magnetic roll rate was obtained from this data via period measurements and it remained below 220 deg/s (0.6 Hz) for the entire flight. Figure 24 shows three recovered projectile carriers from which the GSIS IMUs were retrieved.

Data were successfully collected from both the GSIS IMU and the ARL ISS throughout all the flight experiment trajectories. All these data were processed post flight and delivered to GSIS for their analysis and evaluation. Due to the proprietary nature of the data, the results cannot be discussed within this report.

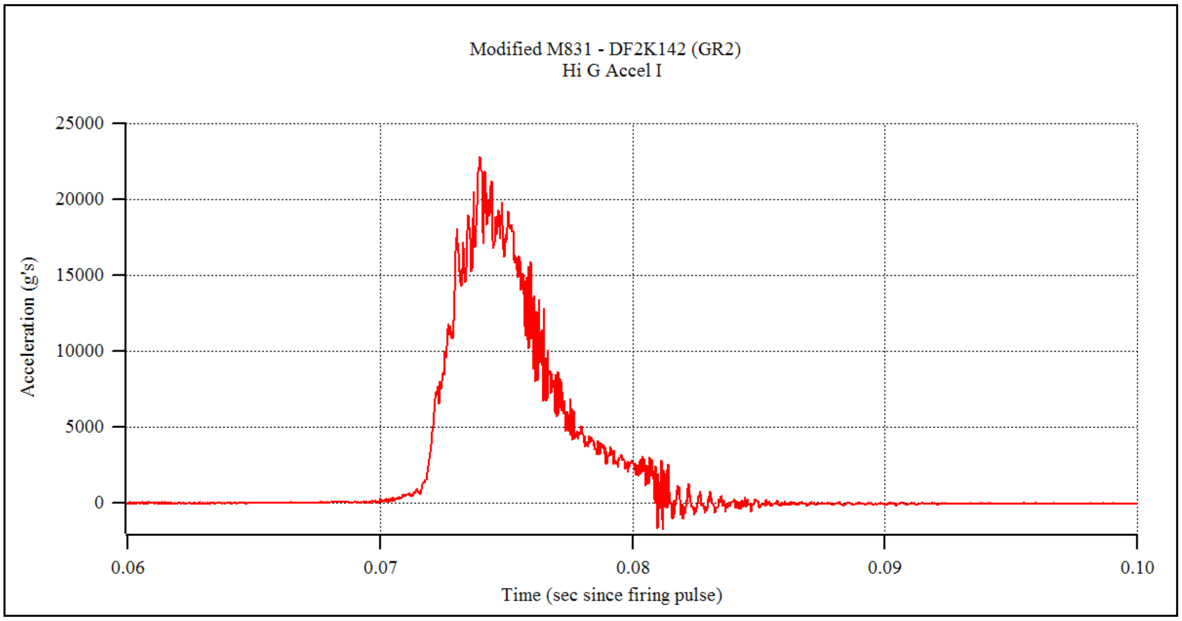


Figure 21. High-G acceleration measured during the launch portion.

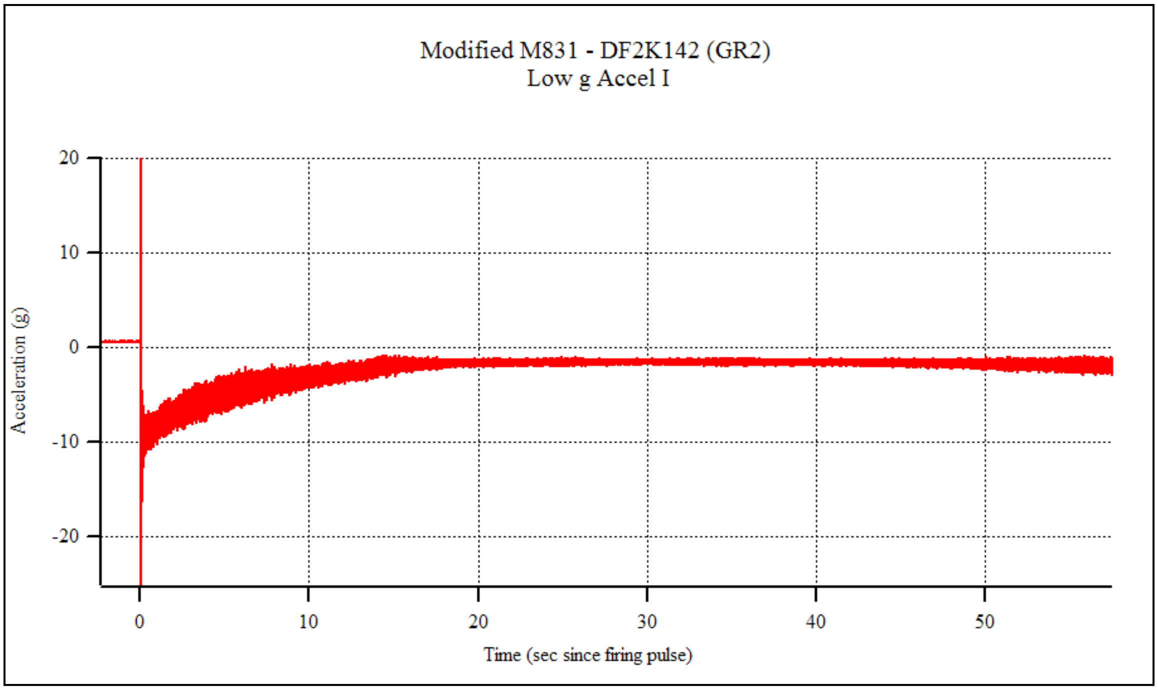


Figure 22. Low-g acceleration measured during the flight portion.

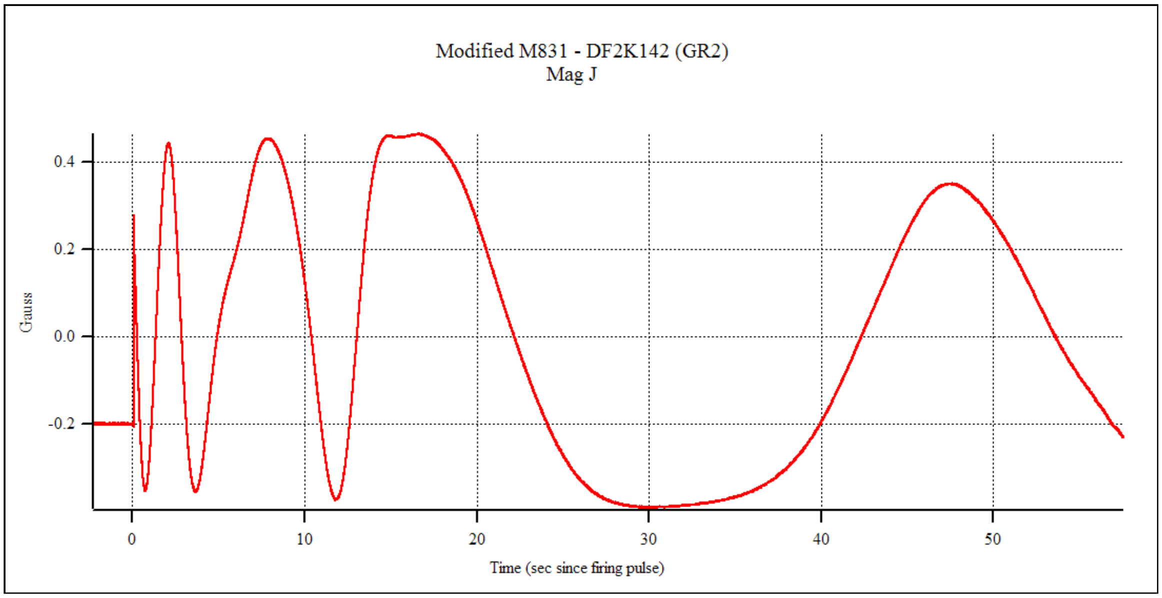


Figure 23. Radial magnetometer data measured during the flight portion.

Figure 24. Recovered high-g carrier projectiles.

6. Conclusions

For this program, ARL designed a telemetry-enabled, gun-launched, instrumented projectile carrier that was used to high-g qualify a developmental IMU provided by GSIS. An ARL-developed sensor suite was included to measure the in-bore and free-flight environment and provide a measure of truth for the GSIS IMU. On-board systems sampled and transmitted real-time, in-flight payload and diagnostic data. The M831 projectile was selected as the carrier but modifications were required to meet the GSIS-specified launch and flight environment requirements. The standard spike-nose forebody was replaced with an ogival section with ample internal volume to house the instrumentation and payload. The fin set was also modified to provide near-zero spin rate while still delivering sufficient stability margin. A rapid-prototype skeleton structure produced using SLA techniques was used to hold and align instrumentation components prior to being potted within the ogive. Also, external access was provided to the power and signal lines from the embedded electronics. With contributions from experts in multiple disciplines, these extensive modifications were made while maintaining predictable aeroballistic performance that met customer requirements and enabled flight experiment design to ensure successful data acquisition and payload recovery. For future experiments, the modified M831 is a gun-launched carrier that can be used to provide a range of payload and environment options. The SLA skeleton fixture is versatile enough to be easily adapted as payload requirements change and the g-loading and spin rate can also be customized as required.

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List of Symbols, Abbreviations, and Acronyms

ARL	U.S. Army Research Laboratory
ATC	Aberdeen Test Center
CAD	computer aided design
GPS	global positioning system
GSIS	Goodrich Sensors and Integrated Systems
GTB	Guidance Technologies Branch
HSTSS	Hardened Subminiature Telemetry and Sensor System
IBHVG2	Interior Ballistics of High Velocity Guns, Version 2
IMU	inertial measurement unit
ISS	Inertial Sensor Suite
PEEK	PolyEtherEther-Ketone
PRODAS	Projectile Design and Analysis System
QEs	quadrant elevations
RF	Radio Frequency
SLA	stereolithography apparatus
T&E	test and evaluation
YPG	Yuma Proving Ground

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