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Impulse noise effect on 4 level QAM Spread Spectrum Signal

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IMPULSE NOISE EFFECT ON 4 LEVEL QAM SPREAD SPECTRUM SIGNAL

Donald C. Johnson

1.0 Summary and Purpose

The intent here is to show that the effect of impulse noise on the error probability for 4 level QAM spread spectrum signals can be predicted from the power level of the noise over the spread symbol time. That is, regardless of the pulse shape or energy concentration of the noise, the error probability is dependent principally only on the energy of the noise.

The measurements taken in both the NCR Department Store tests and the GM Oshawa tests show that impulses occur which raise the noise power level considerably above the background noise for durations on the order one or a few chip times. The incidence of occurrence of such impulses is on the order of fractions of a second. At this occurrence rate, each impulse can have an error probability in the order of 0.1 and still achieve a respectable error rate with 1 to 2 Mb/s signaling rates. The example error probability per impulse is thus 0.1 in the following.

It is shown that, in the specific case of an 11 chip spreading code and a typical receiver filter, the signal power to noise power ratio over a symbol time is somewhere between -4.4 dB and -7.4 dB for an impulse probability of error of 0.1. For other spreading code lengths, the values are different but the 3 dB spread is the same. The significance of this is that it makes the analysis of the impulse noise affect on the these data signals considerably easier. It is only necessary to determine the rms voltage envelope value of the impulse over a spreading symbol time in order to predict it's effect within 1.5 dB at most. Once the rms value is known, the effective level of the impulse concerning error production is known within the above spread of +/- 1.5 dB.

The higher S/N ratio (-4.4 dB) is the upper bound requirement for an impulse with energy concentrated in 1 chip time and the lower value is for gaussian noise. Gaussian noise is the limiting case where the noise power is created by many small impulses during the symbol time and the energy is spread over the multiple chips of the symbol.

2.0 Bandpass Impulse Noise and SS 4-Level QAM Signals

Bandpass noise waveforms can be represented in general by their In Phase (I) and Quadrature (Q) components.

$$N(t) = I(t)\mathrm{Cos}\omega_c t + Q(t)\mathrm{Sin}\omega_c t.$$

The I and Q waveforms represent the envelope of the in-phase and quadrature components.

The frequency ($\omega_c/2\pi$) is any frequency in the passband. It is the demodulation frequency in captured waveforms. If ω_c is in the middle of the passband, then I and Q will maintain nearly the same ratio throughout short impulses of noise. If it is not in the mid-band, then Q+jI will tend to form a rotating vector.

The magnitude of N(t) is

$$N_m(t) = [I^2(t)+Q^2(t)]^{1/2}.$$

This is the envelope of the noise waveform.

A receiver consists of a bandpass filter followed by a demodulator which derives the I and Q components of the received signal. This is followed by a low pass filter which filters the I and Q coefficients. If the bandpass filter has certain symmetry (which it usually does), then the effect of the bandpass filter is the same as that of a low pass filter of 1/2 the bandwidth. The overall filtering effect can be represented by an equivalent baseband low pass filter. The equivalent baseband filter of the I and Q waveforms captured by KII is the actual 25 MHz post-demodulator low pass filter, since the bandpass filter was much wider than 50 MHz.

These KII captured impulse noise signals were further processed through a 3-pole Butterworth low pass filter of 8.25 MHz 3 dB bandwidth. Some of the resultant waveforms are shown in the attached figures. This filter was chosen because it will permit demodulation of the 802.4L planned 11 Mchip/second SS signals. It has a little wider bandwidth than necessary and is not a totally optimum filter. But it is sufficiently accurate for analyzing impulse noise.

See descriptions of the attached figures 2 through 5 in a later section.

Figure 1 illustrates the effect of typical noise impulses on a 4 level QAM spread spectrum signal with 11 chips of spreading.

The upper waveform is that of the optimum 11 chip encoding sequence. In the modulation process, this chip code is used to change the phase (invert the polarity) of the encoded 2-bit data symbol at each change of state of the code. The same code is used to decorrelate the data waveform and achieve the processing gain.

The first and fourth waveforms from the top (labeled noise I and noise Q waveforms) show an example case of the I and Q waveforms where 3 impulsive disturbances occur during the symbol time. The third and fifth waveforms (with the numeric labels) show the effect the decorrelation process has on the noise waveforms. Finally, the I-Q axis at the lower right shows the effect of the noise and signal on the amplitude-phase of the decorrelated signal.

The signal waveform is a filtered replica of the spreading code. The system will sample the composite signal at approximately the midpoint of the vertical lines. For an ideal receiver, the signal will be at optimum amplitude at this time. The phase-amplitude shows the case where the signal phase is 45 degrees. The magnitude of this phasor is 11 X the chip signal amplitude.

The effect of the noise on the composite signal + noise phasor can be examined by looking at the signal and noise separately. Noise impulse 1 has negative I and Q components at the sample time with Q smaller than I. It is represented by phasor number 1 in the phase plane. Impulse 2 is chopped by the decorrelator and has very little effect. It is represented by the small phasor 2 on the phase plane. The effect of impulse 3 is formed in a like manner. In sum, the phasor marked "composite noise" is the vector sum of the 3 random phase noise vectors as they occurred at the sample time.

If the tip of the composite noise phasor in the diagram falls outside the first quadrant, there will be a symbol error. It must be at least 11/sqrt(2) times the spread signal amplitude to do this. This ignores the DPSK effect. If impulses affect 2 consecutive symbols, then the sum of the composite noise vectors must be less than the above to guarantee no error.

3.0 Impulse Probability of Error

The probability of error due to impulse noise can be investigated by looking at two extreme cases.

1. The disturbance is due to a large number of relatively weak impulses and

2. The disturbance is due to just 1 strong impulse.

The extreme of case 1 is steady gaussian noise.

The necessary signal to rms noise envelope power ratio for achieving an error probability of 0.1 will be investigated for the extreme cases.

The steady noise case. The signal to steady noise power necessary to maintain an error probability of 0.1 for 4 level QAM without spreading is 3 dB. This can verified by classical texts. Thus:

S/N power ratio necessary w/o spreading gain	3 dB
S/N gain due to spreading	10.4 dB
S/N necessary with spreading (3-10.4)	-7.4 dB

The necessary signal power (before decorrelation) at the sample instant to gaussian noise power ratio for achieving an error rate of 0.1 errors/symbol is -7.4 dB.

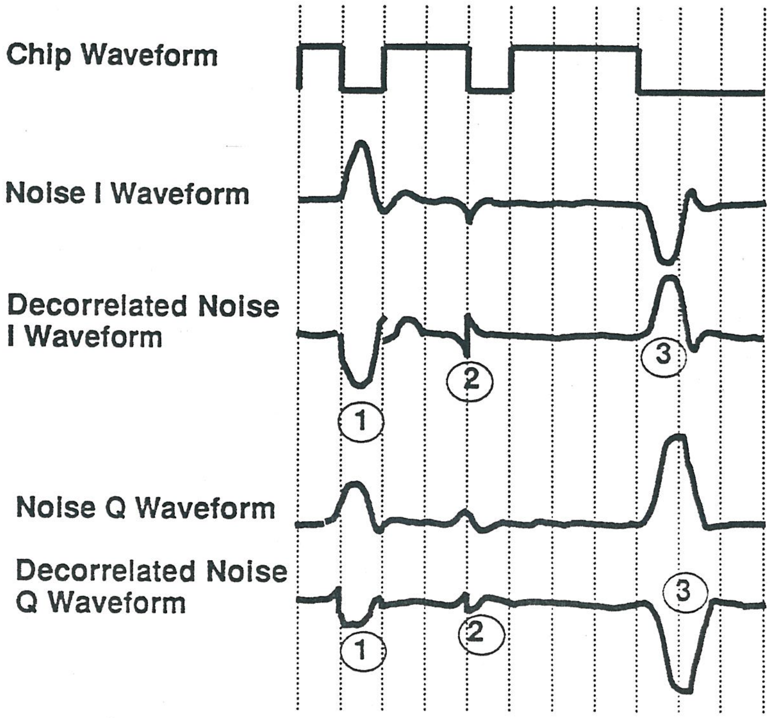
The signal envelope can be 7.4 dB below the noise envelope.

The Single Impulse Case. This will be investigated with the 8.25 MHz 3-pole Butterworth filter described above. A single impulse will create an impulse response magnitude with a shape that is the absolute value of the equivalent low pass filter impulse response. This impulse response shape is shown in figure 2. The signal level necessary to cause this impulse to have a probability of error less than 0.1 will be derived.

This impulse response has an rms value of 40.8 mv. It's magnitude is above 190 mv during 20% of a chip interval. Thus, the impulse will create a composite noise vector as shown in figure 1 at the sample time of 190 mv with no more than 20% probability. If this noise vector is within 3 dB of the composite decorrelated signal amplitude it is just strong enough to cause an error when it has exactly the right phase. The noise will aid the signal on at least 1/2 of it's occurrences so long as it's amplitude is less than that of the composite decorrelated signal. At this level, it will cause an error for 1/2 of the possible phases. But, from the impulse response, the magnitude never exceeds the 80 percentile point by as much as 3 dB.

EFFECT OF IMPULSE NOISE ON SS SIGNAL PHASE

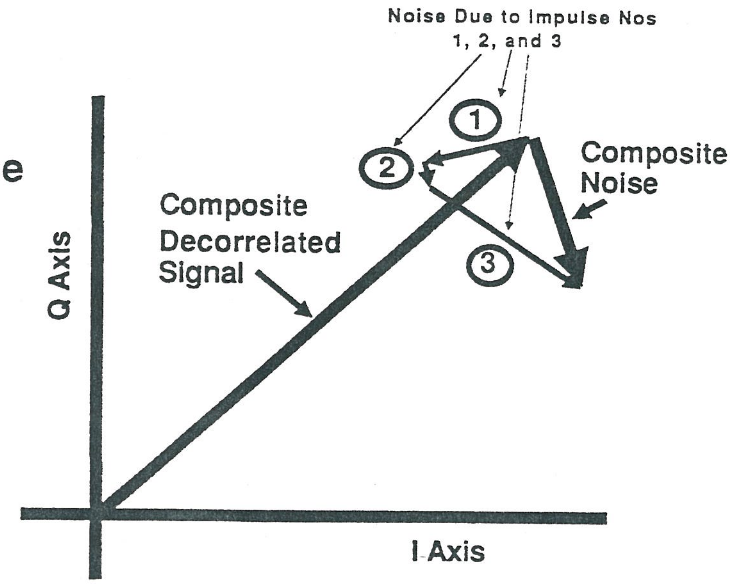
Figure 1



Effect of Impulse Noise on Signal Phase

11 Chip SS Correlation/Decorrlation Sequence
Composite Signal is 11x Voltage-Time Integral of the Spread Signal Chips
Composite Noise is Random Phasor Sum of the Individual Impulse V-T Integrals

Noise will cause an error if either the I or Q composite component exceds sqrt(2) times the composite decorrelated signal amplitude.



The conditions and result are summarized below:

Impulse 80 percentile level	190 mv
Impulse envelope rms level over the 1 us symbol time	40.8 mv
Envelope rms to 80 percentile ratio	-13.4 dB
Signal decorrelation gain (11x)	20.8 dB
N/S(after decorrelator) ratio for just causing error	-3 dB
N/S(after decorrelator) ratio for 50% Pe	0 dB
Most Pessimistic S/N(rms) (-20.8+13.4+3) (Upper Bound)	-4.4
Lower Bound S/N(rms) (-20.8+13+0)	-7.8

The late impulse response undershoot was ignored in the above. This shouldn't affect the results very much.

The best estimate for the necessary rms S/N for achieving an error rate of 0.1 is about -6 dB.

Further Comments. The above comparison only holds for an error probability of 0.1. If it were repeated for very low error probabilities, the necessary S/N for steady noise would increase considerable (4 dB for 0.01 for example). In the single impulse case, only about 2 dB would be needed to achieve 0 error probability.

If very low error probabilities per impulse are needed, then equating the impulse rms value to gaussian noise over the symbol time will over estimate the error rate for single isolated impulses. Thus, the picture would need another look in this case. Thus far, it appears that in the real world, most impulses occur in short bursts. For this reason the rms analysis is probably appropriate for error probabilities as low as 0.01 at least. It is safe for lower probabilities (it overestimates the signal power required) but may be inaccurate.

Another factor not considered is that the receiver signal processing is likely to ignore very high impulse peaks. There is a good likelihood that 5 to 6 dB S/N improvement can be achieved this way. This should be kept in mind when analyzing impulse noise.

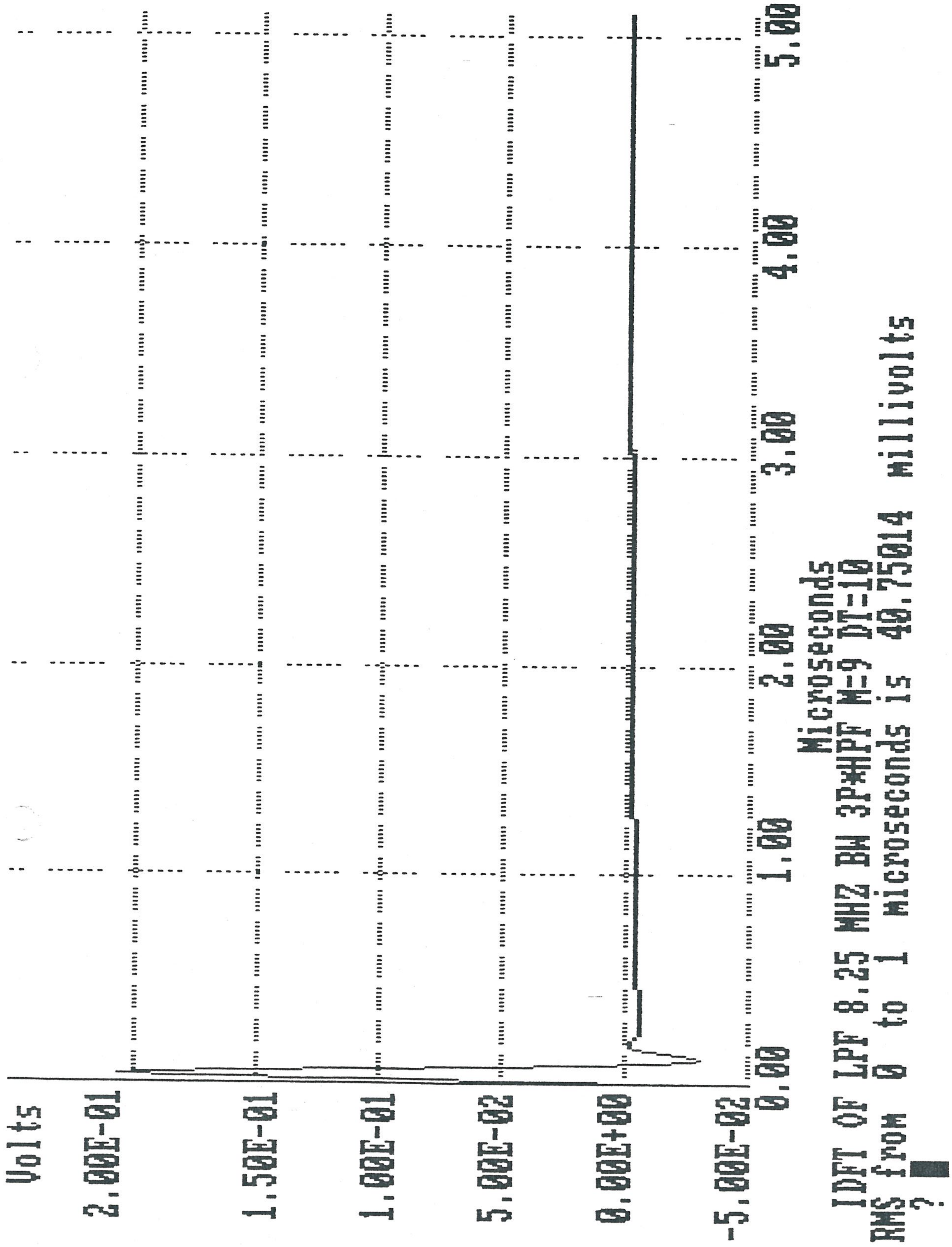

Volts
2.00E-01
1.50E-01
1.00E-01
5.00E-02
0.00E+00
-5.00E-02
0.00
1.00
2.00
3.00
4.00
5.00
Microseconds
IDFT OF LPF 8.25 MHZ BW 3P*HPF M=9 DT=10
RMS from 0 to 1 Microseconds is 40.75014 millivolts
?

Figure 2 A

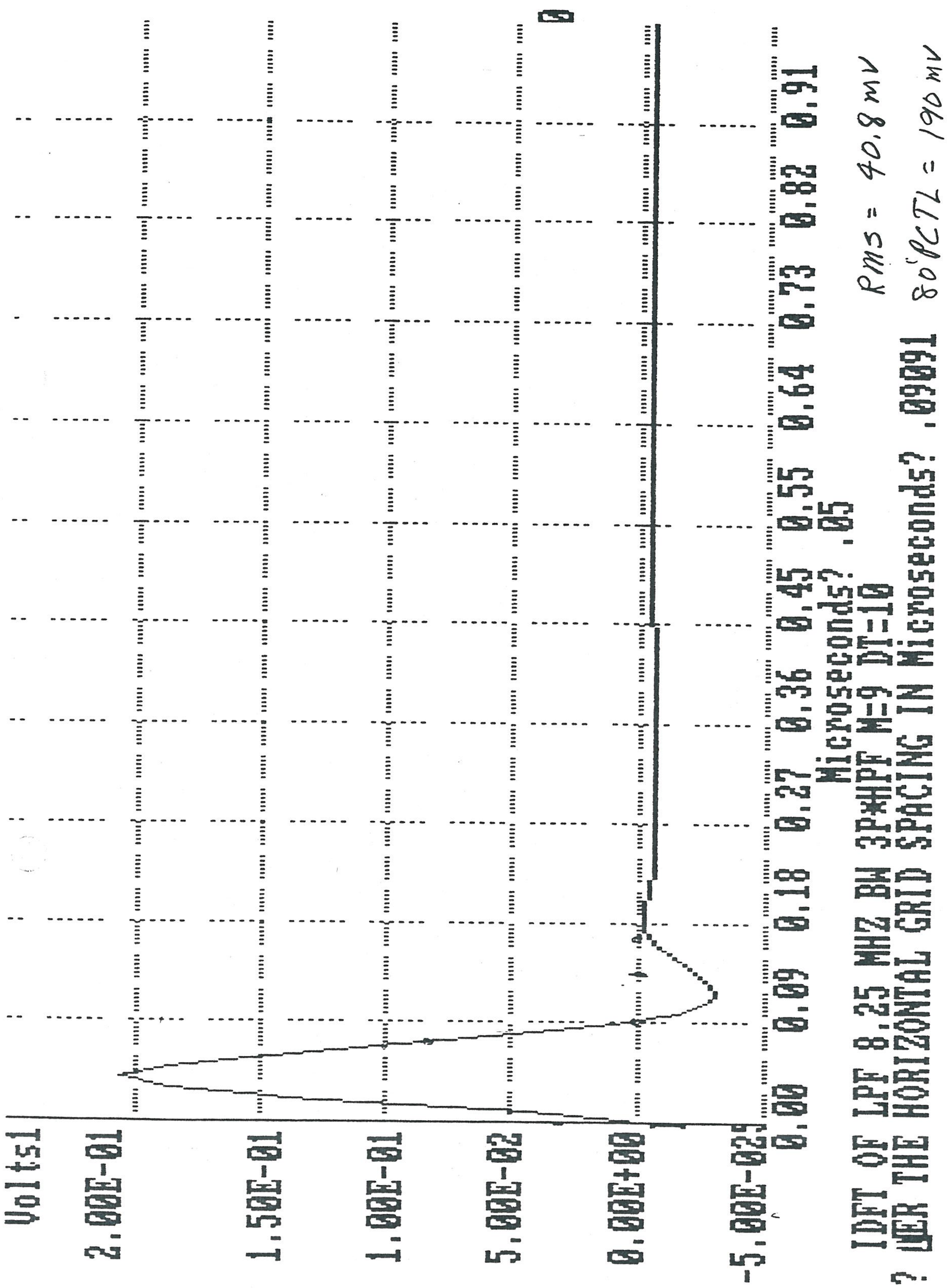

Volts1
2.00E-01
1.50E-01
1.00E-01
5.00E-02
0.00E+00
-5.00E-02
0.00 0.09 0.18 0.27 0.36 0.45 0.55 0.64 0.73 0.82 0.91
Microseconds? .05
IDFT OF LPF 8.25 MHZ BW 3P*HPF M=9 DT=10
? WER THE HORIZONTAL GRID SPACING IN Microseconds? .09091
RMS = 40.8 mV
80' PCTL = 190 mV

Figure 2B

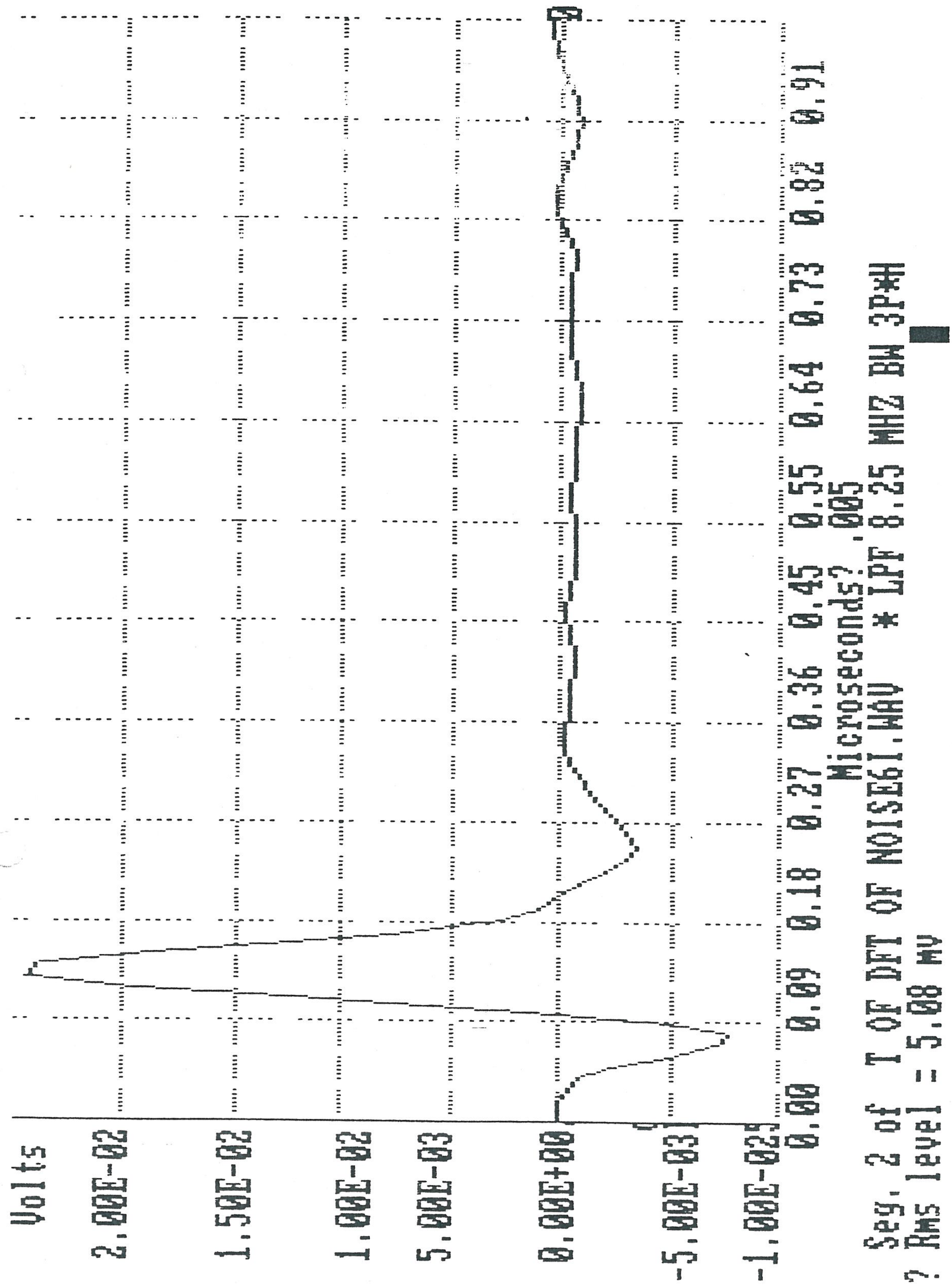

Volts
2.00E-02
1.50E-02
1.00E-02
5.00E-03
0.00E+00
-5.00E-03
-1.00E-02
0.00 0.09 0.18 0.27 0.36 0.45 0.55 0.64 0.73 0.82 0.91
Microseconds? .005
Seg. 2 of T OF DFT OF NOISE6I.WAV * LPF 8.25 MHZ BW 3P*H
? Rms level = 5.08 mV

Figure 3

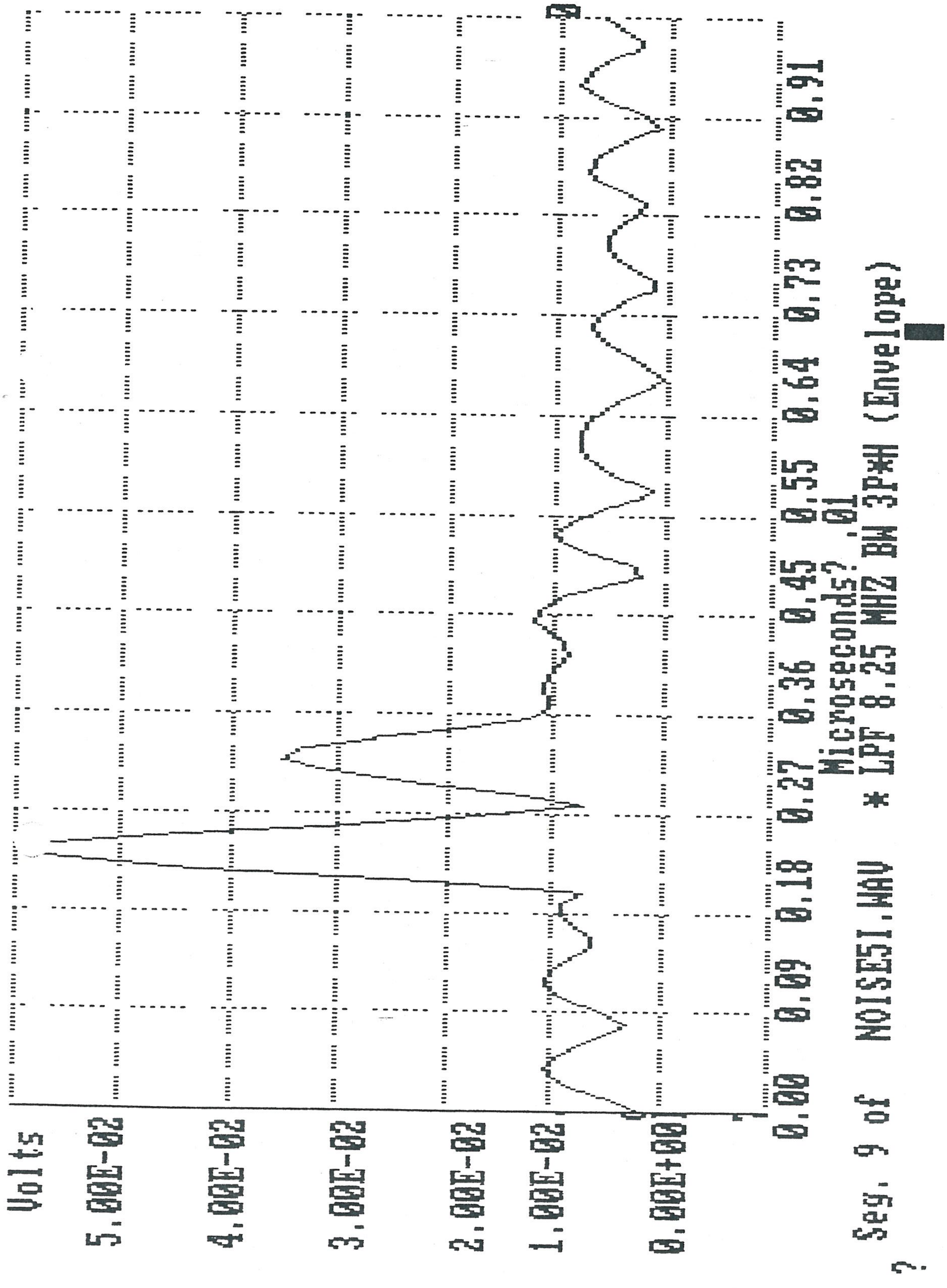

Volts
5.00E-02
4.00E-02
3.00E-02
2.00E-02
1.00E-02
0.00E+00
0.00 0.09 0.18 0.27 0.36 0.45 0.55 0.64 0.73 0.82 0.91
Microseconds? .01
Seg. 9 of NOISE51.WAV * LPF 8.25 MHZ BW 3P*H (Envelope)

Figure 4A

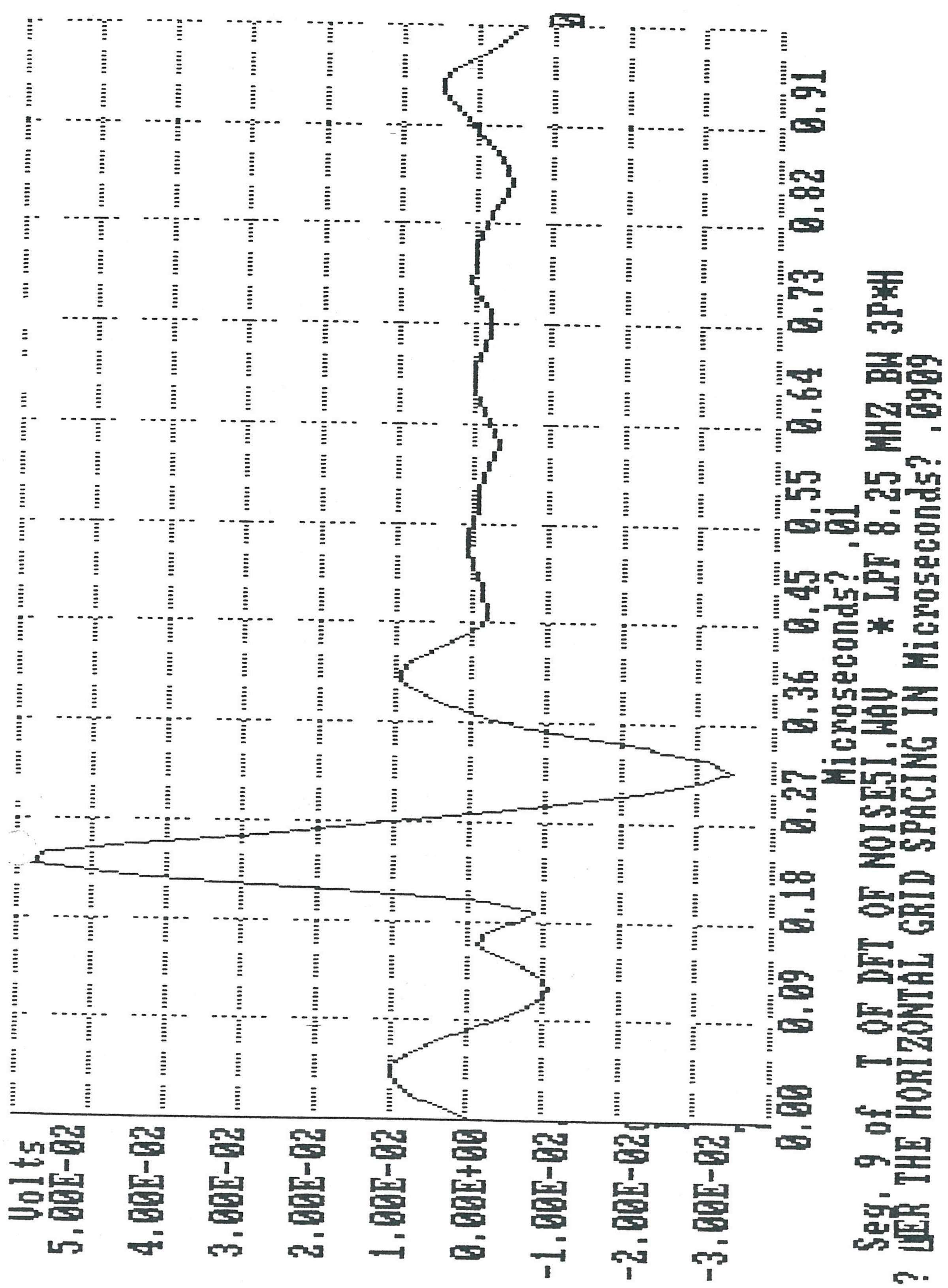

Volts
5.00E-02
4.00E-02
3.00E-02
2.00E-02
1.00E-02
0.00E+00
-1.00E-02
-2.00E-02
-3.00E-02
0.00 0.09 0.18 0.27 0.36 0.45 0.55 0.64 0.73 0.82 0.91
Microseconds? .01
Seg. 9 of T OF DFT OF NOISE51.WAV * LPF 8.25 MHZ BW 3P*H
? ER THE HORIZONTAL GRID SPACING IN Microseconds? .0909

Figure 4B

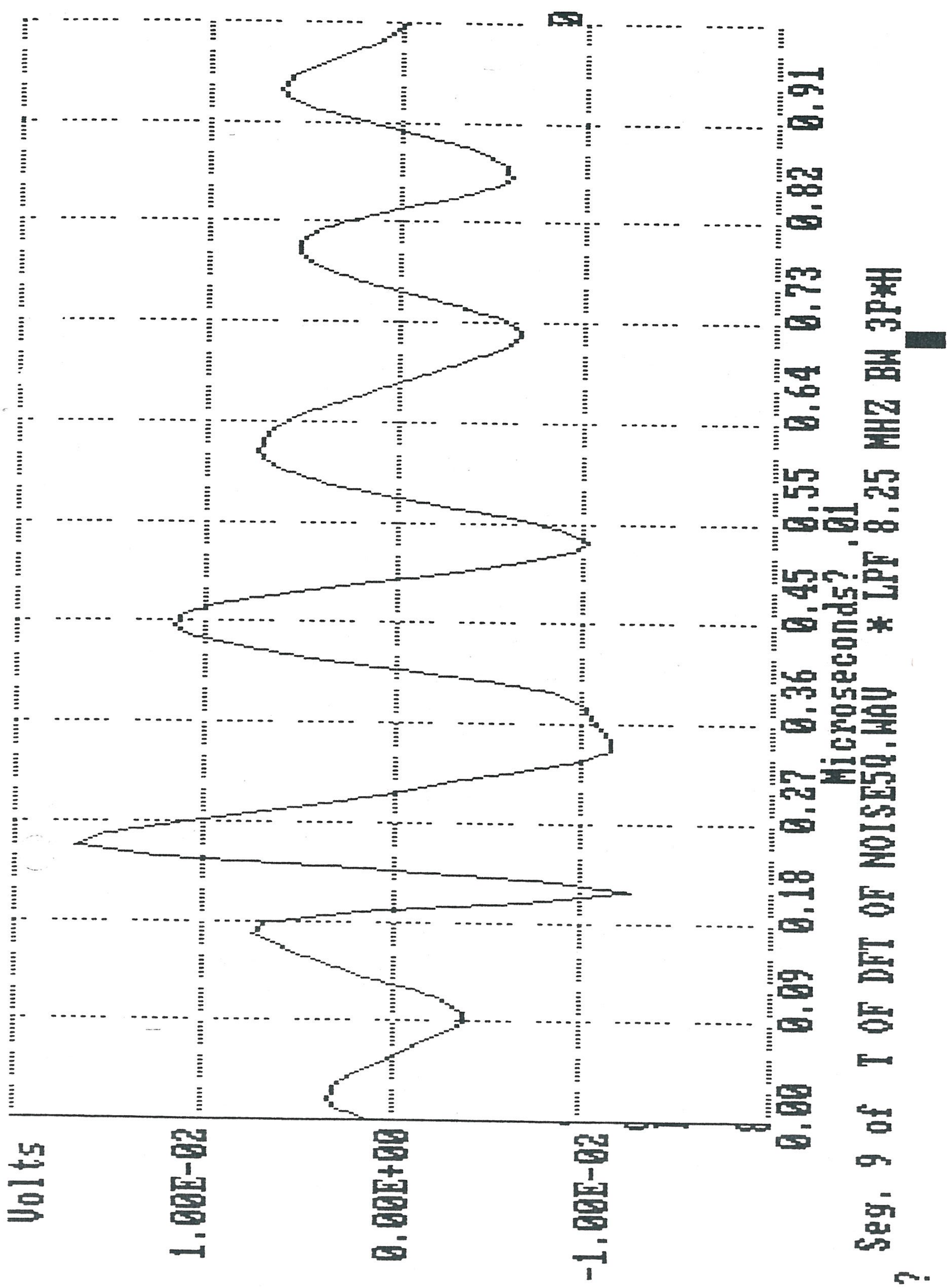

Volts
1.00E-02
0.00E+00
-1.00E-02
0.00 0.09 0.18 0.27 0.36 0.45 0.55 0.64 0.73 0.82 0.91
Microseconds? .01
Seg. 9 of T OF DFT OF NOISE5Q.WAV * LPF 8.25 MHZ BW 3P*H
?

Figure 4C.

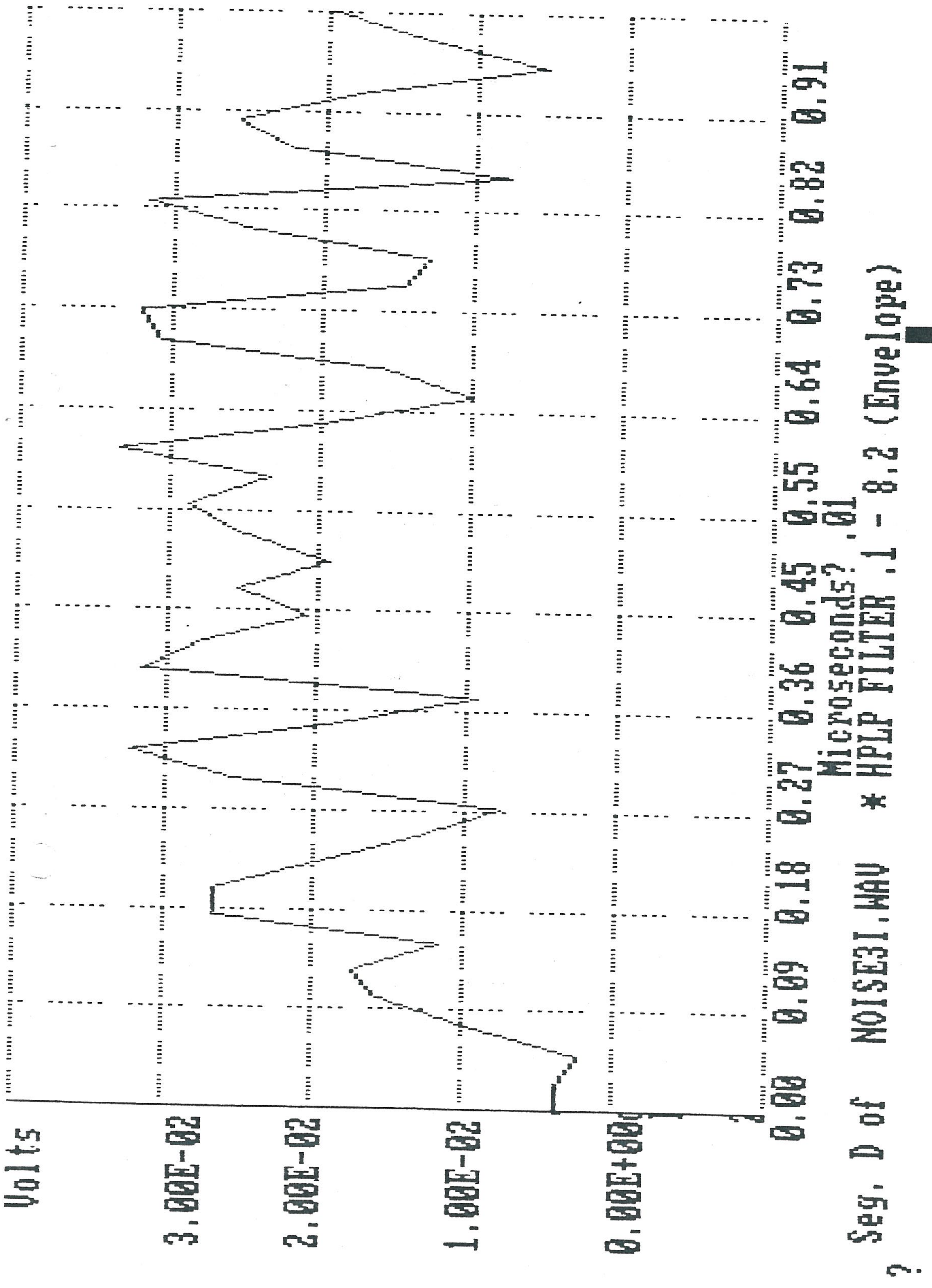

Volts
3.00E-02
2.00E-02
1.00E-02
0.00E+00
0.00 0.09 0.18 0.27 0.36 0.45 0.55 0.64 0.73 0.82 0.91
Microseconds? .01
Seg. D of NOISE31.WAV * HPLP FILTER .1 - 8.2 (Envelope)
?

Figure 5

4.0 Description of Example Waveforms

The impulse response of the 8.25 MHz 3-pole Butterworth filter is shown in figures 2A and 2B.

Figure 3 shows the I component of a noise waveform captured by KII at a department store near Atlanta at 2.4 GHz. This is an example of a noise waveform which probably resulted from 1 isolated impulse.

Typical noise waveforms are created by multiple impulses within the 8.25 MHz resolution time and are represented by the waveforms of figures 4A through 4C. This shows the envelope and the 2 components of a waveform captured at 905 Mhz in the department store near Atlanta. The time scale of figure 4 is divided into chip times at 11 Mchips/second. From the envelope trace, it is likely that this waveform was created by impulsive events about 1 chip time separated.

Figure 5 shows an extreme case where many equivalent excitation impulses must have created the noise.