LINK AVAILABILITY AND BIT ERROR CLUSTERS IN AERONAUTICAL TELEMETRY

Robert P. Jefferis
TYBRIN Corporation

ABSTRACT

Radio frequency power margins in well planned line-of-sight (LOS) air-to-ground digital data transmission systems usually produce signal to noise ratios (SNR) that can deliver error free service. Sometimes field performance falls short of design and customer expectations. Recent flight tests conducted by the tri-service Advanced Range Telemetry (ARTM) project confirm that the dominant source of bit errors and short term link failures are "clusters" of severe error burst activity produced by flat fading, dispersive fading and poor antenna patterns on airborne vehicles. This paper introduces the techniques used by ARTM to measure bit error performance of aeronautical telemetry links.

KEY WORDS

Aeronautical telemetry, link availability, bit error analysis, error clusters

INTRODUCTION

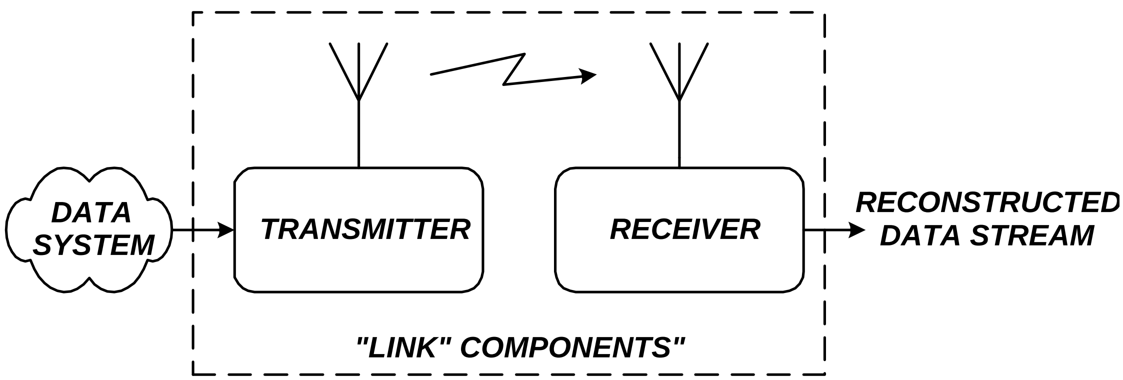
The ARTM project, sponsored by the Office of the Secretary of Defense under its "Central Test and Evaluation Investment Program", is chartered to identify and develop practical improvements to the air-to-ground data telemetry links used in flight vehicle trials over Department of Defense (DoD) "Major Range Test Facility Bases". Desire to increase spectral efficiency, sustain higher data rates and improve link reliability justifies investigation and tests of new modulation methods, adaptive equalizer technology, a variety of transmit and receive diversity techniques as well as error detection and correction schemes (EDAC).

While planning collection and assembly of tools necessary for laboratory and field experiments, searches were made for meaningful performance assessment criteria. Collective ARTM staff experience coupled with literature searches confirmed that germane, quantitative channel models and systematic criteria for link performance assessment did not exist for this application arena. This paper briefly describes the application specific link definition used and introduces top level link performance criteria developed for out of service (OOS) link tests. Specific performance measurement parameters and statistics are defined. Use of these tools is demonstrated with selected examples.

ARTM “LINK” DESCRIPTION

Top level ARTM link tests emphasize end-to-end system performance as indicated by the number of bits found in error at the output of defined system boundaries. Figure 1 depicts the simplified model of telemetry system components that collectively constitute a baseline air-to-ground telemetry “link”. The link definition includes *all* subsystems directly associated with the wireless data transmission, i.e., transmitter functions, transmit antenna, receive antenna, downconverter, demodulator, detector and bit stream reconstruction apparatus.

Figure 1
Link Definition



The transmitter platform is an aircraft or missile. Some form of on-board data acquisition system places desired telemeter information into a *continuous,* time-division multiplex, serial binary digital bit stream. Non-return-to-zero-level (NRZL) is the most common baseband line code. Bit rates are low to intermediate, usually in the range of 100 kilobits per second (kb/s) to 10 megabits per second (Mb/s). Serial data is applied to the first link component, the transmitter. Typically, power supply, baseband line interface, baseband signal processing, modulation, frequency conversion and radio frequency (RF) power amplification functions are in one consolidated transmitter package. The standard DoD test range modulation type is a specific form of continuous frequency shift keying referred to in the defining standard as “PCM/FM”[1]. Non-linear power amplifiers are used to achieve common transmit power levels of about two to ten Watts.

Low gain omnidirectional transmit antennas are the norm since platform orientation relative to the receive antenna is not controlled. RF power is sometimes divided and applied to two or more separate transmit antennas for reduction of signal masking from wings, fuselage or other vehicle surfaces even though resulting arbitrary antenna separation distances often produce harmful self-inflicted cochannel interference. ARTM link tests normally utilize a single “well behaved” transmit antenna, i.e., one with a uniform radiation pattern in aircraft yaw and roll planes.

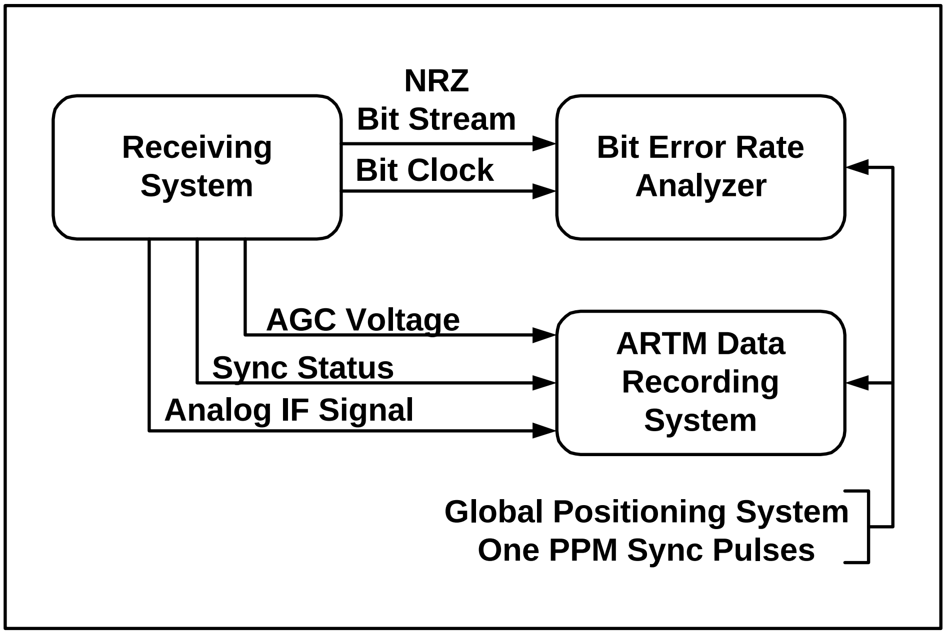
At the receiving station, whether fixed site or mobile, the most common receive antenna is a directional reflector style with single or dual secondary feed antennas. Receive antenna beam width is a crucial factor in overall link performance, narrow beams providing an effective first line of defense against terrain induced frequency selective fading. The consolidated receiver definition includes preamplifiers, downconversion, gain control, demodulation, detection and bit stream reassembly functions.

TEST METHOD

At this time, reliable and efficient link performance measurement demands controlled out-of-service (OOS) tests. Field trials require an air vehicle and link dedicated to the experiment. ARTM experiments are conducted with the system outlined in Figure 2. A pseudo-random binary sequence (PRBS) generator substitutes for the aircraft data system of Figure 1. This allows conventional bit error detection equipment to be used for accumulation of bit error data. Reconstructed NRZ data from the link under test is applied to a model BA25 bit error rate analyzer (BERA) manufactured by SyntheSys Research Incorporated. This analyzer satisfies two critical needs of the application. In addition to conventional real-time bit error detection duties, it captures the *location* of each bit error in a measurement record. Complete time histories of error location and auxiliary events are logged to a large internal disk drive. These features enable versatile and detailed bit-by-bit post-test analysis of error activity.

Channel and general test condition information is acquired by the ARTM data system. Time histories of receiver automatic gain control (AGC) activity and synchronization status is recorded. In addition, a high-speed digitizer can acquire snapshots of the RF signal (at post AGC intermediate frequencies) to facilitate detailed frequency and time domain propagation analysis. Time correlation between the BERA and data acquisition system is established to ± one bit precision with one pulse per minute (PPM) signals from a Global Positioning System (GPS) receiver. Aircraft location time histories are recorded on the test aircraft with an on-board GPS receiver.

Figure 2
Measurement System: Link Performance



Since channel conditions are strongly effected by aircraft location relative to receiving antennas, local terrain characteristics and atmospheric conditions, it is difficult to generalize field experiment designs and extrapolate results to individual flight scenarios. For this reason ARTM tests do not attempt rigorous control of these variables. The most reliable experiment is regarded as one that compares the performance of two link configuration variations tested simultaneously, i.e., side-by-side "link configuration A versus link configuration B" (A:B) experiments. When an A:B test is not desirable or practical, tests are constrained to pre-defined flight path and terrain combinations which produce a reasonable degree of wave propagation repeatability. A small, but growing data base of propagation characteristics for three particular flight corridors over Edwards Air Force Base, California allows increasing reliance on some absolute single link tests.

FLIGHT LINK AVAILABILITY (FLA)

Lacking application specific error performance and diagnostic criteria, attention turned to commercial wireless and landline standards. An attractive starting point was found in International Telecommunication Union Recommendation G.821(G.821)[2]. Even though this recommendation and its related practices were developed for a 64 kb/s "Integrated Services Data Network", the underlying philosophy and rationale embodied in this recommendation were found to be a good fit to critical ARTM evaluation criteria:

- Focus on end-to-end (customer oriented) performance measurement.
- Simplicity and relative measurement ease.

- Low investment in specialized test equipment.
- Reasonably good fit to the application.

Although G.821 event definitions and performance parameters are a reasonably good fit to this application, a number of definition and nomenclature changes were necessary. However, the adaptations do not prevent use of most existing equipment or software containing automated G.821 data analysis. ARTM FLA statistics are readily derived subsets of standard bit error and G.821 data products. What follows is an abbreviated definition list containing essential FLA parameters. Readers interested in more detail, rationale and the differences between FLA and G.821 are referred to G.821 and [3].

EVENT DEFINITIONS

Error **S**econd (ES ≡ A one second interval of transmission time containing at least one bit error and fewer than the number of errors that would indicate a severe error second.

Lost **T**ime (LT) ≡ the number of bit periods in the measurement period, if any, that cannot be counted in categories ES or SES for one of the following reasons:

1. Receiving and detection apparatus lost synchronization with the bit stream or was in a state of acquiring synchronization with the bit stream and the measurement apparatus could not provide accounts of individual bit errors.
2. Error detection equipment in use became temporarily overloaded with bit error processing and could not track errors on a bit-by-bit basis.

LT is expressed in seconds. With the exception of error clusters, presentation of link performance parameters in a specific measurement period include one aggregated figure for LT. Specific derived parameters include or exclude LT as appropriate.

Measurement **P**eriod (MP) ≡ The measurement interval, expressed in seconds and decimal fractions of seconds, over which *relevant* event data is captured.

Severe **E**rror **S**econd (SES) ≡ A one second interval in which the number of bit errors equals or exceeds the equivalent of a 10^{-5} bit error rate (BER) if the same error occurrence rate were to occur on an average basis. This is the ARTM threshold of short-term link failure.

PERFORMANCE INDICATORS

All of the following definitions are fractional components created by normalization to the MP.

Error **F**ree **F**raction (EFF)	$\equiv [1-(\Sigma\ SES + \Sigma\ ES + LT) / MP]$	(1)
Error **S**econd **F**raction (ESF)	$\equiv \Sigma\ ES / MP$	(2)
Available **S**econd **F**raction (ASF)	$\equiv EFF + ESF$	(3)
Failed **S**econd **F**raction (FSF)	$\equiv (\Sigma\ SES + LT) / MP$	(4)
Flight **L**ink **A**vailability (FLA)	$\equiv 1 - FSF$	(5)

Figure 3 is an example of FLA derived from application of equations 1-6 to three A:B comparison flights of PCM/FM and FQPSK-B modulation at 1 Mb/s [4]. This is a scatter, or X-Y plot, each data point revealing the FLA levels achieved simultaneously by A and B systems over a complete flight path record. All MP's are over 700 seconds long. The diagonal dashed line is the line of equal A:B performance. Note that a large number of points are bunched together very close to coordinates (1,1) indicating that both links are capable of delivering comparable error performance most of the time. The congestion at (1,1) is alleviated when the FSF's of the same data sets are plotted similarly as in Figure 4. These presentation forms are equivalent.

Figure 3
Flight Link Availability - ARTM Flight Series #1
1 Mb/s FM versus FQPSK-B

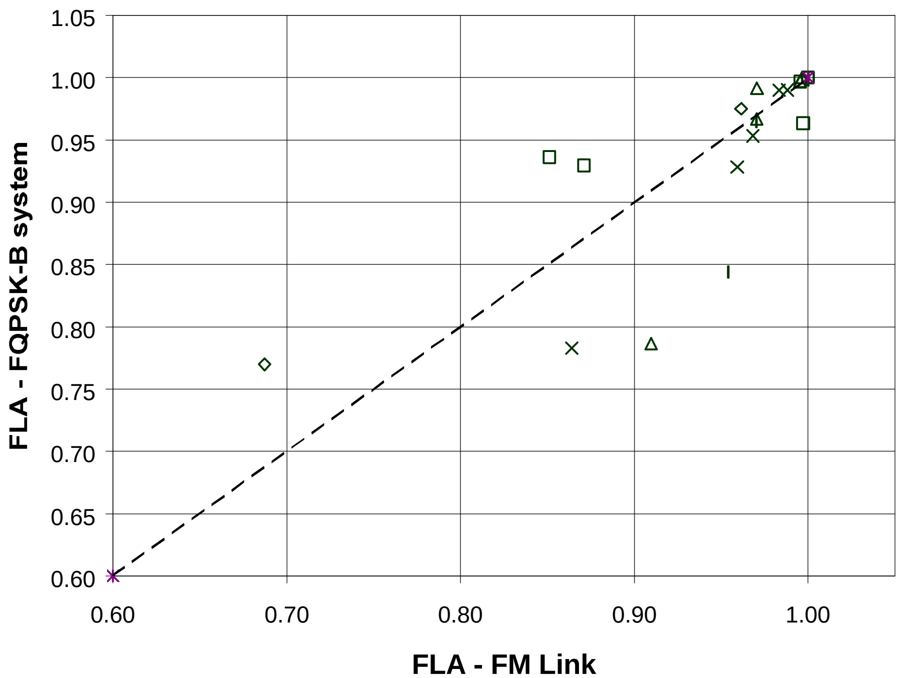
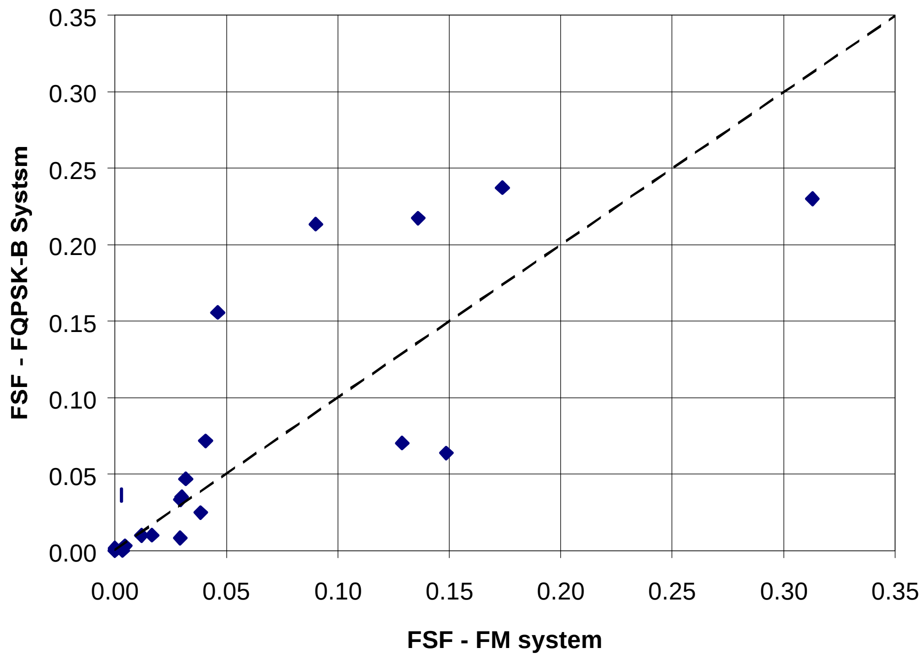


Figure 4
Link Failures - ARTM Flight Series #1
1 Mb/s Fm versus FQPSK-B



ERROR CLUSTERS

Channel probe data and A:B tests of link component variations conducted by ARTM consistently demonstrate that isolated bit errors and conventional error bursts rarely occur until the radio horizon is approached or thermal noise becomes significant for some other reason. This is consistent with the fact that large power margins (15-20 dB or more), narrow antenna beams and fairly fast automatic gain controls are the means used to combat fast flat fading and dispersive fading. Link performance tends to swing quickly between two extremes. Noise crest factors are limited by filters in the receiving station which means that error free transmission is expected in the absence of significant fading. However, for each combination of fade type, delay spread and symbol rate, the links exhibit fade sensitivity thresholds above which performance degrades rapidly. These thresholds are strongly related to the ratio of delay spread to symbol period. As this ratio increases above about 0.1-0.2, sensitivity to delayed images of the LOS ray increases dramatically.

The majority of deep fade events result in bursts of error activity so severe that BER approaches unity. Demodulation and symbol synchronization processes often fail in these intervals as well. Attempts to describe these events as conventional error "bursts" with attendant connotations of reliable statistical structures are not meaningful. For practical diagnostic purposes these events are viewed at a higher level, each one considered a short-term link failure described with an "error cluster" (EC). ARTM developed an automated procedure to isolate and catalog EC's from BERA recording files. Two simple EC identification criteria are used. Cluster onset is defined in terms of an initial BER. Succeeding bit errors become cluster members until the cluster is terminated by a pre-defined period of error free transmission. A wide range of identification parameter values were applied to dozens of BERA records. Reasonable and fairly consistent results were found using an onset threshold of BER=10^{-4} and terminal period of approximately 0.2-0.4 seconds. Each EC is cataloged with its position in the MP, the total number of bit errors in the cluster (including lost time, if any) and the cluster length in seconds. Bit error time histories spanning the EC are also extracted.

Several EC statistics provide useful performance *difference* indicators. Differences are stressed because data must normally be gathered in A:B comparisons or repetitions of controlled experiments. "Cluster Weight" (CW), is the product of cluster length (CL) and total cluster bit errors (CE) and is normalized by referral to a bit rate of 1 Mb/s:

$$CW \equiv (CL \times CE) / \text{bit rate (Mb/s)} \qquad (6)$$

Figure 5 presents EC results from the *same* flight path of three separate test flights. Each symbol on the graph is the CW of an individual cluster, plotted at its MP normalized time location within the MP. These data sets can be considered repetitions of an experiment in the sense that all data share a common flight corridor, flight profile, MP (≅ 720 seconds), airspeed and transmission frequency range (1420-1510 MHz). Thus, time position on the graph can be roughly associated with physical location along the flight path. It is interesting to note the vertical stratification that appears at approximate positions 0.1, 0.4, 0.55, 0.65 and 0.9. This corroborates other evidence that many flight profiles over desert test ranges will produce repeatable zones of dispersive fading. In all three flight set examples, the total number of errors associated with the EC's account for more than 99.9% of the bit errors and all of the LT measured during the tests. *All* of the CW values larger than 1000 contain single or multiple synchronization loss events or LT or both.

Once familiar with EC's they are useful in at least two ways. EC information can be extracted very quickly from a set of test data. A plot such as Figure 5 instantly reveals the general health of a baseline comparison link or serves as a status indicator for new configurations. Being course indicators, link component changes worthy of serious development investments should produce very dramatic changes to EC quantity, CW's or both, when tested over reference flight paths.

Figure 5
Error Clusters - Black Mountain Corridor
5000 Foot Altitude, West to East

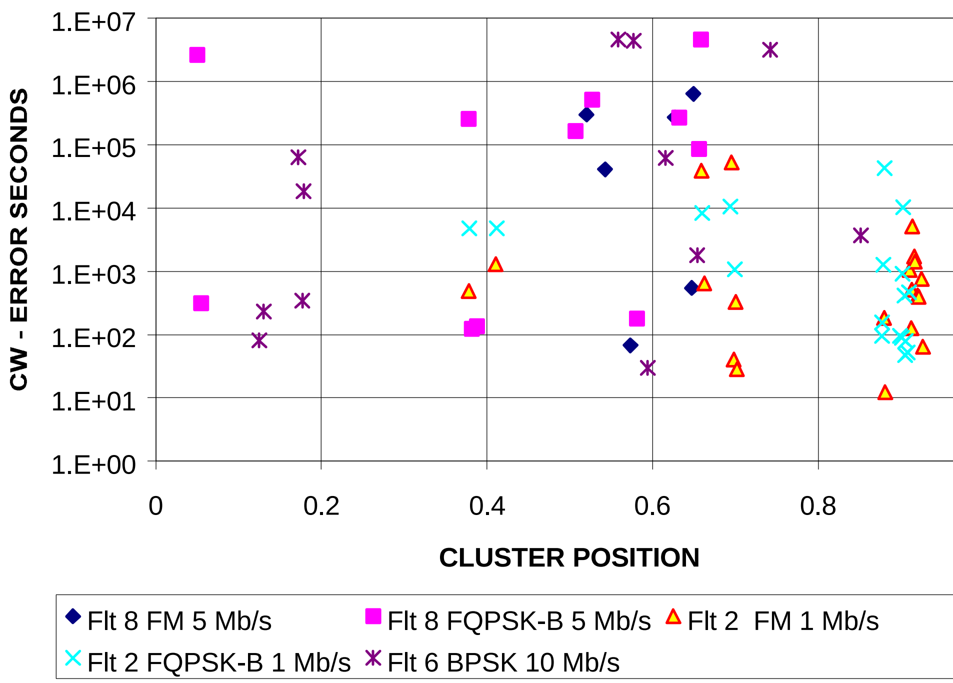
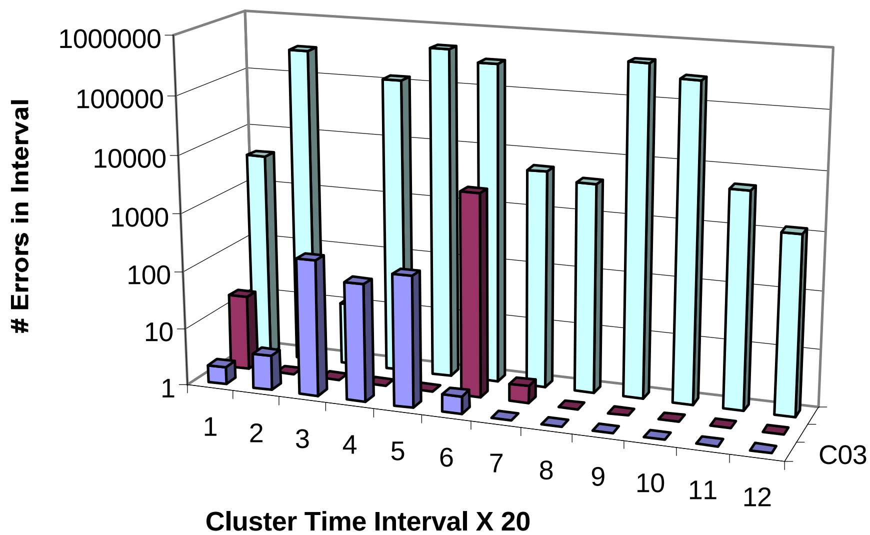


Figure 6 shows error activity contained in three of the clusters from Figure 5. These are all from the FM system and flight 8 and demonstrate the range of cluster structure.

CONCLUSION

The ARTM project has developed simple system level link error performance criteria tailored to the DoD aeronautical telemetry problem. FLA, FSF's and EC's are proving to be useful concepts for evaluating the impact of link component changes and seem to transcend the source of change whether it be modulation, antennas, diversity schemes or EDAC. Further work on the subject of EC's is in progress to establish validity and usefulness. Additional work is recommended to investigate extension of these concepts from OOS testing to in-service testing.

Figure 6
Error Cluster Time History Examples



REFERENCES AND NOTES

[1] Secretariat, Range Commander's Council, "Telemetry Standards, IRIG Standard 106-99", White Sands Missile Range, 1999.
[2] International Telecommunication Union, "Error performance of an international digital connection operating at a bit rate below the primary rate and forming part of an integrated services digital network", ITU-T Recommendation G.821, August, 1996.
[3] Advanced Range Telemetry Project, "Aeronautical Telemetry Link Performance and Service Availability, System Level Parameter Definitions for Test Data Analysis"(draft report, public release pending) 1999, Charles Irving, 412TW/TSDI, Edwards Air Force Base, California.
[4] FQPSK is the acronym for "Feher's Quadrature Phase Shift Keying", a proprietary variation of offset quadrature phase shift keying controlled by DIGCOM Incorporated, El Macero, California.