

# Estimating the Characteristics of the Aeronautical Telemetry Channel during Bit Error Events

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## ABSTRACT

This paper presents estimated aeronautical telemetry channel characteristics during bit error events. A T-39 aircraft was flown around various test corridors while transmitting a filtered 10 Mb/s pseudo-noise (PN) sequence binary phase shift keying (BPSK) signal. The received signal was down converted to 70 MHz, digitized when trigger criteria were met, and stored for later analysis. Received signal strength was also recorded. The first step in data analysis consisted of dividing the fast Fourier transform (FFT) of the recorded signal by the FFT of the expected signal. The received signal strength data was then used to correct for flat fade effects. The resulting signal is the difference (dB) between the expected signal at the receiver intermediate frequency (IF) output and the measured receiver IF output during the error event. This difference is the aeronautical telemetry channel characteristic. The characteristics of this difference signal were then matched against a 2-ray and 3-ray multipath fading model with reflected signal amplitude and path delay as the variables.

## KEY WORDS

Multipath, telemetry channel, bit errors

## BACKGROUND

One challenge facing the aeronautical telemetry community is how to improve data quality while simultaneously accommodating increased bit rates. A good understanding of the cause and distribution of bit errors is critical to understanding the various phenomena causing the errors and minimizing their effect. The Advanced Range Telemetry (ARTM) program has undertaken a series of test flights to collect data

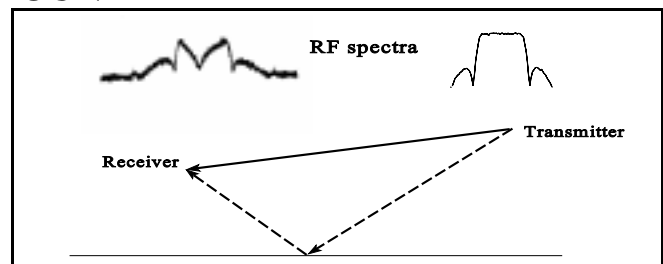


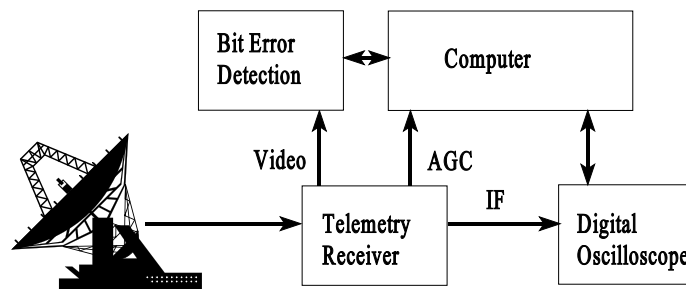
Figure 1. Multipath diagram.

to help understand the problem. The typical aeronautical telemetry channel includes a line-of-sight path between the transmitter and receiver and may also include one or more indirect paths as illustrated in figure 1. The radio frequency (RF) spectrum above the transmitter illustrates a pulse code modulation (PCM)/frequency modulation (FM) signal being transmitted and the spectrum above the receiver shows the signal being received. This received spectrum illustrates the effects of relatively short delay multipath with the indirect signal amplitude being nearly the same amplitude as the direct signal. The depth of the null relative to the expected direct signal power at the same frequency is a measure of the ratio of the amplitude of the indirect and direct paths ( $b$ ). The shape of the null is a function of the amplitude ratio and the difference in the time of arrival of the two signals ( $\tau$ ). The normalized vector sum of the direct and indirect signals as a function of frequency can be calculated using equation (1) where the phase angle between the two signals is  $-2\pi f\tau + \theta$  where  $\theta$  represents the phase shift associated with the reflection.

$$v(f) = 10 \log(1 + b^2 + 2b \cos(2\pi f\tau + \theta)) \quad (1)$$

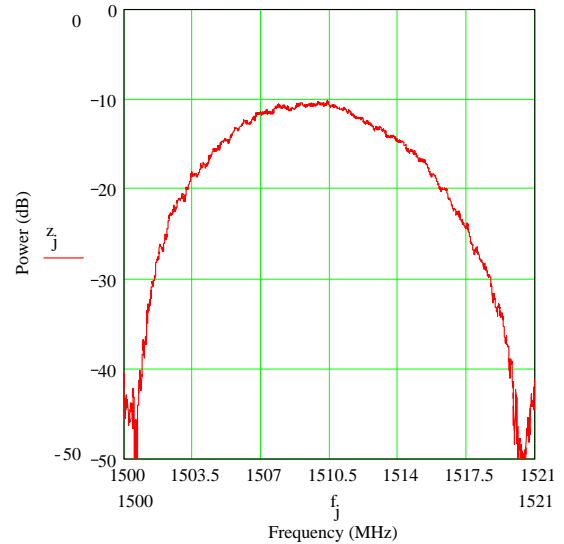
### TEST DESCRIPTION

The transmitter included a 10 Mb/s PN source, a lowpass filter, a BPSK modulator, a linear power amplifier (output about 2 watts), and a nearly omnidirectional antenna mounted on the bottom of the T-39 (top and bottom antennas were used for some flight tests). The receiving system (see figure 2) included an autotracking antenna (typically eight-foot diameter); a wideband telemetry receiver with linear 70 MHz IF and BPSK demodulator outputs; a bit error detector; a digital oscilloscope; a trigger circuit; and a computer. The received signal strength was logged by digitizing the receiver's automatic gain control (AGC) output. The received data was time tagged using a global positioning system (GPS) receiver. The T-39 position was logged on-board the T-39 for correlation with the data recorded at the receiving site.



**Figure 2.** Receiving system.

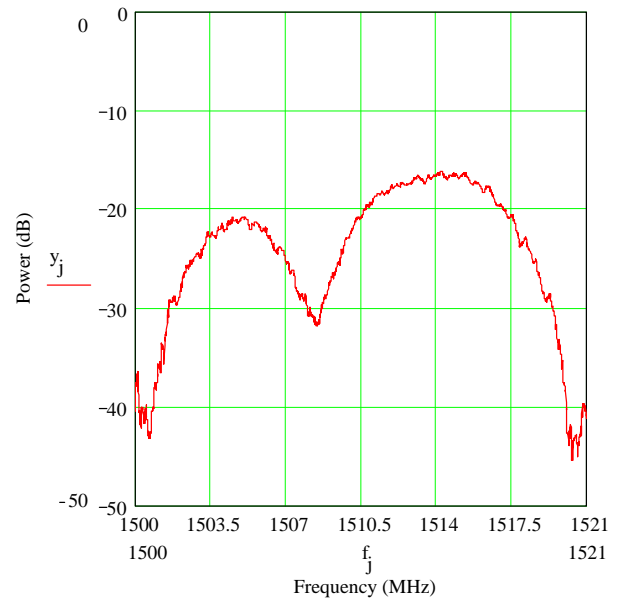
The expected signal is illustrated in figure 3. Figure 3 is the result of taking an FFT of the signal at the receiver IF output with the 10 Mb/s BPSK signal as the input under laboratory conditions. The FFT results were smoothed across frequency to minimize noise. The FFT length was equal to one PN cycle which for this example was 2047 bits. The frequency scale was plotted with actual transmitter frequencies.



**Figure 3.** FFT of expected signal.

### LABORATORY TESTS

Tests were performed with known fading parameters to check out the multipath parameter estimation routine. Figure 4 shows the spectrum with a 20 dB fade ( $b=0.9$ ), a 24 ns delay, and a null 2 MHz below center frequency. The multipath simulator was a Hewlett-Packard 11757B fade simulator. Figure 5 shows the overlay of the measured channel transfer function and a near best fit estimate. In this case the estimate was  $b=0.9$  and  $\tau=26$  ns. For delays less than about one over the bit time, in this case less than 100 ns, a 3 dB error in estimating the depth of the null results in about a 30 to 50% error in the value of the delay. For example, if the reference power level was in error and the null was estimated as 23 dB then  $b=0.925$  and  $\tau=18$  ns; if the null was estimated as 17 dB as shown in figure 6 then  $b=0.85$  and  $\tau=39$  ns. Obviously, if the delay is small, accurate estimation of the

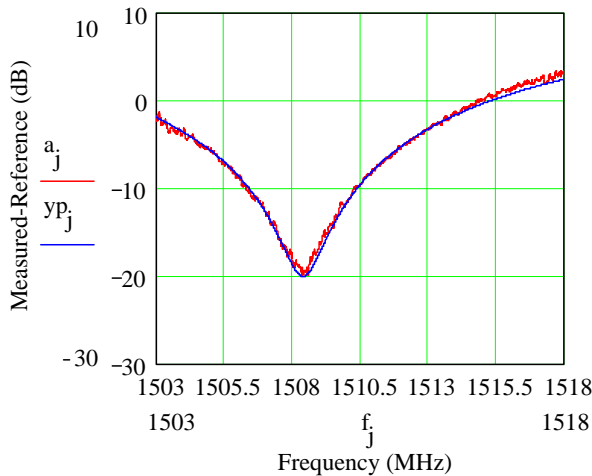


**Figure 4.** FFT of signal with lab fading.

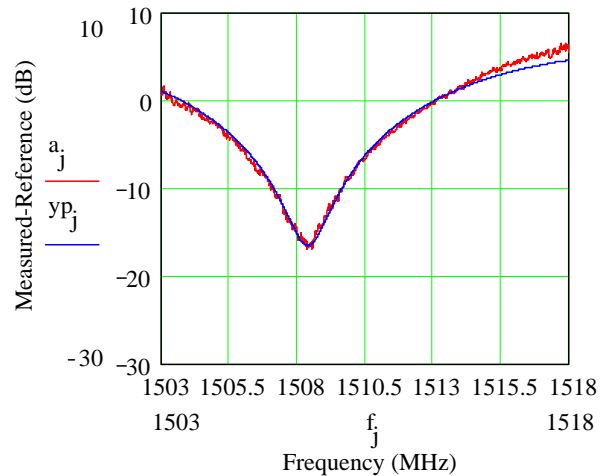
null depth is critical to accurately estimating the delay. An accurate null depth estimate is not critical for accurate delay estimation for delays longer than 1 bit time.

### FLIGHT TESTS

Several flight tests have been conducted over the major test corridors at Edwards AFB, CA at both low and relatively high altitudes. The worst multipath fading occurs on the low altitude flights (as would be expected). The signals were received at Building 5790 which is the main Edwards AFB telemetry receiving site. Flights have been conducted in both the 1435-1525 MHz (commonly called L-band) and the 2310-2390 MHz (commonly called upper S-band) bands. The results in the two bands are similar with one difference being more fading events at the higher frequency band (again as would be expected because of the shorter wavelength). Two flight tests have also been conducted over water at the Pacific Missile Range, Point Mugu, CA. The receiving site for these tests was Laguna Peak. The results presented in this paper are from the first channel sounding flight at Edwards AFB. The test corridor was Cords Road and the flight altitude was about 1300 to 1600 meters. The data were collected as follows: the trigger event was 16 bit errors, when the trigger event occurred the digital oscilloscope captured 10 segments of 100,000 points each at a sampling rate of 200 Ms/s with a segment spacing of 100 ms.



**Figure 5.** Lab fade (red) + estimate (blue).

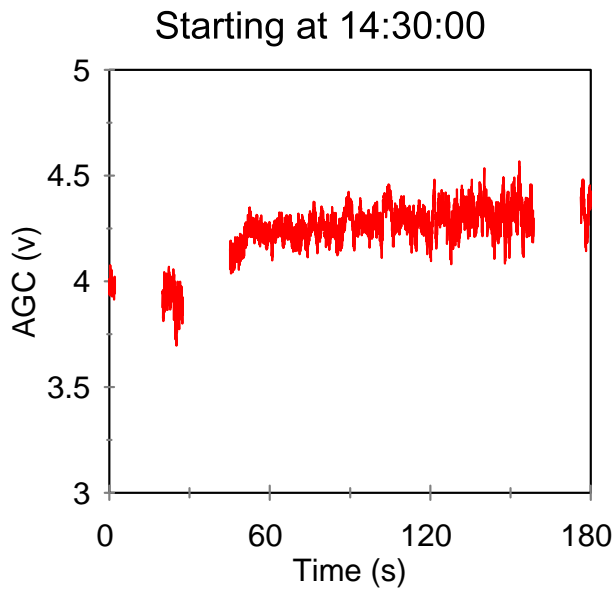


**Figure 6.** Lab fade with 3 dB null depth error.

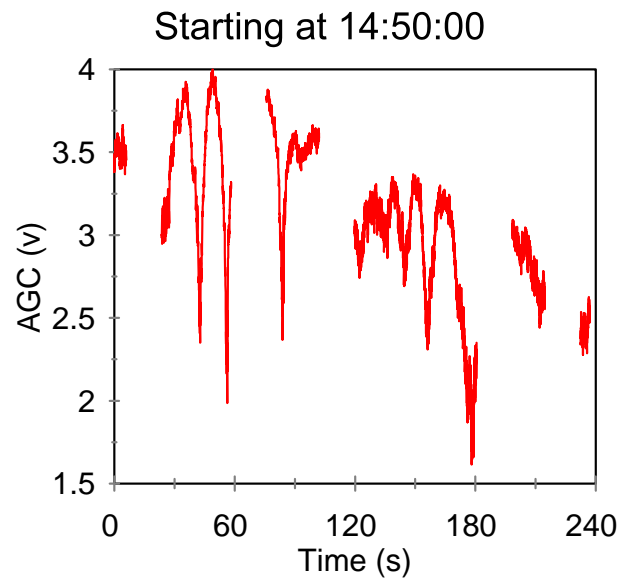
### FLIGHT TEST DATA

Figures 7 and 8 present the AGC values for two portions of the first ARTM channel sounding flight. The blank portions occur because AGC data was not recorded when digital oscilloscope data was being transferred to the computer. The calibration of this

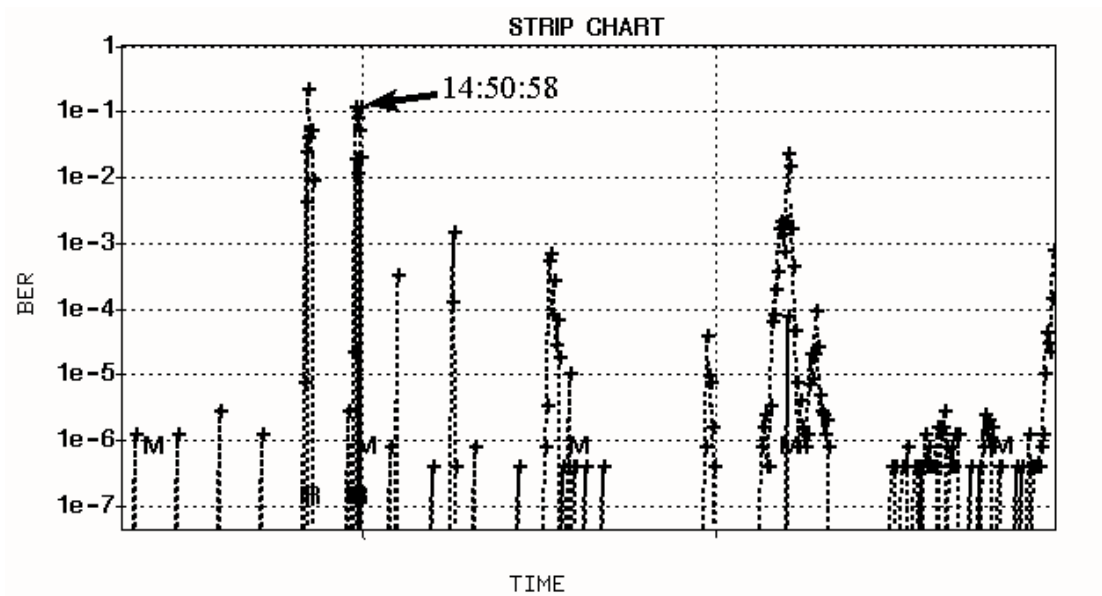
AGC data is: 1.4 volts=0 dB IF SNR, 1.8 volts=12 dB IF SNR, 2.8 volts=24 dB IF SNR, 3.8 volts=36 dB IF SNR. The three intervals where data will be analyzed in this paper are just before the 2<sup>nd</sup> and 3<sup>rd</sup> gaps in figure 7 and just before the 2<sup>nd</sup> gap in figure 8. The T-39 was approximately north-northeast of the receiving site flying West during the interval of figure 7 and northeast of the receiving site flying East during the interval of figure 8.



**Figure 7.** AGC plot (14:30).

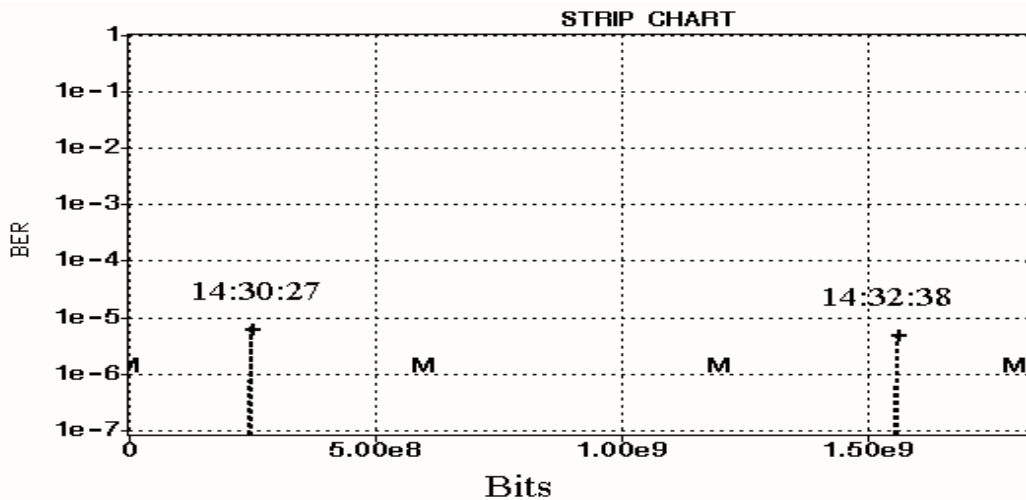


**Figure 8.** AGC plot (14:50).



**Figure 9.** BER versus time for interval 14:50 to 14:54.

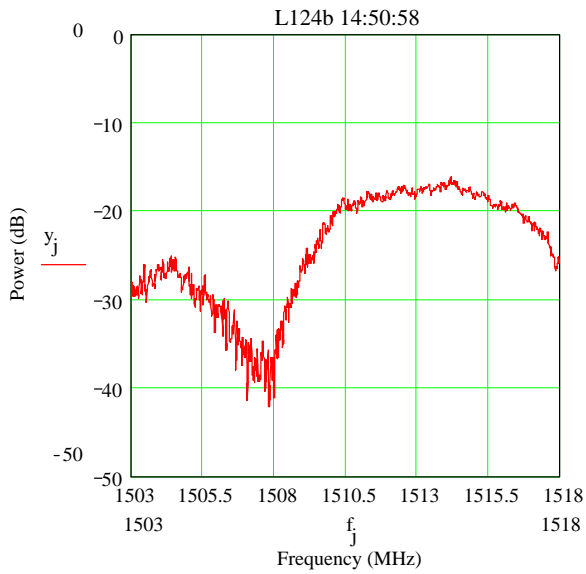
Figure 9 shows the bit error rate per 5 million bits over approximately the same time interval as the AGC plot of figure 8. Note that the major bit error events correspond to the drops in AGC level as expected. The event in figure 9 indicated by the arrow will be the first event analyzed. The system lost synchronization for about 2 seconds during this event. Figure 10 shows the bit errors for the same time interval as figure 7. Note that less than 50 errors occurred during each of the error events.



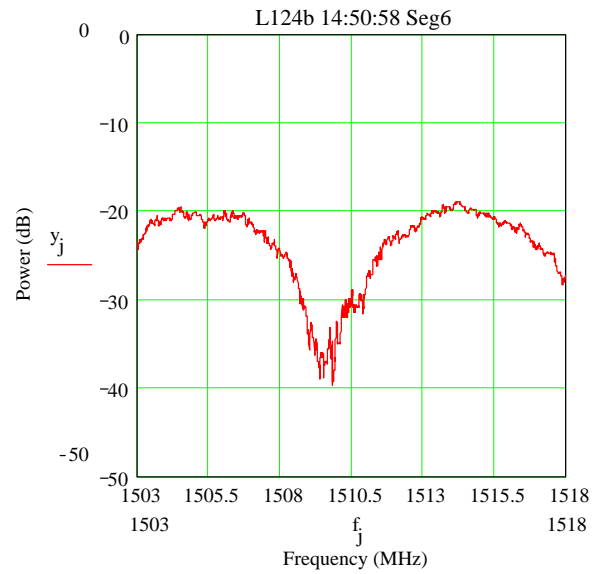
**Figure 10.** BER versus time for interval 14:30 to 14:33.

Figure 11 shows the FFT of the first segment of the data captured at a time of 14:50:58. There is a fairly deep null centered slightly below 1508 MHz. Figure 12 shows the FFT of the segment captured 500 ms later. The null has moved about 2 MHz higher in frequency. The system lost synchronization for about 2 seconds during this fade event. The T-39 was flying away from the receiving site and was about 38 nautical miles from the receiving site. The ground speed of the T-39 was approximately 200 knots. The average received power decreased by about 3 dB from segment 1 to segment 6 as the null moved closer to the center frequency where the highest signal power density occurs.

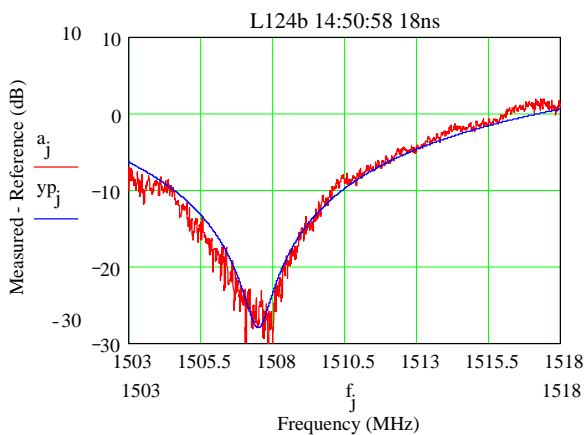
Figure 13 shows the results of fitting a two-ray model to the measured data. A good fit to the measured data was  $b=0.96$  and  $\tau=18$  ns. Essentially the same parameters were a good fit during segment 6. Quite a few multipath events similar to this one have been recorded during the test flights. The largest values of  $b$  have been about 0.99 (minimum phase null assumed, that is, the amplitude of the reflected path is assumed to be smaller than the amplitude of the direct path).



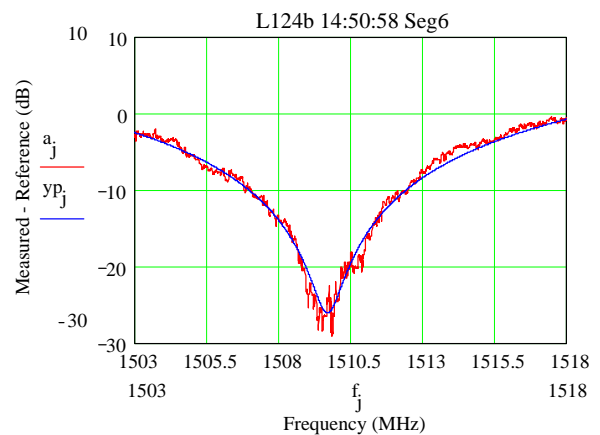
**Figure 11.** Received signal 14:50:58 (seg 1).



**Figure 12.** Received signal 14:50:58 (seg 6).

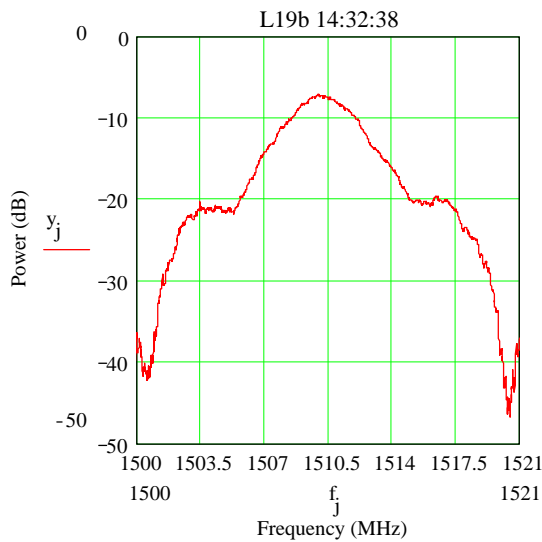


**Figure 13.** Channel estimate 14:50:58 (seg 1).

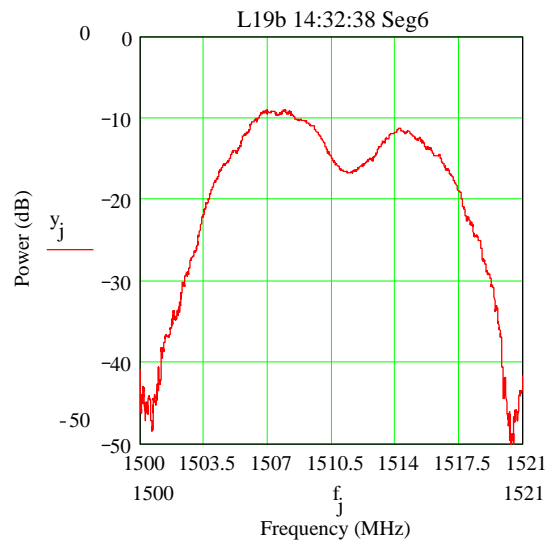


**Figure 14.** Channel estimate 14:50:58 (seg 6).

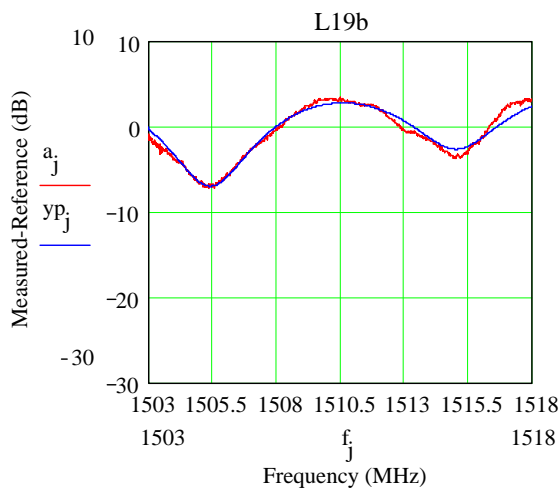
Another fairly common multipath event is illustrated in figures 15-18. This event occurred at 14:32:38. Again, segment 6 occurred 500 ms after the data in figure 15. In this case, the nulls moved lower in frequency (the plane was towards from the receiving site and was about 12 nautical miles from the receiving site). The null moved by approximately 4 MHz in 500 ms. The transfer function in figures 17 and 18 could not be well matched by a 2-ray model therefore a third ray was added with a different delay, phase angle, and relative amplitude. The vector sum of the three rays was then calculated. The parameters for figure 17 were  $b_1=0.4$ ,  $\tau_1=103$  ns,  $b_2=0.15$ ,  $\tau_2=47$  ns. The parameters for figure 18 were  $b_1=0.55$ ,  $\tau_1=104$  ns,  $b_2=0.25$ ,  $\tau_2=47$  ns. Note that figure 7 shows a very large AGC value during this time interval with no AGC dip as would occur with a short delay fade. This fade event caused only about 30 bit errors.



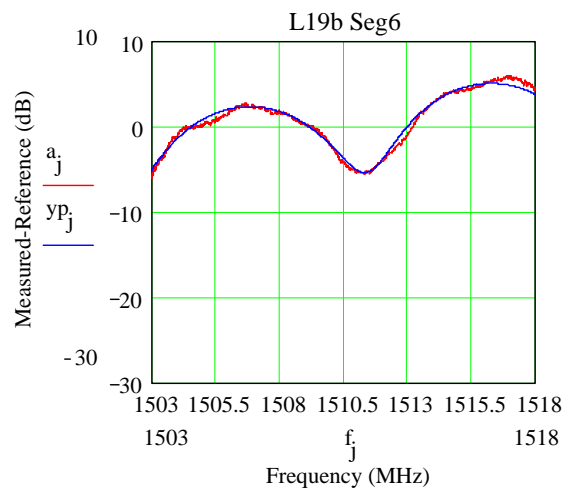
**Figure 15.** Received signal 14:32:38 (seg 1).



**Figure 16.** Received signal 14:32:38 (seg 6).

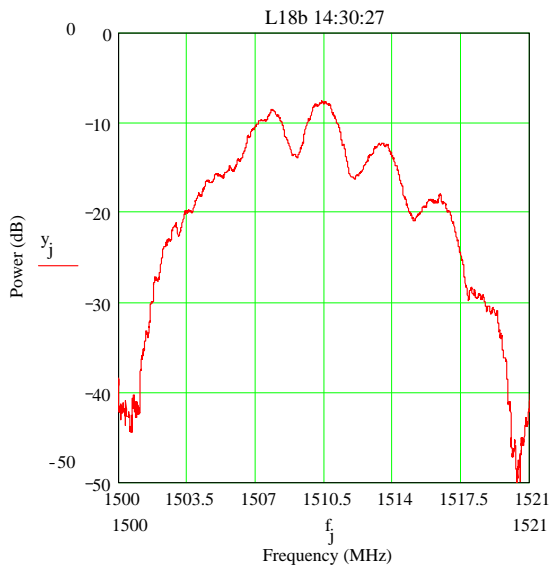


**Figure 17.** Channel estimate 14:32:38 (seg 1).

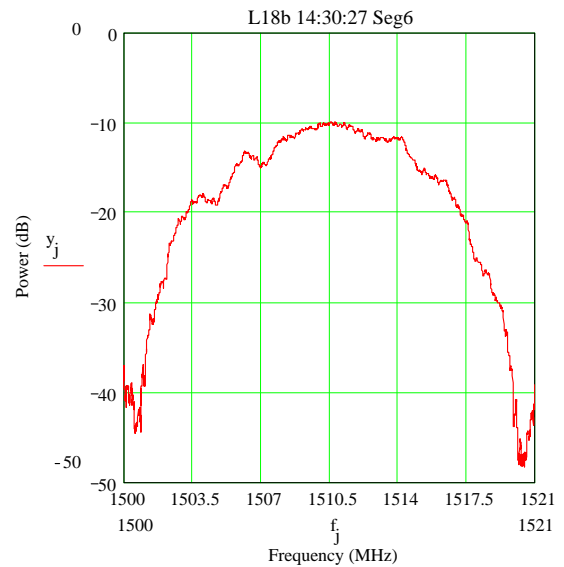


**Figure 18.** Channel estimate 14:32:38 (seg 6).

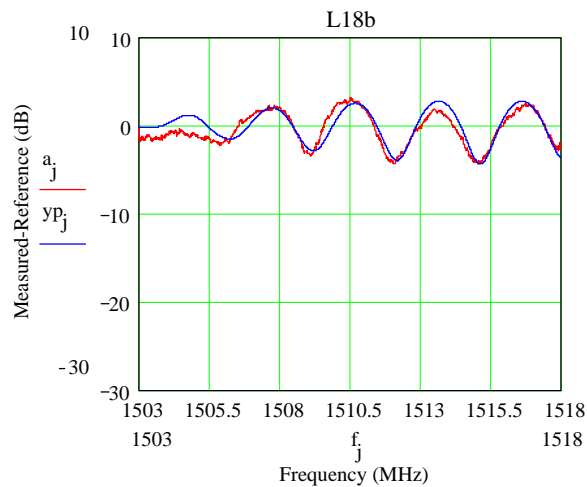
Figure 19 illustrates a relatively long delay multipath event. The lack of symmetry in figure 19 implies that at least a three-ray model is needed to fit the measured data. Figure 20 is the same data set except 500 ms later in time. Note that the structure is less apparent in figure 20. Figure 21 shows the results of fitting a three-ray model to the measured data. The parameters for figure 21 were  $b_1=0.21$ ,  $\tau_1=318$  ns,  $b_2=0.18$ ,  $\tau_2=357$  ns. The plane was flying towards the receiving site and was about 16 nautical miles away. Figure 22 needed a four-ray model with a short delay component added (to produce the slope in the transfer function) to the two long delay components to get a reasonable fit. The parameters for figure 22 were:  $b_1=0.18$ ,  $\tau_1=399$  ns,  $b_2=0.1$ ,  $\tau_2=438$  ns,  $b_3=0.5$ ,  $\tau_3=14$  ns. Again note that figure 7 shows a high AGC value during this interval with only a minor AGC dip. This fade event caused only about 40 bit errors.



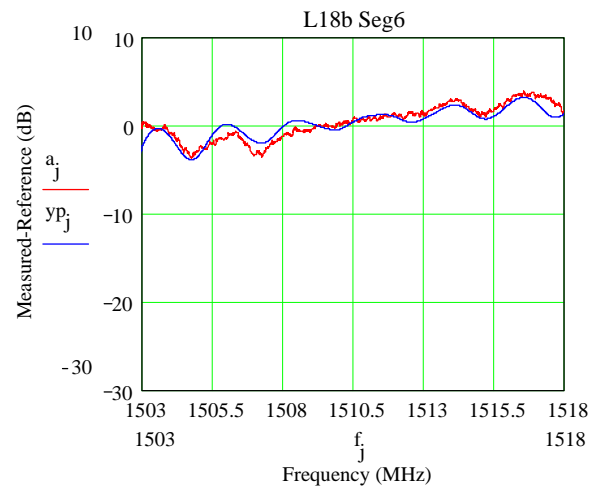
**Figure 19.** Received signal 14:30:27 (seg 1).



**Figure 20.** Received signal 14:30:27 (seg 6).



**Figure 21.** Channel estimate 14:30:27 (seg 1).



**Figure 22.** Channel estimate 14:30:27 (seg 6).

## SUMMARY

The multipath estimation method was shown to accurately estimate the parameters of the multipath fading in a simple two-ray lab experiment. A two-ray model provides a reasonably good fit to many fades measured during the flight tests and a three-ray model provides a good fit to most of the measured fades. The deep fades ( $b > 0.9$ ) that have been analyzed so far have all had estimated delays of less than 50 ns and cause a large number of bit errors and frequently loss of synchronization. Many multipath fade events included delays of 100 to 400 ns with typical maximum values of  $b$  being between 0.2 and 0.6. However, the long delay events analyzed thus far typically only cause a few bit errors (a few exceptions exist). The nulls presented in this report moved at a rate of a few MHz per second. Faster null movement would occur with faster test vehicles or with test vehicles climbing or diving. The events that caused a large number of bit errors typically also have a large drop in AGC value and if frequency selective fading occurred the amplitude of the indirect path is nearly as large as the direct path and the delay is small. The events with strong received signal strength typically had long delays (greater than 100 ns) and only a small number of bit errors.

## ACKNOWLEDGMENTS

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