

ARTM TIER II WAVEFORM PERFORMANCE

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ABSTRACT

One of the charters of the Advanced Range Telemetry (ARTM) program was to develop more spectrally efficient waveforms while trying to maintain similar performance to the legacy waveform, Pulse Code Modulation/Frequency Modulation (PCM/FM). The first step toward this goal was the ARTM Tier I family of waveforms which include Feher patented, quadrature phase shift keying, -B version (FQSPK-B) and shaped offset quadrature phase shift keying, Telemetry Group version (SOQPSK-TG). The final step was development of Tier II, an even more spectrally efficient waveform, multi-h Continuous Phase Modulation (CPM). This paper characterizes the performance of this waveform when applied in an airborne telemetry environment and, where appropriate, comparisons are made with existing Tier 0 and Tier I waveforms. The benefits, drawbacks, and trade-offs when applying this waveform in an airborne environment will also be discussed.

KEY WORDS

Multi-h Continuous Phase Modulation (CPM), spectral occupancy, bit error probability, resynchronization

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 ARTM program was formed to examine and provide solutions to these problems. The first phase (Tier I) of the program was to find a more bandwidth efficient modulation scheme than the current standard, PCM/FM, sometimes referred to as Continuous Phase Frequency Shift Keying (CPFSK). The goal of the new scheme was to perform at least as well as PCM/FM in terms of bit error probability (BEP) and resynchronization time and be compatible with nonlinear amplification. The second phase (Tier II) was to find an even more bandwidth efficient scheme while still trying to satisfy the same goals.

A program called HYPERMOD was started in order to research, define, and develop a Tier II waveform. The waveform that was chosen was a continuous phase modulation scheme that varies the modulation index, h , between two values on a symbol by symbol basis [1, 3]. In addition to this, pulse shaping is performed utilizing a raised cosine pulse. The result of this is a very spectrally efficient waveform but one that is very hard to correctly detect. This led to the design of an FPGA-based trellis demodulator specifically designed to unravel this waveform. This paper provides test results of this waveform/demodulator combination and identifies pros and cons of utilizing this waveform in an airborne telemetry environment. Spectral occupancy, bit error performance, synchronization speed, and distortion (multipath) sensitivity are compared the measure performance with existing Tier 0 and I data where applicable. The final piece of the puzzle, how the waveform performs during an actual flight test, will also be presented.

LABORATORY WAVEFORM PERFORMANCE TESTS

The ARTM program has tested production Tier I ground station demodulators in order to assess demodulator and system level performance in an airborne environment. This assessed performance was based on bit error rate performance, the ARTM developed adjacent channel interference (ACI) tests [15], and other ARTM developed tests such as resynchronization and multipath sensitivity tests. These are all system level tests designed to simulate real-world conditions. Of interest in this paper are the BEP, resynchronization speed, and multipath sensitivity tests. The combined results of these tests, when viewed together, should give an accurate picture of how the waveform will perform in an actual airborne test environment.

The ARTM test station, configured for spectral occupancy, bit error probability, and demodulator resynchronization testing, was covered in detail in the 2002 International Telemetry Conference (ITC) proceedings [5]. One configuration worth mentioning is the multipath sensitivity configuration. This test tries to gain insight into how sensitive the waveform/receiver/demodulator is to a multipath event similar to an airborne scenario.

Through the channel sounding efforts of the ARTM program and the Brigham Young University Telemetry Laboratory, frequency selective fading was found to be the dominant source of short-term telemetry link drop-outs [4]. It was found that for a large amount of these fading events, a two-ray model could be used to describe these drop-outs. Because these fading events are so commonplace, system (receiver/demodulator) sensitivity to these events, or simulated events, is an important parameter to measure in order to ascertain how well a system may function during an actual flight test. Per 1999 ITC proceedings [6], the transfer function of the telemetry channel model can be described with the following equation:

$$h(t) = \delta(t) + \Gamma e^{j\gamma} \delta(t - \tau) \quad 0 \leq \Gamma \leq 1$$

where $\delta(t)$ is the line of site path
 Γ is the strength of the reflected path relative to $\delta(t)$
 γ is the overall phase shift of the reflected path
 τ is the delay of the reflected path

As was stated above, most multipath events can be described with a simple two-ray model which includes the direct line-of-sight path and one reflected path with the range of τ (for the Edwards Test Range) from 20-500ns [6].

PERFORMANCE RESULTS

How well does the ARTM Tier II waveform perform in a multipath environment when compared to classic PCM/FM and to the Tier I waveforms? What advantages are there for using this waveform? Is link availability comparable? What other factors may degrade the performance of the Tier II waveform?

Spectral Occupancy Comparison

Figure 1 shows the modulated spectrum of nonlinearly amplified PCM/FM, Tier I and Tier II waveforms. Various criteria exist for measuring occupied bandwidth. The three shown, 99 percent, 99.9 percent, and -60dBc can be expressed in terms of bit rate as shown in table 1. One newer criteria, channel spacing based upon adjacent channel interference (ACI), is not given here due to its complexity and specific receiving equipment relationships [15]. Depending upon which criteria is chosen, different conclusions can be drawn. The assumption here is that a modulator of good quality is chosen. If a suboptimum modulator is chosen, these bandwidth numbers will only increase.

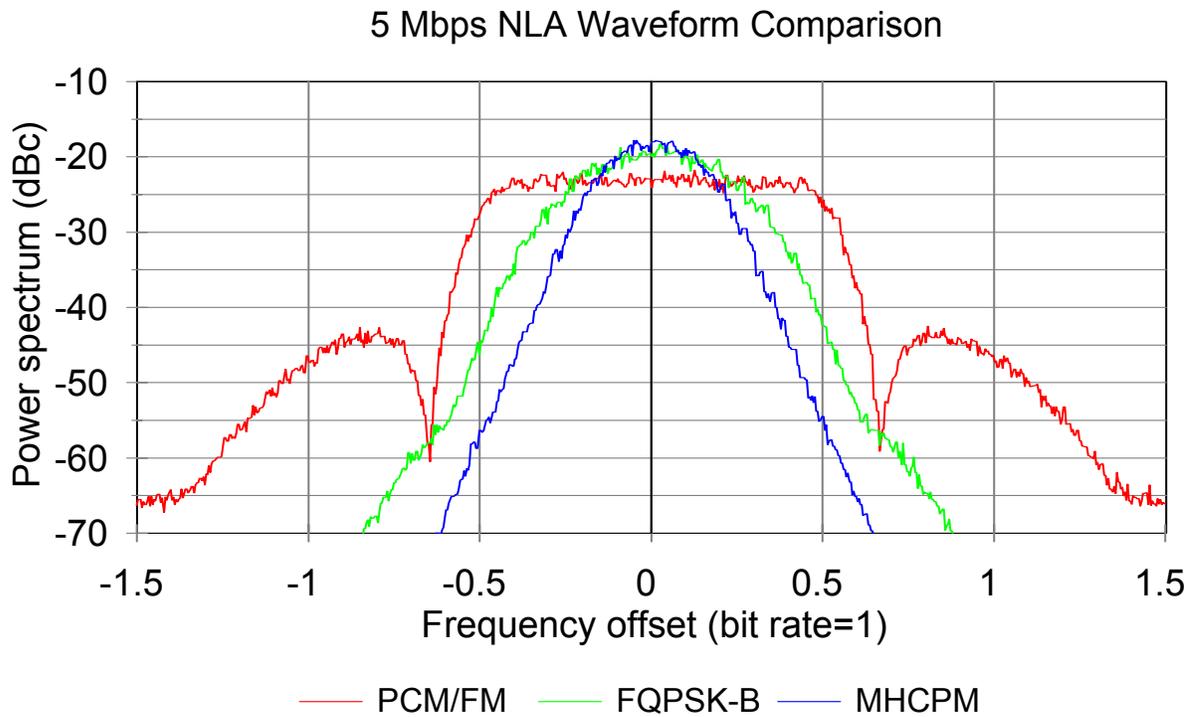


Figure 1 – PCM/FM, Tier I and Tier II Waveforms
(Source: E. Law [14])

Table 1 – Occupied Bandwidth Comparison

Modulation	99% Bandwidth	99.9% Bandwidth	-60dBc Width
PCM/FM	1.2 x bit rate	1.8 x bit rate	3 x bit rate
Tier I	0.8 x bit rate	1 x bit rate	1.8 x bit rate
Multi-h CPM	0.6 x bit rate	0.8 x bit rate	1.4 x bit rate

Bit Error Probability Comparison

One method to test detection efficiency and link performance is to transmit a known bit pattern, detect it, and check for any errors. Figure 2 is a plot of BEP measurements taken with the same transmitting source operating in one of three modes at 5Mbps with differing receive and bit detection methods.

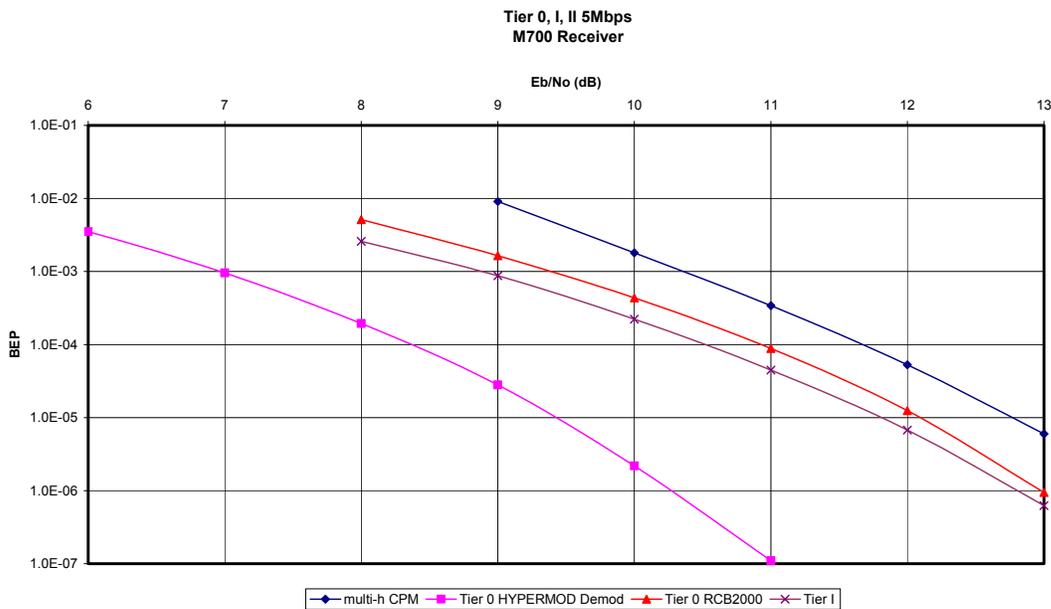


Figure 2 – BEP Comparison Curves, 5Mbps

The curve labeled “Tier 0 RCB2000” is currently the best performer of the family of legacy receiver/bit synchronizer bit detection schemes and is considered the baseline for this comparison. The curve labeled “Tier 0 HYPERMOD Demod” utilizes a telemetry receiver (in this case a Microdyne M700) to down convert the RF signal to a 70MHz IF and then utilizes a Nova Engineering MMD22 to demodulate the Tier 0 waveform. Because of the multi-symbol detection scheme implemented in the demodulator, nearly a 3dB gain in detection efficiency is realized. It is shown here for reference for how well an uncoded telemetry link can perform when frequency occupancy is not a concern. If we concentrate on the remaining two curves, the Tier II waveform suffers roughly a 1dB penalty in detection efficiency when compared to the Tier I waveform.

Table 2 shows the point in which a given system loses bit synchronization. This is an important parameter when comparing the waveforms during a link analysis. Notice the point in which multi-h CPM loses synchronization, it is approximately 5dB sooner than the Tier I waveform.

Table 2 – Synchronization Threshold

Modulation	Threshold (Eb/No)
PCM/FM, RCB2000	3.5dB
PCM/FM, HYPERMOD	2dB
Tier I	4dB
Multi-h CPM	9dB

Resynchronization Tests

The RCC adopted, ARTM synchronization speed tests are designed to represent real-world scenarios when some channel anomaly, usually a flat fade, causes the demodulators to lose synchronization. This test measures the time, in bits, it takes the demodulator to resynchronize. The smaller number of bits the better; less test data are lost. The resynchronization test has two variations. One test assumes a very large signal-to-noise ratio (termed flat fade recovery test) and the second one sets Eb/No to a value of 10dB (termed initial acquisition test). This requires the demodulator to acquire the signal in the presence of noise.

Flat fade recovery and initial acquisition tests were performed on the Tier I and Tier II waveforms. These waveforms were compared due to their coherent detection schemes. To simulate fade characteristics of the telemetry channel, a switch rate (from noise to signal and back) of 210mHz was selected. Lastly, to simulate an accelerating test vehicle Doppler shift) a sweeping carrier was utilized, sweeping at a rate of 2.5kHz/sec. This requires the demodulator first to locate the carrier and then lock onto it. The range in which it swept was set to ± 20 kHz. The carrier sweep was controlled by a triangle wave so the rate in which it swept from end point to end point was constant. Carrier acquisition range was set to ± 100 kHz on the demodulators. (Note: Values down to ± 20 kHz can be selected for improvement in synchronization speed). At each test point, 20 resynchronization times were recorded and an 80th percentile rank of that set was used to establish one number for the resynchronization time.

Figure 3 shows that regardless of the test, flat fade or initial acquisition, CPM will always take longer to resynchronize than the Tier I waveform. In some cases, significantly longer.

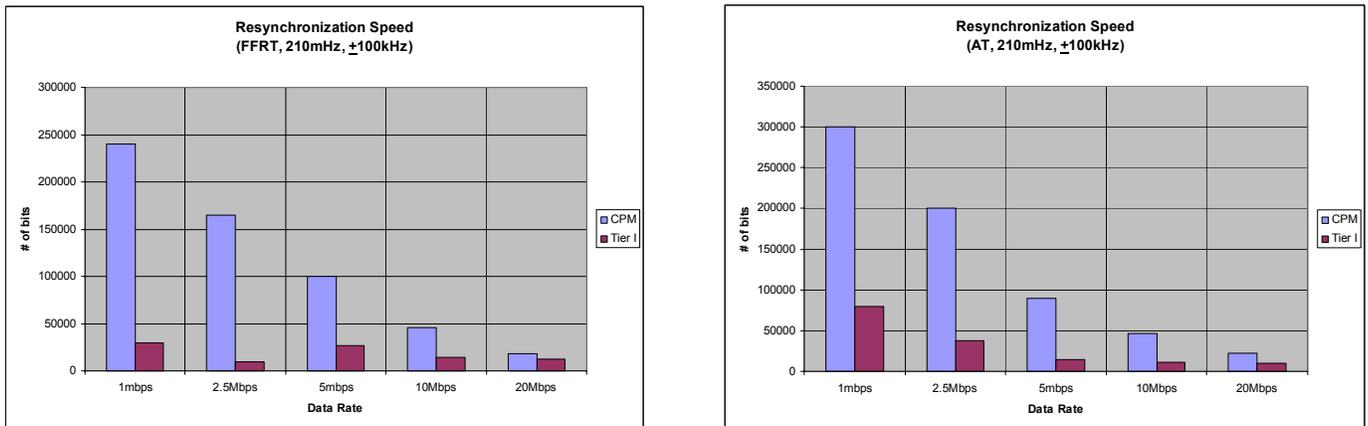


Figure 3 – Resynchronization Speed
Flat Fade Recovery, Initial Acquisition, Sweeping Carrier

Static Multipath Sensitivity Testing

This test is used to characterize waveform sensitivity to static multipath events. Though not a dynamic test, the static test does give some indication of performance in an airborne environment. This test, which is based upon a two-ray, point-to-point microwave link test sometimes referred to as a Static M-Curve test [16]. For this test, γ (in degrees) and τ (in nanoseconds) are fixed and Γ (referred to as path loss in dB in figures 5-7) is varied in order to generate a series of sensitivity curves at various bit rates. Referring to figure 4, the piece of equipment that allows this fixed channel emulation is the Rohde & Schwarz SMIQ with a built-in 6-path fading simulator.

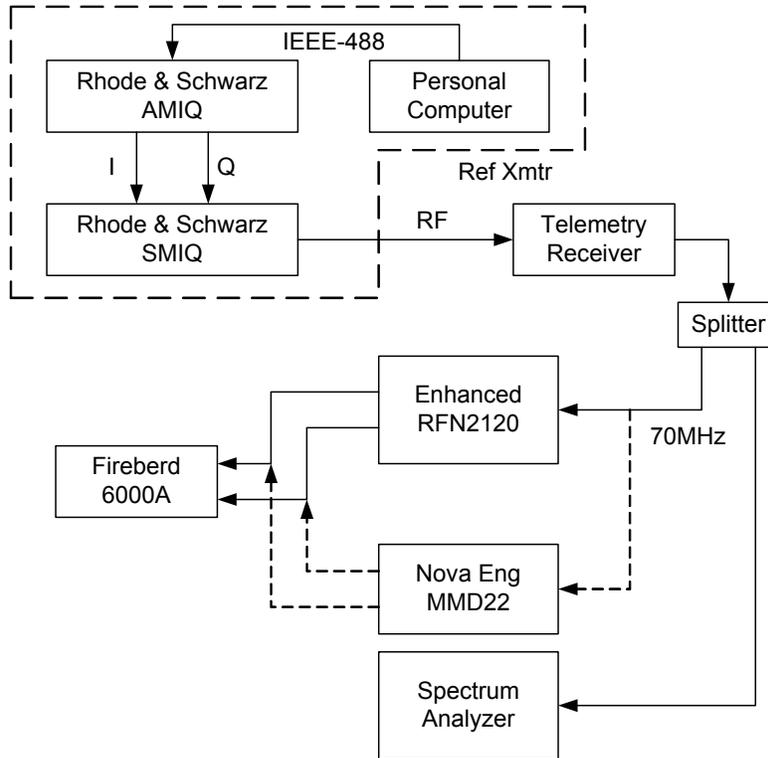


Figure 4 – Static M-Curve Test Block Diagram

Figures 5, 6, and 7 show the results of this test for all three waveforms at a bit rate of 5Mbps. These graphs are just a snap-shot of static multipath performance with the tests done at high values of E_b/N_0 but do give an indication of multipath sensitivity. A more rigorous approach would involve doing the tests for a family of curves at differing E_b/N_0 values for each delay.

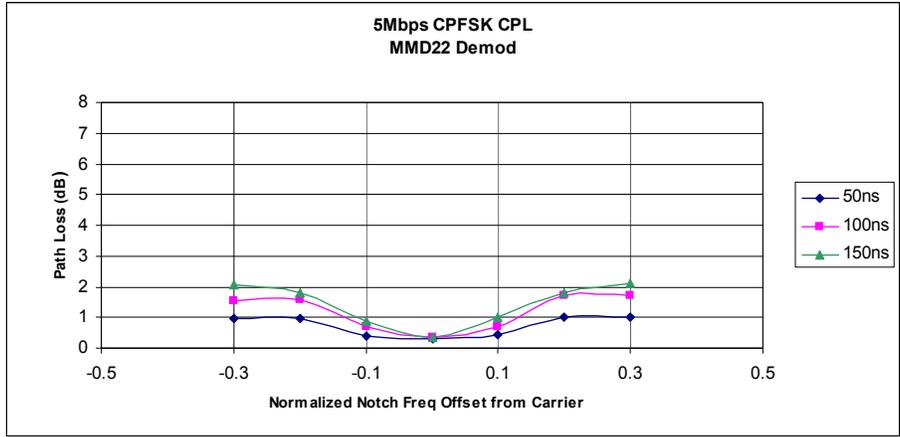


Figure 5 – PCM/FM Critical Path Loss

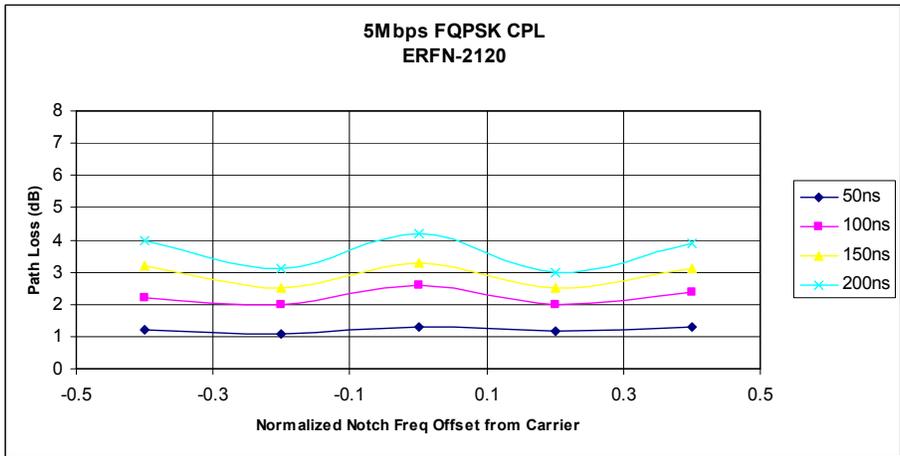


Figure 6 – FQPSK Critical Path Loss

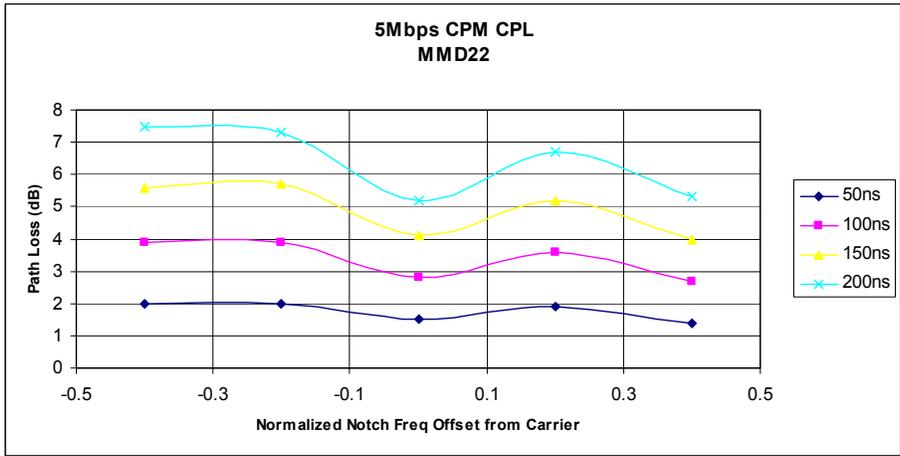


Figure 7 – CPM Critical Path Loss

Notice how much more sensitive the Tier II waveform is to a second ray incident on the receiving antenna. In general, the Tier I waveform is more sensitive to a null placed at the carrier where the Tier 0 and Tier II waveform is more sensitive to a null offset from the carrier. If path loss numbers are analyzed, the curves for CPM have higher path loss numbers. In other words, for equal performance, the second ray requires more attenuation for CPM. For the flight testing, the terrain is the same for both waveforms, so this data says CPM will always under perform the Tier 0 and Tier I waveform in a multipath environment.

Flight Test Results

The goal of the flight testing of the Tier II waveform was to ascertain how well the waveform performed in terms of link availability when compared with the Tier I waveform. The platform for this testing is the ARTM modified Air Force C-12. Two transmitters were installed, a Herley Industries FQPSK transmitter, model 6090, and a Nova Engineering model MMT28 multimode transmitter operating in mutli-h CPM mode. Data rate was set to 10Mbps due to constraints in the source clock on-board the aircraft. It would have been preferable to transmit at a higher rate, thinking potential users of the Tier II waveform would use it at high bit rates because of its lower spectral occupancy. Both waveforms were transmitted through the same antenna located on the belly of the aircraft. Power levels were matched and the same pseudo-random bit sequence (PRBS) was modulated and amplified. Flight paths matched the ones used for channel sounding and Tier 0/Tier I flight testing so any channel anomalies encountered through the test have been analyzed and documented [6].

The data presented covers both total link availability during a test run and individual characterization of selected multipath events comparing the two waveforms. Link availability [4], expressed as a percentage, is defined as:

$$LA(\%) = \left[\frac{ET - (\Sigma SES + \Sigma SLS)}{ET} \right]$$

where *LA* is Link Availability
SES is Severed Error Seconds
SLS is Sync Loss Seconds
ET is Elapsed Time

Four flight paths were utilized, two which are rich in multipath events (Black Mountain and Cords Road), one that is virtually free from multipath with high signal-to-noise ratios throughout the flight path (Alpha Corridor), and one that is again free from multipath events but is flown out to the point both demodulators loose synchronization (Race Track). Link availability for both waveforms are shown for these flight paths in table 3.

Table 3 – Link Availability

Waveform	Link Availability (%)						
	Blk Mtn W-E	Blk Mtn E-W	Cords Rd W-E	Cords Rd E-W	Alpha E-W	Race Trk S-N	Race Trk N-S
Tier II	87.45%	78.18%	80.61%	73.12%	88.58%	97.50%	96.95%
Tier I	95.99%	96.19%	87.55%	82.39%	99.47%	98.14%	98.54%

To gain further insight into these link availability numbers, lets analyze a few specific multipath instances that make up the above numbers. The first set of graphs, figure 8, shows received signal

strength of both signal paths, FQPSK link and CPM link, along with tallied errors during the same time during the flight. This in-flight event, typical for the Edwards test range, is a strong, transient specular reflection event with excess delay, τ , short enough to behave like a flat fade. The time dispersion shown in the graphs is due to the frequency diversity between the signals.

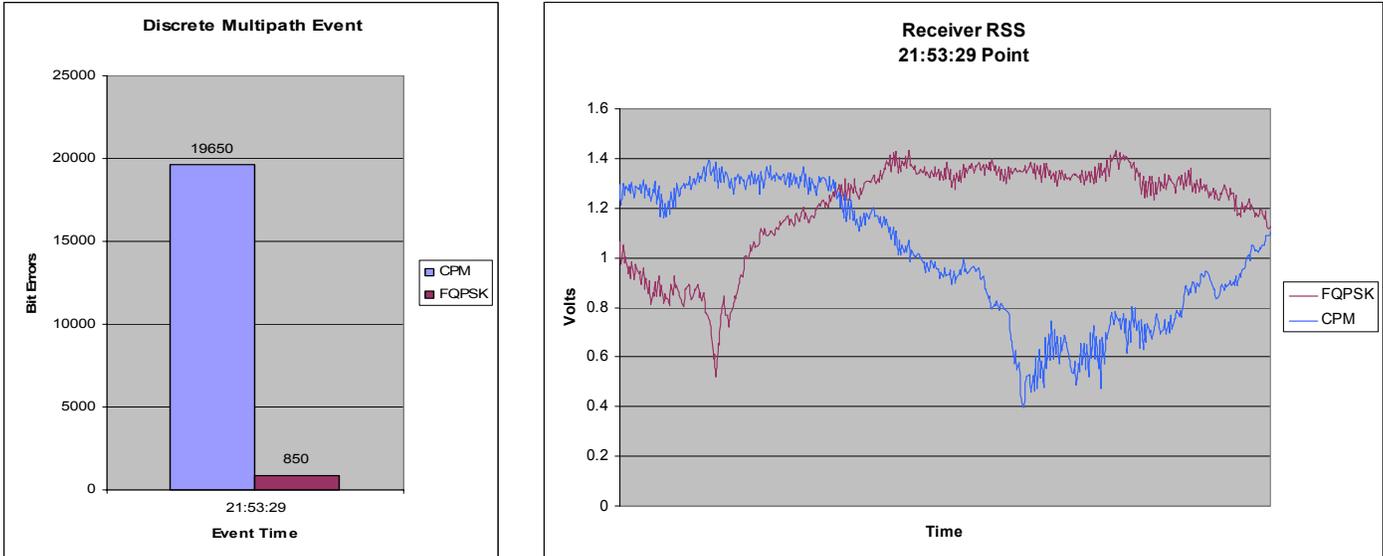


Figure 8 – Discrete Multipath Event, Short Delay (flat fade)

Figure 9 depicts a long delay multipath event that is not evident in the received signal strength (RSS) graph but very evident in the bit error tally graph. The RSS plot shows virtually no signal loss but the bit error graph shows a significant hit on the CPM link.

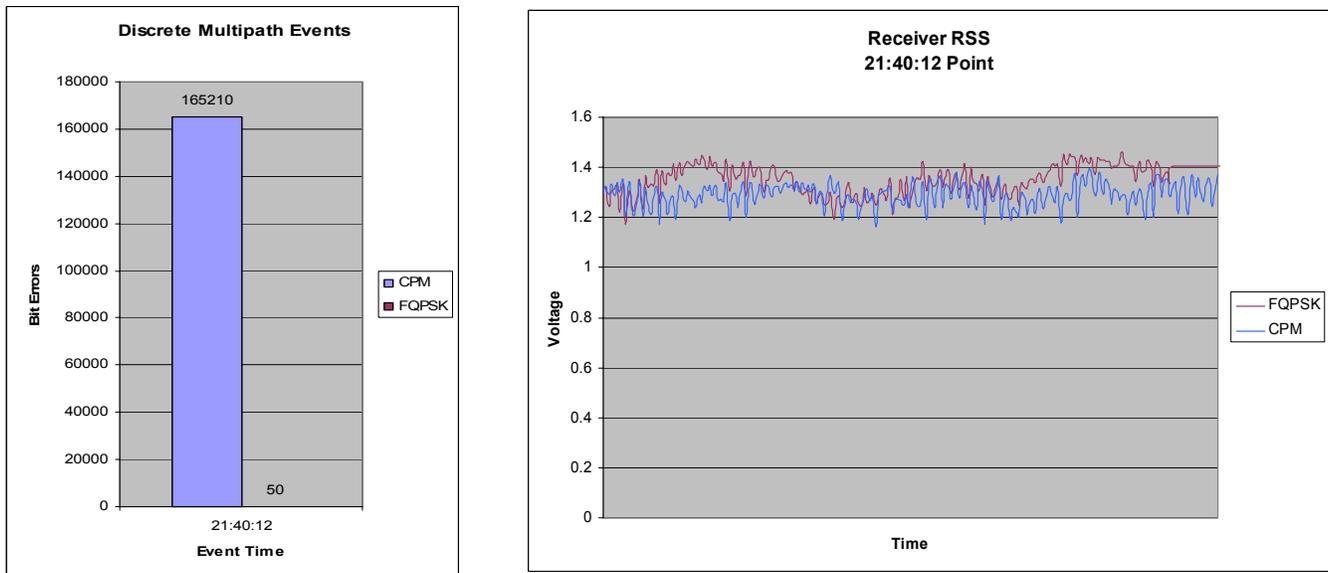


Figure 9 – Discrete Multipath Event, Long Delay (frequency selective fade)

Figure 10 shows the time history of bit errors and RSS while the plane completes a test point, turns, then starts back. This is included in this analysis as a point that simulates a dynamic maneuver to show the effect on both telemetry links. Notice the loss of signal as the belly of the aircraft shadows the receiving antenna and then a flat fade, both events causing synchronization loss in both demodulators.

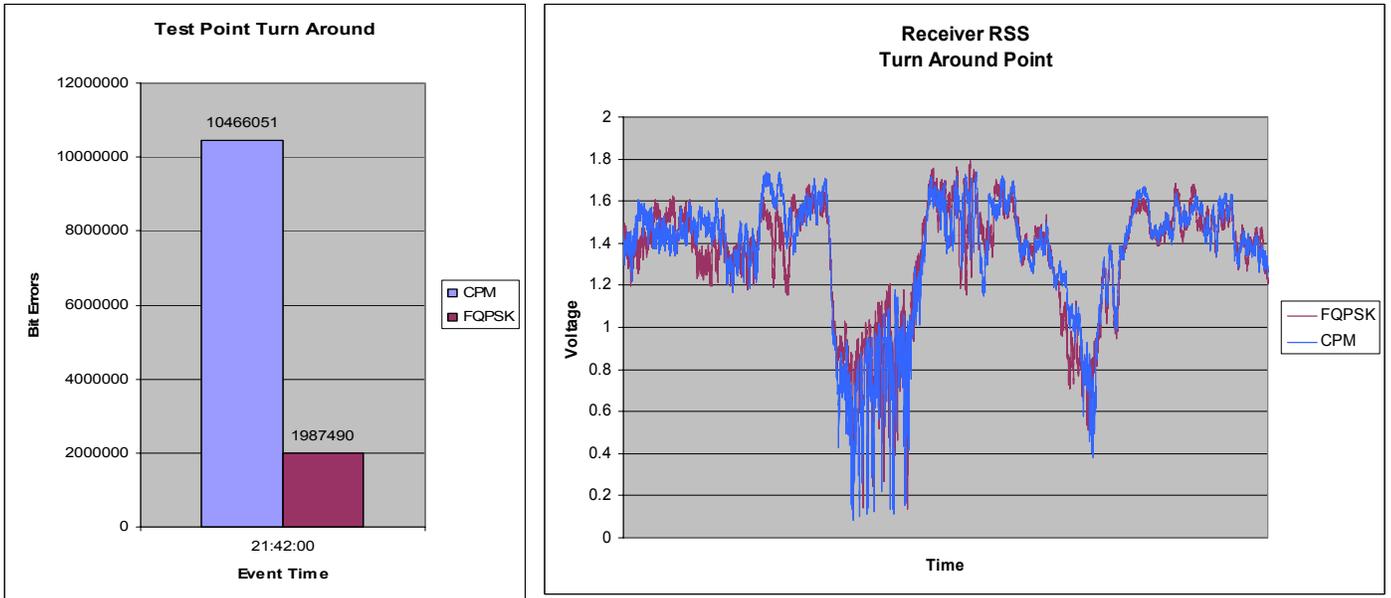


Figure 10 – Discrete Multipath Event, Turn Around Point

Looking back through all of the flight test data, we notice the CPM link is always worse than the Tier I link in both total link availability and discrete multipath events. With the increased synchronization time of the demodulator coupled with the waveforms greater distortion sensitivity, this will be true when both links are compared equally.

One last data point tries to exhibit the fact that the Tier I waveform stays in synchronization longer into smaller values of E_b/N_0 than the Tier II waveform. This flight path is characterized by very little multipath and is intended to show that given the same amount of transmitter power, the Tier I link will remain useable longer than the CPM link. Looking back, if figure 3 has any real-world applicability, as the signal strength gets lower and lower, the Tier I link should still be receiving useable data where the CPM link will lose synchronization.

Figure 11 shows the time history of bit errors and RSS while the plane is on an outback track then completes the test point and turns around to start the test point for the inbound track. Notice the gradual loss of signal as the aircraft reaches the minimum signal-to-noise ratio point. Somewhere along this slope both systems lose synchronization. Then, in the turn, the belly of the aircraft shadows the receiving antenna, which shows up in the plot as zero RSS. As the plane finishes the turn and starts back on the inbound track, RSS gradually increases until both demodulators are back in synchronization. By doing this, the bit error data should show that the Tier I link provides data longer and then recovers faster as the plane comes back into acquisition range. Figure 12 shows this to be indeed true. This graph shows the accumulated bit errors through the same point in space as figure 11. Notice the bit error total for the CPM link increases first (as the CPM demodulator loses synchronization as signal to noise ratio

drops) then decreases last (as a higher signal-to-noise ratio is attained and the demodulator resynchronizes).

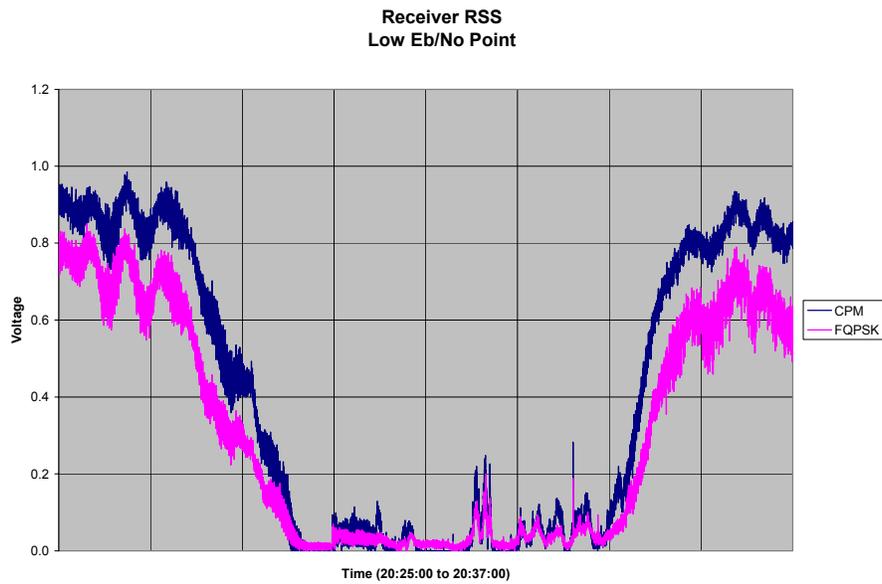


Figure 11 – Receiver RSS, Low Eb/No Point

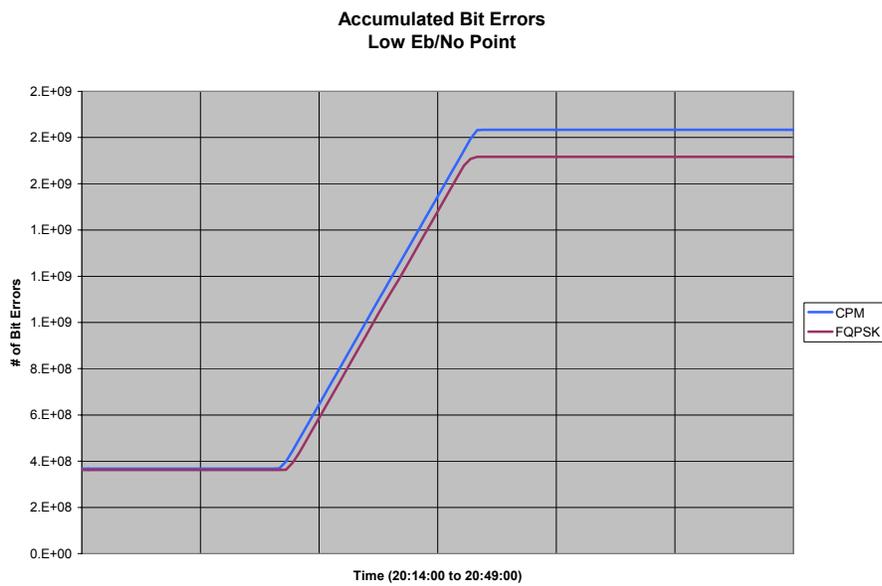


Figure 12 – Bit Errors, Low Eb/No Point

CONCLUSIONS

The ARTM Tier II waveform is the most spectrally efficient of the three ARTM waveforms.

The multi-h CPM waveform, due to its complex generation and detection schemes, loses synchronization roughly 5 to 6dB sooner than the Tier I and PCM/FM waveforms.

Performance, in terms of detection efficiency, suffers a 1 to 3dB degradation when compared to the other two waveforms.

The Tier II waveform is very sensitive to distortion, regardless of the source of this distortion. Sources of distortion could be from generation, channel impairments, or receiver phase noise.

Synchronization time after sync loss, depending upon data rate, is between 2 and 5 times that of the Tier I waveform.

The ARTM Tier II waveform, without equalization or forward error correction, is not as robust a waveform as the other two waveforms. Because of this, the waveform is not a good candidate as a “do all” waveform.

Due to the distortion sensitivity and greater resynchronization time, link availability over time in a multipath rich environment will always be less than the other two waveforms.

Because of its requirements for larger E_b/N_0 values to maintain synchronization, multi-h CPM may not be the best choice for data links that routinely operate at low signal-to-noise ratios.

More work is still required in the areas of receiver phase noise characterization, co-channel interference, and over water testing to fully characterize this waveform for use in an aeronautical telemetry environment.

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