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BIT ERROR RATE CHARACTERIZATION OF HIGH FREQUENCY DIGITAL SIGNALS UTILIZING SAMPLING TECHNIQUES

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Abstract

This thesis develops a bit error rate (BER) measurement technique based on the gaussian statistics of noise in high frequency baseband digital signals. Commercial BER test equipment is currently available, but is very expensive and requires the use of a known transmitted test pattern.

The laboratory implementation of this technique utilized a Tektronix digitizing oscilloscope to sample the signal and a HP minicomputer to process the data. Experiments were designed to cover a wide range of BER values and plots were made of BER vs. clock phase. It was found that when the noise was "purely" gaussian, there was excellent agreement between measured and predicted BERs at 1 Gb/s bit rates. A matching filter was required in order to achieve these results.

The predicted BER of an optical regenerator was characterized at 1.7 Gb/s at the decision circuit input and showed fair agreement with that measured. Discrepancies as great as an order of magnitude were observed at the BER minimum. This was attributed partially to the error detector limitations and also to the non-gaussian phenomena in the regenerator.

Chapter 1 Introduction

The ever increasing use of higher frequency communication systems has necessitated the development of new bit error rate (BER) measurement techniques to help characterize their performance. The ultra wide bandwidth requirements of these systems complicates the process of making accurate measurements. The test equipment must have a much greater bandwidth than that of the system under test or distortion and measurement error will result.

Commercial BER test equipment is custom manufactured, very expensive, and based on a "brute force" bit by bit comparison of the transmitted and received signals. This limits the usage of the equipment to applications where the transmitted signal is known.

This thesis studies the use of statistical techniques in order to determine the BER. The measuring technique works well on all baseband signals, whether the transmitted pattern is known or not. This allows one to measure the performance of a system while in actual operation rather than under artificial test conditions. The equipment is not nearly as expensive as that of the commercial technique but requires more complicated computations in determining the BER.

Laboratory implementation of this technique is based upon measurements derived from a digitizing oscilloscope and produced results which are comparable to those of an Anritsu BER test system. The measurements compared BER vs. clock phase and spanned a variety of BER ranges. The sampling technique is more versatile in that it can accommodate a much wider range of input amplitudes than the commercial error detectors. In addition, error detectors often require an amplifier to boost the input signal amplitude which can be a source of distortion and changes in the signal to noise ratio of the waveform being measured.

Chapter 2 of this thesis derives the theory that underlines the procedure being described. The implementation of the technique requires additional considerations which are discussed in Chapter 3. This chapter also includes the methods used to sample and process the data to derive the BER assuming gaussian signal statistics. Since fiber optics is playing an increasing role in modern communications, this thesis also applies the new technique to a 1.7 Gb/s optical regenerator. The procedures and test setup associated with the regenerator are described in Chapter 4. Chapter 5 is devoted to the experimental results obtained and their comparison with those of an Anritsu error detector. Finally, the conclusions and ideas for future extensions are provided in Chapter 6.

Chapter 2 Bit Error Rate Theory and Derivations

This chapter begins with a brief overview of digital communication systems and bit error rate theory. The operation of an Anritsu error detector is then described. Finally, equations which define the total probability of error are derived. The equations are based on the gaussian nature of random noise sources.

2.1. Digital Communication Systems

The digital signals being analyzed in this thesis will be assumed to contain only binary levels. Therefore, a zero level V(0) or a one level V(1) are the only signal states which can be transmitted or received. Pulse Code Modulation (PCM) is an example of a commonly used transmission code which exhibits these characteristics. The rate at which the digital message is transmitted or received is called the bit rate, B, which has units of bits per second. The two bit rates which are being analyzed within the scope of this thesis are 1.0 and 1.7 Gb/s.

A simplified model for a digital communication data system is shown in Fig. 2.1. The purpose of the system is to transmit the digital message from the source to the destination. Ideally, the received signal should be an exact replica of the transmitted signal. Unfortunately, the existence of noise in the data channel as well as in

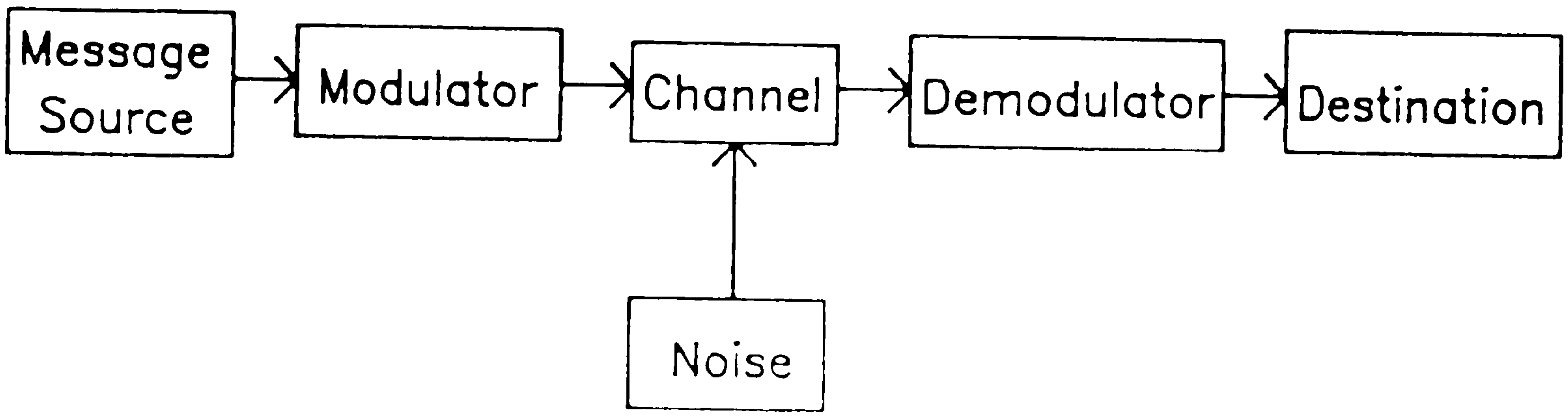


Fig. 2.1. Simplified digital communication system.

the modulator and demodulator circuitry results in the degradation of the original signal when detected at the threshold device.

The received noisy message can be characterized as consisting of two components. The "ideal" digital signal, V(0) and V(1), transmitted at rate B is the first part. The other part is a sample of the additive noise, $n(T_0)$, where T_0 is the sampling point [1]. The communication system can then be modeled from the receiver's point of view, as depicted in Fig. 2.2. The system block diagram shown is that of a typical binary baseband digital receiver [2]. The model is composed of the additive noise process, an equalizing filter, a sampling circuit and a threshold device. X(t) is the noiseless digital message. N(t) represents the accumulation of all additive noise generated within or injected into the modulator, channel and front end of the

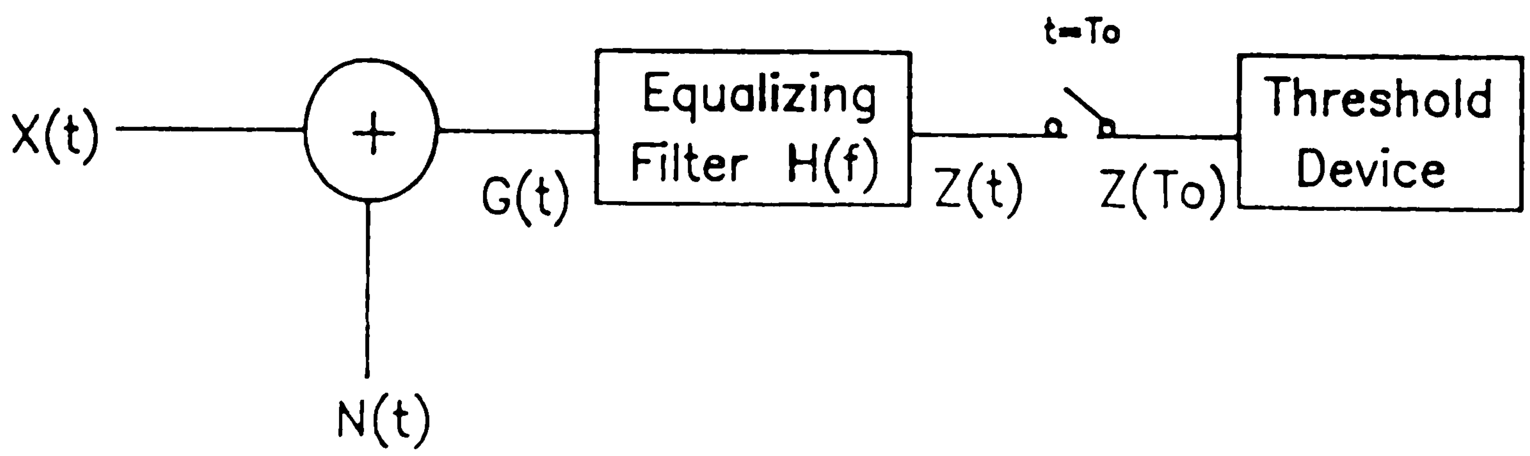


Fig. 2.2. Binary data receiver model.

demodulator. This model serves as a key reference in the derivation of the gaussian equations in Section 2.4.

2.2. Bit Error Rate and Decision Theory

The function of the digital receiver is to determine which digital message was sent and to do so with a minimum of error. This is accomplished through a two step process. First, the received signal is optimized via amplification, pulse shaping and timing circuitry to produce the decision input statistic. This statistic is then injected into the threshold device. A decision circuit is being used as the specific threshold device in this application.

It is the decision circuit which ultimately decides on a binary outcome based on predetermined criteria commonly referred to as the decision rule [2]. The minimax criterion utilized in this thesis selects the decision threshold, D, such that the absolute smallest probability of error is achieved. Once the threshold level is selected, the outcome of the incident decision statistic, $Z(T_0)$, shown in Fig. 2.2, will be determined by

$$\text{Assume } V(1) \text{ transmitted} \Leftrightarrow \text{Given } Z(T_0) > D \qquad (2.01)$$

and

$$\text{Assume } V(0) \text{ transmitted} \Leftrightarrow \text{Given } Z(T_0) < D. \qquad (2.02)$$

The probability of error is commonly expressed in terms of the bit error rate (BER). BER is defined as the ratio of the number of bits detected incorrectly to the total number of bits transmitted. In practice, BER is calculated with respect to time over a given interval using

$$BER = \frac{F_e \text{ (errors/sec)}}{B \text{ (bits/sec)}} = \left(\frac{\text{errors}}{\text{bit}}\right) \qquad (2.03)$$

where F_e is the error frequency and B is the bit rate.

An equivalent description of BER is that it represents the probability of a given bit being identified in error. This is obvious upon inspection of the units in Eq. 2.03. BER measurements typically range from 10^{-4} to 10^{-15} depending upon the application.

2.3. Commercial BER Test Equipment

State of the art commercial test equipment is currently available to automatically measure BER at transmission bit rates in excess of 7.0 Gb/s. Anritsu Corp. and Advantest Corp. are among the primary vendors in this field. The equipment is very sophisticated and typically can take six months to a year for delivery. The cost of a generator and receiver pair is quite high, ranging from $150,000 to $750,000 depending upon the bit rate required.

An Anritsu model MG642A word generator and model MS65A error detector operate up to 2.0 Gb/s and have been used for all optical regenerator associated measurements. All purely gaussian BER measurements have been made using a 3.0 Gb/s Anritsu model MP1604A generator and model MP1605A detector. The BER measurements performed with this equipment are extremely accurate as well as repeatable. For this reason, the Anritsu error detector will be used as a benchmark for comparison of the proposed measurement technique which will be described shortly.

A block diagram which portrays the functionality of the 2.0 Gb/s MS65A error detector [3] is shown in Fig. 2.3. The data pattern input which is to be measured is injected into a pulse shaper where a variable threshold decision is made. A 1:4 demultiplexer is then utilized to divide the 2 Gb/s series data stream into four slower 500 Mb/s parallel signals. This is an elaborate but necessary complication since the Exclusive-OR gates performing the comparator function will not operate much above 500 Mb/s.

A reference pattern generator is incorporated within the detector itself. This generator outputs the identical pattern which was originally transmitted by the MG642A generator through a digital channel to the detector. The replicated pattern is also demultiplexed to four parallel data streams which are input into the Exclusive-OR gates along with the four parallel lines being tested. A "brute force" comparison is then made between transmitted and received data and errors are detected bit by bit. This method is extremely accurate since the error detector knows the exact transmitted pattern in advance.

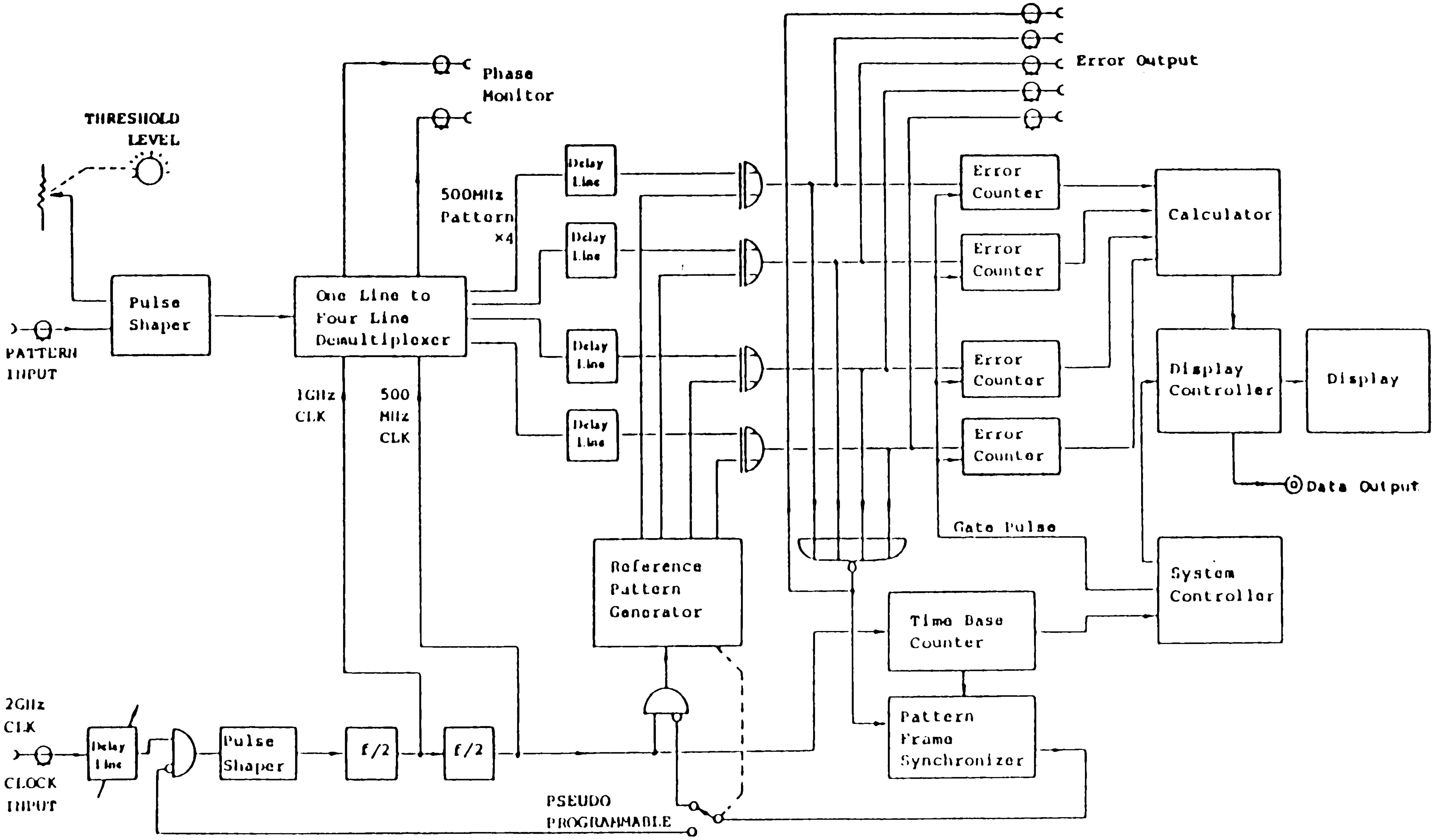


Fig. 2.3. Anritsu MS65A error detector block diagram.

In order for this detection scheme to function, the four parallel lines being measured must be phase matched to compensate for propagation delays and to achieve optimal timing performance. A pattern frame syncronization circuit must also be employed to align the two groups of parallel bit streams with each other. The patterns must be matched up to coincide at the inputs of the Exclusive-OR gates in order to obtain a valid error count. Syncronization is obtained by inhibiting the clocking of the reference pattern generator until the instantaneous error counter stops overflowing prior to the clock counter.

Each Exclusive-OR gate is monitored by a dedicated error counter. The counter is incremented each time the Exclusive-OR gate inputs are different, implying that an error has occurred. The errors are then totalized during a known time interval and converted into bit error rate using the measured clock rate and Eq. 2.03. The BER is then displayed on the LED front panel.

2.4. Derivation of Gaussian BER Equations

An extensive discussion of the sampler output, $Z(T_0)$, will now be presented in order to characterize the signal for a hypothetical analysis of the probability of error. In this section, the noise sources and their associated probability distribution functions are described. The equations are then derived which define the total probability of error. Finally, an approximation will be introduced which greatly simplifies the numerical calculations.

Random noise is a phenomena which occurs within virtually all electronic circuitry and transmission channels [4]. Thermal noise, shot noise, 1/f noise and amplifier noise are common stationary random processes which are well described by gaussian statistics. It is then possible to assume that the noise source N(t) in Fig. 2.2 can be represented with a gaussian probability function. Without loss of generality, a function will be assumed with zero mean value and a mean-square value as described by

$$\overline{N(t)} = \lim_{\tau \to \infty} \frac{1}{\tau} \int_{-\tau/2}^{\tau/2} N(t)\, dt = 0 \qquad (2.04)$$

and

$$\overline{N^2(t)} = \lim_{\tau \to \infty} \frac{1}{\tau} \int_{-\tau/2}^{\tau/2} |\, N(t)\, |^2\, dt = \sigma^2 \qquad (2.05)$$

where σ represents the rms noise voltage or current and τ is the time interval.

The result of adding a zero mean gaussian random variable to an idealized signal X(t) with binary levels V_{X0}, V_{X1} is another gaussian random variable with means V_{X0}, V_{X1} and variances σ_{X0}^2, σ_{X1}^2, respectively [1]. This is proven by a theorem stating that linear transformations on gaussian random variables yields gaussian random variables [5]. Combining this theorem with the principle of linear superposition yields

$$G(t) = N(t) + X(t) \tag{2.06}$$

where G(t) has the gaussian distribution just described. The equalizing filter is a linear, time-invariant circuit whose output Z(t) is given by the time convolution

$$Z(t) = \int_{-\infty}^{\infty} h(\tau)\, g(t-\tau)\, d\tau. \tag{2.07}$$

Z(t) is also gaussian by reason of the linear transformation theorem. $Z(t_0)$ represents the value of Z(t) at sampling time t_0.

The probability density functions for $Z(T_0)$, the threshold circuit input, can now be written by using the constraints assumed. If a binary zero level is transmitted, the gaussian probability density function can be expressed as [6]

$$P_0(y) = \frac{1}{\sqrt{2\pi}\sigma_0} e^{-(y-V_0)^2/2\sigma_0^2}. \qquad (2.08)$$

Similarly, in the case of a one level, the probability density function is

$$P_1(y) = \frac{1}{\sqrt{2\pi}\sigma_1} e^{-(y-V_1)^2/2\sigma_1^2}. \qquad (2.09)$$

Both functions are shown in Fig. 2.4 where y represents the signal amplitude and P(y) is the normalized probability of occurrence of the amplitude. V_0 and V_1 represent the mean transformed binary levels of $Z(T_0)$ with variances σ_0^2 and σ_1^2, respectively. In general, σ_1 will be larger than σ_0 due to the fact that the noise at each level contains contributions proportional to the signal itself [7].

In reference to the decision level, D, shown in Fig. 2.4, there are two possible types of errors which could occur. The hatched areas in Fig. 2.4 provide a graphical representation of the probability of each of the errors. The probability of a "false alarm", $P(E_1/0)$, is given by the integral of the tail of $P_0(y)$ as expressed by

$$P(E_1/0) = \int_D^\infty \frac{1}{\sqrt{2\pi}\sigma_0} e^{-(y-V_0)^2/2\sigma_0^2}\, dy. \qquad (2.10)$$

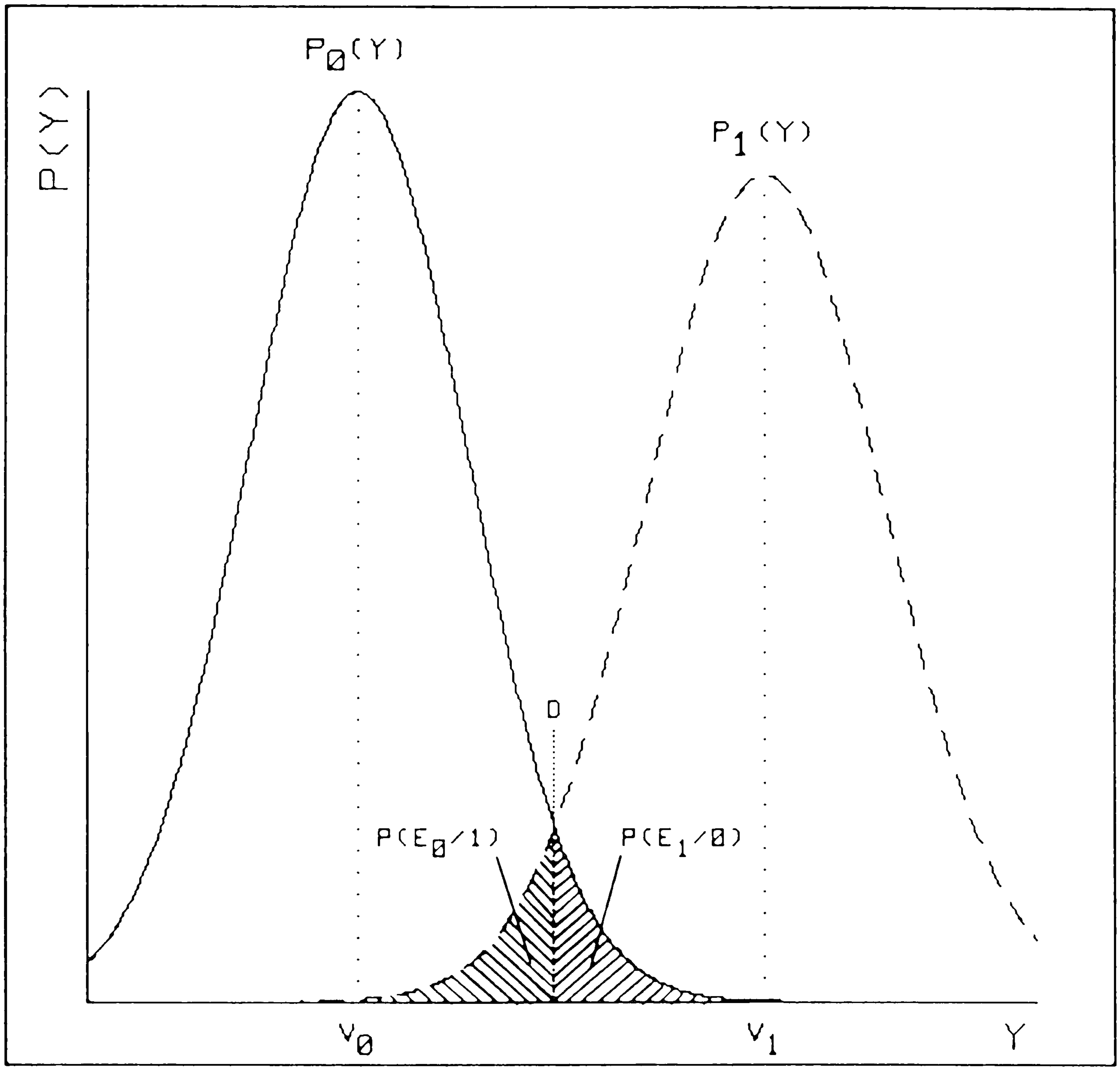


Fig. 2.4. Binary detected probability density functions.

Similarly, the probability of the receiver choosing zero when a one was transmitted, $P(E_0/1)$, is given by

$$P(E_0/1) = \int_{-\infty}^{D} \frac{1}{\sqrt{2\pi}\sigma_1} e^{-(y-V_1)^2/2\sigma_1^2} dy. \qquad (2.11)$$

The total probability of error can then be written as

$$P(E) = P_0 P(E_1/0) + P_1 P(E_0/1) \qquad (2.12)$$

where $P(E_1/0)$ and $P(E_0/1)$ are the conditional probabilities that a bit is misidentified and P_0, P_1 are the probabilities that a zero, one is transmitted, respectively.

$P(E_1/0)$ can be simplified by expressing Eq. 2.10 in terms of the complementary error function, Erfc(x). To accomplish this, the equation is normalized for zero mean and unity variance using the substitution variables

$$z = \frac{y-V_0}{\sigma_0} \qquad (2.13)$$

and

$$dz = \frac{1}{\sigma_0} dy \qquad (2.14)$$

Substitution of Eq. 2.13 and Eq. 2.14 into Eq. 2.10

yields

$$P(E_1/0) = \int_{\frac{D-V_0}{\sigma_0}}^{\infty} \frac{1}{\sqrt{2\pi}} e^{-z^2/2} dz. \tag{2.15}$$

This can be further simplified by defining

$$Q_0 = \frac{| D - V_0 |}{\sigma_0} \tag{2.16}$$

and expressing Eq. 2.15 as

$$P(E_1/0) = \int_{Q_0}^{\infty} \frac{1}{\sqrt{2\pi}} e^{-z^2/2} dz. \tag{2.17}$$

The general Erfc(x) definition is given by [6]

$$\mathrm{Erfc}(x) = \int_{x}^{\infty} \frac{1}{\sqrt{2\pi}} e^{-z^2/2} dz. \tag{2.18}$$

Using Eq. 2.18, Eq. 2.17 can be rewritten as

$$P(E_1/0) = \mathrm{Erfc}(Q_0) = \int_{Q_0}^{\infty} \frac{1}{\sqrt{2\pi}} e^{-z^2/2} dz. \tag{2.19}$$

Since the integral in Eq. 2.19 cannot be evaluated in closed form, the approximation shown in Eq. 2.20 will be made in order to simplify numerical calculations [6].

$$\mathrm{Erfc}(X) \simeq \frac{1}{X\sqrt{2\pi}}\left(1 - \frac{1}{X^2}\right) e^{-X^2/2} \quad , X \gg 1 \qquad (2.20)$$

Calculations which compare Eq. 2.20 and Erfc(X) tables indicate an error of 1.1% at $Q = 4$ and 0.15% at $Q = 6$. This degree of error is tolerable and therefore the approximation is justified. Finally, substitution of Eq. 2.20 into Eq. 2.19 yields

$$P(E_1/0) \simeq \frac{1}{Q_0\sqrt{2\pi}}\left(1 - \frac{1}{{Q_0}^2}\right) e^{-{Q_0}^2/2} \ . \qquad (2.21)$$

Fig. 2.5 shows the conditional probability of error vs. Q relationship for error rates between 10^{-3} and 10^{-12}. It is apparent from the plot that the probability of error varies drastically as a function of Q, especially at low BER. This implies that Q will need to be determined quite accurately and repeatably in order to provide consistent BER measurements. An analogous simplification of $P(E_0/1)$ yields

$$P(E_0/1) \simeq \frac{1}{Q_1\sqrt{2\pi}}\left(1 - \frac{1}{{Q_1}^2}\right) e^{-{Q_1}^2/2} \qquad (2.22)$$

where

$$Q_1 = \frac{| \ D - V_1 \ |}{\sigma_1} . \qquad (2.23)$$

The overall probability of error P(E) can now be expressed in simplified form. Substitution of Eq. 2.21 and Eq. 2.22 into Eq. 2.12 yields

$$P(E) = \frac{1}{\sqrt{2\pi}}\left\{\frac{P_0}{Q_0}\left(1-\frac{1}{Q_0^2}\right)e^{-Q_0^2/2} + \frac{P_1}{Q_1}\left(1-\frac{1}{Q_1^2}\right)e^{-Q_1^2/2}\right\}. \qquad (2.24)$$

In Eq. 2.24 , Q_0 and Q_1 have been well defined, however, probability assignments have yet to be made with respect to P_0 and P_1. The most straight forward treatment of these variables would be to use the "a priori" probabilities, where information is known in

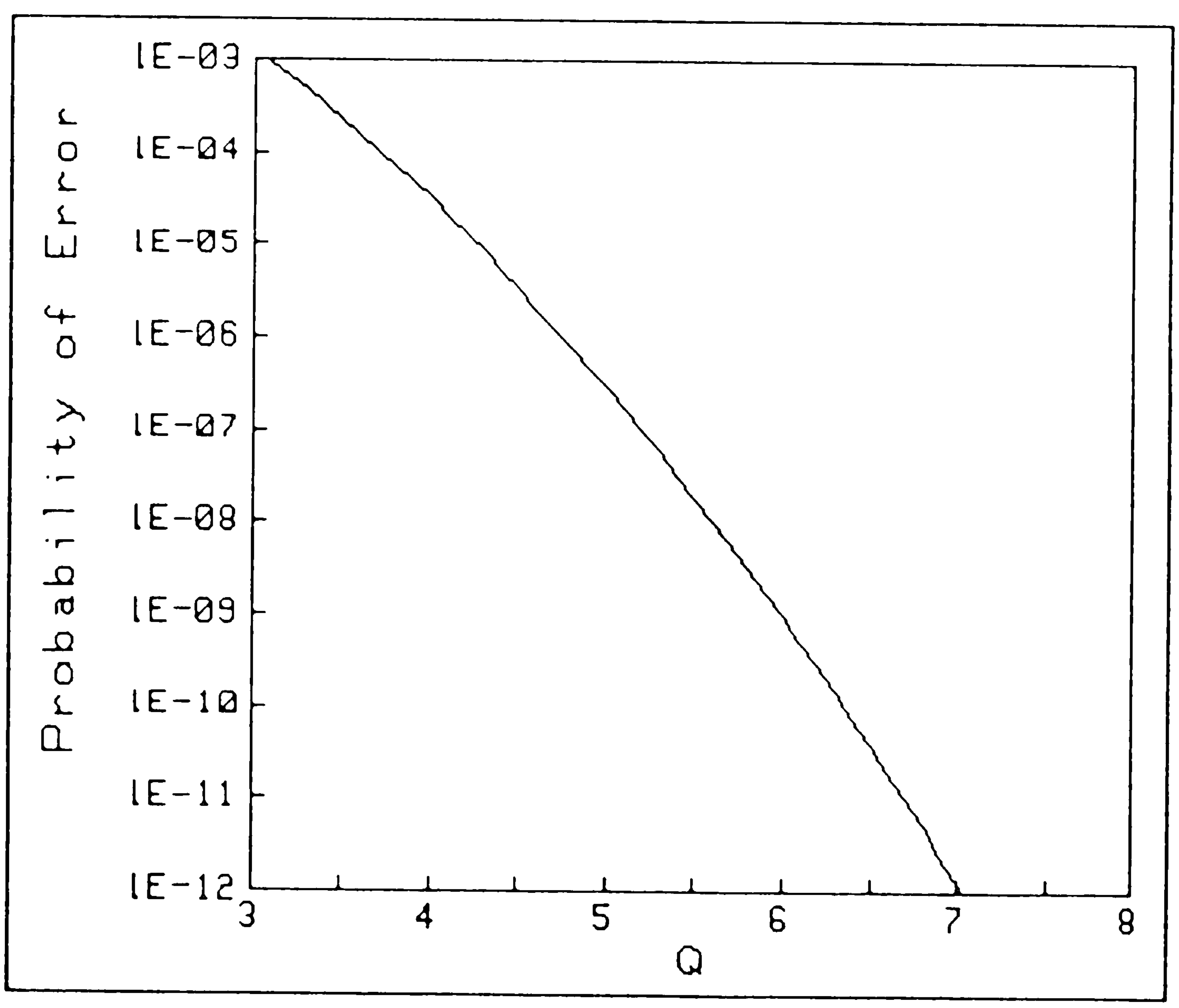


Fig. 2.5. Conditional probability of error vs. Q.

advance about the duty cycle of the transmitted data [1]. A 50% pseudo-random data pattern is used for all measurements in this thesis as well as in many communication systems which dictates that

$$P_0 = P_1 = \frac{1}{2} \, . \tag{2.25}$$

A more general approach, however, will be used instead in order to generalize the equation for unknown duty cycles. A conditional probability, known as "a posteriori" probability, will be calculated based on the observation at the receiver. The decision criterion used here, "maximum a posteriori criterion", chooses the hypothesis that has the maximum probability associated with it.

Therefore, for a given threshold D, if a zero is detected it should be assumed that a zero was transmitted. This is a valid assumption since the probability of a zero sent given a zero detected is typically much greater than the probability of a one sent given a zero detected for the range of error rates being evaluated. Likewise, if a one is detected, it should be assumed that a one was transmitted. This decision process will be repeated with a total sample size of N_s values at each clock phase sampled. This allows one to determine P_0 and P_1 experimentally as

$$P_0 = \frac{N_0}{N_s} \tag{2.26}$$

and

$$P_1 = \frac{N_1}{N_s} \tag{2.27}$$

where N_0 and N_1 are the number of zeros and ones, respectively. The sampling process itself will be described in the next chapter.

Chapter 3 Implementation of Gaussian BER Measurements

This chapter discusses the implementation of the theory presented in Chapter 2 and explains the measurement techniques used. A purely gaussian decision statistic is produced and characterized in order to verify the measurement techniques in an optimal environment. This eliminates the introduction of non-gaussian phenomena as well as timing and interference problems which can often occur in optical regenerators. In Chapter 4, a more specific and practical application will be pursued in the evaluation of a 1.7 Gb/s optical regenerator at the decision circuit input.

3.1. Digital/Gaussian Noise Source

The "ideal" noisy digital/gaussian signal is synthesized using the arrangement of Fig. 3.1. The circuit combines a digital word of variable amplitude with a band-limited noise source using a resistive power combiner/divider. The composite noisy output signal can be assumed to be representative of that which exists in communication systems circuitry. The system noise originates predominantly in gaussian noise sources as

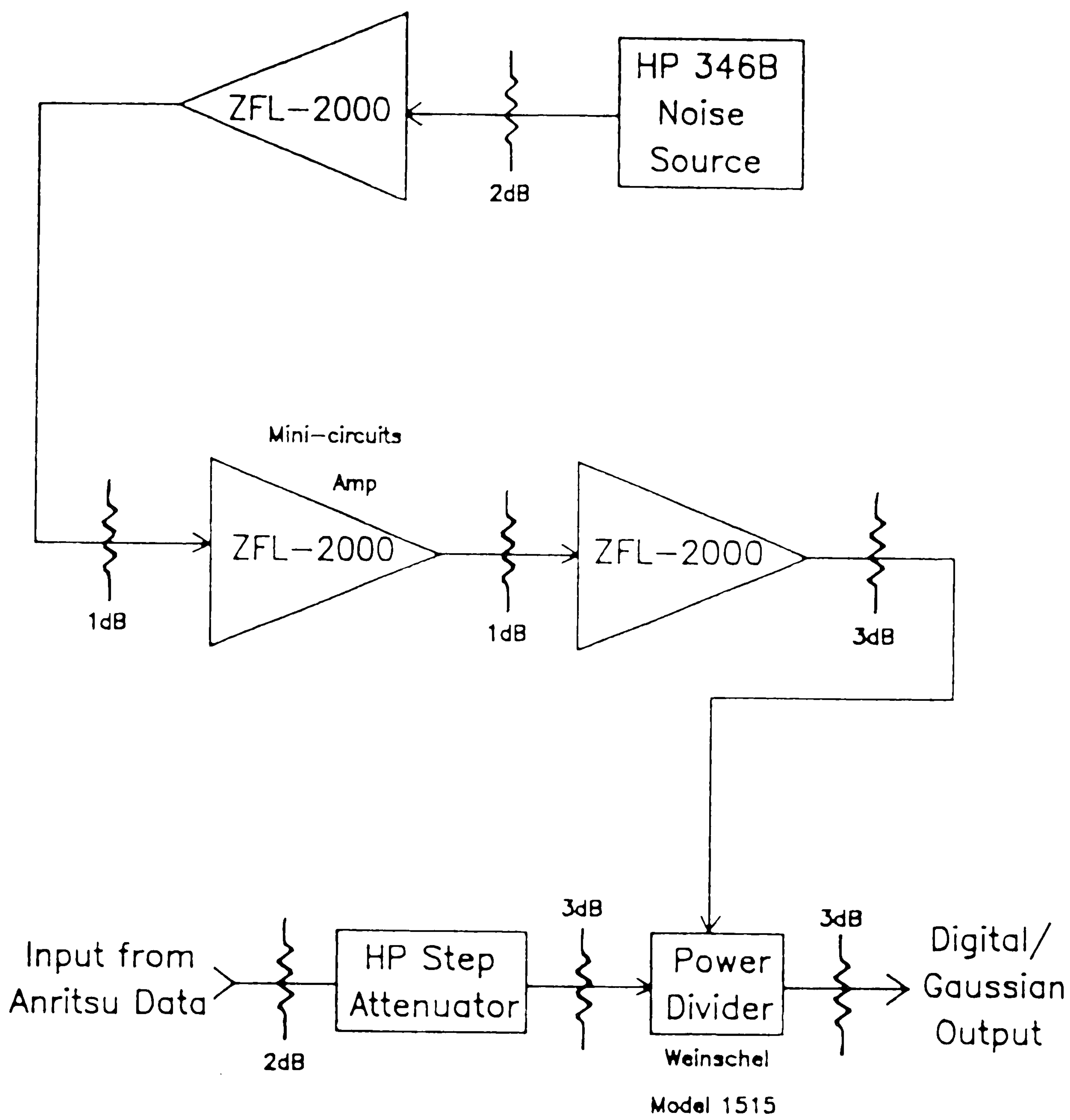


Fig. 3.1. Digital/gaussian noise combiner circuit.

described in Section 2.4. A picture of a typical digital/gaussian output waveform is shown in Fig. 3.2. This particular 1.7 Gb/s waveform exhibits a minimum BER of 1.0 X 10^{-6} using the error detector.

The noise source selected is an HP model 346B noise diode. It is characterized by a low VSWR and broadband

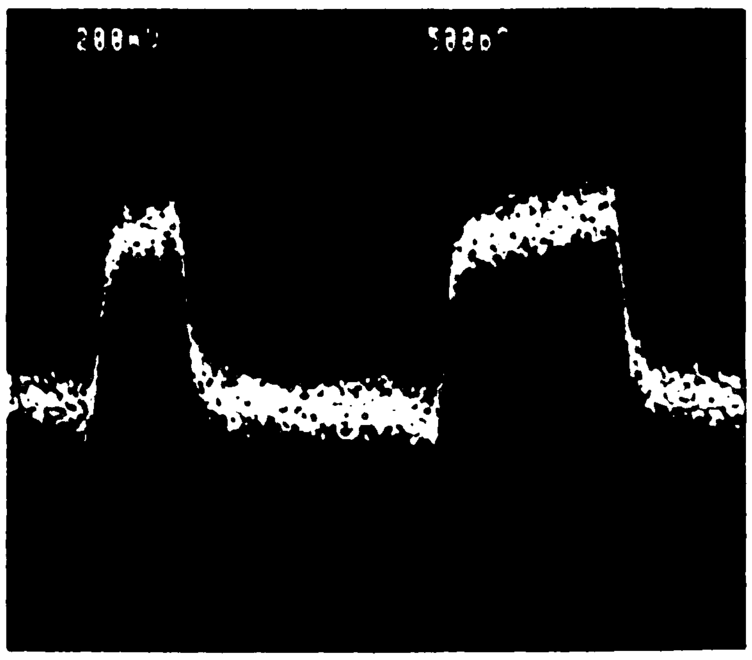


Fig. 3.2. Digital/gaussian output waveform which exhibits a minimum BER of 1.0 x 10^{-6}.

output performance from 10 Mhz to 18 Ghz. This source drives a series of cascaded broadband amplifiers. These are used to amplify the noise to a voltage amplitude which is sufficient to induce errors in the range of BER= 10^{-9}. The three amplifiers also perform a buffering function between the noise source and the resistive combiner. Interstage attenuators are incorporated in the RF path to reduce microwave reflections and to optimize the impedance match. The bandwidth of the cascaded amplifiers is 10 Mhz to 2 Ghz. Therefore, the resultant noise signal to the combiner is classified as band-limited white noise (10 Mhz - 2 Ghz).

The Anritsu digital word generator is used as the signal source. A 50% pseudo-random NRZ data stream of $2^{15}-1$ bits is selected to be the test pattern since it contains many binary sequences typical of PCM signals. The generator data output passes through a programmable RF attenuator which can be varied in 1 dB steps. This allows one to change the Signal to Noise, S/N, ratio as required to achieve the desired BER performance during testing. The data transmission rate is intended to be fixed at 1.7 Gb/s, however, the BER is also evaluated at 1.0 Gb/s for reasons to be discussed later.

3.2. Test Setup for Gaussian Measurements

The digital/gaussian noise source developed in Section 3.1 has been incorporated into a computer controlled measurement system. A block diagram of the test setup is shown in Fig. 3.3. The system computer is an HP 300 Series computer which controls all key test equipment via the HPIB interface. This includes the sweep oscillator, the digitizing oscilloscope, as well as

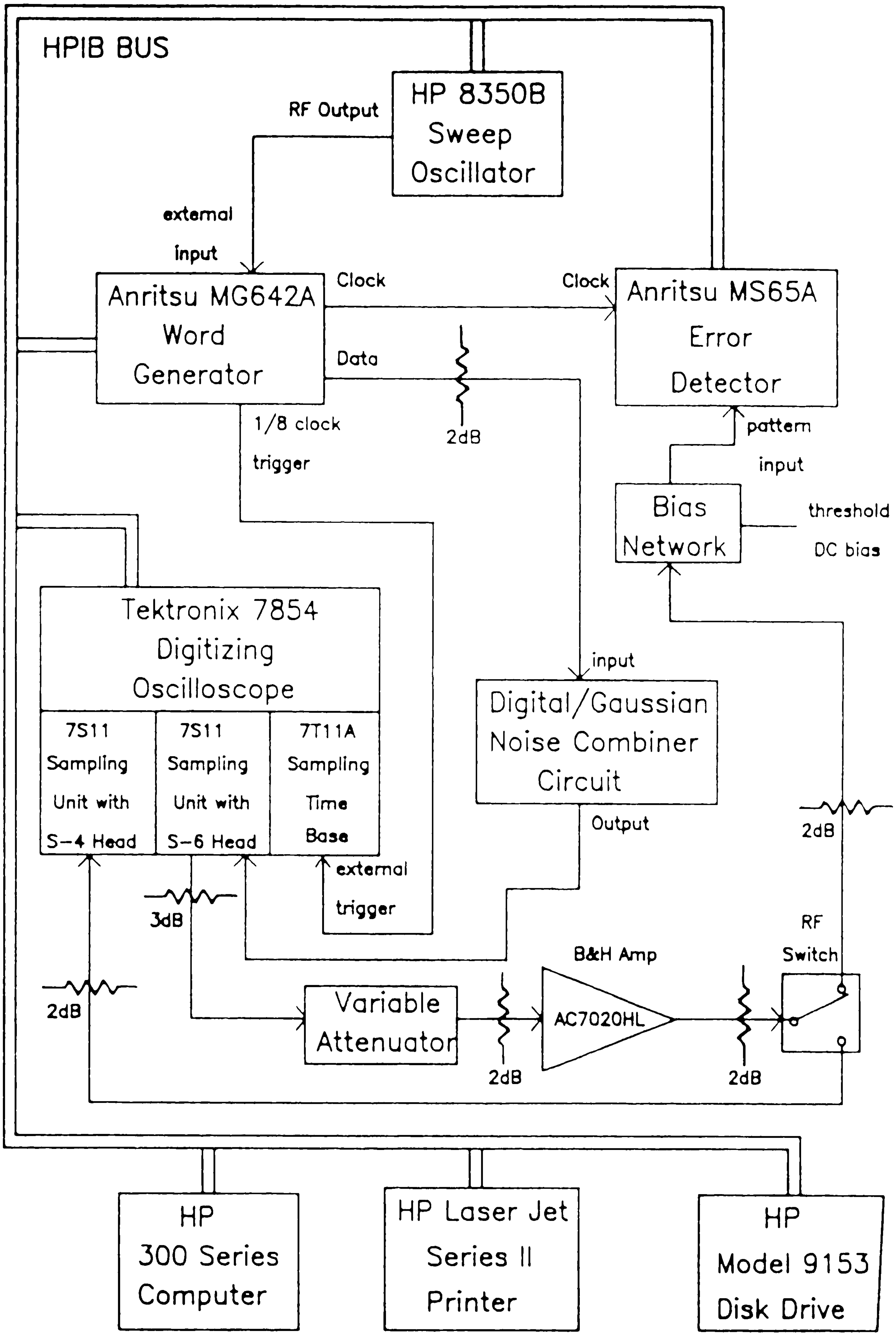


Fig. 3.3. Gaussian measurement test system.

the Anritsu BER equipment. In addition, an HP Laser Jet Series II Printer is interfaced to the system using an HPIB to parallel I/O converter to provide hi-speed test data output.

As indicated in Section 3.1, the digital signal originates in the Anritsu word generator. An HP model 8350B Sweep Oscillator is used to control the digital transmission rate through the external clocking input of the generator. The generator is equipped with an internal clock; however, it does not provide a signal which is stable enough to assure optimal timing results. An external clock signal also adds the capability to program the bit rate using software commands. The word generator utilizes the clock input as a timing reference in deriving the clock, data and trigger output waveforms. In this way, a fixed phase relationship is maintained between the signal outputs which is critical in making stable measurements.

Gaussian noise is mixed with the generator data signal in the combiner circuit. The noisy combiner output then passes through a Tektronix S-6 feed-thru sampling head in the right vertical channel of the oscilloscope. This allows the intermediate signal to be previewed with minimal perturbations when the system output is terminated into the error detector. The typical signal amplitudes at the output of the S-6 head are in the range of 200 to 500 mVpp.

A post amplifier circuit boosts this amplitude in order to satisfy the 0.7 to 2.0 Vpp data input specification of the detector. A B&H Electronics model AC7020HL amplifier is selected for the application and is designed into the output path such that it causes minimal degradation in the signal being measured. The amplifier features an ultra wide bandwidth of 7.5 Ghz and a VSWR of 1.5 which helps to preserve the square pulse shape. In-line attenuators are used to reduce interstage reflections.

The excellent amplifier quality and RF matching is a good design practice to follow when making measurements with the error detector. However, it is important to note that the sampling technique requires no amplifier at all since it could sample the S-6 output directly. The exact same signal must be analyzed by both techniques in order to obtain a valid comparison of the two. In this case it is made after the post amp and any degradation will be common to both. An additional variable attenuator has been provided to equalize all outputs to approximately 800 to 900 mVpp. This is necessary to eliminate erroneous results which could be caused by sampling distortion which can occur in the S-4 sampling head at input levels above 1.0 Vpp.

The post amplified signal is input into an RF switch. The switch is used to direct the output either to the detector or to the AC-coupled S-4 sampling head located in the left vertical channel of the oscilloscope. It is the S-4 head which is ultimately sampling the decision statistic and providing the test data used to calculate the BER. The effects of oscilloscope sampling noise and quantizing error are assumed to be negligible in this application. A bias network has been provided at the detector input to allow its threshold level to be varied with greatly increased resolution using an external voltage supply. This is required to achieve the absolute optimal BER during detector measurements.

3.3. Discussion of Digitizing Technique

The S-4 sampling head in the oscilloscope constructs a digital representation of the data stream being measured [8]. A sequential equivalent-time sampling process is employed in order to create the most accurate facsimile for this type of repetitive input signal. This method allows an equivalent bandwidth to be achieved which is much larger than in real time sampling systems. In sequential equivalent time sampling, many cycles of an input signal are translated into a single cycle of low frequency digitized points. Hi-speed digital pulse edges that would otherwise defy measurement can be accurately digitized using this technique. A graphical representation of this process is shown in Fig. 3.4.

The S-4 sampling head was specifically selected to sample the data signal for a variety of reasons. The S-4

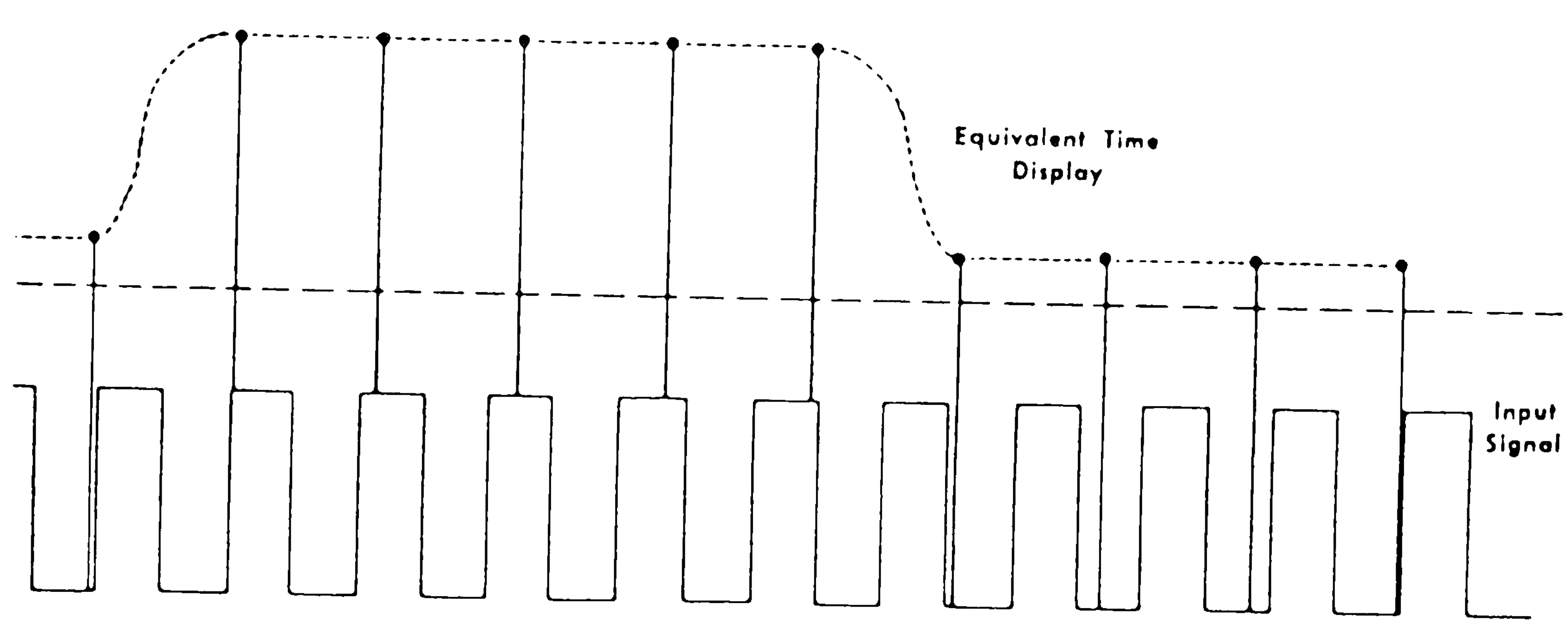


Fig. 3.4. Equivalent time display of real time signal.

features 14 Ghz equivalent bandwidth and a quality 50 ohm internal termination. It also provides a superior dot response optimization than the S-6 head. Non-optimized dot response is a source of waveform distortion and must be avoided.

The displayed waveform in Fig. 3.2 is typical of that created using a pattern sync trigger from the generator into the Tektronix model 7T11A sampling time base. A 1/8 clock trigger will now be used instead which will trigger the oscilloscope every eight clock pulses. This causes the bits of the pseudo-random pattern to be continuously superimposed on top of each other to form an eye diagram of the data stream. An eye diagram of the same data signal shown in Fig. 3.2 is portrayed in Fig. 3.5.

The eye diagram provides a qualitative description of the digital integrity of the data signal. In general,

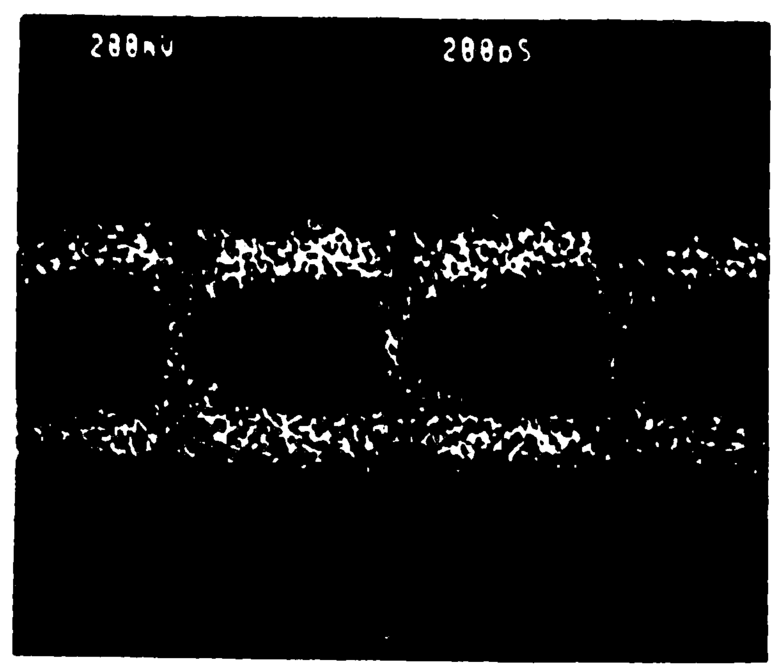


Fig. 3.5. Digital/gaussian eye diagram which exhibits a minimum BER of 1.0×10^{-6}.

the more "open" the aperture of the eye, the better the quality of the BER performance. The optimal eye pattern is obtained by compromising system bandwidth to achieve a

trade-off between system noise and intersymbol interference [9]. These are the two phenomena which limit the overall BER quality. Bandwidth should be minimized to reduce eye closure due to system noise. On the other hand, bandwidth should be maximized in order to reduce the effects of intersymbol interference.

3.4. Statistical Determination of BER

The eye diagrams are used to calculate the BER for a given threshold D and clock phase. Calculation of each BER involves a two step process. First, a valid sample set of data points must be accumulated. Then, the test data must be interpreted and quantized to derive values for all variables in Eq. 2.24. Software algorithms have been written to perform each of these tasks and a listing is available in Appendix A. Computer generated plots are made of BER vs. clock phase at the optimal threshold level. Plots of BER vs. data threshold can also be generated for a given clock phase.

A total of 36 sampling phase subsets are defined between adjacent crossovers on the eye diagram. The first phase subset starts at the left crossover at 0^0 clock phase and the last ends at the right crossover at 360^0. The oscilloscope digitizes the eye diagram into

512 equi-distant points. The point numbers of the 0 and 360^0 phase subsets are then determined using the digital cursors. Finally, the location by point number of the center of each subset is calculated in 10^0 increments.

A sample size of 900 samples for each phase subset is chosen based on computer RAM memory limitations. A sampling aperture 5 points wide about each center is used in accumulating the data samples. This dictates that the center point for a given phase as well as the two points to the right and left are all considered valid points for that phase. The oscilloscope continuously repeats the sampling process until all 36 subsets have acquired 900 voltage samples. The waveform can be sampled as long or as often as required since it is characterized by stationary time-invariant processes as discussed previously. All sampling data is stored on 3.5 inch microfloppy disks to allow subsequent processing.

The Tektronix digitizing process creates one serious problem for obtaining valid BER samples by adding phantom points to the digital display. It does this in order to fill in missing points so that the display is always exactly 512 points and each point number corresponds to the same position. Phantom points are inserted by the oscilloscope precisely between adjacent valid points and can represent up to 1% of the population. These points can cause large errors and must be removed from the sample since points placed between V_0 and V_1 will appear in the middle of the eye diagram. The algorithm therefore invalidates any data point number X during the sampling process whose value satisfies

$$\left|\frac{V(X-1) + V(X-1)}{2} - V(X)\right| \leq .002(Vmax-Vmin) \qquad (3.01)$$

In Eq. 3.01, V(X) is the voltage at point number X and Vmax, Vmin are the absolute maximum, minimum voltages of the first digitizing pass, respectively.

Once all 36 subsets are filled with valid samples, BER calculations can begin. Since the best possible BER performance is desired, the phase which exhibits minimum BER and its associated threshold level must first be identified. This is accomplished by determining P_0, P_1, V_0, V_1, σ_0 and σ_1 for each subset and then calculating BER using Eq. 2.24 with all threshold levels between V_0 and V_1 in 0.1% increments. All combinations of phase and threshold level are checked to find the optimal phase and threshold. This overall optimal threshold is then used to recalculate BER in Eq. 2.24 with the specific P_0, P_1, V_0, V_1, σ_0 and σ_1 from each of the 36 subsets. The resulting data is then plotted as optimal BER vs. clock phase. Test results depicting these types of plots are shown in Chapter 5.

The software which determines P_0, P_1, V_0, V_1, σ_0 and σ_1 for a given phase subset is now briefly described. It first establishes the minimum and maximum values of the voltages and then creates a histogram of voltage cell vs. number of occurrences for each cell. This is done by dividing the voltage span into 100 equal cells and then binning all data samples into the appropriate cell. A typical histogram is shown in Fig. 3.6 for a waveform which exhibits a minimum BER of 1.6×10^{-8} at 180^0 phase.

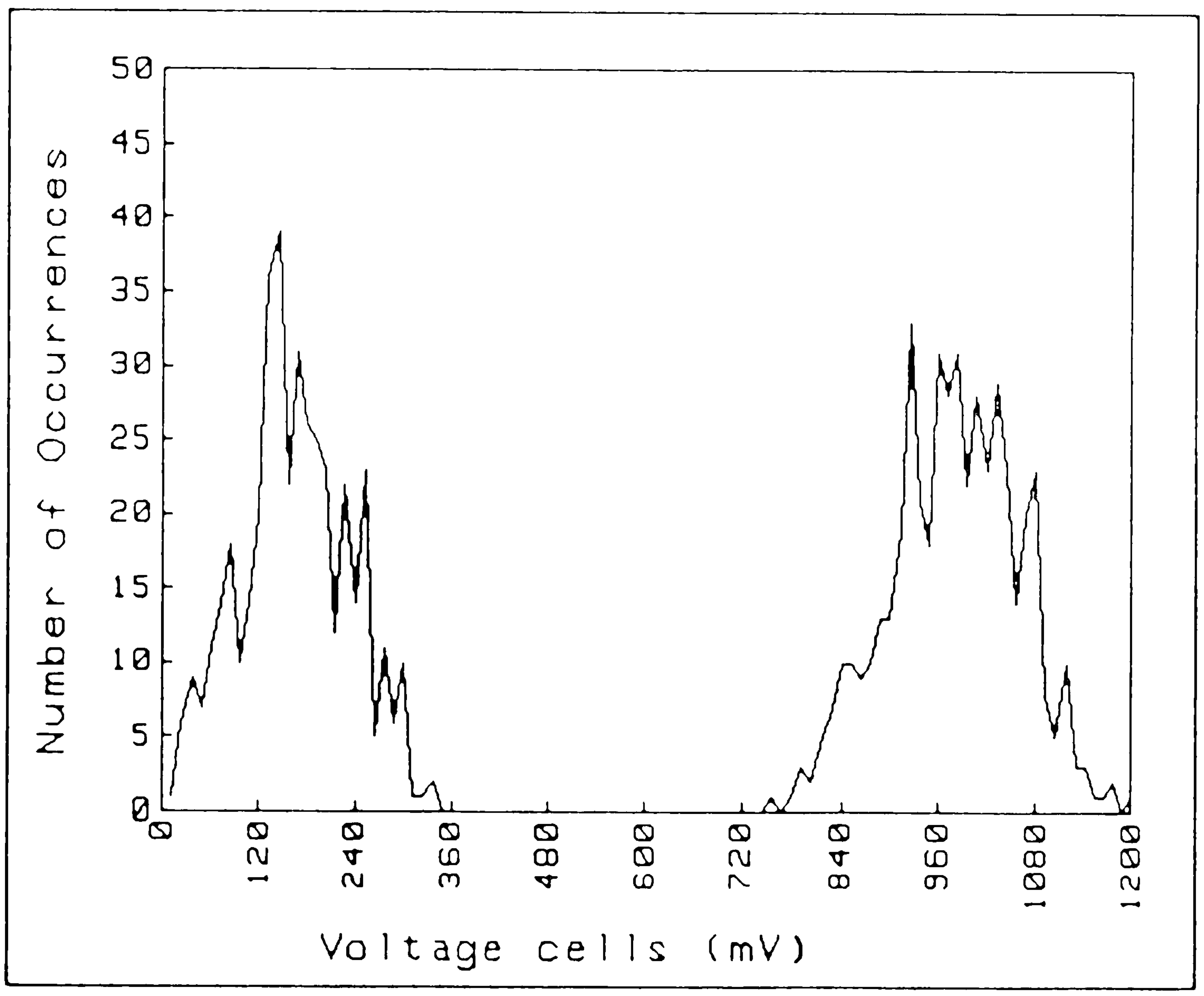


Fig. 3.6. Histogram of voltage cell vs. number of occurrences for a waveform which exhibits a minimum BER of 1.6×10^{-8} at 180^{o}.

Originally, the cells of maximal occurrence in the histogram were intended to be used to determine V_0 and V_1. This is justified since the average V_0 and V_1 should be the most often occurring voltage cells. After observing poor BER repeatability in initial experimental results, the sample means have been used instead. The histogram is still useful as a graphical representation of the voltage distribution for each subset, however, it will not actually be used in calculating the BER.

Calculation of V_0 and V_1 is achieved by first dividing the subset samples into two groups, V0 and V1. The subset sample mean $\bar{V}$ as expressed by

$$\bar{V} = \sum_{k=1}^{N_s} \frac{S_k}{N_s} \tag{3.02}$$

where S_k is sample point k. It is used as the decision criteria in Eq. 2.01 and Eq. 2.02 to associate each sample value with the appropriate zero (group V0) or one (group V1) gaussian distribution. P_0 and P_1 are calculated using Eq. 2.26 and Eq. 2.27 since the total number of zeros N_0 in group V0 and ones N_1 in group V1 can be totalized. Each group is then evaluated separately using

$$V_0 = \sum_{k=1}^{N_0} \frac{V0_k}{N_0} \tag{3.03}$$

and

$$V_1 = \sum_{k=1}^{N_1} \frac{V1_k}{N_1} \quad . \tag{3.04}$$

The sample variance S^2 is defined by Groeneveld [10] as

$$S^2 = \sum_{i=1}^{n} \frac{(X_i - \bar{X})^2}{(n - 1)} \tag{3.05}$$

and is used to calculate σ^2. The factor n-1 in the denominator compensates for finite sample size to assure that S^2 is an unbiased estimator of σ^2. σ_0 and σ_1 can then be expressed as

$$\sigma_0 = \sqrt{\sum_{k=1}^{N_0} \frac{(V0_k - V_0)^2}{(N_0 - 1)}} \tag{3.06}$$

and

$$\sigma_1 = \sqrt{\sum_{k=1}^{N_1} \frac{(V1_k - V_1)^2}{(N_1 - 1)}} \quad . \tag{3.07}$$

Computer programs to implement these equations are included in Appendix A.

Chapter 4 Optical Regenerator Measurements

In this chapter, the functionality of a typical optical regenerator is explained. The actual test setup used in making the regenerator BER measurements is also described. The overall function of the regenerator is to receive a degraded optical input and then to transmit an error free optical output. The S/N ratio and pulse shape of the regenerator output must be as good as the original data of the source transmitter to achieve optimal system performance.

4.1. Regenerator Theory

In a digital communication system, a laser source launches optical data pulses into a single-mode 1.3 micron optical fiber. The pulses degrade as they propagate down the fiber due to channel noise, attenuation, as well as dispersive effects. After passing through kilometers of fiber, the pulses will become severely distorted and exhibit poor S/N ratios. An optical regenerator is then used in the communication system to regenerate the source signal when the performance drops below an acceptable sensitivity level. The sensitivity of an optical receiver is generally expressed in terms of the minimum received optical power necessary to achieve a specific BER.

A simplified block diagram for a 1.7 Gb/s optical regenerator is shown in Fig. 4.1. The optical signal is detected at the input of the regenerator by an avalanche photo-detector diode. The photo-detector converts the light pulses into current pulses which are then converted into voltage at the receiver output. The transimpedance of the low noise pre-amplifier must be optimized for the best gain versus bandwidth trade-off. The input sensitivity is dominated by the S/N ratio established within the optical receiver. This assumes that the linear channel noise and the effects of intersymbol interference are minimal.

The output of the receiver passes through a linear channel which performs pulse shaping as well as automatic gain control functions. The signal is then split into two parts using a power divider buffer circuit. One of the outputs is injected directly into the data input of the decision circuit. The other output is used to provide clock recovery and retiming tasks. The recovered clock signal is directed into the clock input of the decision circuit and the clock phase is set for optimal performance. The output of the decision circuit is noise free, ideally. This waveform, which has greatly

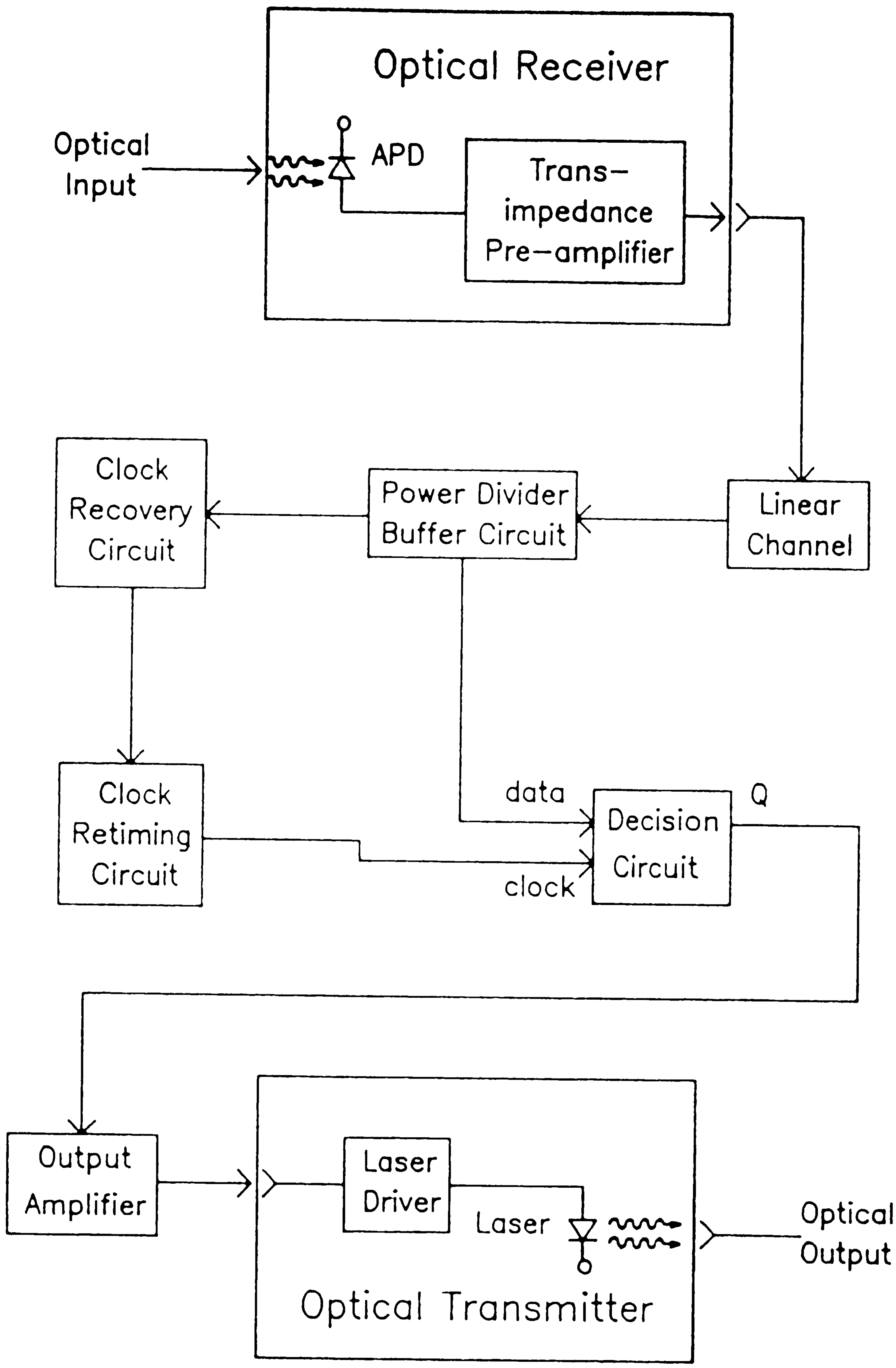


Fig. 4.1. Optical regenerator block diagram.

improved S/N ratio, feeds into the laser driver. The laser driver then modulates the laser to launch the digital signal onto the output fiber. This fiber terminates at the destination receiver or another optical regenerator.

4.2. Regenerator Test Setup

The BER of the optical regenerator is evaluated at the input to the decision circuit. This characterizes the best possible performance achievable by the decision circuit. Modifications to the regenerator have been made in order to accomplish this. The new configuration is shown in Fig. 4.2. The fiber optics are now connected input to output via optical hardware to simulate an optical link. Also note that the decision circuit has been removed from the system.

The optical output passes through a variable optical attenuator. The optical attenuation is varied to set the desired BER minimum. It is then divided two ways in a 3 dB splitter. One output is injected into the optical receiver input and the other feeds a power meter which monitors the incident optical power. The regenerator input is now at the laser driver of the optical transmitter. This input is driven directly by the

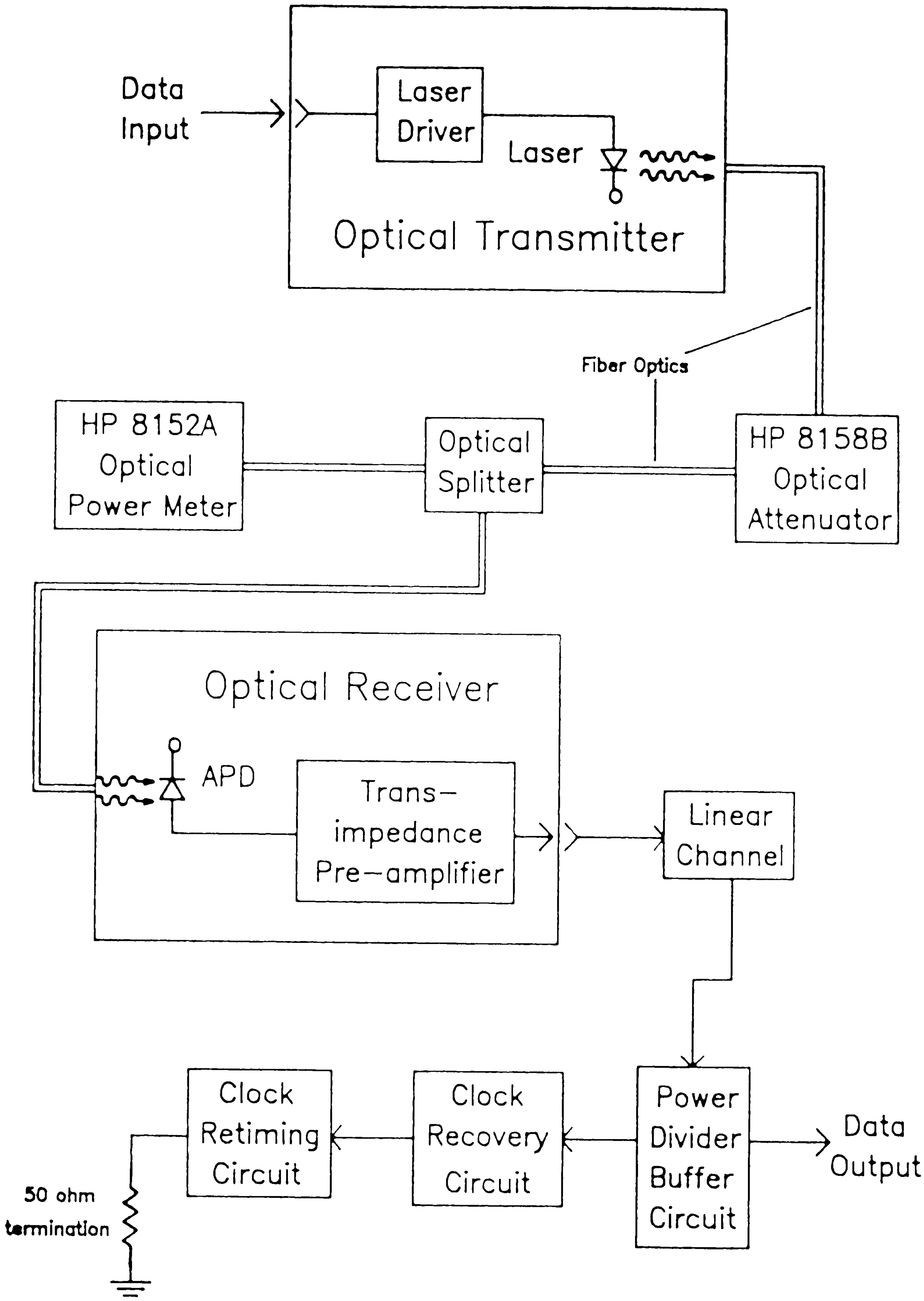


Fig. 4.2. Modified regenerator block diagram for BER measurement of decision circuit input.

Anritsu data generator.

The BER of the power divider output (decision circuit input) is measured by the Anritsu detector as well as the sampling technique. The overall regenerator test setup is shown in Fig. 4.3. It is the same basic circuit as that used in the gaussian measurement test system. The major difference is that the modified regenerator is used in the circuit in place of the digital/gaussian noise source. In addition, the bit rate is 1.7 Gb/s instead of 1.0 Gb/s which is used in the gaussian measurements.

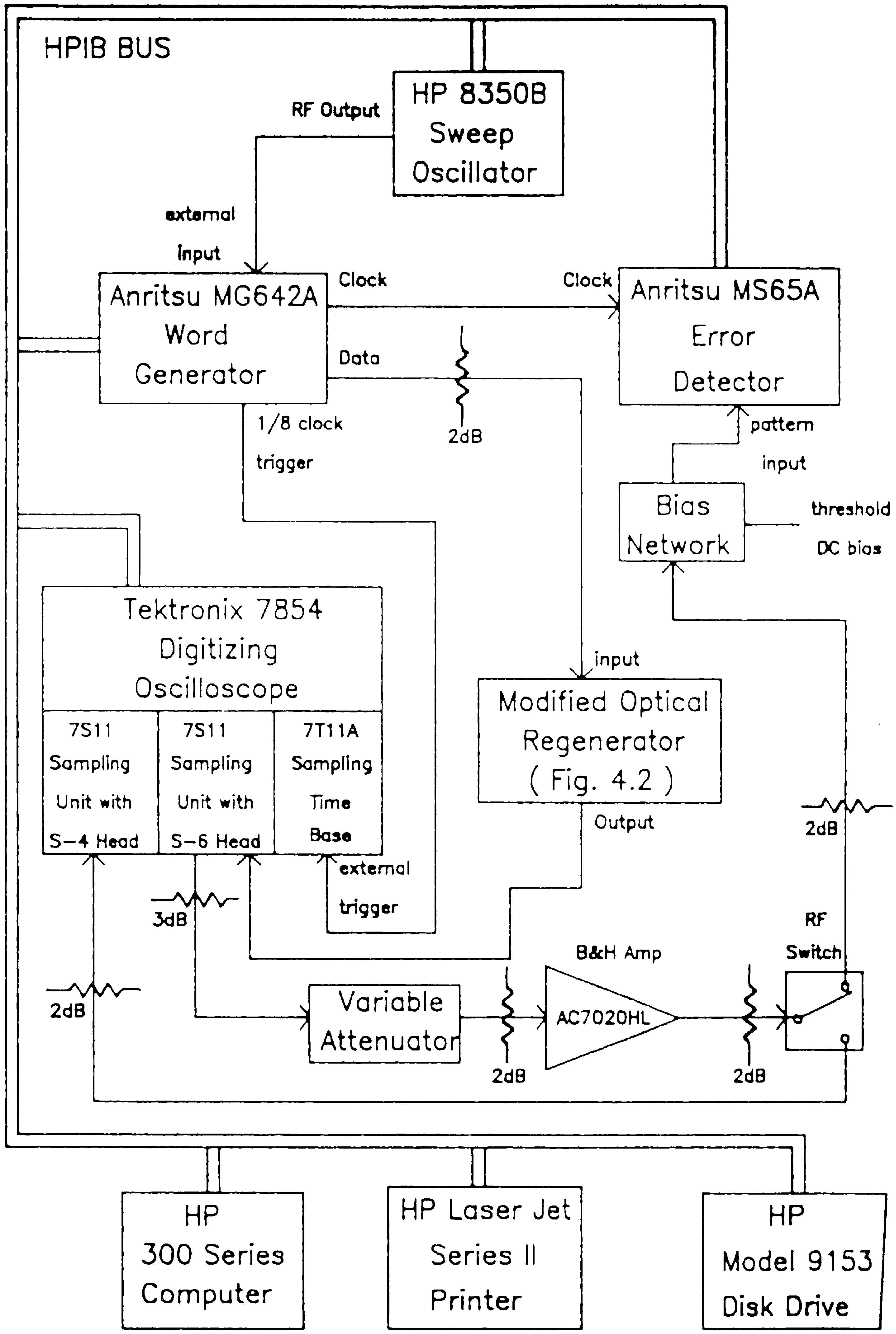


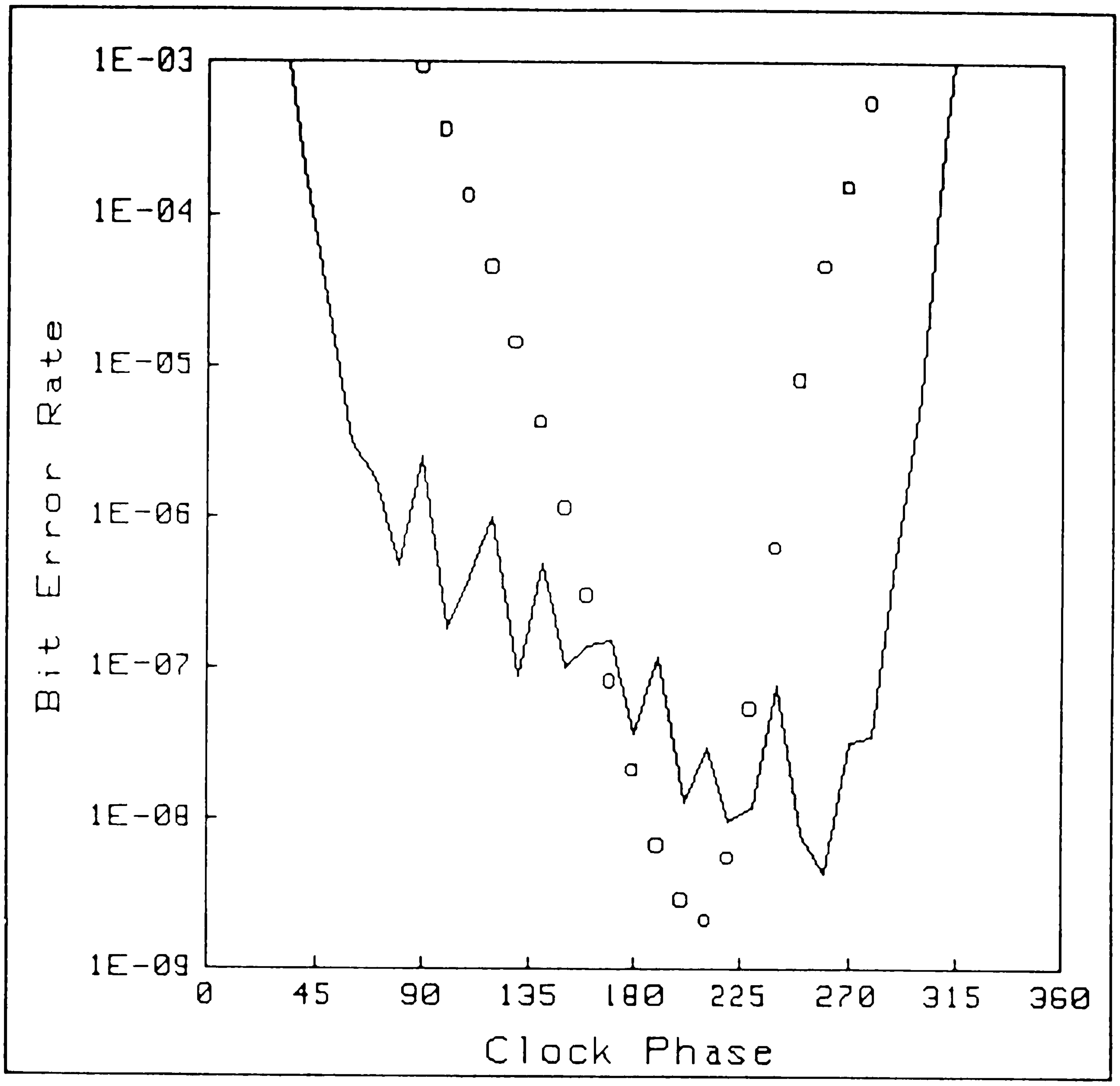
Fig. 4.3. Regenerator measurement test system.

Chapter 5 BER Measurement Results

Comparisons will now be made of BER measurements obtained using the Anritsu detector versus the predicted BERs computed using the sampling technique. The ideal gaussian waveforms will be evaluated first, followed by those of the optical regenerator. The BER will be measured and plotted as a function of clock phase. In this way, a comprehensive comparison is achieved across a wide spectrum of error rates instead of simply comparing them at a single phase such as at minimum BER.

5.1. Gaussian Experimental Results

The results of the initial gaussian measurements are typified by the BER curves in Fig. 5.1. Poor agreement between predicted and measured BER is evident in two aspects of the plot. First, the minimum BER predicted is expected to be the same or better than that measured, which is not the case. The calculations of the predicted curves are based on ideal performance whereas the detector measurements are made using actual circuitry which is degraded by lower order effects such as undesirable detector noise. The other major discrepancy in the plot is that the measured BER vs. phase curve



Anritsu measured BER = o
Predicted BER using sample data = ————

Fig. 5.1. Initial plot of BER vs. clock phase for a gaussian waveform without filtering which exhibits a minimum BER of 2.1 x 10^{-9} at 1.7 Gb/s using a 2 Gb/s Anritsu system.

is much narrower than that predicted. The calculated curve predicts a phase margin of 205^0 at a BER of 1.0×10^{-6} whereas the measured curve is only 90^0.

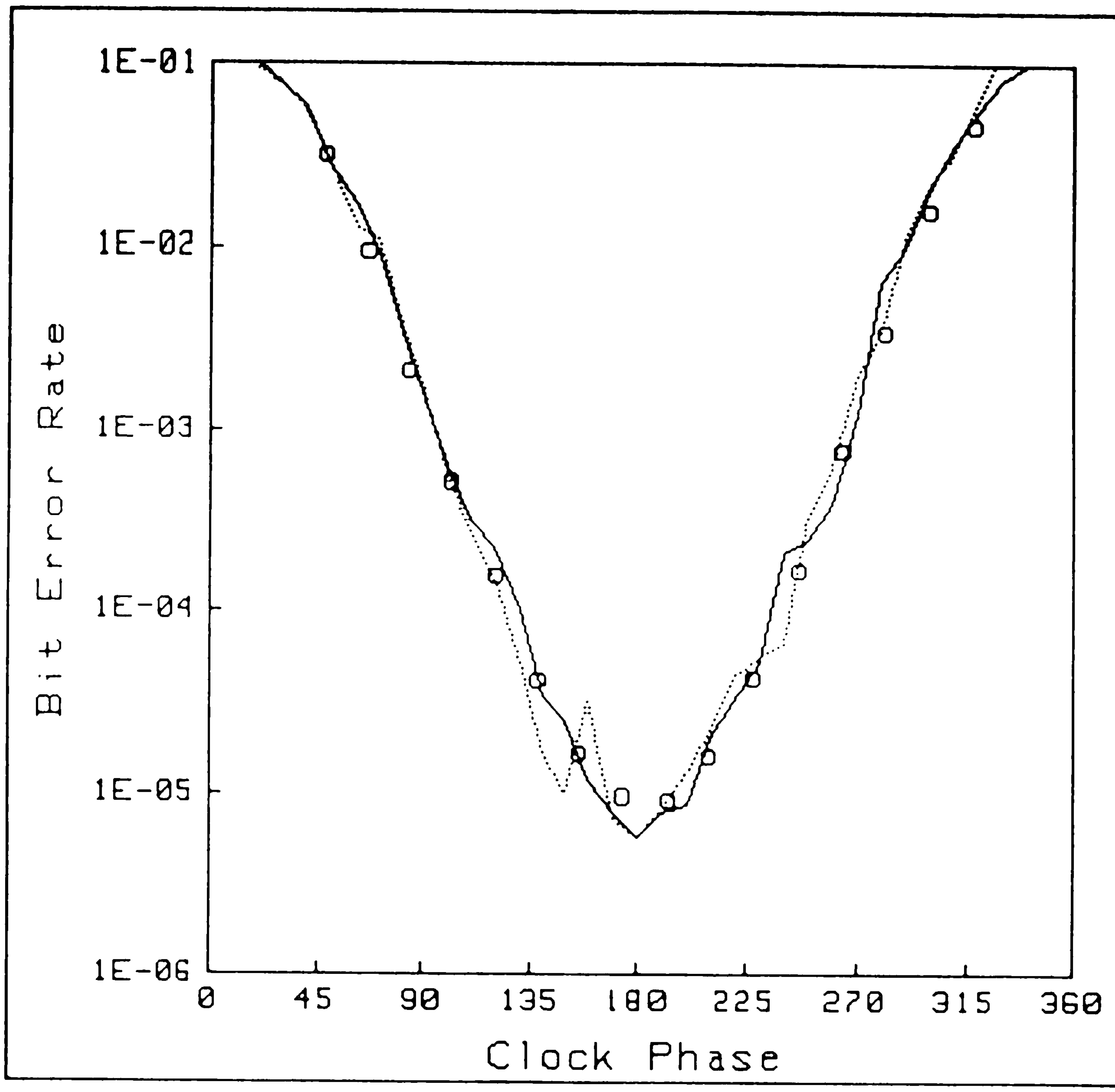
The discrepancies associated with the minimum BER in Fig. 5.1 are attributed to the different bandwidths of the error detector and the sampling oscilloscope. The oscilloscope samples noise impulses up to 14 Ghz whereas the detector only passes signal frequencies to a few gigahertz. The predicted curve minimum is worse than that measured because the calculations via the scope include high frequency noise that the error detector tends to filter out. A 1.0 Ghz low pass filter placed just in front of the RF switch, shown in Fig. 3.3, resolves this problem. The maximum frequency to each is therefore limited to 1.0 Ghz to match the bandwidths.

The narrowed curve of the measured BER in Fig. 5.1 is partially attributed to the timing jitter and setup and hold times of the MS65A error detector. The combination of these effects and limited detector bandwidth results in a detector specification requiring an eye opening greater than 300pS. The overall result of these problems is to narrow the measured curve by as much as 75pS on each side. The Anritsu 3.0 Gb/s detector, which requires less eye opening, will be used instead to minimize these effects. Also, the bit rate will be

lowered to 1.0 Gb/s so that any remaining errors caused by this type of problem will be a smaller percentage of the pulse width. This in turn will be less error when expressed in terms of clock phase.

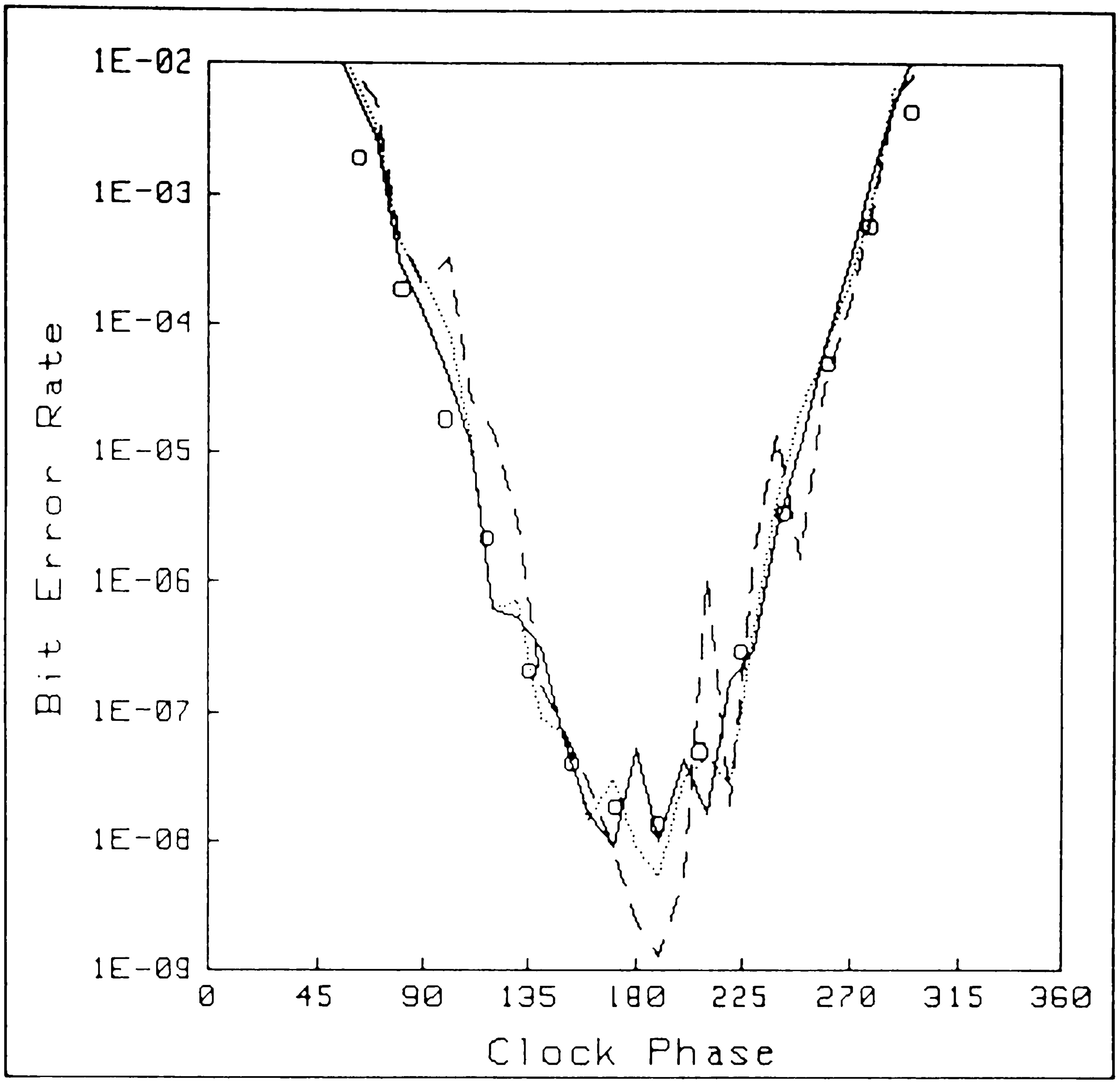
The plot shown in Fig. 5.2 is obtained by implementing the improvements suggested in the last two paragraphs. A minimum measured BER of 9.4×10^{-6} has been selected for this plot. The agreement between measured (circles) and predicted (solid line) is excellent. A second curve, indicated by the dotted line, has been included in Fig. 5.2 in order to demonstrate the repeatability of the measurements. This curve was generated using an independent sample and indicates extremely good repeatability.

Comparisons will also be made at additional BER minimums of 1.4×10^{-8} and 1.0×10^{-10}. This is necessary to check the dynamic range of measurement of the sampling technique. The BER = 1.4×10^{-8} plot is depicted in Fig. 5.3. Good agreement is evident once again between the predicted and measured curves. Additional curves have been added to Fig. 5.3 using sample sizes of 500 and 100 to determine the minimum sample size requirements. The 500 sample curve (dotted line) is still relatively good. The 100 sample curve (dashed line) shows poor BER minimum agreement and degraded repeatability, especially along



Anritsu measured BER = o
Predicted BER using original sample = ————
Predicted BER using a second sample = ...

Fig. 5.2. A plot of BER vs. clock phase for a gaussian waveform with a 1.0 Ghz filter. The minimum BER is 9.4×10^{-6} at 1.0 Gb/s using a 3 Gb/s Anritsu system.



Anritsu measured BER = o
Predicted BER using orig. sample (900 points) = ————
Predicted BER using 500 points of same sample = ...
Predicted BER using 100 points of same sample = - - - - -

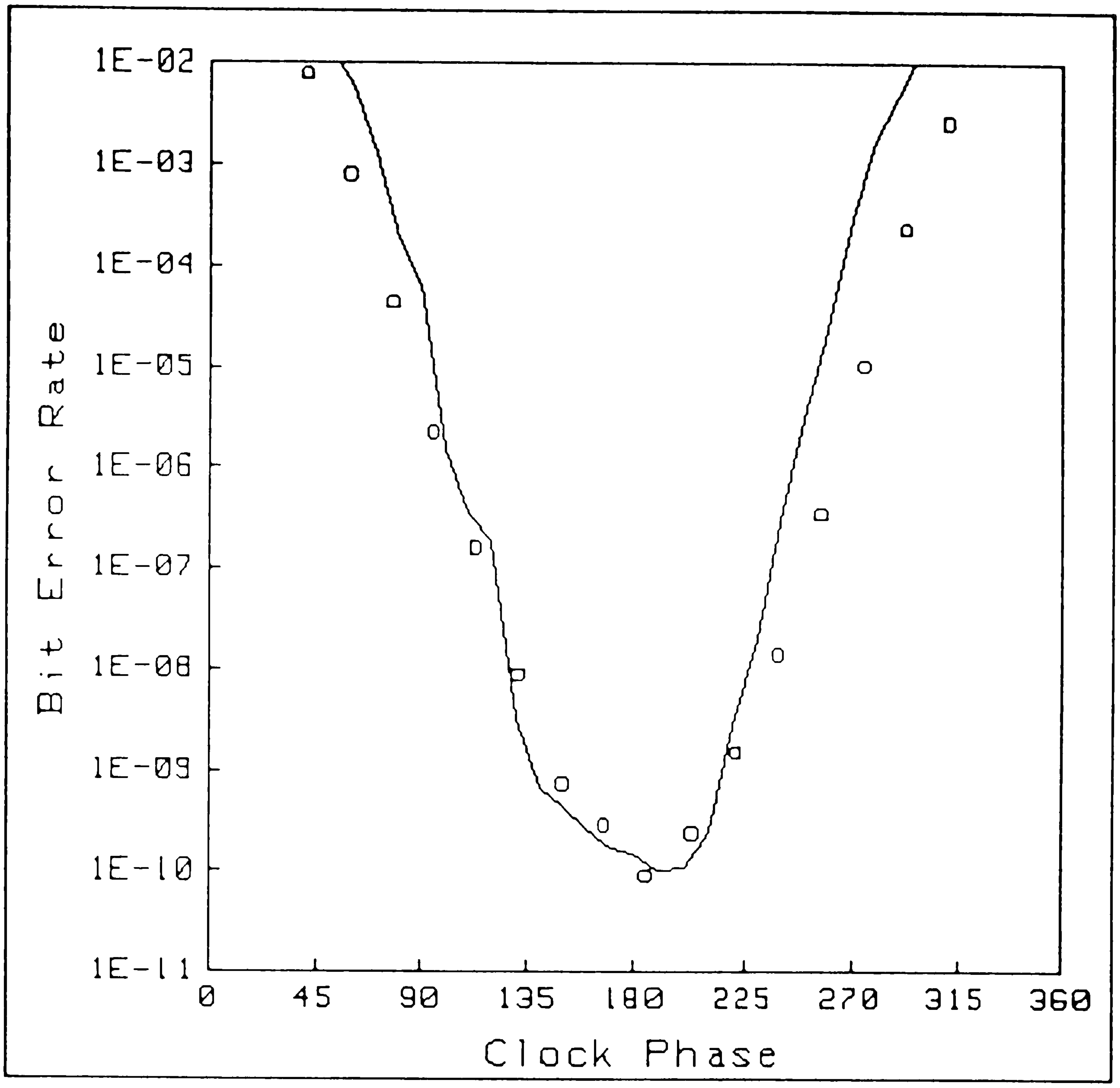
Fig. 5.3. A plot of BER vs. clock phase for a gaussian waveform with a 1.0 Ghz filter using multiple sample sizes. The minimum BER is 1.4×10^{-8} at 1.0 Gb/s using a 3 Gb/s Anritsu system.

the jagged sidewalls of the curve. These results dictate sample sizes of at least 500 samples for quality measurements.

The BER = 1.0 X 10^{-10} minimum is shown in Fig. 5.4. The BER minimums agree almost exactly. Some error is evident in the narrowing of the calculated curve however it is not much considering that the measurements span eight orders of magnitude. BER measurements less than 1.0 X 10^{-10} will not be pursued since so few errors occur that it would require many hours to characterize a single waveform with the error detector.

5.2. Regenerator Experimental Results

The regenerator BER measurements were made using a 1.5 Ghz low pass filter in place of the 1.0 Ghz filter used for the gaussian testing. This filter serves an additional purpose other than the bandwidth matching function described in Section 5.1. The optical power in the link (about 10 feet long) is varied using pure attenuation instead of adding or subtracting lengths of fiber. The optical dispersion will therefore be much less than that typically caused by kilometers of fiber. The filter tends to help simulate the dispersive effects of long regenerator links by degrading the edge speeds



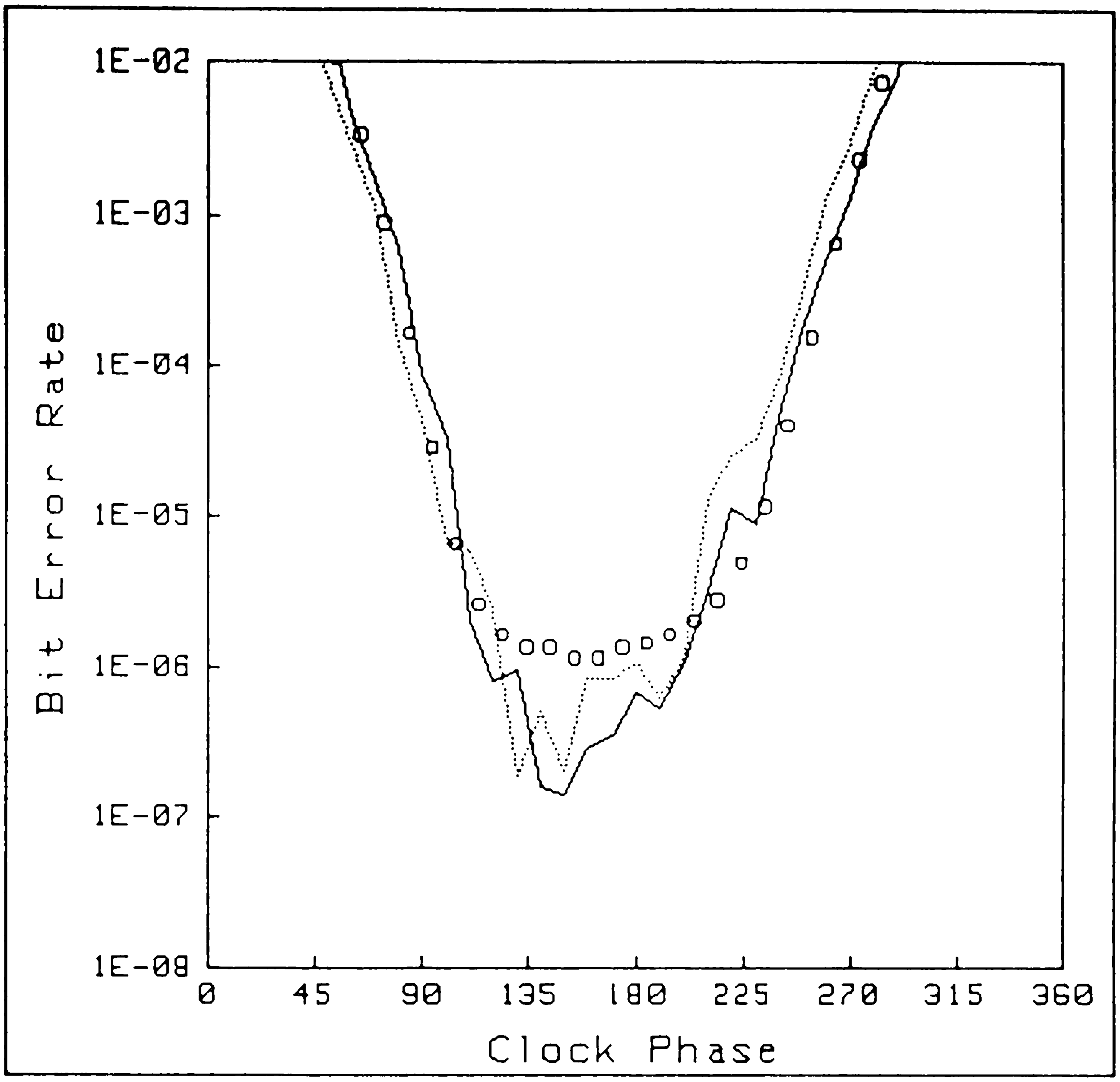
Anritsu measured BER = o
Predicted BER using sample data = ————

Fig. 5.4. A plot of BER vs. clock phase for a gaussian waveform with a 1.0 Ghz filter. The minimum BER is 1.0 x 10^{-10} at 1.0 Gb/s using a 3 Gb/s Anritsu system.

and thereby creating a more realistic system model.

BER curves are generated in a similar fashion as that done for the gaussian measurements. A plot of BER vs. clock phase is shown in Fig. 5.5 for a waveform which exhibits a BER minimum of 1.0 x 10^{-6}. Agreement between the measured (circles) and predicted (solid line) curves is good except at low bit error rate. The predicted BER curve from a second sample set (plotted using dotted line) shows good repeatability with the original curve (solid line). The measured BER curve tends to flatten out at the bottom whereas the predicted curve is lower. This discrepancy is partially attributed to the measuring error in the MS65A error detector associated with the 300 pS eye opening requirement as described in Section 5.1.

The fact that a gaussian model is being used to characterize the regenerator signals, which are not purely gaussian, also contributes to the discrepancies. In addition to the gaussian noise sources within the regenerator, the statistics associated with optical signal tend to be poisson in nature [7]. Still other noise sources such as the avalanche process associated with the APD diode in the receiver are characterized by functions which are not easily expressed in simple analytical form. Fortunately, the gaussian equations used to describe these phenomena are a fair approximation

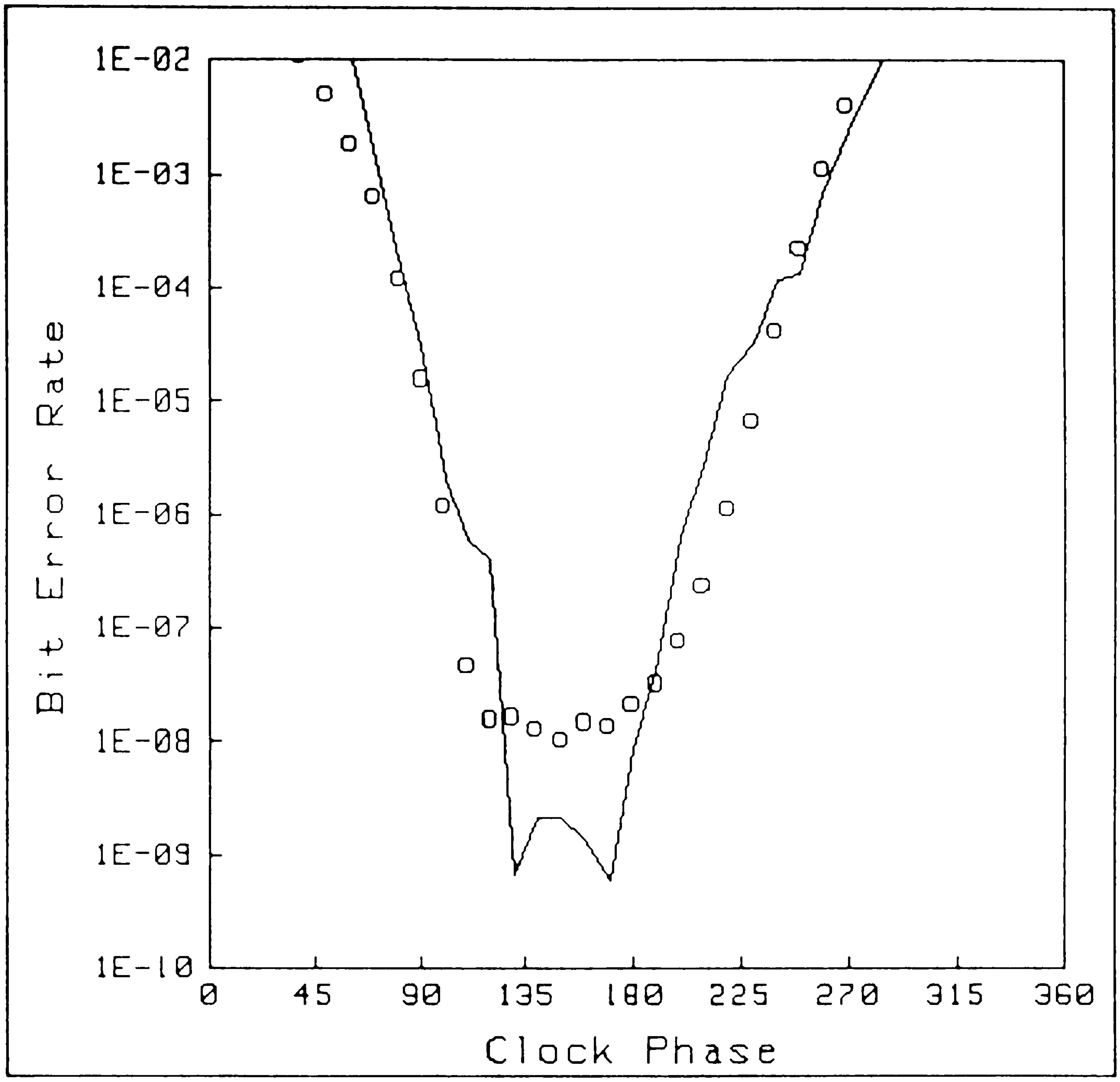


Anritsu measured BER = o
Predicted BER using original sample = ————
Predicted BER using a second sample = ...

Fig. 5.5. A plot of BER vs. clock phase for a regenerated waveform with a 1.5 Ghz filter. The minimum BER is 1.0 x 10^{-6} at 1.7 Gb/s using a 2 Gb/s Anritsu system.

to the actual equations. This is proven by the central-limit theorem [11] which states that the sum of a large number of independent random variables tends to a gaussian distribution.

A second BER plot is generated for a waveform which exhibits a BER minimum of 1.0×10^{-8}. This is depicted in Fig. 5.6. Once again flattening of the measured curve is evident at low bit error rate. Discrepancies at this point indicate predicted BERs which are an order of magnitude, in the worst case, better than those measured.



Anritsu measured BER = o
Predicted BER using original sample = ————

Fig. 5.6. A plot of BER vs. clock phase for a regenerated waveform with a 1.5 Ghz filter. The minimum BER is 1.0 x 10^{-8} at 1.7 Gb/s using a 2 Gb/s Anritsu system.

Chapter 6 Conclusions and Future Extensions

This thesis is concerned with the development of a new bit error rate measurement technique applicable to high frequency baseband digital signals.

The technique developed assumes that all noise contributions in the system are purely gaussian and uses probabilistic ideas in order to determine the BER. Implementation of this technique is achieved by utilizing a relatively inexpensive digitizing oscilloscope to capture the data and some computing equipment to process it.

Tests were set up to compare results obtained using this technique with those from a commercial error detector. Both gaussian and optically regenerated signals with a wide variety of S/N ratios were evaluated to determine the BER vs. clock phase relationship at the optimal threshold level. It was found that a filter is necessary in order to match the bandwidth of the digitizing oscilloscope to that of the error detector. With the filter in place, the results obtained for pure gaussian signals showed excellent agreement between measured and predicted BERs. When the signal is from an optical regenerator, the greatest discrepancy between the two was of an order in magnitude. Some of this difference is attributed to the error detector itself and can be reduced with a detector which has improved eye opening characteristics. This agreement confirms the assumption that the non-gaussian regenerator phenomena, such as poisson statistics in the optics, are well approximated by gaussian theory, as implied by the central-limit theorem.

However, the regenerator results could be further improved by developing more accurate equations, as done in Chapter 2, which take into account the regenerator noise statistics.

A limitation of the sampling system, as implemented, is the speed at which it can digitize and transfer data to the computer. It typically took about 15 minutes to acquire 900 valid samples at 36 phases (32,400 points). This situation could be greatly improved if a dedicated interface which incorporates flash A/D converters under microprocessor control was constructed and used instead.

The applications of the technique developed are not limited to the determination of BER vs. clock phase which has been demonstrated in this thesis. The same BER measurement technique can be used to generate information about BER vs. threshold level at a fixed phase or to provide phase margin or eye margin measurements. In addition, the optical sensitivity of the regenerator can be derived by performing a linear regression of BER vs. optical power.

Appendix A Sampling and BER Calculations Software

Appendix A contains the BASIC software developed during the course of this thesis in order to implement the measurement concepts described in Chapter 3.

```
1      !********************************************
2      !  RE-STORE"T_WEF_BER<  >:CS80,702,1"
3      ! LATEST SOFTWARE UPDATE-- 7/14/88  (08:46 AM)
4      !********************************************
5      !
6      Ber_test
7      END
8      !
9      !*********************************************************************
10      SUB Ber_test  ! T_WEF MAIN LOOP
11     !*********************************************************************
12     OPTION BASE 1
13     !  WRITTEN BY W.E.FULMER - 11/20/86
14     !  PROGRAM DIGITIZES TEK7854(W/ 7S11,7T11 PLUG-INS)
15     !  DATA POINTS ARE TRANSFERRED TO 9836, STORED IN AN ARRAY AND PLOTTED
16     !  POINTS ARE GRAPHED AMPLITUDE RANGE VS. OCCURENCE
17     !  SENSITIVITY IS THEN CALCULATED FROM THE GAUSSIAN NATURE OF THE POINT
18     !  DISTRIBUTION.
19     COM /Wave/ Wave$[8000],Wavehead$[130],Dig_array(1080),X_plot(1080),Y_plot(
1080)
20     COM /T/ T_point(1030)
21     COM /Dig/ V_1,V_0,Vmiddle,Occur_ampl(1:2000),Total_cells,D,Vsamp_size,Vali
d_samp(0:35,0:920),Cell_0,Cell_1,Ber,Phs
22     COM /Hpib/ Tek1,Tek2,Tek3,Tek4,Tek5,Tek6,Tek7,Tek8,Tek9,Hard_disk,Atten_dr
iv,Scope,Freq_ct,Opt_pm,Opt_atten,Sweep_osc,Data_acq,Anr_ber,Anr_prog,Tek_ct
23     COM /Pp/ Printing,Comment$[60]
24     COM /Dstorm/ P_w,Xzero,Xmult,Xun$[10],Yzero,Ymult,Yun$[10]
25     COM /Zip/ Subset_len,Subset_pt(100),Valid_pt(100),Samp_count(0:35),Unfill_
ct,Bin_pt(100)
26     COM /Curs/ INTEGER X_over1,X_over2
27     COM /Sav/ Filenam$[10],Choice$[1]
28     COM /Sig/ Best_fit_0(10),Best_fit_1(10),Sigma_0(10),Sigma_1(10),Unoccur_0,
Unoccur_1,P_0(10),P_1(10),P_e(10),Q_0(10),Q_1(10)
29     COM /Vvv/ Vmin,Vmax,Vspan,Vcell
30     COM /Strait/ Vsamp_ave,Sig_0,Sig_1,V0_count,V1_count,V0_ave,V1_ave,V_zero,
V_one,Q_zero(0:35),Q_one(0:35),P_zero(0:35),P_one(0:35),P_error(0:35)
31                         ! UNOCCUR=UNNORMALIZED OCCURRENCES AT V_0 OR V_1
32     DIM Heading$[25]
33 Start:     !
34     GINIT
35     PRINTER IS 1
36     PRINT CHR$(12)
37     GRAPHICS ON
38     GCLEAR
39     I=0
40     Scope=708
41     Data_acq=709
42     Atten_driv=702
43     PRINT TABXY(1,1),"     ENTER ADDRESS OF PRINTER DESIRED(701 OR 26)"
44     INPUT Printing
45     DUMP DEVICE IS Printing
46     PRINT TABXY(1,1),"                                              "
47     CSIZE 4
```

```
48    PRINT TABXY(11,5),"    ENTER FILENAME TO BE USED FOR DATA STORAGE "
49    PRINT TABXY(11,7),"          OR RETRIEVAL -(ex. SAMPLE15)"
50    INPUT "FILENAME=?",Filenam$
51    PRINT CHR$(12);
52    PRINT TABXY(11,5),"           ENTER A DESCRIPTIVE COMMENT  "
53    INPUT Comment$
54    PRINT CHR$(12);
55    PRINTER IS Printing
56    Esc$=""
57    PRINT Printing;Esc$&"&l8D"  ! 8 LINES PER INCH
58    PRINT Printing;Esc$&"&a25L"  ! LEFT MARGIN= COLUMN 25
59    PRINT Printing;Esc$&"(s16.66H"  ! COMPRESSED
60    PRINT Printing;Esc$&"*t100R"  ! MINIATURIZE GRAPHICS
61    PRINT CHR$(12);
62    PRINT "Data File Description- ";Comment$
63    PRINT "DATE=";DATE$(TIMEDATE),"   TIME=";TIME$(TIMEDATE)
64    PRINT
65    PRINT "Data Storage Filename-";Filenam$
66    PRINT
67    PRINTER IS 1
68 Bak:  !
69    CSIZE 4
70    MOVE 15,65
71    LABEL "ENTER ""N"" TO CREATE A NEW VALID SAMPLE"
72    MOVE 15,50
73    LABEL "ENTER ""S"" TO CALCULATE P(E) USING STORED DATA"
74    INPUT "Selection=?",Choice$
75    GCLEAR
76    IF Choice$="N" OR Choice$="n" THEN GOTO New_data
77    IF Choice$="S" OR Choice$="s" THEN
78      MASS STORAGE IS ":CS80,700,1"
79      ASSIGN @Path_1 TO Filenam$
80      ENTER @Path_1;Vsamp_size,Ber,Xmult,Ymult,Yzero,P_w
81      REDIM Valid_samp(0:35,1:Vsamp_size)
82        ENTER @Path_1;Valid_samp(*)
83      ASSIGN @Path_1 TO *        ! CLOSES I/O PATH
84      Vsamp_size=50
85      DIM Tv_samp(0:35,1:920)
86      REDIM Tv_samp(0:35,1:Vsamp_size)
87       FOR X=0 TO 35
88       FOR Y=1 TO Vsamp_size
89       Tv_samp(X,Y)=Valid_samp(X,Y)
90       NEXT Y
91       NEXT X
92      REDIM Valid_samp(0:35,1:Vsamp_size)
93      MAT Valid_samp= Tv_samp
94       PRINT TABXY(10,10),"DO YOU WISH ALL TEST DATA? (Y or N)"
95       PRINTER IS Printing
96       PRINT "Sample Size=";Vsamp_size,"BER=";Ber
97       PRINT "Xmult=";Xmult,"Ymult=";Ymult,"Yzero=";Yzero,"P_W=";P_w
98       INPUT D$
99       IF D$="Y" THEN
100        FOR Phs=0 TO 35
101        Phase=DROUND(Phs*10,3)
102        PRINT "***************************************************************
********"
103        PRINT "  PHASE = ";Phase;" Degrees"
104        PRINT "***************************************************************
********"
105        FOR Jx=1 TO Vsamp_size
106         PRINT "PT#";Jx;"=";Valid_samp(Phs,Jx),
107        NEXT Jx
108        NEXT Phs
109      END IF
110      PRINTER IS 1
111      Total_cells=100 ! ASSUME FOR PREVIOUSLY STORED DATA
112   REDIM Occur_ampl(1:Total_cells)
```

```
113     GOTO Occur_master
114   END IF
115   GOTO Bak      ! RE-ENTER CHOICES
116 New_data: Total_cells=100      ! DIVIDES THE V SPAN INTO 100 EQUAL CELLS
117   REDIM Occur_ampl(1:Total_cells)
118   CSIZE 4
119   MOVE 10,50
120   LABEL "ENTER THE DESIRED SAMPLE SIZE(1-2000)"
121   INPUT Vsamp_size
122   PRINTER IS Printing
123   PRINT "VALID SAMPLE SIZE=";Vsamp_size
124   PRINTER IS 1
125   GCLEAR
126   CSIZE 5
127   MOVE 10,65
128   LABEL "ADJUST SENSITIVITY TO THE DESIRED BER"
129   MOVE 10,50
130   LABEL "SWITCH FROM SCOPE TO RCVR AS REQUIRED"
131   PRINTER IS 1
132   PRINT TABXY(20,50);"ENTER THE BER ACHIEVED!- ( ex. 2.5E-9 )"
133   INPUT "BER=?",Ber
134   PRINTER IS Printing
135   PRINT "BER=";Ber
136   PRINTER IS 1
137   PRINT CHR$(12)
138   SYSTEM PRIORITY 0
139   OFF KEY
140   !-----------------------------------------------------------------
141   !THIS SECTION ACQUIRES THE SAMPLE POPULATION FOR THE ERROR CALCULATIONS
142   !-----------------------------------------------------------------
143   CALL Data_storm("5 1 2 >P/W","ACQ",0)
144   PRINTER IS Printing
145   PRINT
146   PRINT "COMMENTS- ";Comment$
147   PRINT
148   PRINT "          POINTS PER WAVEFORM= ";P_w
149   PRINT "                      Xoffset= ";Xzero
150   PRINT "                  Xmultiplier= ";Xmult
151   PRINT "                       Xunits= ";Xun$
152   PRINT "                      Yoffset= ";Yzero
153   PRINT "                  Ymultiplier= ";Ymult
154   PRINT "                       Yunits= ";Yun$
155   PRINT
156   PRINT
157   PRINTER IS 1
158   CALL Cursor
159   CALL Samp_builder  ! ACQUIRES VALID_SAMP(*) FROM SUCCESSIVE WAVEFORMS
160   CALL Samp_saver    ! STORES VALID_SAMP(*) ON DISK
161   GOTO Start
162   !-----------------------------------------------------------------
163   !THIS SECTION BUILDS AND PLOTS OCCURRENCE VS CELL# FOR EACH OF THE
164   !PHASE SAMPLE SETS
165   !-----------------------------------------------------------------
166 Occur_master:  !
167           PRINTER IS 1
168           GCLEAR
169           PRINT TABXY(5,10),"ENTER ""M"" FOR MANUAL SELECTION OF V_1,V_0"
170           PRINT TABXY(5,8),"ENTER ""A"" FOR AUTO SELECTION OF V_1,V_0"
171           INPUT Gate$
172           IF Gate$="M" OR Gate$="m" THEN
173            Selector=1 ! MANUAL
174            GOTO Brick
175           END IF
176           IF Gate$="A" OR Gate$="a" THEN
177            Selector=2 ! AUTO
178            GOTO Brick
179           END IF
```

```
180             GOTO Occur_master
181 Brick: !
182       DIM Xax$[25],Yax$[25],Title$[45],Phs$[25]
183       Xax$="Voltage cells"
184       Yax$="Number of Occurrences"
185      !-------------------------------------------------------
186      ! THIS SECTION FINDS Vmin ERROR FOR 180 DEGREES PHASE SUBSET
187      !-------------------------------------------------------
188      Phs=18
189      Occur_builder(Selector)
190      V_zero=V_0
191      V_one=V_1
192      Gc_sigma(1)
193      PRINTER IS Printing
194      PRINT
195      PRINT "PROBABILITY OF ERROR USING MAXIMAL OCCUR 1&0 (180 DEGREE PHASE)"
196      PRINT
197      PRINT " Vthreshold         Q_zero          Q_one          BER"
198      Ber_min=1
199      FOR Jib=1 TO 999
200      D=V_zero+(V_one-V_zero)/1000*Jib
201      Prob_error(0) ! NO PRINTING
202      IF FRACT(Jib/20)=0 THEN PRINT D;TAB(20);Q_zero(Phs);TAB(35);Q_one(Phs);T
AB(50);P_error(Phs)
203      IF P_error(Phs)<Ber_min THEN
204       Dmin_mo=D
205       Ber_min=P_error(Phs)
206      END IF
207      NEXT Jib
208      PRINT
209      PRINT "D threshold optimal=";Dmin_mo,"BER minimum=";Ber_min
210      PRINT CHR$(12);
211      V_zero=V0_ave
212      V_one=V1_ave
213      Gc_sigma(1)
214      PRINTER IS Printing
215      PRINT
216      PRINT "PROBABILITY OF ERROR USING V_0,1average (180 DEGREE PHASE)"
217      PRINT
218      PRINT " Vthreshold        Q_zero          Q_one          BER"
219      Ber_min=1
220      FOR Jib=1 TO 999
221      D=V_zero+(V_one-V_zero)/1000*Jib
222      Prob_error(0) ! NO PRINTING
223      IF FRACT(Jib/20)=0 THEN PRINT D;TAB(20);Q_zero(Phs);TAB(35);Q_one(Phs);T
AB(50);P_error(Phs)
224      IF P_error(Phs)<Ber_min THEN
225       Dmin_ave=D
226       Ber_min=P_error(Phs)
227      END IF
228      NEXT Jib
229      PRINT
230      PRINT "D threshold optimal=";Dmin_mo,"BER minimum=";Ber_min
231      Error_opt=1
232      FOR Phs=0 TO 35 STEP 3
233    Occur_builder(Selector) !BUILDS OCCUR. VS. RANGE USING SELECTOR CHOSEN
234       PRINTER IS 1
235    CALL Gc_sigma(1)   ! CALCULATES SIGMA 1&0 BASED ON SAMPLE STATISTICS
236    PRINTER IS Printing
237    PRINT
238    PRINT "PROBABILTY OF ERROR USING V_ZERO,ONE=V_0,1(MAXIMAL OCCUR.)"
239    PRINTER IS 1
240    V_zero=V_0
241    V_one=V_1
242    D=Dmin_mo
243    CALL Prob_error(1) ! CALC. PROB. OF ERROR GIVEN SIGMA0,SIGMA1, AND D
244    PRINTER IS Printing
```

```
245   GOSUB Djammer
246   PRINTER IS Printing
247   PRINT
248   PRINT "PROBABILTY OF ERROR USING V_ZERO,ONE=V0_AVE,V1_AVE"
249   PRINTER IS 1
250   V_zero=V0_ave
251   V_one=V1_ave
252   D=Dmin_ave
253   CALL Prob_error(1)
254   PRINT
255   GOSUB Djammer
256   PRINT
257   IF Ber_min<Error_opt THEN
258     Error_opt=Ber_min
259     D_opt=Dmin
260   END IF
261       PRINTER IS 1
262       Phs$=VAL$(10*Phs)
263       Phs$=" @"&Phs$&" degrees phase"
264       Title$="VOLTAGE DISTRIBUTION"&Phs$
265       Ymax=MAX(Occur_ampl(*))
266       IF Ymax<50 THEN Ymax=50
267    Wef_plot(Total_cells,Ymax,Xax$,Yax$,Title$,Occur_ampl(*))!PLOT OCCUR vs C
ELL
268    GCLEAR
269   NEXT Phs
270   PRINTER IS Printing
271   PRINT CHR$(12);
272   D=D_opt
273   PRINT "            Dopt=";D
274   PRINT
275   PRINT "PROB. OF ERROR USING Dopt from best phase/ V_0,V_1 RECALC. AT EACH
PHASE"
276   PRINT "Phase(deg)   Q(ZERO)         Q(ONE)         P(ZERO)          P(ONE)
    P(ERROR)"
277   PRINT
278   FOR Phs=0 TO 35
279   Phase=Phs*10
280   Gc_sigma(0)
281   V_one=V1_ave
282   V_zero=V0_ave
283   Prob_error(0)
284    PRINTER IS Printing
285    PRINT Phase;TAB(12);Q_zero(Phs);TAB(28);Q_one(Phs);TAB(42);P_zero(Phs);TA
B(57);P_one(Phs);TAB(69);P_error(Phs)
286    PRINTER IS 1
287    NEXT Phs
288    PRINTER IS Printing
289    PRINT CHR$(12);
290    GOTO 307
291   PRINTER IS 1
292 Djammer:   !JAMS D FROM V_0 TO V_1 GIVEN SIGMA,V_0,1
293      Ber_min=1
294      FOR Jib=1 TO 999
295      D=V_zero+(V_one-V_zero)/1000*Jib
296      Prob_error(0) ! NO PRINTING
297      IF P_error(Phs)<Ber_min THEN
298       Dmin=D
299       Ber_min=P_error(Phs)
300      END IF
301      NEXT Jib
302      PRINTER IS Printing
303      PRINT "D threshold optimal=";Dmin,"BER minimum=";Ber_min
304      PRINTER IS 1
305    RETURN
306    !
307    ! MAIN PROGRAM END
```

```
308   SUBEND
309   !************************************************************************
310   !************************************************************************
311   ! THIS IS THE END OF THE MAIN PROGRAM
312   !************************************************************************
313   !************************************************************************
314   !
315   !********************************************************************
316   SUB Cursor              ! WAVEFORM MUST BE IN SCOPE MEMORY
317                           ! ACQUIRES LEFT AND RIGHT (1&2) CROSSOVERS
318                           ! UNITS ARE IN POINTS
319   !********************************************************************
320   COM /Hpib/ Tek1,Tek2,Tek3,Tek4,Tek5,Tek6,Tek7,Tek8,Tek9,Hard_disk,Atten_dr
iv,Scope,Freq_ct,Opt_pm,Opt_atten,Sweep_osc,Data_acq,Anr_ber,Anr_prog,Tek_ct
321   COM /Pp/ Printing,Comment$
322   COM /Curs/ INTEGER X_over1,X_over2
323     COM /Dstorm/ P_w,Xzero,Xmult,Xun$,Yzero,Ymult,Yun$
324 Freez:    !
325     PRINTER IS 1
326     OUTPUT Scope;"STORED DOT"
327     OUTPUT Scope;"CRS2-1"             ! CURSOR #1 AND 2 ON
328     LOCAL 7
329     PRINT "SET CURSOR 1 TO LEFT CROSSOVER AND CURSOR 2 TO RIGHT CROSSOVER "
330     PRINT
331     PRINT " PRESS CONTINUE WHEN READY"
332     PAUSE
333     REMOTE 7
334     LOCAL LOCKOUT 7
335     OUTPUT Scope;"CRS1 HCRD SENDX"          ! SENDS LOCATION OF CURSOR#1
336     ENTER Scope;X_over1$
337     X_over1=(VAL(X_over1$))/Xmult           ! CONVERTS TO CURSOR#1 PT.#
338     PRINTER IS Printing
339     PRINT "LEFT CROSSOVER PT. OCCURS AT PT.#";X_over1
340     OUTPUT Scope;"CRS2-1 HCRD SENDX"        ! SENDS DELTA CURSOR #2-#1
341     ENTER Scope;X_over2$
342     X_over2=X_over1+(VAL(X_over2$))/Xmult        !CONVERTS TO CURSOR #2 PT.#
343     PRINT "RIGHT CROSSOVER PT. OCCURS AT PT.#";X_over2
344     Sub_center=(X_over1+X_over2)/2
345     PRINT " PHASE CROSSOVER CENTER OCCURS AT PT.#";Sub_center
346     PRINTER IS 1
347     IF ABS(X_over2-X_over1)<100 THEN
348      PRINT "LESS THAN 100 POINTS BETWEEN CROSSOVERS"
349      GOTO Freez
350     END IF
351     PRINT CHR$(12)
352   SUBEND
353   !
354   !********************************************************************
355   SUB Samp_saver      ! THIS SUBPROGRAM STORES VALID_SAMP(*) ON DISK
356   !************************************************************************
357     COM /Zip/ Subset_len,Subset_pt(*),Valid_pt(*),Samp_count(*),Unfill_ct,Bi
n_pt(*)
358     COM /Dig/ V_1,V_0,Vmiddle,Occur_ampl(*),Total_cells,D,Vsamp_size,Valid_s
amp(*),Cell_0,Cell_1,Ber,Phs
359     COM /Sav/ Filenam$,Choice$
360     COM /Dstorm/ P_w,Xzero,Xmult,Xun$,Yzero,Ymult,Yun$
361    !
362     MASS STORAGE IS ":CS80,700,1"
363     F_size=(8*Vsamp_size)+100  ! ADD'L 100 BYTES ADDED
364     CREATE BDAT Filenam$,36,F_size !CREATES 36 RECORDS,W/(8*Vsamp_size)+100
bytes
365     ASSIGN @Path_1 TO Filenam$     ! OPENS I/O PATH TO FILE
366     OUTPUT @Path_1;Vsamp_size,Ber,Xmult,Ymult,Yzero,P_w
367     OUTPUT @Path_1;Valid_samp(*)
368     ASSIGN @Path_1 TO *          ! CLOSES I/O PATH
369     PRINTER IS 1
370     PRINT TABXY(1,2),"DATA STORAGE COMPLETE                           "
```

```
371     WAIT 4
372   SUBEND
373   !**********************************************************************
374   SUB Samp_builder
375   !**********************************************************************
376   !***   BUILDS A VALID SAMPLE OF POINTS AT 36 EQUIDISTANT CLOCKING PHASES
377   !-------------------------------------------------------------------
378   !   SUBSET_LEN MUST BE ODD!!
379     COM /Wave/ Wave$,Wavehead$,Dig_array(*),X_plot(*),Y_plot(*)
380     COM /Zip/ Subset_len,Subset_pt(*),Valid_pt(*),Samp_count(*),Unfill_ct,Bi
n_pt(*)
381     COM /Dig/ V_1,V_0,Vmiddle,Occur_ampl(*),Total_cells,D,Vsamp_size,Valid_s
amp(*),Cell_0,Cell_1,Ber,Phs
382   COM /Curs/ INTEGER X_over1,X_over2
383     COM /Hpib/ Tek1,Tek2,Tek3,Tek4,Tek5,Tek6,Tek7,Tek8,Tek9,Hard_disk,Atten_
driv,Scope,Freq_ct,Opt_pm,Opt_atten,Sweep_osc,Data_acq,Anr_ber,Anr_prog,Tek_ct
384   COM /Pp/ Printing,Comment$
385     REDIM Valid_samp(0:35,1:Vsamp_size)
386     MAT Valid_samp= (0)
387     MAT Samp_count= (1)
388     Unfill_ct=0
389     Subset_len=5     ! SETS # OF POINTS PER SUBSET
390     Uspan=(Subset_len-1)/2
391     !
392     CALL Data_storm("5 1 2 >P/W","ACQ",0)  ! ACQUIRES DIG. PTS TO FIND ABSOL
UTE MIN AND MAX
393     V_0_crude=MIN(Dig_array(*))  ! USED ONLY FOR UNFILL FUNCTION
394     V_1_crude=MAX(Dig_array(*))
395     Seg=(X_over2-X_over1)/36
396     !
397     REPEAT
398       PRINTER IS 1
399       CALL Data_storm("5 1 2 >P/W","ACQ",0) !ACQUIRES DIG PTS. FROM SCOPE AN
D STORES IN DIG_ARRAY(*)
400   !-------------------------------------------------------------------
401 Acquire:  !SELECTS SUBSETS OF X POINTS FROM DATA STREAM BETWEEN CROSSOVERS
402           !SUBSET ARE THE PTS. IN THE VALID INTERVAL RANGE PER WAVEFORM STORED
403        FOR Phs=0 TO 35
404         IF Samp_count(Phs)>Vsamp_size THEN GOTO Next_phs
405         Center=INT(X_over1+Phs*Seg)
406         FOR Point=(Center-Uspan) TO (Center+Uspan)
407           IF Samp_count(Phs)>Vsamp_size THEN GOTO Next_phs
408          !CHECKS DATA FOR ERRONEOUSLY FILLED POINTS AND DISREGARDS
409           Xfill=(Dig_array(Point-1)+Dig_array(Point+1))/2
410           IF ABS((Xfill-Dig_array(Point))/(V_1_crude-V_0_crude))>.002 THEN
411            Valid_samp(Phs,Samp_count(Phs))=Dig_array(Point)! SAVES SELECTED PT
S IN SUBSET_PT(*)
412            Samp_count(Phs)=Samp_count(Phs)+1
413           ELSE
414 Remove:  !
415             Unfill_ct=Unfill_ct+1   ! COUNTS # OF POINTS REMOVED
416             PRINT TABXY(1,1),"POINT#";Point;"= ";Dig_array(Point);" REMOVED DU
E TO LINEAR FILL                "
417           END IF
418         NEXT Point
419         PRINT TABXY(10,Phs+4);Phs*10;"degree phase count=";Samp_count(Phs)
420 Next_phs:  NEXT Phs
421     Samp_compl=1
422     FOR Phs=0 TO 35
423     IF Samp_count(Phs)<Vsamp_size THEN Samp_compl=0
424     NEXT Phs
425   UNTIL Samp_compl=1   ! REPEAT UNTIL ALL 36 SUBSETS ARE FILLED
426   PRINT TABXY(1,1),"SAMPLE COMPLETE                                        "
427   BEEP
428   BEEP
429   !**********************************************************************
430   !**************     END OF SAMP_BUILDER SUBPROGRAM    ********************
```

```
431    !************************************************************************
432    SUBEND
433    !
434    !************************************************************************
435    SUB Occur_builder(Selector)  ! SELECTS V_1 & V_0
436                                 ! CONVERTS VALID_SAMP(*) TO CELL# vs. OCCURRENCE
437    !************************************************************************
438      COM /Zip/ Subset_len,Subset_pt(*),Valid_pt(*),Samp_count(*),Unfill_ct,Bi
n_pt(*)
439      COM /Dig/ V_1,V_0,Vmiddle,Occur_ampl(*),Total_cells,D,Vsamp_size,Valid_s
amp(*),Cell_0,Cell_1,Ber,Phs
440      COM /Sig/ Best_fit_0(*),Best_fit_1(*),Sigma_0(*),Sigma_1(*),Unoccur_0,Un
occur_1,P_0(*),P_1(*),P_e(*),Q_0(*),Q_1(*)
441      COM /Vvv/ Vmin,Vmax,Vspan,Vcell
442      COM /Pp/ Printing,Comment$
443 Bounds:      ! THIS SECTION OBTAINS V_1,V_0 AND VMID(unnormalized)
444              ! METHOD 1(SELECTOR=1)
445              !     V_0 , V_1 WILL BE MANUALLY ENTERED BY OPERATOR
446              ! METHOD 2(SELECTOR=2)
447              !     V_0 , V_1 WILL BE CALCULATED BASED ON MAXIMAL OCCURRENCE
448      PRINTER IS Printing
449      PRINT CHR$(12);
450      PRINTER IS 1
451      IF Selector=1 THEN
452        PRINTER IS 1
453        PRINT "ENTER V_1 VALUE (in V)"
454        INPUT "V_1=?",V_1
455        PRINT "ENTER V_0 VALUE (in V)"
456        INPUT "V_0=?",V_0
457        Vmiddle=(V_1+V_0)/2
458        PRINTER IS Printing
459        PRINT "MANUALLY INPUT V_1,V_0 SEQUENCE"
460        PRINT "V_0=";V_0
461        PRINT "V_1=";V_1
462        PRINT "Vmiddle=";Vmiddle
463        Vmax=MAX(Valid_samp(*))
464        Vmin=MIN(Valid_samp(*))
465        Vspan=Vmax-Vmin
466        Vcell=Vspan/Total_cells
467        MAT Occur_ampl= (0)
468        FOR Jib=1 TO Vsamp_size
469          IF Valid_samp(Phs,Jib)<V_0 OR Valid_samp(Phs,Jib)>V_1 THEN Skot
470            IF Valid_samp(Phs,Jib)=V_1 THEN
471            Cell_no=Total_cells
472            GOTO Nolk
473            END IF
474          Cell_no=INT((Valid_samp(Phs,Jib)-Vmin)/Vcell)+1
475 Nolk:  Occur_ampl(Cell_no)=Occur_ampl(Cell_no)+1
476 Skot: NEXT Jib
477        Cell_0=INT((V_0-Vmin)/Vcell)+1
478        Cell_1=INT((V_1-Vmin)/Vcell)+1
479        Unoccur_0=Occur_ampl(1)
480        Unoccur_1=Occur_ampl(Total_cells)
481        PRINTER IS Printing
482        PRINT " # OF OCCURRENCES IN ZERO(V_0) LEVEL CELL=";Unoccur_0
483        PRINT "  # OF OCCURRENCES IN ONE(V_1) LEVEL CELL=";Unoccur_1
484        PRINTER IS 1
485      END IF
486      IF Selector=2 THEN
487        MAT Occur_ampl= (0)
488        !------------------------------------------------------------
489        ! Vmin,Vmax,Vspan,Vcell IS FOR RECALCULATED FOR EACH PHASE SUBSET
490        !------------------------------------------------------------
491        Vmin=1.E+99
492        Vmax=-1.E+99
493        FOR Jib=1 TO Vsamp_size
494        IF Valid_samp(Phs,Jib)<Vmin THEN Vmin=Valid_samp(Phs,Jib)
```

```
495        IF Valid_samp(Phs,Jib)>Vmax THEN Vmax=Valid_samp(Phs,Jib)
496        NEXT Jib
497        Vspan=Vmax-Vmin
498        Vcell=Vspan/Total_cells
499        !-------------------------------------
500        ! CELLS DATA POINTS
501        !-------------------------------------
502        FOR Jib=1 TO Vsamp_size
503            IF Valid_samp(Phs,Jib)=Vmax THEN !RESETS MAX PT. INTO HIGHEST CELL
504            Cell_no=Total_cells
505            GOTO Qak
506            END IF
507          Cell_no=INT((Valid_samp(Phs,Jib)-Vmin)/Vcell)+1
508 Qak:   Occur_ampl(Cell_no)=Occur_ampl(Cell_no)+1
509 Skom:  NEXT Jib
510        !----------------------------------------------------------------
511        ! FINDS CELL# OF ZERO LEVEL (BASED ON MAXIMAL OCCURRENCE)
512        !----------------------------------------------------------------
513        Bell=0
514        Cell_0=1
515        Block=INT(Total_cells/2)
516        FOR Jib=1 TO Block
517          IF Occur_ampl(Jib)>Bell THEN
518            Bell=Occur_ampl(Jib)
519            Cell_0=Jib     ! CELL # OF "0" LEVEL
520          END IF
521        NEXT Jib
522        !----------------------------------------------------------------
523        ! FINDS CELL# OF ONE LEVEL (BASED ON MAXIMAL OCCURRENCE)
524        !----------------------------------------------------------------
525        Bell=0
526        Cell_1=0
527        FOR Jib=Block+1 TO Total_cells
528          IF Occur_ampl(Jib)>Bell THEN
529            Bell=Occur_ampl(Jib)
530            Cell_1=Jib     ! CELL # OF "1" LEVEL
531          END IF
532        NEXT Jib
533        V_0=(Cell_0-.5)*Vcell+Vmin  ! VALUE OF "0" LEVEL IN mV
534        V_1=(Cell_1-.5)*Vcell+Vmin  ! VALUE OF "1" LEVEL IN mV
535        Vmiddle=(V_0+V_1)/2
536        Unoccur_0=Occur_ampl(Cell_0)  !UNNORMALIZED # OF OCCURRENCES IN CELL 0
537        Unoccur_1=Occur_ampl(Cell_1)  !    "        "  "     "     "  "   1
538        PRINTER IS Printing
539        IF Selector=1 THEN PRINT "V_0,V_1 are manually entered"
540        IF Selector=2 THEN PRINT "V_0,V_1 calculated based on maximal occurren
ce"
541        PRINT
542        PRINT "Vmin=";Vmin;"   Vmax=";Vmax;"   Vspan=";Vspan;"   Vcell=";Vcell
543        PRINT "CELL # OF ZERO LEVEL =";Cell_0
544        PRINT " CELL # OF ONE LEVEL =";Cell_1
545        PRINT "V_0=";V_0
546        PRINT "V_1=";V_1
547        PRINT "Vmiddle=";Vmiddle
548        PRINT "# OF OCCURRENCES IN ZERO LEVEL(V_0) CELL=";Unoccur_0
549        PRINT " # OF OCCURRENCES IN ONE LEVEL(V_1) CELL=";Unoccur_1
550        PRINT
551      GOTO Noprint
552      PRINT "CELL#/ # OF OCCURRENCES IN CELL"
553      PRINT
554      FOR Jib=1 TO Total_cells
555        PRINT "CELL#";Jib;"=";Occur_ampl(Jib),
556      NEXT Jib
557 Noprint:    !
558        PRINTER IS 1
559      END IF
560 Flow:SUBEND
```

```
561   !
562   !
563   !**********************************************************************
564   SUB Gc_sigma(Z)   !
565                     ! SIGMA IS CALCULATED FOR THE GAUSSIAN CURVE
566   !**********************************************************************
567     COM /Zip/ Subset_len,Subset_pt(*),Valid_pt(*),Samp_count(*),Unfill_ct,Bi
n_pt(*)
568     COM /Dig/ V_1,V_0,Vmiddle,Occur_ampl(*),Total_cells,D,Vsamp_size,Valid_s
amp(*),Cell_0,Cell_1,Ber,Phs
569     COM /Wave/ Wave$,Wavehead$,Dig_array(*),X_plot(*),Y_plot(*)
570     COM /Hpib/ Tek1,Tek2,Tek3,Tek4,Tek5,Tek6,Tek7,Tek8,Tek9,Hard_disk,Atten_
driv,Scope,Freq_ct,Opt_pm,Opt_atten,Sweep_osc,Data_acq,Anr_ber,Anr_prog,Tek_ct
571     COM /Pp/ Printing,Comment$
572     COM /Sig/ Best_fit_0(*),Best_fit_1(*),Sigma_0(*),Sigma_1(*),Unoccur_0,Un
occur_1,P_0(*),P_1(*),P_e(*),Q_0(*),Q_1(*)
573     COM /Strait/ Vsamp_ave,Sig_0,Sig_1,V0_count,V1_count,V0_ave,V1_ave,V_zer
o,V_one,Q_zero(*),Q_one(*),P_zero(*),P_one(*),P_error(*)
574     COM /Vvv/ Vmin,Vmax,Vspan,Vcell
575     !
576     GOTO Skipper
577     !-----------------------------------------------
578     ! THIS SECTION FINDS ALL CELLS WITH NO OCCURRENCES
579     !-----------------------------------------------
580     Mt_cells=0
581     PRINT "EMPTY CELL LOCATOR SECTION-- ALL CELLS LISTED ARE EMPTY"
582     PRINT
583     PRINT "CELL#'S";
584     FOR Jib=Cell_0 TO Cell_1
585       IF Occur_ampl(Jib)=0 THEN
586         PRINT Jib;
587         Mt_cells=Mt_cells+1
588         IF Mt_cells>50 THEN GOTO Too_many
589       END IF
590     NEXT Jib
591 Too_many:  PRINT
592     PRINT "THE TOTAL # OF EMPTY CELL= ";Mt_cells
593     IF Mt_cells=0 THEN
594       Min_occur=9.E+150
595       FOR Sx=1 TO Total_cells
596         IF Occur_ampl(Sx)<Min_occur THEN
597           Min_occur=Occur_ampl(Sx)
598           D_cell=Sx
599         END IF
600       NEXT Sx
601    !  D=Vmin+(D_cell-.5)*Vcell    ! UN-NORMALIZED  D
602     ELSE
603    !  D=Vmin+(.5)*Vspan           ! UN-NORMALIZED  D
604     END IF
605     !
606     !----------------------------------------------------
607     ! THIS SECTION CALCULATES SIGMA 0 & 1 USING STRAIGHT STATS
608     !----------------------------------------------------
609 Skipper:   !
610         Vsamp_ave=0
611         FOR Jib=1 TO Vsamp_size
612          Vsamp_ave=Vsamp_ave+Valid_samp(Phs,Jib)
613         NEXT Jib
614         Vsamp_ave=DROUND(Vsamp_ave/Vsamp_size,6)
615     V0_count=0
616     V1_count=0
617     V0_ave_s=0
618     V1_ave_s=0
619      FOR J=1 TO Vsamp_size
620       IF Valid_samp(Phs,J)<=Vsamp_ave THEN
621         V0_count=V0_count+1
622         V0_ave_s=V0_ave_s+Valid_samp(Phs,J)
```

```
623        ELSE
624          V1_count=V1_count+1
625          V1_ave_s=V1_ave_s+Valid_samp(Phs,J)
626        END IF
627      NEXT J
628      !
629      V0_ave=DROUND(V0_ave_s/V0_count,6)
630      V1_ave=DROUND(V1_ave_s/V1_count,6)
631      !
632      Sig_1_sum=0
633      Sig_0_sum=0
634      FOR J=1 TO Vsamp_size
635        IF Valid_samp(Phs,J)<=Vsamp_ave THEN
636          Sig_0_sum=Sig_0_sum+(Valid_samp(Phs,J)-V0_ave)^2
637        ELSE
638          Sig_1_sum=Sig_1_sum+(Valid_samp(Phs,J)-V1_ave)^2
639        END IF
640      NEXT J
641      Sig_0=DROUND(SQR(Sig_0_sum/(V0_count-1)),6)
642      Sig_1=DROUND(SQR(Sig_1_sum/(V1_count-1)),6)
643      IF Z=0 THEN Sigma_out
644        PRINTER IS Printing
645        PRINT "STATISTICAL CALCULATIONS SECTION @ ";Phs*10;" DEGREES PHASE"
646        PRINT "Vphase subset ave=";Vsamp_ave
647        PRINT
648      PRINT "V(0) AVE=";V0_ave,
649      PRINT "V(1) AVE=";V1_ave
650      PRINT "V(0) COUNT=";V0_count,
651      PRINT "V(1) COUNT=";V1_count
652      PRINT "SIGMA 0=";Sig_0,
653      PRINT "SIGMA 1=";Sig_1
654      PRINTER IS 1
655         !
656 Sigma_out:  SUBEND
657    !
658    !
659    !*************************************************************************
660    SUB Prob_error(Z) !CALCULATES BER given sigma_0,sigma1,V_0,V_1,D
661    !*************************************************************************
662      COM /Dig/ V_1,V_0,Vmiddle,Occur_ampl(*),Total_cells,D,Vsamp_size,Valid_s
amp(*),Cell_0,Cell_1,Ber,Phs
663      COM /Sig/ Best_fit_0(*),Best_fit_1(*),Sigma_0(*),Sigma_1(*),Unoccur_0,Un
occur_1,P_0(*),P_1(*),P_e(*),Q_0(*),Q_1(*)
664      COM /Strait/ Vsamp_ave,Sig_0,Sig_1,V0_count,V1_count,V0_ave,V1_ave,V_zer
o,V_one,Q_zero(*),Q_one(*),P_zero(*),P_one(*),P_error(*)
665      COM /Vvv/ Vmin,Vmax,Vspan,Vcell
666      COM /Pp/ Printing,Comment$
667        Q_zero(Phs)=DROUND((ABS(D-V_zero))/Sig_0,6)   ! CALC. Q0
668        P_zero(Phs)=DROUND(1/(Q_zero(Phs)*SQR(2*PI))*(1-1/((Q_zero(Phs))^2))*E
XP(-((Q_zero(Phs))^2)/2),6)! CALC. P_0
669                  ! WHERE P_ZERO IS THE PROB. OF A "0" BEING MISTAKEN FOR A "1"
670        Q_one(Phs)=DROUND((ABS(D-V_one))/Sig_1,6)   ! CALC. Q1
671        P_one(Phs)=DROUND(1/(Q_one(Phs)*SQR(2*PI))*(1-1/((Q_one(Phs))^2))*EXP(
-((Q_one(Phs))^2)/2),6)! CALC. P_1
672                  ! WHERE P_1 IS THE PROB. OF A "1" BEING MISTAKEN FOR A "0"
673        P_error(Phs)=DROUND((P_zero(Phs)*V0_count+P_one(Phs)*V1_count)/Vsamp_s
ize,5)
674                  !
675        IF Z=0 THEN Prob_out
676        PRINTER IS Printing
677      PRINT "*****PROBABILITY OF ERROR CALCULATIONS (using Dopt from 180 degre
e SUBSET)******"
678      ! PRINT "****************************************************************
***************"
679                  !
680        PRINT "Q_0=";Q_zero(Phs);
681        PRINT "     PROB. OF 0 BEING MISTAKEN FOR A 1= P_0 =";P_zero(Phs)
```

```
682        PRINT "Q_1=";Q_one(Phs);
683        PRINT "    PROB. OF 1 BEING MISTAKEN FOR A 0= P_1 =";P_one(Phs)
684        PRINT "TOTAL PROB. OF ERROR= P_E =";P_error(Phs)
685        PRINTER IS 1
686       !
687 Prob_out:  SUBEND
688    !***********************************************************************
689    SUB Kbd_interrupt
690    !***********************************************************************
691    !-------------------------------------------------------------------!
692    !                    *****KEYBOARD INTERRUPT*****                    !
693    !-------------------------------------------------------------------!
694    !
695 Kbd_interrupt:                 ! KBD INTERRUPT
696      BEEP 4000,.2
697      BEEP 3600,.2
698      PRINTER IS 1
699      DISP "INVALID KEY HAS BEEN SELECTED!!!"
700      WAIT .4
701    SUBEND
702    !***********************************************************************
703    SUB Wef_plot(Xmax,Ymax,Xax$,Yax$,Title$,Plot_xy(*))  !PLOTS OCCUR vs CELL
704    !***********************************************************************
705     COM /Pp/ Printing,Comment$
706     SYSTEM PRIORITY 0
707     OFF KEY
708     PRINTER IS 1
709     PRINT CHR$(12)
710     GRAPHICS ON
711     GINIT
712     VIEWPORT 0,130,0,100
713     FRAME
714     LORG 5
715     CSIZE 5
716     MOVE 70,95
717     LABEL Title$
718     CSIZE 5
719     MOVE 65,4
720     LABEL Xax$
721     MOVE 5,50
722     DEG
723     LDIR 90
724     LABEL Yax$
725     LDIR 0
726     VIEWPORT 20,120,14,90
727     FRAME
728     WINDOW 0,Xmax,0,Ymax
729     CLIP OFF
730     CSIZE 4
731     LORG 8
732      FOR I=0 TO 10
733      MOVE -Xmax*.01,Ymax*.1*I
734      LABEL USING "DDDD";Ymax*.1*I ! LABELS Y-AXIS
735      NEXT I
736      LORG 6
737      FOR I=0 TO 10
738      MOVE Xmax*.1*I,-Ymax*.01
739      LABEL USING "DDD";Xmax*.1*I
740      NEXT I
741     CLIP ON
742     FOR I=0 TO 10
743     LINE TYPE 4
744      MOVE 0,Ymax*I*.1
745      DRAW Xmax,Ymax*I*.1
746     LINE TYPE 3
747      MOVE Xmax*I*.1,0
748      DRAW Xmax*I*.1,Ymax
```

```
749    NEXT I
750    LINE TYPE 1
751    FOR I=0 TO 50
752     MOVE 0,Ymax*I*.02
753     DRAW Xmax*.01,Ymax*I*.02  ! DRAW Y-AXIS TICKS
754     MOVE Xmax*I*.02,0
755     DRAW Xmax*I*.02,Ymax*.015  ! DRAW X-AXIS TICKS
756    NEXT I
757    MOVE 1,Plot_xy(1)
758    FOR I=1 TO Xmax
759    PLOT I,Plot_xy(I)   ! PLOTS OCCURRENCE PARAMETER
760    NEXT I
761    Esc$="
762    PRINT Printing;Esc$&"&a15C"  ! MOVES CURSOR TO COLUMN 15
763    PRINT Printing;Esc$&"*r1A"  ! STARTS GRAPHICS AT CURRENT CURSOR
764    DUMP GRAPHICS
765    !
766    SUBEND
767    !
768   !******************************************************************
769   SUB Data_storm(P_w$,Ave_acq$,Xfer_only)
770   !******************************************************************
771   ! VERSION 2D-(11/13/86)-WEF
772   ! VERSION 3D-(12/04/86)-WEF- DATA STORM MOD. FOR IMPROVED SPEED
773                                   !XFER_ONLY=1 FOR ARRAY XFER ONLY,NO AQR
774                                   !AVE_ACQ="ACQ" FOR PSEUDO,"AVE" FOR AVE
775                                   !EX. P_W$="5 1 2 >P/W" FOR 512 PTS/WVM
776   ! VERSION 4D-(4/05/87)-WEF- DATA STORM MOD. FOR IMPROVED SPEED
777                                   !LABELS CHANGED TO PRINT TABXY
778                                   !SCOPE UNHANG SOFTWARE ADDED
779   !  PROGRAM ACQUIRES WAVEFORM FROM SCOPE,FINDS MULTIPLIERS AND DATA
780   !          MATRIX
781   !******************************************************************
782     COM /Wave/ Wave$,Wavehead$,Dig_array(*),X_plot(*),Y_plot(*)
783    COM /Hpib/ Tek1,Tek2,Tek3,Tek4,Tek5,Tek6,Tek7,Tek8,Tek9,Hard_disk,Atten_dr
iv,Scope,Freq_ct,Opt_pm,Opt_atten,Sweep_osc,Data_acq,Anr_ber,Anr_prog,Tek_ct
784     COM /Pp/ Printing,Comment$
785     COM /Dstorm/ P_w,Xzero,Xmult,Xun$,Yzero,Ymult,Yun$
786   !******************************************************************
787  !NORMALIZED HORIZ.&VERT. TIME BASE MUST BE PRESET BEFORE CALLING DATA_STORM
788     SYSTEM PRIORITY 0
789     OFF KEY
790     DISP ""
791   !  NOTE: SAMPLING UNIT MUST BE SET BEFORE CALL DATASTORM . OTHERWISE THE C
URRENT UNIT WILL BE USED!!
792     GOTO Faster
793     GCLEAR
794     GRAPHICS ON
795     CSIZE 15
796     MOVE 20,80
797     LABEL "DATA STORM"
798     MOVE 15,60
799     LABEL "IN PROGRESS"
800     CSIZE 10
801     MOVE 15,35
802     LABEL "DO NOT DISTURB!!!"
803 Faster:     PRINTER IS 1
804             PRINT TABXY(25,17),"DATA STORM IN PROGRESS"
805             PRINT TABXY(25,18),"    DO NOT DISTURB!"
806     IF Xfer_only=1 THEN GOTO Yank
807   !-------------------------------------------------------------------
808   ON TIMEOUT 7,4 GOSUB Un_hang
809     OUTPUT Scope;P_w$                   ! SETS THE # OF POINTS/WAVEFORM
810     OUTPUT Scope;"SCOPE"    ! SCOPE
811     IF Ave_acq$="ACQ" THEN GOTO Eye_acq  ! IF= "ACQ" ACQUIRES WAVEFORM
812     OUTPUT Scope;" 1 0 AVG"          ! ELSE,INITIATES TEK7854 AVE. SAMPLING
813     GOTO Yank
```

```
814 Eye_acq: OUTPUT Scope;"SCOPE AQR"       ! INITIATES SCOPE ACQUIRE
815 Yank: OUTPUT Scope;"STORED DOT"           ! CLEARS AQR ERROR
816      Spx=0
817      OUTPUT Scope;"0 WFM SENDX" ! PUTS WFM # INTO X REG., SENDS
                                     WAVEFORM TO TEK OUTPUT BUFFER
818     !IF Spx<>210 THEN 1206
819      WAIT .5
820      ENTER Scope;P_w,Xzero,Xmult,Yzero,Ymult
821      REDIM Dig_array(1:P_w)
822      ENTER Scope;Dig_array(*)
823      OUTPUT Scope;"SCOPE"
824      OFF DELAY
825      GOTO No_preamble
826      !
827 Un_hang:      ! UNHANGS TEK SCOPE
828               CLEAR 708
829               OFF TIMEOUT
830               FOR I=1 TO 10
831               BEEP I*1000,.1
832               NEXT I
833               GOTO Faster
834       RETURN
835      ENTER Scope;Wavehead$,Wave$        ! STORES HEADING AND DATA STREAM
                                              IN STRING VARIABLES
836     !*********************************************************************
837     ! THIS SECTION ACQUIRES P/W,SCALE FACTORS AND OFFSETS FROM WAVEHEAD$
838     !*********************************************************************
839      Colon=POS(Wavehead$,CHR$(58))+1
840      Wavehead$=Wavehead$[Colon]           ! REMOVES WFMPRE ENCDG:
841      Colon=POS(Wavehead$,CHR$(58))+1
842      Wavehead$=Wavehead$[Colon]           ! REMOVES ASC,NR.PT:
843      Comma=POS(Wavehead$,CHR$(44))-1
844      P_w=VAL(Wavehead$[1,Comma])           ! ACQUIRES P/W FROM WAVEHEAD
845      Colon=POS(Wavehead$,CHR$(58))+1       ! FINDS POS. OF CHAR. AFTER COLON
846      Wavehead$=Wavehead$[Colon]
847      Colon=POS(Wavehead$,CHR$(58))+1
848      Wavehead$=Wavehead$[Colon]            !  REMOVES ALL THRU XZERO:
849      Comma=POS(Wavehead$,CHR$(44))-1
850      Xzero=VAL(Wavehead$[1,Comma])         ! ACQUIRES XZERO FROM WAVEHEAD
851      Colon=POS(Wavehead$,CHR$(58))+1
852      Wavehead$=Wavehead$[Colon]            ! REMOVES ALL THRU  XINCR:
853      Comma=POS(Wavehead$,CHR$(44))-1
854      Xmult=VAL(Wavehead$[1,Comma])         ! ACQUIRES XMULT FROM WAVEHEAD
855      Colon=POS(Wavehead$,CHR$(58))+1
856      Wavehead$=Wavehead$[Colon]            ! REMOVES ALL THRU XUNIT:
857      Comma=POS(Wavehead$,CHR$(44))-1
858      Xun$=Wavehead$[1,Comma]               ! ACQUIRES XUNITS STRING VAR.
859      Colon=POS(Wavehead$,CHR$(58))+1
860      Wavehead$=Wavehead$[Colon]            ! REMOVES ALL THRU YZERO:
861      Comma=POS(Wavehead$,CHR$(44))-1
862      Yzero=VAL(Wavehead$[1,Comma])         ! ACQUIRES YZERO FROM WAVEHEAD
863      Colon=POS(Wavehead$,CHR$(58))+1
864      Wavehead$=Wavehead$[Colon]            ! REMOVES ALL THRU YMULT:
865      Comma=POS(Wavehead$,CHR$(44))-1
866      Ymult=VAL(Wavehead$[1,Comma])         ! ACQUIRES YMULT FROM WAVEHEAD
867      Colon=POS(Wavehead$,CHR$(58))+1
868      Wavehead$=Wavehead$[Colon]            ! REMOVES ALL THRU YUNIT:
869      Semi_col=POS(Wavehead$,CHR$(59))-1
870      Yun$=Wavehead$[1,Semi_col]            ! ACQUIRES YUNITS STRING VAR.
871     !*********************************************************************
872     !*********************************************************************
873     ! THIS SECTION REMOVES COMMAS FROM DATA STREAM AND PLACES DATA POINTS
        INTO NORMALIZED(-4 TO 4) NUMERIC ARRAY DIG_ARRAY(*)  PT#1 THRU P_W
874     !******************************
875      Wave$=Wave$[6]
876      FOR I=1 TO P_w-1
877        Comma=POS(Wave$,CHR$(44))-1
```

```
878      Dig_array(I)=VAL(Wave$[1,Comma])
879      Wave$=Wave$[Comma+2]
880    NEXT I
881    Dig_array(I)=VAL(Wave$)
882    PRINTER IS 1
883    PRINT "TRANSMISSION AND ARRAY STORE COMPLETE"
884    OUTPUT Scope;"SCOPE"              ! SELECT SCOPE MODE
885    GOTO No_preamble
886   !*********************************************************************
887      PRINTER IS Printing
888    PRINT
889    PRINT
890    PRINT "         POINTS PER WAVEFORM= ";P_w
891    PRINT "                    Xoffset= ";Xzero
892    PRINT "                Xmultiplier ";Xmult
893    PRINT "                     Xunits= ";Xun$
894    PRINT "                    Yoffset= ";Yzero
895    PRINT "                Ymultiplier= ";Ymult
896    PRINT "                     Yunits= ";Yun$
897    PRINT
898    PRINT
899    PRINT " ABSOLUTE DATA w/ MULT. AND OFFSETS"
900 No_preamble:PRINTER IS 1
901           PRINT TABXY(25,17),"                          "
902           PRINT TABXY(25,18),"                       "
903   !****************************************************************
904   !********** END OF SUBPROGRAM DATA STORM **************************
905   !****************************************************************
906   SUBEND
907   !----------------------------
908   !
909   !*********************************************************************
```

References

[1] Martin S. Roden, Digital and Data Communication Systems, Englewood Cliffs, N. J., Prentice-Hall, Inc., 1982.

[2] Edward C. Jordan, Reference Data for Engineers: Radio, Electronics, Computer, and Communications, Indianapolis, Indiana, Howard W. Sams & Co., Inc., seventh edition, 1985.

[3] Anritsu Corporation, Instruction manual for MS65A Error Detector.

[4] American Telephone and Telegraph, Telecommunications Transmission Engineering, volume 1, 1974.

[5] Henry Stark and Franz B. Tuteur, Modern Electrical Communications, Englewood Cliffs, N.J., Prentice-Hall, Inc., 1979.

[6] Ferrel G. Stremler, Introduction to Communication Systems, Reading, Ma., Addison-Wesley Publishing Co., 1977.

[7] R. G. Smith and S. D. Personick, Topics in Applied Physics, New York, N. Y., Springer-Verlag, volume 1, 1980.

[8] Tektronix Inc., Manual for 7S11 Sampling Unit.

[9] Hewlett Packard, Fiber Optics Handbook, 1984.

[10] Richard A. Groeneveld, An Introduction to Probability and Statistics using BASIC, New York, N. Y., Marcel Dekker, Inc., 1979.

[11] R. E. Ziemer and W. H. Tranter, Principles of Communications, Boston, Ma., Houghton Mifflin Co., 1985.

Vita

The author was born on July 14, 1958 in Phoenixville, Pennsylvania. He is the son of Mrs. Anna Joan Fulmer and Mr. William E. Fulmer Sr. In 1976, he graduated from Great Valley High School in Malvern, Pennsylvania. He attended the University Park campus of the Pennsylvania State University as an undergraduate and became a member of Eta Kappa Nu. In 1980, he received a Bachelor of Science degree in Electrical Engineering. He continued his graduate studies at Lehigh University and will complete the requirements for the Master of Science degree in Electrical Engineering in 1988. Mr. Fulmer is currently employed as a senior developmental engineer working in the field of ultra high speed testing at the Microelectronics Division of AT&T Technologies in Reading, Pennsylvania.

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by

William E. Fulmer

Abstract

This thesis develops a bit error rate (BER) measurement technique based on the gaussian statistics of noise in high frequency baseband digital signals. Commercial BER test equipment is currently available, but is very expensive and requires the use of a known transmitted test pattern.

The laboratory implementation of this technique utilized a Tektronix digitizing oscilloscope to sample the signal and a HP minicomputer to process the data. Experiments were designed to cover a wide range of BER values and plots were made of BER vs. clock phase. It was found that when the noise was "purely" gaussian, there was excellent agreement between measured and predicted BERs at 1 Gb/s bit rates. A matching filter was required in order to achieve these results.

The predicted BER of an optical regenerator was characterized at 1.7 Gb/s at the decision circuit input and showed fair agreement with that measured. Discrepancies as great as an order of magnitude were observed at the BER minimum. This was attributed partially to the error detector limitations and also to the non-gaussian phenomena in the regenerator.

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