CPFSK, FQPSK-JR and ARTM CPM ON A ROCKET LAUNCH

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ABSTRACT

A rocket launch, as high dynamics target, was used to demonstrate X-band tracking and also to verify high bit rate frequency planning while demonstrating significant bandwidth reduction with IRIG standard advanced modulation methods. X-band tracking by a modified 8-foot mobile telemetry antenna was excellent. Three separate S-band transmitters with three separate wraparound antennas were launched as a piggyback payload on an Enhanced Orion sounding rocket at White Sands Missile Range (WSMR) to compare the performance of 10 Mbs and 20 Mbs bit error rate (BER) pattern data transmission from CPFSK, FQPSK-JR and ARTM CPM modulation formats under high dynamic conditions. The test is more remarkable in that another S-band wideband spread spectrum signal was also transmitted with good success. These results show that all three modulation methods performed well during ignition and liftoff, low aspect angle (receiving through the rocket motor plume during ascent from a tracker near the launch pad), spin stabilization antenna lobe fades and payload tumbling. Spectrum pictures are provided to show the dramatic reduction in transmission bandwidth from CPFSK to FQPSK-JR to ARTM CPM. Confirmation of the preflight RF adjacent channel interference planning procedures from IRIG 106-05 is described by spectrum pictures and data quality measurements.

KEY WORDS

RF bandwidth, modulation type versus bandwidth, adjacent channel interference, aeronautical telemetry signal spacing, FQPSK transmission in a dynamic environment

INTRODUCTION

The Office of Secretary of Defense (OSD) Test and Evaluation (T&E) Science and Technology (S&T) Spectrum Efficient Technologies focus area funded a project at White Sands Missile Range (WSMR) to modify one of their existing 2200-2400 MHz (S-band) eight foot diameter telemetry autotrack antenna systems to support 7850-8050 MHz (X-band). X-band tracking capability was tested by aircraft flight tests and on a high dynamic launch vehicle. WSMR contracted the modification to ViaSat, the manufacturer of the original S-band antenna system. WSMR was able to schedule a piggyback payload on an Enhanced Orion sounding rocket with an X-band antenna for the tracking and data transmission demonstration. And, there was room on the piggyback payload for another T&E/S&T test to compare high bit rate PCM with three different modulation types under high dynamic rocket launch conditions. The PCM for all three transmitters was generated by a pseudo random bit sequence (PRBS) pattern generator in order to measure bit errors of a 2047 bit length pattern. This paper makes a direct comparison of the total bit errors and the bit error rate of the CPFSK, FQPSK-JR and ARTM CPM telemetry links. Spectrum pictures are provided to illustrate the differences in signal bandwidth of the three types of modulation and more importantly to show how well the Range Commanders Council (RCC) Inter Range Instrumentation Group (IRIG) adjacent channel interference (ACI) planning procedures [1] [2] work for frequency management and mission planning.

Other publications [3] describe the new WSMR X-band telemetry tracking antenna that is field changeable in a half hour from S-band to X-band and a half hour to change back to S-band. That new range capability was developed as a T&E/S&T project to quantify the problems of operating at higher frequencies requested from the World Administrative Radio Council due to the limited bandwidth of existing telemetry bands. Existing telemetry bands are being reduced by auction for commercial applications such as satellite radio and cellular phones while data rates are increasing. Comparison of the high bit rate X-band telemetry data to the same data transmitted at S-band is described.

FLIGHT VEHICLE CONFIGURATION

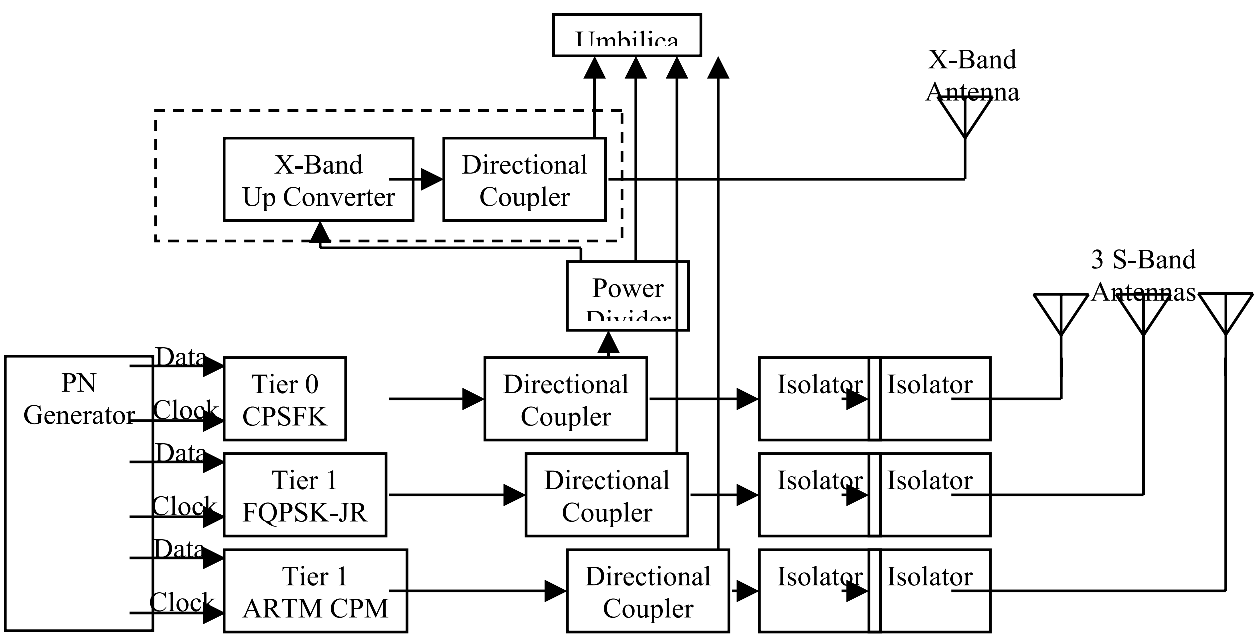


Figure 1a: Payload Antennas for X-band Tracking and S-band Modulation Comparison

There were separate wraparound antennas for each of the three S-band radio frequency (RF) links and a fourth wraparound antenna for the X-band RF link to provide sufficient link margin on each link. Each wraparound antenna provided about – 5 dBi gain that precluded sharing an antenna by multiple transmitters feeding a power divider. The four antennae are shown in Figures 1a and 1b of the piggyback payload. Note the one inch wide aluminum strip covering the joints where the two ends of each wraparound antenna meet. This strip was required to prevent friction heating during supersonic flight of uneven antenna ends caused by manufacturing errors. The aluminum strip inadvertently provided a superb periodic signal block as the rocket was spin stabilized at approximately 4.5 Hz rate. This periodic signal block provided an excellent periodic signal fade to measure signal acquisition time by the ground station demodulators. Figure 2 shows the internal payload components. Figures 3 and 4 show the piggyback payload beneath the primary payload of an L-band receive and S-band transmit antenna in the same skin or radome for translated wideband GPS signals radiated at 2210.0 MHz. On the piggyback payload in Figure 1b the top antenna radiates 20 Mbs FQPSK-JR at 2229.5 MHz. The next antenna below radiates 10 Mbs CPFSK at 7975.0 MHz. The next antenna below the X-band antenna radiates 10 Mbs CPFSK at 2250.5 MHz. There is space for the payload access door to service the batteries, PRBS generators and transmitters before the last antenna at the bottom for 20 Mbs ARTM CPM at 2269.5 MHz.

Figure 1b: Payload Antennas for X-band Tracking and S-band Modulation Comparison

The three S-band transmitters for the three types of modulation are flight rated commercial off-the-shelf (COTS) transmitters from three different manufacturers – Nova Engineering, Quasonics LLC and Herley Industries. All three transmitters are rated for 5 watts output. A COTS X-band transmitter was not available and was derived an upconverter to conduct the X-band tracking and data transmission tests. The 10 Mbs CPFSK transmitter output was fed to a power splitter and half the signal sent to a mixer where it was upconverted from 2250.5 MHz to 7975.0 MHz then amplified to 2 watts to feed the X-band wraparound antenna. The three batteries on two of the three pallets are the largest, heaviest components of the payload.

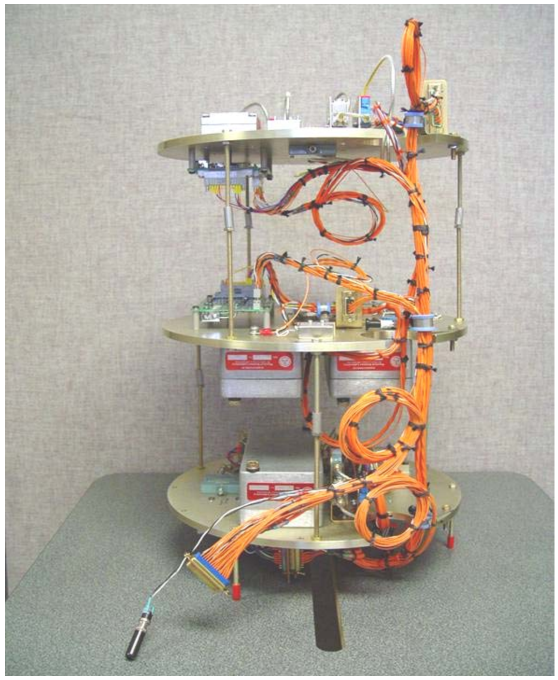


Figure 2: 2 PRBS Generators, 3 S-band Tx's, S-to-X-band up converter and PA, and Batteries

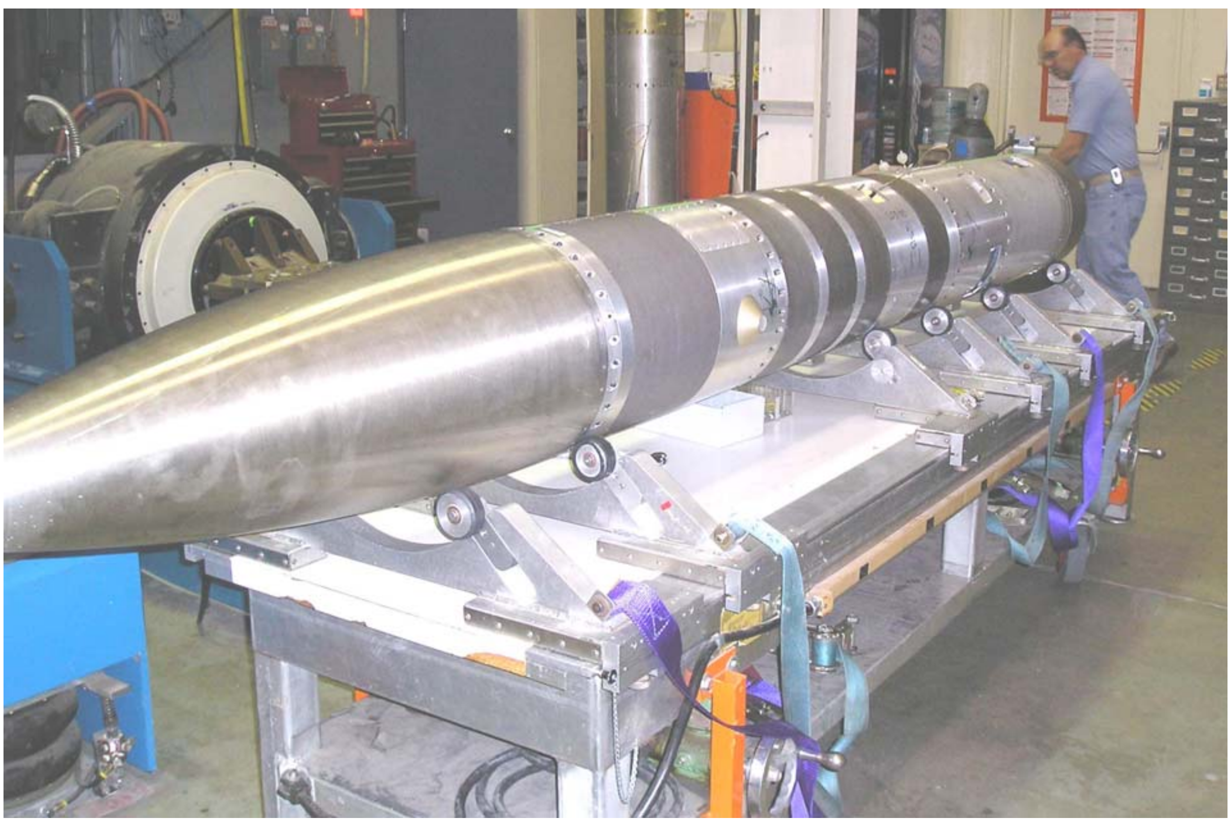


Figure 3: Nosecone, Primary Translated GPS Payload, X-band Antenna and 3 S-band Antennae
Piggyback Payload for Modulation Comparison-Parachute Recovery System

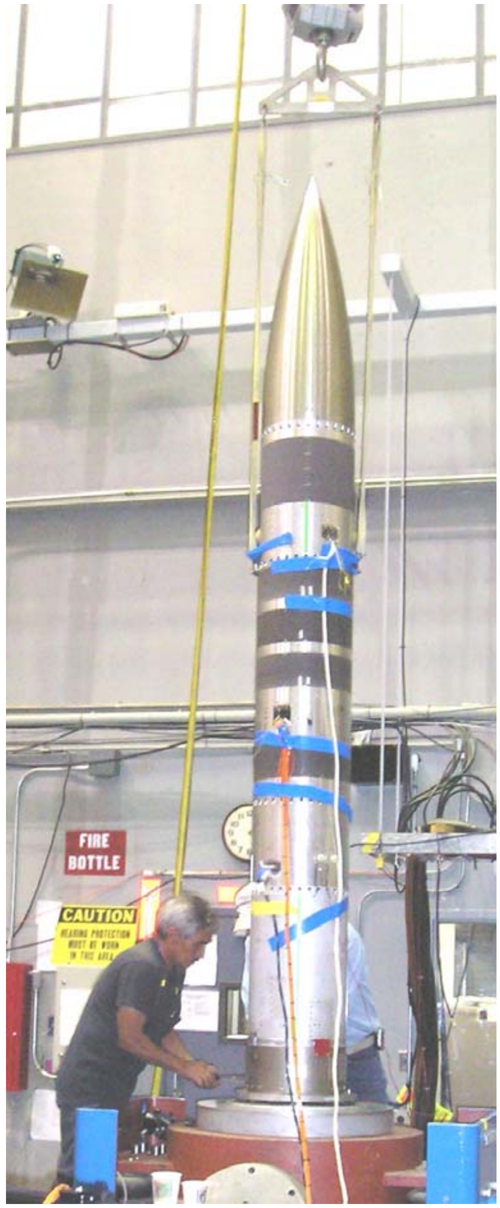


Figure 4: Vertical Vibration Test

FREQUENCY CONSIDERATIONS

COTS transmitters were selected for the test. The available CPFSK transmitter could support a maximum of 12 Mbs with 10 Mbs being chosen as the bit rate for the FM test. Following the examples of assigning multiple carrier frequencies in [1] and [2] the calculations for selecting five S-band frequencies for aircraft flight testing prior to the rocket launch are shown below. The narrow band housekeeping link was deleted from the rocket payload. The approved operating band for all S-band signals was 2200 to 2290 MHz. Assume Law's adjacent channel interference (ACI) carrier separation criteria [2] and resistive-inductive-capacitive (RLC) final IF filters for the telemetry receivers providing 70 MHz IF signal to external Multi Mode demodulators for CPFSK, FQPSK-JR and ARTM CPM. The Multi Mode demodulators provide digital IF filtering of the 70 MHz IF signal from the receiver. The FM demodulator is a multi symbol detector providing up to 3 dB improvement in signal to noise ratio performance, as compared to the traditional non-coherent delay line discriminator that makes a single bit hard detection, at the expense of a minor increase in signal acquisition time.

Low guard = BTGRS/2*r_b = 0.7 x 10 = 7 MHz
DFTGRS:T1 = 0.45 * 10 + 0.7 * 20 = 18.5 MHz
DFT1:T0 = 0.45 * 20 + 1.2 * 10 = 21 MHz
DFT0:T2 = 0.35 * 20 + 1.2 * 10 = 19 MHz
DFT2:TM = 1 * 0.25 + 0.5 * 20 = 10.25 MHz
Hi guard= 1.2 / 2 * 20 = 1.5 MHz

Total required spectrum for three mode experiment 7+18.5+21+19+10.25+1.5 = 77.25 MHz. With these minimum bandwidths calculated the carrier frequency assignments were chosen as:

– TGRS 2210.5 Mhz, 4 Mbs
– SOQPSK 2229.5 Mhz, 20 Mbs
– FM 2250.5 Mhz, 10 Mbs
– CPM 2269.5 Mhz, 20 Mbs
– FM 2250.5 MHz 250 Kbps (deleted)
– FM 7975.0 Mhz 10 Mbs

Figure 5 shows the S-band spectrum with three transmitters with different types of modulation plus the Translated GPS spread spectrum link fit within the 2200-2290 MHz band. Bit error rate results during vertical vibration tests showed error free data on the three PCM telemetry links.

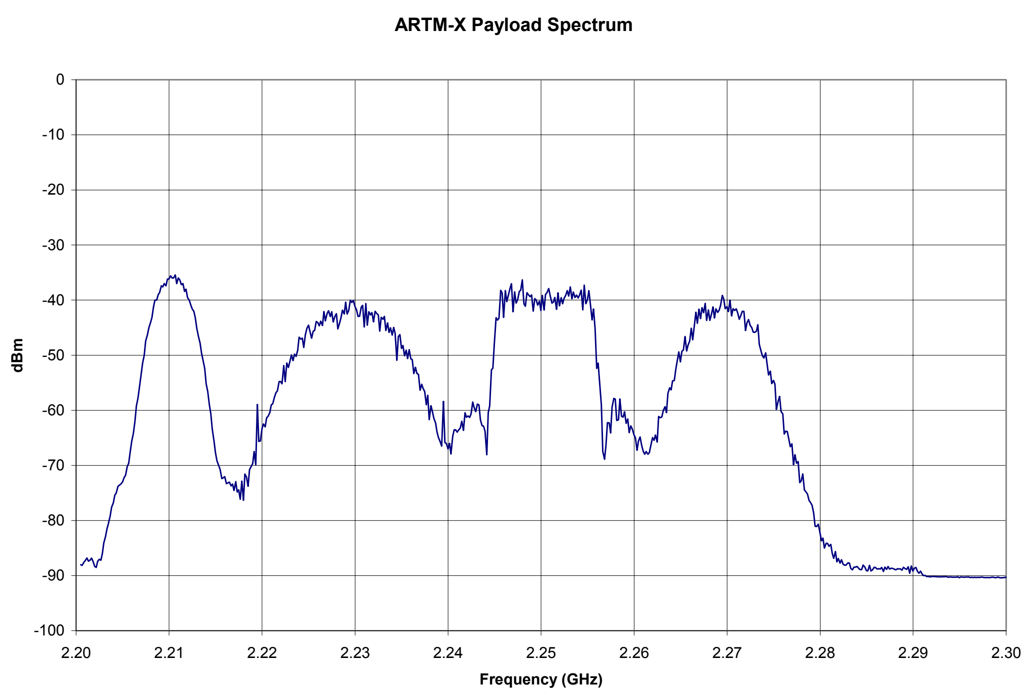


Figure 5: Four S-band Transmitters with Translated GPS, CPM, FM and SOQPSK

GROUND STATION CONFIGURATION

The S-band RF link data was acquired by the NASA owned 30-foot antenna located about a half mile from the launch rail to obtain maximum signal perturbations. The rocket trajectory was directly away from the 30-foot antenna for worst case aspect angle (degrees from directly aft) to produce signal transmission through the plume. The X-band RF link data was acquired by an eight foot antenna on the roof of the Range Operations Control Center located about eight miles from the launch rail for a side look of the trajectory to improve the aspect angle.

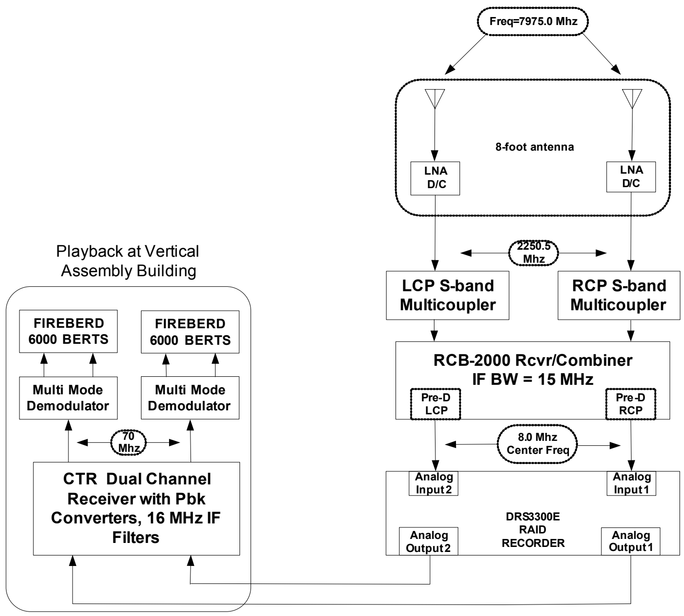


Figure 6: 8-foot X-band Antenna at J-13 Telemetry Station

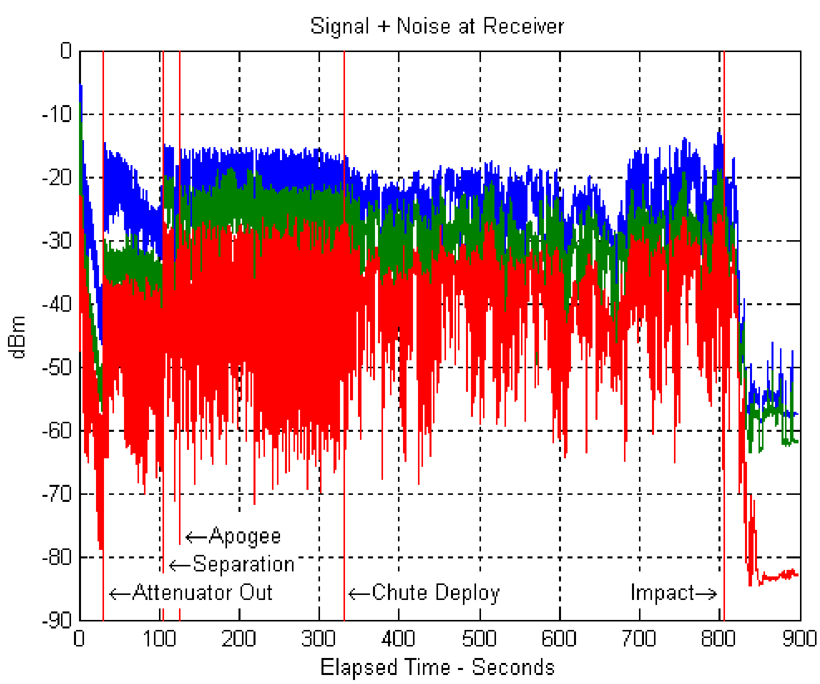
Both antennas were placed in autotrack mode prior to ignition and autotracked the entire mission with no operator intervention. The 30 foot antenna tracked on the 2210.5 MHz signal to avoid aluminum strip fades. The signal strength plots in Figures 7 through 9 and BER plots in Figure 13 show the eight foot antenna losing signal before the 30 foot antenna during the parachute descent for recovery of the payload because the eight foot antenna was blocked by a mountain that was not in the path between the payload and the 30 foot antenna.

Predetection recording of Right Circular Polarization (RCP) and Left Circular Polarization (LCP) signals from the X-band ground tracking antenna were made at a predetection carrier frequency of 8 MHz. Predetection recording of the TGRS RCP S-band signal and the GPS L1 reference signal were made at the VAB. The three S-band receivers for RCP signals on the 30 foot antenna provided the automatic gain control voltage (AGC) outputs to an analog-to-digital converter card in a personal computer (PC) for logging signal strength values at 20 samples per second. The total bit error count and BER plots of the S-band links were made from demodulated data feeding link analyzer test sets in real time and logging the counts on a PC hard disk drive. The X-band total bit error count and BER plots were made by predetection signal playbacks to the demodulators after the flight.

G/T of the 30 foot antenna at S-band is typically 20 dB. The 30 foot antenna beamwidth is approximately 1 degree. G/T of the 8 foot antenna at 2250.5 MHz is typically 9 dB with 4 degree beamwidth and at 7975 MHz was measured at 16.2 dB with a 1.1 degree beamwidth. Actual flight trajectory was very close to the predicted trajectory with apogee near 60 km altitude and 40 km down range. The rocket speed at motor burnout was slightly above Mach 3.5 as predicted.

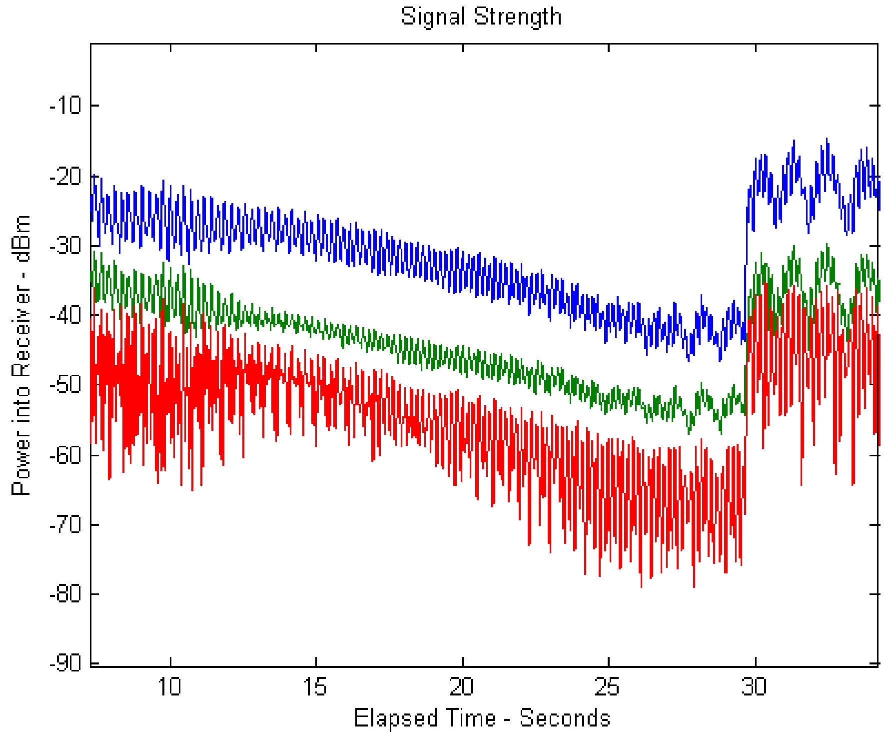
LAUNCH TEST RESULTS

Figure 7 is a plot of ground station receiver AGC voltage or link signal strength as measured at the 30-foot antenna ground station during the launch. Signal strength is measured as power into the receiver. This full mission duration signal strength plot shows the times of the major events. Signal strength decreases rapidly from ignition to motor burnout near T + 23 seconds and manual switch removal of 20 dB attenuation in front of the low noise amplifiers (LNA) when the antenna operator observes burnout. Signal strength changes little during the rest of the flight because the rocket is already at a long distance from the tracker. Signal perturbations from the aluminum strip covering the ends of the wraparound antennas cause deep periodic fades at the rocket spin rate of about 4.5 Hz. Post flight review quickly determined that the 1 millisecond (ms) AGC attack time followed by a 200 ms hold period before AGC release of the two microwave receivers used for the FQPSK-JR and ARTM CPM links showed the 4.5 Hz rate deep fades but could not resolve the amplitude of the fade. The Microdyne Model 1400-WB telemetry receiver AGC time constant was symmetrical for attack and decay times with no AGC hold period and shows much deeper fades. Figure 8 shows a shorter time period (ignition to motor burnout) than Figure 7 for better resolution of the fade durations. Plotting signal strength or AGC voltages was not sufficient to show the fade depths. MatLab processing of IF power showed deeper fades.



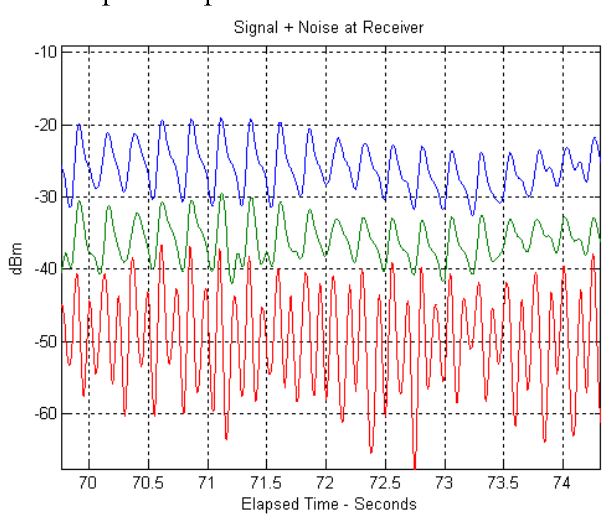
Top (blue): FQPSK-JR; Mid (green): ARTM CPM; Bottom (red): CPFSK

Figure 7: S-band Signal Strength Measured at the NASA 30-foot Antenna Receiver Input

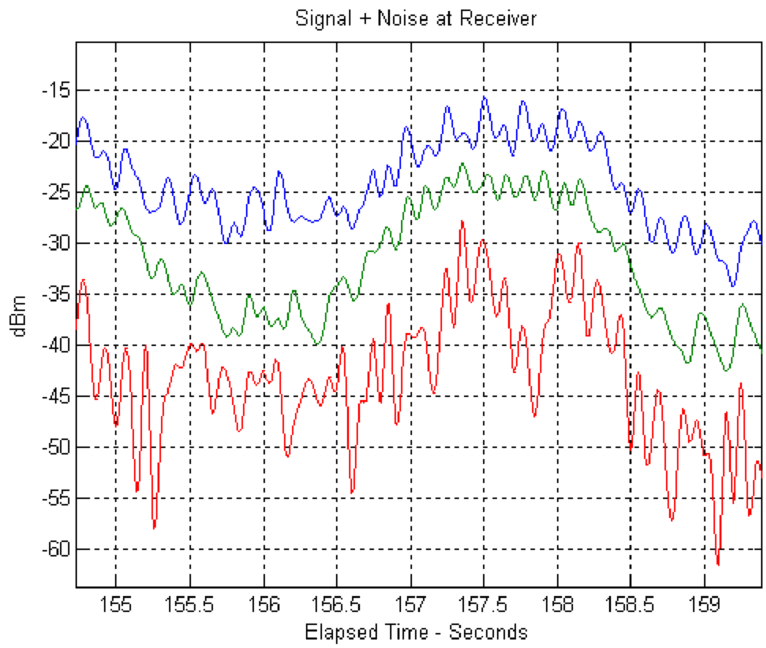


Top (blue): FQPSK-JR; Mid (green): ARTM CPM; Bottom (red): CPFSK
Figure 8: S-band Signal Strength Measured at the NASA 30-foot Antenna Receivers

The top two traces in Figure 9 show the microwave receiver 200 ms AGC hold feature prevents tracking the signal fades at the spin rate while the bottom trace without the 200 ms AGC hold feature more closely tracks the fast signal fade. Figure 10 is included to show there is no change in spin rate caused fades after rocket motor separation when the fins are clear of the payload. Rocket tumbling prevents a simple comparison of fins versus no fins.



Top (blue): FQPSK-JR; Mid (green): ARTM CPM; Bottom (red): CPFSK
Figure 9: S-band Signal Strength Measured at the NASA 30 Foot Antenna, Before Separation



Top (blue): FQPSK-JR; Mid (green): ARTM CPM; Bottom (red): CPFSK

Figure 10: S-band Signal Strength Measured at the NASA 30 Foot Antenna, After Separation

The sample rate of the AGC voltages was 20 samples per second. Post flight processing of the predetection (down converted intermediate frequency (IF) signal at 8 MHz center frequency) to calculate the in-band to out-of-band signal power produces signal plus noise over noise measurements that more clearly show the aluminum strip signal fades at the rocket spin rate in Figure 11. Figure 12 using the same post flight processing method on TGRS predetection data for an S-band antenna without the aluminum strip shows no spin rate fading.

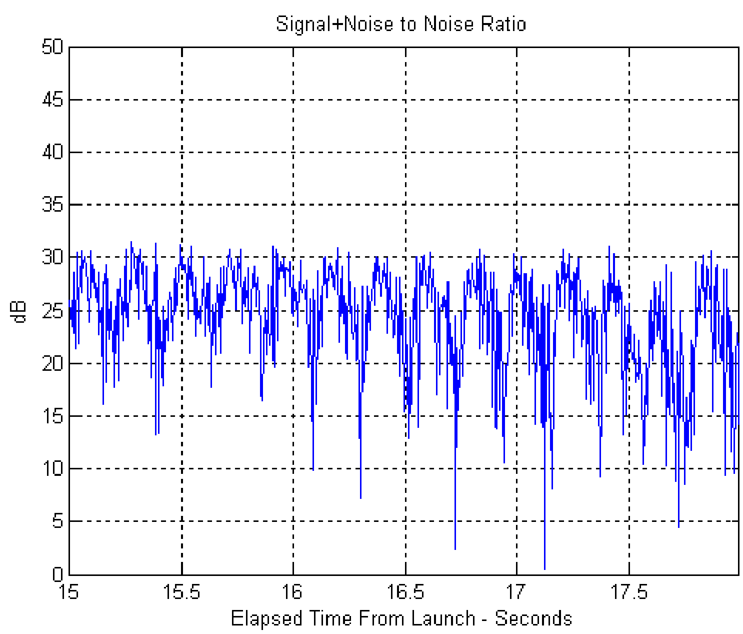


Figure 11: X-band Spin Rate Fades in (Signal + Noise)/Noise Measured at the 8-foot Antenna

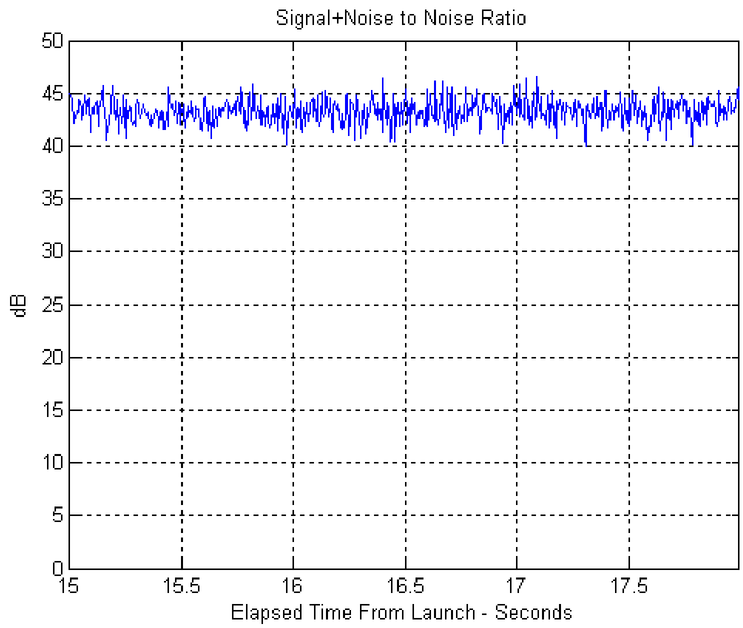


Figure 12: TGRS S-band (Signal + Noise)/Noise Measured at the 30-foot Antenna

The lengthy signal strength and (S+N)/N descriptions were necessary to show the fast, deep fades caused by the aluminum strip covering the antennas. These fades are confirmed as shorter than one inch strip width divided by the circumference of the rocket but still sufficient to cause demodulator loss of lock confirmed by all three S-band real-time link analyzers that showed loss of PRBS pattern lock at each revolution. The main point is that the demodulators quickly reacquired the signal when (S+N)/N was sufficient. Figure 13 shows the accumulated bit error count history for all three types of modulation. To compare the three types of modulation the two 20 Mbs PCM stream errors were divided by two to normalize the bit error count to the 10 Mbs PCM stream bit error count. The FM demodulator is a multi symbol detector rather than a single bit hard decision detector but has a signal acquisition time much faster than the FQPSK-JR and ARTM CPM coherent signal demodulators. The total bit error accumulation in millions of bits is quite low considering the spin rate deep fades due to the aluminum strip. All three links show a large total error count increase at ignition but then a very slow increase throughout the remainder of the flight. In fact, the error accumulation slope tends toward zero increase after de-spin by the parachute deployment. The similar slopes of the three curves indicate similar fast demodulator re-acquisition of the signal after a fade. An important point to remember is that FQPSK-JR uses differential encoding per RCC recommendations where two bits will be in error for each actual symbol error due to the coding scheme.

Plots of the link analyzer PRBS pattern synchronization appear very similar to PCM frame synch lock from a decommutator to show all the S-band links are nearly error free throughout the flight. Link availability and error free seconds are very high [3] as a direct result of fast demodulator re-acquisition on all three S-band links. See [4] for detailed acquisition measurements with and without FEC coding.

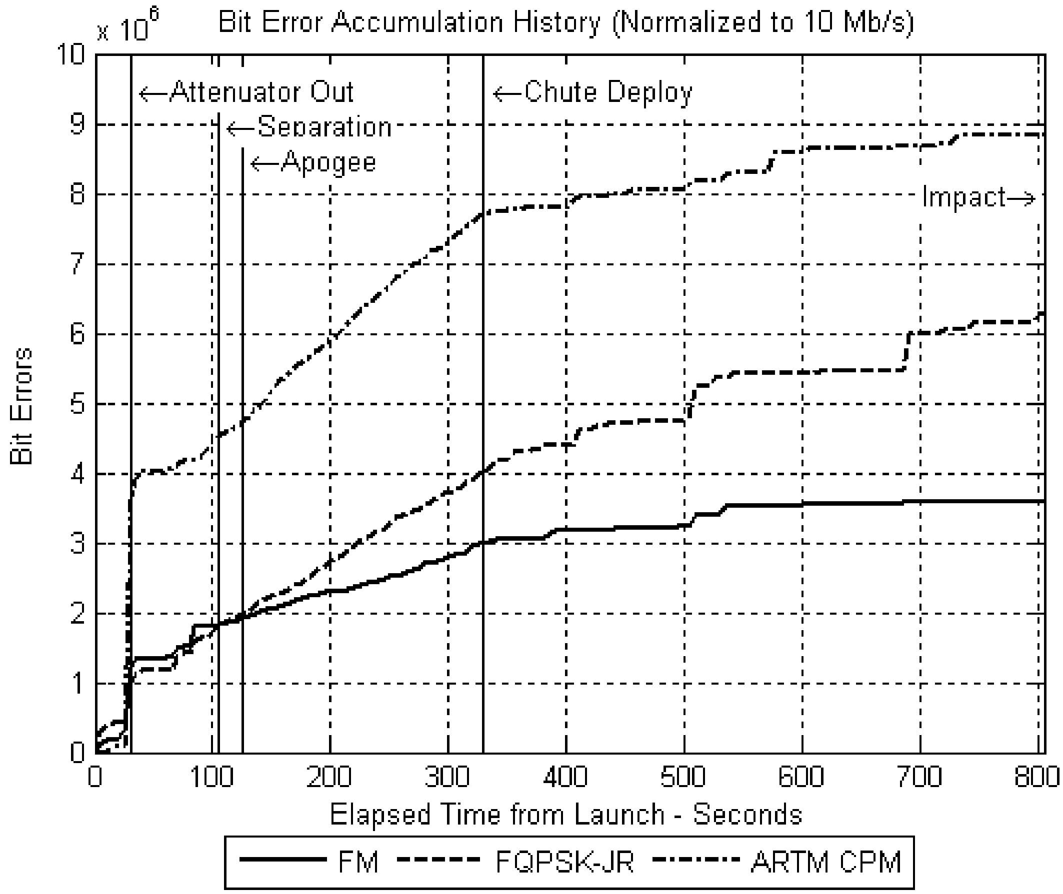


Figure 13: S-band Bit Error Accumulation History Measured at the NASA 30-foot Antenna

CONCLUSIONS

1. Transmission bandwidth is significantly reduced from CPFSK to FQPSK-JR and from FQPSK-JR to ARTM CPM.
2. The IRIG 106-05 Appendix A RF Considerations carrier selection calculation methods are excellent and were proven by bit error rate measurements and spectrum measurements.
3. Demodulator acquisition time for higher order modulation formats such as QPSK was sufficiently fast for a high dynamics vehicle signal perturbations including plume, separation, maneuvering, tumbling and high spin rate blockage. Mitigation techniques such as side look and multiple tracking sites are often used to avoid these signal perturbations.
4. The Telemetry Working Group (TWG) of IRIG has been methodically revising and adding new standards and test methods for the advanced types of modulation and new generation of telemetry receivers and demodulators. Use of these new capabilities has already begun at several test ranges and common standards are available for mission planning for joint range activities.

ACKNOWLEDGEMENTS

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