ASSESSING TELEMETRY RECEIVER DATA QUALITY METRICS USING RCC 118-22 TEST PROCEDURES

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ABSTRACT

A Data Quality Encapsulation (DQE) protocol for improving telemetry link quality has been standardized in IRIG 106. A receiver periodically inserts a Data Quality Metric (DQM) in the recovered data so that downstream equipment, such as a Best Source Selector (BSS) or Antenna Control Unit (ACU), can improve overall link quality. A comprehensive set of test procedures has been published in RCC 118-22 V2 R2 to quantify DQM performance over channel conditions typically encountered in aeronautical telemetry environments. This paper examines each test and presents measured results comparing the block DQM Bit Error Probability (BEP) estimate versus the actual measured Bit Error Rate (BER) from a receiver under test. The objective is to verify that the current test procedures and associated support equipment are sufficient for accurate and efficient receiver DQE testing. This is a crucial step towards realizing the tremendous potential DQM can provide for telemetry systems.

KEY WORDS

Data Quality Metric (DQM), Data Quality Encapsulation (DQE), RCC118

INTRODUCTION

A Data Quality Encapsulation (DQE) protocol for improving telemetry link quality has been standardized and added to IRIG 106 [1]. It provides a reliable metric for estimating data quality for real-time link monitoring and is a vital ingredient for optimal Best Source Selection [2]. Test methods have been developed [3][4] and published in RCC 188-22 V2 R2 chapter 11 [5] to measure the DQM accuracy under a variety of typical aeronautical telemetry channel conditions and ensure vendor interoperability. In general, the test setup needs to synthesize RF telemetry signals and measure both the BER and DQM of a receiver under test. The goal is to verify that the estimated data quality metric (DQM) represents the actual quality of each DQE data packet. Various test setups are described ranging from individual RF equipment and components, noise test sets, or an integrated Receiver Analyzer (RA) capable of automating the individual tests and data collection. The procedures are intentionally written to allow flexibility in the specifics of frequencies, bit rates, coding, and modulation types to be tested. This paper describes using the RCC 188-22 test procedures (11.1-11.6) to test a telemetry receiver and presents the results. The overall objective of this effort is to verify that the document is complete and to identify any potential areas that need further detail or test parameter adjustments. In addition, these results will provide a baseline for future DQM testing. This paper describes the equipment setup, the measured results, recommended modifications, and a summary of the findings.

TEST PROCEDURES FOR ASSESSING DATA QUALITY METRICS

Table 11-2 in the test document lists the individual DQM tests to be performed. They outline the detailed procedures for characterizing how the estimated DQM compares with the measured BER under various RF channel conditions including both static and dynamic Additive Noise (AWGN), adjacent channel interference (ACI), multipath, and resynchronization.

Table 11-2. Test Matrix for Data Quality Metric Testing

Test Number	Test Description
11.1	BER vs BEP with Additive Noise
11.2	DQM (BEP) Step and Dwell Response
11.3	BER vs BEP with Adjacent Channel Interference
11.4	BER vs BEP for Static 3-Ray Multipath Channel Conditions
11.5	BER vs BEP for Static 2-Ray Multipath Channel Conditions
11.6	DQM (BEP) Resynchronization Response

Table 1: Test Matrix for DQM Testing from RCC 118-22 V2 R2

Each test method includes a section describing the equipment setup, detailed procedure, and data reduction. Of the listed setup options, we have selected an approach with a high degree of automation for running the tests, collecting the data, and analyzing the results. A block diagram of the equipment setup is shown in Figure 1. The receiver analyzer runs test scripts for each of the DQE/DQM tests (11.1-11.6). It creates an RF test signal and takes in the resulting DQE clock and data streams from the receiver under test. In addition to collecting BER and DQM statistics, it also outputs a real-time analog version of the DQM for display and capture using an external digital scope. Between the internal statistics collection and the external DQM versus time captures, all the results described in the data reduction sections can be created.

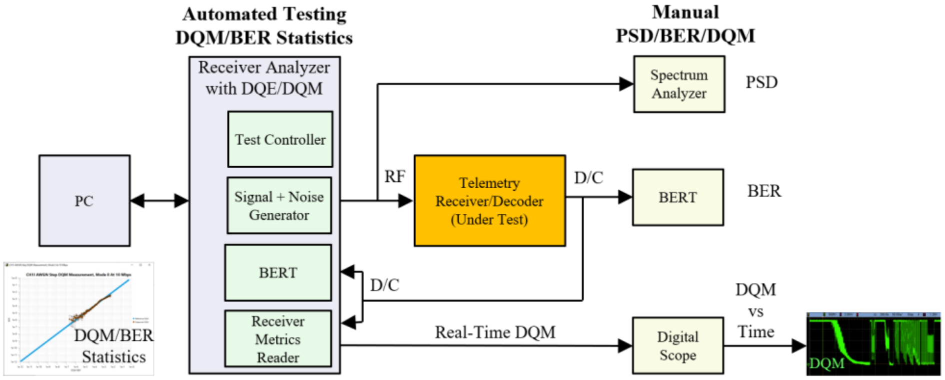


Figure 1: Setup for DQE/DQM testing and measuring BER vs BEP

The test document describes the purpose, steps, and results to be collected for each test. It is flexible in the sense that the specific modulation type, coding scheme, code rates, and baseband data rates are left up to the test conductor. Since there are an infinite number of combinations, a standard parameter set covering the common telemetry modulations, coding schemes, and a moderate data rate have been selected for this specific testing. The entire set of configurations listed in Table 2 will be measured for each of the six tests (11.1-11.6).

Signal Types	Modulation Type	Coding Type	DQE Payload Size (Bits)	Data Rate (Mbps)
ST1	PCM/FM	None	4096	5
ST2	SOQPSK	None	4096	20
ST3	STC	None	3200	10
ST4	ARTM-CPM	None	16384	15
ST5	SOQPSK	LDPC r=2/3, k=4096	4096	20
ST6	SOQPSK	LDPC r=4/5, k=1024	1024	5
ST7	SOQPSK	LDPC r=1/2, k=4096	4096	5
ST8	STC	LDPC r=2/3, k=4096	4096	5

Table 2: Modulation and Coding Parameters

The testing will be conducted as follows: 1) configure the receiver under test for the desired mode, 2) load the Receiver Analyzer with the corresponding test script, 3) verify that the observed BER and DQM indicate error-free operation, 4) set external scopes into acquire mode, and 5) initiate the automated test. After all tests are completed, save the receiver analyzer results and scope captures. Figure 2 shows an example of the DQM value versus time for both uncoded and coded signals. To better illustrate the comparison, the time axis of the coded results has been adjusted to align with the uncoded. During the 11.1 AWGN test, the noise level slowly increases causing the DQM value to start high and end low. The 11.2 step and dwell and 11.6 resynchronization tests examine step changes in signal quality in both time and BER versus BEP correlation. The 11.3 ACI test slowly moves an adjacent channel interfering signal towards the desired resulting in the DQM starting high and ending low. Tests 11.4 and 11.5 corrupt the signal with multipath to cover a wide range of channels from easy to difficult. Note that DQM for the coded signal (red) indicates that the DQE block quality is either “very good” or “very bad” as would be expected with FEC.

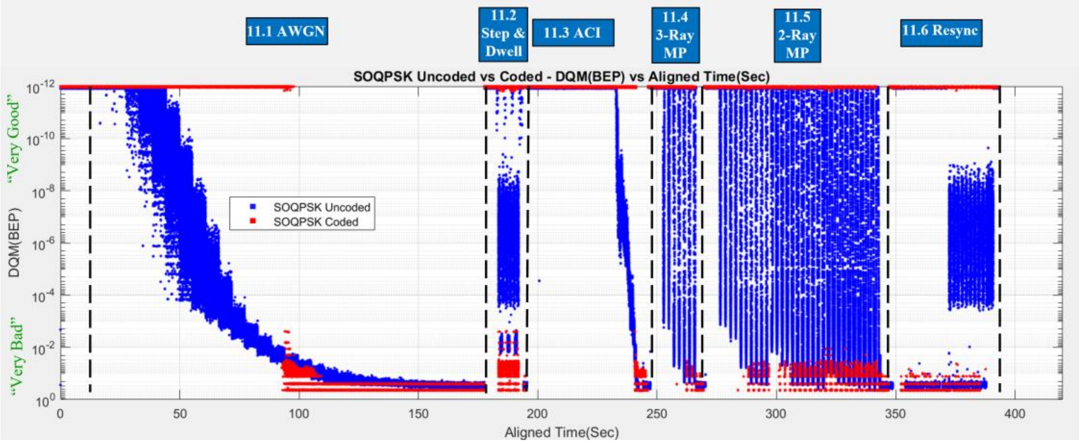


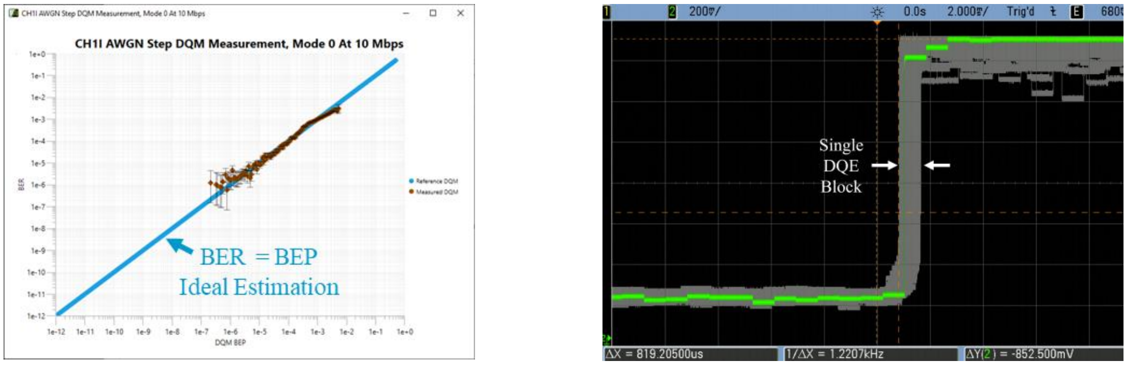
Figure 2: Example of DQE 11.1-11.6 automated testing (DQM/BEP vs Time)

DATA REDUCTION OF DQM TEST RESULTS

The purpose of the DQM value is to provide an accurate estimate of the actual BEP for each DQE block to use in link monitoring and to provide downstream equipment, such as a Best Source Selector, sufficient information for optimal maximum likelihood detection when multiple sources are available. The DQM binning method described in section 11.0 using M=256 and N=256 is used in calculating the DQM and BER statistics. This provides resolution better than 0.1 error exponent and significantly shortens required measurement times. Since the key results from this testing are DQM correlation plots, it is worth explaining the individual measurements and how the DQM accuracy might impact the performance of a post-processed multichannel telemetry system.

When the DQE function is enabled in a receiver, a DQM value is periodically inserted into the output TM data stream. This value should reflect the estimated BEP for that specific DQE block of TM data bits. This provides data quality information that allows downstream equipment to potentially improve the overall link quality. The receiver analyzer processes each DQE block and records the DQM value and measured bit errors based on a known PN data pattern. The DQM bin accumulator corresponding to the DQM value is updated with the number of errors and total bits and this process repeats over many DQE blocks. At the end of the measurement process, the BEP of the DQM bin is plotted against the measured BER to form the DQM correlation curve.

If the BEP (DQM) estimate is perfect, it will match the actual measured BER resulting in a point on the ‘ideal’ 45 degree line on a log-log BER/BEP curve (DQM correlation plot). With estimation error, the point will lie off the ‘ideal’ line. It has been shown that the worst-case system performance loss can be bounded by this estimated versus actual error amount [6]. It is also worth mentioning that measuring points at very low error rates can take a long time and they are typically shown with confidence bars indicating a statistical level of uncertainty. To characterize the DQM step response, an oscilloscope will be used to capture a real-time synthesized DQM analog signal relative to the step change. The DQM value should correlate with the actual signal quality. Examples of a DQM correlation and DQM step response capture are shown in Figure 3. Notice that the estimated DQM step response consistently changes from a low to high value and persistence verifies that the transition region spans a single DQE frame. This is typically the case when the receiver resynchronization is fast compared to the DQE period. However, this DQM transition can span multiple DQE frames if resynchronization is slow or unsteady.



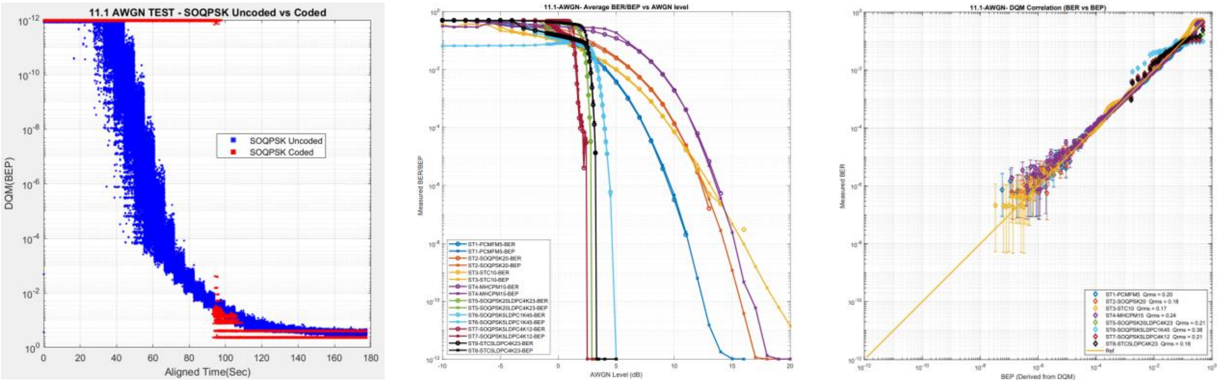
A) DQM/BEP Correlation

B) DQM Step Response

Figure 3: Primary Data Reduction Results – DQM Correlation and Step Response

11.1 BER VERSUS ESTIMATED BEP (DQM) WITH ADDITIVE NOISE

This test method measures the ability of the receiver to provide an accurate assessment of signal quality (DQM) in the presence of additive white Gaussian noise (AWGN). This is accomplished by comparing the actual BER using a known PN pattern versus the estimated BEP (DQM) when the receiver is subjected to a signal corrupted with AWGN. After an initial noise level versus BER calibration is performed, the actual BER versus estimated BEP is observed over a range of approximately 10^{-2} to 10^{-7} without coding and 10^{-2} to 10^{-12} for tests with coding. The resulting values are continuously collected for each parameter set. To gain insight into how DQM changes with different AWGN levels, plots of DQM versus time, average measured BER versus estimated BEP, and measured BER versus BEP correlation curves are presented in Figure 4.



A) DQM/BEP vs Time B) Average BER/BEP vs AWGN C) DQM Correlation

Figure 4: 11.1 Static AWGN test example results

The plot on the left shows the behavior of DQM versus time for both an uncoded and coded mode. The noise level starts out low (no errors for either mode) and gradually increases until both modes lose lock. Notice that uncoded DQM (blue) monotonically decreases from max to min while the coded DQM/BEP (red) is either very good (better than $1e^{-12}$) or very bad (worse than $1e^{-3}$) as is expected when using FEC. The middle plot shows the measured average BER and estimated BEP from DQM for each AWGN step. There is excellent agreement between measured and estimated average BER for all tested modes. The plot on the right shows the resulting DQM correlation plot that continuously ran over the entire test time. The root mean square (RMS) of the differences between DQM and BER error exponents are defined as Qrms and are shown in the legend. Again, there is excellent agreement between the actual BER and estimated DQM/BEP values at an individual DQE block level.

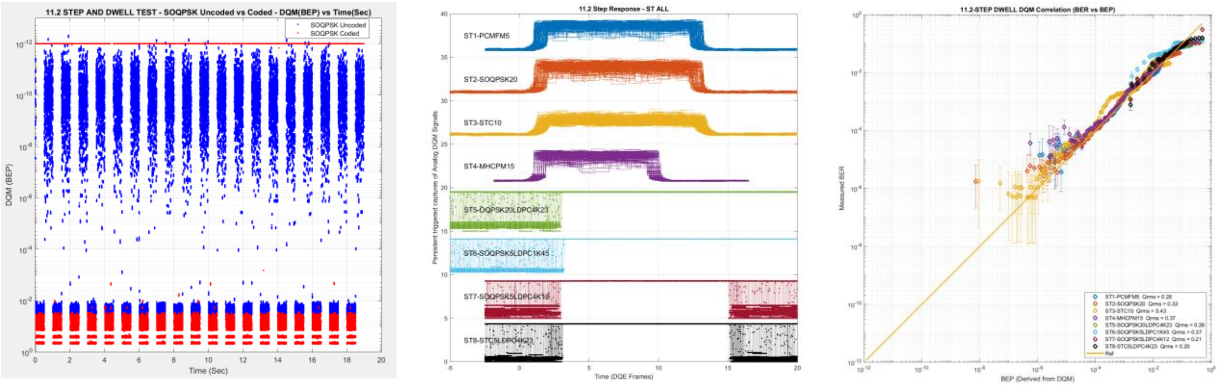
11.2 STEP AND DWELL RESPONSE

The 11.2 step and dwell test characterize the ability of the receiver to provide a fast and accurate assessment of signal quality when there is an abrupt change in signal quality. For this test, a step change in noise level will be used that results in a BER of approximately 1e^{-2} and 1e^{-7}. These levels are chosen such that the demodulator will maintain synchronization and that the resulting DQM distributions are visually distinct (do not overlap). In addition to the correlation plot, a DQM versus time plot showing the noise step response is required for this test. Note that this test focuses on the dynamic DQM response as opposed to the static accuracy in 11.1.

Figure 5 shows DQM versus time on the left side for uncoded and coded SOQPSK responding to rapid changes between two noise levels. In addition to clearly showing the rapid signal transition between SNR levels, it also illustrates the fact that in AWGN the DQM values follow a binomial probability distribution with greater spread as the error rate (P_b) or block size (n) decreases. The formula for the probability of exactly i bit errors occurring in a n bit block with error probability Pb is shown in Equation 1. This explains why the individual DQM values should not just equal the average. Excessive averaging can change the DQM distribution to where it no longer matches the actual block BER distribution, resulting in poor correlation scores.

$$\Pr(i\ errors\ out\ of\ n\ bits) = \binom{n}{i} P_b^i (1 - P_b)^{n-i} \tag{1}$$

A key performance objective for this test is that the DQM values at the transition between SNR levels should only span a single DQE block before reflecting the new quality condition. The middle plot presents persistent step responses for each of the test modes from Table 2. They are vertically stacked to allow direct comparisons among the various modulation and coding combinations. The four lower plots are uncoded and all respond over the span of a single DQE frame. Note that STC uses 3200 bits to match its block physical layer structure. The four upper plots are coded and either have very good or very bad quality estimates as expected. The coded modes with smaller 1K block sizes can be seen to respond faster than the 4K blocks (still within a single DQE block). The SNR levels for this test are selected such that the demodulator does not have to resynchronize. Finally, the DQM correlation plots on the right show good performance for all modulations and coding schemes tested.

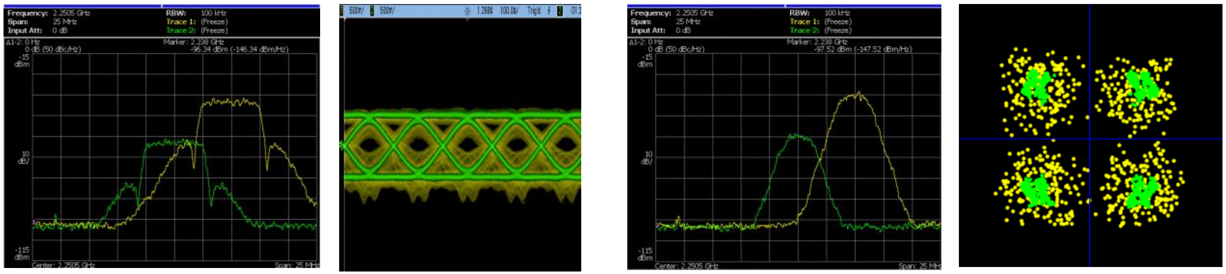


A) DQM/BEP vs Time B) DQM Step Responses C) DQM Correlation

Figure 5: 11.2 Step and dwell response example results

11.3 BER VERSUS ESTIMATED BEP (DQM) WITH ACI

This test method provides a means to assess the ability of the receiver to provide accurate signal quality estimates in the presence of adjacent channel interferers at a set C/I ratio. The basis of comparison is BER versus estimated BEP (DQM) when the received signal is corrupted by adjacent channel interference. This test was conducted using a 5 Mbps IRIG 106-compliant waveform for the interferer at a -20 dB C/I ratio. Figure 6 illustrates the impact of an adjacent channel interferer (yellow) on the desired TM signal (green). It shows the spectrum for both PCM/FM and SOQPSK along with the impact on the respective eye-pattern and constellation used for data recovery. As the signals get closer, the error rate generally increases.



A) PCM/FM spectrum

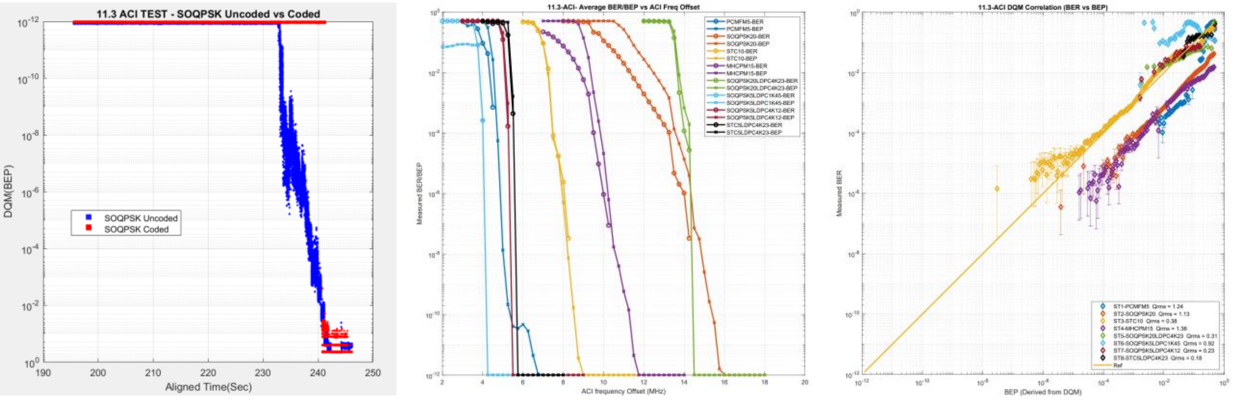
B) PCM/FM Eye Diagram

C) SOQPSK spectrum

D) SOQPSK Constellation

Figure 6: Examples of ACI impairment

Figure 7 shows the results of test 11.3 where the interferer moves closer in frequency towards the victim, causing the DQM to get progressively worse as seen in the DQM vs Time plot (left). The average BER/BEP for a given frequency separation (middle), and the DQM correlation plot (right) are also presented. The middle plot illustrates that different modulation and coding schemes have different susceptibility to adjacent channel interference. It makes sense that narrower bandwidth signals are less affected. Although coding makes the signal more robust, it also expands the bandwidth which causes greater overlap with the interferer. The DQM correlation plots on the right show mostly adequate performance for all modulations and coding schemes tested.



A) DQM/BEP versus Time

B) BER/BEP vs ACI Freq Offset

C) DQM Correlation

Figure 7: 11.3 ACI test example results

11.4/11.5 STATIC 3-RAY/2-RAY MULTIPATH CHANNEL CONDITIONS

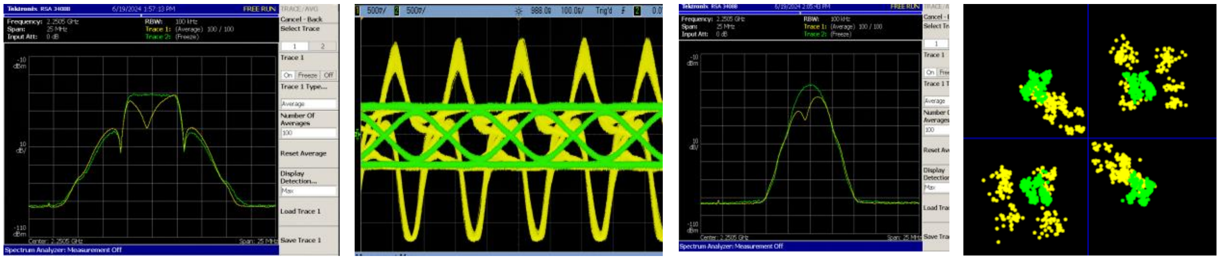
Tests 11.4 and 11.5 assess the ability of the receiver to provide an accurate estimate of signal quality in the presence of multipath. Mathematical models with parameters for 3-ray and 2-ray multipath channels are defined that approximate typical impairments experienced in an aeronautical telemetry channel. The 3-ray test corrupts the signal with multipath channel conditions of varying severity (Mild, Moderate, Severe). The 2-ray test specifies five reflection strengths (Γ), three path delays (τ), and eleven different phase difference values (γ) for a total of 165 different static multipath channels as produced by the following multipath model equation 2.

$$r(t) = s(t) + \Gamma_1 s(t - \tau_1)e^{j\gamma_1} + \Gamma_2 s(t - \tau_2)e^{j\gamma_2} + n(t) \tag{2}$$

An alternative approach is to add a small frequency offset (<< 1 Hz) on the Γ_1 specular reflection path to slowly rotate through all phase differences for a couple of cycles as seen in equation 3. This may be easy to synthesize with DSP-based signal generators and it has the advantage of testing the complete range of phase differences.

$$r(t) = s(t) + \Gamma_1 s(t - \tau_1)e^{j2\pi f_1 t} + \Gamma_2 s(t - \tau_2)e^{j\gamma_2} + n(t) \tag{3}$$

Figure 8 shows how multipath can affect the transmitted signal in the frequency domain and degrade the ability of the demodulator to recover the TM data (distorted eye-pattern or constellation). The addition of the multipath components effectively creates frequency selective fading in the transmitted signal with the severity based on the strength, phase difference, and delay of the reflection. The data quality can be severely compromised under these channel conditions resulting in good test cases for the receiver's ability to accurately estimate DQM.

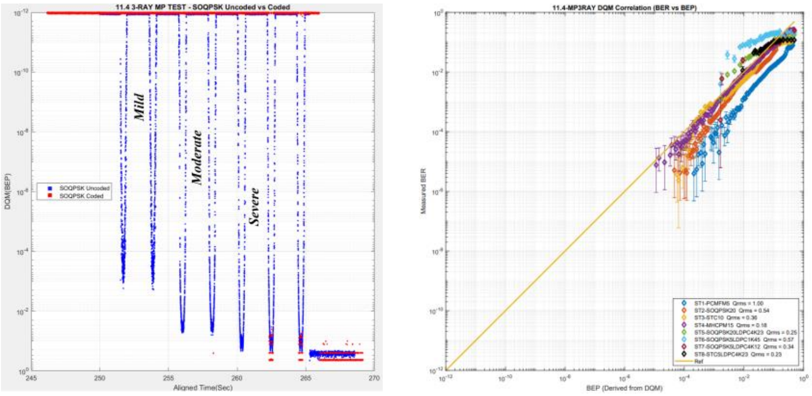


A) PCM/FM spectrum B) PCM/FM Eye Pattern C) SOQPSK spectrum D) SOQPSK Constellation

Figure 8: Examples of Multipath impairment

Figure 9 shows results from the 11.4 3-ray multipath test. The multipath parameters for the mild, moderate, and severe channels are listed on the left. The middle plot shows DQM versus time as the three channel conditions are applied. Notice that a couple of cycles of phase difference are run for each of the cases. The DQM correlation plot on the right shows reasonably accurate BEP estimation over the entire span of this challenging multipath test.

3-Ray MP	Mild	Moderate	Severe
Γ1 (dB)	-3	-1.5	-1
τ1 (ns)	50	50	50
γ1 (deg)	0-360	0-360	0-360
Γ2 (dB)	-20	-20	-20
τ2 (ns)	155	155	155
γ2 (deg)	90	90	90

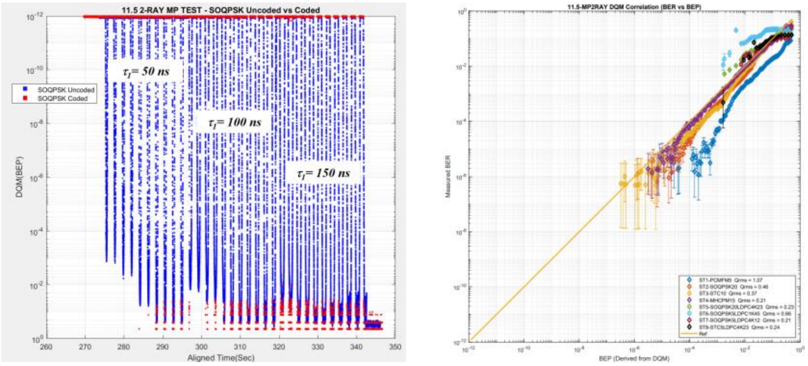


A) 3-Ray Parameters B) DQM/BEP versus Time C) DQM Correlation

Figure 9: 11.4 3-Ray Multipath Channel example results

Figure 10 shows results from the 11.5 2-ray multipath test. The multipath parameters for 2-ray channels are listed on the left with stronger reflections and longer delays typically degrading the data quality the most. The middle plot shows DQM versus time as the various channel conditions are applied. As with the previous test, a couple of cycles of phase difference are run for each of the cases. The DQM correlation plot is on the right and shows consistently accurate BEP estimation over the entire span of 2-ray testing.

2-Ray MP	Mildest to Worst
Γ1 (dB)	-3,-2.5,-2,-1.5,-1,-0.5
τ1 (ns)	50,100,150
γ1 (deg)	0-360



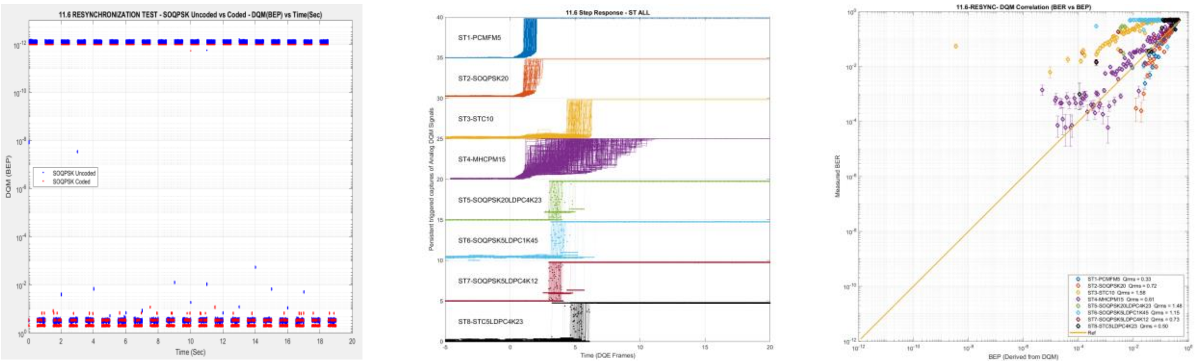
A) 2-Ray Parameters B) DQM/BEP versus Time C) DQM Correlation

Figure 10: 11.5 2-Ray Multipath Channel example results

11.6 RESYNCHRONIZATION RESPONSE

The 11.6 resynchronization response test measures the ability of the receiver to provide a signal quality assessment that immediately and accurately reflects maximum BEP upon signal outage and valid BEP when the outage ends, as the receiver resynchronizes. Two SNR conditions, very high and moderate, are tested. In addition to the correlation plot, a DQM versus time plot showing the resynchronization response is required for this test.

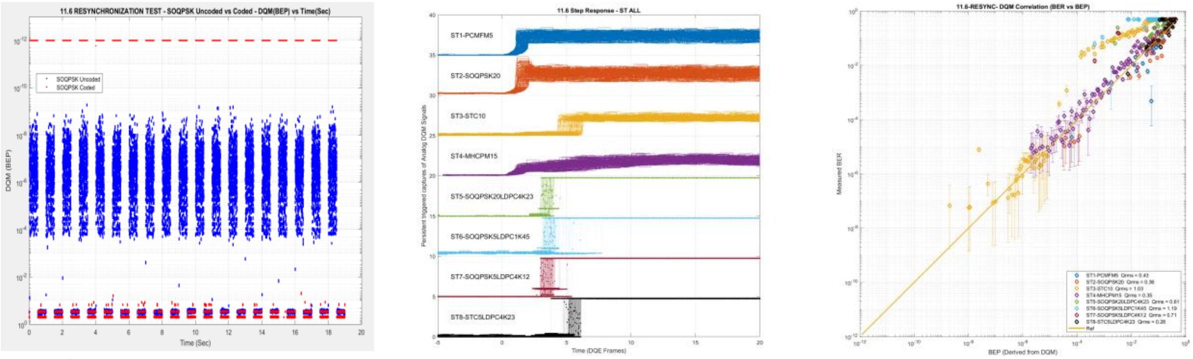
In cases where the modulation acquires quickly relative to the DQE block size, the DQM values should quickly reflect the true BER (in roughly one DQE frame). Figure 11 shows DQM versus time on the left. The middle plot presents persistent step responses for the test modes from Table 2. They are vertically stacked to allow comparisons among modulation and coding combinations. For this test the demodulator must either partially or completely resynchronize. The DQM correlation plots show good performance for all modulations and coding schemes tested.



A) DQM/BEP vs Time B) DQM step responses C) DQM Correlation

Figure 11: DQM resynchronization response with very high SNR

Figure 12 shows the results when a moderate SNR is used. It is worth noting that loss of lock may likely result in loss of DQE frame sync, particularly for block coded waveforms (STC and LDPC) where the DQE frames are tied to the code blocks. This means that the receiver may either pad DQE frames to maintain frame sync or output partial DQE frames to maintain data rate, but not both. The latter may account for the “flyers” observed.



A) DQM/BEP vs Time B) DQM step responses C) DQM Correlation

Figure 12: DQM resynchronization response with moderate SNR

DQE/DQM TESTING OBSERVATIONS

A	DQM Test Terminology	BER is used to indicate a ***measured*** value where BEP is ***estimated*** from the DQM value.
B	DQM testing is not about receiver sensitivity	DQM is all about accurately estimating the recovered TM quality – not about the receiver sensitivity performance. Whether the TM quality is good or bad, the accuracy of the DQM indication is what is being tested.
C	Distribution of DQM values	For AWGN channels, the DQM values should follow a binomial probability distribution instead of a single averaged value. For example, using 4096 bits at an average BER of 10^{-5}, the DQM values should be spread over a range of around 10^{-3} to 10^{-7}. As the block size or average BER increases, the spread of the DQM distribution narrows.
D	DQM Correlation	The confidence interval of the DQM correlation bin values should contain the ideal BEP=BER line. Indicators of poor DQM correlation performance include points with a large estimation error (particularly measured errors at mimimum BEP), horizontal or vertical segments, or significant gaps not related to the test stimulus.
E	DQM Step Response	If the modulation step response is fast relative to the period of a DQE frame, the new DQM value should accurately reflect the actual BER level within a single DQE frame. Timing misalignment or DQM averaging can smear the response over multiple frames causing slow convergence and poor correlation with the actual BER.
F	Selection of TM Signal Types	It is impossible to test all TM modes and channel conditions. Select test parameters that exercise modulation/coding/system options that verify the various DQE formats.
G	Automated Real-Time Testing	DQE/DQM testing requires dynamic signal generation, precise data capture, and specialized equipment. Automating the test execution, data collection, and results reduction to the maximum extent possible is highly recommended for efficiency, accuracy, and repeatibility. Real-time results can be checked using TM recordings and off-line processing if desired.
H	Receiver Operating Modes	Testing of both single-channel and combiner operation is recommended as well as any other speciality modes such as adaptive equalization.
I	Test Time/Resolution	Measuring DQM correlation results at low error rates can require long run times. A practical approach is to first run through all the tests in a reasonable time frame with longer runs reserved for individual tests based on the results. Resolutions of 1 dB are sufficient for uncoded modulations while steps of 0.1 dB over a narrower range are recommended for coded modes.
J	Uncoded vs Coded Testing	A starting point for appropriate Eb/N0 ranges and step sizes can be determined from theoretical values for each particular modulation/coding mode. Adjust the ranges as required.
K	Multipath Generation	The standard lists discrete phase difference values (γ) for the multipath parameters. A signal generator capable of implementing a slow phase rotation (frequency offset) that exercises all phase differences is simpler, more complete, and is recommended.
L	DQE Block Size	The standard does not call out a specific block size. At a minimum, it is recommended to test 1K, 3200, and 4K bit block sizes as these are the most commonly used settings.
M	Average DQM/BEP vs Frame-by-Frame DQM/BEP	Unlike the dynamic tests, 11.1 AWGN and 11.3 ACI are suitable for comparing the average BER to the average BEP at each individual channel setting. The results should agree reasonably well since they represent the means of a large sample size. If not, this may indicate a bias in the receiver processing approach.
N	11.2 Step and Dwell	The current suggestion of 8,10,12 Eb/N0 levels in the 11.2 step and dwell test produce DQM distributions with overlapping values. Eb/N0 levels that produce a BER corresponding to $1e^{-2}$ and $1e^{-7}$ make the SNR transitions clearly discernable.
O	11.6 Resynchronization Artifacts	Resynchronization artifacts may be present in the resynchronization test and are more prevelant with advanced modulations, coding, and shorter DQE block sizes. Be aware that DQM estimation is degraded prior to demodulator lock. This test should be conducted with both long and short outage periods to understand DQM behavior. Be aware that the step response could validly span multiple DQE frames if the receiver synchronization is slow or unsteady.
P	Pass/Fail Criterion	There is currently no Pass/Fail criterion. It is recommended to adopt a minimum level of performance as is done with diversity combiner operation (5.16, 5.26) or transmitter spectral mask compliance (9-7). The 11.1-2 tests are well suited for adding minimum Pass/Fail thresholds in the form of a mask or RMS error of the exponent differences.

Table 3: DQE/DQM Testing Observations

CONCLUSION

This paper has taken a comprehensive look at testing the DQE protocol and DQM estimates over the dimensions of different modulations, coding schemes, and block sizes. This is the first known publication of reference results from performing RCC 118 chapter 11 DQE/DQM testing. Issues and recommendations regarding performing the test procedures have been presented. A validated test standard with efficient test methods is the key to promoting widespread deployment and use of this game-changing capability. The major conclusions from this paper include:

- *The RCC 118-22 DQE/DQM test framework is sufficient for DQE/DQM characterization.*
- *Modification to test parameters have been recommended based on the conducted testing.*
- *Example test results have been presented to serve as an achievable performance baseline.*
- *The 11.2 (step and dwell) and 11.6 (resynchronization) tests dynamically transition between channel conditions resulting in partially mixed DQE frames that can create outlier DQM values. These artifacts vary with the modulation type, coding scheme, and distribution of signal outage lengths. However, the results should generally follow the ideal BEP=BER line.*
- *Testing should include enough modes to verify the DQE format adheres to variations based on different IRIG modulation and coding alternatives as well as other operational settings.*
- *Automated testing should be used as much as possible for repeatability and accuracy.*
- *Minimum levels of performance should be determined and included like other RCC 118 tests such as the diversity combiner operation or transmitter spectral mask compliance.*

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