PERFORMANCE CHARACTERIZATION OF MULTI-BAND ANTENNAS FOR AERONAUTICAL TELEMETRY

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ABSTRACT

This paper baselines the performance of common, single band telemetry blade antennas in two telemetry bands and compares that performance to two very differing multi-band antenna designs. A description of each antenna is presented followed by flight testing results and conclusions. Results are in the form of received signal strength versus geographic location, derived in-flight antenna patterns, link availability, and bit error analysis.

KEY WORDS

integrated Networked Enhanced Telemetry (iNET), multi-band antenna, global positioning system, antenna patterns

INTRODUCTION

Test programs that transmit flight test data have long needed the flexibility to transmit in any portion of the available aeronautical telemetry spectrum 1435-1525MHz (lower L-Band), 1755-1850MHz (upper L-Band), 2200-2290MHz (lower S-Band), 2360-2395MHz (upper S-Band) in order to mitigate spectrum crowding prevalent at many of the major test ranges. This paper deals with the airborne telemetry antenna, one of the key elements of this transmission chain.

Classical telemetry systems usually employ band specific blade antennas of the monopole variety for aeronautical telemetry applications. While a viable method of transmitting the telemetry signal, the band of operation is usually limited to only one of the three currently available bands for aeronautical mobile telemetry. Two separate efforts were undertaken to attack this dilemma from two differing perspectives.

The first effort was a multi-year Small Business Innovative Research (SBIR) contract with Toyon Research Corporation. The focus of the initial work was to develop a flight qualified L-Band telemetry antenna with a shaped radiation pattern. The shaped pattern created a null which could be oriented in the direction of nearby Global Positioning System (GPS) antennas to improve isolation and thereby limit Radio Frequency Interference (RFI) to GPS systems operating on the L1 frequency of 1575.42 MHz [1]. Antenna size, weight and ease of installation were all considerations to be optimized as well. Since the location of nearby GPS antennas varies from aircraft to aircraft, the antenna had to allow for pointing of the null in any azimuth direction. The resulting prototype antenna performed well so an enhancement effort was undertaken to expand frequency coverage to include the other telemetry bands while still maintaining the GPS null and physical properties of the L-Band only antenna.

The second effort was through the Science and Technology, Spectrum Efficient Technology initiative (S&T SET) in support of the integrated Network Enhanced Telemetry (iNET) program. This contract was through NuRad Technologies which included a two-phased effort of providing a multi-band antenna first, followed by a quadrant steering multi-band antenna. The multi-band offering was an off-the-shelf unit with a specified frequency range of 0.5-3.0GHz.

The antennas used as a reference for both multi-band antennas were standard airborne blade antennas available through several manufacturers. In this case, the lower L-Band antenna was manufactured by Tecom (model 101002A) and the S-Band antenna was manufactured by Haigh-Farr (model 6030-2). Figure 1 shows all four antennas. The antennas were mounted to an interchangeable doubler plate required for installation onto the test aircraft as shown on the Toyon and two reference blade antennas. In this figure, NuRad antenna is shown installed on the aircraft. Figure 2 shows the antenna installation location on the aircraft, in this case the NuRad antenna is installed. All of these antennas are linearly polarized.

Figure 1 – Airborne Antennas

Figure 2 – Aircraft Antenna Installation Location

In order to assess antenna performance, a series of flight test were structured and conducted utilizing the airspace within Edwards AFB and China Lake NWC known as restricted area 2508 (R2508). A description of the aircraft and ground systems and flight test points are described below.

AIRCRAFT AND GROUND STATION SYSTEM DESCRIPTION

In order to accomplish the flight test points described below, a system had to be configured to carry out the testing. This system was broken into two parts, the airborne system and the ground station system.

A Beechcraft C-12 was configured with a transmit system to transmit known data from each test antenna located on the bottom of the aircraft. The system utilized a 5W (Quasonix LLC), multimode test transmitter (one for L-Band and one for S-Band) transmitting a 5Mbps, 2^{11}-1 pseudo-random bit sequence (PRBS). The modulation mode selected for all of the testing was Shaped Offset Quadrature Phase Shift Keyed – Telemetry Group version (SOQPSK-TG). The outputs of both the lower L-Band transmitter and S-Band transmitter were measured and matched. The output of the test transmitter was then routed through an isolator network (one for L-Band operation, one for S-Band operation) and then sent to the external test antenna.

The ground station consisted of a 5 meter receive antenna with tracking capabilities. An RCB2000 (L3 Communications Telemetry East) telemetry receiver was connected to left hand and right hand circular polarizations from the antenna. The received intermediate frequency (IF) for channel 1 and channel 2 were sent to external RF Networks 2120 demodulators. The combined channel was demodulated by the internal RCB2000 demodulator. Data and clock outputs from each demodulator were sent to separate Fireberd 6000A bit error analyzers. Error statistics were polled on 10 second intervals from each of the Fireberds via the IEEE-488 communication bus. In addition to bit error logging, receiver automatic gain control (AGC) levels from CH1 and CH2 were also sampled at a 20Hz rate and recorded. Prior to flight testing, receiver AGC levels were calibrated with existing bore sight capabilities to give a direct reading of signal to noise ratio (SNR) from the AGC values. A block diagram for both transmit and receive systems is shown in Figure 3.

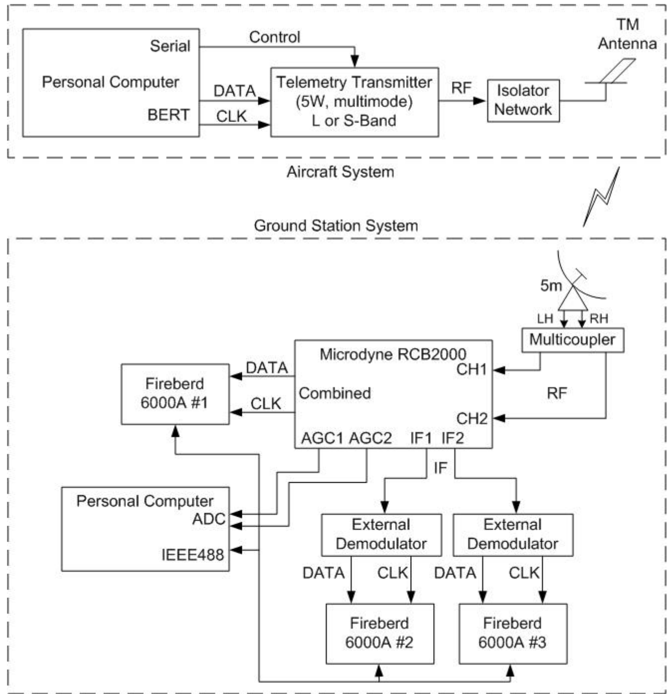


Figure 3 – Aircraft and Ground Station Block Diagram

FLIGHT TESTING DESCRIPTION

Test points were developed to characterize the performance of the L-Band and S-Band reference blade antennas and then compare that to the performance of the two multi-band antennas. Two test points for each antenna configuration were flown to fully characterize antenna performance in a simulated test scenario. The first point, BER1, was a flight path known as Cords Rd. This path is known to support multipath and has been well characterized by the Advanced Range Telemetry (ARTM) program. Also, this flight path provided nearly 360 degrees of look angles (at nearly a constant elevation angle) from the receive antenna which characterized aircraft antenna coverage. Flight path was approximately 83NM with the longest slant range being 61NM. Altitude for this test point was a constant 5000 feet MSL with a constant speed of 200 knots. The test point had two elements, a west to east path (BER1 W-E) and the return east to west path (BER1 E-W). The second test point, LR1, was meant to characterize a different part of the antenna pattern with a different look angle to the aircraft. This test point started at 4500 feet MSL and climbed directly away from the receive antenna to 20,000 feet MSL @ 1500fpm. Once at 20,000 feet the aircraft leveled off and continued at that altitude at 160 knots to the end of the test point (LR1 S-N). The return path was just the opposite of the outbound path (LR1 N-S). Flight path was approximately 90NM with the longest slant range being 90NM. It should be noted at this time that the Toyon antenna with the L-Band antenna pattern notch was directed towards the front of the aircraft. See Figure 4 for a map representation of the test points and flight paths.

Six flights were flown to derive baseline performance for the reference blade antennas in both L-Band (Flight 104) and S-Band (Flight 105), test the Toyon antenna in L-Band (Flight 107) and S-Band (Flight 106), and finally test the NuRad antenna in L-Band (Flight 109) and S-Band (Flight 108). For all of the testing, the L-Band frequency was centered at 1470.5MHz (lower L-Band) and the S-Band frequency was centered at 2350.5MHz (lower S-Band).

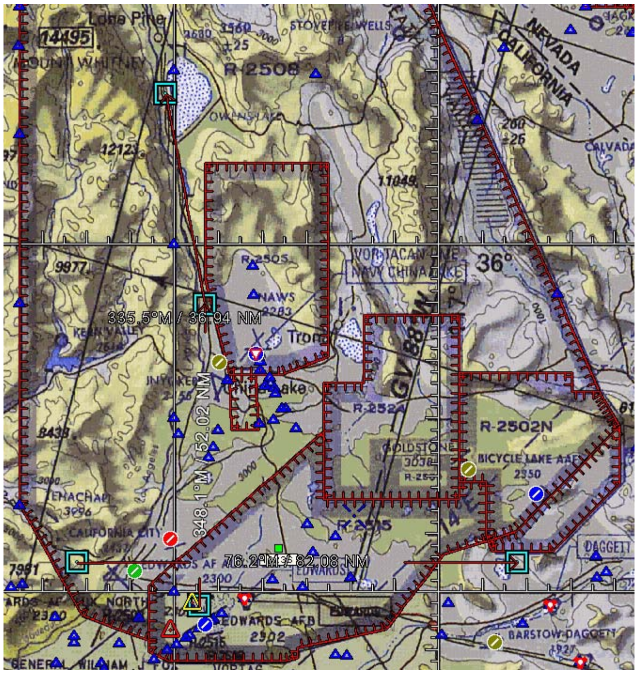


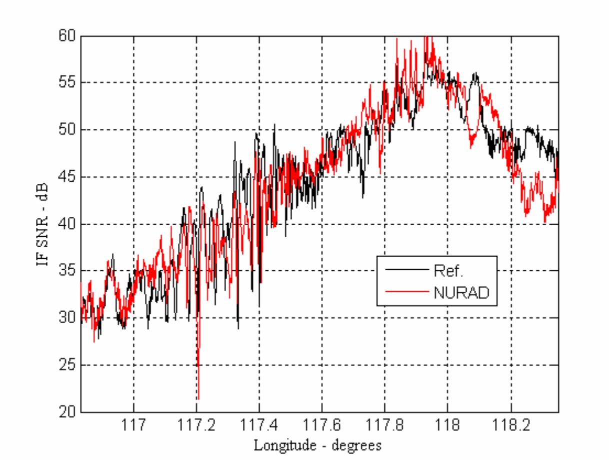
Figure 4 – Test Points

TEST RESULTS

Test results are grouped into two categories, RF data and bit error data. The RF data consists of received SNR versus aircraft location and derived antenna patterns. The bit error data consists of link availability, average bit error rate (BER), and total bit errors for each test point.

Signal to Noise Ratio versus Location

Baseline signal to noise ratio numbers were calibrated versus AGC values and recorded prior to flight testing. This calibration information was then used to derive the plots in Figures 5 and 6 based upon recorded AGC values and aircraft position correlated in time. Figure 5 relates the NuRad antenna to the reference blade in L-Band and S-Band on two passes of test point BER1. Note the traces on both graphs nearly overlap illustrating that pattern performance is nearly identical in both bands. Figure 6 shows the Toyon antenna plotted against the reference blade. In Figure 6a, during the BER1 W-E test point, the Toyon suffers by approximately 10dB throughout the test point. Also note the dramatic fall off of SNR near a longitude of 118. This is expected due to the receive antenna looking into the L-Band pattern notch of the antenna. In Figure 8b in S-Band, the Toyon exhibited better performance than the reference blade. Also, note the step in SNR. This occurred when the aircraft transitioned from straight and level flight at 20,000 feet to a slight pitch-down attitude of roughly 3 degrees. From this point to the end point note that the pattern of the Toyon antenna is roughly 3dB better when looking at the nose of the aircraft.



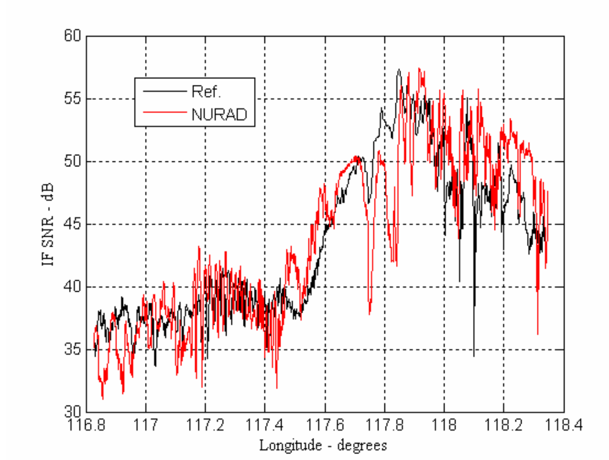
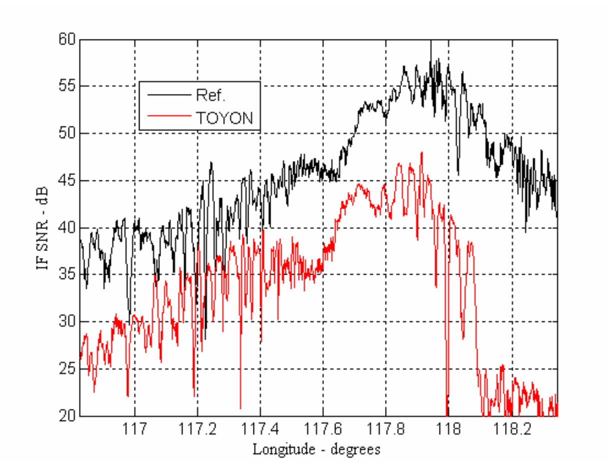


Figure 5a – SNR vs. Position (L-Band/BER1 E-W) Figure 5b – SNR vs. Position (S-Band/BER1 W-E)



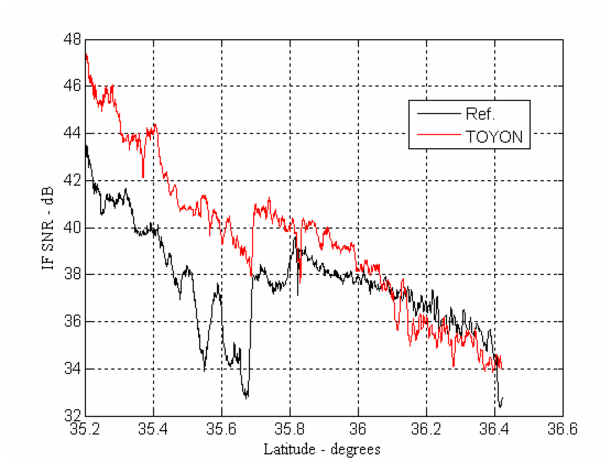


Figure 6a – SNR vs. Position (L-Band/BER1 W-E) Figure 6b – SNR vs. Position (S-Band/LR1 N-S)

Antenna Patterns

Coarse antenna patterns in the aircraft yaw plane were constructed from receiver IF SNR, receive antenna pointing angle, and aircraft position data from the BER1 runs. The range of receive antenna look angles on reciprocal headings of BER1 provided nearly complete coverage of the yaw plane as shown in figures 7 and 8. IF SNR was normalized assuming a free space incremental distance d, attenuation factor of $1/d^2$ relative to the IF SNR measured at the closest approach, or shortest slant range d_0. The aircraft yaw plane was viewed at very shallow angles ranging from 0.3 to 1.7 degrees. Slant range varied from 11NM to 58NM. Figure 7 compares the reference blades to the NuRad antenna. Performance is comparable in both frequency bands. The average IF SNR of each antenna was 52dB in Figure 7a and 51dB in Figure 7b confirming that under these conditions the performance of both antennas is practically identical. Figure 8a clearly shows how the Toyon design reduces energy at angles ranging from approximately 310 to 70 degrees. Figure 8b reveals a more uniform S-band pattern for the Toyon antenna, but the average normalized IF SNR was 45.5dB, about 6dB lower than the reference and NuRad antennas.

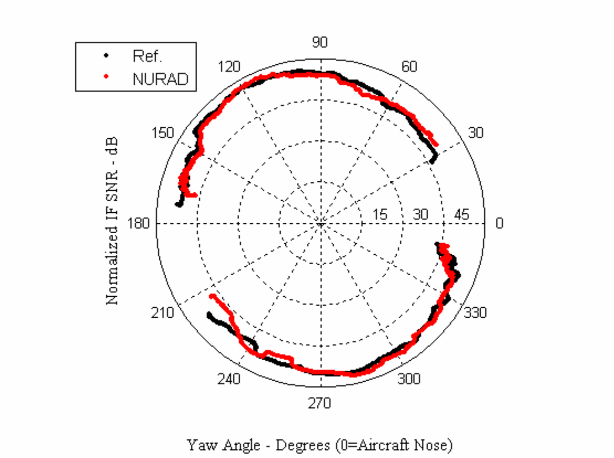


Figure 7a – NuRad L-Band Antenna Pattern

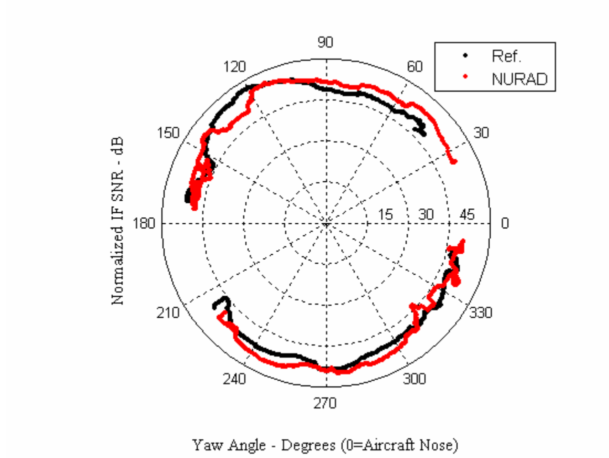


Figure 7b – NuRad S-Band Antenna Pattern

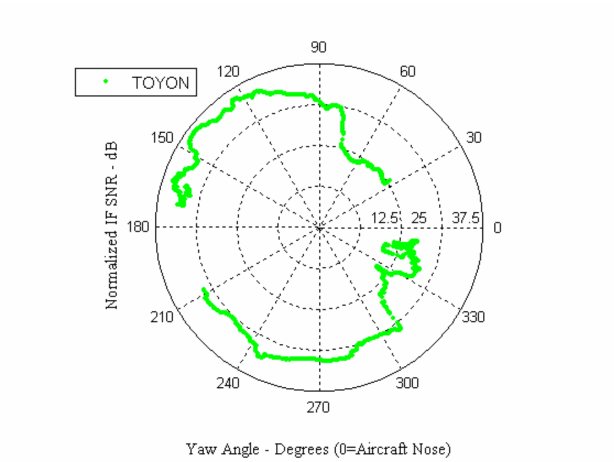


Figure 8a – Toyon L-Band Antenna Pattern

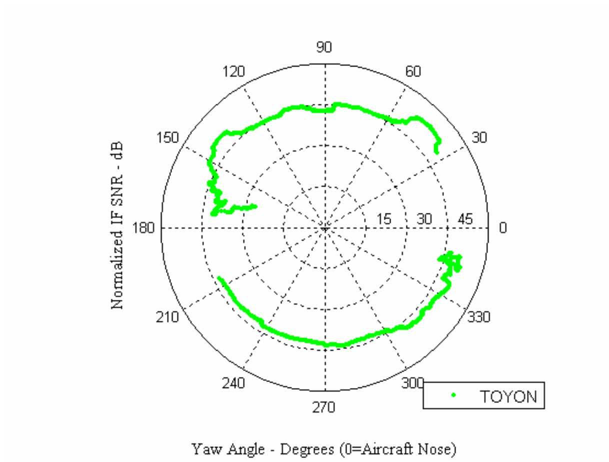


Figure 8b – Toyon S-Band Antenna Pattern

Link Availability

Based upon the error statistics captured on each test point, link availability (LA) was calculated. Referring back to Figure 3, we'll notice that error statistics were captured for both receive antenna polarizations and the combined signal. LA was calculated for all three conditions on all of the test points. The definition of LA for these series of tests is shown below in Equation 1.

$$LA(\%) = \left[\frac{TotalRunTime - SeverelyErroredTime}{TotalRunTime} \right] \times 100\% \qquad \text{Equation 1}$$

TotalRunTime – Total length of the test point or interval of interest

SeverelyErroredTime – 10 second interval where bit error rate $\geq 1 \times 10^{-3}$

Tables 1 through 3 show LA numbers for the reference blade antennas, Toyon antenna, and finally the NuRad antenna. Columns where N/A appears means no numbers are available due to system anomalies or other circumstance.

Table 1 – LA for Blade Antenna Baseline

Flight 104, L-Band Baseline				**Flight 105, S-Band Baseline**			
Run	RHCP	LHCP	Combined	Run	RHCP	LHCP	Combined
LR1 S-N	100	100	100	LR1 S-N	100	100	N/A
LR1 N-S	100	100	100	LR1 N-S	100	100	100
BER1 W-E	91	92	91	BER1 W-E	97	99	99
BER1 E-W	90	90	92	BER1 E-W	92	93	93

Table 2 – LA for Toyon Antenna

Flight 107, Toyon L-Band				**Flight 106, Toyon S-Band**			
Run	RHCP	LHCP	Combined	Run	RHCP	LHCP	Combined
LR1 S-N	100	100	100	LR1 S-N	N/A	N/A	N/A
LR1 N-S	48	53	74	LR1 N-S	100	100	100
BER1 W-E	71	81	87	BER1 W-E	85	93	96
BER1 E-W	73	75	80	BER1 E-W	68	71	73

Table 3 – LA for NuRad Antenna

Flight 109, NuRad L-Band				**Flight 108, NuRad S-Band**			
Run	RHCP	LHCP	Combined	Run	RHCP	LHCP	Combined
LR1 S-N	100	100	100	LR1 S-N	100	94	100
LR1 N-S	100	100	100	LR1 N-S	100	100	100
BER1 W-E	94	94	95	BER1 W-E	96	94	96
BER1 E-W	92	92	93	BER1 E-W	93	91	97

Link availability numbers for the reference blade antennas are very typical numbers for SOQPSK-TG at 5Mbps over these test points as characterized by the ARTM Program. Each test with column values less that 100% experienced some type of catastrophic multipath event while tests with column values at 100% experienced much less severe multipath events.

Link availability numbers were very good for the NuRad antenna in both bands and track the reference blade antenna results very well. The LA data in tables 1 and 3 are typical of what previous experiments have shown on these flight paths with 5 Mbps transmissions. The S-band LA numbers are slight better than their L-band counterparts. This is due to multipath reflected ray power reduction in the narrower beam of the receive antenna at the higher frequency.

Link availability suffered on the Toyon antenna on the LR1 N-S test point due to the deliberate L-Band antenna null for GPS isolation purposes. As previously mentioned, the null was oriented forward on the aircraft which, for this point, resulted in the receive antenna looking right at the nulled pattern.

Bit Error Data

During each test point for all of the flights, bit error data was polled and logged. Bit errors were monitored for both right-hand and left-hand circular polarizations (RHCP, LHCP) in addition to the combined output. In this testing, pre-detection Optimal Ratio Combing (ORC) [3] was used to combine right and left-hand circular polarizations. Figures 9 and 10 show total bit errors recorded for the reference blade and NuRad antennas for all three receive configurations on both directions of the BER1 test point.

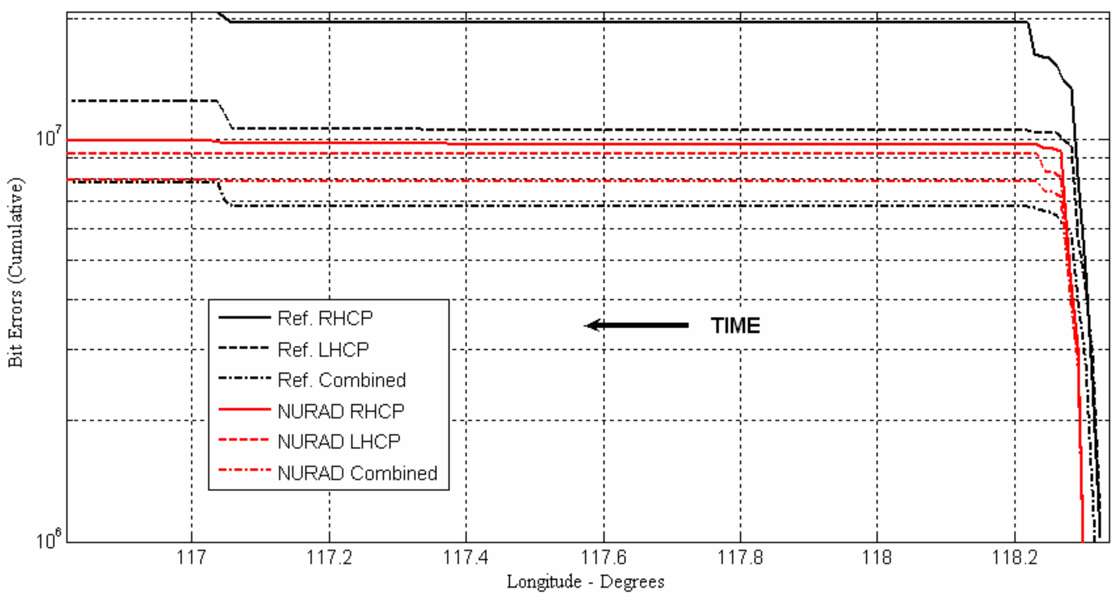


Figure 9 – Bit errors vs. Receive Antenna Polarization (L-Band BER1 W-E)

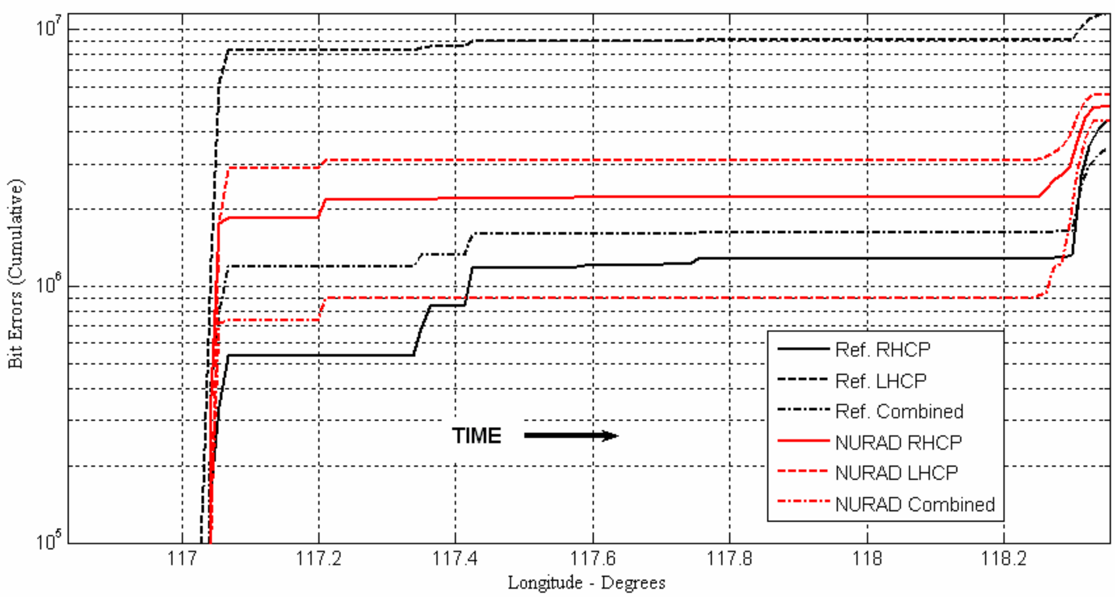


Figure 10 – Bit errors vs. Receive Antenna Polarization (L-Band BER1 E-W)

These graphs are very informative and shed light on the characteristics of this particular aeronautical telemetry channel. It is clear for these test points that link margin is not an issue otherwise gradual increases in bit errors would be observed at each end of the graphs. Notice there are long, error free intervals between error events. When these error events do occur, they are usually catastrophic causing a large number of bit errors usually associated with demodulator synchronization loss. Comparing bit errors versus polarization we do not see any diversity exhibited, i.e. the error events occur at the same time on both receive polarizations. Channel sounding measurements on BER1 have shown that the dominant channel impairment is 2-ray specular multipath propagation. At 5 Mbps the excess propagation delay is less than 5% of the SOQPSK-TG symbol period. Thus, the fading is essentially flat and the major fade events are coincident and deep. The fact that pre-detection combining recovers somewhere between 2 and 3dB of the 3dB polarization loss suffered by the individual channels accounts for the small system performance advantage seen in tables 1 and 3, as well as figures 9,10, and 11.

Figure 11 illustrates bit errors averaged over the length of the test point for right hand and left hand circular receive polarizations and the combined signal versus the exact same test point as in Figures 9 and 10. When comparing Figure 11 with Figures 9 and 10, it is observed that data do not correlate. For this channel, long error free intervals are interrupted by multipath events lasting as long as seconds [4, 5] causing demodulator resynchronization and large error tallies. These events negatively bias the average bit error rate numbers. For this transmission channel, average bit error rate is not a good measurement of link performance.

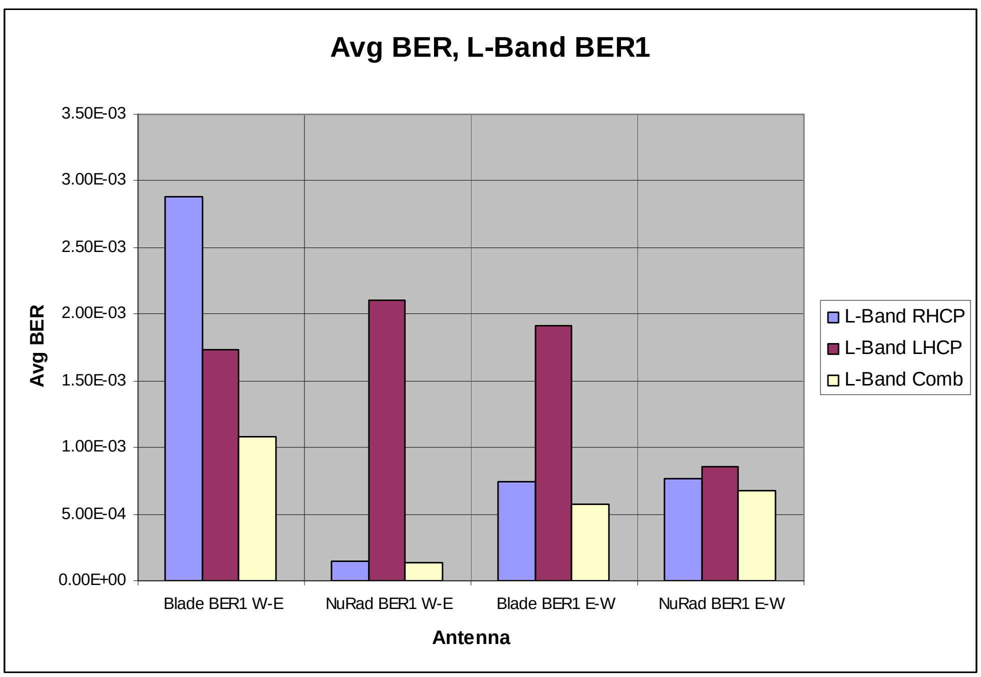


Figure 11 – Average Bit Errors vs. Receive Antenna Polarization (L-Band BER1)

CONCLUSIONS

- Performance of the Toyon antenna was limited by the constraints placed on its design. The requirement to utilize the same physical structure and maintain a pattern null resulted in weaker performance on L-Band and at low elevation angles. A taller antenna without the internal parasitic elements for pattern shaping would certainly have yielded a cleaner pattern but would not have met the objectives of the SBIR under which it was initially developed.

- SNR information, derived antenna patterns, and bit error analysis all lead to the conclusion that the NuRad multi-band antenna performed very well and in some instances better than the reference blade antennas.
- The telemetry channel in which these tests were conducted can be characterized as multipath limited causing large tallies of bit error during discrete times. The channel is typically not noise limited.
- Average bit error rate is not a good metric to use to characterize system performance in this aeronautical channel. Long error-free intervals are observed interrupted by catastrophic multipath events rendering an averaging method painting an incomplete picture.
- For this transmission channel, theoretical gains normally associated with optimal ratio combining were not observed.
- Both multi-band antennas are viable solutions based upon the need of the end user.

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