# THE DESIGN OF A 21st CENTURY TELEMTRY SYSTEM WITH SOQPSK MODULATION AND INTEGRATED CONTROL

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## ABSTRACT

This paper describes a telemetry system developed for the EA-18G Flight Test program. The program requires transmission of a number of data streams, in IRIG-106 Chapter 4 PCM, Chapter 8 Mux-All 1553, Ethernet, and Fibre Channel formats. The initial requested data rate was in excess of 30 Mbits/sec. The telemetry system must operate at a range up to about 120 miles, at several test ranges, and with several different aircraft maneuvering configurations. To achieve these requirements, the Flight Test Instrumentation group at Boeing Integrated Defense Systems in Saint Louis, developed a telemetry system in conjunction with industry partners and test range customers.

The system transmits two telemetry streams with a total aggregate rate on the order of 20 Mbits/sec. Each telemetry stream consists of up to four PCM streams, combined in a Teletronics Technology Corporation (TTC) Miniature Adaptable Real-Time Multiplexer Unit (MARM) data combiner. It uses Nova Engineering multi-mode transmitters capable of transmitting PCM-FM or Shaped Offset Quadrature Phase Shift Keying[1] (SOQPSK). The transmitter also provides Turbo-Product Code (TPC) Forward Error Correction[2] (FEC) to enhance range and improve link performance. Data collection units purchased from outside vendors or developed by Saint Louis Flight Test Instrumentation, translate Ethernet and Fibre Channel information into traditional PCM streams. A Boeing Flight Test Instrumentation developed control system provides flexible selection of streams to be combined into each telemetry stream, and functional control of antenna selection and transmitter operation.

## KEYWORDS

Keywords: SOQPSK, Hypermod multi-mode transmitter, Instrumentation control system, Turbo Product Code (TPC) Forward Error Correction (FEC), Instrumentation Control Unit (ICU)

## INTRODUCTION

The EA-18G System Development and Demonstration (SDD) Program represents a significant step forward into 21st century instrumentation and telemetry systems for Boeing IDS Flight Test


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Instrumentation. In the past a single 5 Mbit/s PCM-FM stream with a range limit of approximately 80 miles was adequate. Now, a number of Ethernet and Fibre Channel streams, in addition to traditional analog parameters and 1553 Mux All streams are being telemetered. The quantity and bandwidth of the data streams as well as the distances involved for the flying maneuvers cause the flight test telemetry system to be considerably more complex.

Flight testing for the program consists primarily of verifying performance of jamming equipment which is being transitioned from the EA6B aircraft to an EA-18G aircraft. The primary maneuver consists of an approximate 120-mile “race track”, during which time the aircraft jamming pods are aimed at a designated target. The aircraft maintains a relatively flat profile during the maneuver. Some traditional dynamic flying maneuvers will also be performed, but the range required for these maneuvers will be significantly less, approximately 40-50 miles.

This set of circumstances represents a mixed blessing for telemetry performance. On one hand, the racetrack maneuver is simple compared to normal dynamic flying maneuvers typically seen with military fighter jets. On the other hand, the jamming equipment communicates on a considerable number of Ethernet and Fibre Channel busses, at significant aggregate and burst data rates.

## BACKGROUND AND SYSTEM REQUIREMENTS

The Boeing Saint Louis Integrated Defense Systems Flight Test Instrumentation team previously developed a telemetry system for the F/A-18E/F Super Hornet Flight Test Program, which transmitted a single 5 Mbit/s PCM-FM stream primarily at the Patuxent River Naval Air Weapons Station. Telemetry performance for that flight test program was adequate to provide a range of about 80 miles under most flying conditions. However, on certain aircraft, some days, and with particular flight attitudes, the telemetry performance was less than desired.

With this knowledge, the Boeing IDS Flight Test Instrumentation team began conversations with customer and industry teammates involved in the EA-18G SDD program. Initially, a substantial amount of data on multiple streams was desired to be telemetered – about 30 to 40 Mbits/sec. In addition, the infrastructure of the telemetry receiving stations at the Patuxent River and China Lake test sites would have to be upgraded. The Boeing Flight Test Instrumentation team designed a telemetry system to best meet the needs of customers and teammates.

The solution proposed by Boeing consisted of two combined streams of SOQPSK modulation, with Forward Error Correction. Each telemetry stream transmits about 8 Mbits/sec of actual data, which escalates to nearly 10 Mbits/s after adding the effects of PCM data formatting, data combining, and forward error correction. The initial solution included a specific combination of the data streams that would be combined into the two transmitted streams. Some flexibility in selecting one PCM stream for each telemetry stream was included. The customer, however, desired that all the PCM data streams be selectable for either telemetry stream. This allow for maximum flexibility if only one telemetry stream were required.

## SYSTEM DESIGN PHILOSOPHY

The Boeing IDS Flight Test Instrumentation designed telemetry system is integrated with a pilot display for both control and preflight setup. It uses a Ground Support Unit (GSU) for preflight setup, system verification, and system troubleshooting. A block diagram of the telemetry system is shown in Figure 1.

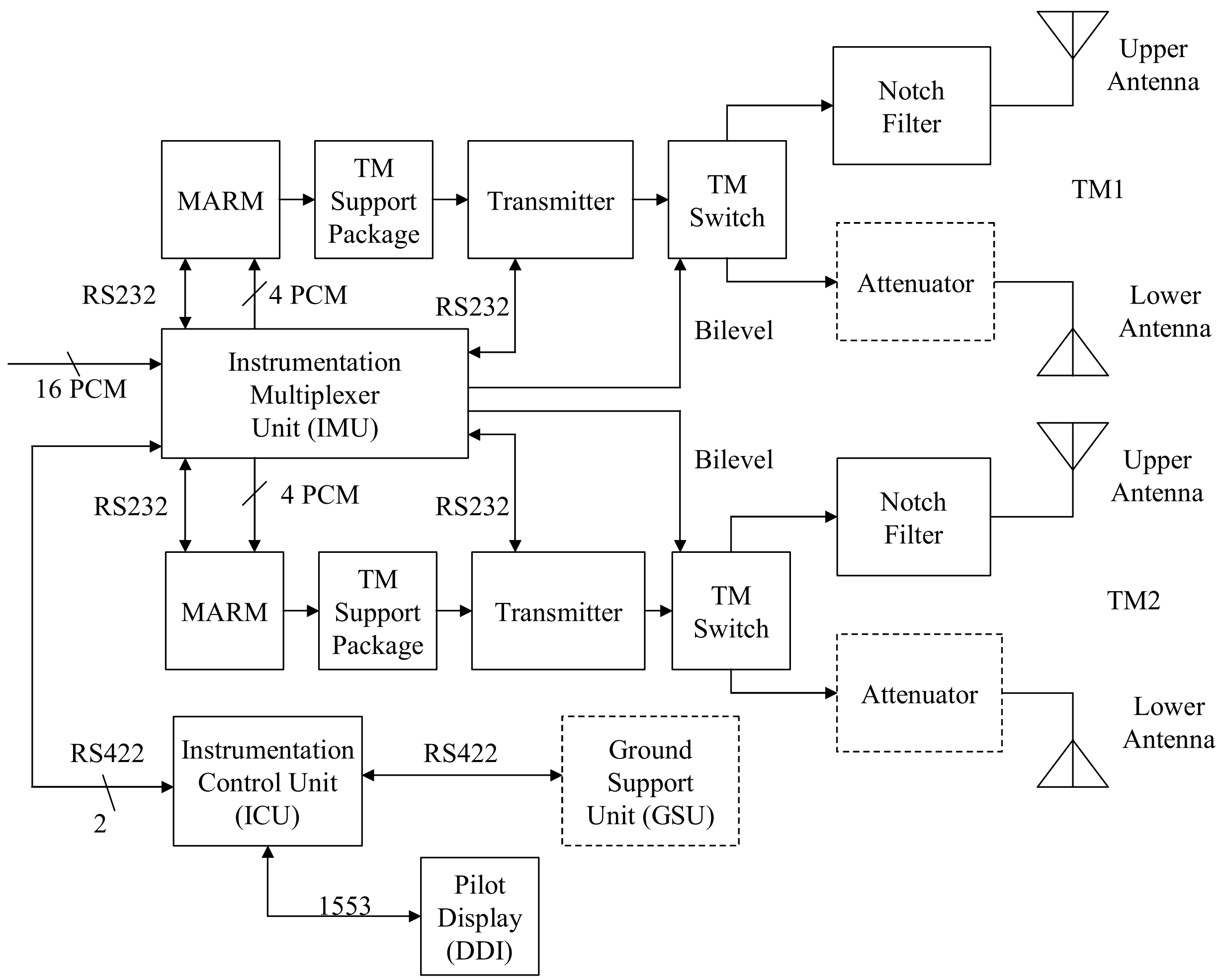


**Figure 1. Telemetry System Block Diagram**

The considerations for the design and operation of the telemetry system are as follows:

- The system was designed to be flexible. Most functions can be accessed through a single serial connection during pre-flight or from the pilot display during flight.
- Normal telemetry control functions are also available from the pilot display.
- After brief interruptions in Flight Test power, the operating state of the system (frequency, power level etc) is automatically restored.

- The ability to select antenna configuration between upper antenna only, lower antenna only, or a split between the two antennas was implemented to reduce deep pattern nulls at the "waterline". This feature was beneficial despite significant signal loss in the switch.
- Traditional antenna locations were chosen and found to be about the optimum choices. See Figure 2.
- The system was designed to be as compatible as possible with the ground stations at Patuxent River and China Lake. This means that certain features (e.g. Forward Error Correction) can be turned off during preflight
- Minimum bandwidth balanced with overall performance was a primary objective. This was the driving factor behind the use of a Tier 1 waveform (SOQPSK), two streams, Forward Error Correction, a 20W output, and Upper-L band frequencies (1710-1850 MHz).
- Heat was also a major factor in the system installation design.
- The system was designed to require a minimal setup, available from a single remote connection to the Ground Support Unit during pre-flight.
- The schedule did not allow for development of futuristic technologies. Only currently available commercial products (either off-the-shelf, or with some customizing) were suitable.

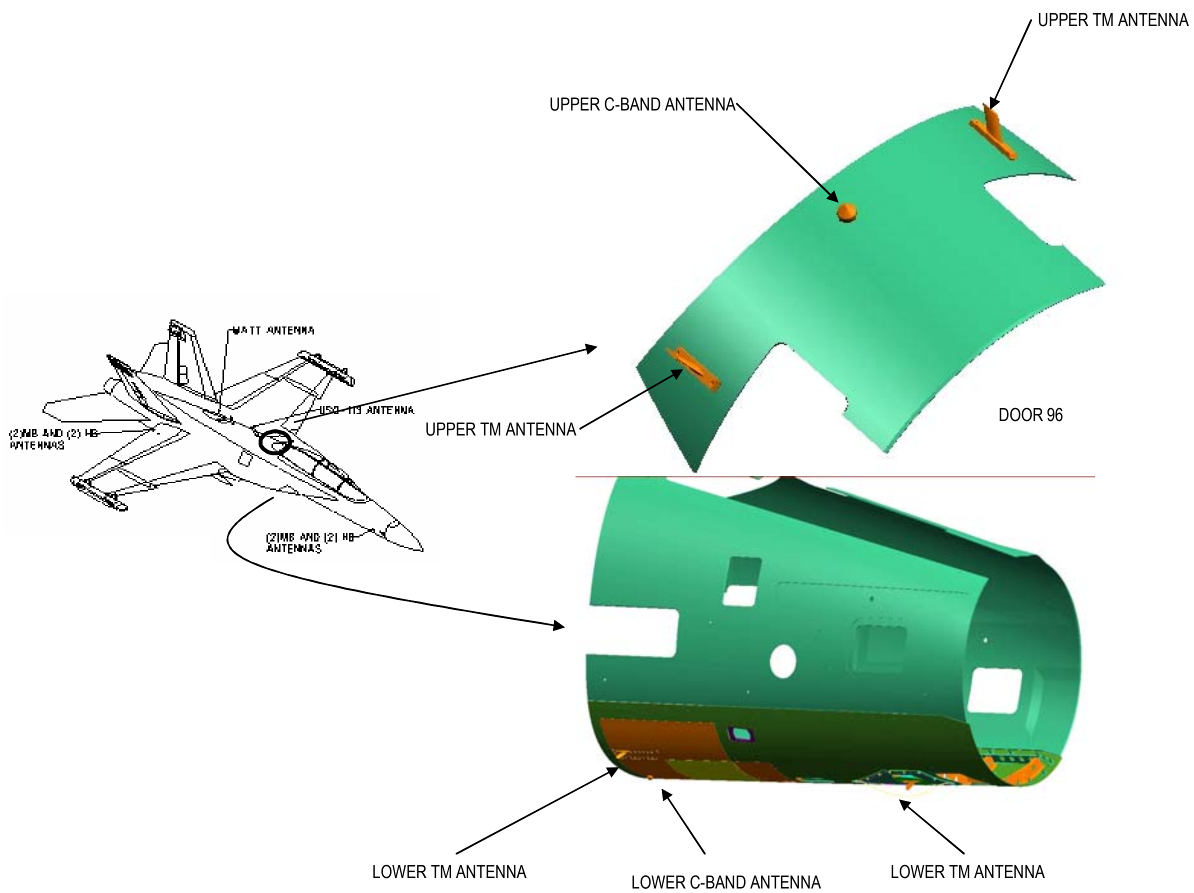


**Figure 2. Antenna Locations**

## DETAILED SYSTEM DESCRIPTION

The system consists of the following:

- Pilot display system
  - Flight Test menu on a cockpit Digital Display Indicator (DDI)
  - Dedicated front- and rear-seat control panels for use with selected functions when the Flight Test display is not selected
- Control and PCM Selector Units[3]
  - Boeing Instrumentation Control Unit (ICU)
  - Boeing Instrumentation Multiplexer Unit (IMU)
- Data Combiner Units – TTC MARMs
- Telemetry Transmitters and Telemetry Support Packages
  - Nova multi-mode Hypermod transmitter
  - L3 Telemetry East Telemetry Support Package
- Telemetry switching, filtering, and antennas
  - Dow Key switch with Haigh-Farr power divider
  - K&L Microwave GPS notch filter
  - Haigh-Farr upper-L band blade antennas

The pilot display system consists of an Advanced Mission Computer (AMC), which communicates with the DDI, and the Boeing Flight Test dedicated control panels. The protocol to communicate between Flight Test equipment and production avionics allows the Flight Test equipment to paint menu information on the display. It also allows Flight Test to interpret button depressions from the pilot. This paradigm allows Flight Test to modify menu contents and functions without costly and time-consuming Operational Flight Program (OFP) modification and integration testing.

The ICU and IMU, developed by Boeing IDS Flight Test Instrumentation, allow for loading of setup information for the transmitters and data combiners during preflight. They also provide in-flight control of the transmitter and antenna selection. In addition, the IMU accepts multiple PCM streams, provides buffering for onboard recording, and allows any of these streams to be routed to the data combiners for each of the two telemetry streams. Any stream routed through the IMU may be sent to either telemetry stream. This flexibility allows for flight-to-flight reconfiguration of the system depending on the flight test mission and allows critical streams to be routed to a single transmitter for situations where range telemetry restrictions prevent two telemetry streams from being used.

The TTC MARM data combiners combine up to four PCM streams to be transmitted in each telemetry stream. This unit creates an overall PCM format with overhead information, which is decombined in a ground-based unit.

The L3 telemetry support package provides cipher text for each combined data stream. It also provides a differential data and clock to the transmitter, as well as power to the transmitter and

MARM unit. The Nova multi-mode transmitter is a 20-watt Upper L-Band (1710-1850 MHz) transmitter, which can transmit any of the three Advanced Range Telemetry (ARTM) tier 0/1/2 waveforms without requiring external premodulation filtering or level setting.

The Dow Key switch allows remote selection of the upper antenna, lower antenna, or a split configuration. A Haigh-Far splitter is mounted in each Dow Key switch, and two configurations are available: a 50:50 split or a 70:30 split. The K&L Microwave filter is used on the upper antenna side, with a significant attenuation at the 1575 L1 GPS frequency to mitigate GPS interference issues. The telemetry antennas are Haigh-Farr blade antennas.

## RECORDED AND TELEMETERED STREAMS

An important aspect of the EA-18G telemetry and instrumentation systems is the number of different data streams to be recorded and telemetered. A diagram of these streams and the selection mechanism is shown in Figure 3.

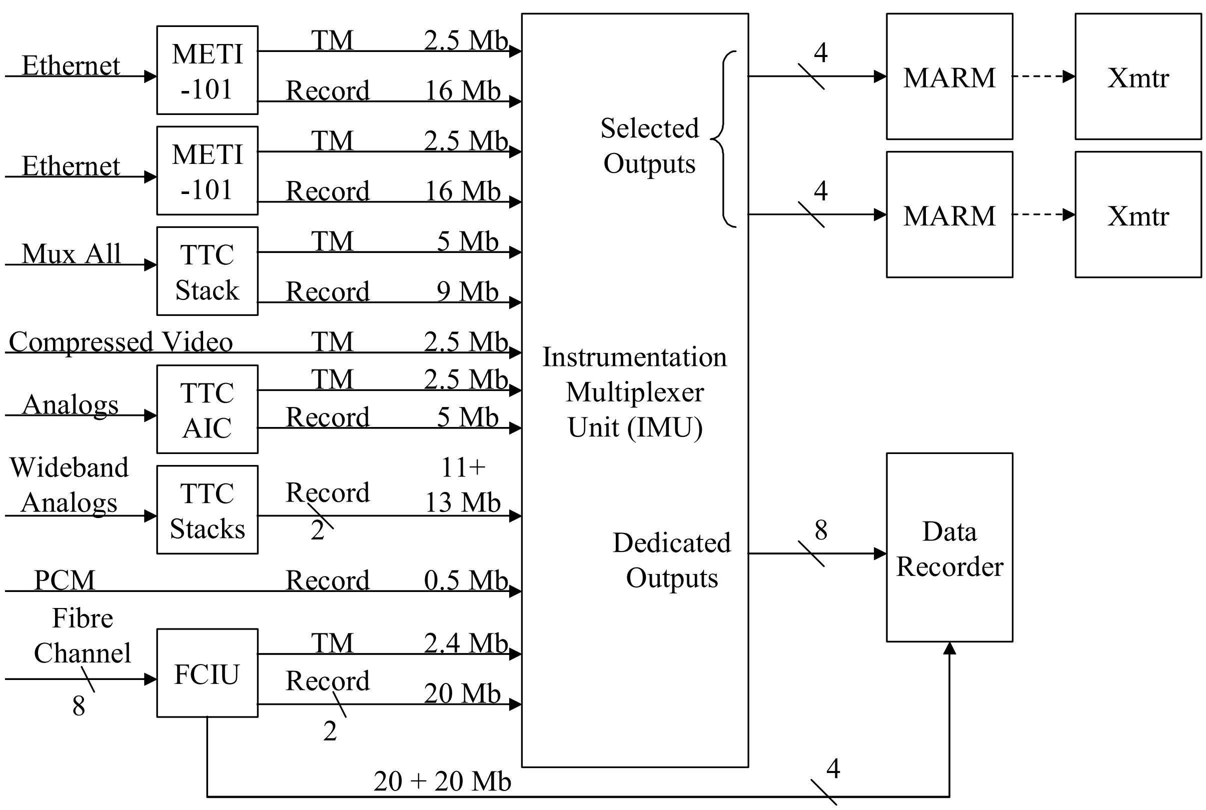


**Figure 3. Recorded and Telemetered PCM Streams**

The data streams used to construct the telemetry streams are as follows:

- TTC-designed METI-101 modules monitor two busses of Ethernet traffic and provide a full output and bit-rate-limited telemetry output as an RS422-style differential data/clock pair. The bit-rate limited output is required because the Ethernet streams may contain bursts of high-rate data which are not critical to real-time telemetry monitoring.
- MIL-STD-1553 busses are encoded into two separate Mux-all streams: a full stream with all busses for recording, and a limited stream with specific busses for telemetry.
- Several NTSC video signals are recorded on a separate solid state video recorder, and a selected one of these signals is compressed for telemetry.
- Low-rate analog parameters are recorded at a 5Mbit/sec rate. A subset of these is selected for telemetry at 2.5 Mbits/sec. Wideband analog signals are recorded, but are not normally telemetered.
- Another low-rate PCM stream is recorded but not normally telemetered.
- Eight Fibre Channel streams are monitored by a Boeing-designed Fibre Channel Interface Unit[4] (FCIU). Specific groupings of these Fibre Channel streams are programmed for capture by the FCIU, depending on specific flight test mission requirements. The FCIU also provides a single bit-rate limited PCM stream for recording.

The IMU provides a mechanism for selecting PCM streams for telemetry. Any stream routed through the IMU can be sent to either telemetry stream. This flexibility allows for flight-to-flight reconfiguration of the system depending on the flight test mission. It further means that critical streams may be routed to a single transmitter for situations where range telemetry restrictions prevent two telemetry streams from being used.

## EXPECTED SYSTEM PERFORMANCE

The primary performance issues are bandwidth, bit-error performance at the desired range, multipath/fading performance, and reacquisition time. These concerns need to be weighed against risk, volume, and cost.

A comparison of the aggregate data rates of selected typical streams versus the final transmitted bit rate is shown in Table 1. Also shown are the escalation factors resulting from data formatting; most of the data was formatted into an IRIG 106 Chapter 8-like stream, using 20-bit words rather than 24-bit words to conserve telemetry bandwidth. Also shown is the 11% data rate escalation caused by MARM major frame data formatting. Finally, the transmitter Forward Error Correction penalty adds about 26% to the final bit rate. For this example, the overall bit rate increases from 14 Mbits/sec to 20.9 Mbits/s. This is a total increase of about 49% for both telemetry streams. The total -60dBc bandwidth for both streams is on the order of 31.4 MHz for SOQPSK. This compares to a bandwidth around 41.6 MHz for PCM-FM (this figure is for comparison only; practical considerations preclude using this kind of bandwidth at any test site).

| Parameter | TM1 | TM2 | Units |
|---|---|---|---|
| Aggregate Data Rate | 7.5 | 6.5 | Mbits/sec |
| Data Formatting | x 1.00 | x 1.14 | Multiplying factor |
| MARM formatting | x 1.10 | x 1.10 | Multiplying factor |
| FEC | x 1.26 | x 1.26 | Multiplying Factor |
| Transmitted Bit Rate | 10.5 | 10.4 | Mbits/sec |
| Bit Rate Escalation | 40% | 60% | Percent |
| | | | |
| Transmitted Bandwidth(-60dBc) SOQPSK | 15.8 | 15.6 | MHz |
| Transmitted Bandwidth(-60dBc) PCM-FM | 20.9 | 20.7 | MHz |

**Table 1. Bit Rate Comparison**

The primary baseline for determining telemetry range is a relative comparison with the flight test results for the F/A-18E/F Engineering Manufacturing Development (EMD) program, flown at Patuxent River, Maryland. This is the same test site and receiving stations to be used for the EA-18G program, which is essentially an F/A-18F model aircraft. This baseline was verified with an independent link analysis, and results from the baseline evaluation were found to be reasonable and somewhat conservative.

| Approach | Data Rate Mbits/sec Per stream | TM Range Approximation (compared to baseline) | Multipath Improvement | Notes |
|---|---|---|---|---|
| SOQPSK with FEC | 10 | 109% | Yes | |
| SOQPSK w/o FEC | 10 | 55% | Yes | |
| PCM-FM | 5 | 77% | Yes | With Nova demod |

**Table 2. Telemetry Performance Comparison**

The table shows the relative performance of the proposed EA-18G telemetry system versus the baseline 5 Mbit/sec PCM-FM performance for the F/A-18E/F EMD Flight Test program. The range for the F/A-18E/F program was about 80 miles, and the full configuration with FEC is expected to produce a range on the order of 88 miles. A link analysis performed using the EA-18G expected cable losses and FEC improvement shows that this baseline analysis is fairly conservative, and gives a range of about 120 miles under the same condition. For PCM-FM, the analysis above assumes use of the Nova demodulator to add an additional 3dB performance improvement using a phase trellis technique[5].

The net improvement using the Turbo Product Code (TPC) Forward Error Correction (FEC) in the Nova transmitter is expected to be about 6dB[6]. This corresponds to a substantial range increase of about 50%. The TPC code used in the Nova transmitter is the (64, 57) code, which results in a significant performance improvement with a modest increase in bandwidth.

However, there is a potential that acquisition time may be significantly affected by presence of this error correction scheme, because a $64^2$ –long block of bits must be acquired before the demodulator can fully lock on the acquired signal. This is an issue for fading and for aircraft maneuvers in which the aircraft rolls through pattern nulls. For the "racetrack" maneuver in which the aircraft banks only minimally, this should not be a problem. The normal configuration would be to transmit only with the lower antenna, where interference nulls between upper and lower antennas are not present. For more dynamic maneuvering, however, the lower antenna would be shaded by the aircraft structure, necessitating the use of a split antenna configuration with the corresponding interference nulls.

For this reason, the authors plan to perform a laboratory investigation into the performance of the system under the influence of fading, multipath, and the rolling of the aircraft through nulls in the overall antenna pattern. The primary focus of this investigation will be to determine under what expected flight conditions FEC and adaptive equalization[7] may not perform well.

A final issue involves risk. One of the authors has previously performed an investigation into FQPSK performance and the implementation of an FQPSK system[8]. This investigation indicated that the overall risk associated with Tier 1 implementations was generally low, and that setup and related issues are actually significantly less arduous than legacy PCM-FM systems.

## CONCLUSION

The EA-18G Flight Test telemetry system represents a 21st Century system. It features an integrated avionics and ground support system that allows for changes by the pilot in flight and for instrumentation engineers during preflight. It is flexible, allowing for compatibility with test site ground stations. It provides advanced capabilities such as Turbo Product Code (TPC) Forward Error Correction (FEC) and Adaptive Equalization to reduce multipath errors, with minimum program risk.

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