THE EVALUATION AND INTEGRATION OF AN INSTRUMENTATION AND TELEMETRY SYSTEM WITH SOQPSK MODULATION AND CONTROL INTEGRATED WITH AVIONICS DISPLAYS

John A. Wegener, MSEE
Associate Technical Fellow

And

Robert N. Zettwoch, MSEE, Associate Technical Fellow
Michael C. Roche, BSCpE, Engineer Flight Test

The Boeing Company - Integrated Defense Systems
Flight Test Instrumentation and Data Processing – Saint Louis

ABSTRACT

This paper describes the integration activities associated with the instrumentation and telemetry system developed for an F/A-18 Hornet Flight Test program, including bench integration, avionics integration, and aircraft ground and flight checkout.

The system is controlled by a Boeing Integrated Defense Systems (IDS) Flight Test Instrumentation-designed Instrumentation Control Unit (ICU), which interfaces to an avionics pilot display and Ground Support Unit (GSU) to set up the instrumentation during preflight and control the instrumentation during flight. The system takes in MIL-STD-1553, analog parameters, Ethernet, Fibre Channel, and video, and records these with onboard recorders. Selected subsets of this data may be routed to the telemetry system, which features two RF streams, each of which contains up to four PCM streams combined into a composite by a data combiner. The RF streams are transmitted by multi-mode digital transmitters capable of PCM-FM or Shaped Offset Quadrature Phase Shift Keying (SOQPSK), with selectable Turbo-Product Code (TPC) Forward Error Correction (FEC).

This paper describes integration of the system with the IDS Flight Test Integration Test Bench (ITB), production avionics integration facilities, and final aircraft ground checkout and initial flight tests. It describes results of integration activities and bench evaluation of the telemetry system.

KEYWORDS

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

INTRODUCTION

The System Block Diagram of Figure 1 shows the instrumentation system implementation along with associated avionics and ground support equipment. This system is based on instrumentation, telemetry, and Fiber Channel Interface Unit (FCIU) designs described in previous ITC papers by the authors[1,2,3]. This paper presents a summary below:

The Instrumentation Control Unit (ICU) and Instrumentation Multiplexer Unit (IMU) are Boeing IDS-designed units which provide a central point for pilot control of the airborne system via avionics displays and dedicated flight test control panels, as well as the interface for the Ground Support Unit (GSU) for preflight, troubleshooting, and system configuration.

The ICU communicates with the Advanced Mission Computer (AMC) via a format protocol established between IDS Flight Test and Avionics groups. This protocol allows flight test to define the screen contents and responses to button pushes, without requiring extensive avionics integration regression for flight test menu changes.

The IMU buffers PCM from the sources shown in the figure to the airborne recorder, and sends eight of these to data combiners in the Telemetry System block to be transmitted in two RF streams. During preflight, the Instrumentation Operations Engineer (IOE) selects which streams are to be telemetered and configures the two data combiners for each bit rate.

The data recorder records up to 12 channels of PCM. The ICU allows the pilot to turn on the recorder (i.e. “record on”) and to view the % media used via the DDI display. An error indicator on the Glare Shield panel lights when there is a recorder error, and a reset switch on the panel allows for soft reset of the recorder without cycling Flight Test power.

The video system consists of a Video Buffer Switch (VBS), Video Recorder, and video compressor. The VBS presents three of these to the video recorder and one to the video compressor. The IOE selects the choice of video sources. A status indicator on the DDI display indicates that the video recorder is recording.

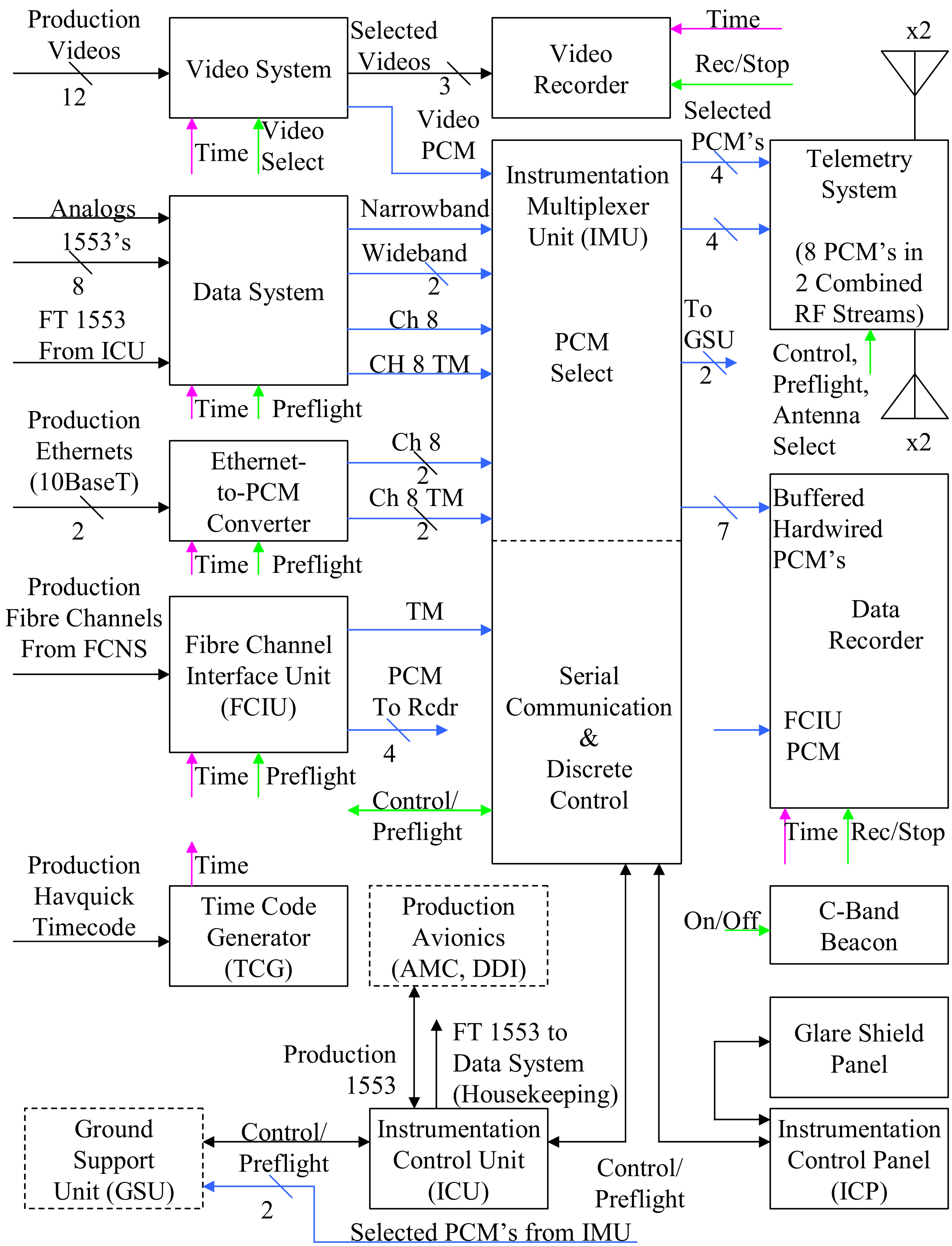

Figure 1. System Block Diagram

The Fibre Channel Interface Unit (FCIU) has been upgraded[4] to incorporate a bit rate-limited TM output and other capabilities in the same footprint. Its PCM outputs "throttle" based on the FC bus bit rate. The FCIU TM output is limited to a specific fixed programmable bit rate to limit the transmitted bandwidth.

The Ethernet-to-PCM converter is part of the Teletronics Technology (TTC) data system. This unit takes in 10BaseT Ethernet packets and formats them into a PCM stream according to an IRIG 106 Chapter 8-like PCM format. Each of two Ethernet inputs are formatted into a recorder output and a TM output, with the latter bit rate limited to a specified value.

The Data System is a TTC system consisting of an Airborne Instrumentation Controller (AIC) and a number of MCDAU stacks. These are configured into narrowband stacks, and two wideband stacks. The TTC system is loaded via a CAIS bus from the AIC through the ICU-controlled IMU. The AIC also receives a dedicated housekeeping data (run number, media percent remaining and others) via a dedicated 1553 bus sourced by the ICU.

The Time Code generator receives time code from a Havquick interface from the avionics system and supplies time to the ICU, FCIU, data system, data recorder and video recorder.

The ICU Controls power to the C-Band beacon via a relay. Beacon on/off is controlled via the pilot DDI display, and a status is provided in the housekeeping word transmitted to the ground.

Finally, the Ground Support Unit (GSU) is a rugged, carrier-qualified unit that houses equipment to preflight, troubleshoot, and configure the airborne system. It includes Boeing-written PCM and 1553 Real-Time display and preflight software, loader software from Boeing or third parties for loading and configuring airborne units, and software to communicate with the ICU. It also has a "DDI Simulator" capability that simulates DDI display communication from the cockpit, which is available with or without Avionics power on, which is used by the IOE in setting initial system settings such as transmitter frequency, production video selection, and TM PCM source selection.

TIMELINE SUMMARY OF INTEGRATION ACTIVITY

The design of the instrumentation system for this F/A-18 Hornet Flight Test Program began in early 2004. Telemetry requirements necessitated a reduced-bandwidth modulation such as SOQPSK[5] and the ability to transmit eight PCM streams in the form of two combined RF streams.

At the same time, design of the airborne instrumentation and ground support equipment began, as well as initial work on software generation for format generation, loading, and preflight. Design of the Instrumentation Test Bench (ITB) and its associated cabling and test equipment began in May of 2004.

Initial ICU Avionics integration was performed with ICU 1553 interface hardware in early 2005, driven by a single-board VME computer. This featured a hand-coded version of a display, used to validate the basic symbology, screen placement, and pushbutton response.

The initial IMU was installed on the bench in 2005, and the bench was populated with instrumentation equipment as it became available. Development of the ICU flight unit was delayed by checkout of the unit's General Purpose Processor (GPP), and so a work around "pseudo ICU" was put together to allow ICU firmware development to proceed. This interim ICU implementation was delivered to the bench in Spring 2005. An initial version of the flight ICU was delivered to the bench in early 2006.

A check was performed with a telemetry facility in January of 2006. In addition, a radiating test was performed with the bench TM system in a hangar to verify that the transmitter output was sufficient to perform a preflight check at the GSU when set to low power (less than 1 mW).

When the flight ICU was made available in January 2006, the final stage of ICU firmware was begun to integrate communication with the instrumentation system "peripherals", and to make the unit operation more robust. Much of this firmware could not be fully written or checked out with the interim ICU because of a low-level software problem specific to the interim implementation.

Final avionics integration was performed when portions of the bench were tested in the Avionics facility in April 2006. This also afforded an opportunity to record data from real avionics boxes in a simulated flight scenario, which gave data processing an opportunity to validate they had a proper understanding of protocols and decoding of flight test measurands to be acquired from the avionics equipment.

INTEGRATION RESULTS

The basic result of the integration was that a working system of airborne equipment, ground support equipment, and related software was delivered to the aircraft approximately 6 weeks ahead of scheduled power-up of the aircraft for ground checks, and 12 weeks ahead of first flight. Although there were some bugs and performance issues, these were expected with a system this complex and none of these prevented the team from readying the instrumentation for successful operation on the scheduled first flight date.

Issue or Test	Result or Consequence
Data System	
Hardware	See discussion below.
Format generation & loading software	Minor issues, resolved.
ICU	Power-on hangup occasionally with 1.0 firmware. Fixed in 1.1 release, delivered before aircraft ferried to the customer test site.
IMU	Identified possible issue with beacon control which could cause beacon to come on under certain failure conditions. Fixed in IMU firmware and in wiring to relay driver hardware.
Data Recorder	Loss of control noted in record mode(infrequently). Occasional corruption of media contents when powered down in record mode.

Issue or Test	Result or Consequence
	Both problems fixed before aircraft ferried to the customer test site.
Telemetry System	See Telemetry Bench Evaluation section below.
FCIU	Unexpected telemetry errors during final avionics lab check. Fixed with firmware revision. Minor issue with mapping inputs due to FC Network Switch wiring, resolved. FCIU and FCPU used in ground aircraft checkout to assist Avionics troubleshooting.
TCG	Update rate to Avionics GPS source found to be too slow, causing time jumps and backups with FCIU. TCG firmware updated.
Ethernet-to-PCM Converter	Firmware mod performed to split out low-level addressing information. Issue with reported time code format, resolved.
Video System	See discussion below
Hangar Operation (transmitter at low power)	Not good with equalizer engaged (as expected); Performance with equalizer off was quite good.
Ground Support Unit (GSU)	
Hardware	Some reliability issues noted with computer hardware. See discussion below.
Software	Preflight display software initially unstable due to RTX hardware calls. Effort in work to update these calls to Windows to keep future support manageable.

Table 1. Integration Results Summary

Table 1 summarizes the integration findings. Though the table focuses on specific issues, the overall system – hardware and software – performed very well and only a few of these issues were more than minor. The vast majority of the issues were resolved prior to initial aircraft ground checks, and the reaction from Flight Test Instrumentation personnel at the test sites was surprise that a system of this complexity operated with so few problems.

Integration of the video system resulted in changes to aircraft wiring. Shortly before the integration, Navy personnel (who were providing the recorder GFE) performed a similar integration with their supplier, and identified several operational issues, which were resolved. Boeing was to turn the recorder on and off and obtain media remaining information via serial commands. After problems were experienced doing so, and based on the complexity of ongoing support, it was decided to control the recorder through bilevel hardware commands, which had worked reliably during the earlier tests at the customer facility. This was successfully implemented. This fix provided basic video recorder on/off function, and media percent remaining was provided as a housekeeping measurand, calculated (roughly) by the ICU based on an empty initial media device.

The TTC data system largely functioned as expected, and Boeing format generation and loading software were validated with moderate effort. The MCDAU stacks, however, exhibited a problem during start-up where they would audibly "ring" at several hundred Hertz, for varying periods of time, sometimes continuously. The team performed a number of checks, and determined that the ringing was the result of current spikes that would occur under a variety of conditions, principally stack size, and a power supply with a lower current limit (the current spikes were on the order of 10 Amperes per stack). Powering the stacks via the transformer rectifier was initially determined by the team to be acceptable to prevent the ringing. However, once the units were delivered for initial aircraft ground checks, it was determined that some stacks were initializing incorrectly and the failure rate of stack power supplies was unacceptable, both believed to be caused by the ringing issue. An alternate fix was determined by the team, associated with adding external components to a power supply inhibit pin. The implementation of this fix is in work as of this writing.

The Ground Support Unit has performed well as a whole, but vendor-supplied computer hardware was not 100% reliable. Four computers were ordered for the program, and several of these have experienced temperature-related issues or general unreliability.

The DAC cards in the GSU require calls to a real-time operating system called RTX. Using RTX to likewise communicate with the computer's decom card has resulted in somewhat unstable preflight software, but this has now been resolved for current versions of the decom card. For future support, however, a plan is in work to update the software to use Windows drivers in place of the RTX drivers.

TELEMTRY SYSTEM BENCH EVALUATION

In conjunction with the primary integration activity, Boeing IDS Flight Test also performed a separate bench evaluation of the telemetry system.

Most of the tests performed used SOQPSK as the modulation of choice, although PCM-FM and Multi-h CPM were functionally checked. Tests were performed with and without the Turbo-Product Code (TPC) Forward Error Correction (FEC)[6].

In general, the system performed functionally as expected. The TTC MARM combiner and RMOR decombiner performed their functions as expected in both a hard-wired configuration as well as through the transmitter, receiver, and demodulator. An operational issue of some significance, however, was the fact that this system requires a significant amount of setup which must match between the airborne and ground sides.

Test	Result	Comments
RF Power Output		
Low Power	-2.5 to -8.5dBm	Somewhat lower than design goal, Varying over the band, but workable
Spectral Mask		Meets RCC 106-06 Appendix A, But with a minor spur on LSB barely above mask. Not a performance issue.
BEP Performance		Varied over band and with different SN's; Nova re-design produced consistent results

Test	Result	Comments
		and met 1st Flight schedule. See discussion below.
Acquisition Time		
Without FEC	3.5mS	Results consistent over bit rate; 1 Mbps acquisition somewhat worse
With FEC	~5mS	
With short dropout (<1mS)		Results not consistent. Test setup issue, not pursued further.
With Combiner/Decombiner	Tens of Ms; Some variability	Results difficult to measure due to PLL acquisition and buffering in decombiner. Not a performance issue.
Demodulator Adaptive Equalizer	Functional Performance verified	Unable to perform desired acquisition time test due to budget and schedule constraints.
Hangar Operation (transmitter at low power)		Not good with equalizer engaged (as expected); Performance with equalizer off were quite good.
PCM-FM Performance		Performance as expected, but not a focus of this evaluation.
Multi-h CPM Performance		Acquisition time worse than SOQPSK; BEP performance slightly worse; Not a focus of this evaluation.

Table 2 TM Evaluation Summary

Table 2 shows the results of the TM evaluation. Tests not shown in the table (such a RF power output at "high" power) produced nominal results and so are not included.

The acquisition time test was performed in a setup as described in RCC 118 Volume 2, Section 7 (as a starting point). The times for SOQPSK were quite good, and FEC added only a relatively small time to the numbers. The test with combiner and decombiner produced acquisition times which were much longer than with the transmitter and demodulator alone, as expected. The behavior of the decombiner phase locked loops, buffers, and frame acquisition strategy, however, produced results that were somewhat difficult to analyze and reproduce consistently.

Likewise, the team set out to perform a series of tests on the demodulator CMA Adaptive Equalizer[7]. The basic performance of the equalizer was functionally checked, but budget and schedule constraints prevented further testing. Performance of the Adaptive Equalizer in hangar-based preflight was, as expected, not suitable due to the number of complex early reflections at high amplitude, which the technique is not designed to handle.

This evaluation identified an issue with the BEP performance of the transmitter-demodulator combination. Initial units delivered to Boeing showed a variation in performance over the operating band on the order of up to 4dB, and substantial degradation with certain serial number units at higher bit rates. Furthermore, the absolute performance of certain serial number units was below the expected performance of a normal transmitter-demodulator combination even at midband (on the order of 1.5dB).

After reviewing the findings with Boeing, Nova engineers identified an issue in how the transmitter was initially designed, and developed a fix for the problem. They reworked an initial unit and delivered it to Boeing, who re-ran the test to verify acceptable performance over the band and at higher bit rates. Nova subsequently re-worked all the transmitters and delivered them in time to meet the first flight installation schedule.

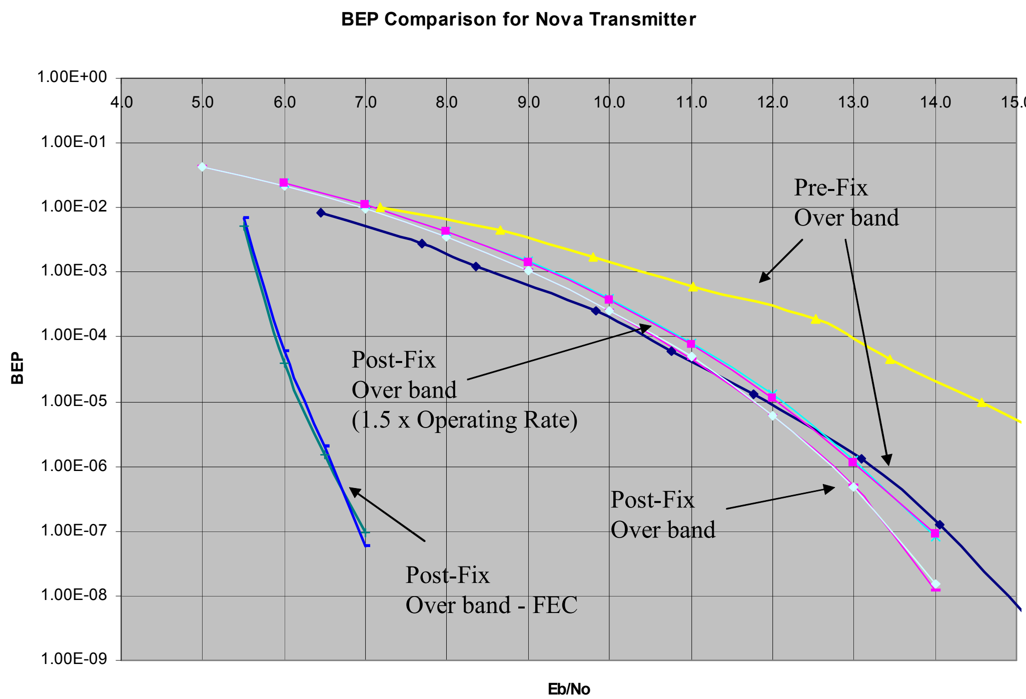

Figure 2 BEP Comparison for Nova Transmitter

The results are shown in Figure 2. The "Pre-Fix" curves show the variability at the operating data rate over the band. "Post-Fix" curves for the operating rate fit exactly on top of each other. Performance at 1.5 times the operating rate is a few tenths of a dB worse, with band edge curves likewise indistinguishable from each other. The graph also shows the substantial performance advantage of FEC, which adds about 6dB of margin at a BEP of 1 in 10^7. Note also that the FEC curves are for the operating data rate; the performance penalty for the 26% increase in transmitted bandwidth is worked into the curves, so they all represent the same (real) data throughput.

CONCLUSION

This F/A-18 Hornet Flight Test instrumentation system integrates Avionics displays to allow pilot control and configuration, as well as preflight. The system integration and telemetry evaluation produced a reliable, working system, which produces quality data. This paper has detailed system test results and lessons learned to aid future instrumentation system integrators in the task at hand.

REFERENCES

1. Wegener, John A. and Roche, Michael C., "The Design of a 21st Century Telemetry System with SOQPSK Modulation and Integrated Control", Proceedings of the International Telemetering Conference, Las Vegas, October 24-27, 2005.

2. Wegener, John A. and Zettwoch, Robert N., "An Instrumentation Control System that Utilizes an Avionics Pilot Display Interface", Proceedings of the International Telemetering Conference, San Diego, October 18-21, 2004.

3. Zettwoch, Robert N., "Flight Test Monitoring of Avionic Fibre Channel Networks for Recording and Telemetry", Proceedings of the International Telemetering Conference, Las Vegas, October 20-23, 2003.

4. Ibid.

5. Hill, Terrance J., "An Enhanced, Constant Envelope, Interoperable Shaped Offset QPSK (SOQPSK) Waveform for Improved Spectral Efficiency", Proceedings of the International Telemetering Conference, San Diego, October 23-26, 2000.

6. Geoghegan, Mark, "Extending the Range of PCM/FM Using a Multi-Symbol Detector and Turbo Coding", Proceedings of the International Telemetering Conference, San Diego, October 21-23, 2002.

7. Geoghegan, Mark, "Experimental Results for PCM/FM, Tier 1 SOQPSK, and Tier II CMA Equalization", Proceedings of the International Telemetering Conference, San Diego, October 18-21, 2004.

ACKNOWLEDGEMENTS

The authors would like to acknowledge the assistance of many Boeing Flight Test teammates, especially John Trousdale, Anita Johnson, Donald Sullenger, William G. Henry, Gordon Blase, and Richard Harris. This paper could not have been completed without their assistance.

They would especially like to recognize Roxanne Baker, who performed the duties of principal integrator prior to becoming the lead Instrumentation Operations Engineer on the first test aircraft. She worked many long hours hand-in-hand with the principal author of this paper and her contributions to this effort cannot be overstated.