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EDL-M531 **404 476** DA 36-039 SC-87499

Improvement In Gaussian Signal Perception By Deterministic Signal Injection And Harmonic-Zone Detection

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TECHNICAL MEMORANDUM
No. EDL-M531
8 February 1963

IMPROVEMENT IN GAUSSIAN SIGNAL PERCEPTION BY DETERMINISTIC SIGNAL INJECTION AND HARMONIC-ZONE DETECTION

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Prepared for the U.S. Army Electronics Research and Development Laboratory under Contract DA 36-039 SC-87499

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IMPROVEMENT IN GAUSSIAN SIGNAL PERCEPTION BY DETERMINISTIC SIGNAL INJECTION AND HARMONIC-ZONE DETECTION

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1. ABSTRACT

An experimental investigation of perception of narrowband, Gaussian signals was performed. A new technique, using a reference sine wave, a stiff limiter, and a harmonic-zone filter was investigated. The technique used both energy and gross phase characteristics of the Gaussian signal in the perception process. The comparison of this new technique with energy detection showed equal signal perception at 3-db lower S/N ratios for perception probabilities greater than 0.5 at fixed, false-alarm probabilities of 10^{-3}, 10^{-4}, 10^{-5}, and 10^{-6}.

2. INTRODUCTION.

The search for improvement in perception of a narrow-band, Gaussian signal in the presence of narrow-band receiver noise has led to the investigation of deterministic signal injection reported herein. The term "perception" used in this report includes the following processes:

(1) Linear Filtering: processing waveforms to separate desired from undesired frequencies by linear, frequency-selective circuits.

(2) Harmonic-Zone (HZ) Generation: processing narrow-band waveforms through a nonlinear device to generate narrow-band, harmonic zones.

(3) Detection: processing a narrow-band waveform through a nonlinear device and a video filter.

(4) Decision: processing a waveform through a nonlinear device which categorizes the presence or absence of signal in the waveform.

(5) Deterministic Signal Injection: inserting a reference sine wave in a receiver to change the receiver's noise characteristics.

Note that perception in conventional receivers includes processes 1, 3, and 4.

The word detection has been frequently used with two distinct definitions in describing a receiver's operation. The older and more widely used definition relates to the process which goes on in a detector. This is analogous to modulation and modulator, reception and receiver, where the noun form stands for the device and the verb form stands for the process. The second and more narrowly used meaning comes from the field of Information Theory and is synonymous with perception as defined above. It is believed that using the same word with two distinct definitions in the same narrow field is confusing and, therefore, the second meaning of detection should be replaced by the word perception. In addition, the word perception, by explicit definition, includes the decision process which is inherent in an automatic receiver.

It is predicted that a significant improvement in signal perception can be achieved by investigating new decision methods and processes.

2.1 Definition of the Problem.

A narrow-band, Gaussian signal is defined as one whose center frequency is at least ten times the half-power bandwidth, and whose amplitude probability-density function is Gaussian. The narrow-band Gaussian signals considered in this investigation had a phase probability-density function which was uniform.

A harmonic zone is defined as a frequency band in the output of a nonlinear device that is harmonically related to a narrow-band waveform at the input to the device. The characteristics of the harmonic zones are a function of both the input waveform and the nonlinear device.[1-4] The application of harmonic-zone detection to narrow-band, Gaussian signals was based on the hypothesis that information contained in the gross phase characteristics of the signal could be used in the decision process in addition to the information contained in the energy of the signal. Since the phase probability-density functions (pdf) of both the signal and the receiver noise are the same, it is not at all obvious that the phase information can be used. Both the signal and the receiver noise are assumed to have a uniform phase pdf. The gross phase information can be used in perception by injecting a reference, deterministic waveform.

The phase information in a Gaussian noise signal contains up to 50 percent of the available information in a communication channel.[5-7] Earlier theoretical investigations[8] have shown that for weak signals (where the signal power is at least 10-db weaker than the noise power), the energy measurement is the optimum reception technique. Optimum is used in the sense of maximizing the likelihood ratio of the probability-density function of signal-plus-noise to the pdf of noise. This analysis is based on the assumption that the chi-squared amplitude pdf which results from the linear addition of two, independent, normal distributions can be treated as a normal distribution. While this assumption may be satisfactory for the weak-signal case, it is not believed to be satisfactory for the strong-signal case where the signal power is at least 10-db greater than noise power.

1-4 See references 1 through 4 in Section 6.

2.2 Outline of the Experimental Technique.

The harmonic-zone detection technique used in the experimental investigation to test the above hypothesis is shown in a block diagram in Figure 1. The experimental equipment will be described in Section 3. The point of interest here is the lower part of the block diagram shown within the dashed lines. The output of the band-pass filter is linearly added to a reference sine wave. The combined waveform is coupled to a limiter whose output is applied to a harmonic-zone amplifier and filter. The purpose of this arrangement is to utilize the gross phase information in the Gaussian signal in addition to the energy information in the perception process.

The level of the reference sine wave is adjusted for "stiff limiting". The frequency of the sine wave is selected so that its 9th harmonic appears in the center of the HZ filter. The original band-pass filter's center frequency was 2.72 Mc with a bandwidth of 83 kc. The center frequency was selected so that the separate harmonic content generated in the limiter will not appear within the 150-kc bandwidth of the HZ filter which is centered on 28.9 Mc. The principle of the operation is as follows:

The level of the reference sine wave is set 35-db above the receiver-noise level. At this ratio, the limiting process is controlled almost entirely by the sine wave. The energy in the HZ filter is maximum and almost sinusoidal. When a noise signal is added at the input, the ratio of sine wave to total noise (noise signal plus receiver noise) decreases. The energy in the HZ filter decreases as a nonlinear function of the ratio of waveforms. There are two effects which occur simultaneously. The energy in the HZ filter decreases as a function of signal energy, which moves the center frequency of the HZ energy out of the HZ filter, and the bandwidth of the energy in the HZ filter widens as a function of the gross phase structure of the noise. It is this simultaneous exploitation of energy (amplitude) and phase information which improves signal perception.

The reference sine-wave frequency is offset from the center frequency of the signal to provide both amplitude and phase changes as the signal is injected. If the two frequencies were the same, then the spectrum in the HZ filter would only widen as the noise waveform introduced phase modulation. This was investigated experimentally and was found to be not as effective as the offset HZ-filter technique.

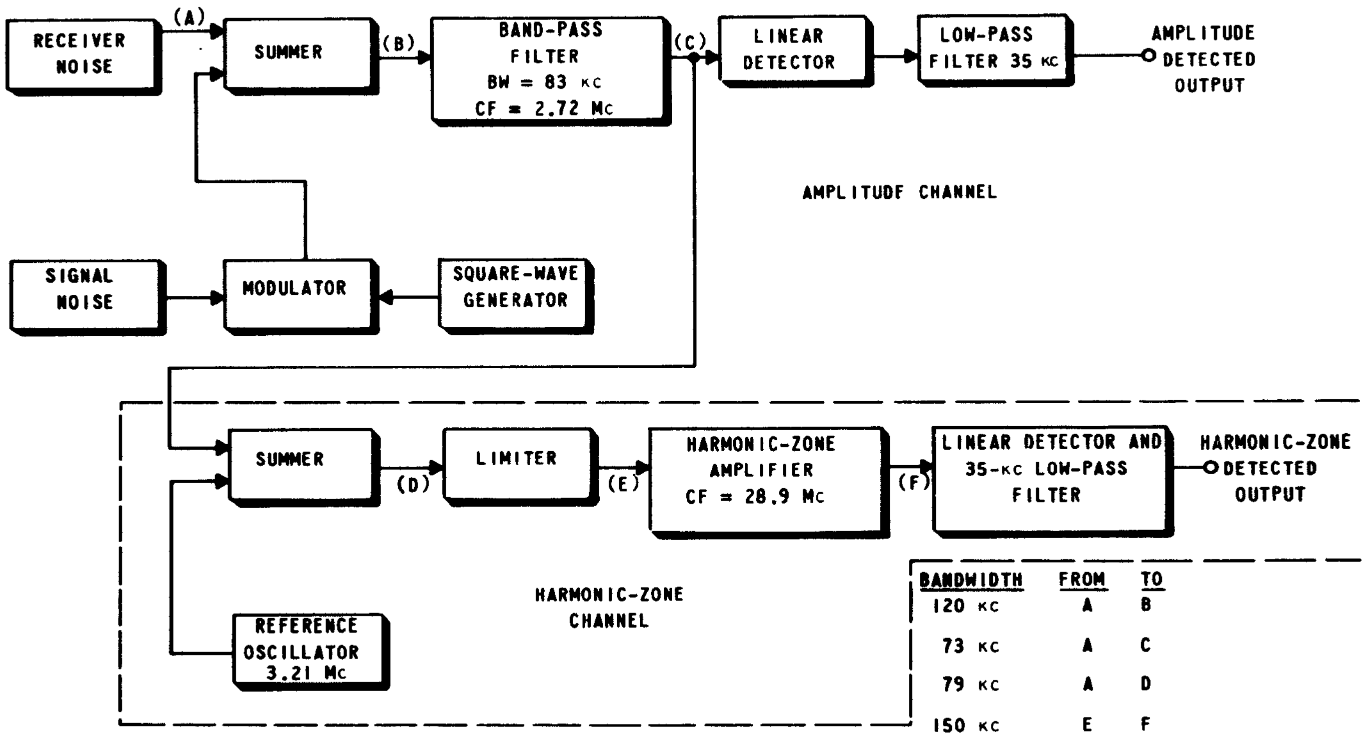

Figure 1

Block Diagram of Experimental System

2.2 -- Continued.

The processes described above are complex and difficult to communicate. The experimental equipment and techniques described in the next section will help clarify this introductory material.

3. EXPERIMENTAL EQUIPMENT.

Refer to Figure 1 for the equipment block diagram. The two noise sources are General Radio, 1390-A, random-noise generators. The two noise sources are linearly summed in a circuit with a 91-kc bandwidth. The summer's output is applied to a band-pass filter whose center frequency is 2.72 Mc and whose bandwidth is 83 kc. This band-pass filter is analogous to the band-pass IF filter of a superheterodyne receiver. The output of the band-pass filter is applied to two separate channels. The upper channel is a conventional amplitude or energy detector. A half-wave linear rectifier is coupled to a 35-kc bandwidth video filter. This conventional amplitude-detection channel provides a means for experimental control. The accuracy of the results from the HZ detection channel can be determined by a comparison with results from the conventional channel which, in turn,may be compared with theoretical curves available for this technique.

The HZ channel is shown within the dashed lines in Figure 1. The output from the band-pass filter is summed with a sine wave from a reference oscillator. The combined waveforms are coupled to a symmetrical limiter circuit. This limiter was designed as close to an ideal symmetrical limiter as was practical in one stage. The measured limiter's characteristic is shown in Figure 2. The bandwidth of the limiter circuit is well above the 11th harmonic of the input waveform. The level of the sine wave is set so that "stiff" limiting of the sine wave is achieved. The added noise waveform makes for additional limiting, but the change is small. The frequency of the sine wave is set at 3.21 Mc so that its 9th harmonic is centered in the HZ filter at 28.9 Mc. The energy in the band-pass filter is centered on 2.72 Mc with about an 80-kc bandwidth. The direct harmonic energy of the waveforms from this filter will not appear within the 150-kc bandwidth of the HZ filter.

The output from the HZ amplifier is coupled to a half-wave linear detector. The video bandwidth of both the amplitude and the HZ channel is 35 kc. The over-all bandwidth of the two channels is almost the same. This equality of bandwidth was verified experimentally by injecting square wave signals into both channels. Figure 3 shows the response of the two channels to square waves with pulse repetition frequencies of 1, 3, and 6 kc. Time goes from left to right in the traces. The HZ channel responds slightly faster than the amplitude channel. The overshoot in the HZ-channel's response is due to additional tuned circuits in the HZ amplifier.

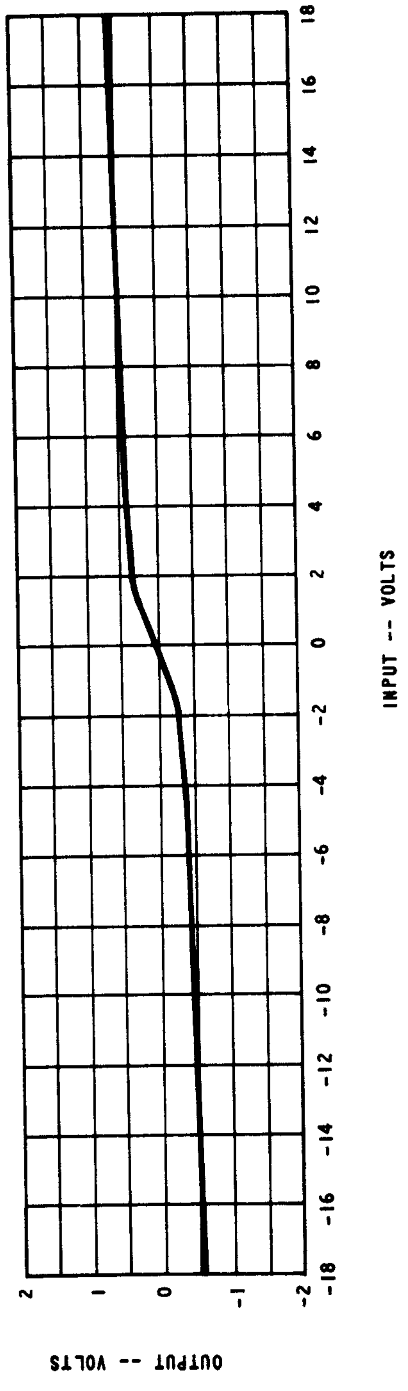

Figure 2

Measured Transfer Characteristic of Symmetrical Limiter

1-KC SQUARE WAVE

3-KC SQUARE WAVE

6-KC SQUARE WAVE

Figure 3

Response of Amplitude Channel and
HƵ Channel to Input Square Waves

3.1 Test and Measurement Equipment.

The test and measurement equipment that was used with the experimental equipment is listed below. Pertinent comments about its application are included.

(a) Receiver Noise Source. General Radio, Random Noise Generator (Type No. 1390-A); noise spectrum is reasonably flat from dc to 5 Mc.

(b) Square-Wave Noise Signal Source. Laboratory-fabricated modulator; uses a square-wave generator and a GR random-noise generator as inputs.

(c) Modulating Signal. Hewlet-Packard, Square Wave Generator, Model 211A.

(d) S/N Ratio. Measured by a Millivac R. M. S. Noise Voltmeter (MV-19FW1). S/N was monitored at point (C), and point (D) as shown in Figure 1.

(e) Oscilloscope. Tektronix 531 and 545 oscilloscopes were used to observe the outputs of the amplitude channel and the harmonic-zone channel on an alternate-sweep basis.

(f) Recording Camera. Dumont Oscilloscope-Record Camera (Model Z97) recorded the outputs from the amplitude and HZ channels.

(g) Spectrum Analyzer. Polarad Model TSA; Freq. Head STU-1.

3.1.2 Summer Circuit. The summer circuit had been previously developed for another experiment. Both the receiver-noise input and the noise-signal input to the summer are isolated by buffer amplifiers which were designed with a center frequency of 2.72 Mc. The noise-signal amplifier's bandwidth is 120 kc, and the receiver-noise amplifier's bandwidth is 100 kc. Both employ a single-tuned stage, a high input impedance, and a 50-ohm output impedance as shown in Figure 4. The outputs from the noise-buffer amplifiers closely approximate a normal or Gaussian distribution.

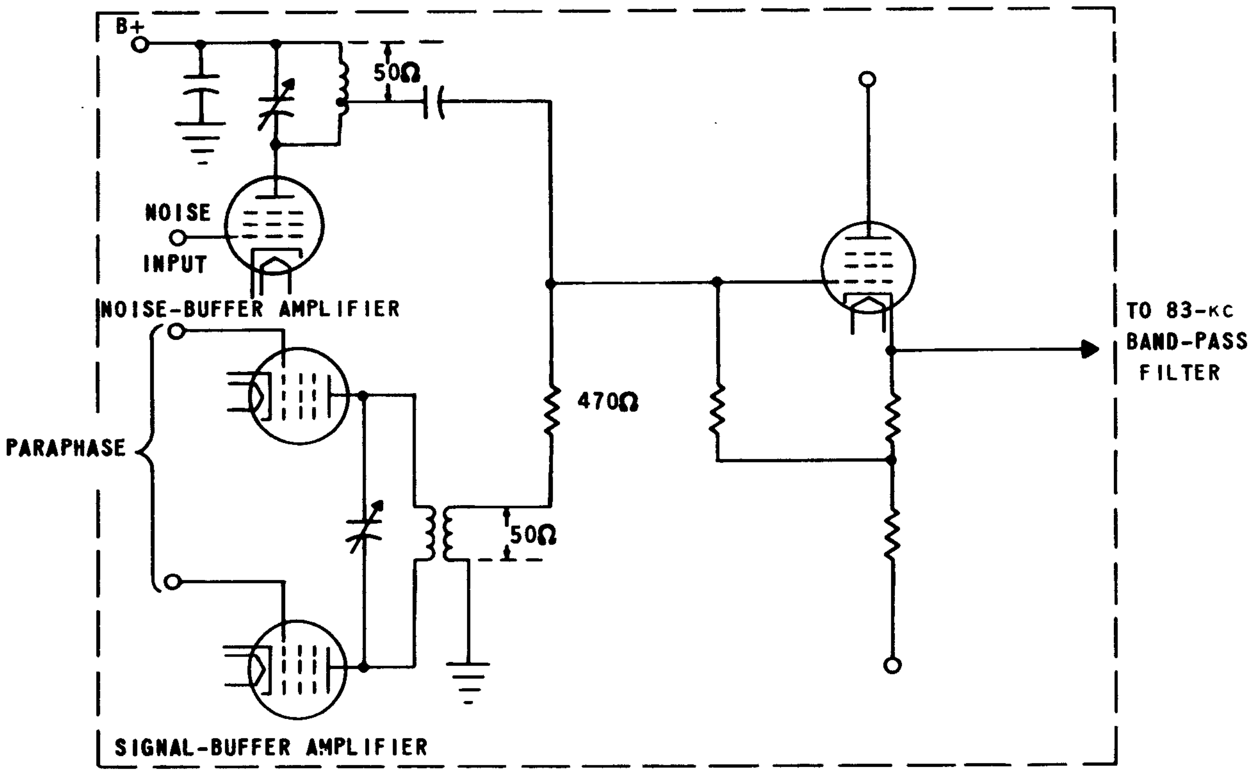

Figure 4

Narrow-Band Summer Circuit

3.1.2 -- Continued.

The receiver-noise buffer amplifier consists of a single tube with a tuned plate circuit. The output is taken from a 50-ohm tap on the coil. The noise-signal buffer amplifier consists of two tubes in a paraphase configuration. The output is provided by a transformer having a coupling coefficient greater than 0.9 and a 50-ohm output impedance. The outputs are isolated by a 470-ohm series resistor. This arrangement provides approximately 20-db isolation between the noise-signal buffer amplifier and the receiver-noise buffer amplifier. The outputs were summed across a common resistor at the input to a cathode follower.

3.1.3 Multiple-Pole, 83-kc Band-Pass Filter. The band-pass filter is a K-type filter with M-derived, L-matching end sections. The filter has a cathode-follower input and a cathode-follower output to provide high input impedance and low output impedance. The filter has a center frequency of 2.72 Mc and a bandwidth of 83 kc. At one octave from the half-power points the filter has more than 35-db attenuation.

The over-all bandwidth was measured at several points as shown in the table in Figure 1. The over-all bandwidth was also checked by injecting a square wave into the system and comparing the rise time as shown in Figure 3.

3.1.4 Harmonic-Zone Detectors. Almost identical detectors were used to detect the amplitude-channel waveforms and the harmonic-zone channel waveforms. Both detectors use a half-wave linear rectifier. The video filter is a K-type filter with M-derived, L-matching end sections. The filter has a bandwidth of 35 kc, with less than 2-db attenuation from dc to 32 kc, and more than 40-db attenuation at 40 kc. The input and output impednace is 25 kilohms.

3.1.5 Broad-Band Summer. The summer consists of two, pentode, RC amplifiers, isolated by two resistors which provide approximately 15-db isolation. The amplifier outputs are added across a common resistor in the grid circuit of a cathode follower. Figure 5 shows the manner in which the signal and noise amplifiers are connected to the summer circuit. The circuitry of the summer following the band-pass filter slightly increases the net bandwidth into the limiter.

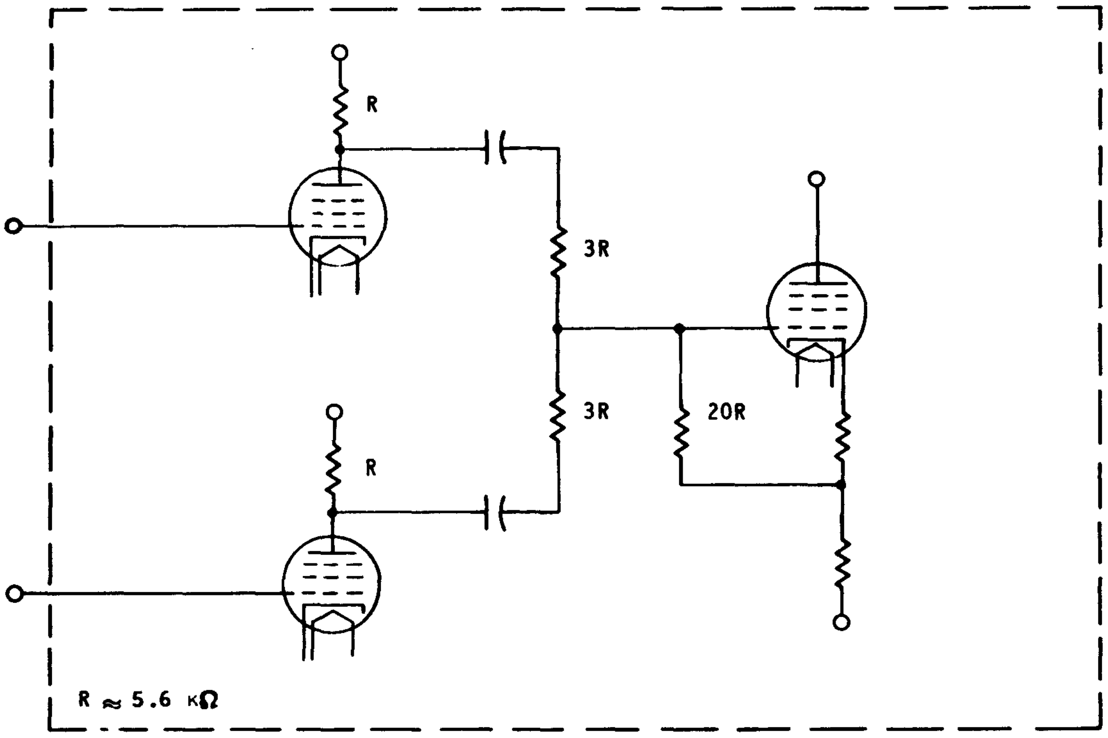

Figure 5

Broad-Band Summer Circuit

3.1.6 Limiter Circuit. The almost ideal limiter consists of a low-Q (Q less than 4) tuned circuit in the plate of a pentode tube which, in turn, is coupled to the grids of four cathode followers in parallel, as shown in Figure 6. The output of each cathode follower is coupled to two parallel groups of series diodes (A and B). Group A limits on about plus 0.15-volt positive input and Group B limits on about minus 0.15-volt negative input. The resultant, output, random square wave from the limiter is coupled into a broad-band cathode follower to preserve the high-frequency components in the output.

A gain control is provided at the input to the limiter, enabling the voltage into the diodes to be controlled from zero to 50 volts. The limiter's transfer characteristic was shown in Figure 2. The harmonic content of the limiter's output was observed up to 120 Mc on a spectrum analyzer.

3.1.7 Harmonic-Zone Amplifier. The HZ amplifier is a band-pass amplifier whose 150-kc bandwidth is centered on 28.9 Mc. The gain of the amplifier is approximately 45 db. The input impedance is 10 kilohms, and output impedance is 600 ohms.

3.2 Additional Test Equipment Used in the Quantitative Measurement.

In the quantitative measurement of perception probability (P_p), the following additional equipment was employed:

CLIC is an equipment developed at these laboratories for statitistical measurements. CLIC is an acronym for Clipping, Limiting, and Integration by Counting. The operation of the CLIC system may be explained with the aid of the block diagram and waveforms shown in Figure 7. The equipment consists of one (or two) ac amplifier, followed by a dc restorer, a bottom clipper, a stiff limiter, a Chance oscillator, and a digital counter. The input video waveform is amplified and stripped of its mean or dc component. The reason for the use of ac amplification is to avoid the instability inherent in a high-gain dc amplifier. The output from the ac amplifiers is clamped to ground by a dc restorer.

The dc restorer's output, shown in Figure 7A, is fed to a clipper whose clipping level is determined by a preset threshold voltage. The waveform at the clipper's output, shown in Figure 7B, is that portion of the

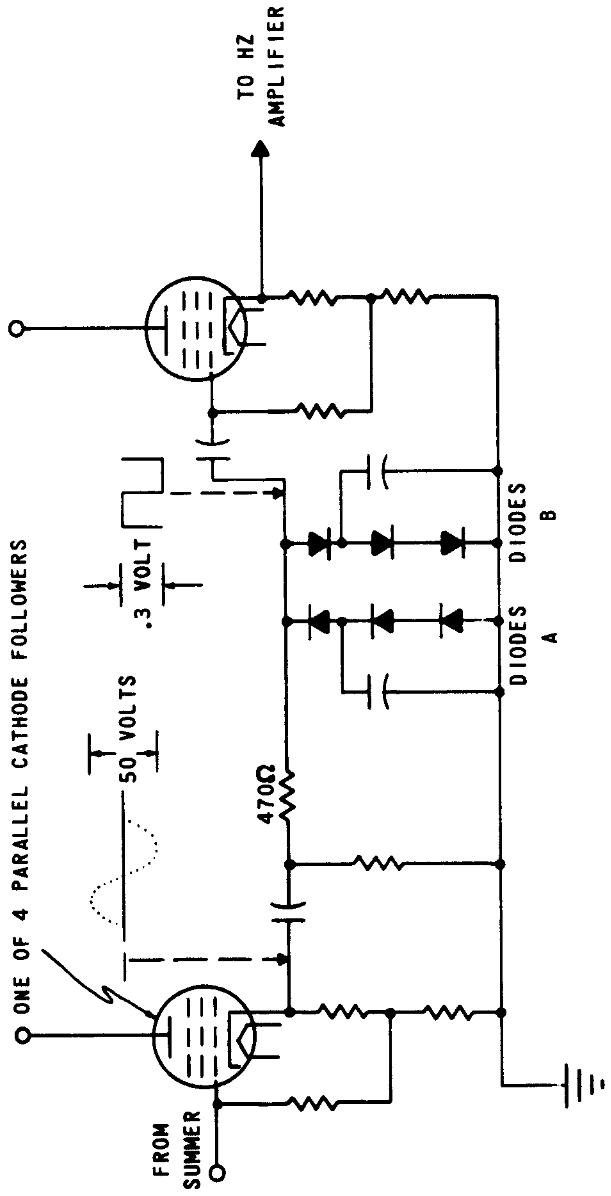

Figure 6
Limiter Circuit

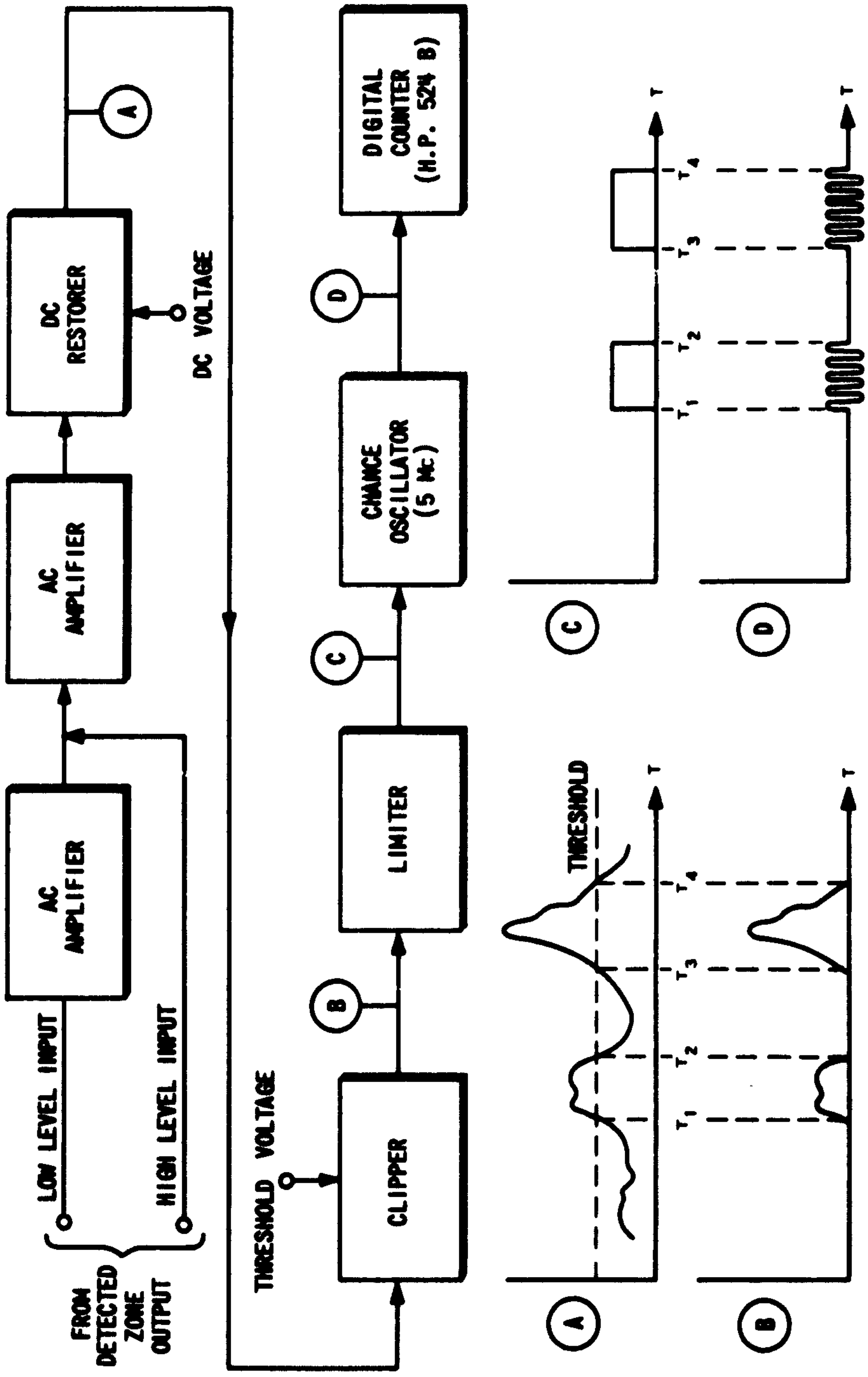

Figure 7

CLIC System

3.2 -- Continued.

total waveform which lies above the threshold. This waveform is processed through a hard limiter which results in rectangular waveforms as shown in Figure 7C. The limiter's output is now an analog of the time that the total waveform is above the threshold level. An analog to digital conversion is accomplished by a Chance oscillator. The rectangular waveforms from the limiter are converted into groups of 5-Mc clock pulses in the Chance oscillator as shown in Figure 7D. These clock pulses are coupled to a digital counter (Hewlett-Packard model 524B). Note that the integration here is not signal integration, which narrows information bandwidth, but a digital integration of an area where the integration in CLIC is performed by counting after the video waveform is processed through the threshold device. It is of interest to note that the information processing circuits in CLIC have a wider bandwidth than that of the band-pass filter which defines the receiver's bandwidth.

It may be possible to improve signal perception by wide-band, information-processing circuitry which utilizes more information in the signal than do present receiving techniques.

3.3 Experimental Procedures.

The experimental procedures employed in measuring perception probability were as follows:

The receiver-noise source (see Figure 1) was connected to the summer. The receiver-noise level was set so that the sine-wave reference to receiver-noise ratio was +35 db. The Millivac RMS noise voltmeter was used to set this ratio. The output from the amplitude channel was coupled to the CLIC and the threshold in the CLIC was set to produce a particular false-alarm probability. The false-alarm probability was computed from the ratio of the number of alarms which occurred to the maximum number which could occur over the time interval of measurement. The false-alarm time interval was set to provide at least 10 false alarms so that a reasonable average false-alarm probability was measured. In the measurement of signal perception, false-alarm probability is not critical; that is, a change in false-alarm probability by a factor of two will result in a change in S/N ratio of less than 0.5 db for most perception probabilities. This eases the experimental measurement techniques.

3.3 -- Continued.

After the false-alarm probability had been determined, the signal-noise source was connected to the summer. The input S/N ratio was measured at the output of the band-pass filter. The S/N ratio was changed in 2-db increments to provide a sufficient number of data points for the construction of a smooth curve of perception probability as a function of the S/N ratio for each false-alarm probability. This probability was determined by the ratio of the number of alarms which were measured to the maximum number of alarms which could occur in the time interval of measurement. Since the number of counts increases with the S/N ratio, the data should be more accurate for large S/N ratios. The region where perception probability was 0.5 or greater was considered the most important region. The data obtained in the amplitude channel was compared with theoretical curves supplied by Mr. S. Gee of these laboratories, which were based on derivations of C. W. Helstrom.[8] The objective in accuracy was to achieve experimental curves within 0.5 db of the theoretical curves. The measurement of amplitude detection provided an experimental control for the harmonic-zone detection.

As stated above, the sine-wave reference to receiver-noise ratio was set at +35 db. This had been found experimentally to be almost the best ratio for improvement in signal perception. The output of the HZ channel was coupled to the CLIC, and the noise output was used to set the desired false-alarm probability. The experimental procedures that followed were identical with those described above for the amplitude channel. There was no integration employed between the detector and the threshold unit. Without integration, the decision about the presence or absence of a signal is made in a time almost equal to the reciprocal of the band-pass filter. This is labeled N=1 in the graph, which corresponds to a decision on one pulse for the perception of pulse signals.

4. EXPERIMENTAL RESULTS.

A comparison of amplitude detection and HZ detection was made for N=1 and false-alarm probabilities of 10^{-3}, 10^{-4}, 10^{-5}, and 10^{-6}. This is the region of main interest, although measurements at lower false-alarm probabilities would also be of interest. Unfortunately, with the IF bandwidth of 80 kc employed in this investigation, a prohibitively long time would be necessary to set the false-alarm probability. Furthermore, any transient interference would upset the accuracy of the measurement.

The experimental results are shown in Figures 8, 9, 10, and 11. These figures show graphs of perception probability as function of the S/N ratio for four false-alarm probabilities. The improvement in signal perception with HZ detection is determined by the additional S/N ratio which must be added to amplitude detection to obtain a particular probability of perception. The improvement in perception with HZ detection was tabulated at perception probabilities of 0.1, 0.5, 0.9 and 0.95, and is presented in Table 1. The improvement is shown in the Δdb columns for each P_{FA}.

The accuracy of measured data is indicated by the agreement (within 0.5 db) of the experimental and theoretical amplitude-detection curves. A conservative estimate of the accuracy of the probability of perception (P_p) for the experimental HZ-detection curves is 1 db. Even with this convervative estimate, there is a significant improvement shown with HZ detection. In the region of greatest importance, where P_p exceeds 0.9, the improvement in perception ranges between 2 and 4 db.

4.1 Qualitative Data.

In addition to the quantitative data described above, a qualitative comparison of HZ detection and amplitude detection was made by observing their outputs on an oscilloscope for square-wave inputs. A photograph of the video outputs from both the HZ channel and the amplitude channel was made and is shown in Figure 12. The picture shows a comparison of the two channels for the three input S/N ratios of 0, +10, and +20 db. The ratio of sine-wave reference to receiver noise in the HZ channel was 35 db. The signal was gated on and off with a square wave at a PRF in the audio range. The residual noise output of the two channels can be observed during the time that the signal is off. This residual noise level was equalized by visual (subjective) means. The qualitative improvement in perception probability in the HZ channel can be seen where the

4.1 -- Continued.

input S/N ratio is +20 db. If a threshold level is assumed at 1 centimeter above the base line for each waveform, the HZ channel shows over 0.9 probability of exceeding the threshold while the amplitude channel shows about 0.5 probability of exceeding the threshold. If the threshold level is assumed at 1/2 centimeter above the base lines, the HZ channel shows almost unity probability of exceeding the threshold while the amplitude channel shows about 0.9 probability. This qualitative comparison is verified by the quantitative comparison in Figure 6 for the case $P_{FA} = 10^{-4}$.

4.2 Experimental Results with Signal Integration.

The results discussed above were obtained with no signal integration after detection. The HZ technique employed in this experiment was predicted to offer improvement in perception for input S/N ratios of +10 db or larger. When signal integration is employed, so that the input S/N ratio is less than +5 db, very little improvement in perception was expected. The HZ technique reduces to straight energy detection at low S/N ratios.

Experimental data was obtained with signal integration for ten times the reciprocal of the bandwidth of the band-pass filter (N = 10). The data showed that HZ detection and amplitude detection produced results that were within 0.5 db of each other in the region of input S/N ratios from 0 to +4 db. There may be other nonlinear processes that improve signal perception in this region, but none have been investigated at this time.

TABLE 1

COMPARISON OF AMPLITUDE DETECTION WITH DETERMINISTIC SIGNAL INJECTION AND HARMONIC-ZONE DETECTION

	$P_{FA} = 10^{-3}$			$P_{FA} = 10^{-4}$			$P_{FA} = 10^{-5}$			$P_{FA} = 10^{-6}$		
P_p	S/N for HZ Det. (db)	S/N for Amp. Det. (db)	Δdb	S/N for HZ Det. (db)	S/N for Amp. Det. (db)	Δdb	S/N for HZ Det. (db)	S/N for Amp. Det. (db)	Δdb	S/N for HZ Det. (db)	S/N for Amp. Det. (db)	Δdb
0.1	2.0	3.9	1.9	3.7	5.1	1.4	4.8	6.2	1.4	7.1	8	0.9
0.5	8.5	10.2	1.7	9.6	11.7	2.1	10.3	12.1	1.8	11.4	13.6	2.2
0.9	15.8	18.4	2.6	16.0	19.4	3.4	16.7	20.0	3.3	17.0	20.4	3.4
0.95	17.5	20.9	3.4	17.6	22.1	4.5	18.0	22.5	4.5	18.4	22.6	4.2

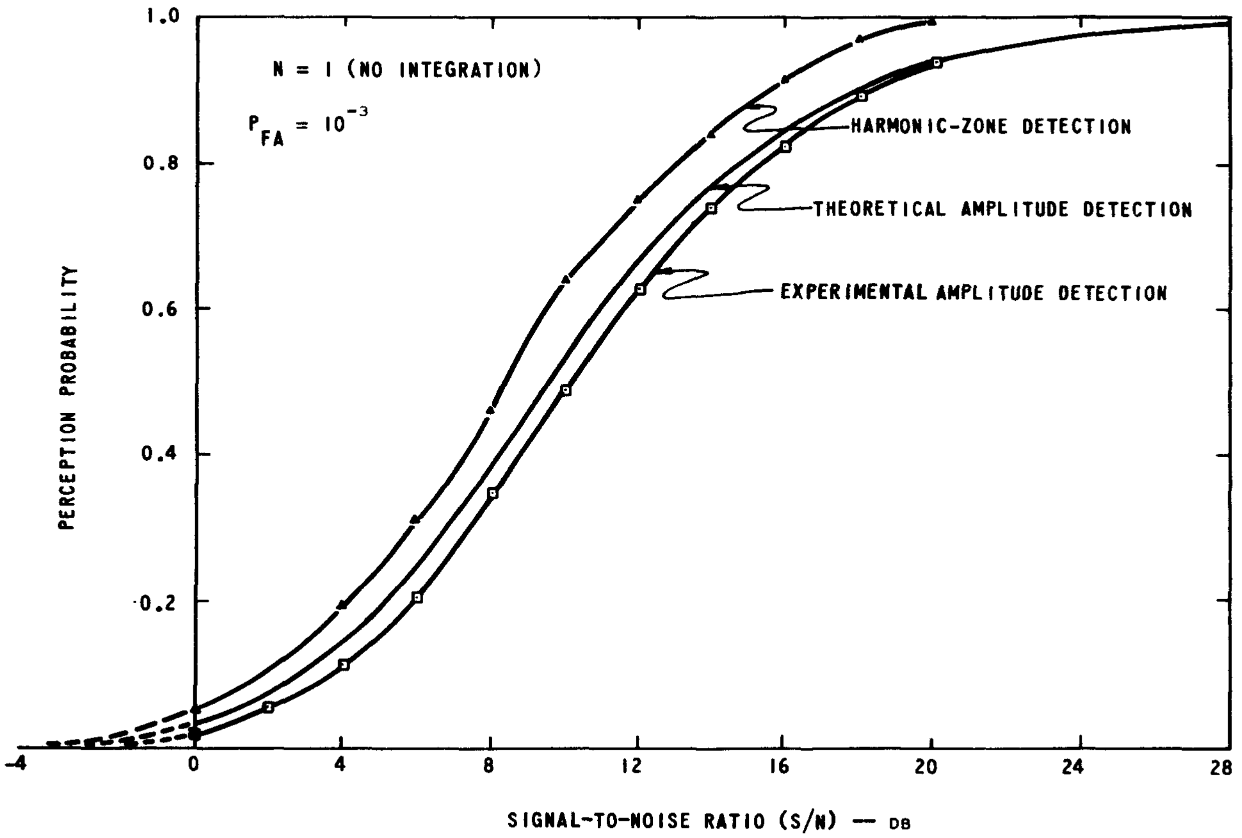

Figure 8
Perception Probability of a Narrow-Band
Gaussian Signal in White
Gaussian Noise -- $P_{FA} = 10^{-3}$

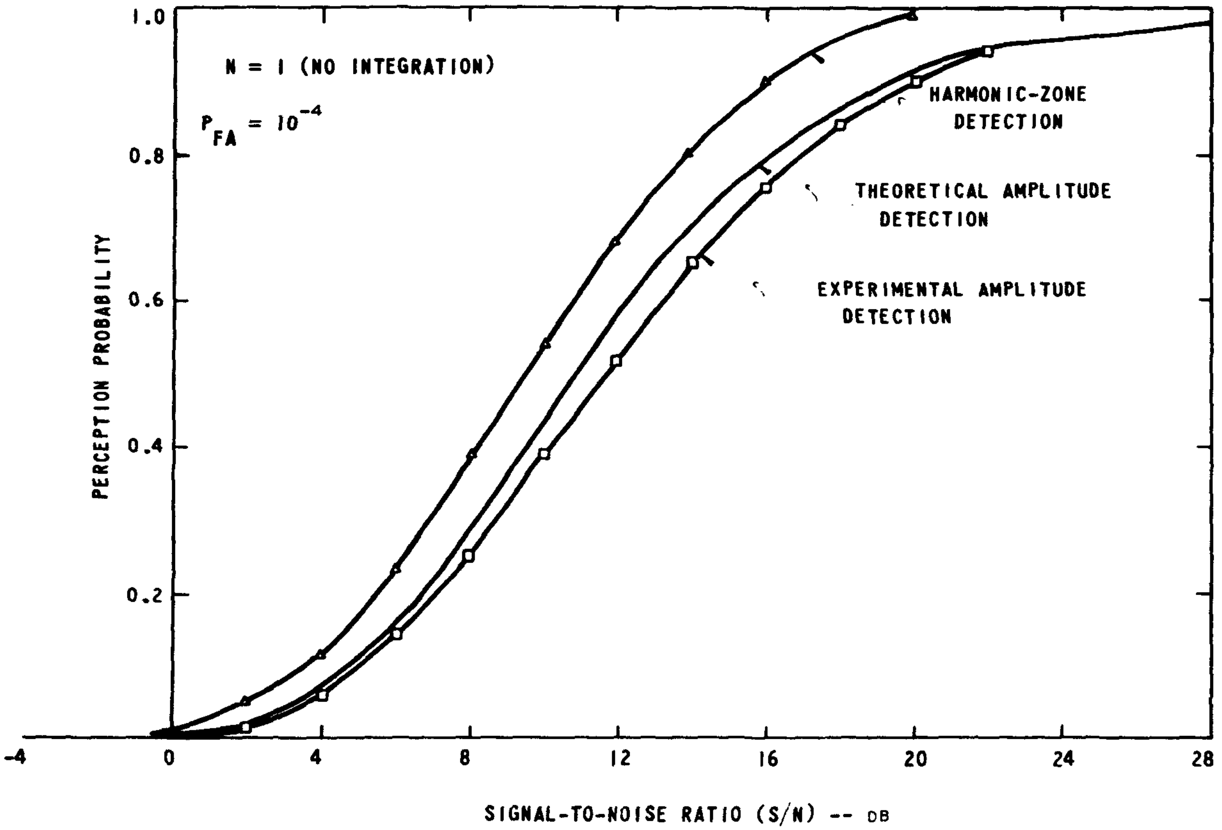

Figure 9
Perception Probability of a Narrow-Band
Gaussian Signal in White
Gaussian Noise -- $P_{FA} = 10^{-4}$

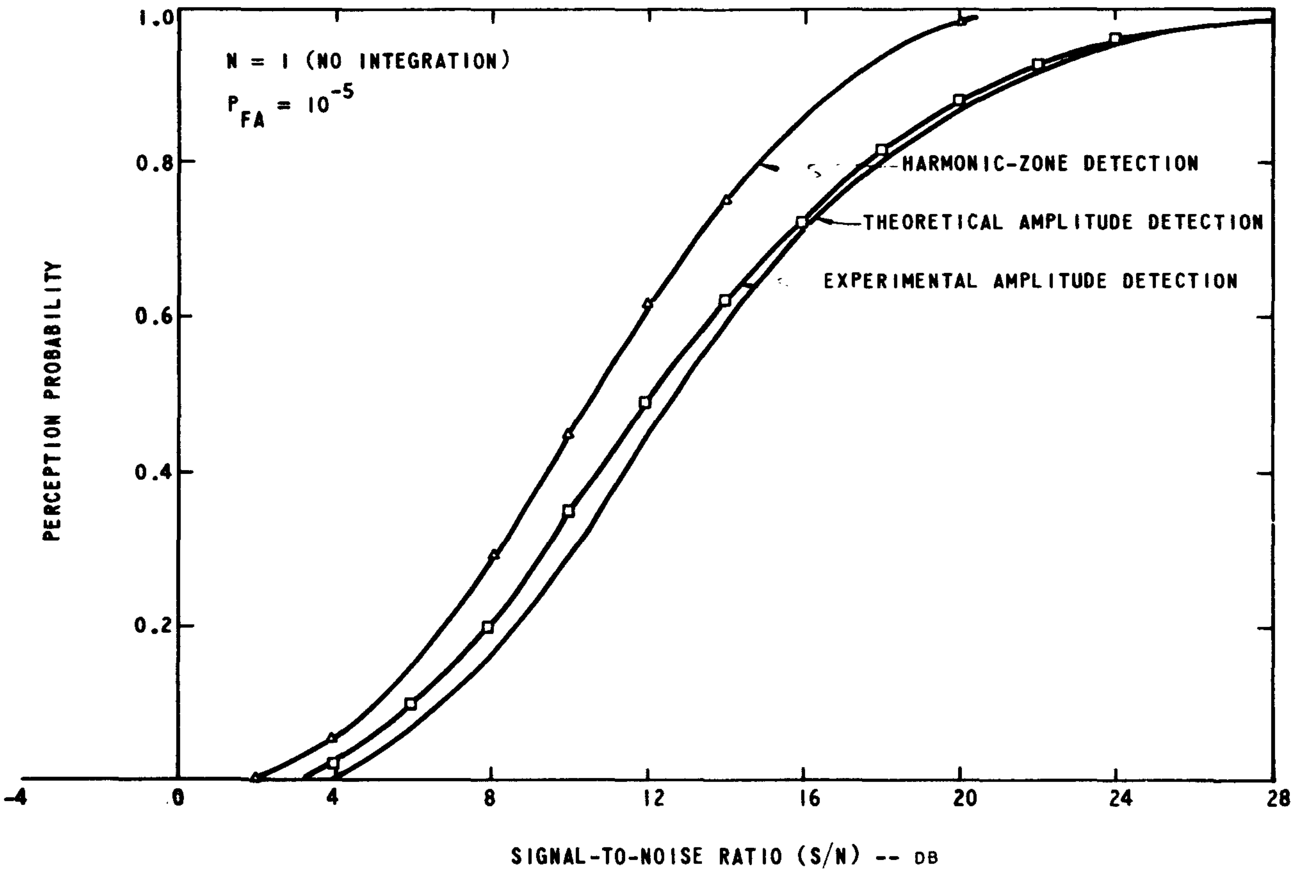

Figure 10

Perception Probability of a Narrow-Band Gaussian Signal in White Gaussian Noise -- $P_{FA} = 10^{-5}$

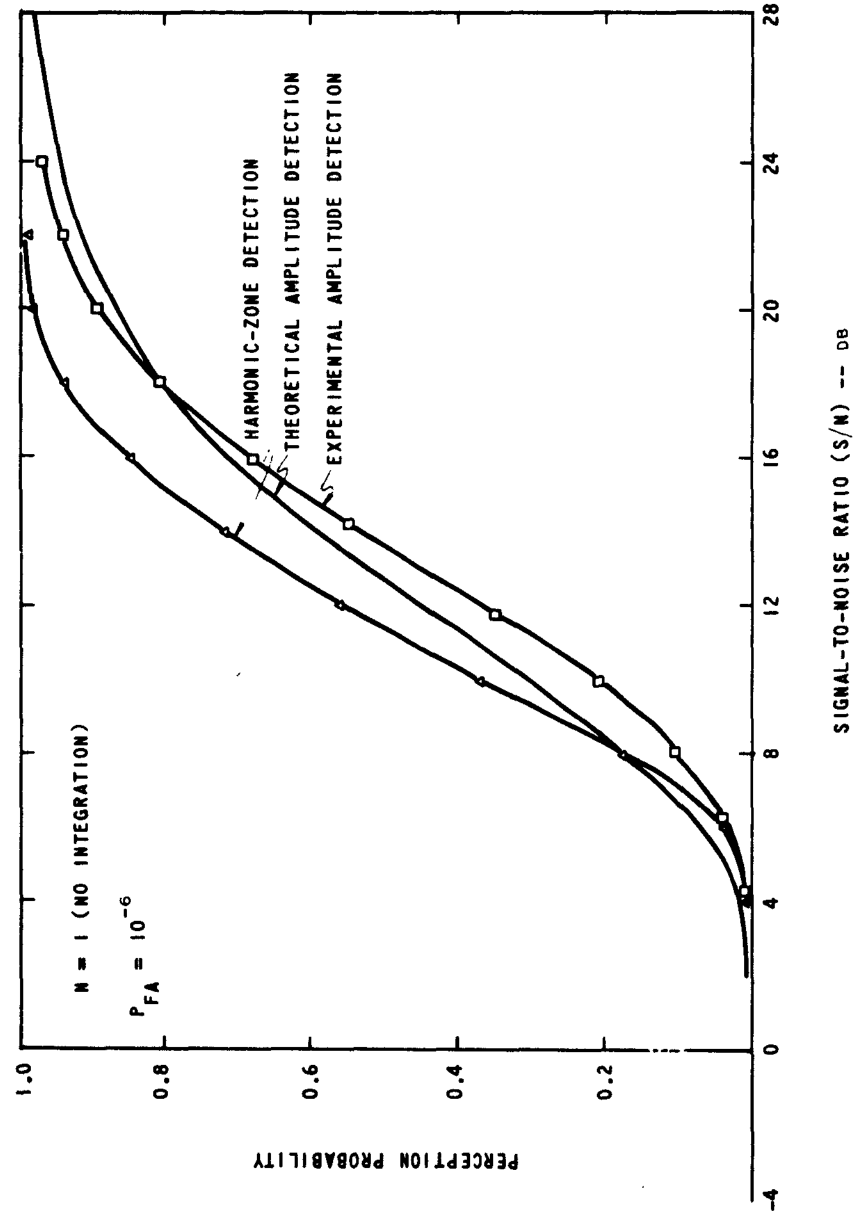

Figure 11
Perception Probability of a Narrow-Band Gaussian Signal in White Gaussian Noise -- $P_{FA} = 10^{-6}$

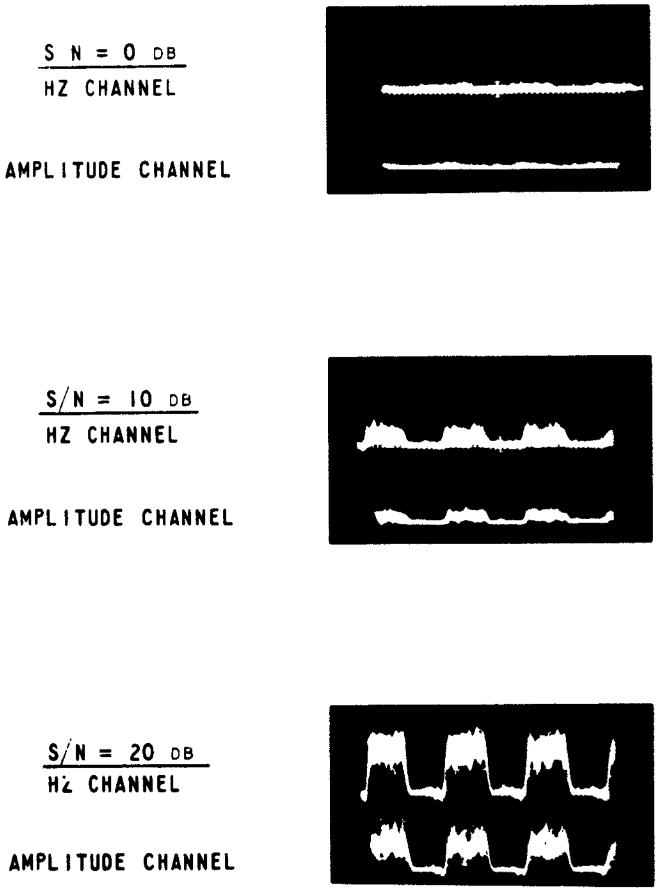

Figure 12
Photograph of the Video Output from the HZ Channel and the Amplitude Channel

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5. SUMMARY AND CONCLUSIONS.

The results of the experimental investigation have confirmed the hypothesis that information contained in the gross phase structure of a random waveform can be used to improve signal perception. This can be done without prior knowledge of the signal phase, other than that the phase probability-density function is random.

The harmonic-zone detection technique investigated and described herein showed over 3-db improvement in S/N ratio as compared with amplitude detection of a narrow-band,Gaussian signal for no integration. A summary of the results obtained is presented in Table 1.

On the basis of the results obtained, it is concluded that further improvement in signal perception can be obtained by additional nonlinear processing of the signal. Nonlinear processing will enable additional information in the signal to be used in the decision process. There is a continuous trade-off of improved signal perception for complexity of nonlinear processing up to the point where full use is made of information in the signal.

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Electronic Defense Labs., Mountain View, Calif
IMPROVEMENT IN GAUSSIAN SIGNAL PERCEPTION BY DETERMINISTIC SIGNAL INJECTION AND HARMONIC-ZONE DETECTION - Arthur Weiner and William R. Kelly. Technical Memorandum EDL-M531, 8 February 1963 (Contract DA 36-039 SC-87499).

An experimental investigation of perception of narrow-band, Gaussian signals was performed. A new technique, using a reference sine wave, a stiff limiter, and a harmonic-zone filter was investigated. The technique used both energy and gross phase characteristics of the Gaussian signal in the perception process. The comparison of this new technique with energy detection showed equal signal perception at 3-db lower S/N ratios for perception probabilities greater than 0 5 at fixed false-alarm probabilities of 10^{-3}, 10^{-4}, 10^{-5}, and 10^{-6}.

1. Gaussian
2. Signal
3. Detection
4. Deterministic
5. Perception
6. Injection
7. Harmonic
8. Zone
9. Narrow
10. Band
11. Reference
12. Sine
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