

# **PERFORMANCE TRADE-OFFS WHEN IMPLEMENTING TURBO PRODUCT CODE FORWARD ERROR CORRECTION FOR AIRBORNE TELEMETRY**

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## **ABSTRACT**

Hardware implementing forward error correction (FEC) is currently available for utilization by the airborne telemetry system designer. This paper will discuss the potential benefits along with drawbacks when using this technology. Laboratory testing is supplemented with real-world flight testing. Performance results comparing FEC and non-FEC systems are presented for both IRIG-106 Pulse Code Modulation/Frequency Modulation, PCM/FM, (or Continuous Phase Frequency Shift Keying, CPFSK, with filtering, or ARTM Tier 0) and Shaped Offset Quadrature Phase Shift Keying, Telemetry Group version (SOQPSK-TG or ARTM Tier I) waveforms.

## **KEY WORDS**

Turbo Product Codes (TPC), Forward Error Correction (FEC), HYPERMOD, bit error probability, resynchronization, PCM/FM, SOQPSK-TG

## **INTRODUCTION**

Over the past several years, the Government telemetry community has been losing precious radio frequency (RF) spectrum to commercial interests. This coupled with increasing data rates has forced the Government to invest time and resources into finding more robust and bandwidth-efficient means of transmitting test data. The Advanced Range Telemetry (ARTM) program was created and tasked to investigate these areas. For increased robustness of the telemetry link, one area explored was forward error correction (FEC). Forward error correction is known for its ability to increase detection performance, leading to a more robust link. The HYPERMOD Program, commissioned by the ARTM Program, developed telemetry hardware in the form of an airborne transmitter and ground station demodulator. One feature of this hardware is the implementation of one form of FEC. This paper will explore the potential gains and losses associated with the forward error correction implemented in the HYPERMOD hardware when applied to an airborne telemetry link.

## HARDWARE DESCRIPTION

The HYPERMOD line of products, from Nova Engineering, implements a proprietary version of forward error correction called Turbo Product Codes (TPC) from Advanced Hardware Architectures (AHA). This form of FEC was attractive due to its large coding gain, rate flexibility, simple structure and commercially available encoder and decoder development hardware and integrated circuits. The specific implementation of the TPC chosen has a block size of (32,26) x (32,26) where 32 is the block length and 26 is the message length. The encoder (or transmitter in this case) transforms a block of 26x26 (676 bits) message bits into a longer block of 32x32 (1024 bits) codeword bits. For a detailed explanation of the encoding and decoding process for AHA's implementation of Turbo Product Codes, refer to the listed references.

Encoding of the incoming bit stream is done by the HYPERMOD transmitter itself. The encoding process is relatively simple and is accomplished within a field programmable gate array (FPGA) internal to the transmitter. Encoding can be enabled either by an external jumper setting or through a software control panel on a laptop connected through a serial port to the transmitter.

Decoding of the encoded stream is far more complex necessitating the use of the AHA decoding hardware. This hardware is internal to the demodulator and can be activated on the front panel of the demodulator. The bit rate setting for the demodulator is the original, uncoded bit rate.

## SPECTRAL OCCUPANCY

Referring back to the discussion above, the HYPERMOD hardware implements a (32,26) code. Knowing this, with binary data and including cyclic redundant check (CRC) bits (4) and block synchronization bits (16), the amount of coding overhead can be calculated:

$$\% \text{ Overhead} = \{ 1 - 1 / [(32^2 + 16) / (26^2 - 4)] \} 100 = 35.4\%$$

Or, in more familiar terms of code rate,

$$\text{Code Rate} = 1 / [(32^2 + 16) / (26^2 - 4)] = 0.646$$

This says that the spectral occupancy with FEC enabled should roughly be 55% wider (half again more than the original data rate) when compared to the uncoded case. Another way of stating this is in terms of bit rate. A user who requests frequency bandwidth for a 5Mbps telemetry stream will now request bandwidth for a 7.7Mbps telemetry stream.

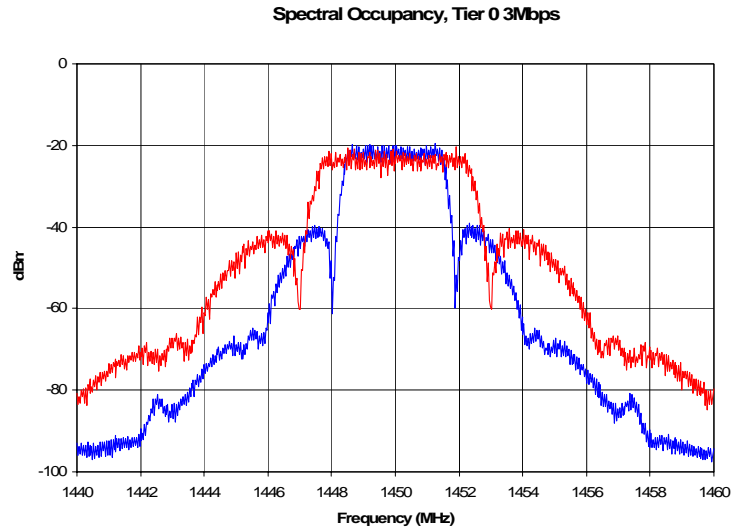


Figure 1 – Spectral Occupancy, 3Mbps PCM/FM

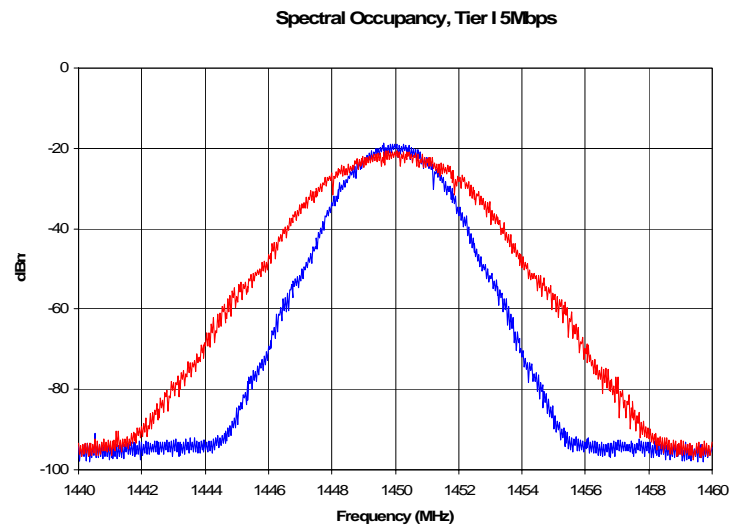


Figure 2 – Spectral Occupancy, 5Mbps SOQPSK-TG

### BIT ERROR PROBABILITY

The first test performed was bit error probability (BEP). The test set-up used is shown in Figure 3. The transmitter was used as the source of the coded and uncoded data. The output of the 10W transmitter was attenuated, mixed down to 70MHz, and filtered prior to the HP3708, Noise and Interference Test set which injects calibrated additive white Gaussian noise (AWGN). This allowed direct control of the bit energy to noise density ratio, or  $E_b/N_0$ , values. At this point it should be noted that there is NOT a telemetry receiver (addition of phase noise and filtering) in the down conversion chain and thus BEP versus  $E_b/N_0$  numbers presented here are not representative of complete system level performance. To

finish out the test set, a bit error rate analyzer, a Fireberd 6000A, was used to acquire and generate bit error statistics.

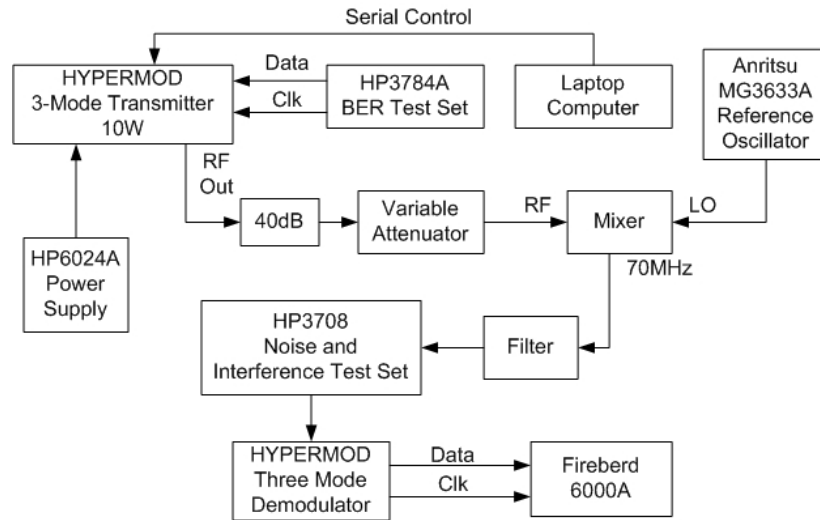


Figure 3 – Additive Noise Test Set-up

Data for differing data rates are presented in Figures 4-6. For the coded case, block error probability may have made more sense but that test capability was not available. As is the case with block codes, when several bits are in error, exceeding the code's correction capability, the block cannot be assembled correctly and the entire block is in error. This leads to very large chunks of data being in error instead of individual bits. Also, the value of  $E_b/N_0$  is referenced to the uncoded case in order to compare detection efficiencies on an equal basis.

It should be noted here that for the data presented in this paper, differential encoding for the Tier I waveform was enabled throughout the testing of the transmitter/demodulator. Differential encoding/decoding is used to resolve potential phase detection ambiguities that are inherent in QPSK, OQPSK, and FQPSK modulation methods. The effect of differential encoding/decoding is evident in the bit error probability (a shift to the right in detection efficiency) and resynchronization speed results (more consistent times). It is possible for the system to function without differential encoding/decoding and experiments were conducted to verify this idea. For this case, the coding resolves the ambiguity but at the cost of resynchronization speed and resynchronization event to resynchronization event consistency.

### HYPERMOD TPC FEC Comparison 1Mbps (Data Rate)

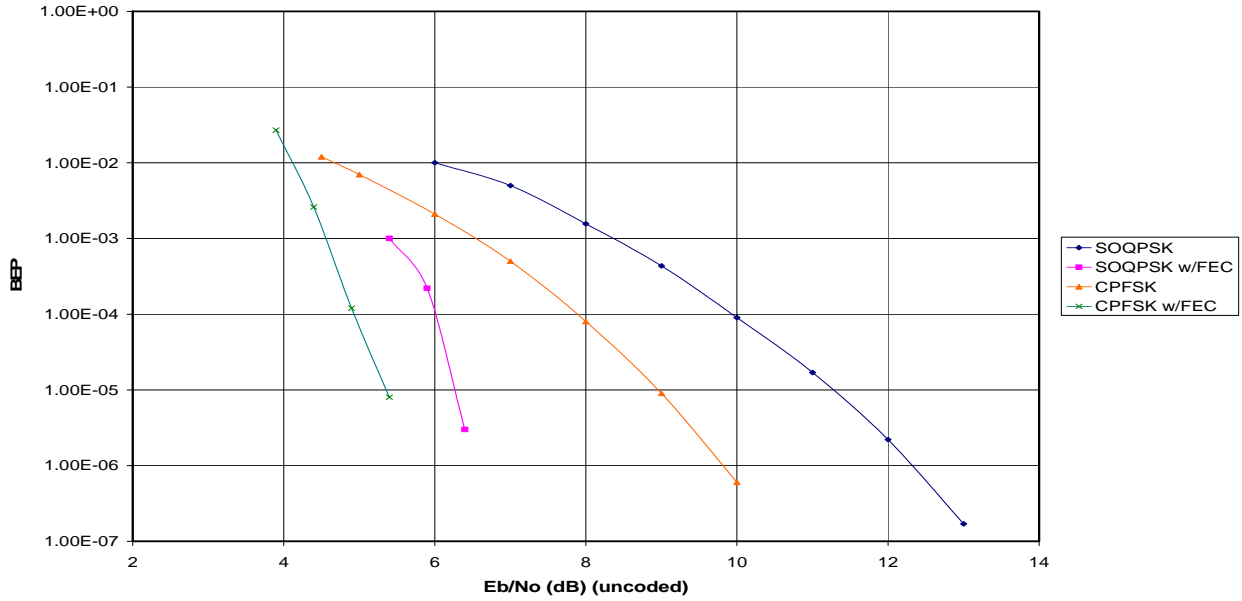


Figure 4 – Bit Error Probability, 1Mbps

### HYPERMOD TPC FEC Comparison 5Mbps (Data Rate)

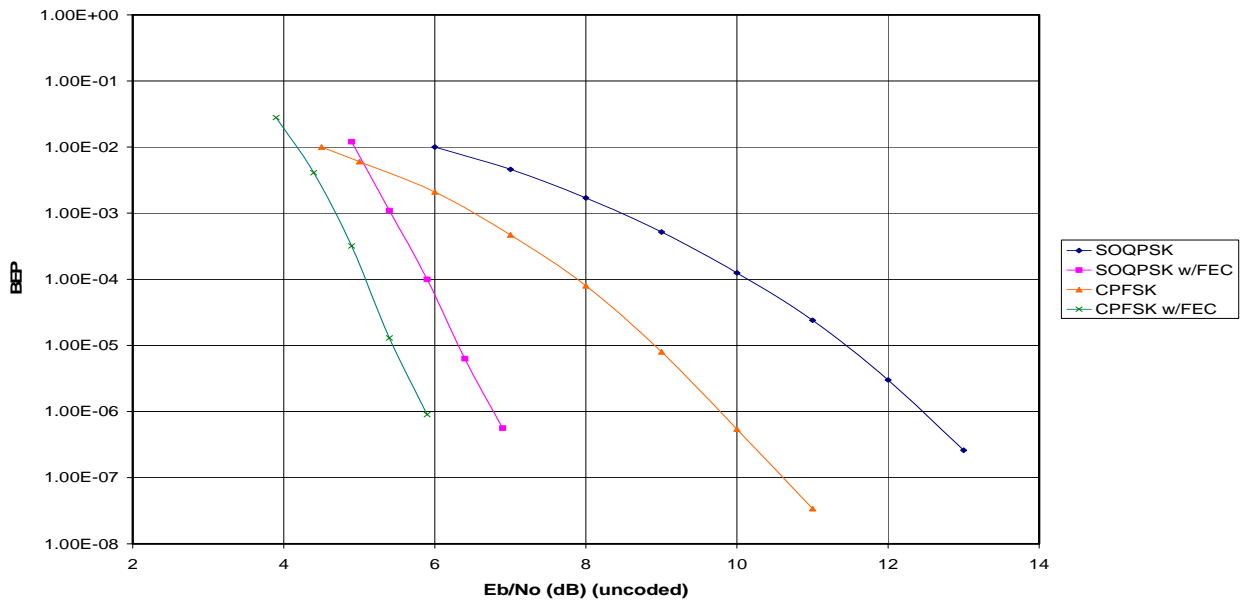


Figure 5 – Bit Error Probability, 5Mbps

**HYPERMOD TPC FEC Comparison  
9Mbps (Data Rate)**

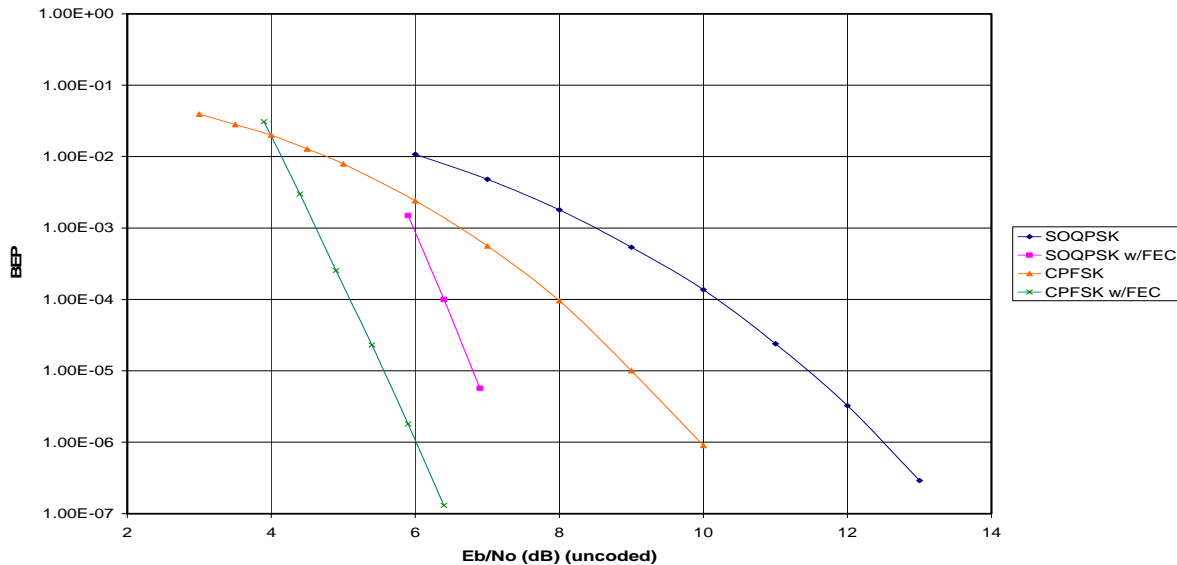


Figure 6 – Bit Error Probability, 9Mbps

Reviewing the data, we see the steepness exhibited on the coded curves. This is typical for coded systems, they are either providing error-free data (or nearly error-free data) or out of synchronization. It should be noted the demodulator used in these tests implements multi-symbol detection for the PCM/FM waveform. Similar testing will have to be done in order to characterize coding gain for conventional frequency modulation (FM) detectors.

**SYNCHRONIZATION THRESHOLD**

Synchronization threshold was tested utilizing the same test set-up as in Figure 3.  $E_b/N_0$  was decreased until the demodulator indicated symbol synchronization was being intermittently lost and the first pattern synchronization slip occurred on the Fireberd bit error rate analyzer. Synchronization threshold was declared when the demodulator showed no symbol synchronization and lost pattern synchronization was excessive. The results of this test are shown in Table 1.

	SOQPSK-TG (dB)	SOQPSK-TG w/FEC (dB)
1Mbps	4.6	3.3
5Mbps	4.2	3
9Mbps	3.9	3.6
15Mbps	4	2.5

	PCM/FM (dB)	PCM/FM w/FEC (dB)
1Mbps	1.5	1.6
5Mbps	1.6	1.5
9Mbps	1.8	1.4

Table 1 – Resynchronization Threshold

A quick look at the data reveal the PCM/FM threshold is not improved nor is it degraded. The coded SOQPSK-TG stream does stay in synchronization longer but the threshold could be limited by the demodulator structure.

## RESYNCHRONIZATION SPEED

The test set-ups shown in Figures 7 and 8 are for testing the resynchronization speed of the demodulator with and without forward error correction applied to the data. There are two variations of this test, the fast fade recovery test, Figure 7, and the acquisition time test, Figure 8. The fast fade recovery test was designed to simulate flat fades where before and after the fade the signal to noise ratios are very high. The acquisition test was designed to test the demodulator's resynchronization speed after a flat fade in the presence of noise. Test set-ups are very similar between the two tests with the difference being the addition of the noise and interference test set (HP3708) in the signal chain. The demodulator acquires the signal in the presence of noise in the initial acquisition test where as it does not in the fast fade recovery test. For both tests, the transmitter is configured to transmit either coded or uncoded sequence of randomized one's per IRIG-106. For the fast fade recovery test, this transmitted signal is sent to one input of a PIN diode switch. For the initial acquisition test, the output is sent to the HP3708 for adding calibrated noise then to the PIN diode switch. Broadband, additive white Gaussian noise (AWGN) is sent to the other input of the switch and a pulse generator is connected to the control port of the switch. The cycle rate of the switch is determined by this pulse generator. The common port of the switch is then sent to the demodulator. The levels of signal and noise going into the switch are matched to eliminate any automatic gain control (AGC) action on the front-end of the demodulator, which could skew resynchronization results. The demodulator's derandomizer is enabled and FEC decoder is enabled if applicable. The switch control and the data output of the demodulator is then monitored with a digitizing oscilloscope. By triggering on the switch control signal and waiting for the data to settle to an all ones pattern, the user can measure the resynchronization speed of the demodulator under test by measuring the time between the trigger event and an all one output. At each test point, 20 resynchronization times were recorded and an 80<sup>th</sup> percentile rank of that set was used to establish one number for the resynchronization time.

Carrier acquisition range for the demodulator is another variable in the tests. The HYPERMOD demodulator has a user configurable carrier acquisition ranges from  $\pm 100\text{kHz}$  to  $\pm 20\text{kHz}$  in 20kHz steps. For consistency and to simulate most real-world demodulator configurations, the tests were run with the carrier acquisition set to the full range of  $\pm 100\text{kHz}$ .

Resynchronization results for initial acquisition and fast fade recover for both PCM/FM and SOQPSK-TG are shown in Figures 9 and 10. It should be no secret that there is additional time required for the decoding hardware to synchronize and each of the figures points this out. In the case of Tier 0, significant overhead time is associated with FEC resynchronization from on the order 100's of bits to many thousands of bits. For Tier I, there is roughly a tenfold increase in resynchronization time. At first glance, these numbers look ominous, but in most aeronautical environments, the synchronization losses from multipath and shadowing far exceed the resynchronization time. For instance, say a 5Mbps, Tier I stream suffered a 1 second dropout due to multipath, which is not an unusual occurrence. Therefore, 5,000,000 bits were lost. In addition to that, 20,000 bits are needed to resynchronize. The resynchronization time constitutes only 4% of the total number of bits lost.

The forward error corrected data will always take longer to resynchronize because not only does the demodulator have to regain synchronization, but also the decoder hardware. Uncoded resynchronization times only include the front-end demodulator while FEC numbers include both.

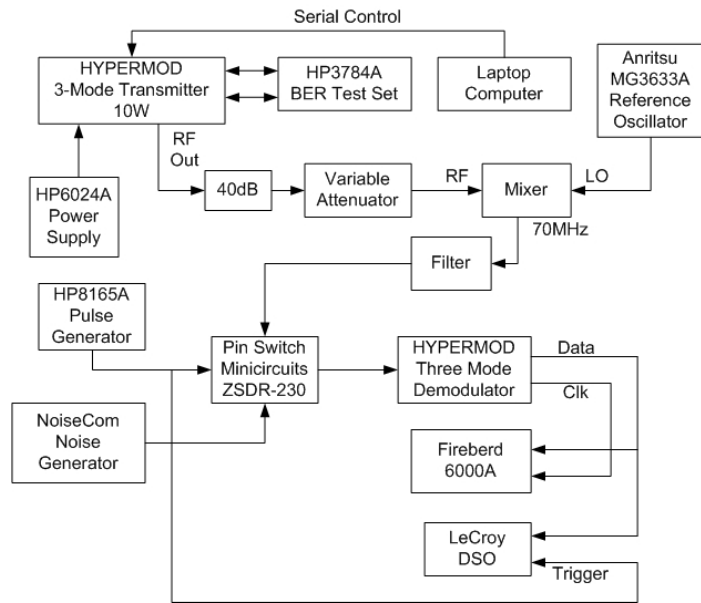


Figure 7 – Fast Fade Recovery Time Test Block Diagram

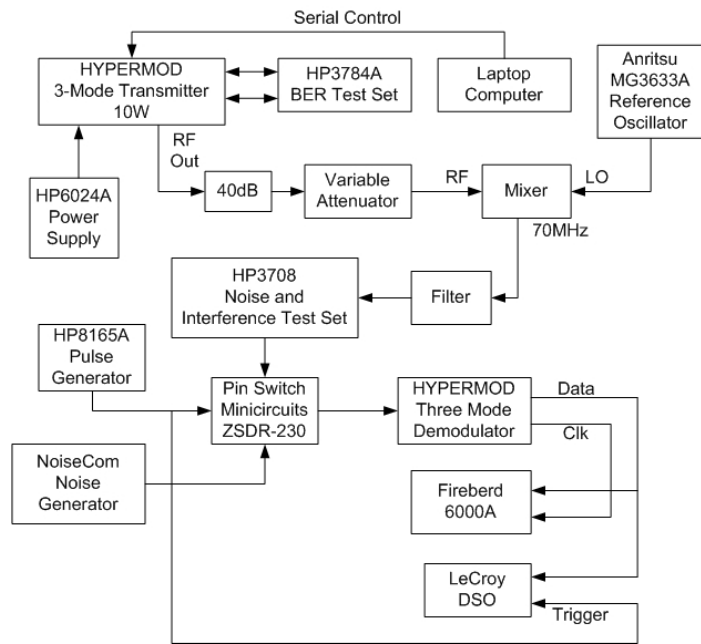


Figure 8 – Acquisition Time Test Block Diagram



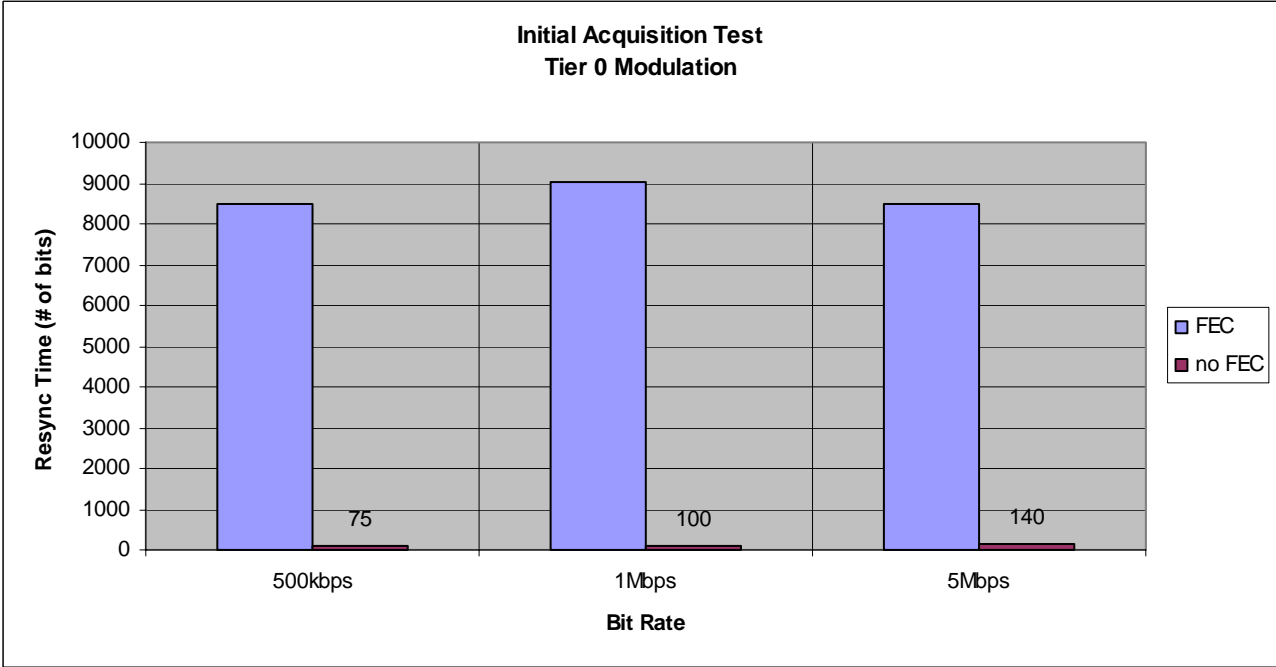
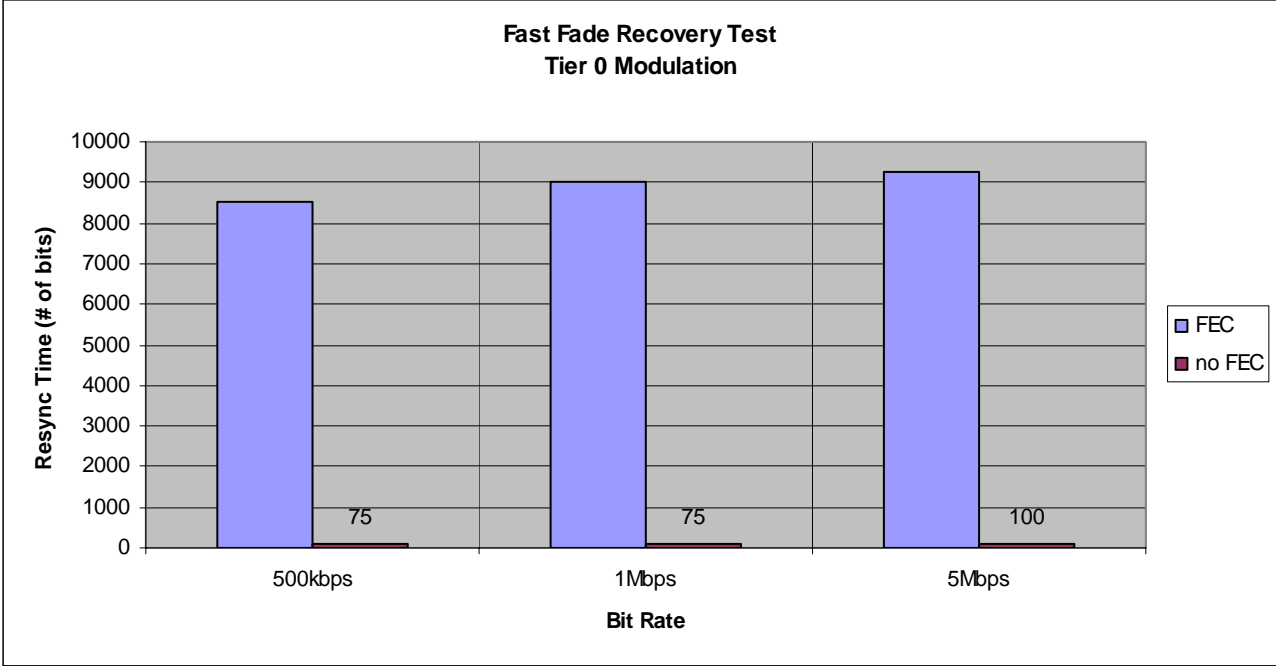


Figure 9 – Tier 0, Fast Fade Recovery/Initial Acquisition

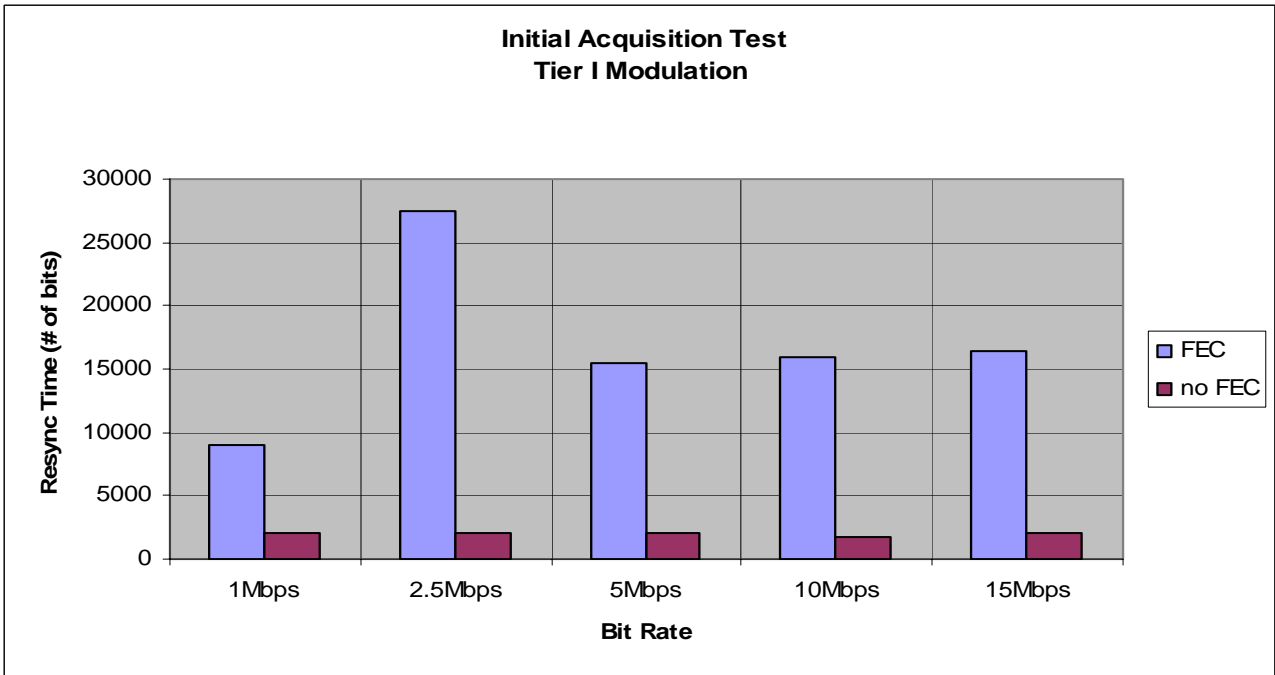
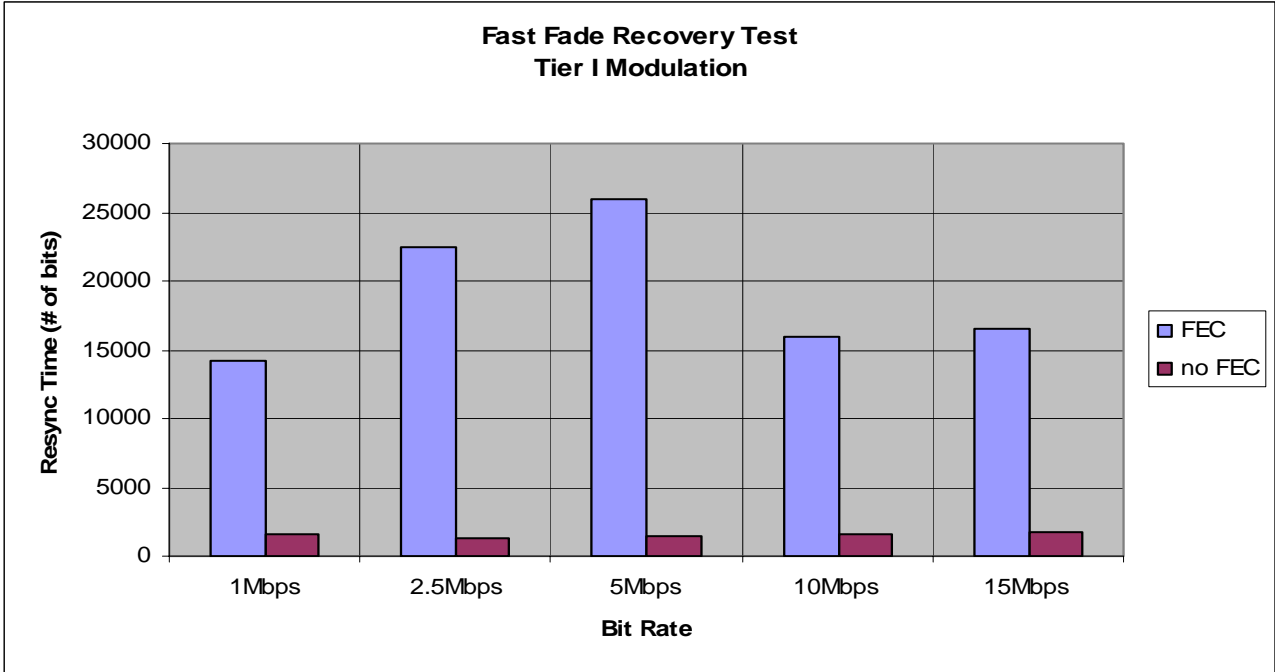


Figure 10 – Tier I, Fast Fade Recovery/Initial Acquisition

## FLIGHT TESTING

Flight testing took place comparing coded and uncoded telemetry streams. These tests were conducted over familiar flight paths in the L-Band aeronautical telemetry band. The Tier I waveform was flown over two flight paths and the reference Tier 0 waveform over one of those flight paths. In the aircraft, two Nova Engineering transmitters were used as the source of the modulated 2047 PN-sequence. Both transmitters were 10W units with their outputs isolated, combined, and sent to the ground via the same wideband airborne antenna. The carrier only power levels were matched prior to the antenna port. This was done in order to equalize the transmitter output power thinking the end user would either enable or not enable FEC with the same transmitter and thus utilizing the coding gain but at the same time scheduling more spectrum and suffer in signal to noise ratio at large slant ranges. On the ground, the combined signal was received, sent through two receivers for tuning and down conversion, then sent to two MMD44s for demodulation. Out of each demodulator came data and clock which were sent to two Fireberd 6000 bit error rate analyzers. One Fireberd captured error statistics for the FEC link, and one captured error statistics for the uncoded telemetry link. The two center frequencies were separated by 30MHz which resulted in time dispersion between individual error events in the bit error files.

One figure of merit used in this comparison is Link Availability. The data presented covers link availability during each test run. Link availability, expressed as a percentage, is defined as:

$$LA(\%) = \left[ \frac{ET - (\Sigma BadBitsTime)}{ET} \right] \times 100\%$$

where *LA* is Link Availability

*ET* is Elapsed Time

*BadBitsTime* is the total time of bits that are determined to be in error in the given amount of elapsed time. Depending upon the bit error analysis equipment used, these individual terms are given many names

Since we were using the Fireberd as the bit error analysis tool that has performance metrics built-in, the following equation was used to calculate Link Availability:

$$LA(\%) = 1 - \left[ \frac{UnavailableSeconds}{AvailableSeconds} \right] \times 100\%$$

where *UnavailableSeconds* is a calculated Fireberd parameter related to the time the link is unavailable

*AvailableSeconds* is a calculated Fireberd parameter related to the time the link is available

Two flight paths were utilized, one with known multipath events (Cords Rd) and one that is free from multipath events but is flown out to the point where both demodulators lose synchronization (Race Track). The flight paths are shown in Figure 11. A data rate of 5Mbps for the SOQPSK-TG tests was chosen to reflect current real-world requirements. A data rate of 3Mbps for the PCM/FM tests was chosen to approximately maintain the same bandwidth requirements between the two tests. Link availability for both modulations are shown in Tables 2 and 3. Table 2 shows the amount of time, in seconds, in which the link was *available*. For this paper, the definition for *available* means a bit error rate less than 1 in  $1 \times 10^3$  bits. It would have been desirable to decrease this threshold to 1 in  $1 \times 10^5$  bits but the hardware used did not allow for this change.

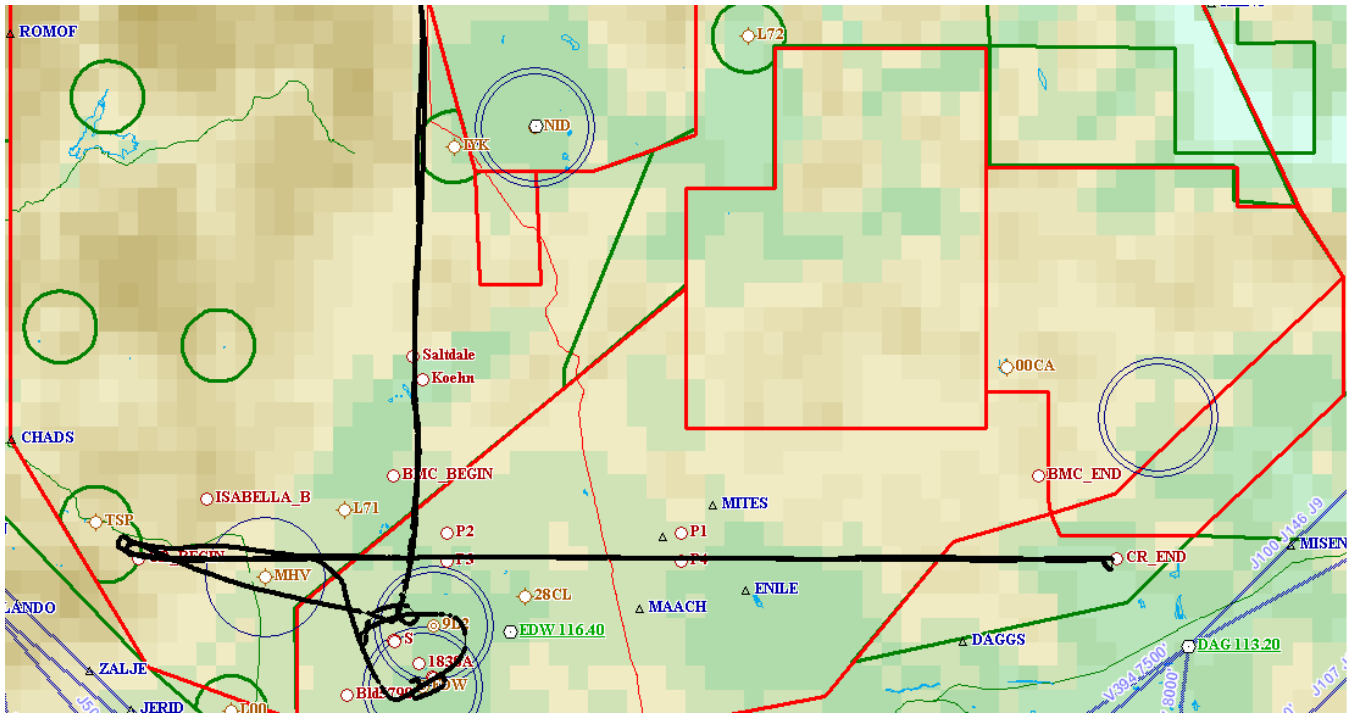


Figure 11 – Flight Path

Waveform	Link Availability				Total Mission
	RT S-N	RT N-S	Cords Rd W-E	Cords Rd E-W	
SOQPSK-TG	51.44%	73.16%	76.68%	85.69%	58.05%
SOQPSK-TG w/FEC	46.07%	87.49%	75.45%	89.43%	60.49%

Table 2 – Link Availability, Tier I

Waveform	Link Availability		
	Cords Rd W-E	Cords Rd E-W	Total Mission
PCM/FM	91.22%	94.88%	86.33%

Table 3 – Link Availability, Reference, Tier 0

Waveform	Available Seconds				
	RT S-N	RT N-S	Cords Rd W-E	Cords Rd E-W	Total Mission
SOQPSK-TG	970	950	1115	1216	5252
SOQPSK-TG w/FEC	942	1071	1104	1258	5343

Table 4 – Available Seconds, Tier I

Another way to present the data is a plot of accumulated bit errors versus time and compare the two streams. This is a way of showing graphically when and to what extent the bit errors occur for each waveform.

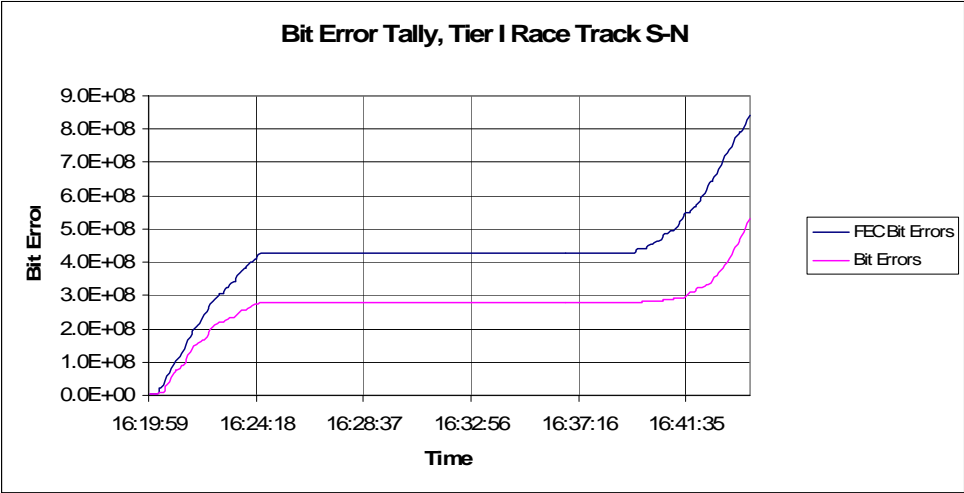


Figure 12 - Accumulated Bit Errors, Race Track S-N

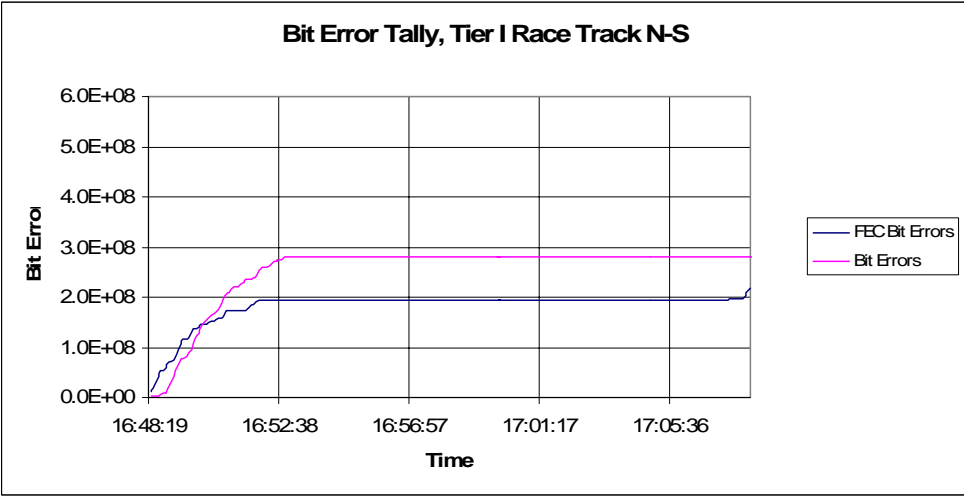


Figure 13 - Accumulated Bit Errors, Race Track N-S

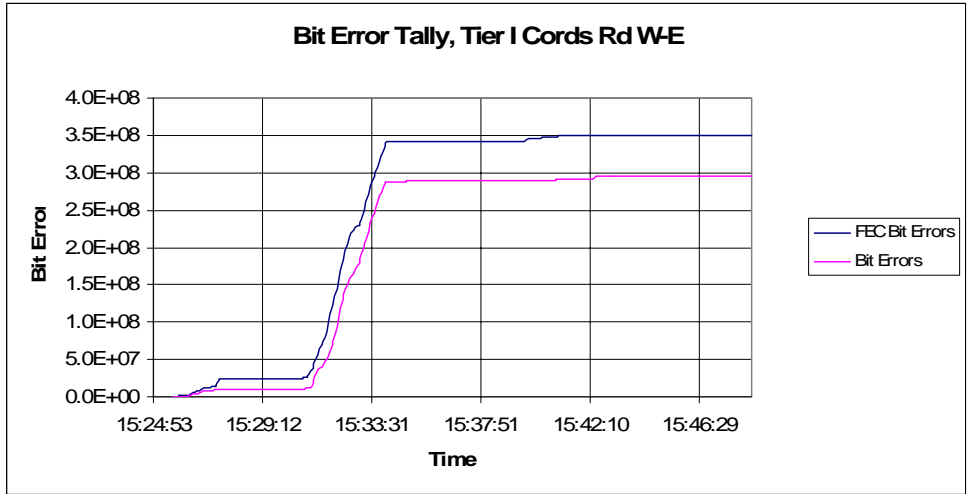


Figure 14 – Accumulated Bit Errors, Cords Rd W-E

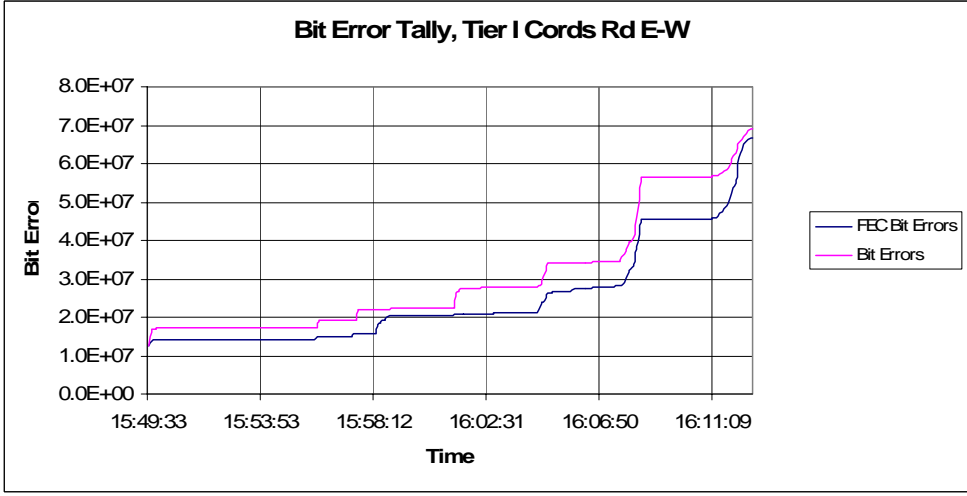


Figure 15 – Accumulated Bit Errors, Cords Rd E-W

A few real-world issues should be noted prior to analyzing the numbers in Tables 2 & 3. First, there is a high power radar that sweeps through the test range at a 13 second interval causing bit error bursts in the received data. Second, there are certain receive antenna look angles in which the antenna pattern from the aircraft are not desirable. Of the data presented, the Race Track was inhibited by poor antenna patterns (in the S-N path) and the Cords Rd path was inhibited by the radar. Now, looking over the link availability numbers, we notice the low link availability numbers in Table 2 when compared to the numbers in Table 3. This is due to the poor antenna pattern (Race Track) and radar interference (Cords Rd). It should also be evident that the Tier 0 (PCM/FM) waveform is not as susceptible to the radar interference as the Tier I (SOQPSK-TG) waveform.

The reference numbers (Table 3) show that Cords Rd is better from E-W than W-E. This matches the link availability data for the Tier I waveform. If the Tier I results are judged only against themselves, we can conclude some interesting results. In the RT S-N path with the undesirable antenna pattern, we notice the coding cannot correct this type of distortion. At the start of the return path (RT N-S), when the antenna pattern was better, the coded link at first was worse but then gained an advantage. This is

because at low signal to noise ratios (large slant ranges), the coded link was providing useful data where the uncoded link was not. This can be seen in Figure 13 between times 16:48:00 and 16:52:00. This is also true in Figure 15 at the furthest point from the receive antenna at time 15:49:33. These are examples of the coding gain at work correcting bit errors at low  $E_b/N_0$  values. These two cases are certainly instances in which forward error correction aids the telemetry link.

For multipath susceptibility, during the Cords Rd E-W flight path at time 15:58.12 (see Figure 15) there were significant frequency selective fading events in rapid succession. This was verified at the ground station and subsequent review of the receive spectrum analyzer display video and receiver automatic gain control logs. One notices the increase first in the uncoded link and then more severely in the coded link. As was mentioned, this time dispersion in events is caused by the offset in carrier frequencies between the two signals. Another example lies in the Cords Rd W-E flight path. At the start of this run, 15:25:00, the antenna looks through multiple windmills and into mountainous terrain. These two physical phenomena coupled together lead to frequency selective fading. As can be seen from the data in Figure 15, the coded link produces more bit errors at this time than the uncoded link. For these cases, the longer resynchronization time penalized the coded link resulting in more bit errors during these multipath events.

The last column in Tables 2-4 labeled “Complete Mission” are given for reference. These numbers included time on the runway, maneuvering to/from test points, maneuvering in/around the airfield, two landings, and taxi time.

## CONCLUSIONS

Spectrum expansion of roughly 55% when compared to an uncoded waveform occurred due to the increase in data rate due to coding overhead. This expansion is for this specific block size, other block sizes will offer different spectral expansions.

Bit error curves are very steep for forward error corrected links. In real-world airborne scenarios, the link is either providing corrected, error-free data it isn't.

Measured coding gains at the  $1 \times 10^{-5}$  point were approximately 3dB for PCM/FM (Tier 0) and 4-5dB for differentially encoded SOQPSK-TG (Tier I).

Resynchronization thresholds were lower with the encoded stream, but not by a significant margin. Optimization within the demodulator may be required in order to achieve lower synchronization thresholds. Lower resynchronization levels mean the demodulator/decoder does not incur the time penalty, in bits, required to reacquire and lock onto the signal.

Synchronization was far more consistent with differential encoding enabled. This allowed the demodulator to acquire symbol synchronization and did not rely on the coding to perform the same function. When differential encoding was disabled, synchronization thresholds varied by more than 2-3dB in  $E_b/N_0$ .

Though Range issues were noted, valuable flight data was presented. After analysis, flight data showed coding gains at low signal to noise ratios which is to be expected from theory and lab testing results.

Resynchronization speed of the forward corrected link did not seem to have a large negative impact on overall link availability numbers when compared to the uncoded link though negative impacts (larger numbers of bit errors) during frequency selective fading events were noted and explained.

Large gains in link availability were not noticed for the coded link though available seconds were greater for 3 of the 4 flight paths.

Link availability numbers will naturally vary with flight scenario. It is expected that forward error corrected links operating at lower signal-to-noise ratios will have a more significant improvement in link availability when compared to uncoded links.

It is believed that forward error correction does have a place in aeronautical telemetry for flight scenarios where the platform will be operating at low signal to noise ratios (low  $E_b/N_0$  values) and not in multipath rich environments. This gain will have to be weighed against the spectral expansion due to the coding overhead.

### **ACKNOWLEDGEMENTS**

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