

TELEMETRY STREAMS USING SPIRAL WRAP ANTENNA

**Avi Soffer¹, Stephen DiCristina¹, Vincent Cascella¹, Derek O'Rear²,
Praveen Sajeev¹, Jin Hwan Choi¹**

U.S. Futures and Concepts Command - Combat Capabilities Development Command

¹Armaments Center, Picatinny Arsenal, NJ 07806

²Aviation and Missile Center, Redstone Arsenal, AL 35898

ABSTRACT

The acquisition of in-flight telemetry is critical for the performance characterization of precision-guided munitions. However, custom antenna development for projectiles with non-standard diameters is often cost-prohibitive and time-intensive. This paper presents a methodology for adapting a flight-proven Commercial Off-the-Shelf (COTS) conformal antenna into a spiral-wrap configuration for a reduced-diameter projectile. The research details the mechanical integration process and validates radio frequency performance through anechoic chamber testing and dynamic link analysis. The link analysis demonstrated that the expected signal-to-noise ratio remains above the 10^{-6} bit error rate threshold throughout the entire flight trajectory. Operational survivability and continuous data transmission were successfully validated through a series of six high-G live-fire tests, achieving a 100% telemetry success rate with zero dropped frames. Results indicate that the spiral-wrap integration provides a robust, cost-effective solution for rapidly instrumenting non-standard munitions while maintaining highly reliable telemetry performance in extreme launch environments.

Keywords: Telemetry, Conformal Antenna, Spiral-Wrap Antenna, RF Telemetry, Precision-Guided Munitions, Projectile Instrumentation, RF Gain Patterns, Anechoic Chamber Testing

INTRODUCTION

The collection of in-flight telemetry data is a mission-critical requirement for the test and evaluation of modern precision-guided munitions. Reliable radio frequency (RF) communications are essential for transmitting performance data including GPS position, inertial measurements, and control system behavior from the projectile to ground stations. This data enables engineers to verify system performance in operational environments, diagnose anomalies, and confirm compliance with design and safety requirements.

The success of this telemetry link depends heavily on antenna performance. Projectile antennas must maintain consistent radiation characteristics while surviving extreme launch environments

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characterized by high setback acceleration, spin rates, pressure loading, thermal exposure, and corrosive propellant gases [1]. Following muzzle exit, the antenna must continue to operate reliably throughout dynamic flight conditions involving orientation changes and high velocities.

Antenna integration presents additional challenges when developmental projectiles deviate from standard munition diameters. While high-performance antennas exist commercially, they are typically optimized for common calibers. Custom antenna development for each new form factor is costly and time-intensive, requiring extensive electromagnetic modeling, fabrication, and iterative validation [2]. Furthermore, alternative solutions such as blade antennas may introduce aerodynamic consequences or lack the necessary survivability for gun-launch environments.

A practical alternative is the adaptation of proven Commercial Off-the-Shelf (COTS) antenna designs to new geometries. This approach can significantly reduce cost, schedule, and technical risk while maintaining acceptable RF performance. To mitigate potential risks in the field, 3D simulations and analyses are conducted to identify problematic areas and verify system components prior to live-fire testing.

In this instance, a link analysis was conducted to simulate the antenna's performance and ensure a sufficient signal-to-noise ratio (SNR) is maintained throughout the mission profile. Link analysis is an engineering study that calculates the performance of a communication link between a transmitter and a receiver. For a projectile, this involves analyzing the signal path from the on-board antenna to a ground station to predict the SNR, which serves as the primary indicator of signal quality. This analysis considers several critical factors: transmitter power, antenna gain, distance or range, and receiver sensitivity.

By modeling these variables, engineers can ensure that the telemetry link is robust enough to transmit critical data without dropouts or corruption, even under challenging flight dynamics and environmental conditions.

This paper describes the successful adaptation of a large caliber conformal antenna into a spiral-wrap configuration to support a smaller projectile diameter. The work includes mechanical integration methods, RF validation through anechoic chamber testing, and survivability validation through six live-fire tests. Results demonstrate that spiral-wrap integration provides a practical methodology for rapidly instrumenting projectiles while maintaining reliable telemetry performance.

SYSTEM DESIGN

The overall telemetry system consists of the data collection electronics, a power source, an RF transmitter, and a spiral-wrap antenna. The data collection and processing electronics are detailed in a companion paper [3]; this section focuses on the components directly related to RF transmission.

Transmitter. A low-power COTS transmitter was used to send telemetry data through the antenna to a ground station. The operating frequency was in the S-band frequency range.

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Batteries. The telemetry system was powered by rechargeable lithium-polymer batteries configured in a 2s2p arrangement, providing a total capacity of 240 mAh, sufficient power for 45 minutes of continuous operation.

Antenna. A conformal antenna originally designed for large caliber artillery projectiles, shown in Figure 1, was adapted for this application. In the intended configuration, it exhibits a horizontal gain pattern depicted in Figure 2.

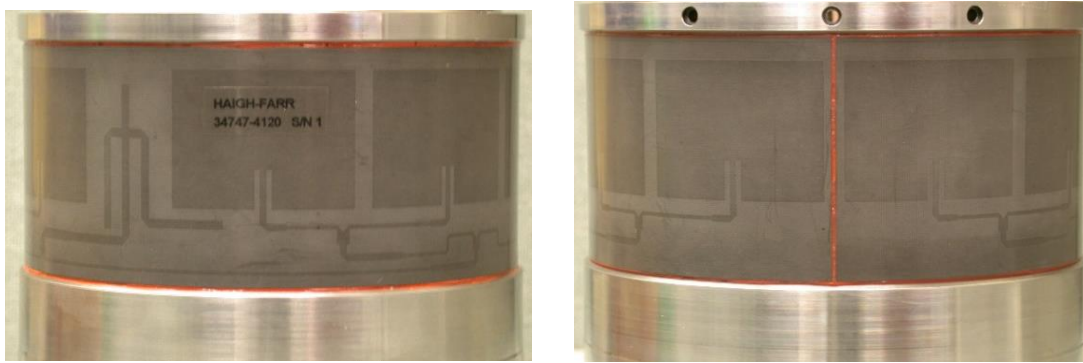


Figure 1: Conformal antenna in its intended configuration [Front (L) and Back (R)].

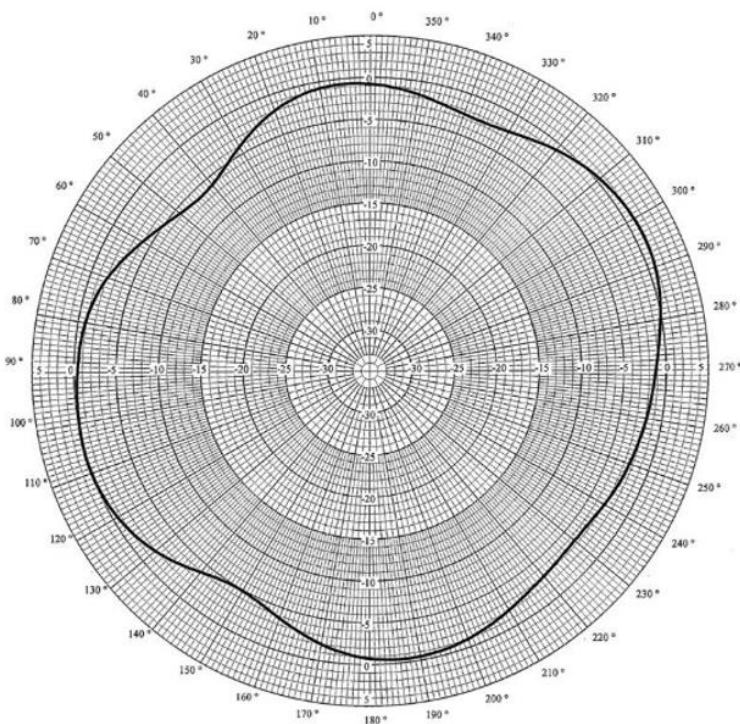


Figure 2: Original conformal antenna roll plane gain pattern.

Antenna Integration and Verification

The test article used in this program had a smaller body diameter than the antenna, precluding direct circumferential installation. To accommodate the geometry, the antenna was installed in a spiral-wrap configuration along the projectile. This preserved the length of the antenna while

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allowing it to conform to the reduced diameter. However, this introduced risks including radiation pattern distortion, gain degradation, and alteration of polarization characteristics.

To verify acceptable RF performance prior to flight testing, the antenna was installed on a 3D-printed surrogate projectile body and evaluated in an anechoic chamber, Figure 3, using standard far-field characterization procedures. The antenna was mounted on a rotational positioner and illuminated by a calibrated reference antenna. Two primary pattern cuts were collected: a Roll Plane cut, measured by rotating the projectile about its long axis, and a Pitch/Yaw Plane cut, measured by rotating the projectile end-over-end. These cuts characterize the antenna's performance during roll, pitch, and yaw movements.



Figure 3: Anechoic chamber setup at Picatinny Arsenal

The resulting data was processed in Microsoft Excel to generate the polar radiation plots shown in Figure 4, which were subsequently provided to the manufacturer for comparison against historical baseline data.

Engineering review concluded that the modified radiation patterns showed only minor degradation and remained suitable for telemetry applications. Overlapping antenna segments in the spiral configuration were expected to produce limited mutual coupling, potentially forming a small array effect and slightly biasing radiation toward broadside directions. The measured gain patterns demonstrate quasi-omnidirectional radiation behavior required for projectile telemetry applications [4]. The roll plane gain pattern in Figure 4 shows a relatively uniform azimuthal distribution, which is necessary to maintain a reliable telemetry link regardless of projectile orientation during flight. The pitch/yaw pattern similarly shows no substantial asymmetry, indicating that the spiral-wrap installation did not significantly distort the antenna's polarization response. A gain reduction of approximately 5 dBi is observed in the wrapped configuration relative to the manufacturer's specified nominal performance.

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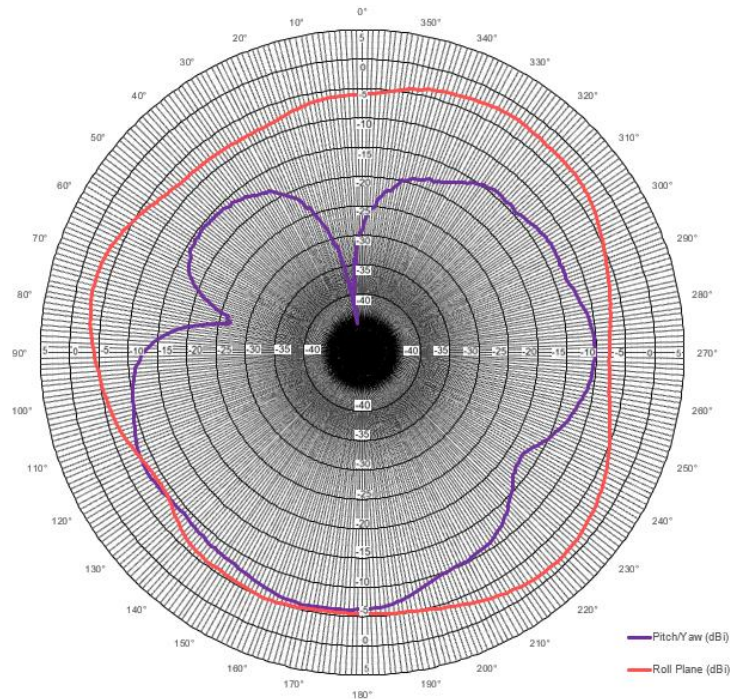


Figure 4: Twisted antenna gain patterns

Link Analysis

After verifying the viability of the antenna gain patterns, a dynamic link analysis was conducted by the Telemetry Branch at Picatinny Arsenal utilizing a simulated flight trajectory. This analysis, which is a standard and critical step in evaluating telemetry systems, models the expected Signal-to-Noise Ratio (SNR) against the projectile's downrange distance. The results are visualized in Figure 5.

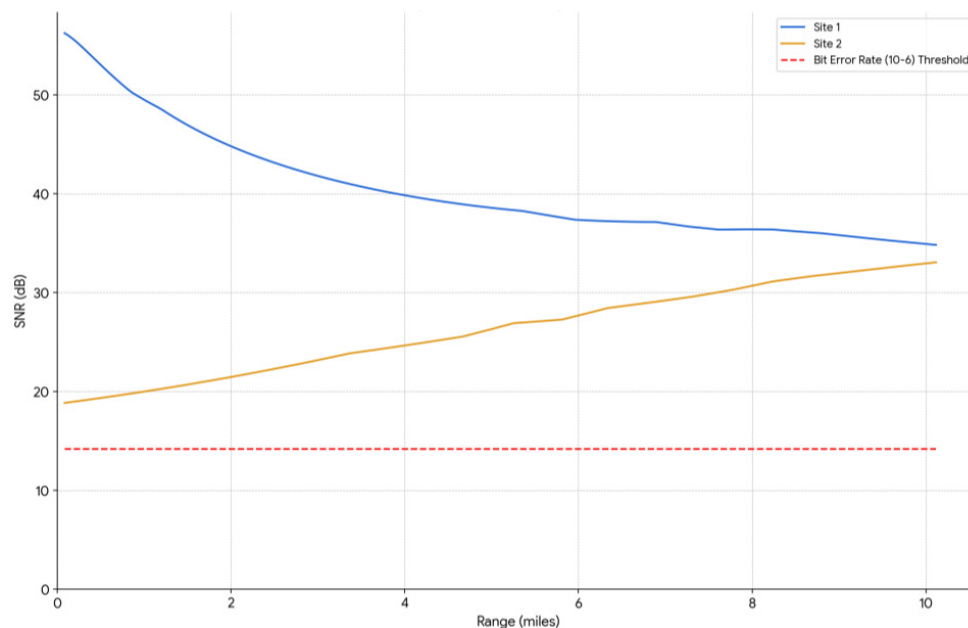


Figure 5: Link Analysis of Spiral Wrap Antenna

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To ensure continuous data acquisition, the simulation incorporates two receiver ground stations. Site 1 is positioned closer to the launch origin to capture early flight dynamics, while Site 2 is located further downrange to maintain tracking through the mid-course and terminal phases. The dashed red line indicates the minimum SNR threshold required to maintain a Bit Error Rate (BER) of 10^{-6} , serving as the baseline for a reliable telemetry data link.

The analysis demonstrates that the estimated SNR for the projectile remains consistently above the BER threshold for the duration of the mission. The overlapping coverage between Site 1 and Site 2 ensures that as the signal from the first station begins to degrade at longer ranges, the second station acquires a strong signal. This confirms that the spiral-wrap antenna configuration provides sufficient gain to maintain a robust, uninterrupted telemetry connection throughout the entire flight trajectory.

Mechanical Integration

To integrate the antenna, a surrogate projectile body was fabricated at U.S. Army Combat Capabilities Development Command (DEVCOM) Aviation and Missile Center (AvMC) and custom modified to accommodate instrumentation. First, a spiral groove was machined into the projectile's surface. The groove was engineered with sufficient depth to ensure the antenna and its bonding adhesive remained fully recessed below the projectile's outer diameter, preventing interaction with the launch tube. This channel also provided protection from aerodynamic forces during flight and maintained a consistent wrap diameter for the antenna.

Further modifications included drilling a central passthrough to route the antenna's coaxial cable from the internal transmitter to the external mounting location. A final cutout was machined to house a Micro-D Miniature (MDM) connector, which provided the interface for the shorting plug and system arming.

For final assembly, the antenna was seated within the groove and secured using a high-strength, environmentally resistant epoxy. The assembly was clamped during the curing process to ensure a solid bond. The complete mechanical modifications and the final integrated antenna are shown in Figures 6 and 7.



Figure 6: Front of machined surrogate body

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Figure 7: Rear of surrogate projectile with installed wrap antenna

RESULTS & FINDINGS

Six flight tests were conducted to validate the performance and survivability of the integrated spiral-wrap antenna system. The results from all six missions successfully demonstrated that the modified COTS antenna provides a robust and reliable telemetry link in a launch environment.

System Performance. Across all six flight profiles, the telemetry system maintained a continuous and uninterrupted RF link with the ground receiving stations. The spiral-wrap antenna provided consistent signal transmission, enabling the real-time capture of the full navigation data stream from the projectile. No data dropouts or signal degradation attributable to antenna performance were observed during flight. The quality of the received signal was sufficient for successful demodulation and analysis at the ground stations, confirming the antenna's effectiveness in a dynamic flight environment.

Survivability. All of mechanical and electrical components withstood the test environment. This demonstrates that the described mechanical integration method, utilizing a machined groove and high-strength epoxy, is sufficient to ensure the antenna's survivability in the setback and rotational environment of a projectile launch.

Validation of Anechoic Chamber RF Analysis. Successful telemetry reception validated pre-flight anechoic chamber measurements. Comparison of original and modified radiation behavior confirmed the spiral configuration introduced acceptable gain reductions without compromising link reliability.

The original antenna provided approximately 0 dBi peak gain. The modified configuration demonstrated approximately -5 dBi peak gain while maintaining required omnidirectional coverage. This performance remained sufficient for reliable telemetry transmission.

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Mission Objective Fulfillment. Ultimately, the successful operation of the spiral-wrap antenna enabled the program to meet its primary test objective: real-time verification of the system performance. By providing a reliable data link, the antenna proved to be a critical enabling component for the overall success of the test series. The telemetry system successfully collected data on all six tests, without any frame drops, meeting all program objectives for real-time verification. The receiving stations acquired and decommutated the TM streams, providing data necessary to validate performance.

LESSONS LEARNED

A key lesson learned involves the depth of the spiral groove machined into the surrogate projectile body. The groove was intentionally designed to be deep to ensure the epoxied antenna would not extend beyond the projectile's outer diameter and interfere with the launch tube. This approach successfully mitigated risk and prevented a potential no-test or failure scenario. However, the antenna's conservative deep placement likely had a negative effect, albeit minor, on the system's aerodynamic performance. For future iterations, a shallower groove could be explored. A less-intrusive groove, perhaps with a textured surface to ensure adhesion, could minimize the aerodynamic impact. Alternatively, the use of a filler material to smooth the surface over the antenna could be investigated to achieve an aerodynamically cleaner profile without affecting RF performance.

FUTURE APPLICATIONS & TACTICAL RELEVANCE

The successful demonstration of a survivable, COTS-based antenna solution provides crucial enabling technology, particularly for scenarios demanding rapid development and fielding. While a major Program of Record would likely invest in a fully custom antenna optimized for a specific munition's diameter, the spiral-wrap methodology presented here offers a validated, cost-effective, and agile alternative for several critical tactical situations:

Urgent Operational Needs. When a new threat emerges, warfighters may require a modified or new munition capability on an accelerated timeline. The ability to adapt a proven, off-the-shelf antenna to a new or existing projectile body allows for the rapid prototyping and fielding of instrumented or networked munitions, bypassing the long lead times associated with custom antenna development.

Niche Capabilities. Specialized systems, such as those for electronic warfare, sensor deployment, or unique mission sets, are often produced in much smaller quantities than standard munitions. For these programs, the non-recurring engineering (NRE) cost of a custom antenna design can be prohibitive. This proven COTS adaptation method provides a cost-effective pathway to imbue these niche systems with high-performance data link capabilities.

Technology Demonstration and Prototyping. Before committing to a large-scale program, this methodology allows for the development of prototype systems. By demonstrating the core concept of a networked or data-transmitting projectile with readily available hardware, the technical risks

for a future, larger program are significantly reduced. The lessons learned from this type of effort, such as optimizing groove depth for better aerodynamics, directly inform the design of the eventual custom wrapped antennas.

The operational value of this work lies not in presenting a specific hardware configuration or a universal solution, but in establishing the foundational template for a new, agile methodology. This single success does not suggest that any COTS antenna can be fitted to any projectile. Instead, its true value is in providing the first, validated entry into a potential repository of proven integration techniques.

Future rapid development programs, when faced with a similar challenge, could reference this spiral-wrap configuration as a proven starting point. They could leverage the lessons learned from this effort, such as the trade-offs between groove depth and aerodynamic performance, to adapt the technique for their specific needs, rather than starting from first principles. By incrementally building this repository with a variety of proven configurations, the paradigm can shift from slow, deliberate development to agile, responsive capability enhancement. This approach allows warfighters to adapt in the field, because the foundational ability to create a survivable data link on an accelerated timeline, a capability this work has successfully demonstrated, becomes a repeatable, scalable process.

CONCLUSION

This paper details a successful and cost-effective solution for providing robust telemetry transmission for projectiles with non-standard body diameters. By adapting a COTS conformal antenna into a spiral-wrap configuration, this program overcame the high costs and long lead times associated with custom antenna development. The approach was systematically validated through anechoic chamber testing and six live-fire tests, which confirmed that the modified antenna's performance was suitable for the mission. The spiral-wrap modification yielded lower peak gains but was still an acceptable trade-off that ensured a reliable data link was maintained throughout the flight profile. These results validate that retrofitting a standard antenna is a viable strategy for specialized applications. The process presented in this paper: adapting a proven COTS antenna, validating its performance, and integrating it using a robust mechanical technique, offers a proven template for rapidly instrumenting projectiles. However, while this method provides a template for agile development, further development and mission-specific qualification would be required before any tactical deployment on a different projectile configuration.

The ultimate success of this method was demonstrated across six live-fire tests, in which the spiral-wrapped antenna survived the launch environment and provided continuous, a high-quality data link throughout the flight profile. These results validate that retrofitting a standard antenna is a viable and highly effective strategy. Furthermore, this validates the mechanical integration method using a machined groove and high-strength epoxy as a survivable solution for projectile instrumentation.

The validated performance of this antenna in a demanding test and evaluation role provides a strong foundation for future applications. The demonstrated survivability across six live-fire events

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and the reliability of the RF link under gun-launch conditions represent the critical enabling characteristics for any operational use case requiring robust airborne telemetry. Further development and mission-specific qualification would be required before tactical deployment.

This approach not only enables critical data collection for test and evaluation but also paves the way for enhanced communication capabilities on the future battlefield. Future work could refine this method by optimizing the antenna groove depth to further improve the projectile's aerodynamic performance, bringing the test article's flight characteristics even closer to the operational munition.

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