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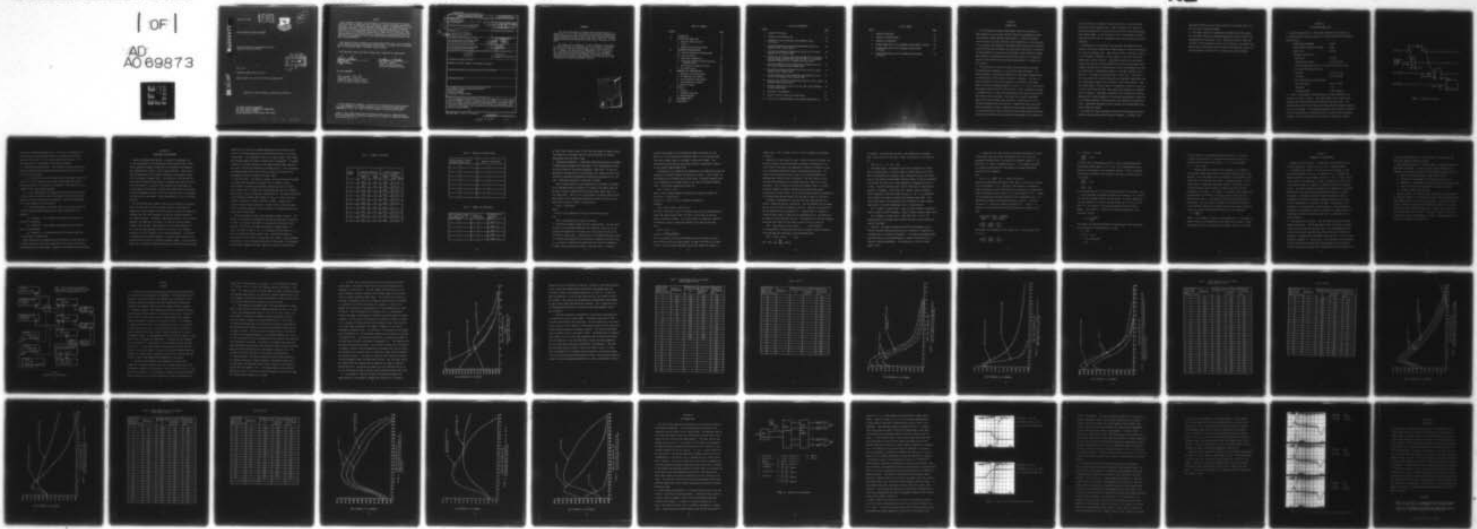
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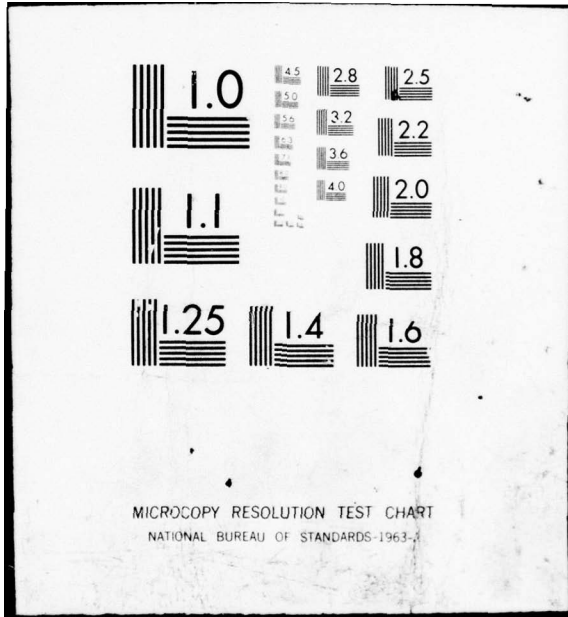
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IFM RECEIVER TEST AND EVALUATION

Passive Electronic Countermeasures Branch
Electronic Warfare Division

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TECHNICAL REPORT AFAL-TR-79-1049

Interim Report for Period May 1978 to November 1978

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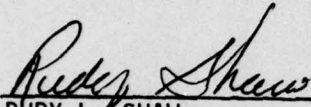
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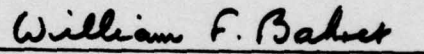
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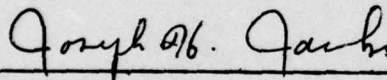
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This technical report has been reviewed and is approved for publication.


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20. ABSTRACT (Continue on reverse side if necessary and identify by block number) The Instantaneous Frequency Receiver (IFM) is a lightweight, low cost receiver which has potential for use in Electronic Warfare Systems. It is also susceptible to erroneous frequency reporting when presented with simultaneous signals. This report summarizes work done with the IFM receiver to statistically characterize the simultaneous signal problem areas and proposes possible methods of mitigating these problems.			

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FOREWORD

This report describes an in-house effort conducted by Mr. R. L. Shaw and Dr. J. B. Y. Tsui of the Passive Electronic Countermeasures Branch, Electronic Warfare Division, Air Force Avionics Laboratory, Wright-Patterson AFB, Ohio, under Project 7633, Task 1115. The work reported herein was performed during the period 1 May 1978 to 1 Nov 1978.

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SECTION I
INTRODUCTION

1. The Instantaneous Frequency Measurement (IFM) radar receiver has been proposed for various USAF and USN Electronic Countermeasures (ECM) and Electronic Support Measures (ESM) systems. To make such systems viable requires a receiver which has a high probability of pulse detection in a very dense electromagnetic environment while remaining cost effective. The IFM receiver has attributes (cost and weight) which make it attractive for such systems, but the receiver has inherent signal detection problems which should be considered when evaluating the receiver as a system component or when evaluating the processing requirements of a system using the receiver.

2. IFM receivers use a series of delay lines which measure frequency by converting the frequency to a well defined phase difference. The phase difference is measured and decoded as an equivalent frequency which is encoded into a digital format and output to registers. The time it takes to encode any particular frequency is a function of the longest delay line and the frequency detection circuitry. In a 2 to 4 GHz receiver the encoding time typically is 100 to 125 ns. After successfully encoding a frequency there is a dead time associated with the receiver during which new signals are not processed. This dead time is usually terminated shortly after the no input energy condition. During the 100 to 125 ns frequency encoding period the receiver's frequency encoding circuits are highly susceptible to noise or additional pulsed inputs contaminations. If a second pulsed RF signal arrives during the encoding period the actual frequency word reported by the receiver may correspond to the frequency of

the first pulse, the frequency of the second pulse, or may not be associated with either frequency input. What is reported is a function of the relative amplitudes of the pulses and the relative time delay between pulse leading edges. It was the intent of this investigation to examine quantitatively the extent of erroneous encoding during these pulse overlap conditions.

3. Manufacturers of IFM receivers have typically considered the simultaneous (0 time delay between pulse leading edges) as a worst-case condition for reporting ambiguous data. These sources typically indicate a range of 0 to 10 dB power differential in input signals as the area in which the encoded data could be incorrect. Experimental results for simultaneous signals show that the discrete probability of incorrectly encoding either frequency (probability of erroneous data) during a simultaneous pulse overlap condition has a maximum peak (peaks) at 1 dB power separation and is about 22%. The range of the problem area is about 16 dB. This data is relatively consistent with published data, but additional experiments show that simultaneous signals do not represent a worst-case condition. When the leading edges of the two signals are separated in time (but within the critical encode time) the power range, peak, and probability of erroneous data all increase. Experiments conducted at 60 ns between pulse leading edges show the discrete probability of erroneous data peaking at about 43% at 5 dB power separation, with the range of the problem area spreading to 50 dB. Experiments conducted at 100 ns between pulse leading edges show similar peaks and spreads.

4. The results of these experiments indicate the IFM frequency encoding problem to be more severe than previously imagined. The effects from

synchronized emitters and multipath conditions could highly affect the IFM utility in a dense environment.

5. This report consists of experiments performed on one IFM receiver, but the authors believe the problems encountered with this receiver are representative of the generic class. Additional testing of other IFM receivers is being pursued to support this conclusion. The authors also believe that incorporation within the receiver of techniques similar to those discussed in Section VII will greatly reduce these problems.

SECTION II
IFM RECEIVER UNDER TEST

1. Receiver Characteristics - The receiver used for this analysis was a Litton-Amecom IFM receiver (Contract No. TSC 352-032) with the following characteristics:

Instantaneous Bandwidth	2-4 GHz
Dynamic Range (Frequency encoding)	55 dB
Sensitivity	-55 dBm
Frequency Characteristic	
Resolution	1.25 MHz
Frequency word output	11 bits (binary)
	(During experiments 10 bits or 2.5 MHz resolution was used)
Pulse width (PW) characteristics	
PW range	.125 to 32 μ sec
PW output	8 bits (binary)
Pulse amplitude (PA) characteristics	
Amplitude range	-55 to -30 dBm
Resolution	1 dB
Amplitude Output	6 bits (binary)

2. Timing - The essential timing characteristics associated with this receiver are shown in Figure 1. The leading edge of the incoming radio frequency (RF) pulse begins the IFM frequency measurement cycle. One hundred twenty (120) ns after the pulse leading edge the frequency encoding circuits are strobed. The frequency measurement cycle requires a minimum of 120 ns of undisturbed (no overlaps) RF pulse to assure correct frequency encoding. The trailing edge of the RF pulse (or composite RF pulses)

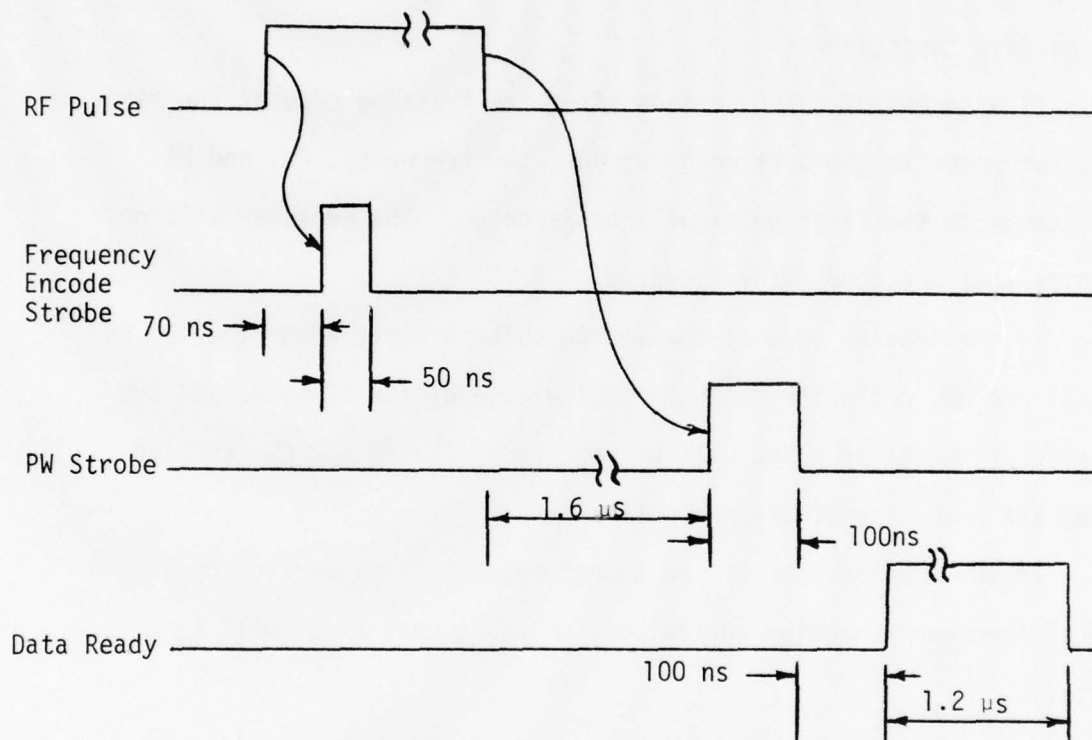


FIGURE 1: Essential IFM Timing

ends the pulse width measurement cycle. This cycle is completed $1.6 \mu\text{s}$ after the trailing edge and the PW word is strobed into its holding register 100 ns later. 100 ns after the pulse width strobe a $1.2 \mu\text{s}$ data ready pulse is transmitted to the receiver processor.

3. Ambiguities and missed pulses - The following timing characteristics describe situations where ambiguities and missed pulses could occur for pulse overlap conditions.

a. If a second RF pulse arrives after the trailing edge of the first pulse, but prior to the data ready strobe, the frequency, PW, and PA associated with the first pulse will be reported. The receiver will not recognize that a second pulse occurred.

b. If the leading edge of the second pulse arrives after the 120 ns critical region, but prior to the trailing edge of the first pulse, the frequency of the first pulse will be reported. The PA and PW reported will be the composite of the two pulses.

c. If the leading edge of the second pulse arrives during the 120 ns critical frequency encoding period, one of three conditions will be reported:

(1) Condition 1 - The frequency associated with the first RF pulse will be reported.

(2) Condition 2 - The frequency associated with the second RF pulse will be reported.

(3) Condition 3 - A frequency word will be reported which has no relationship to either pulse.

Which conditions will predominate during the pulse overlap condition is a complex function of the relative amplitude of the pulses, the relative timing between pulse leading edges, frequencies, and absolute pulse amplitude.

SECTION III
EXPERIMENT CONSIDERATIONS

1. General Experiment Consideration - As stated in paragraph II-3, if the leading edges of two incoming RF pulses are within the critical 120 ns encode and register strobe time of the receiver, the frequency word reported shall conform to one of three conditions. Either one of the two frequencies will be correctly encoded or the frequency report will be erroneous (erroneous data). The objective of this work was to characterize statistically the extent of erroneous data which will occur. Since the problem is a function of the relative pulse amplitudes and leading edge time differential, the tests were constructed to make these variables independent (as much as time and resources permit) of frequency and absolute pulse amplitudes. These considerations led to the following approach.

2. Two RF generators were pulsed at the same Pulse Repetition Frequency (PRF), with the same PW, with a constant relative time differential between pulse leading edges, and with arbitrarily selected RF frequencies. The power level for one RF generator (called the reference generator) was randomly selected. The power of the second generator (called variable generator) was swept over the range of the receiver and the reported frequency word recorded. When the power of the variable generator is at or near the lower detection limits of the receiver, the frequency reported will be the frequency of the reference generator. As the power is increased in the variable generator, a range of power levels will be encountered which results in erroneous frequency reports. As the variable power level is further increased the frequency associated with the variable

generator may or may not be reported depending upon the absolute amplitude of the reference generator and the relative position of the pulses leading edges. This experiment results in a range of power levels around the reference power level where erroneous data is encountered. If enough samples are collected, estimates can be made concerning power separation of signals in dB versus probability of erroneous data. If the frequencies and reference power levels are arbitrarily chosen, this data will be independent of absolute frequency and power levels.

3. Data Collection - Ten samples of typical raw data which were collected by following the technique of paragraph III-2 are shown in Table 1. Sample number 1 indicates the reference generator was set at 3333 MHz with a power level of -20 dBm, the variable generator was set at 3094 MHz and the power varied as discussed in paragraph III-2. The power differential column indicates erroneous data started to occur at -23 dBm (3 dB below -20 dBm) and ended at -21 dBm (1 dB below -20 dBm). Sample number 3 indicates erroneous data occurred at (-37 dBm +4 dBm) -33 dBm and sample number 7 indicates there was a direct transition of frequency readings and no erroneous data occurred.

4. The raw data shown in Table 1 was tabulated as shown in Table 2. The number of occurrences are tabulated by considering each power differential in Table 1 and counting the number of times each dB differential level occurred. For example, the power differential of sample number 1 of Table 1 indicates a range of [-1, -3] or erroneous data occurred at -3, -2, and -1 dB around the reference power level. Note that the Number of Occurrences column of Table 2 indicates the total number of times erroneous data occurred. Since the power differential of each sample in the example was obtained by sweeping the power range of the receiver, each dB level

Table 1: EXAMPLE OF RAW DATA

Sample Number	Reference Generator		Variable Generator	
	Frequency (MHz)	Power (dBm)	Frequency (MHz)	Power Differential (dB)
1	3333	-20	3094	[-1,-3]
2	3694	-29	3486	[-2,-3]
3	2164	-37	3388	[+4,+4]
4	3705	-37	2855	[-1,+4]
5	2147	-32	3261	[+3,+4]
6	3006	-48	2808	[+1,+3]
7	2235	-44	2072	----
8	3811	-38	2871	[+1,+2]
9	2908	-41	2102	[-2,-3]
10	2147	-32	3261	[0,+1]

Table 2: EXAMPLE OF TABULATED DATA

dB differential around a reference power level	Number of Occurrences
+4	3
+3	3
+2	3
+1	4
0	2
-1	2
-2	3
-3	3

Table 3: EXAMPLE OF FOLDED DATA

dB difference around a ref. power level (absolute value)	Number of Occurrences	Probability of erroneous data
0	2	$2/10 = .2$
1	6	$6/20 = .3$
2	6	$6/20 = .3$
3	6	$6/20 = .3$
4	3	$3/20 = .15$

of Table 2 was visited a total of ten times (the number of samples taken). The probability of erroneous data for each dB differential could be approximated from this type of data.

5. Conditional Probability - Conditional probability was used in a number of applications throughout this experiment in the interpretation of data and justification of statistical approaches. Each time it is used its application and approach shall be discussed, but a general review of this statistical technique and appropriate notation may be beneficial at this time. Conditional probability is defined as follows:

Given a sample space S , we are sometimes only interested in outcomes of an experiment which are elements of a subset of the sample space (B). We have to define a probability set function with B rather than S as the sample space. That is, for a given event A , we want to define $P(A|B)$, where $P(A|B)$ is the conditional probability of event A occurring given event B has occurred. $P(A|B)$ is by definition:

$$P(A|B) = P(A \cap B)/P(B)$$

where

$P(A \cap B)$ is the probability of event A and event B occurring
and

$P(B)$ is the probability of event B occurring.

6. Conditional Probability Application to Gathered Data - The data shown in Table 2 can be folded around the 0 dB differential level and we can consider the probability of erroneous data versus absolute value of dB difference in power levels. The objective for considering absolute values is to divorce the probabilities from having to reference directional data (i.e., we want to statistically characterize the receiver irrespective of power levels being above or below a reference level). We want to

consider the probability of erroneous data when two signals are X dB apart (i.e., we are assuming an incoming signal is at an arbitrary power level and a second signal is X dB above or below this signal). The probabilities which could be calculated from data as tabulated in Table 2 can not produce these probabilities.

The objective is to determine the probability of erroneous data given two signals are X dB apart (denote this objective as P(B)). P(B) is equal to the probability of erroneous data and the signal X dB above reference level or the probability of erroneous data and the signal X dB below reference level. This becomes mathematically equal to:

$$P(B) = P(B|X+) + P(B|X-)$$

where X+ and X- denote respectively power levels above and below X dB

but $P(B|X+) = P(B|X+) P(X+)$

and $P(B|X-) = P(B|X-) P(X-)$ by conditional probability

therefore

$$P(B) = P(B|X+) P(X+) + P(B|X-) P(X-)$$

The $P(B|X+)$ and $P(B|X-)$ terms in the above equation can be approximated by taking the appropriate dB levels in Table 2 and dividing by the total number of samples collected. It is also obvious to assume the probability of selecting X above or below the reference level would be the same.

Then

$$P(X+) = P(X-) = \frac{1}{2}$$

$$\text{and } P(B) = \frac{P(B|X+) + P(B|X-)}{2}$$

This is equivalent to folding the summed data points around 0 dB level and dividing by twice the sample number for power differentials not equal to 0 dB. For 0 dB signal separation the divisor remains the number of

samples taken. This is shown in Table 3 for the example data tabulated in Table 2.

7. Generation of the Probability Curve - None of the data collected, tabulated or operated upon by the methods discussed in Paragraphs III-4 or III-6 allows a true ogive to be generated or cumulative probability curve to be extrapolated which sufficiently characterizes the receiver. For example, we can graph that data of Table 3 as discrete probability of erroneous data versus dB level differential. But this results in only considering the probability of erroneous data when signals are exactly X dB apart. This is obvious since each dB difference level is in itself a Binomial Probability density distribution (we have either good or erroneous data in each level). We can not say anything about the probability of erroneous data when two signals are less than or equal to X dB apart.

As stated in paragraph III-7 each dB level has associated with it a Binomial Probability density distribution. Let the probability of erroneous data in the nth dB level be denoted as $P(B|S_n)$. These are the empirically derived probabilities of paragraph III-6. Suppose there is a method of selecting the dB levels in which we are interested and call the probability of selecting the nth dB level as $P(S_n)$. The probability of getting erroneous data, given two signals are less than or equal to S_n dB, is given by:

$$P(B) = P(S_0) P(B|S_0) + P(S_1) P(B|S_1) \dots + P(S_n) P(B|S_n)$$

If the probability of selecting any dB level is equally likely (an assumption based upon the uniformity of the environment) then:

$$P(S_0) = P(S_1) = P(S_2) = \dots = P(S_n)$$

$$\text{and: } P(B) = \frac{1}{n+1} \sum_{I=0}^n P(B|S_I)$$

For example: Using the data in Table 3, the probability of erroneous data if two signals are less than or equal to 2 dB apart can be found to be:

$$P(B) = \frac{1}{3} [.2 + .3 + .3] = .267$$

8. The Sample Space - The approach specified in paragraph III-2 represents one datum sample. The total number of samples which exist in the space is governed by the frequency range, frequency accuracy, and dynamic range of the receiver and the power leveling accuracy of the test equipment. The receiver under test has a 2 GHz bandwidth and frequency accuracy of 2.5 MHz. This means there are 800 (2 GHz/2.5 MHz) ways of choosing each generator's frequency. The receiver has a dynamic range of 56 dB and the RF attenuators used have a power accuracy of 1 dB. This combination implies there are 56 ways of choosing the reference power level. The total sample space to be considered is the combination of these elements taken one at a time with replacement and is calculated below.

No. of samples in sample space = (ways to choose reference frequency) x (ways to choose variable frequency) x (ways to choose reference power level).

$$\text{No. of samples in sample space} = (800) (800) (56) = 35.84 \times 10^6$$

The magnitude of the sample space indicates the need to apply statistical sampling techniques.

a. Sampling - The sampling method and statistical approaches as previously discussed indicate each dB level as a function of probability of erroneous data is a binomial distribution. If we make the assumption that each distribution can be approximated by a normal distribution we can develop a sampling methodology. This assumption is valid for large sample values.

b. Assume that p is that fraction of erroneous data which will exist in the sample space and we wish to estimate p by p' so that we are reasonably confident that p' lies within an acceptable range of p . We want $P(|p'-p|<\epsilon)$ with a confidence level of γ . If N samples are taken, p' is equal to S_n/N where S_n is the number of erroneous data points occurring in the N samples.

Then

$$P(|p'-p|<\epsilon) = P\left(\left|\frac{S_n}{N} - p\right|<\epsilon\right) = P(N(p-\epsilon)<S_n<N(\epsilon+p))$$

Binomial distributions by definition have a mean (μ) of Np and a variance (σ^2) of Npq (where $q = 1-p$). Because of the inability to integrate a normal distribution, normal distributions are converted to a standardized normal distribution curve of mean (μ) of 0 and variances (σ^2) of 1. Numerical approximations have been tabulated for this standardized curve. To approximate a binomial distribution which has a mean of $\mu = Np$ and a variance of $\sigma^2 = Npq$ with a normal distribution of $\mu = 0$ and $\sigma^2 = 1$, subtract μ from both sides and divide both sides of the inequality by σ .

Then

$$P\left(\frac{N(p-\epsilon)-Np}{(Npq)^{1/2}} < \frac{S_n-Np}{(Npq)^{1/2}} < \frac{(\epsilon+p)N-Np}{(Npq)^{1/2}}\right)$$

$$P\left(\frac{-\epsilon N^{1/2}}{(pq)^{1/2}} < \frac{S_n-Np}{(Npq)^{1/2}} < \frac{\epsilon N^{1/2}}{(pq)^{1/2}}\right)$$

And we want this probability to be larger than γ , the confidence interval (C.I.).

$$P\left(\frac{-\epsilon N^{1/2}}{(pq)^{1/2}} < \frac{S_n-Np}{(Npq)^{1/2}} < \frac{\epsilon N^{1/2}}{(pq)^{1/2}}\right) \geq \gamma$$

If $\gamma = .95$ and $\epsilon = .05$ then

$$\frac{.05N^{\frac{1}{2}}}{(pq)^{\frac{1}{2}}} = 1.96$$

The value 1.96 is the tabulated value of Z (from a standardized normal distribution table), where Z is $(1 + \gamma)/2$. This transformation occurs because of the symmetry of the confidence interval. Since p is derived from binomial distribution the maximum of the product pq never exceeds $\frac{1}{4}$ and yields

$$\frac{.05N^{\frac{1}{2}}}{(\frac{1}{4})^{\frac{1}{2}}} = 1.96$$

and $N = 384$

This approximation for N is the worst-case condition for the given ϵ and γ . As the experiment progresses and samples are collected ϵ as a function of N and the confidence interval can be revised. If after N samples we find the estimate for p to be p' and the estimate for σ^2 to be the estimator S^2 , a new range of ϵ can be established which reflects the N samples. This interval is given by the following equation for a 95% confidence interval.

$$\epsilon = 1.96 \frac{(p'(1-p'))^{\frac{1}{2}}}{(N)^{\frac{1}{2}}}$$

For example, one experiment yielded the following data after 295 samples were collected at 16 dB separation in signals.

$$p' = .297$$

$$p'(1-p') = .209$$

$$\epsilon = 1.96 (.457/(295)^{\frac{1}{2}})$$

$$\epsilon = .052$$

For this example if many samples were taken and their p' calculated it should be true that 95% of them would contain the true value of p and the p would lie within the range $p' \pm \epsilon$. Or in this example $p' \pm \epsilon = [.245, .349]$.

c. Another aspect of sampling to be considered is the method of selecting the random samples and the non-infinite dynamic range of the receiver. One signal power level is considered to be uniformly distributed from 0 to -55 dBm and this signal is randomly selected. If the second signal is swept over the dynamic range of the receiver, as previously discussed, then the number of samples acquired for each dB difference is a variable. For example, if the power of the random signal were selected to be -55 dBm, it is obvious, because of the receiver's dynamic range, that a -1 dB through -56 dB power difference could not be obtained. The total number of samples for each power differential can be derived by making such considerations at every random samples dB level and is given by the following equation for non-folded data.

$$N' = \frac{56-n}{56} N$$

where N' is the number of samples at n dB separation, N is the number of samples taken at 0 dB separation, and 56 comes from the number of power differences levels for a receiver with a dynamic range of 0 to -55 dBm.

SECTION IV
HARDWARE TEST CONFIGURATION

1. Hardware Test Configuration - The physical test configuration used in these experiments is shown in Figure 2 and is summarized below.
2. RF Generation and Control - RF continuous wave (CW) power is generated by RF generators #1 and #2. RF generator #2 is a frequency synthesizer which has a visual readout accuracy of 1 KHz. To obtain similar visual display for RF generator #1, power is tapped from its RF line by a directional coupler and supplied to a Hewlett Packard (HP) frequency counter. CW signals from each RF generator are transmitted to pin diodes which modulate the signals and deliver pulsed RF signals to variable attenuators. The power associated with each modulated RF signal is independently controlled by variable attenuators which have a range of 121 dB in combinations of 10 dB and 1 dB steps. The accuracy of the attenuators is consistent with HP specifications for these attenuators. Attenuated and modulated RF signals are combined in a power divider and distributed to either the receiver under test or a power meter via a manual RF switch.
3. Pulse Generation and Control - The PIN diodes are driven by the HP 8403A PIN modulators. The PIN modulators control the width of the modulating pulse and supply driving power only. The pulse repetition rate and the relative pulse positions are controlled by the HP 1900A pulse generator. Throughout this experiment a pulse width of 1 μ sec at a pulse repetition frequency of 1 KHz was used. The pulse width, pulse repetition rate and the relative pulse positions were determined by removing the RF input to the receiver under test and connecting the test generator to

an Aertech DM 204BP detector. The video output of the detector was read with a Tektronix 7904 oscilloscope.

4. Power Reading and Control - All power readings associated with this experiment are CW power. To read the power associated with each RF generator incident upon the receiver, the following procedure was used:

- a. Manual RF switch was placed in power meter position
- b. Attenuator of RF generator to be read was placed at 0 dB
- c. Attenuator of RF generator not read was placed at full attenuation
- d. Input to PIN diode of RF generator to be read was removed
- e. CW power at power meter was read

5. Receiver Output - The receiver under test detects and digitizes the RF input and transmits a 10 bit parallel digital word which describes the input frequency and a 1.2 μ sec data ready signal. The digital word was visually analyzed by observing the HP 1600 Logic Analyzer. The Logic Analyzer has three modes which were used: 1) mode 1 allows the 10 bits to be displayed as logic 0's and 1's; 2) mode 2 displays 10 bits as a unique dot on a CRT (called mapping); 3) mode 3 allows expansion of the map around a manually set digital word.

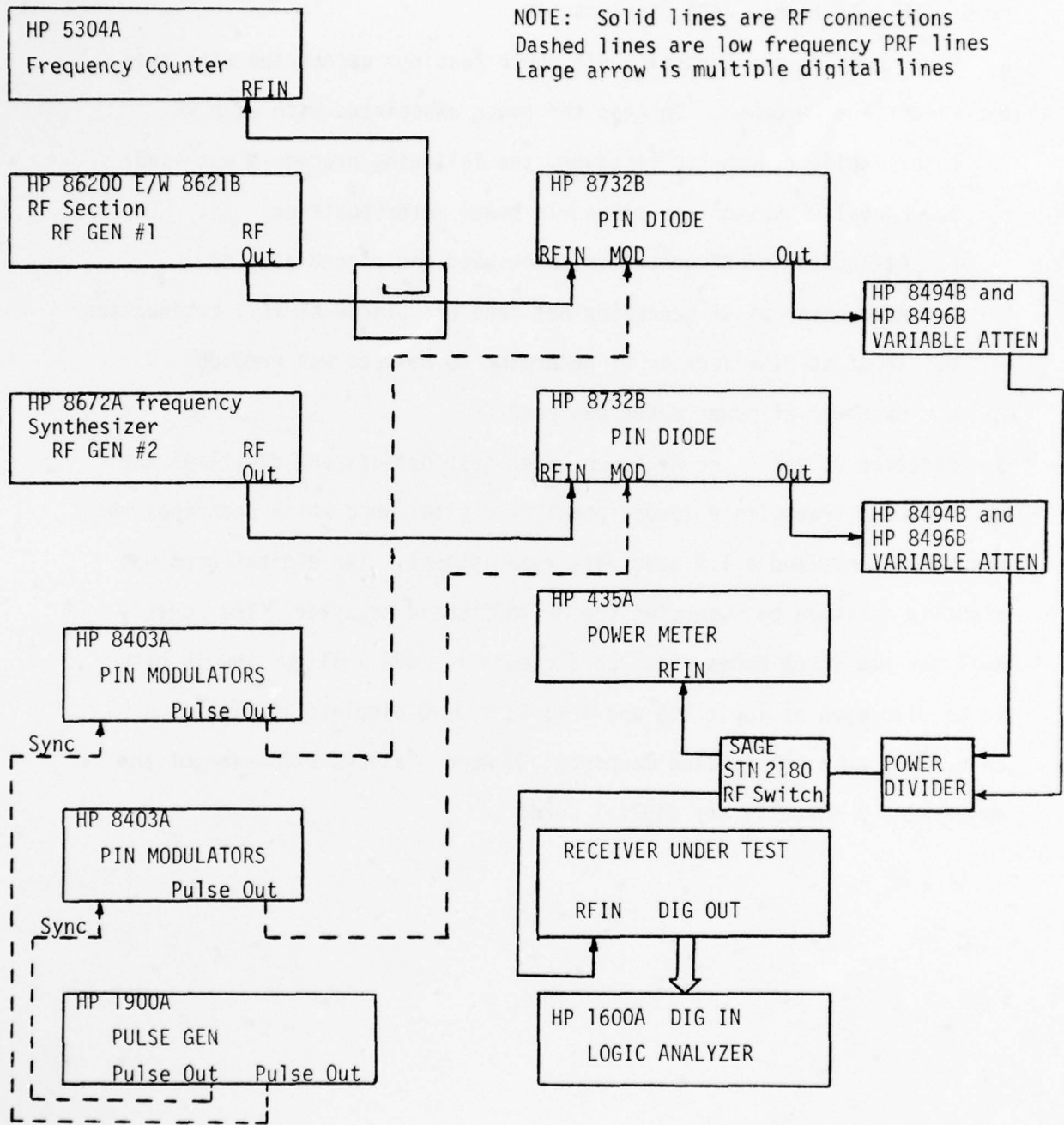


Figure 2
 Hardware Test Configuration

SECTION V

TESTING

1. Initially, the approach to evaluating the statistical characteristics of the receiver was systematically implemented. This method was soon replaced by a more statistically valid approach, but a discussion of the systematic method and resulting data does represent some interesting aspects of the receiver under test and of receiver testing in general.

2. Systematic Approach - This method was initially considered and implemented because of the rapidity of the sampling set-up time. As shown in Figure 2 one of the RF sources was an HP 8621B sweeper with frequency readings obtained by a counter via directional coupler. This generator is manually controlled and it is time consuming to set it to an accuracy of three significant digits. The second RF source was an HP 8672A frequency synthesizer which has a built-in digital readout and is quickly incrementally tuned. If the sweeper could be set a minimal number of times the savings in time would be significant. In addition to the frequency set up time there is a large amount of time required to adjust and read power levels. If the reference power level was set only once for many samples, time could be saved. Of course limiting the reference power and frequency to specific areas increases the probability of biasing the data because of the limited number and nonrandomness of the samples.

a. The above testing method was implemented by setting the RF sweeper at a reference frequency level and a reference power level, and incrementally sweeping the synthesizer in 50 MHz steps over the 2 to 4 GHz range of the receiver. At each frequency increment the power differential where erroneous data occurred was measured by viewing the generated fre-

quency word at each dB level of the sweep. If the frequency word changed by less than 4 bits (± 10 MHz) the frequency word was considered a valid report. This method results in 41 (the number of 50 MHz increments) samples per reference power setting. By leaving the reference generator set at the same frequency, switching the associated attenuator 10 dB, and again sweeping the band, additional data samples are easily obtained.

b. This method was implemented with 0 time delay between the leading edges of the RF pulses, with the reference generator set at 2.2, 3.0, and 3.8 GHz, and reference power levels at -40, -30, -20, and -10 dBm. The total number of samples per reference frequency setting were 164 and the total number of samples in the experiment were 492. The raw data collected was operated upon by the techniques discussed in paragraph III, and the discrete distribution curve for each reference frequency setting is shown in Figure 3. As can be seen by reviewing Figure 3, the data as collected by this approach appears to be frequency dependent and as such can not be considered a valid representation of the receiver characteristics with any degree of certainty. The graph of the composite data does show some interesting characteristics when compared to data collected by another method and these characteristics are discussed in paragraph V-3b. The variance of the data resulted in a more general testing approach.

3. Random Approach - This testing approach utilizes random selection of the reference frequency, variable frequency, and reference power level. A random number was generated by the internal program in an HP 9825A calculator under the mnemonic "rnd". This random number was multiplied by appropriate factors to range the frequencies between 2 and 4 GHz and range the reference power between 0 and -55 dBm.

a. Initially the RF pulses were set with 0 time separation between leading edges. The method of detecting the leading edge separation is discussed in paragraph IV-3. Each data sample involved setting the reference frequency, variable frequency, and reference power level according to the calculator generated random number. The raw data was collected as discussed in paragraph III-2 with an erroneous frequency output considered as a deviation of ± 10 MHz from either set frequency. A total of 335 samples were collected at 0 dB separation and the tabulated data as shown in Table 4. $P(E)$, the probability of erroneous data, is calculated by dividing the number of occurrences of erroneous data by the number of samples collected. In the case of 0 dB separation, the number of samples collected is 335. Because of folding the data and the dynamic range of the receiver, in all other power separations, the number of samples is a variable as discussed in paragraph III-8c. The deviation (ϵ) associated with each power level differential for a 95% confidence interval was calculated as discussed in paragraph III-8b. The cumulative probability of erroneous data shown in the table was calculated as discussed in paragraph III-7. The probability of erroneous data and the associated ϵ as a function of power level differential is graphed in Figure 4 and the probability of erroneous data and the cumulative probability of erroneous data as a function of power level differential are plotted in Figure 5. The data for the given input conditions indicates a 16 dB differential where erroneous data occurred. This only means that of the samples taken no erroneous data was detected at a power differential larger than 16 dB. The cumulative probability curve indicates that 97% of the time data would be good if the two signal spread were larger than 16 dB.

b. As a matter of interest, the data collected per reference frequency setting in the systematic approach was combined into a composite

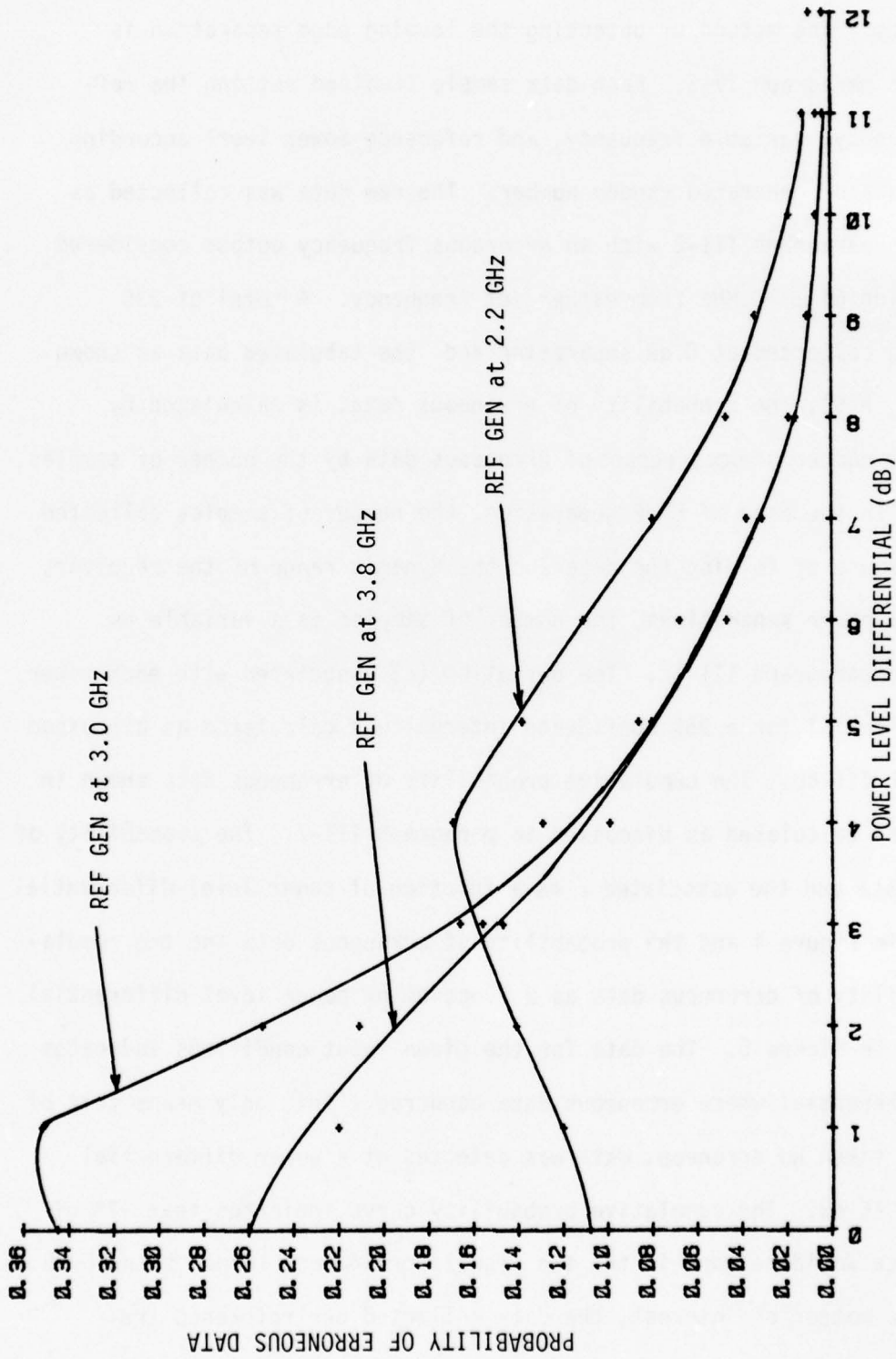


FIGURE 3
Probability Curves Generated from
Systematic Data, 0 ns Delay

probability curve and compared to the data collected in the random approach. Figure 6 shows the systematically acquired data superimposed upon the calculated curves for the expected deviation ϵ at a 95% C.I. for the randomly acquired data. As can be seen from this plot, the curves are quite well matched. This implies the systematically acquired data could probably be used if more points were chosen for inclusion. This is especially true if automated testing ability is utilized so that many systematic points are available.

c. The only variable not accounted for in the previous experiment was time separation of pulse leading edges. To determine the effect of this parameter two additional tests were made. The time separation of the pulses was set at 60 ns and 316 samples at 0 dB separation were collected using the random generation approach previously discussed. This data and associated plots are shown in Table 5 and Figure 7 and 8. The probability of erroneous data peaked at 43.2% at 5 dB signal separation and the problem area spread to 50 dB separation. The time separation of pulses was then extended to 100 ns and 245 data samples were collected at 0 dB separation. This data and associated plots are shown in Table 6 and Figure 9 and 10. In this case, the probability of erroneous data was maximum at 14 dB signal separation at 42.5% and the problem area width was 48 dB. The discrete probability curves for each time-separated experiment are shown superimposed in Figure 11.

Table 4: Folded Random Data at 0 ns Between Leading Edges of Pulses

dB Difference Around a ref Power Level (Absolute Value)	Number of Occurrences	Probability of Erroneous Data P(E)	ϵ differential at 95% (C.I.) Confidence Interval	Cumulative Probability of Erroneous Data
0	66	.197	.043	.019
1	147	.223	.032	.211
2	128	.198	.031	.206
3	107	.169	.029	.198
4	66	.107	.024	.178
5	53	.087	.022	.164
6	31	.052	.018	.148
7	20	.034	.015	.133
8	14	.025	.013	.121
9	13	.023	.012	.111
10	12	.022	.012	.103
11	9	.016	.011	.096
12	8	.015	.011	.090
13	8	.016	.011	.085
14	3	.007	.007	.079
15	2	.004	.006	.075
16	1	.003	.005	.070
17				.067
18				.063
19				.060
20				.057
21				.054
22				.052
23				.050
24				.048
25				.046
26				.045
27				.043
28				.041

Table 4 (Cont'd)

dB Difference Around a ref Power Level (Absolute Value)	Number of Occurrences	Probability of Erroneous Data P(E)	ϵ Differential at 95% (C.I.) Confidence Interval	Cumulative Probability of Erroneous Data
29				.040
30				.039
31				.037
32				.036
33				.035
34				.034
35				.033
36				.032
37				.032
38				.031
39				.030
40				.029
41				.029
42				.028
43				.027
44				.027
45				.026
46				.025
47				.025
48				.024
49				.024
50				.023

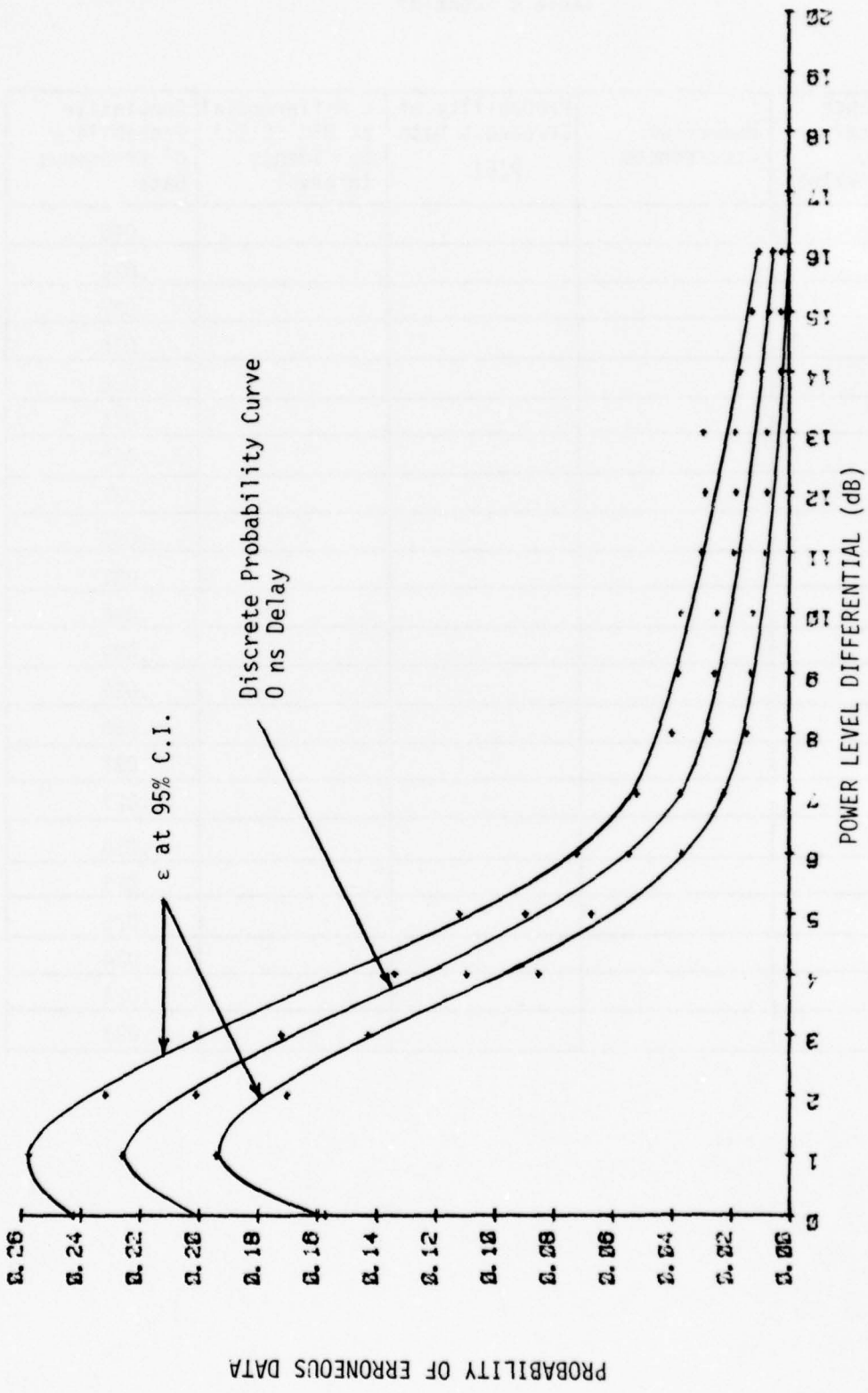


FIGURE 4: Discrete Probability Curve Generated Randomly with 0 ns Between Pulse Leading Edges

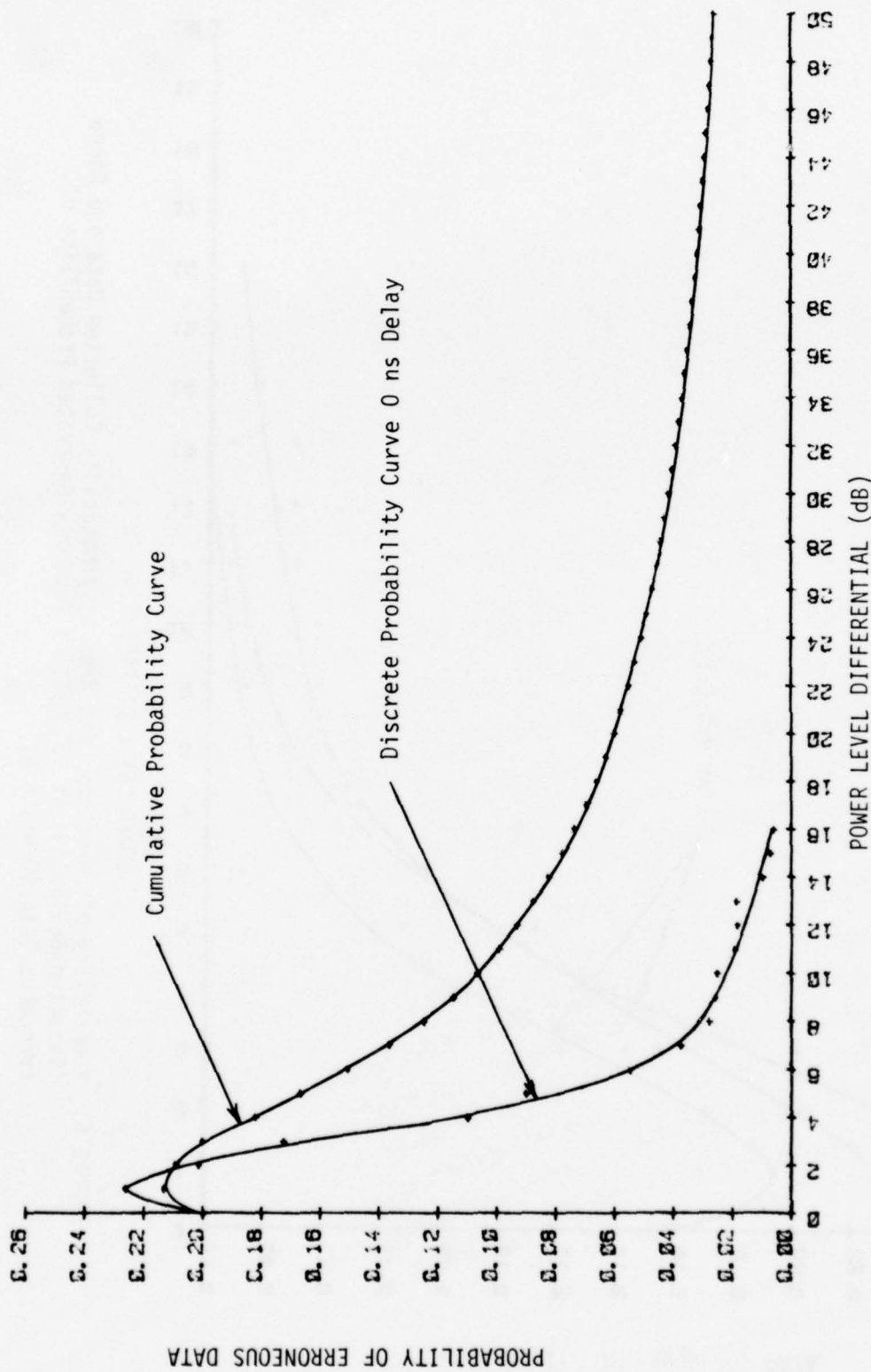


FIGURE 5: Discrete and Cumulative Probability Curves for 0 ns Delay Between Pulses Leading Edges

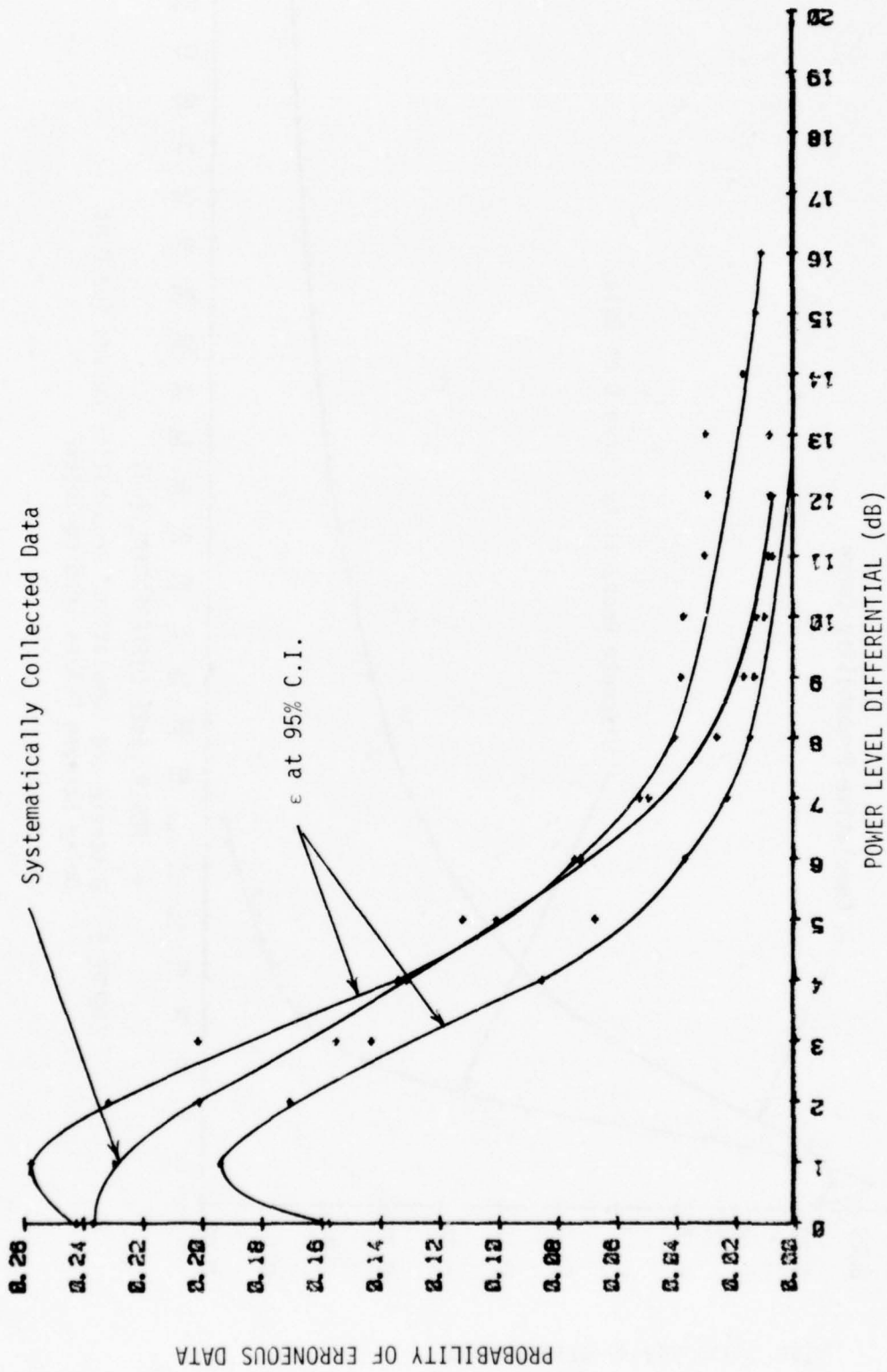


FIGURE 6: Probability of Erroneous Data from Systematically Collected Data and Range (Expected Deviation) at 95% C.I. of Randomly Generated Probability of Erroneous Data (0 ns Delay)

Table 5: Folded Random Data at 60 ns Between
Leading Edges of Pulses

dB difference around a ref power level (absolute value)	Number of Occurrences	Probability of Erroneous data P(E)	ϵ differential at 95% (C.I.) Confidence Interval	Cumulative Probability of erroneous data
0	88	.279	.049	.279
1	180	.290	.036	.285
2	208	.341	.038	.304
3	218	.365	.039	.319
4	245	.418	.040	.339
5	248	.432	.041	.354
6	238	.423	.041	.364
7	226	.410	.041	.370
8	211	.391	.041	.372
9	194	.369	.041	.372
10	173	.335	.041	.369
11	157	.311	.040	.364
12	149	.302	.040	.359
13	149	.309	.041	.356
14	127	.270	.040	.350
15	121	.264	.040	.344
16	117	.261	.041	.340
17	104	.239	.040	.334
18	95	.224	.040	.328
19	87	.211	.039	.322
20	80	.200	.039	.316
21	65	.167	.037	.310
22	55	.145	.035	.302
23	53	.143	.036	.296
24	49	.138	.036	.290
25	43	.125	.035	.283
26	38	.114	.034	.277
27	37	.116	.035	.271
28	31	.100	.033	.265

Table 5 (Cont'd)

dB Difference Around a ref Power Level (Absolute Value)	Number of Occurrences	Probability of Erroneous Data P(E)	ϵ differential at 95% (C.I.) Confidence Interval	Cumulative Probability of Erroneous Data
29	20	.068	.028	.259
30	24	.084	.032	.253
31	17	.062	.028	.247
32	15	.057	.028	.241
33	15	.060	.029	.236
34	15	.063	.031	.231
35	14	.061	.031	.226
36	11	.052	.029	.222
37	12	.058	.032	.217
38	12	.061	.034	.213
39	12	.065	.036	.210
40	7	.029	.025	.205
41	4	.028	.025	.201
42	2	.013	.018	.197
43	1	.009	.016	.192
44	1	.010	.017	.188
45	1	.011	.019	.184
46	1	.012	.021	.181
47	1	.014	.024	.177
48	1	.016	.027	.174
49	1	.018	.032	.171
50	1	.022	.038	.168

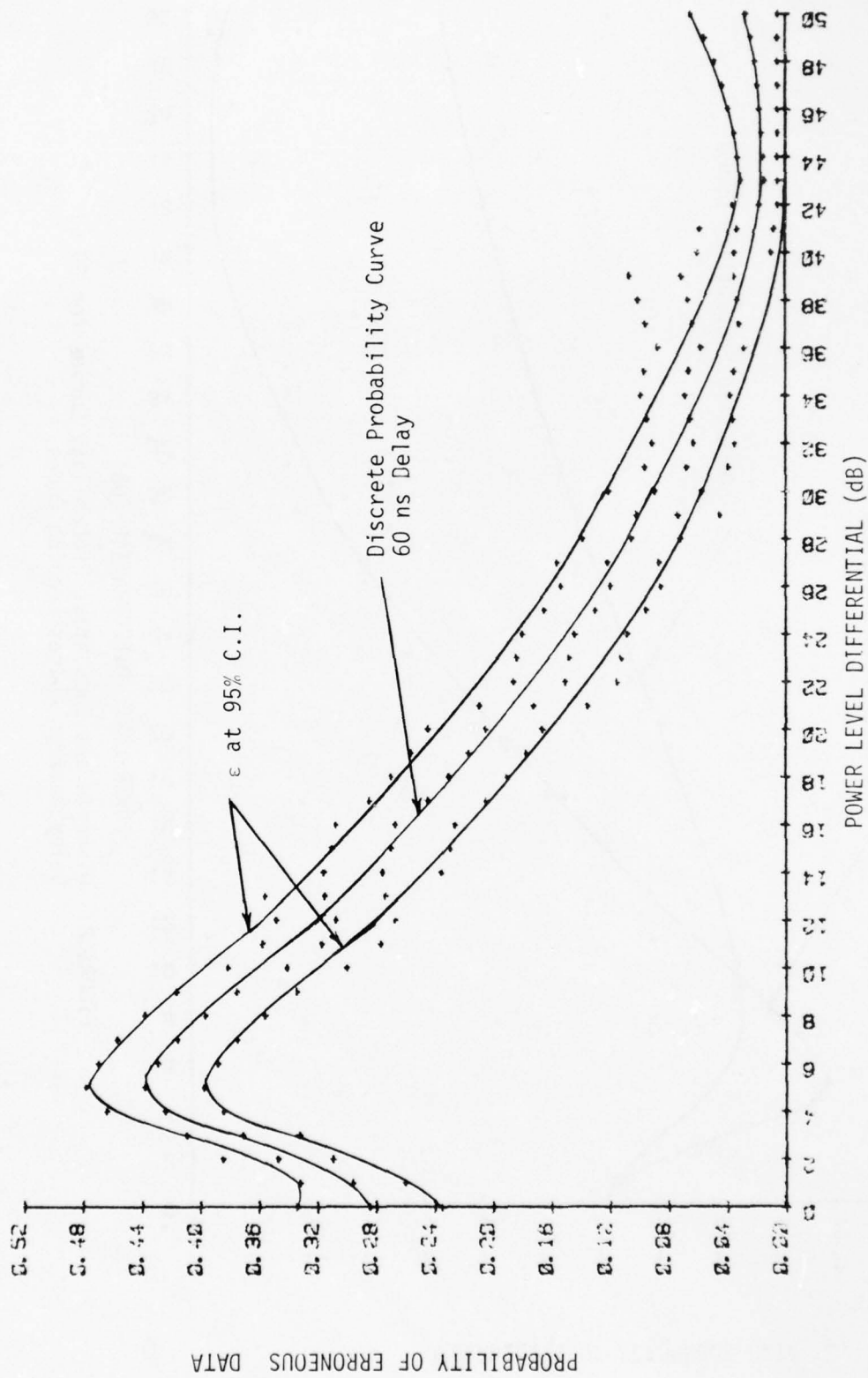


FIGURE 7: Discrete Probability Curve Generated from Random Data with 60 ns Delay Between Pulse Leading Edges

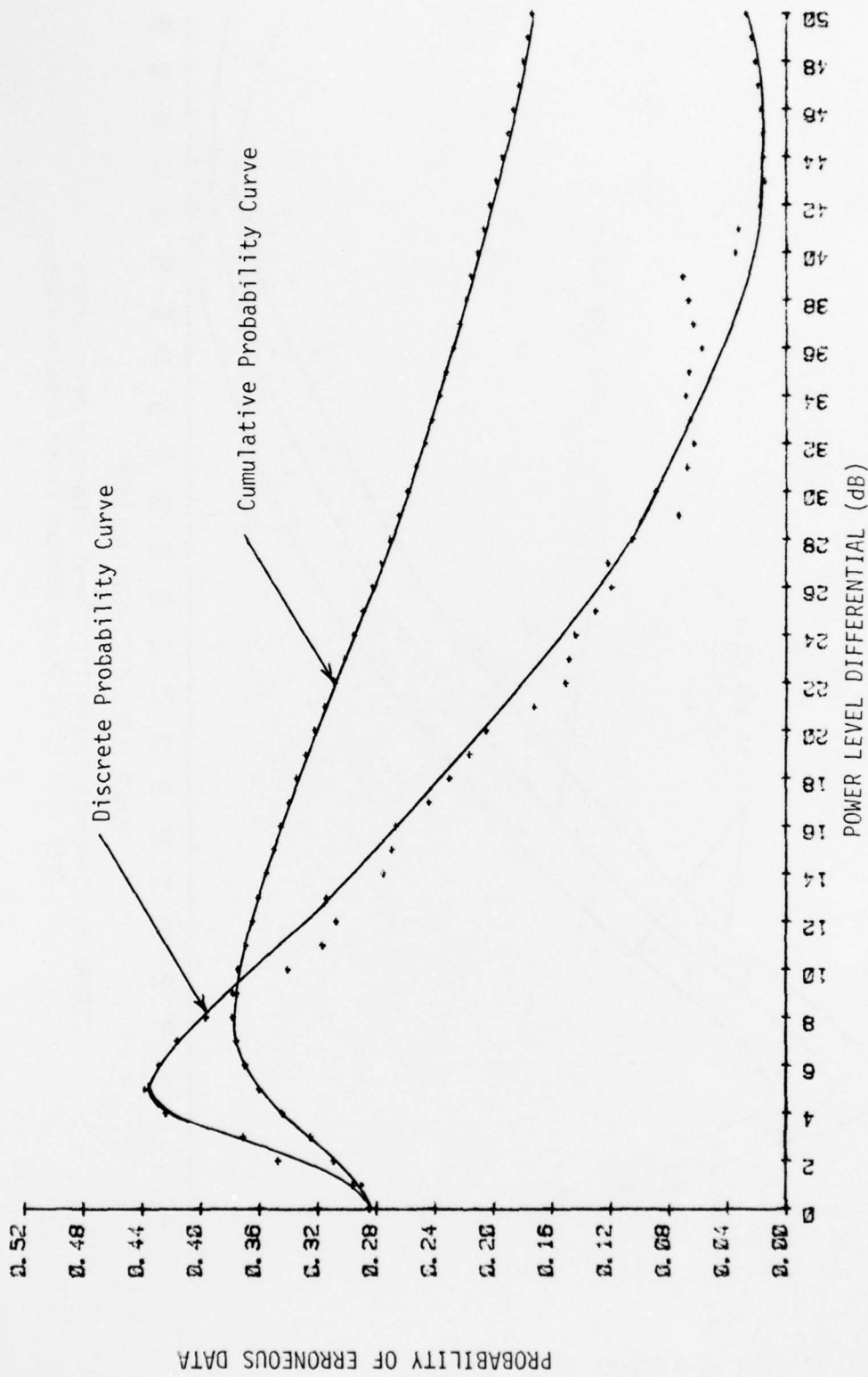


FIGURE 8: Discrete and Cumulative Probability Curves for 60 ns Delay Between Pulses Leading Edges

Table 6: Folded Random Data at 100 ns Between Leading Edges of Pulses

dB Difference Around a ref Power Level (Absolute Value)	Number of Occurrences	Probability of Erroneous Data P(E)	ϵ Differential at 95% (C.I.) Confidence Interval	Cumulative Probability of Erroneous Data
0	19	.064	.031	.064
1	48	.083	.025	.073
2	59	.104	.028	.083
3	77	.139	.031	.097
4	113	.207	.037	.119
5	119	.222	.039	.136
6	148	.282	.042	.157
7	163	.316	.044	.177
8	185	.367	.046	.198
9	200	.405	.048	.219
10	192	.397	.048	.235
11	193	.409	.049	.250
12	189	.409	.049	.262
13	193	.428	.050	.274
14	187	.425	.051	.284
15	179	.417	.051	.292
16	175	.419	.052	.300
17	168	.413	.052	.306
18	156	.392	.053	.310
19	162	.420	.054	.316
20	158	.421	.055	.321
21	139	.382	.055	.324
22	126	.357	.055	.325
23	125	.364	.056	.327
24	121	.364	.057	.328
25	116	.361	.058	.329
26	102	.328	.057	.329
27	97	.322	.058	.329
28	91	.314	.059	.329

Table 6 (Cont'd)

dB difference Around a ref Power Level (Absolute Value)	Number of Occurrences	Probability of Erroneous Data P(E)	ϵ Differential at 95% (C.I.) Confidence Interval	Cumulative Probability of Erroneous Data
29	82	.294	.059	.327
30	81	.301	.060	.327
31	78	.303	.062	.326
32	71	.287	.062	.325
33	68	.288	.063	.324
34	64	.285	.065	.323
35	57	.267	.065	.321
36	52	.255	.066	.319
37	46	.238	.066	.317
38	37	.204	.064	.314
39	36	.210	.067	.312
40	32	.198	.068	.309
41	26	.173	.066	.306
42	25	.178	.070	.303
43	18	.142	.066	.299
44	15	.125	.065	.295
45	7	.066	.052	.290
46	5	.049	.047	.285
47	5	.055	.053	.280
48	1	.016	.031	.275

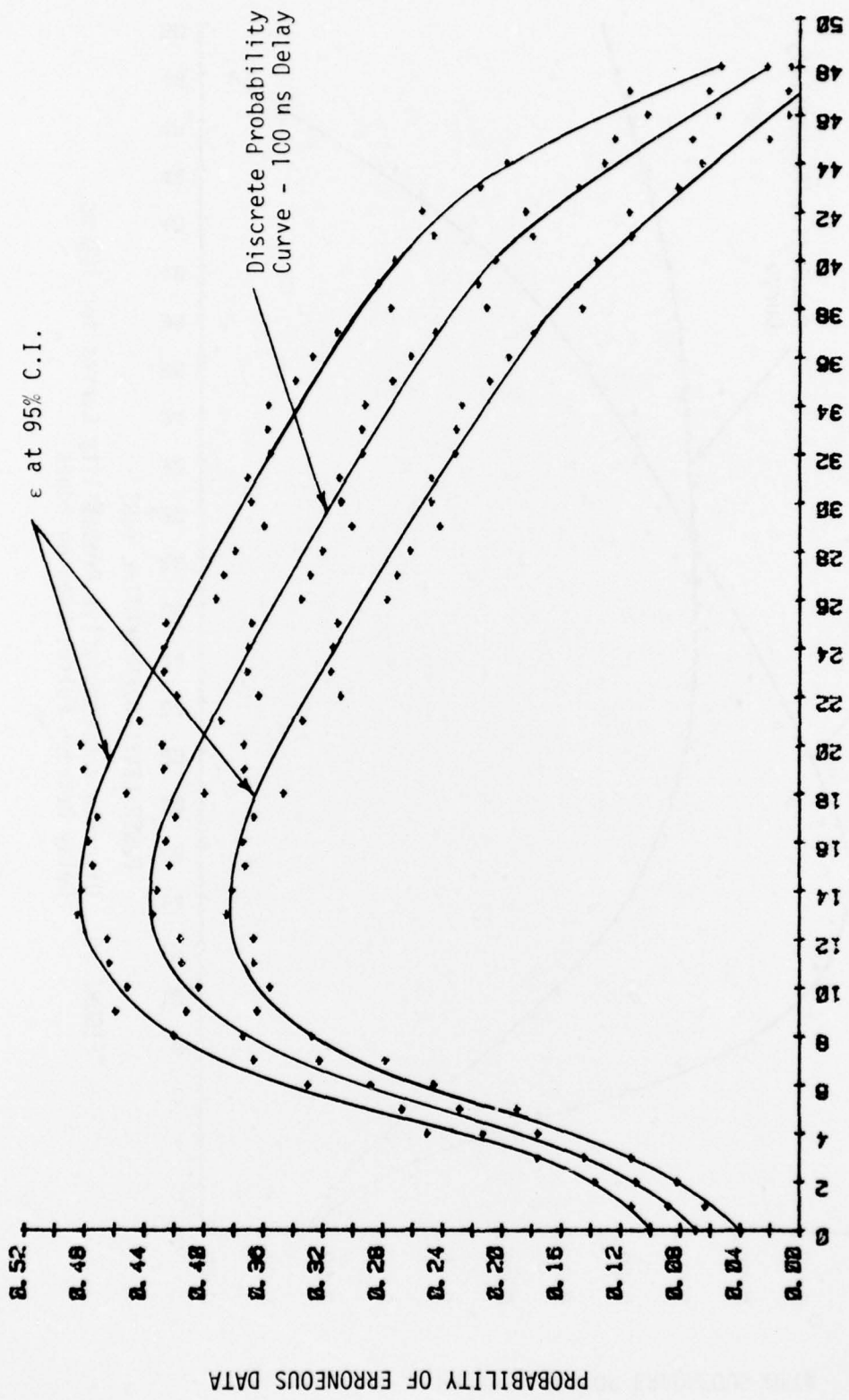


FIGURE 9: Discrete Probability Curve Generated from Random Data with 100 ns Delay Between Pulses Leading Edges

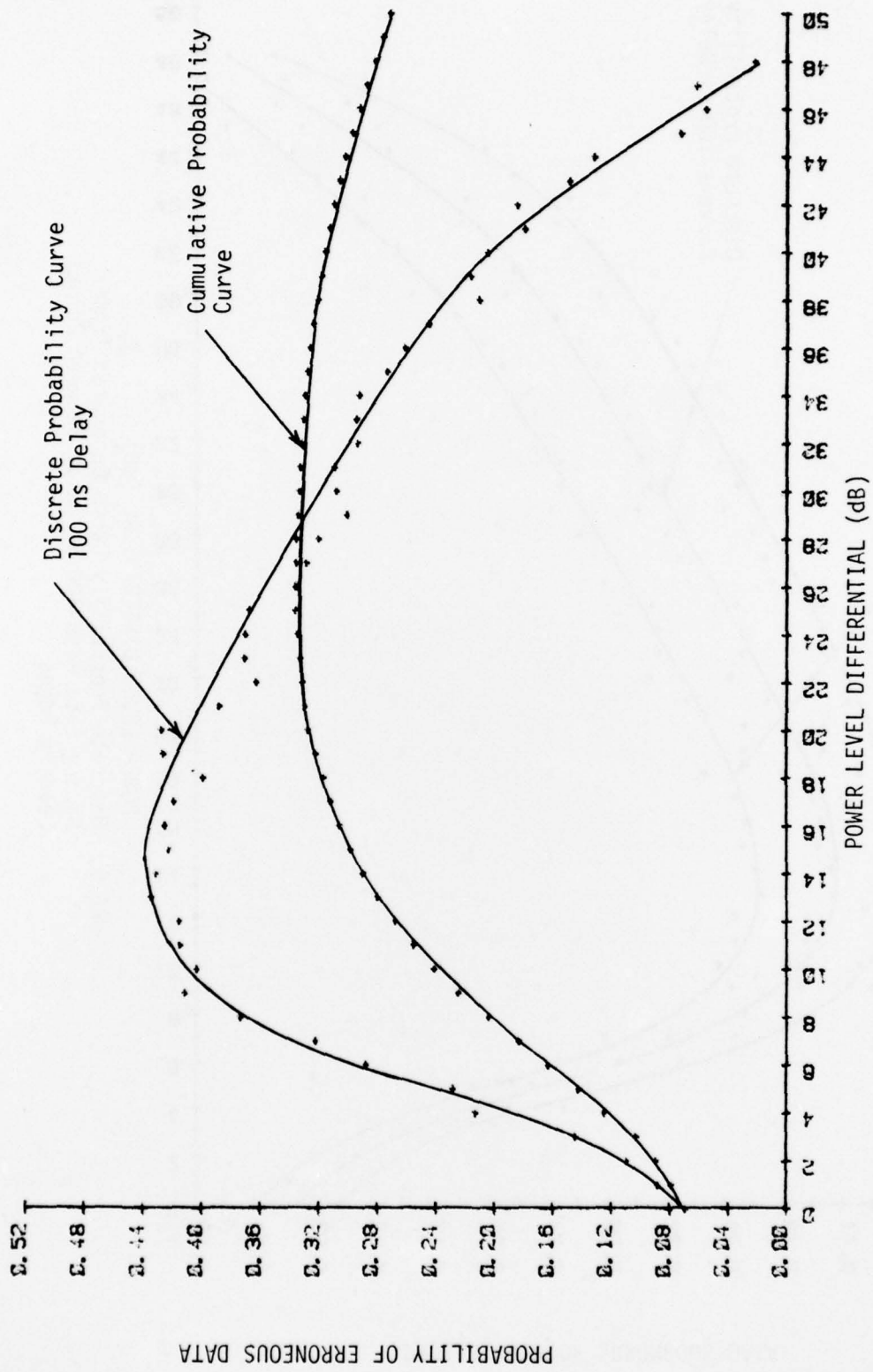


FIGURE 10: Discrete and Cumulative Probability Curves for 100 ns Delay Between Pulses Leading Edges

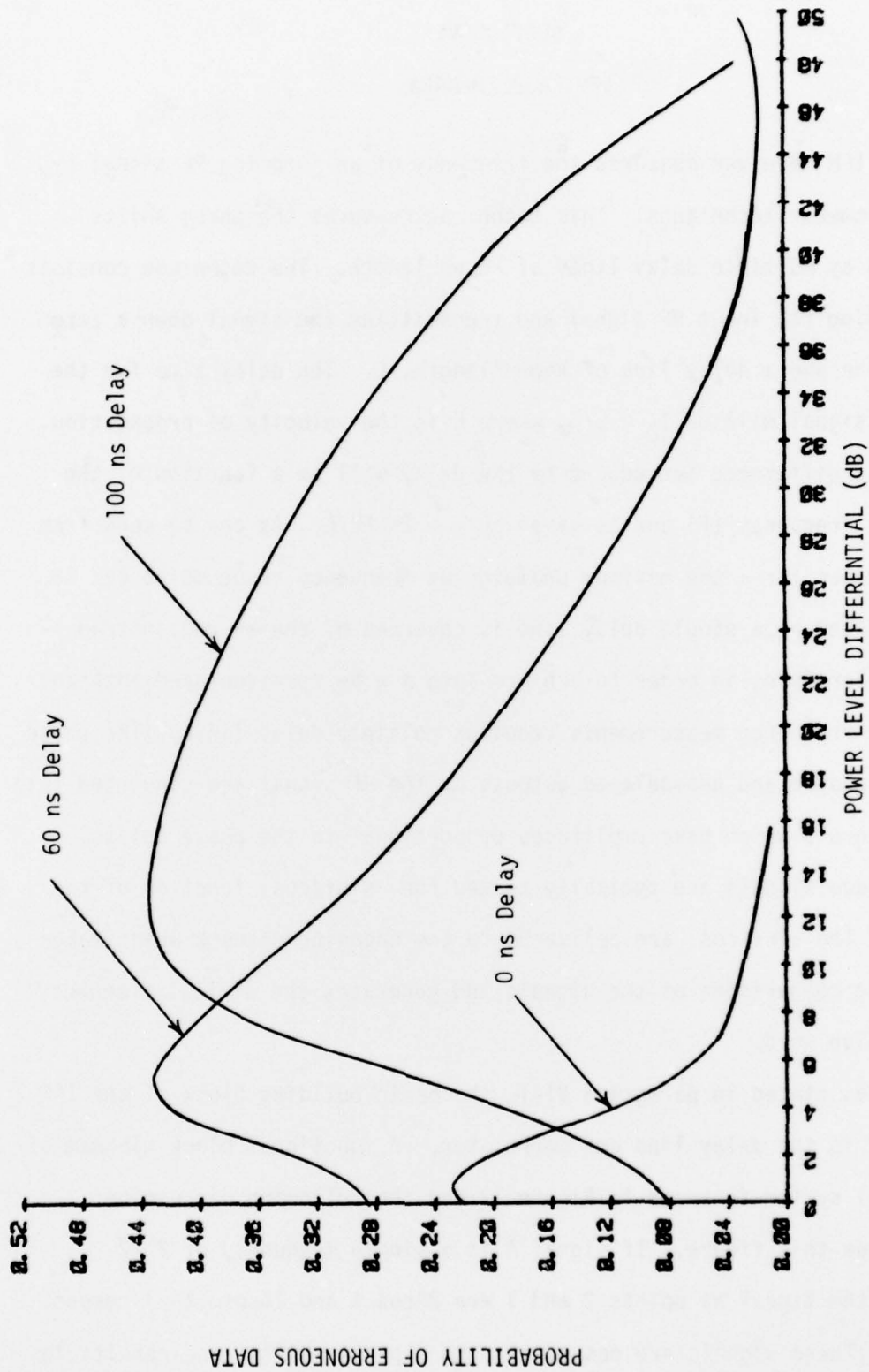
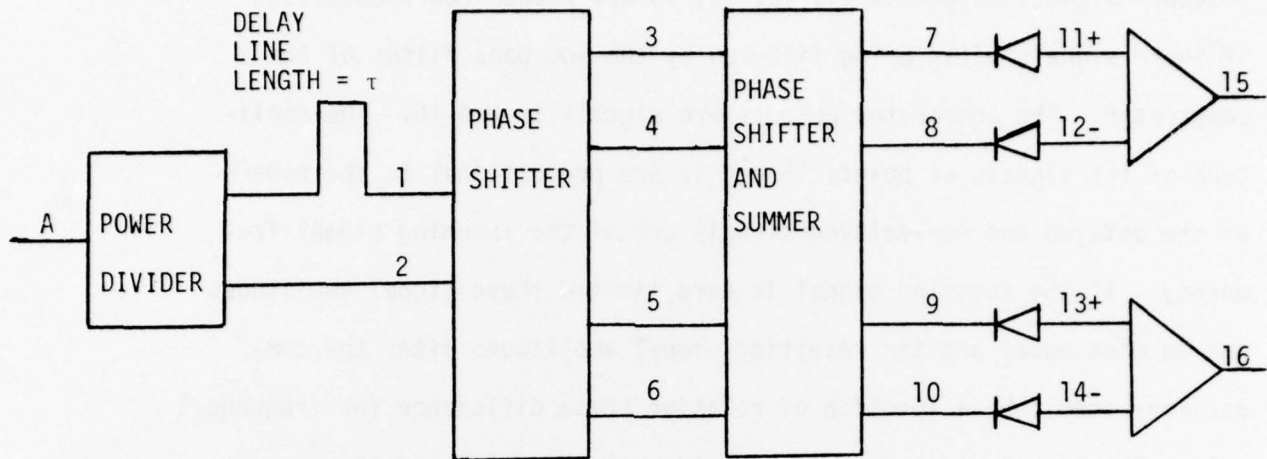


FIGURE 11: Discrete Probability Curves for 0, 60, 100 ns Delay Between Pulses Leading Edges

SECTION VI
IFM PROBLEM AREA

1. The IFM receiver measures the frequency of an incoming RF signal by interferometer techniques. This technique measures the phase shifts produced by multiple delay lines of known length. The technique consists of dividing the input RF signal and transmitting the signal down a zero delay line and a delay line of known length, L . The delay time for the delayed signal will be $T_D = L/C$, where C is the velocity of propagation. The phase difference introduced by the delay will be a function of the incident frequency (F) and is given by $\tau = 2\pi FL/C$. As can be seen from the equation for τ the maximum unambiguous frequency range which can be accommodated by a single delay line is governed by the 2π radian transition. Therefore, in order to achieve both a wide receiver bandwidth and accurate frequency measurements requires multiple delay lines. The phase of the delayed and non-delayed outputs of the RF signal are converted into video signals which have amplitudes proportional to the phase delays. These video signals are typically termed the $\sin\tau/\cos\tau$ function of the signal. The $\sin\tau/\cos\tau$ are delivered to the encoding network which makes amplitude comparisons of the signals and generates the digital frequency descriptive word.

2. As was stated in paragraph VI-1, the basic building block of the IFM receiver is the delay line and correlator. A functional block diagram of a typical system is shown in Figure 12 and the following discussion references this figure. If signal A is a single frequency of $2\sqrt{2}A\cos\omega t$, the signal at points 2 and 1 are $2A\cos\omega t$ and $2A\cos\omega(t-\tau)$ respectively. These signals are passed through a phase shifter and results in

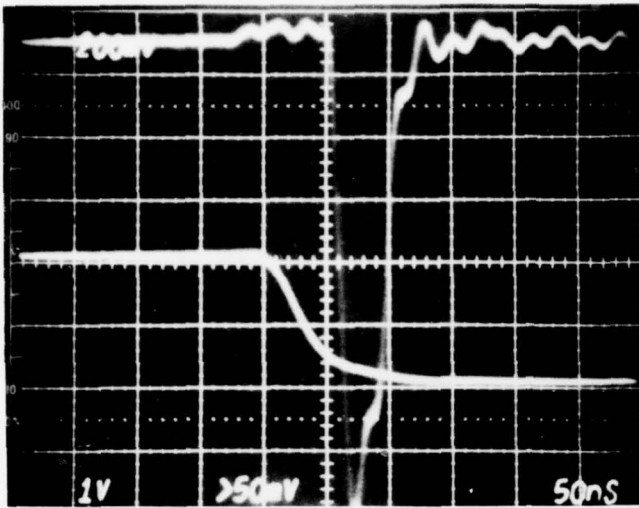


- | | | | | | |
|----|-------------------------------------|-----|---|-----|------------------------|
| A. | $2\sqrt{2} A \cos \omega t$ | 7. | $-A \sin \omega t + B \cos \omega(t-\tau)$ | 15. | $2AB \cos \omega \tau$ |
| 1. | $2B \cos \omega(t-\tau)$ | 8. | $-A \cos \omega t + B \sin \omega(t-\tau)$ | 16. | $2AB \sin \omega \tau$ |
| 2. | $2A \cos \omega t$ | 9. | $A \sin \omega t + B \sin \omega(t-\tau)$ | | |
| 3. | $\sqrt{2} B \cos \omega(t-\tau)$ | 10. | $A \cos \omega t - B \cos \omega(t-\tau)$ | | |
| 4. | $-\sqrt{2} A \cos \omega t$ | 11. | $\frac{A^2}{2} + \frac{B^2}{2} - AB \cos \omega \tau$ | | |
| 5. | $\sqrt{2} B \sin (\omega t - \tau)$ | 12. | $\frac{A^2}{2} + \frac{B^2}{2} + AB \sin \omega \tau$ | | |
| 6. | $\sqrt{2} A \cos \omega t$ | 13. | $\frac{A^2}{2} + \frac{B^2}{2} + AB \sin \omega \tau$ | | |
| | | 14. | $\frac{A^2}{2} + \frac{B^2}{2} + AB \sin \omega \tau$ | | |

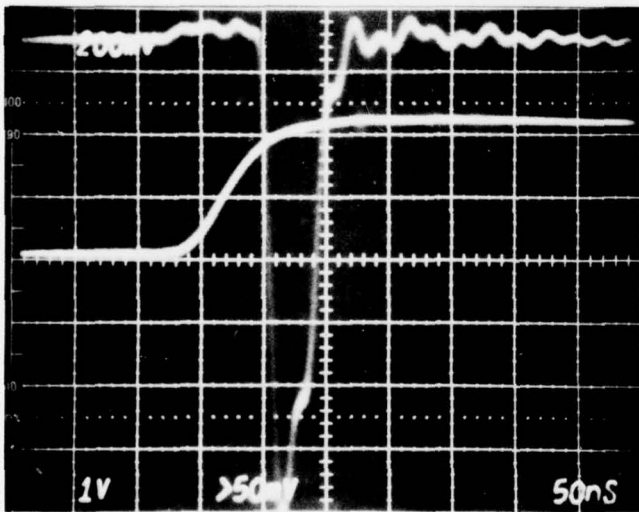
FIGURE 12: Correlator and Comparator

signals 3, 4, 5, 6. These signals are phase shifted, summed, and detected. Signals at points 11, 12, 13, 14 are pseudo-representations of these signals after being filtered by the low pass filter of the comparator. The comparator outputs are signals 15 and 16. The amplitude of the signals at points 15 and 16 are proportional to the power of the delayed and non-delayed signals and of the incoming signal frequency. If the incoming signal is hard limited these signal amplitudes can be made equal and the resulting signal amplitudes after the comparators should be a function of relative phase difference (or frequency) only. The technique as discussed divides the bandwidth of the system into four quadrants, by additional threshold and comparison circuits the quadrants can be further subdivided, but physical ambiguities, inherent in correlators usually limit quantizing to 5 bits or 11.25° ($360^{\circ}/2^5$). Achieving wider unambiguous bandwidths then requires multiple delay lines and correlators, and comparators operating in parallel/series configurations. After all $\cos\tau/\sin\tau$ comparisons are made the encoded word is strobed into storage registers. The length of time required from the pulse leading edge until register strobe is a function of the signal transition through the longest delay line, correlator, and the frequency encoding network. In the receiver under test, the register strobe occurs 120 ns after signal detection. Typical comparator outputs for two different frequencies (not occurring simultaneously) and their corresponding strobes for the receiver under test are shown in Figure 13.

3. When a signal of the form $A\cos\omega t + A'\cos\omega't$ is introduced into the circuit of Figure 12 the outputs at points 15 and 16 are a function of A , A' , ω , and ω' . In the case of two signals, hard limiting does not allow us to disregard the output dependency of the $\cos\tau/\sin\tau$ amplitudes on the



FREQUENCY 2.858 GHz
 ATTENUATOR 30 dB (-34 dBm)
 $\cos\tau$ and Encode Strobe Pulse



FREQUENCY 3.317 GHz
 ATTENUATOR 31 dB (-33.4 dBm)
 $\cos\tau$ and Encode Strobe Pulse

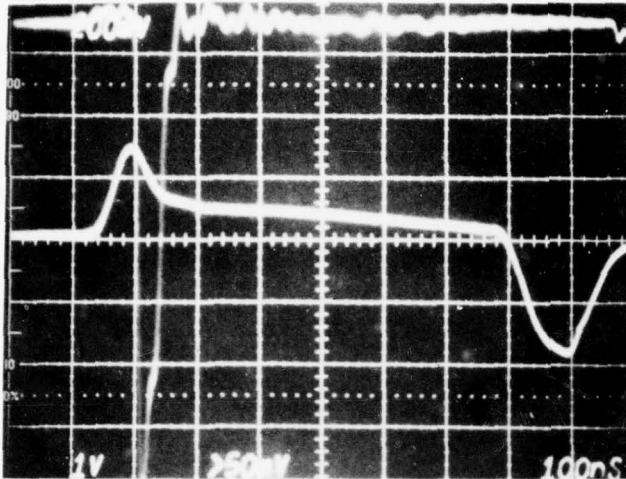
FIGURE 13: Typical $\cos\tau/\sin\tau$ Output and Strobe Pulse

A and A' input powers. The output frequency encoded shall fluctuate with absolute magnitude, relative magnitude and frequencies of the incoming signals. With hard limiting used in the network it would appear that A and A' would be of equal magnitude but the "capture effect phenomenon" of the limiting amplifier negates the assumption. The hard limited amplifier is output power limited. When two signals are introduced into the amplifier both shall be reduced but not necessarily in equal proportion, nor will their relative magnitudes after limiting be proportional to their relative amplitude prior to limiting. An additional aspect of practical receivers is that the amplitude frequency response curve is not flat across the frequency spectrum. These two considerations could account for the 16 dB spread in the problem area when the receiver is presented with simultaneous signals.

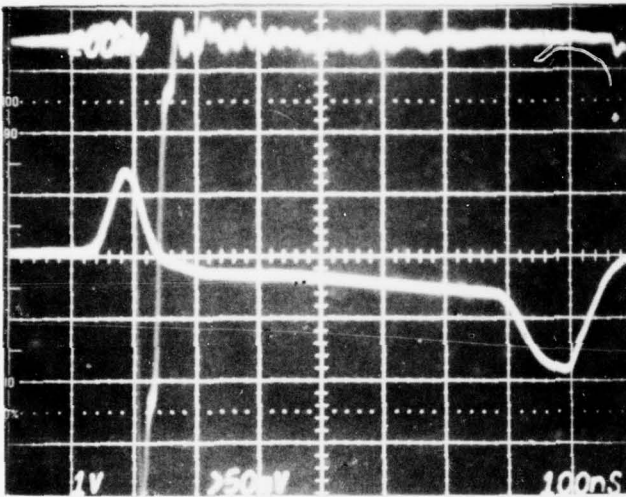
3. A problem associated with concurrent pulses, which are delayed in time, is the transient condition at the time of the encoding strobe. As was discussed in paragraph VI-2, to achieve a large bandwidth and a good frequency accuracy requires multiple delay lines, correlators, and comparators. The transition of a signal through each network is a function of the delay line, correlator and comparator transition times. When considering only a single pulse or two pulses which are time coincident the transition times through the multiple networks is not significant. This is obvious since the receiver by design must allow for the slowest transition to occur prior to encoding. But when signals are introduced which are delayed in time the second signal may not have totally transitioned each network when the encoding register are strobed. This problem will surface when the time delay between leading edges is larger than the strobe time minus the longest delay time. Another cause of signal transition at encode

time is the limited bandwidth of the video networks. If the networks has infinite bandwidth the transitions between states at the $\cos\tau/\sin\tau$ outputs would occur instantaneously. Realistically, there is time required between steady states resulting in transitions at the strobe time. The transient state of the encoding network could be caused by either or both of the conditions discussed and could result in problems (erroneous data) being encountered over the total dynamic range of the receiver. Figure 14 shows typical $\cos\tau/\sin\tau$ comparator outputs when the system has an input of both signals appearing in Figure 13.

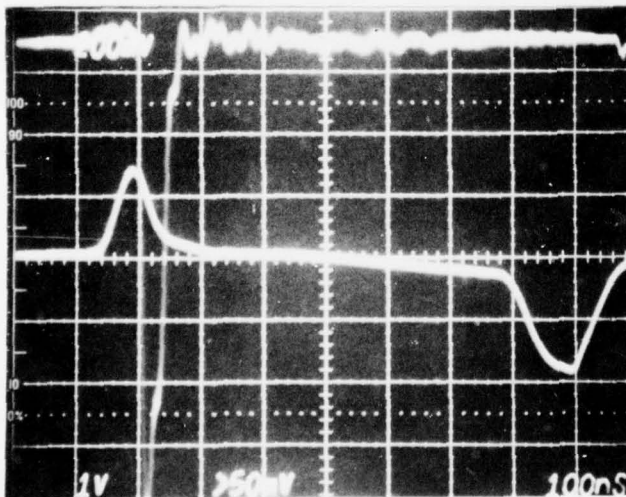
When the signals represented in Figure 13 are introduced simultaneously note there is a 60 ns delay in leading edges. Figure 14 shows the output of the same $\cos\tau/\sin\tau$ output with various attenuation in the 3.317 GHz signal. In each case the digital frequency word output was erroneous. These figures show the dependency of the $\cos\tau/\sin\tau$ output upon signal power. Also note that the system is in a transition state at the time of the register strobe.



FREQUENCY	POWER
2.858 GHz	-34 dBm
3.317 GHz	-32.4 dBm



FREQUENCY	POWER
2.858 GHz	-34 dBm
3.317 GHz	-34.4 dBm



FREQUENCY	POWER
2.858 GHz	-34 dBm
3.317 GHz	-33.4 dBm

FIGURE 14: \cos/sin and Encode Strobe for Two Signals Delayed 60 ns

SECTION VII

CONCLUSIONS

The IFM receiver's statistical characteristics, for pulses which have leading edge overlap during the critical encode time of the receiver, indicate that simultaneous signals (0 time delay between pulse leading edges) do not represent a worst-case condition for incorrectly encoding pulse frequency. But rather worst-case conditions occur when the pulses leading edges are displaced in time (while still remaining within the critical encode time). It appears this problem is a result of the output of the comparator network being in a state of flux at the time of the encoding strobe. If this is the case the extent of the power differential in signals, where problems could occur, extends over the dynamic range of the receiver. A viable solution to this problem, which will be considered in future work, could be to detect the transition of the video output or of the $\cos\tau/\sin\tau$ outputs caused by the second pulse in near real time and extend the strobe timing to be consistent with the second pulse detection. This would result in strobing the encoding networks after the second pulse has settled into a steady state. The probability of bad data should then appear to be similar to the probabilities associated with signals which have 0 time delay.

REFERENCES

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