WHY ARE WE HATIN' ON ARTM CPM?

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ABSTRACT

Why hasn't the Aeronautical Mobile Telemetry community adopted IRIG 106 compliant ARTM CPM as their preferred waveform for the transmission of telemetry data? Telemetry receivers in the market place today exhibit gains in detection efficiency and resynchronization speed that far exceed products of just a few years ago. Past papers have shown the link performance comparison between the new waveform standard SOQPSK-TG and ARTM CPM has narrowed since ARTM CPM was first standardized. This paper will present the latest performance comparison between these two waveforms during a controlled test throughout various flight conditions. The testing is presented and performance comparisons are made between the waveforms. This comparison will use traditional methods combined with several new performance metrics presented in this paper. To conclude, Link Availability, the measure of overall link performance is presented illustrating how closely these waveforms perform.

KEY WORDS

ARTM CPM, SOQPSK-TG, IRIG 106, Spectrum Relocation Fund, Link Availability, Data Quality Metric, Trellis Run Length

INTRODUCTION

Of the three telemetry waveforms in IRIG 106, PCMFM, SOQPSK-TG and ARTM CPM, only ARTM CPM has failed to gain any level of acceptance by the Aeronautical Mobile Telemetry (AMT) community. Perhaps this is due to previous work [1] which concluded that even with the excellent spectral occupancy offered by the waveform the initial vendor offerings of receiver/demodulators suffered from synchronization loss at greater values of E_b/N_o, longer resynchronization times, and sensitivity to excessive phase noise when compares to like products for PCMFM and SOQPSK-TG. Follow-on laboratory characterization work in [2] concluded with the statement "*Given the measured performance of current generation ARTM CPM receiver/demodulators, this modulation scheme should be considered a viable modulation scheme for AMT*". Still today the AMT community is skeptical. This paper will address the last piece of characterizing the performance of ARTM CPM; performance in a real-world test environment over various types of telemetry channels with a comparison to a baseline of SOQSK-TG. The goal of this paper is to inform the AMT community that ARTM CPM is (and has been) "ready for prime time".

Given the amount of data that was collected and the numerous ways to analyze comparative link performance, there is no way a complete analysis of the flight testing can be presented here. Instead an example analysis is shown to illustrate the process that was followed for analyzing the data for the test points during the flights. An overall comparison of link performance concludes this paper.

THE NEED FOR FLIGHT TESTING

The Spectrum Relocation Fund (SRF) program at Edwards AFB had one primary goal; test, analyze, and assess the performance of recently installed range upgrades. Upgrades included new antenna feeds, telemetry receivers, receiver status monitoring, and multiband/multimode/coded airborne transmitters. These upgrades will enable the Range to support current and future telemetry systems implementing any combination of Space-Time coding (STC), Low Density Parity Check (LDPC) forward error correction, any IRIG 106 modulation schemes, operating in any of the telemetry bands specified in IRIG 106. Secondary to programmatic requirement to test was the opportunity to assess, characterize, and document the gains associated with the technologies standardized in IRIG 106.

FLIGHT TEST CONFIGURATION

The flight test program was designed to stress each of the technologies in IRIG 106. The emphasis of the testing was to assess and demonstrate the gains in telemetry link reliably that can be expected when implementing STC and LDPC. A secondary objective, and the subject of this paper, was to assess how recent advancements in receiver technology benefitted ARTM CPM modulation. Expressed another way, *has telemetry receiver technology progressed to the point where the selection of modulation scheme isn't a major concern when designing a telemetry link*? In order to provide a relative assessment, a reference signal was simultaneously transmitted during all of the testing. Though this added equipment complexity in both the aircraft and ground station, it is the only way to provide a direct comparison. By transmitting a reference and test signal during each flight many of the normal pitfalls when performing comparison testing during separate flights are negated e.g. differences in flight path, weather conditions, antenna tracking, EIRP, ground station performance (system G/T), etc. Minimum channel spacing recommendations in IRIG 106 were used for center frequency scheduling. This minimized differing transmission channel characteristics due to large differences in center frequencies.

The aircraft was configured with a transmitter tray that housed two multimode, multiband, coded, STC-enabled transmitters that allowed all of the combinations of test configurations required to simultaneously transmit power level matched reference (REF) and test (TEST) signals. The reference signal for this testing was SOQPSK-TG, the generally accepted baseline for telemetry links in use today. Both of these signals were sent out either a bottom/top or bottom-only antenna configuration depending upon the requirements of the test. The transmitters used internal data and clock with a pseudo random bit sequence (PRBS-23) clocked at 5MHz. Since the transmitters were STC-enabled and were using internal data and clock, each could operate as two independent transmitters or as single STC transmitters. The on-board telemetry system recorded time-stamped aircraft positional information used later for data analysis.

The ground station for this testing was an SRF-upgraded EAFB range receive site with operators supporting these missions as “real” test missions. A 10 foot parabolic dish was used to receive the radio frequency (RF) signals. Left hand (LHCP) and right hand circular polarization (RHCP) are then derived and sent to channel 1 (CH1-LHCP) and channel 2 (CH2-RHCP) of each of four receivers connected to the antenna via multicouplers. The receivers were configured to maximal ratio combine CH1 and CH2 with the best channel select option enabled resulting in 3 signals each for REF and TEST. Up until this point in the receive chain this is a typical telemetry receive station. Where it differed from other upgraded ground stations at EAFB was the data sink (control room versus local test equipment) and the added equipment required to capture the necessary flight test data. The data capture equipment consisted simply of two telemetry receiver status loggers, a REACH bit error rate test set (BERT) with 8-channel capability, two intermediate frequency (IF) recorders, and a GPS-enabled network time server. The antenna control unit log file was recorded but this did not require a separate piece of test equipment. A block diagram showing the ground station configuration is shown in Figure 1. Each flight the aircraft and ground station equipment captured and recorded time-stamped information resulting in the following data products:

1. REF Receiver Status log (Channel 1, Channel 2, Combined) @ 1 sample per second
2. TEST Receiver Status log (Channel 1, Channel 2, Combined) @ 1 sample per second
3. Antenna Control Unit log @ 10 sample per second
4. Reach BERT @ 1 sample per second
5. Reference Receiver CH1 and CH2 IF Recording
6. Test Receiver CH1 and CH2 IF Recording
7. Aircraft Positional Information @ 1 sample per second

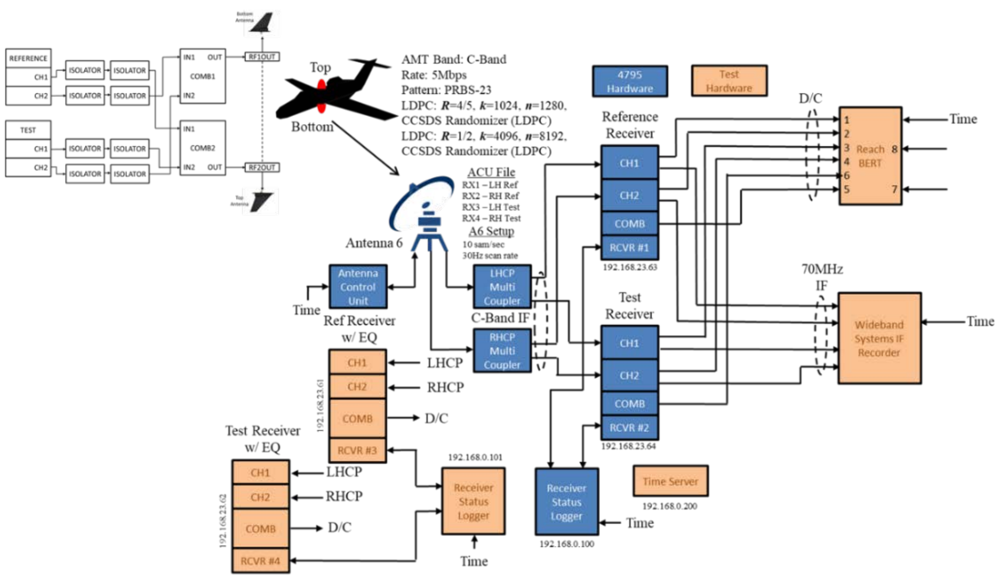

Figure 1 - Ground Station and Transmitter Tray Configuration

Based upon years of flight testing at EAFB, three flight profiles were designed to create three distinct transmission channels: a channel limited by multipath, one limited by noise, and one limited by the composite antenna transmission pattern from the aircraft. The multipath limited channel (points C/D) was created by flying low in both mountainous and flat terrain. This flight path results in a channel that exhibits both long and short delay multipath. The noise limited channel (points H1/H2) was created by flying away from the receive station to the point in which the link is dominated by noise. This profile is flown at a high altitude resulting in higher antenna elevation angles minimizing multipath affects. The composite antenna pattern channel (points M1/M2 and M5/M6) was created by flying circles at two constant aircraft bank angles in clockwise and counterclockwise directions. By doing this the ground station antenna “sees” different cuts of the composite antenna pattern. This point was flown at a higher altitude to mitigate any multipath channel condition as antenna pattern anomalies are virtually indistinguishable from a multipath event when reviewing the data post flight. These flight profiles along with the test point nomenclature are tabulated in Table 1. The tables show the complete listing of flights that occurred during the SRF-sponsored testing, only data captured and analyzed for Flights 211 and 214 were used for this paper.

Table 1 – Flight Test Configurations

Aircraft Configuration				
Flight	**Reference Signal**	**Test Signal**	**Antenna Configuration**	**Reason for Test**
1 (F211)	SOQPSK-TG	ARTM CPM	Bottom Only	Modulation Mode Comparison
2 (F212)	SOQPSK-TG	SOQPSK-STC	Top & Bottom (50/50)	Antenna Pattern Mitigation Assessment
3 (F213)	SOQPSK-TG	SOQPSK-LDPC (**R**=4/5, *k*=1024)	Bottom Only	FEC Assessment
4 (F214)	SOQPSK-TG	ARTM CPM	Bottom Only	Finish Flight 1 (F211)
5 (F215)	SOQPSK-TG	SOQPSK-LDPC (**R**=1/2, *k*=4096)	Bottom Only	FEC Assessment

Test Points			
Point	**Description**	**Limiting Channel Condition**	**Flight Conditions**
M1/M2, M5/M6	Antenna Pattern Circle ($10^0/50^0$ Bank Angle)	Composite Antenna Pattern	13K' MSL, 160 knots
C/D	Cords Rd (W-E, E-W)	Multipath	5K' MSL, 200 knots
H1/H2	Isabella/Owens S-N, N-S	Noise	5K'-30K', Best Climb, 160 knots

TELEMETRY LINK PERFORMANCE METRICS

Historically two performance parameters have been used to characterize the performance of a telemetry link. First, any combination of receiver signal strength/automatic gain control (AGC) level/signal to noise ratio (SNR) was captured and plotted. Second, bit error data was captured and Link Availability was calculated [4]. How the receiver is reacting to channel anomalies tells the experienced researcher many things about what is happening with the link. BERT data gives further insight and allows for a Link Availability calculation (Equation 1) which is the one true metric of system level link performance.

$$LA = \left[\frac{(T_M - (\sum SES + LT))}{T_M}\right](100\%) \qquad \text{Eq. 1}$$

where: T_M – measurement period
SES – Severely Errored Second, a one second interval in which the number of bit errors equal or exceed $\underline{1\text{x}10^{-5}}$ as if these errors were random
LT – Lost Time, number of bit periods in the measurement period that are not included in *SES* attributed to synchronization loss or BERT overload

Antenna pointing error should also be considered. An improperly pointed should not bias the results of a link analysis. Though an incorrectly pointed antenna is an error source, it is not attributed to the telemetry transmit/channel/receive chain which are under test. To aid in the link analysis for this paper and potentially future papers, three new metrics are presented. Two of these metrics are the result of the combined effort of receiver developments and standardization. IRIG 106 Chapter 2 Appendix 2G [3] defines a real-time link quality metric appropriately titled Data Quality Metric (DQM). DQM places a numerical value to the quality of a packet of data. The equations that define how the numerical DQM value is determined and scaled is shown in Equation 2. It becomes apparent after reviewing the equations that the key in determining the data quality is an assessment of the bit error probability of the received data.

$$DQM = \frac{-log_{10}(LR)}{k}(2^n) \text{ and } LR = \frac{BEP}{(1-BEP)} \qquad \text{Eq. 2}$$

where: *BEP* – bit error probability
LR – log-likelihood ratio weighting factor
k – exponent of lowest *BEP*
n – number of DQM bits

(Note: When the source data is known, as is the case for this testing, BEP is a <u>*known*</u> *quantity, BER=BEP. In the general case the source data is not known hence BEP must be estimated.)*

Once an estimate of BEP is determined E_b/N_o can be determined. Given a BEP and the modulation method (which the receiver <u>must</u> know to demodulate the signal), then an estimate of E_b/N_o can be determined. As an example, most telemetry receivers are capable of detecting SOQPSK-TG at a BER=1×10^{-5} resulting in an $E_b/N_o \sim 12$dB. Thus knowing the estimated BEP and modulation scheme the estimated E_b/N_o is known.

The third new metric presented here is Trellis Run Length (TRL). The IRIG 106 modulation schemes are described by signal states: a sequence of bits maps to a sequence of signal states in a unique way. The transition from one signal state to another signal state may be represented by a state diagram. If time is included, the state diagram unwraps into a trellis diagram [7]. Just as a bit sequence maps to a sequence of states, the same bit sequence maps to a path through the trellis. In a typical receiver, the detection algorithm processes the received signal and attempts to find the path through the trellis (or state sequence) that most closely matches the received signal [8]. At each step in the trellis, the possible trellis paths are compared to the received signal using a quality metric to determine which of the possible trellis paths is the single best path. TRL monitors the metrics to determine the quality of the bit decisions. The lower the corruption (multipath, additive noise, phase noise, etc.) present in the received signal, the greater the number of consecutive symbols have high-quality bit decisions. Higher corruption leads to a smaller number of consecutive symbols with high-quality bit decisions. The TRL metric captures this property and produces a value proportional to the number of consecutive symbols with high-quality bit decisions. In this case, a large trellis run length provides higher confidence that symbols are being detected correctly. Captured and recorded trellis run length is another metric used to evaluate how well a telemetry link was performing at any given time.

FLIGHT TEST DATA ANALYSIS

The flights for the modulation comparison occurred over two flights, 211 and 214. Flight paths for these flights are shown in Figure 2. The aircraft system was configured to transmit 5Mbps with a known pattern of PRBS-23 for both SOQPSK-TG (as the REF signal) and ARTM CPM (as the TEST signal) using a single transmitter. These signals were isolated, combined, power matched, and transmitted via the bottom antenna only. The REF signal was centered at 4405.5MHz with an EIRP=+35.6dBm, the TEST signal was at 4415.5MHz/+35.4dBm.

Flight 211 SOQPSK v ARTM CPM			
Test Point	Start Time	End Time	Duration
Mission	14:03:13	16:02:18	1:59:05
M2	14:16:02	14:21:57	0:05:55
M1	14:25:45	14:32:09	0:06:24
M6	14:37:17	14:38:28	0:01:11
M5	14:42:19	14:43:22	0:01:03
C	14:53:18	15:17:07	0:23:49
D	15:19:00	15:40:53	0:21:53

Flight 214 SOQPSK v ARTM CPM			
Test Point	Start Time	End Time	Duration
Mission	9:00:07	10:30:16	1:30:09
H1	9:06:09	9:38:46	0:32:37
H2	9:41:22	10:15:44	0:34:22
C	10:19:55	10:21:42	0:01:47

Figure 2 – Flight Paths with Test Point Times, Flight 211 and Flight 214

Flight data analysis started with determining antenna pointing error. As previously explained, any bias to the LA calculation by an improperly pointed antenna needs to be removed from the data. Pointing error is determined using the aircraft time-stamped positional data, time-stamped antenna azimuth (Az) and elevation (El) pointing angles, and the rotational center of the antenna in latitude, longitude, and altitude. A calculation is made determining where the antenna should have been pointed. These Az/El angles are then compared with the actual pointing angles. The difference in these angles are the pointing errors. Figure 3 illustrates the resulting pointing error for both Az and El for both flights. There is also a reference line plotted for the 3dB full beamwidth for the antenna calculated at the frequency of the test. A close inspection of the plots shows only several instances of Az/El error that would cause a 3dB or more decrease in signal strength. Further investigation of the receiver SNR and BERT files at these times show correlated dips in signal strength but none of these events caused bit errors. Therefore there is no need to remove these times for consideration when calculating LA for either flight.

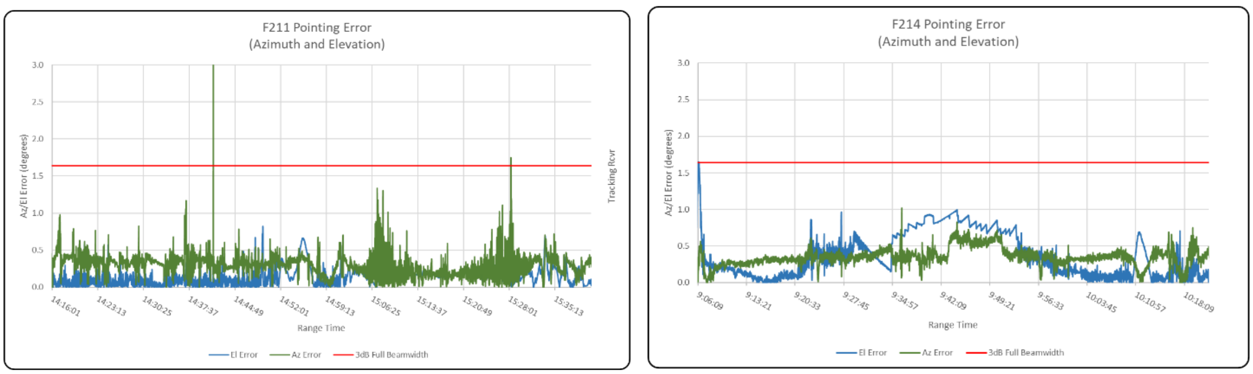

Figure 3 – Antenna Pointing Error

Next, individual test point analysis for the REF and TEST signals was accomplished. Receiver SNR is plotted and evaluated first as it gives an indication as to how the channel is affecting the transmitted signals. Next, estimated DQM and E_b/N_o are compared to the receiver SNR data to verify consistency and to look for any points of interest. Lower SNR values or signal corruption due to multipath should correlate with lower DQM and estimated E_b/N_o and should be consistent between modulation methods. Any points that are not correlated are further investigated. Also plotted along with this data is TRL. This new receiver metric gives an indication on how well the demodulator is making decisions and also gives an indication on the quality of these decisions. Finally, LA calculations are made using the BERT data. By this time in the analysis process the resulting LA should not be a surprise given the data analyzed before this calculation is made.

Given the amount the testing that was completed it is impossible to cover each test point in this paper. Instead, one test point will be analyzed to illustrate the process that was used. Test Point C during Flight 211 is a good point to analyze as it exhibited several interesting channel conditions during the point. Point C (see Figure 2) starts over mountainous terrain, transitions into a flat valley, then ends where line-of-sight is lost at the maximum slant range of the point. First, antenna pointing error during the test point is plotted to insure no link errors can be attributed to the antenna. Second, receiver SNR is plotted to help illustrate the channel conditions throughout the point and to also identify areas of interest. Figure 4 first shows plots of pointing error then estimated SNR for both received polarizations. With knowledge of the terrain throughout the flight path the SNR plot makes perfect sense. At the start of the point SNR is low due to signal blockage by the mountain range. As the aircraft progressed along the test point path it cleared the mountains and descended to 2500’ AGL which provided a multipath rich channel with both long and short delay multipath. This is observed at 14:55:19. At 15:00:00 and 15:01:42 there are multipath events which are a well-known, repeatable events along this test point. At 15:14:00 the aircraft flies over a mountain ridge so SNR drops as line-of-sight is gradually lost. Prior to the end point there are rapid variations in SNR caused by the numerous mountains in/around the aircraft.

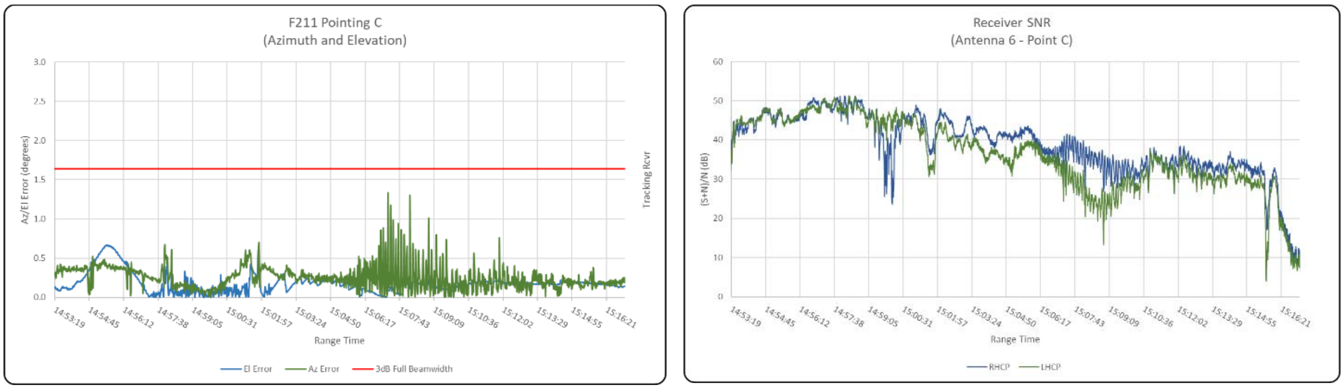

Figure 4 – Antenna Pointing Error and Receiver SNR (Point C)

Generally speaking the DQM and estimated E_b/N_o values track the explained channel anomalies very well. When the signal was corrupted by multipath DQM values dropped accordingly. When signal strength dropped so did DQM. There are differences in how the waveforms were affected by these channel anomaly events though. There are some events where SOQPSK-TG was adversely affected more than ARTM CPM and vice versa. One possible explanation lies in the occupied spectrum of the waveforms. With less occupied spectrum ARTM CPM is less susceptible to multipath. Conversely, if both waveforms were affected by multipath ARTM CPM was more affected as there are a greater numbers of variations in DQM and E_b/N_o present during these events. Notice the DQM of the combiner for both waveforms, it was very happy most of the time. A happy combiner indicates some level of polarization diversity in C-Band.

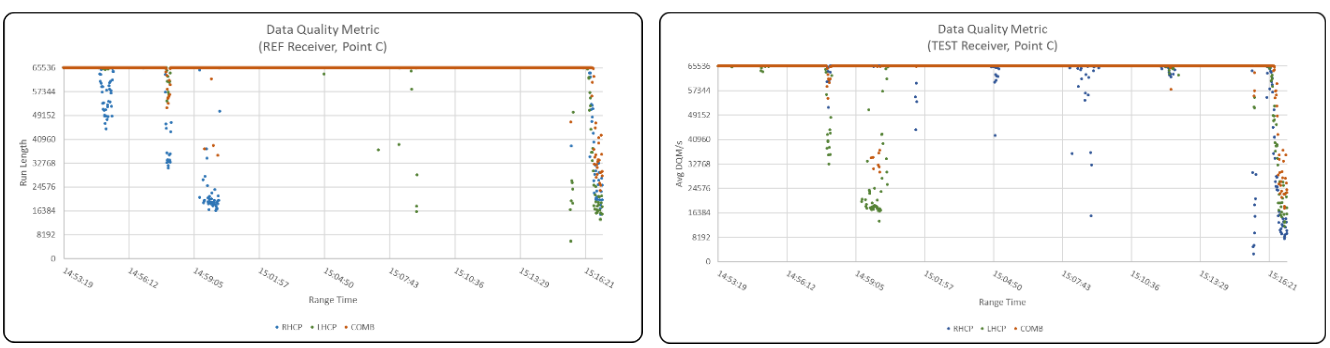

Figure 5 – Data Quality Metric Comparison (Point C)

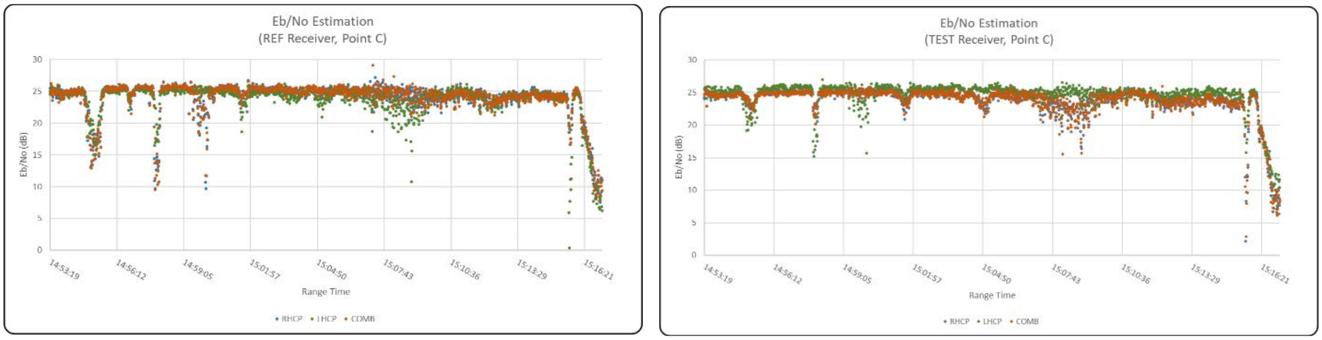

Figure 6 – Estimated E_b/N_o Comparison (Point C)

Trellis Run Length tells us what we already knew, an ARTM CPM demodulator has a harder job of making correct bit decisions than does an SOQPSK-TG demodulator. ARTM CPM is a complex waveform [3] and the variation in TRL between the waveforms tells a story. The SOQPSK-TG demodulator makes higher quality bit decisions more consistently than the ARTM CPM demodulator. Even though there is greater TRL variation for ARTM CPM, the demodulator is still pretty confident on the trellis paths chosen.

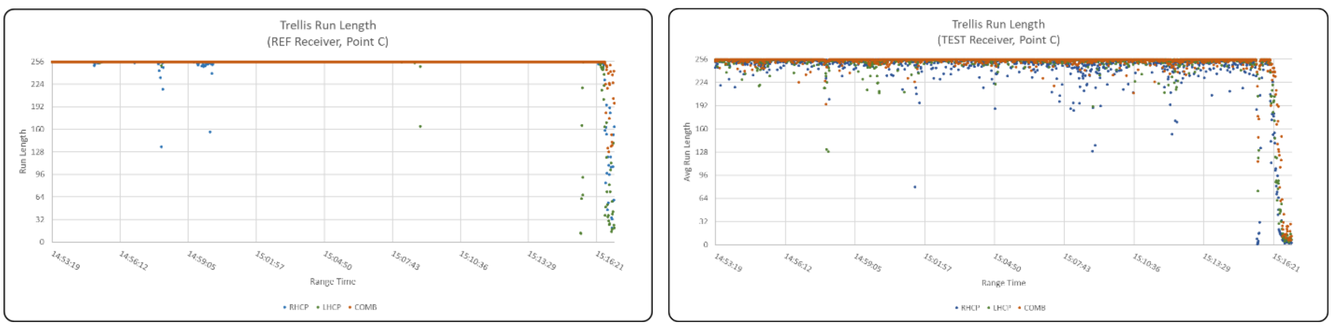

Figure 7 – Trellis Run Length Comparison (Point C)

All of these detailed metrics are very informative and tell a lot about how the signal is corrupted and how that affects the received signal. But what the end user wants to know is: "*How good is my real-time data going to be?*" When that question is asked, the one overall assessment of link performance used to answer that question is Link Availability. For Point C, LA is shown in Table 3 calculated using BERT data from both the REACH and internal receiver BERTs. Given the analysis so far for this test point, these results should be expected. The ARTM CPM telemetry link is on terms with the SOQPSK-TG link. ARTM CPM has a smaller occupied bandwidth making it less susceptible to multipath than SOQPSK-TG but that is balanced with being a more difficult waveform to detect during disruptive channel conditions.

Table 3 – Link Availability (Point C)

Link Availability												
	Flight 211 Receiver BERTs						Flight 211 REACH BERT					
	LHCP		RHCP		COMB		LHCP		RHCP		COMB	
Test Point	REF	TEST	REF	TEST	REF	TEST	REF	TEST	REF	TEST	REF	TEST
C	97.7%	97.5%	96.2%	95.7%	99.8%	99.3%	97.5%	97.1%	95.9%	95.5%	99.1%	99.1%

Having covered the process for data analysis for one test point providing a basis for the Link Availability result, LA results for all of the test points for both flights can be presented. Tables 4 and 5 show LA results per test point broken down into each polarization and combined outputs comparing the TEST signal with the REF signal.

Table 4 – Flight 211 Link Availability

Flight 211 LINK AVAILABILITY												
	Receiver BERTs						REACH BERT					
	LHCP		RHCP		COMB		LHCP		RHCP		COMB	
Test Point	REF	TEST	REF	TEST	REF	TEST	REF	TEST	REF	TEST	REF	TEST
Mission	93.7%	93.5%	89.5%	88.2%	98.4%	97.8%	93.6%	92.9%	89.3%	88.2%	98.2%	97.7%
M2	94.7%	93.2%	88.5%	85.4%	99.7%	99.2%	94.6%	94.4%	86.5%	85.1%	99.4%	99.2%
M1	98.2%	98.2%	90.9%	89.0%	99.7%	100.0%	98.2%	97.9%	91.7%	89.3%	99.7%	100.0%
M6	54.9%	54.9%	62.0%	59.2%	83.1%	76.1%	57.7%	56.3%	56.3%	59.2%	83.1%	76.1%
M5	65.1%	64.8%	60.3%	66.2%	87.3%	83.1%	66.7%	60.3%	58.7%	60.3%	84.1%	82.5%
C	97.7%	97.5%	96.2%	95.7%	99.8%	99.3%	97.5%	97.1%	95.9%	95.5%	99.1%	98.7%
D	98.2%	97.2%	98.4%	97.6%	99.8%	99.8%	98.3%	97.5%	98.4%	97.6%	99.9%	99.8%

Table 5 – Flight 214 Link Availability

Flight 214 LINK AVAILABILITY												
	Receiver BERTs						REACH BERT					
	LHCP		RHCP		COMB		LHCP		RHCP		COMB	
Test Point	REF	TEST	REF	TEST	REF	TEST	REF	TEST	REF	TEST	REF	TEST
Mission	96.0%	95.2%	91.8%	90.2%	98.9%	98.4%	95.8%	95.3%	91.9%	90.1%	98.9%	98.4%
H1	98.6%	98.1%	94.2%	92.3%	99.8%	99.4%	98.6%	98.2%	94.3%	92.2%	99.7%	99.4%
H2	97.6%	96.7%	96.3%	94.9%	99.2%	98.7%	97.7%	96.8%	96.4%	95.2%	99.2%	98.7%
C (short)	100.0%	100.0%	56.1%	50.5%	100.0%	100.0%	100.0%	100.0%	57.0%	52.3%	100.0%	100.0%

For both flights, 211 and 214 LA numbers are derived from both BERTs. Notice the very close correlation between the two results. More importantly, notice the very close correlation between LA results between the TEST and the REF signals.

Most, if not all telemetry transmitters and telemetry receivers currently in use today already implement ARTM CPM. The change to a more spectrally efficient waveform for not only spectrally conjected areas but also for every day telemetry mission support is trivial. This paper presented system-level Link Availability results in a real-world flight test modulation comparison that support making this change. Other performance metrics (DQM, estimated E_b/N_o, TRL) were presented that can also be used to further understand the effects channel anomalies have on the telemetry signal. These metrics help explain and support the Link Availability results.

WHAT YOU SHOULD GET OUT OF THIS PAPER

- The majority of telemetry links are not noise limited so the difference in detection efficiency (Figure 8) between ARTM CPM and SOQPSK-TG will not be a major contributor to differences in Link Availability. The test data presented supports this conclusion.

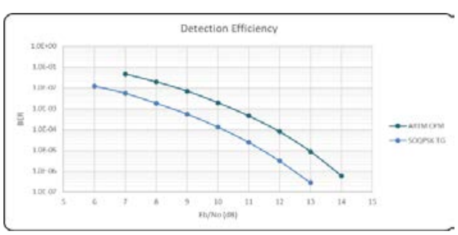

Figure 8 – Eb/No vs BER

- Differences in link performance at the telemetry "system level", which LA characterizes, are indeed inconsequential. Regardless of the comparison (per mission basis, per test point, per polarization, per combined output) the comparison was favorable. Each attains those overall LA numbers differently for sure, but in the end they get to the same LA performance level.
- With less occupied bandwidth ARTM CPM will be less susceptible to multipath events when compared to SOQPSK-TG. But, when ARTM CPM is affected, during these times SOQPSK-TG will outperform ARTM CPM. SOQPSK-TG is a more robust waveform compared to ARTM CPM and the variability in TRL illustrates and confirms this conclusion.
- The balance of OBW with waveform robustness, along with gradual receiver developments have made ARTM CPM a viable modulation choice for telemetry links
- "*Has telemetry receiver technology progressed to the point where the selection of modulation scheme isn't a major concern when designing a telemetry link*?" Yes, ARTM CPM is ready for prime time.
- Don't be a hater.

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