FOCAS USER'S GUIDE
(Fiber Optic Cable Simulator)

DEC - TR 470

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February 3, 1987

Keywords: FOCAS, fiber optics, optical cable, optical fiber optical communications

ABSTRACT

FOCAS is a tool for determining the sensitivity of optical communications links to design parameters. It assists designers in assessing the importance of: optical source/optical fiber spectral characteristic mismatches; source edge shapes; optical fiber length, chromatic and intermodal dispersion, and attenuation characteristics; optical receiver bandpass, phase shift, and gain

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OVERVIEW

FOCAS (Fiber Optic CAble Simulator) is a tool for sensitivity modelling of optical communications links. It assists designers in assessing the importance of:

* optical source/optical fiber spectral characteristic mismatches

* source edge shapes

* optical fiber parameters: length, chromatic and intermodal dispersion, and attenuation characteristics

* optical receiver bandpass, phase shift, and gain (or attenuation)

In addition, FOCAS supports modelling the PWB interconnect between the optical receiver output and the remaining system electronics. It is structured to be easily expandable to incorporate models of the circuitry following the receiver.

FOCAS offers wide range of outputs for maximum flexibility:

- * standard voltage vs. time display
- * EYE pattern - (also calculates timing jitter from ISI and DCD)
- * power spectrum and/or phase shift of the signal at any point in the circuit
- * transfer function of individual circuit elements
- * data file of voltage crossings, extrema locations and values, timing jitter, and per cent noise margin

FOCAS is structured in a manner which permits changes to the detailed physical models included to be performed in a fairly simple straightforward manner. This feature is intended to assure that FOCAS can be extended as our knowledge base expands.

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INTRODUCTION TO FOCAS

FOCAS is a tool intended to simulate the behavior of point-to-point Fiber Optic CAble circuits. FOCAS performs the circuit analysis in the frequency domain, then transforms the results back into the time domain. All input waveforms are assumed to be periodic in time.

Once FOCAS is installed on a system, the user creates a simulation model by simply invoking the editor and creating the file, e.g. "MODELXYZ.". At the system prompt, RUN FOCAS invokes the simulator. FOCAS provides prompts to the user for any further input data required. (See section V. and Appendix 1 for details.)

A simulation circuit is composed of a series of cascaded two terminal pair networks as shown below. Output voltages are based on terminal pair differentials. FOCAS provides output in both graphical and tabular form. The graphics files provide direct graphical output on REGIS terminals. Output data files provide an interface to graphing routines for various types of display devices.

The FOCAS output files are:

```
MODELXYZ.TG  = time domain graph in REGIS
MODELXYZ.TD  = time domain data file
MODELXYZ.FG  = frequency domain graph in REGIS
MODELXYZ.FD  = frequency domain data file
MODELXYZ.PD  = phase vs. frequency data file
MODELXYZ.PG  = phase vs. frequency graph in REGIS
MODELXYZ.DAT = times at which output voltage waveform
               crosses specified voltage levels
```

A UIS graphics routine is included with FOCAS installation for microVax users.

Units are ohms, nanohenries, nanofarads, nanoseconds, gigahertz, mhos, centimeters (except as noted). Input format is similar to the FORTRAN F or I, (decimal points need not be supplied for whole numbers) formats. In addition the suffixes M, K, and U are interpretted as: M = *.001; K = *1000; and U = *.000001

```
----------
|  #1    |---O-----
|  GEN   |        |
|        |---O-   |     -------     -------     --------
----------    |    -O---| #3  |--O--|     |--O-|RCVR  |--O
              |         | TEE |     |FIBER|    |      |
----------    |    -O---|     |--O--|     |--O-|------|--O
|  #2    |---O-   |     -------     -------
|  GEN   |        |
|        |---O-----
----------
```

II. FOCAS SIMULATION MODELS

A FOCAS simulation model is a file comprised of a maximum of 500 network subsections which describe the circuit being simulated as a sequence of cascaded two terminal pair networks; control statements which specify the type of output information requested; and comments which describe the circuit in English.

FOCAS reads only the first 1000 lines of any input simulation model. All other lines are ignored. In addition, comments encountered in the first 1000 lines of the model are also ignored.

A simulation circuit is a file of sequential (line by line) network statements. The order in which the network statements appear is the same as the order in which the network subsections are connected. Generators must always be specified first and are added in series.

Arbitrary bit patterns are created by cascading multiple GEN generators. To determine the output waveform from a series of casaced GEN's, one considers their simple superposition over a SINGLE period of the bit pattern.

When a bit pattern begins and ends in ONE's, superposition could lead to overshoot at the period boundaries (Figure 1). This condition does not coreespond to the behavior of physically real data streams. A real data channel carrying this repetitive data stream would not show such an overshoot. Hence, FOCAS automatically checks for and corrects bit patterns with leading and trailing ONE's. Figure 2 represents the same repetitive bit string as that of Figure 1, but with the FOCAS checking enabled. (See Section A. Optical Transmitter Models for more detail.)

The name of the network type is placed first on a network statement line. This is followed by a series of parameter names with each name followed by its numeric value. Only the first three characters of the network name are recognized and need be included. Parameter names are either one or two characters, additional characters in two character parameter names are ignored. Names and numeric values must all be separated by at least one space, equal sign, or comma. For instance, the following are acceptable and equivalent:

```
TEE R1 1. L1 1.0 R 10.
TEE R1=1.,L1=1.0,R=10.
TEE R1=1 ,L1=1  ,R=10
TEE  R1  1  L1  1  R  10
```

In addition the suffixes M, K, and U are interpretted as: M = *.001; K = *1000; and U = *.000001. Thus the following are equivalent: TEE R1=5000 L1=.0031 C=.000002 and TEE R1=5K L1=3.1M C=2U.

Unspecified network parameters default as follows: series impedance elements (R,L) default to zero and shunt admittance elements (G,C) default to zero. Frequency dependent parameters (i.e., skin effect) are ignored if the required inputs are absent.

Simple shunt resistor loads, series terminators, resistor dividers, etc., are created by specifying the appropriate parameters in the TEE or DELTA network. A TEE or DELTA network with no parameters specified reduces to a simple series connection.

Exclaimation points are used to define comments, all characters to the left of an exclamation point are ignored by the program. Plus signs are ignored.

Generator resistance is the sum of all specified generator resistances, and generator DC offset is the sum of all specified DC offsets. If different periods are specified for the multiple generators in a simulation model, the maximum of all of the individually specified periods is used as the period of the composite.

A. OPTICAL TRANSMITTER MODELS

The transmitter behavior is broken down into its electronic, or time varying behavior: the bit pattern and edge rates and shapes; and into its spectral characteristics. The spectral characteristics are entered as parameters in the optical fiber network model called FIBER. The electronic behavior is entered as a series of periodic asymmetric trapeziodal generators.

As noted in the previous section, FOCAS will automatically limit the output amplitude of the optical transmitter. The limiting is accomplished by a combination of input specification conventions and automatic checking. FOCAS assumes that data streams are coded using the minimal number of generators possible; i.e. n consecutive "HIGH" or "ON" bits are represented by a single generator of pulse width n*BIT, where BIT is the single bit time.

When a data stream begins and ends in ones, and simple superposition would result in the overshoot of the HIGH level, FOCAS automatically combines the GEN's for the first and last bits into a single, wider GEN to create the desired input data pattern. As an example, consider the identical waveforms shown in Figures 2 & 3. Both represent the repetitive pattern: 10110 10010 10101 10011 but have different simulation models. Figure 2 was produced by an eight GEN FOCAS model in which FOCAS detected overlapping leading and trailing ONE's. The 8 ns wide first GEN and the 16 ns wide last GEN were automatically combined to create a seven GEN model in wich the last GEN is 24 ns wide. In effect, the pattern has been left circularly shifted by one bit position to yield: 01101 00101 01011 00111, which is equivalent to the initial pattern. The model which produced Figure 3 codes this second pattern directly, using only seven GEN's.

Experimentally, LED transmitters show a variety of electronic behaviors, characterized by the shapes of their rising and falling edges. For simple transmitters (Figure 4a), the edge characteristics are dominated by a single slope, either with or without ringing. A more complex behavior, best modelled by a slope change on the rising edge, is also observed (Figure 4b).

FOCAS can model all of these cases as series collections of periodic asymmetric trapezoidal generators (GEN's), followed by an optional series inductance and resistance with a shunt capacitance (TEE). The TEE network provides a more realistic waveform and the desired ringing behavior. However, when an exact replication of the rising and falling edges of the optical transmitter is required because it is not all filtered out by the cable, one may use the SOURCE network section described in Section II-A-3 of this manual.

Figure 5 shows a schematic of the series generators (GEN #1 through GEN #NGEN) followed by a series inductance and resistance with a shunt capacitance (TEE in Fig. 5), forming half a TEE network. This model is represented as:

```
! SIMULATION OF TRANSMITTER ELECTRONIC BEHAVIOR
GEN PW=pw  PER=per TR=tr TF=tf
        1             1     1

GEN PW=pw     DEL=del TR=tr  TF=tf
        2           2     2      2

GEN PW=pw  DEL=del  TR=tr  TF=tf
        3        3      3      3

   .
   .
   .

GEN PW=pw      DEL=del      TR=tr      TF=tf
       ngen         ngen        ngen        ngen

TEE R1=r C=c L1=l
```

Each generator specification requires the following parameters:

- TR = 10-90 % risetime in nanoseconds
- TF = 10-90 % falltime in nanoseconds (default=TR)
- PW = "ideal" pulse width or bit time
- PER = pulse repetition period in nanoseconds
- DC = DC offset voltage in volts (default=0)
- AMP = pulse amplitude in volts (default=1)
- DEL = pulse delay in nanoseconds (default=0)
- BW = bandwidth in gigahertz of a low pass filter following the GEN, (default = 50% risetime)

Normally, this specification could become quite cumbersome when modelling large data streams. In order to simplify the data input process FOCAS will set defaults according to rules based on the typical behaviors observed for optical transmitters.

To understand how FOCAS sets default values for GEN's one need only consider the following conventions.

Each simple device, with no slope change on its rising edge, requires only one generator for each series of consecutive HIGH levels. The period and bandwidths for all generators in a data stream are the same. Hence, models representing transmitters with the simple behavior need specify only the pulsewidth and delay for all pulses beyond that created by the first generator. The first generator spec must include at least TR, TF, PER, PW. Subsequent generators are assumed to have the same TR, TF, AMP, PER, and BW values unless otherwise specified.

Devices characterized by edges with dual slopes require a pair of generators for each pulse. Hence, the dual slope case always requires an even number of generators. The rise and fall times of all odd numbered generators are equal to the rise and fall times of the first generator, and the rise and fall times of all even numbered generators are equal to those of the second generator.

FOCAS automaticlly sets default values for TR, TF, PER, AMP, and BW based on this information. If none of the input parameters except PW and DEL are defined for the second generator, the single slope case is assumed. Then, in a sequence of two or more generators, all with the same rise and fall times, bandwidths and amplitudes, one need only define PW and DEL for the second through the last generators. In the absence of any other specification, FOCAS will automatically set the default values of TR, TF, PER, and BW equal to the values assigned for the preceeding generator. If a new value is entered for one of the intermediate GEN sections, all subsequent GEN's will default to that value unless a new specification is defined later. The largest period (PER) of any of the GEN's will be assumed for all.

When the first and second GEN's have unequal risetimes defined, FOCAS will assume that the dual slope case is intended. The parameters of all even numbered generators are set equal to their respective values for the second GEN. Similarly, odd numbered GEN's assume the parameter values of the first GEN.

The optional TEE network in the transmitter is specified by:

L1 = series inductance in nanohenries (default=0)
R = series resistance in ohms (default=0)
C1 = shunt capacitance in nanofarads (default=0).

1. SINGLE SLOPE TRANSMITTERS

In general, there are an infinite number of combinations of L1, R1, C, and the generator rise/fall times (tr/tf) that will give the desired 10-90% rise/fall times (TR/TF) for the LED transmitter.

Tables 1 and 2,on the next two pages, are provided to simplify the LED model setup.

All entries in tnese Tables assume that L1=15 nanohenries and that C=0.04 nanofarads. FOCAS will NOT set these values automatically. They must be defined by the user. Input values for R1 in the TEE network, and for tr and tf in the GEN network are read from the Tables.

In order to approximate the basic LED edges, the user must first determine the general shape of the rising and falling edges as shown on Figures 6a-f. Once the decision to use underdamped (Fig. 6a,d,e) critically damped (Fig. 6b), or overdamped (Fig. 6c) edges has been made, the user will define the desired 10-90% rise and fall times of the device, TR and TF, to select the proper input values for tr and tf from the Tables.

Figures 6a-e illustrate how the edge shapes may vary while the 10-90% risetime remains the same. In all three cases, L1=15 nh, C=0.04 nf, and the LED output risetime, TR, is on the order of 4.1ns. However, by changing the values of R1 and tr, the shapes of the curves have been modified.

It should be noted that overshoot or ringing behavior will generally be seen only on the fastest edge of the device. For the LED's characterized to date, this is the rising edge. The slower (falling) edge of a real device will behave as though it were critically damped. It is not possible to simulate this exact behavior in FOCAS. Rather, the user will select the TEE section parameters which most nearly approximate the faster (rising) edge. The fact that the falling edge is slower will tend to compensate for this difference somewhat (Fig. 6d). This limitation of FOCAS is not very serious because experimental data have shown that the cable filters out most of the detailed structure of the LED transitions.

The entries in Tables 1 and 2 correspond to the LED 10-90% times into the optical fiber. The leftmost column lists the value of generator 10-90% time (tr/tf) to be inputted into the simulation model to obtain the desired value out of the LED section. The top of each column indicates the type of behavior (under, over, or critically damped) and the value of R1 or BW to be specified in the LED model.

SINGLE SLOPE LED SETUP PARAMETERS

L1 = 15.   C = 0.04   all cases

Tr	R1 = 48.73 overdamped	R1 = 38.73 critically damped	R1 = 28.73 underdamped
0.1	3.62	2.60	1.75
0.2	3.62	2.61	1.76
0.3	3.62	2.61	1.77
0.5	3.64	2.64	1.80
0.6	3.66	2.66	1.82
0.7	3.67	2.68	1.85
0.9	3.72	2.75	1.93
1.0	3.75	2.78	2.00
1.1	3.78	2.82	2.02
1.2	3.82	2.86	2.06
1.3	3.85	2.90	2.12
1.4	3.89	2.95	2.17
1.5	3.93	3.00	2.22
1.6	3.98	3.05	2.28
1.7	4.02	3.10	2.34
1.8	4.07	3.16	2.41
1.9	4.12	3.22	2.47
2.0	4.18	3.27	2.54
2.1	4.21	3.34	2.60
2.2	4.27	3.40	2.68
2.3	4.32	3.46	2.75
2.4	4.37	3.52	2.83
2.5	4.43	3.59	2.90
2.6	4.48	3.65	2.97
2.7	4.54	3.72	3.05
2.8	4.60	3.79	3.13
2.9	4.66	3.86	3.21
3.0	4.72	3.90	3.29
3.1	4.78	4.00	3.37
3.2	4.84	4.07	3.46
3.3	4.91	4.15	3.54
3.4	4.97	4.22	3.63
3.5	5.04	4.30	3.71
3.6	5.10	4.37	3.80
3.7	5.17	4.45	3.89
3.8	5.24	4.53	3.98
3.9	5.31	4.60	4.07
4.0	5.38	4.68	4.16
4.2	5.52	4.85	4.34
4.4	5.66	5.01	4.52
4.5	5.73	5.10	4.61

TABLE 1. LED PARAMETERS FOR 1.7 < < 5.0

FAST LED SINGLE SLOPE SETUP PARAMETERS

Tr	TEE with R1=20. ringing L1=15. C=0.04	no TEE, generator BW=0.5 no ringing; RC type behavior L1=15. C=0.04
0.5	1.35	BW too low
0.6	1.37	0.74
0.7	1.40	0.85
0.8	1.44	0.95
0.9	1.48	1.04
1.0	1.52	1.14
1.1	1.56	1.23
1.2	1.61	1.30
1.3	1.66	1.40
1.4	1.72	1.50
1.5	1.77	1.58
1.6	1.83	1.68
1.7	1.89	1.76
1.8	1.96	1.87
1.9	2.02	1.95
2.0	2.09	2.05
2.1	2.15	2.14
2.2	2.23	2.25
2.3	2.30	2.34
2.4	2.37	2.44
2.5	2.45	2.54
2.6	2.53	2.64
2.7	2.61	2.73
2.8	2.70	2.83
2.9	2.78	2.93
3.0	2.87	3.03
3.1	2.96	3.13
3.2	3.05	3.23
3.3	3.14	3.33
3.4	3.23	3.42
3.5	3.32	3.52
3.6	3.42	3.62
3.7	3.51	3.72

TABLE 2. FAST RISE LED SETUP PARAMETERS 1.4 < < 3.5

Transmitter Example 1 - Use of Transmitter Parameter Tables

Suppose, for example, that one wishes to model an LED with 10-90% rise and fall times of 1.8ns and 4.6ns, respectively. If the rising edge is observed to overshoot the saturation level when turning on, one would select an UNDERDAMPED case to represent the LED. Next, it is necessary to determine which Table to use. A quick review will show that the third column of Table 1 corresponds to underdamped responses with rise/fall times from 1.75 to 4.6ns for output. By selecting tr=0.5ns and tf=4.5ns from Table 1, one can create the LED transmitter model given below:

```
! SAMPLE LED TRANSMITTER MODEL - electronic behavior
GEN PW=30 PER=50 TR=0.5 TF=4.5
TEE L1=15 C=0.04 R1=28.73
.OUT V1=0
.END TX=50 DC=.5
```

The output waveform is shown in Figure 6e. Note that, the falling edge, because it is slower than the rising edge, does not overshoot as much.

Transmitter Example 2 - AT&T LED with single slope edge

Consider next, the experimental data shown for an AT&T LED in Figure 7a. This LED has underdamped 10-90% rise and fall times of 1.33 ns and 1.66 ns, repectively. In this instance, Table 1 is inadequate to define the GEN and TEE parameters, so Table 2 must be consulted. According to the Table, R1 should be set equal to 20 ohms; tr = 0.5 ns; and tf = 1.3 ns:

```
! MODEL OF AT&T LED's ELECTRONIC RESPONSE
! TR=1.3   TF=1.66
GEN PW=40 PER=80 TR=0.5 TF=1.3
TEE L1=15 C=0.04 R1=20.
.OUT V1=0.
.END TX=80 DC=.5
```

Figure 7b shows the FOCAS output for this model.

The input parameters of the TEE network have not been set to default at L1=15 and C=0.04 in order to allow additional flexibility to the user. If the waveform generated using the values recommended in Tables 1 and 2 does not provide a satisfactory match to the desired LED behavior, one may implement the full TEE (see NETWORKS section), and try to obtain a better match by trial an error.

2. DUAL SLOPE TRANSMITTERS

Setting up a simualtion model for a dual slope transmitter is more complex than for a single slope device. Ten-to-ninety per cent rise and fall times do not convey enough information to specify dual sloped edges.

Figures 8 & 9 illustrate a simple construction that can be used to define the model for a device with this more complex edge characteristic. Figure 8a shows a typical step response of an LED with dual sloped edge transitions. In Figure 8b, the step response has been approximated by tangent lines. After the tangents are constructed, one may read the values of A1, A2, R1, R2, F1, F2, and P1 directly. These parameters are interpreted as follows:

- A1 = amplitude of first GEN
- A2 = amplitude of second GEN
- R1 = 0-100% risetime of first GEN, also the delay of the second GEN with respect to the starting time of the first GEN.
- R2 = 0-100% risetime of second GEN
- F1 = 0-100% falltime of first GEN
- F2 = 0-100% falltime of second GEN
- P1 = pulse width or single bit time

The transmitter model then takes the form of two cascaded GEN's for each group of consecutive logical HIGH's.

```
!DUAL SLOPE OPTICAL TRANSMITTER MODEL TEMPLATE
!
GEN PW=P1  PER=per TR=r1  TF=f1  AMP=a1 BW=bw
GEN PW=P2  TR=r2  TF=f2  AMP=a2  DEL=R1
```

The values in the model are related to the measured values by the following:

(1) r1 = 10-90% risetime of first GEN = 0.8 * R1

(2) r2 = 10-90% risetime of second GEN = 0.8 * R2

(3) P2 = ideal pulse width of second GEN = P1 - R1

(4) f1 = 10-90% falltime of first GEN = 0.8 * F1

(5) f2 = 10-90% falltime of second GEN = 0.8 * F2

(6) a1 = A1/(A1+A2) = normalized amplitude of first GEN

(7) a2 = A2/(A1+A2) = normalized amplitude of second GEN

Figure 9 shows how the superposition of these two GEN's produces the desired waveform.

The next example shows how to apply this technique to a Sumitomo LED with slow (dual sloped) rising and falling edges.

Transmitter Example 3 - Sumitomo LED dual slope edges

Figure 10a shows the experimentally measured rising edge of a Sumitomo LED. Although there is no overshoot for this device, one notes that there is a slope change of the edge. Consequently, to simulate this LED, two GEN's will be required with different TR, TF, AMP, and starting points (DEL).

Figure 10b shows the experimental falling edge for the same device.

Drawing tangents to the curves and reading from the scale in the photo (50 mv/div vertical; 500ps/div horizontal), one obtains the following characteristics:

R1 ~ 1.5 ns   R2 ~ 1.38 ns   F1 ~ 1.8 ns   F2 ~ 3.5 ns

A1 ~ 220 mv   A2 ~ 55 mv.

From the data shown, P1, the pulse width cannot be determined. Hence it is sufficient to assume that P1 is large enough that the rising and falling edges are independent of each other. For this example, we will let P1 be 40 ns and the period be 80 ns.

Equations (1)-(7) give the following model parameters:

r1 = 0.8 * 1.5 = 1.2   r2 = 0.8 * 1.38 = 1.1

f1 = 0.8 * 1.8 = 1.44   f2 = 0.8 * 3.5 = 2.5

a1 = 220/275 = 0.8   a2 = 55/275 = 0.2

The simulation model for the Sumitomo LED with step response as shown in Figure 10 is given by:

```
! SIMULATION OF DUAL SLOPE SUMITOMO LED's ELECTRONIC RESPONSE
GEN PW=40 PER=80 TR=1.2 TF=1.44 AMP=0.8
GEN PW=40 TR=1.1 TF=2.5 DEL=1.5 AMP=0.2
```

Figure 11 shows the simulated rising edge for this device. Note that the tangent approximation alone results in a model with sharp breaks in the curve (Fig. 11a). However, including the bandlimiting filter on the output of the GEN's smooths out the calculated curve (Figure 11b).

3. EXACT MODELS OF REAL DEVICES

There may be occasions in which the approximate edge shapes obtained using the GEN and TEE functions are not sufficiently accurate. This is most likely to occur when one is doing noise and timing jitter budgets. The exact shapes of both rising and falling edges of the source then become significant.

In these cases, one may create a data file to model to help simulate the behavior of interest. This is accomplished by digitizing the source output, and placing either the time domain (type 2) or frequency domain response (type 1) into data file SOURCE.DTA. Data points must be specified at equal time (frequency) intervals. The number of data points, NT, in SOURCE.DTA must be a power of two and must be less than or equal to 2**13 (8192). The first point corresponds to time zero (DC component in frequency domain). Time domain data is entered one point at a time in FORTRAN F20.3 format. Part of one such file is shown below:

```
.
.
.
0.431
0.454
0.477
0.500
0.523
.
.
```

Frequency domain data is entered with the real and imaginary part of each entry on a line in FORTRAN 2E16.2 format as shown below:

```
234.1,22.5
15.7,9.14
21.4,-34.7
```

To use the data stream specified in SOURCE.DTA as the generator input for FOCAS, one uses the SRC network section instead of the GEN. SRC tells FOCAS to read data fiel SOURCE.DTA, whether the data is the frequency or time domain representation, how many data points to read, and the time interval between points. If necessary, SRC will also have FOCAS calculate the power spectrum of the input waveform. (See Section IV-N for more information.)

B. RECEIVER MODELS

The optical receivers can be represented either as bandpass filters or as AC couplers with gain. These two cases will be treated separately.

1. Bandpass Filter

A special BPF network subsection has been created to represent a trapezoidal bandpass filter. The frequency response of the bandpass filter is shown below as $\log_{10} P(w)$ vs. angular frequency in octaves, where P(w) is proportional to optical power.

```
                   .--------------.     <- - P(AA) = P(BB) = 1.
                  .|              |.
P(w1) = .5 - ->  . |              | .      <- - P(w2) = 0.5
                .| |              |.
               . | |              | | .
              .  | |              | |  .
       . . . .   | |              | |   . . . . . P(A)=P(B)=1.E-5
             ^   ^ ^             .^ ^   ^
             |   | |              | |   |
             A  w1 AA            BB w2  B
```

In order to specify the trapezoidal bandpass filter, one must define the slopes of the rising and falling edges of the trapezoid, S1 and S2 in dB/octave. The slopes default to 6 dB/octave. In addition, the frequencies f1 and f2, (corresponding to w1 and w2 above) at which the transfer function is at one-half peak, must be defined. An optional gain parameter, K, may also be specified.

Phase shift is assumed to be a constant, PH, for w<w1, and constant at -PH for w>w2. For angular frequencies between w1 and w2, the phase shift is linear with angular frequency, crossing zero radians at the frequency midway between w1 and w2. Figures 14a and 14b show two different BPF models with identical transfer functions, but different phase shifts. If one specifies PH equal to zero radians, the degenerate case of no phase shift is encountered.

Figures 12-14 illustrate the transfer functions for some typical bandpass filters. All of these transfer functions are obtained directly from FOCAS (as described in section II D). The curves are graphed as P(frequency) vs. frequency, rather than $\log_{10}$ P(w) vs. w(octaves) as required to display the linearity of the trapezoid's edges. In this scale, the curvature of the edges is related to S1 and S2. In all cases, the larger S1 and/or S2 are, the faster the curves fall off to zero.

Figure 12 shows the transfer function of a bandpass filter with 3 dB points (half amplitude) at 100 MHz and 1 GHz. The slopes of both edges are specified to be 3 dB/octave. Consequently, the low frequency edge of the full bandpass region (AA) occurs at 200 MHz, and the high frequency edge of the full bandpass region (BB) occurs at 0.5 GHz.

Figure 13a shows the response of a bandpass filter with the same half-power points, but with 6 dB/octave edges. Note that the steeper edges imply that the flat center region is wider for same half-power bandwidth than for the 3 dB/octave case.

Figures 13b and 13c compare responses typical of optical receivers with F1 = 1 MHz and F2 = 200 MHz for two different edge rates.

2. AC COUPLER WITH GAIN

An alternate receiver model is comprised of a simple AC coupler (HPF section) followed by a voltage dependent voltage generator (EAMP section) with limited bandwidth and specified gain. This section will provide a phase shift in addition to band-limiting characteristics. However, it must be stressed that the timing jitter and noise margin obtained are highly dependent upon the phase relationship introduced by using this model

To get an idea how significant this effect can be, consider the response of an optical receiver comprised of a high pass filter with input capacitance of 0.2 nanofarads and shunt output resistance of one thousand ohms followed by a bandlimiting amplifier with a gain of 1.585, to a repetitive 10110 10010 10101 10011 bit stream sent down a 3.38 kilometer fiber optic cable. Figure 15a shows the data stream as it emerges from the receiver. Figure 15b shows the EYE pattern obtained at the receiver output. Note that the maximum timing jitter for this case is on the order of 0.6 nanoseconds. The noise margin is approximately 56%.

To test the signal sensitivity to receiver changes and phase shift, the input capacitance of the high pass filter section is the reduced to 0.05 nanofarads, while all other circuit parameters are left unchanged. Figures 16a & 16b show how drastically the output signal is altered. From Figure 16a, it becomes clear that the distortion of the pulse shape for consecutive HIGH levels has increased. Similarly, the timing jitter, as seen in Figure 16b has more than tripled to 2.2 nanoseconds, and the noise margin is reduced to roughly 44%.

In order to try to understand the difference in the behavior of these two receiver models, one compares the amplitude and phase shift of the their transfer functions. Figure 17 shows that there is only a very slight difference in the magnitudes of the two receiver transfer functions. However, from Figure 18, it becomes clear that there is a significant difference in the phase shifts introduced by the two receivers at low frequencies. This difference is responsible for the increased timing jitter observed.

C. CABLE MODEL

The fiber optic cable model used in FOCAS accounts for chromatic dispersion; intermodal dispersion; fiber attenuation; and the mismatch between the minimum dispersion wavelength of the fiber and the maximum optical power wavelength of the source. It is assumed that the cable transfer function can be treated as the product of transfer functions due to the individual effects:

(8) $Gtot(w,L) = P_{LED}(w,L) * Gc(w,L) * G_{IM}(w) * Ga(w)$

(9) $Gtot(w,L)$ = cable transfer function at angular frequency w and wavelength L

(10) $P_{LED}(w,L)$ = optical source output power at angular frequency w and wavelength L

(11) $Gc(w,L)$ = fiber chromatic dispersion transfer function at angular frequency w and wavelength L

(12) $G_{IM}(w)$ = fiber intermodal dispersion transfer function at angular frequency w

(13) $Ga(w)$ = fiber attenuation transfer function at angular frequency w

The fiber optic cable is modelled by a single network subsection, FIBER, which accounts for the characteristics of both the optical fiber and the optical source.

The basic physical assumptions of the model are:

1. Sellmeier's equation is valid for describing the chromatic dispersion of the cable, i.e. the dispersion coefficient, D in ns/(nm-km), is given by the equation:

(14) $$D = 1.176 * \left\{ \mathrm{SQRT}\left[Do^{2} + \frac{(0.85*So*FWHM)^{2}}{8} \right] \right\}$$

where one has:

Lo = minimum dispersion wavelength of the fiber

Lc = peak power wavelength of the source

So = slope of the dispersion curve in ns/(nm**2-km)

FWHM = half max width of source spectral distribution

$$\text{(15)}\quad Do = \frac{So}{4} * \left[Lc - \frac{Lo^{4}}{Lc^{3}} \right]$$

2. Chromatic dispersion delays wavelength component L by an amount proportional to fiber length.

(16) T = D*X**(L-Lc) = delay introduced to spectral component at wavelength L with respect to Lc

(17) Gc(w) = exp{ jw*T} = phase shift introduced to spectral component at wavelength L with respect to a component at the central wavelength, Lc

= exp{ jw*D*X*(L-Lc)}

3. The optical transmitter power spectrum can be approximated by a Gaussian wavelength distribution.

$$\text{(18)}\quad P_{LED}(w,L) = \frac{1}{Z} \exp\{ - (L-Lc)^{2}/Z^{2}\} \quad \text{where}$$

(19) Z = F/[2*sqrt(ln 2)] = standard deviation of the source spectrum

F = width of the spectral source at half power in nanometers

4. The fiber attenuation is exponential with fiber length.

(20) Ga(w) = exp{-K*A} = fiber transfer function due to attenuation

(21) A = [ro + rw*(L-Lc)]*X = fiber attenuation in dB

(22) K = (ln 10)/10 = 0.2306 = dB conversion factor

ro = DC optical power attenuation of the fiber in dB/km

rw = wavelength dependent optical power attenuation of the fiber in dB/(nm-km)

5. The intermodal dispersion of the fiber is described by a Gaussian distribution of effective optical path lengths, (Xeff = X**Qm).

(23) $G_{IM}(w) = \exp\{ -(d^{2})\}$ where

(24) d = (0.1325 * w * Xeff)/FI

(25) Bm = FI/Xeff = modal bandwidth of the fiber in Gigahertz

FI = cable bandwidth due to intermodal dispersion in GHz-km

Xeff = X**Qm = effective modal cable length

X = fiber physical length in kilometers

Qm = intermodal length scale factor

The electronic response of the optical cable is described by the integral of Gtot(w,L) over all wavelengths:

$$(26)\quad Pe(w) = \int_{-\infty}^{\infty} Gtot(w,L)\, dL$$

$$= \exp\{ -a + b^{2} - c^{2} - d^{2} - j(2bc) \}$$

a = K*ro*X

b = K*K'*rw*F*X

c = w*K'*F*D*X

d = 0.1325*w*(X**Qm)/FI

K = (ln 10)/10 = 0.23026

K'= 1/[4*sqrt(ln 2)] = 0.30028

Details on how the cable model is used are provided in Section IV-D. of this report.

D. FOCAS OUTPUTS

FOCAS provides output in several formats for maximum flexibility. It provides files which can by graphed directly on a REGIS terminal merely using the DCL "type" command. These files are denoted by the filetype extensions: .tg, .fg, or .pg after the simualtion model name. The character "g" denotes a graphical file, and the characters "t", "f", and "p" denote time, frequency, and phase respectively. For example, a simulation model in file fit. was used to produce the time domain waveform in Figure 2. The graph was obtained on a VT240 simply by typing: ty fit.tg after the $-prompt.

If, for some reason, the user requires the numerical data from which waveforms are derived, he simply types one of the the files with filetype extension: .td, .fd, or .pd The character "d" denotes that the file contains raw data data. "t", "f", and "p" retain their previous meanings. In the example above, the data used to generate the graph in Figure 2 is displayed by typing the command: ty fit.td after the $-prompt. A partial listing of fit.tg is given below. The first column is time in nanoseconds; the second column is voltage. Negative times correspond to time during the previous cycle of the bit pattern or waveform.

-32.000	0.000
-31.086	0.000
.	.
.	.
.	.
-0.914	1.000
0.000	1.000
.	.
.	.
.	.
8.229	0.659
9.143	0.555
10.057	0.450
10.971	0.346
.	.
.	.
.	.

Because it is often useful to have both the time and frequency domain responses of a network to understand its behavior, FOCAS provides both. Placing the control statement .OUT after a network subsection tells FOCAS to write the output waveform at that point in the circuit. The time domain representations, modelxyz.td and modelxyz.td are also created whenever FOCAS is run. If, in addition, the user wants the power spectra of the various waveforms, he need only include the control statement: .FDG (Frequency Data & Graph) in the simulation model. Similarly, to obtain plots of the phase shift (in radians) vs. frequency (in Megahertz), one includes the control line: .PDG (Phase Data & Graph) in the simulation model.

1. TIME DOMAIN OUTPUT FILES

FOCAS provides three different file types to represent time domain information. The .tg and .td files contain descriptions of the voltage as a function of time. When the .EYE option has been invoked (See Control Statements section), these files contain the EYE pattern. To view the EYE pattern on a REGIS terminal, simply type: ty modelxyz.tg for simulation model named modelxyz. For devices which use a different graphics format, file modelxyz.td can be used to generate a graph whose data points have horizontal co-ordinates listed in the first column of modelxyz.td, and corresponding vertical co-ordinates listed in the second column of modelxyz.td.

The last time domain file is the MODELXYZ.DAT file, which contains:

- i) the times of specified voltage level crossings of the output waveform(s)
- ii) times of the relative maxima and minima of the output waveform(s)
- iii) timing jitter observed at the two edges of the EYE pattern.

Timing jitter is only computed when the EYE pattern output is specified. In addition, the threshhold voltage, Vt, must be specified as the crossing level in the statement: .OUT V1=Vt. Alternatively, the waveform can be centered at zero volts, and the statement: .OUT V1=0 included to get proper timing jitter results.

MODELXYZ.DAT is only created when at least one of the time domain outputs actually crosses the specified voltage level, or the DV option specified (i.e. locations of maxima and minima requested). If no crossings occur, or if no crossing or min/max locations have been requested, no modelxyz.dat file is created.

If the .OUT statement in model, fit., which created Figure 2, is changed to: .OUT V1=0 V2=.5 V3=2 then FOCAS generates file fit.dat as shown on the following page:

```
$ty fit.dat

CROSSOVER & EXTREMA TIMINGS FOR: fit.

TIMING ACCURACY IN NANOSECONDS =          0.156

CROSSOVER TIMING IN NANOSECONDS,

 NETWORK          7              7             7
 VOLTAGE        0.000          0.500         2.000
 DELAY          0.000          0.000         0.000

               54.219          9.623         0.000
               61.094         15.999         0.000
              126.094         33.621         0.000
              141.094         40.000         0.000
                0.000         49.623         0.000
                0.000         64.001         0.000
                0.000         73.621         0.000
                0.000         80.000         0.000
                0.000         89.623         0.000
                0.000         95.999         0.000
                0.000        105.625         0.000
                0.000        112.002         0.000
                0.000        121.627         0.000
                0.000        144.001         0.000
```

The network number indicates that the waveform is being analyzed after network subsection number 7. The voltage headings on the three columns indicate that the columns give the times at which the waveform crosses 0 volts, 0.5 volts, and 2.0 volts respectively. The delay header in all three columns is zero because the waveform was not shifted in the .OUT statement (TO=0 or unspecified). Crossing times are only calculated over one period. As can be seen from Figure 2, the waveform crosses V=0.5 fourteen times during a single period from zero to 160 nanoseconds.

This example also illustrates two more characteristics of the voltage crossing computations. The waveform remains constant at zero approximately from 57 to 59 ns and again between the times of 126 and 139.6 ns. The end points of the constant value intervals are given in fit.dat. Zeroes are used as place holders for the last ten positions in the V=0.0 column. Similarly, the waveform of Figure 2 never crosses the two volt level. Hence the entire V=2.0 column contains zeroes.

Section III. of this report (Control Statements) provides details on the use of .OUT and its various options. It also includes an example of a .DAT file with both voltage crossings and waveform extrema locations.

2. FREQUENCY DOMAIN OUTPUT FILES

The power spectrum of the signal (i.e. the waveform observed with a spectrum analyzer) at any point in the network is readily obtained from the .fg and .fd files. These files represent the complex magnitude of the frequency domain response of the network at the specified terminal pair. The power spectrum of a signal provides information about the relative strengths of the various frequency components in the signal. To generate the power spectrum, one includes: .FDG in the simulation model.

Figure 20 shows the power spectrum of the 10110 10010 10101 10011 signal whose time domain reponse is shown in Figure 2. Figure 20 represents the bit stream before it has gone through any other circuit elements. Yet it is already quite complex. The graph in Figure 20 was obtained by typing: type fit.fg after the $-prompt on a REGIS terminal. As in the case with the time domain data, fit.fd provides a tabular listing of the data used to produce the output graph. The first column in the .fd file represents frequency in Megahertz; the second column is the amplitude of the power spectrum, normalized to the magnitude of the strongest frequency component.

Clearly, interpretting the power spectrum of a signal at an arbitrary point in a network excited by such a complex power spectrum can be difficult. Fortunately, one is usually more interested in the frequency response of a certain portion of the network. The transfer function, the power spectrum of the response to a stimulus which is a step function in the frequency domain, is often used to characterize the bandwidths of individual circuit components. Figures 12-14 provide just such information about the bandpass filter that is used in modelling the optical receiver.

In order to generate the frequency domain step response with FOCAS, one must define the proper time domain input. This is simply a delta-function in the time domain. However, because FOCAS assumes that all of its generators are periodic, one must approximate the delta-function as closely as possible. A GEN with very steep rise and fall times, and a very narrow pulse width, which is several orders of magnitude less than its period, works quite well. This model will automatically require 32768 frequency terms unless the FF option is specified in the .FDG control line.

```
!     INPUT FOR TRANSFER FUNCTION GENERATION
!
!             R in GEN below must the the input
!             impedance of the circuit being investigated
!             to allow for maximum power transfer
!
GEN TR=.05 PW=.0625 PER=1000 AMP=2 R=x
```

The captions under Figures 12, 13, and 17 illustrate how a model to compute transfer functions is defined. The delta-function impulse is applied to the circuit, and the frequency domain response viewed.

As an example of the usefulness of this facility, consider the problem of determining the effect that the difference between the peak source wavelength, Lc, and the minimum dispersion wavelength of the cable, Lo, has on the bandwidth of the optical fiber. Models are run in which the fiber is driven by the delta-function impulse, with only the difference between Lo and Lc changing. The widths of the transfer functions (power spectrum at the fiber output) are compared at the 50% power level. Figure 21 shows two such runs. In the top example with (Lo-Lc) of 100 nanometers, the fiber half-power bandwidth is approximately 90 MHz. In the lower example, with Lo and Lc equal, the half-power bandwidth has doubled to 180 MHz.

When one is interested in the phase shift introduced by a particular circuit element as well as its transfer function, the .pg and .pd files are used. Again the circuit element is stimulated with a impulse. The control statement: .PDG invokes the phase shift calculation. However, one now views the .pg file for an output graph of phase shift in radians vs. frequency in megahertz. Figure 18 shows two such plots.

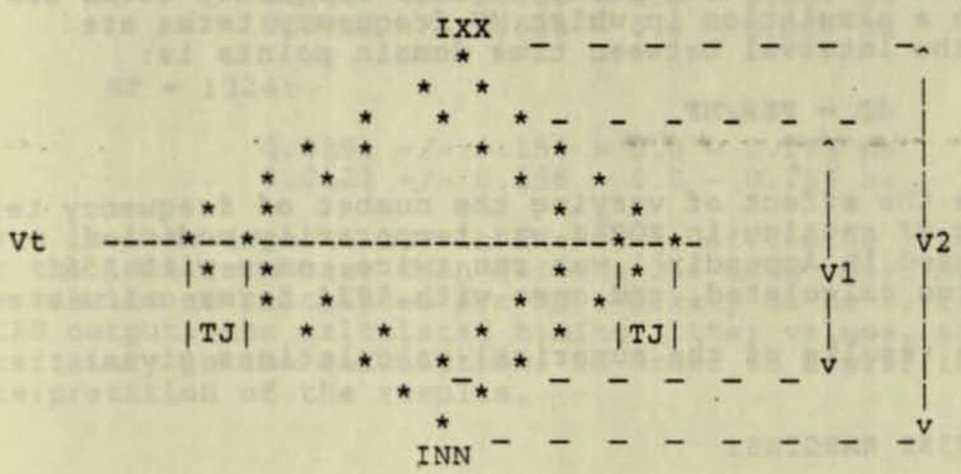
NOTE: As seen in this section, FOCAS can generate as many as seven (.tg, .td, .fg, .fd, .pg, .pd, and .dat) files. Consequently, it is adviseable to run FOCAS in it's own subdirectory and/or to regularly delete unwanted output files. Otherwise, FOCAS rapidly becomes a disk eater.

3. TIMING JITTER & PERCENT NOISE MARGIN

Calculation of timing jitter and per cent noise margin are both controlled by the .OUT control statement.

In order to calculate timing jitter, one must run an EYE pattern, and specify V1=Vt in the single .OUT statement, where Vt is the threshold voltage. For convenience, one may start by centering the waveform about the zero volt axis, then specify .OUT V1=0, to get an estimate of the timing jitter. The two timing jitter values returned correspond to the two edges of the EYE pattern. The timing jitter calculation is quite sensitive to phase shifts introduced (see discussion on optical receiver models) and to an accurate specification of the threshhold voltage (or center voltage)

Percent noise margin, N, is defined as the ratio of the maximum voltage swing to the minimum voltage swing of the waveform. It is most easily interpretted in terms of the EYE pattern. However, the computation of N is not restricted to those cases in which one requests an EYE pattern output. The drawing below illustrates the physical interpretation both N and timing jitter (TJ):



The percent noise margin, N, is defined as:

N = (V1/V2) * 100

V1 is the difference between the minimum of all the maxima (INX) and the maximum of all the minima (IXN):

V1 = INX - IXN.

V2 is the difference between the maximum of all the maxima (IXX), and the minimum of all the minima (INN):

V2 = IXX - INN.

Although it is easier to interpret N with an EYE pattern, the calculation can be run wherever an extremum calculation is requested by specifying DV in the .OUT line.

When EYE pattern output is specified, only TJ and N are displayed on the terminal screen. However, the .dat file contains all the crossover and extrema timings and the values of the extrema voltages, as well as TJ and N.

Appendix 1 contains a sample calculation of TJ and N, showing the simulation model and .dat file generated.

E. ACCURACY

The accuracy limit of FOCAS, assuming valid models, is determined by the number of frequency terms computed, and hence by the resolution in both the frequency and time domains. Angular frequency terms are taken at intervals of 2*PI/PER. No fewer than 256 nor more than 32768 angular frequency terms are computed. In a simulation in which NF frequency terms are calculated, the interval between time domain points is:

dT = PER/NF

To illustrate the effect of varying the number of frequency terms, the automatic NF setting in FOCAS was temporarily modified. The model listed in Appendix 1 was run twice, once with 256 frequency terms calculated, and once with 1024 terms calculated.

Comparing the results of the numerical calculations gives:

PERCENT NOISE MARGINS:

			256 terms	1024 terms
NETWORK: 8	N	=	80.4805%	81.0621%
NETWORK: 9	N	=	65.1786%	65.8887%
NETWORK: 10	N	=	65.1786%	65.8887%
TIMING JITTER ACCURACY		=	0.625	0.156 NS
TIMING JITTER (at LED output)		=	0.0417 0.0018	0.0391 NS 0.0123 NS

Clearly, the noise margin calculation is quite insensitive to the value of NF. Noise margin is computed as the ratio of extrema voltages, which are all rounded to the nearest millivolt. Hence minor point-by-point variations in magnitude are of no significance.

Timing jitter, however, depends directly on the differences in threshhold crossing times at the two edges of the EYE pattern. The expected error in crossover points is +/- one half the time increment. Because the timing jitter calculation involves the difference between two crossover times, the uncertainty is equal to a full time increment, NF/PER. As a result, when large bit streams are used to determine worst case timing jitter, one must use more frequency points than for short stream of bits through the same physical system. If NF were not increased, a long bit stream (large PER) could actually produce less accurate timing jitter calculations than a short data stream.

The equivalence of the timing jitter calculations for the two different NF values is obvious when this timing uncertainty is taken into account. The timing jitter values are actually:

NF = 256:

0.0417 +/- 0.625 = 0.0 - 0.667 ns
0.0018 +/- 0.625 = 0.0 - 0.626 ns

NF = 1024:

0.0391 +/- 0.156 = 0.0 - 0.195 ns
0.0123 +/- 0.156 = 0.0 - 0.168 ns

There is less uncertainty in the range of timing jitter values for the 1024 term case than for the 256 term case. Hence the results as calculated are more likely to be correct. FOCAS outputs the calculated timing jitter values, and the uncertainty in the calculation, in order to assist in interpretation of the results.

A similar timing discrepancy arises when crossovers and/or extrema are calculated, as shown below. The uncertainty in these time computations is one half the time increment (i.e. PER/(2*NF)). Differences in crossover timings are quite small as shown.

CROSSOVER TIMING IN NANOSECONDS - 256 frequency terms

NETWORK	8	9	10
VOLTAGE	0.000	0.000	0.000
DELAY	0.000	0.000	0.000
	11.171	11.184	10.625
	17.494	17.380	17.819
	35.170	35.186	34.611
	41.486	41.378	41.824
	51.170	51.168	50.608
	65.528	65.519	65.908
	75.170	75.174	74.611
	81.486	81.378	81.824
	91.170	91.182	90.625
	97.494	97.380	97.819
	107.170	107.179	106.605
	113.488	113.372	113.814
	123.169	123.158	122.599
	145.528	145.519	145.908

CROSSOVER TIMING IN NANOSECONDS - 1024 frequency terms

NETWORK	8	9	10
VOLTAGE	0.000	0.000	0.000
DELAY	0.000	0.000	0.000
	11.167	11.181	10.625
	17.494	17.372	17.813
	35.165	35.176	34.609
	41.490	41.392	41.823
	51.167	51.163	50.608
	65.527	65.508	65.913
	75.165	75.174	74.609
	81.490	81.392	81.823
	91.167	91.181	90.625
	97.494	97.372	97.813
	107.178	107.188	106.602
	113.488	113.381	113.821
	123.171	123.160	122.604
	145.527	145.508	145.913

The extrema locations again depend on differences between several consecutive points. In addition some smoothing of the waveform is performed to eliminate identifying artifacts of the numerical procedures as extrema. Consequently the differences in extrema are more noticeable than in crossovers. In fact, the 256 term case failed to identify the minimum at 61.563 ns which was found by the 1024 term case. This lack is not of great concern as the minimum located at 59.688 ns for the 256 term case correctly picks the mimimum magnitude of the region (Figure 23).

MAXIMA AND MINIMA TIMING IN NANOSECONDS

NETWORK 8
DELAY 0.000

NF = 256 MAXIMA	NF = 256 MINIMA	NF = 1024 MAXIMA	NF = 1024 MINIMA
5.625	14.590	5.625	14.570
24.688	38.594	23.203	38.568
30.000	59.688	29.688	58.047
45.767	78.594	45.859	61.563
69.784	94.590	69.766	78.568
85.767	110.598	85.859	94.570
101.779	131.563	101.797	110.599
117.756	141.875	117.734	130.078
152.813	0.000	151.172	141.563

CONTROL STATEMENTS

Control statements are preceded by a period. They are:

.END - Input terminating statement, must be present as last statement in input file. Has three optional variables: TX, DC, FS.

TX sets the horizontal display full scale in nanoseconds. TX must be positive and defaults to the pulse repetition period.

DC shifts the vertical display axis and all displayed waveforms by the defined voltage. DC does not alter the locations calculated for voltage crossings.

FS sets the vertical voltage scale. FS defaults to two. The ordinate scale will show a maximum of +/- 9.9 volts with one decimal place. The output graphics waveform display defaults to a vertical axis from zero volts to two volts.

.EYE - Has the same function and variables as .END . In addition, .EYE generates a repeated eye pattern when TX is less than the generator period, and invokes calculation of timing jitter at the edges of the EYE. TX should be set to an integral divisor of the bit time.

An EYE pattern will only be calculated when a single waveform is to be displayed. If more than one .OUT statement appears in the simulation model, FOCAS will display the error message, "**** ONLY ONE OUTPUT ALLOWED FOR EYE *****", and stop.

The .EYE statement simply folds the time axis back to zero time at the time interval specified by TX. This time resetting also applies to the MODELXYZ.DAT file. Hence the relative skew of cross-over timing is stored and easily interpreted.

Display width is twice the width of the time interval and the display is centered. The parameter TO in the .OUT statement may be used to shift the eye pattern as described on the following page.

In order to get the most information from the EYE pattern, the user must define a worst case pulse pattern, one which contains the highest and lowest frequencies of interest. It should have ONE-ZERO-ONE at the maximum pulse rate, and lowest frequencies of interest. It should have ONE-ZERO-ONE at the maximum pulse rate, and ONE-ONE-ONE---ZERO-ZERO-ZERO---ONE-ONE-ONE--- where the length of the high and low states is such that the frequencies of interest are well within any band limiting of the network. Usually a low frequency equal to one fourth the highest frequency (the pulse/sample/bit rate) is more than adequate. Appendix 2 has a model for generating a good pulse pattern for the 4b5b FDDI code (E6E6E6E63E6E6E6E6).

.OUT - Creates a plot file for the voltage output wavefor of the network it follows. Up to four .OUT statements are allowed in a single simulation model. If .EYE is used (i.e. and eye pattern is requested) only one .OUT is permitted. The output files are: modelxyz.tg, modelxyz.td, modelxyz.fg, modelxyz.fd, modelxyz.pd, and modelxyz.pg. A termin with a graphics capability is required to display th .tg, .fg, and .pg files.

.OUT has six optional variables: V1, V2, V3, TO, DC, and DV.

If any or all of the Vi's are specified, the file MODELYXZ.DAT is created which contains the crossover timing for the specified output at the voltages V1, V2, or V3. A maximum of six such specifications are allowed per simulation, the rest are ignored. The actual crossing times are calculated assuming that no shift in the waveforms or the vertical axis has been performed. The equal sign (=) is required in the specification of the Vi's in .OUT.

TO is a delay in nanoseconds which shifts the waveform and the crossover time calculation for the output to the left (minus time). TO must be positiv and defaults to zero. A shift of the waveform to th left by N nanoseconds is equivalent to a shift to th right by (PER - N) nanoseconds. Similarly, if one w to shift the wavform to the right (toward increasing time) by N nanoseconds, it is necessary merely to specify TO=(PER-N) in the appropriate .OUT statement.

Figures 19 and 22 illustrate the use of TO.

In Figure 19a, the 50% point of the leading edge of the output waveform occurs at time zero (standar FOCAS default for the time domain graphs). It is often desireable to align the output graph with the waveform beginning to rise at time zero (as one wou normally align an oscilloscope trace). In order to to this, one must shift the waveform by an amount equal to:

```
(27)      TO = { PER - 0.625*TR1     if DEL1 = 0
               {       or
               { DEL - 0.625*TR1     if DEL1 .ne. 0

                 TR1  = 10-90% risetime of 1st GEN
                 DEL1 = delay of first GEN
```

NOTE: 0.625*TR1 corresponds to one-half the 0-100% risetime of the (first) GEN. Figure 22 is a simple illustration of right and left shifts using TO.

The parameter, DC, shifts the displayed waveform vertically by the an amount equal to the value of DC; the shift is for the waveform corresponding to the paticualr .OUT statement, and does not change the vertical axis labeling.

Use of the parameter DC in either the .OUT or the .END statement does NOT change the calculated locations of the voltage level crossings. FOCAS will compute the crossing locations as though the shift in the axis (.END) or in the waveform (.OUT) has not occurred. DC only acts the the graphical output.

DV is used to indicate that the times at which the output waveform achieves it relative extrema (minima and maxima) are to be calculated and the results written into the .dat output file. One need only include DV on the .OUT line to find extremum locations. Figure 23 gives the output waveforms and .dat file for the model given below.

```
!SIMULATION OF 4 5b PATTERNS THRU 62.5/125 CABLE
! Bit pattern:  10110 10010 10101 10011, repeats
GEN PW=8 PER=160 TR=4.4 TF=7  dc=-.5
GEN PW=16 DEL=16
GEN PW=8 DEL=40
GEN PW=8 DEL=64
GEN PW=8 DEL=80
GEN PW=8 DEL=96
GEN PW=8 DEL=112
GEN PW=16 DEL=144
TEE L1=15 C=0.04 R1=38.73
!  Led tr=5. ns   tf=7.3 ns
.OUT V1=0  DC=2. dv
FIBER X=3.38 SO=.0000909 LO=1349 FI=1.127 AO=.74 LC=1291 FW=126
.OUT V1=0. DC=1. dv
bpf f1=1U f2=2  s1=6 s2=8
.OUT v1=0 dv
.End TX=320 DC=1 FS=4
```

CONTROL STATEMENTS (cont.)

.FDG - Creates the frequency domain plots of the power spectrum (or transfer function) for the waveforms at every point in the simulation model at which .OUT is specified. Two files, modelxyz.fg and modelxyz.fd are created when .FDG is specified. The first file (.fg) is a REGIS file, which when typed on a REGIS device, graphs the power spectra (transfer functions) directly. The second file (.fd) can be used as the input to a graphics routine which interprets the first column of data as amplitudes and the second as frequencies (in Megahertz) to generate the power spectra in some other graphics format.

.FDG has one optional variable: FF. If FF is specified after .FDG, it indicates that a fast run is requested, and the number of frequency terms calculated will autmatically be limited to 8192 or fewer. This facility is particularly useful when calculating transfer functions, which would otherwise require the full 32768 terms, and thus be quite time consuming to run.

.PDG - Creates the phase shift plots of the power spectrum (or transfer function) for the waveforms at every point in the simulation model at which .OUT is specified. Two files, modelxyz.pg and modelxyz.pd are created when .PDG is specified. The first file (.pg) is a REGIS file, which when typed on a REGIS device, graphs the phase shift vs. frequency directly. The second file (.pd) can be used as the input to a graphics routine which interprets the first column of data as phase shifts in radians, and the second column as frequencies (in Megahertz) to generate the phase shift graphs in some other graphics format.

NETWORK DESCRIPTIONS

The networks are as follows:

```
GEN     - A trapezoidal waveform voltage generator
SINE    - A sinewave generator
EAMP    - Voltage dependent voltage generator
IAMP    - Voltage dependent current generator
TEE     - The standard T circuit with series L and shunt C
DELTA   - The standard PI circuit with series L and shunt C
LINE    - A transmission line, skin effect for stripline
FIBER   - Fiber optic cable dispersion model
HPF     - High Pass Filter
XFORMER - Transformer
FILTER  - Cosine frequency domain filter
SHUNT   - Polynomial expression for a shunt impedance
SERIES  - Polynomial expression for a series impedance
BPF     - Trapezoidal bandpass filter with gain
```

Units are ohms, nanohenries, nanofarads, nanoseconds, gigahertz, mhos, centimeters (except as noted). Input format is similar to the FORTRAN F or I, (decimal points need not be supplied for whole numbers).

A. GEN Network

```
          ---------
   ---|           |
   |  |           |---|\
   +  |   LPF     |   | \-- R --O
   V  |           |   | /-------O
   -  |           |   |/
   |  |           |---
   ---|           |
          ---------
```

The GEN is a periodic trapezoidal waveform generator followed by low pass filter and a unity voltage gain buffer with an output impedance equal to R.

```
AMP ----          /-------\              /-------\
     /\          /         \            /
     \/         /           \          /
DC -------/                  \---------/
  0 -----------------------------------------------------
              <---- PW--->
               <TR>       <TF>
              <--------- PER --------->
 <- DEL->
```

Parameters:

PW = "ideal" pulse width or bit time. i.e. the time between the decisions to turn on and turn off

TR = 10-90 % risetime (leading edge) in nanoseconds. The 0-100 % risetime is computed to obtain the specified risetime with or without a specified bandwidth for the low pass filter.

TF = 10-90 % falltime (trailing edge) in nanoseconds. The 0-100 % risetime is computed to obtain the specified risetime with or without a specified bandwidth for the low pass filter. (default=TR)

PER = pulse repetition period in nanoseconds

AMP = pulse amplitude in volts, defaults to one.

DEL = pulse delay in nanoseconds, measured from the leading edge. Defaults to zero.

BW = filter bandwidth in gigahertz, defaults to 50 divided by the risetime.

DC = DC voltage offset in volts, defaults to zero

R = generator output resistance in ohms, defaults to zero.

If several GEN sections are cascaded together to form a data stream, FOCAS automatically sets some conditions to simplify user input. FOCAS compares the risetimes of the first two GEN sections. If they are not equal, and the second is nonzero, a dual slope leading edge is assumed. If they are equal, or if the second risetime is not specified(i.e. initially zero), a singly sloped leading edge is assumed.

In all cases, only the first GEN need specify PER and BW. Whenever any of the input parameters is missing from a subsequent GEN specification, FOCAS automatically determines whether to use the single or dual slope model. For the single slope case, TR, TF, and AMP are all set to the values specified for the first GEN. For the dual slope case, all odd numbered GEN's are assigned the TR, TF, and AMP values of the first GEN; all even numbered GEN's receive the values specified by the user for the second GEN.

Similarly, FOCAS automatically checks if the first and last bits in a periodic data stream are one's. If they are potentially overlapping one's, i.e., the optical transmitter does not have time to completely turn off before receiving another signal to turn on, FOCAS will combine the first and last GEN 's in such a manner as to preserve the data integrity without apparently driving the transmitter output beyond its maximum level.

The user is cautioned, however, that this checking only occurs between the first and last GEN sections. It is assumed that the user has exercised care in defining all internal GEN sections to eliminate the potential for signals that are "more on than on".

NOTE: Using a non-zero R value does not allow access to the voltage generator voltage with the .OUT statement, if this is desired use an external R. If an .OUT statement is placed in the midst of several GEN sections, without R specified, an arithmetic fault due to division by zero will occur.

B. SINE Network

SINE is sinewave generator which in the frequency domain is a delta function at the frequency fo. It has an output impedance R. In the time domain:

F(t) = AMP * SIN (2 PI F t + PHI) + DC

Parameters:

AMP = Peak sinewave amplitude, defaults to one.

F = sinewave frequency in GHz, must be an exact multiple of the simulation reciprocal period.

DEL = delay in nanoseconds, defaults to zero. (PHI = -W * DEL)

DC = dc voltage offset in volts, defaults to zero.

R = generator output resistance in ohms, defaults to zero.

C..TEE Network

```
O----- R1 --- L1 -+---+- L2 --- R2 -----O
                  |   |
                  |   |

                  C   G (R)

                  |   |
O-----------------+---+-----------------O
```

Parameters:

R1, R2 = series resistances in ohms, default to zero. Will have a skin effect component if F1 or F2 are specified respectively.

L1, L2 = series inductances in nanohenries, default to zero. Will have an internal inductance component if F1 or F2 are specified respectively.

C = shunt capacitance in nanofarads, defaults to zero.

G (R) = shunt conductance in mhos, defaults to zero. Either G or R (in ohms) may be specified. If both are specified by mistake, the R value supersedes the G value.

F1, F2 = The skin effect break frequencies in gigahertz, defined as the frequency at which the skin effect resistance is equal to the dc resistance. Skin effect resistance and internal inductance are assumed to be square-root frequency dependent. Default to infinity (no skin effect).

The skin effect model is:

$$Rac = \text{conductor resistance} = R1\ SQRT\left(1. + (F/F1)^{2}\right)^{1/4}$$

for conductor 1 (R1,L1) where F is the frequency.

$$Xint = \text{internal conductor inductive reactance} = Rac - R1$$

for conductor 1. Appropriate substitutions are made for conductor 2 (R2,L2).

D. FIBER Network

A model of the dispersion in a fiber optic cable. The model assumes intermodel dispersion based on a gaussian distribution of path lengths and chromatic dispersion based on a source with a gaussian spectral density and a linear material dispersion coeficient for the cable. The fiber cable delay is not included.

$$P(w) = e^{-a + b^2 - c^2 - d^2 - j\,2\,b\,c}$$

$$a = K\ Ao\ X^{Qc} \quad = \text{Static attenuation term}$$

$$b = K\ K'\ Aw\ FWHM\ X^{Qc} \quad = \text{Wavelength dependent attenuation}$$

$$c = w\ K'\ FWHM\ D\ X^{Qc} \quad = \text{Wavelength dependent time delay}$$

$$d = 0.1325\ w\ X^{Qm}/FI \quad = \text{Intermodal dispersion}$$

$$K = \ln(10)/10$$

$$K' = 1./(4\ \mathrm{SQRT}(\ln 2))$$

Parameters:

Ao = DC optical power attenuation of cable in db per kilometer (Km). Defaults to zero.

Aw = wavelength dependent optical power attenuation in db per nanometer-kilometer. Defaults to zero. Note that Aw is positive when attenuation increases with wavelength.

FWHM = optical source half power full bandwidth in nanometers. Defaults to zero.

LC = optical source center wavelength in nanometers used in calculating D when LC specified with LO and SO

LO = cable minimum dispersion wavelength in nm.; used in calculating D when LC, LO and SO specified

SO = slope of cable dispersion curve at LO in nanoseconds per (nanometer*2)-kilometer; used in calculating D when SO, LC, and LO specified

FI = cable bandwidth in GHz-Km due to intermodal dispersion. Defaults to infinity.

X = cable length in Km. Defaults to zero.

FIBER NETWORK (cont.)

Qm = Intermodal length scale factor (default=1)

Qc = Chromatic length scale factor (default=1)

D = fiber material dispersion coefficient in nanoseconds per nanometer-kilometer; calculated as below; If D is not specified, FOCAS automatically calculates D from the input values LC, LO, SO using the following equations:

$$D = \left\{ SQRT \left[Do^{2} + \frac{(0.85 \times SO \times FWHM)^{2}}{8} \right] \right\} *1.176$$

$$Do = \frac{SO}{4} \left(LC - \frac{LO^{4}}{LC^{3}} \right) \quad \text{Sellmeir's Equation}$$

E. HPF Network

A high pass filter or ac coupler.

```
O----- C ------+------O
               |
             G (R)
               |
               L
               |
O--------------+------O
```

Parameters:

C = capacitance in nanofarad, must be present.

G = shunt conductance in mhos, either G or R must be specified.

R = shunt resistance in ohms, if present it overrides an input G value and G = 1/R.

L = shunt inductance in nanohenries, defaults to zero.

F. EAMP Network

EAMP is a voltage dependent voltage generator with a specified bandwidth and output resistance.

```
             ------ R ---O
O---        |
+           +
Ei          E = GAIN X Ei
-           -
            |
O-----------+------------O
```

Parameters:

GAIN = voltage gain, defaults to one
BW = filter bandwidth in gigahertz, defaults to 50 divided by the minimum risetime.
R = generator output resistance in ohms, defaults to zero.

The filter does not change the infinite input impedance of IAMP and has the low pass filter frequency domain response:

$$F(w) = \frac{1}{1 + j\, w/(2\, PI\, BW)}$$

NOTE: Using a non-zero R value does not allow access to the voltage E with the .OUT statement, if this is desired use an external R.

G. IAMP Network

IAMP is a voltage dependent current generator with a specified bandwidth and output conductance.

```
              ----------------+--O
   O---       |               |
   +                          |
   Ei         I = GAIN X Ei   G (R)
   -          ^               |
              |               |
   O----------+---------------+--O
```

Parameters:

GAIN = current gain in mhos, defaults to one
BW = filter bandwidth in gigahertz, defaults to 50 divided by the minimum risetime.
G = generator output conductance in mhos, defaults to zero.
R = optional output resistance in ohms, if present G = 1/R; overriding an input G value.

The filter does not change the infinite input impedance of IAMP and has the low pass filter frequency domain response:

$$F(w) = \frac{1}{1 + j\, w/(2\ PI\ BW)}$$

H. LINE Network

```
             ----------------
     O-------()      ZO        )--------O
             ----------------
                        |
     O------------------+----------------O
             <------- X ------>
```

Parameters:

ZO = characteristic impedance in ohms
TD = propagation delay in nanoseconds per unit X
X = line length
R = series line resistance in ohms per unit X. Defaults to zero.
TC = stripline conductor thickness in cm, used to calculate skin effect. Defaults to zero; no skin effect.
WC = stripline conductor width in cm, this optional parameter will calculate R in ohms/cm. If present, will over-ride an input value for R. Skin effect assumes WC>>TC and a symmetric stripline.
Q = relative conductor resistivity compared to copper. Defaults to one.
D = dielectric loss tangent, assumed to be independent of frequency, i.e., the real part of the shunt impedance has the same frequency dependence as the imaginary part (capacitive reactance).
F1, F2, F3, K1, K2 = generate a variation in line capacitance as a function of frequency. Default to zero.

Conductor losses will not be calculated if both R and WC are zero or absent.

The frequency variable capacitance is A piece-wise linear model with log frequency as follows:

The value of line C is computed from the input values for ZO and TD, and the capacitance per unit length is:

F < F1,	C
F1 < F < F2,	C * (1 + A ln(F/F1))
F2 < F	C * (1 + A ln(F2/F1) + B ln(F/F2))

Where A = K1/ln(F2/F1), K1 is the fractional change in capacitance from F1 to F2

B = K2/ln(F3/F2), K2 is the fractional change in capacitance from F2 to F3

K. SERIES Network

Provides a series impedance expressed as a polynomial:

$$Z = K \frac{A0 + A1*S + A2*S^{2} + A3*S^{3} + A4*S^{4}}{B0 + B1*S + B2*S^{2} + B3*S^{3} + B4*S^{4}}$$

Where: S = j w; the complex radian frequency

Units must be consistent, and a scaling in the frequency domain will scale in the output time domain.

To avoid dividing by zero, the real part of the numerator is not allowed (by the program) to be less than 10^{-16}. In addition, if none of the Bi's are specified, then B0 is set equal to one.

Input parameters are: A0, A1, A2, A3, A4, B0, B1, B2, B3, B4, and K.

A0, A1, A2, A3, A4, B0, B1, B2, B3, and B4 as the coefficients described above. Each defaults to zero (with the exception of B0 as described above).

K = scaling parameter, defaults to 1

EXAMPLE:

```
O---- R -- L -- C ----O          Z = R + s*L + 1/(s*C)

O---------------------O          A0 = 1
                                 A1 = RC
                                 A2 = LC
                                 B1 = C
```

L. DELTA Network

```
O--+----+------- R --- L ---------+----+--O
   |    |                         |    |
   |    +-------- RP -----------+ |    |
   |    |                         |    |

   C1   G1 (R1)                  C2   G2 (R2)

   |    |                         |    |
O--+----+-------------------------+----+----O
```

Parameters:

R = series resistance in ohms, defaults to zero.

L = series inductance in nanohenries, defaults to zero.

RP = parallel series resistance in ohms, defaults to infinity.

C1, C2 = shunt capacitances in nanofarads, default to zero.

G1 (R1), G2, (R2) = shunt conductances in mhos, default to zero. Either G or R (in ohms) may be specified. If both are specified by mistake, the R value supersedes the G value.

M. BPF Network

BPF is a bandpass filter model with a frequency response which is trapezoidal in $\log_{10} P(w)$ vs. angular frequency (w) in octaves.

The bandpass region is shown below:

```
                         .---------------.      <- - P(AA) = P(BB) = 1.
                        .|               |.
                       .                   .
P(w1) = .5 - ->       .  |               |   .       <- - P(w2) = 0.5
                     .|                      |.
                    .                          .
                  .   |  |               |   |   .
          . . . .                                . . . . . . P(A)=P(B)=1.E-5
                |     |  |               |   |   |
                A    w1 AA              BB  w2   B
```

The phase shift as a function of frequency is a constant, PH, for w<w1 and -PH for w>w2. Between w1 and w2 the phase shift is linear with frequency, and zero at the midpoint between w1 and w2:

```
PH    * * * *
             |      *
             |           *
                              * * * *   -PH
             |                |
             w1               w2
```

Input parameters are:

F1 = frequency in Gigahertz at the low frequency 3 dB point of the trapezoid (corresponding to w1)

F2 = frequency in Gigahertz at the high frequency 3 dB point of the trapezoid (corresponding to w2)

S1 = slope of the low frequency edge of the trapezoid in dB/octave (default = 6 dB/octave)

S2 = slope of the high frequency edge of the trapezoid in dB/octave (default = 6 dB/octave)

K = gain (default = 1.)

PH = constant phase shift for frequencies less than or equal to w1, and the negative of the phase shift for frequencies greater than or equal to w2

N. SRC Network

SRC is not a true network section in the sense that it models circuit behavior. Rather, it provides the interface between FOCAS, and the user defined file, SOURCE.DTA which contains a digitized input data stream of interest. The purpose of providing this interface is to allow the user to investigate complex edge behavior (turnon and turnoff ringing) of real optical sources.

SOURCE.DTA may contain either the time or frequency domain representation of the input waveform. The number of points, NT, in SDOURCE.DTA must be a power of 2, less than or equal to 8192. For time domain data, the input format is FORTRAN F20.3. For frequency domain data, it is FORTRAN 2E16.2. (See section II-A-3 for examples.)

In addition to requiring that a data file named SOURCE.DTA be in the directory, the explicit input parameters are:

NT = number of points in SOURCE.DTA; must be a power of two, less than or equal to 8192

DT = time interval between consecutive data points (ns) in SOURCE.DTA or used to generate the frequency domain representation in SOURCE.DTA

PER = period of waveform in ns

TYPE = 1 if SOURCE.DTA contains frequency domain representation
2 if SOURCE.DTA contains time domain representation

R = source output resistance in ohms, defaults to zero

V. RUNNING FOCAS

A. INSTALLATION

FOCAS may be installed on any system on which FORTRAN is available. The two fortran programs: FOCAS.FOR and FFT842.FOR are required. FOCAS.FOR contains the main FOCAS program and all of its subroutines and functions except FFT842.FOR, the fast Fourier transform subroutine. These two programs are maintained separately to save recompilation time after frequent FOCAS.FOR enhancements. FFT842.FOR is quite stable. The 20,000-page page file quota is required for installation. Once the two fortran files are loaded on the system, one may get started by typing the commands:

```
$ FOR FOCAS,FFT842
$ LINK FOCAS,FFT842.
```

If a VT24X, or other REGIS display device is used, no other routines are required to view graphs of the output waveforms. For a microVax display (VR260) the program CIRCUIT_GRAPH.FOR provides UIS graphics support. CIRCUIT_GRAPH.FOR must also be compiled and linked before it can be run:

```
$ FOR CIRCUIT_GRAPH
$ LINK CIRCUIT_GRAPH.
```

Other types of graphics display devices will require their own graphing routines to work on the output files: modelxyz.td and modelxyz.fd. These two files, created by FOCAS, contain the data for the time and frequency domain outputs, respectively.

B. JOB SUBMISSION

1. Interactive Mode:

Before FOCAS can be run, the user must create a file containing the simulation model. The filename can be from one to thirty-one alphanumeric characters long followed by a period (.): modelxyz. To run the simulation, one then types:

```
$ RUN FOCAS
```

The program will respond with a header and a prompt for the input file name, requiring the name, with the period included:

```
          Fiber Optic CAble Simulator  FOCAS
                Revision  10 OCTOBER 1986

Enter the input file name: modelxyz.
```

If the period (.) is not included in the filename, the error message: %FOR-F-FILNOTFOU, file not found will be printed out and execution of FOCAS stopped. To restart, type RUN FOCAS and respond with the filename, including the period.

As modelxyz. is being read in, it is also printed out on the display. Once the model has been read into memory, a message indicating the number of frequency terms that will be required is printed. Run time depends on the number of frequency terms, between 256 and 32,768 in powers of two, and the number of network sections in the model.

Busy messages are printed out at least every one to two minutes for large simulations to let the user know how well the simualtion is progressing.

When the simulation is complete, the bell on the terminal sounds, and a FORTRAN STOP message is displayed.

The simulation automatically generates the output graphics and data files named to correspond to the input model name and the files' respective contents:

```
modelxyz.tg = time domain REGIS graph
modelxyz.td = time domain data file
modelxyz.fg = frequency domain REGIS graph
modelxyz.fd = frequency domain data file
```

unless and EYE Pattern has been requested. When an EYE pattern is requested, the frequency domain results are surpressed.

In Appendix 2, the simulation model e63e6. is run with EYE pattern output requested. FOCAS first reads and prints the model, then types a message indicating that the frequency domain response files will not be generated because of the EYE pattern output specification.

Next a message indicating that 1024 frequency terms are required is printed out. The purpose of this message is to allow the interactive user to gauge the total run time required and progress through the simulation. Each of the frequency terms is required for each of the twenty-nine circuit sections in the model. Consequently, one should anticipate some delay prior to completion of the job.

The messages "FOCAS IS ALIVE & WELL . . . freq. term: nnn" indicate progress through the compute intensive portion of the simulation.

In some instances, the total number of frequency terms computed will be less than the number that were required. This may occur if a potential overflow condition is detected. In such cases, the job terminates normally, but the timing uncertainty will be higher because of the fewer frequency terms computed. The following warning message will be printed:

*** WARNING - reduced accuracy ***

If, however, fewer than 128 frequency terms are computed before encountering an overflow, the job will terminate with the message: NOT ENOUGH TERMS TO USE RESULTS .

Finally, results of the voltage crossing calculation and the FORTRAN STOP message indicate normal completion of the job. Slightly more five minutes of CPU time were required to run this job.

To view the output graphs on a REGIS terminal (e.g. VT240), one types the command: type modelxyz.td

or

type modelxyz.fg

for the time domain and frequency domain responses respectively. If a printer is attached to the terminal, a hardcopy of the displayed graph is obtained by pressing the "Shift" and "F2" keys simultaneously. The examples given at the end of this manual discuss how to scale the graphs and provide sample outputs.

2. BATCH JOB SUBMISSION

For large FOCAS simulations, it will generally be desirable to submit batch jobs and be notified of their completion. In general, if more than ten to fifteen network subsections are used, and 512 or more frequency terms required, it is advisable to run the simulation in batch mode. This frees the user to do other work while awaiting analysis results.

In order to submit a batch job, two .com files are required. The first, focas.com, is simply the command to submit the batch job and notify the user when it is completed:

focas.com

```
$submit focas_batch/log_file=[user.subdirectory]focas.log/notify/nopr
```

The second file, focas_batch.com, contains the specification for the simulation model to be run, and for the user to be notified by electronic mail when the job is completed.

focas_batch.com

```
$!   .com file for submitting modelxyz. as a batch FOCAS job
$!       Note:  all filespec's MUST contain the full file
$!              specification, including disk id. and directory
$!
$run disk:[user.subdirectory]focas.exe
disk:[user.subdirectory]modelxyz.
$mail /sub="FOCAS modelxyz. completed" nl: nodename::username
```

Focas_batch.com must be editted to reflect the new model name every time a new batch job is to be submitted. The mail message assures that the user will be notified of the completion of the batch job even if he has logged off the system. In addition, the file, [user.subdirectory]focas.log contains all the outputs that are normally written to the screen during an interactive FOCAS run.

VI. EXAMPLES

#1

In this example, a fiber optic cable is driven with a 10110 10010 10101 10011 pattern repeated at a 160 ns interval. The generator 4.4 ns rise and 7.0 ns fall times are critically damped by a TEE as described in Table 1, resulting in the optical transmitter having a 10-90% rise time of 5 ns and a 10-90% fall of 7.3 ns. The optical source has a spectral bandwidth of 126 nanometers, centered at 1291 nanometers.

The 3.38 kilometer fiber optic cable a minimum dispersion wavelength of 1349 nanometers, attenuation of 0.74 db/km, and an intermodal dispersion of 1.127 Ghz-km. The slope of the cable's dispersion curve at 1349 nanometers is 9.09 * 10-5 ns/(nm*2)-km. These characteristics are typical of the 62.5/125 cable tested in the lab.

The fiber output is ac coupled in to a receiver amplifier which makes up for fiber losses and which has a bandwidth of 200 MHz.

Three waveforms (Figure 26) are graphed: the optical transmitter output, the fiber output, and the bandwidth limiting EAMP output. The output graphics vertical display has a magnitude of four volts, as specified in the .END statement by the parameter FS. The value DC=1 in the .END statement indicates that the vertical display is shifted down by 1 volt, to begin at -1.0 volts. Hence the vertical display extends from -1.0 volt to +3.0 volts. The horizontal full scale displacement is 320 nanoseconds, as specified by TX in the .END statement. The output of the optical source has been displaced by 1.9 volts to permit easier viewing. Similarly, the output of the cable has been displaced by 1 volt. FS was chosen to accomodate the full range of values from -1.0 volts to the displaced peaks of the transmitter output.

```
!SIMULATION OF 4 5b PATTERNS THRU 62.5/125 CABLE
!  Bit pattern:  10110 10010 10101 10011, repeats
GEN PW=8 PER=160 TR=4.4 TF=7
GEN PW=16 DEL=16
GEN PW=8 DEL=40
GEN PW=8 DEL=64
GEN PW=8 DEL=80
GEN PW=8 DEL=96
GEN PW=8 DEL=112
GEN PW=16 DEL=144
TEE L1=15 C=0.04 R1=38.73
!  Led tr=5. ns    tf=7.3 ns
.OUT V1=0  DC=1.9
FIBER X=3.38 SO=.0000909 LO=1349 FI=1.127 AO=.74 LC=1291 FW=126
.OUT V1=0. DC=1.
HPF C=.2 R=1000
EAMP GAIN=1.585 BW=.2
.OUT V1= 0                !Receiver bandwidth = 200 Mhz
.END TX=320 DC=1 FS=4
```

#2 USE OF .EYE STATEMENT TO GENERATE EYE PATTERN

In this example, the same physical situation is run as in example 1. A 20 bit pattern is repeated at 160 ns intervals and propagated along a fiber optic cable. Note that the .END statement has been replaced by the .EYE statement to create the Eye Pattern output. In addition, only one .OUT statement may be present when EYE pattern output is requested. The frequency domain calculation is also surpressed.

The parameter, TX in the .EYE statement controls the time scale of the graph. It is generally most useful to set TX equal to a single bit time. However, by reducing TX, one may increase the resolution along the time scale if necessary. Care should be taken to assure that TX is an integral divisor of the bit time.

The value of FS is reduced to increase vertical resolution. This is possible becaue only one waveform, with a magnitude less than one is being graphed.

```
!SIMULATION OF 4 5b PATTERNS THRU 62.5/125 CABLE
! Bit pattern:  10110 10010 10101 10011, repeats
GEN PW=8 PER=160 TR=4.4 TF=7
GEN PW=16 DEL=16
GEN PW=8 DEL=40
GEN PW=8 DEL=64
GEN PW=8 DEL=80
GEN PW=8 DEL=96
GEN PW=8 DEL=112
GEN PW=16 DEL=144
TEE L1=15 C=0.04 R1=38.73
! Led tr=5. ns   tf=7.3 ns
FIBER X=3.38 SO=.0000909 LO=1349 FI=1.127 AO=.74 LC=1291 FW=126
HPF C=.2 R=1000
EAMP GAIN=1.585 BW=.2     !Receiver bandwidth = 200 Mhz
.OUT V1= 0
.EYE TX=8 DC=.5 FS=1
```

This model produces the EYE pattern shown in Figure 27.

APPENDICES

APPENDIX 1 - TIMING JITTER AND PERCENT NOISE MARGIN

The following simulation model requests an EYE pattern output. Only the third .OUT statement will be processed. The first two are preceeded by "!" and will be ignored.

In addition, the first GEN has a DC offset of -0.5 volts which serves to center the enter input waveform about zero volts. The .OUT statement after the BPF model of an optical receiver specifies V1=0 as the threshhold voltage for calculating the timing jitter. In addition, by specifying "DV" in the .OUT statement, the extrema values are computed, and hence, the percent noise margin may be found.

```
!SIMULATION OF 4 5b PATTERNS THRU 62.5/125 CABLE
! Bit pattern:  10110 10010 10101 10011, repeats
GEN PW=8 PER=160 TR=4.4 TF=7  dc=-.5
GEN PW=16 DEL=16
GEN PW=8 DEL=40
GEN PW=8 DEL=64
GEN PW=8 DEL=80
GEN PW=8 DEL=96
GEN PW=8 DEL=112
GEN PW=16 DEL=144
TEE L1=15 C=0.04 R1=38.73
!.OUT DV
! Led tr=5. ns  tf=7.3 ns
FIBER X=3.38 SO=.0000909 LO=1349 FI=1.127 AO=.74 LC=1291 FW=126
!.OUT DV
bpf f1=1U f2=2  s1=6 s2=8
.OUT v1=0 dv
.EYE TX=8 DC=.5
```

If the EYE option were not specified, the output waveform would be the bottom trace in Figure 23.

The output file fibc.dat follows:

CROSSOVER & EXTREMA TIMINGS FOR: fibc.

TIMING ACCURACY IN NANOSECONDS = 0.625

CROSSOVER TIMING IN NANOSECONDS,

NETWORK	10
VOLTAGE	0.000
DELAY	0.000

2.612
1.819
2.612
1.820
2.602
1.913
2.609
1.820
2.609
1.820
2.609
1.821
2.601
1.912

NOTE: Times are wrapped around one bit period of 8 ns for the EYE pattern

TIMING JITTER = 0.0939 0.0107 NS

PERCENT NOISE MARGINS:

NETWORK: 10 % NOISE MARGIN = 65.1786

MAXIMA AND MINIMA TIMING IN NANOSECONDS

NETWORK 10
DELAY 0.000

MAXIMA	MINIMA
3.750	14.464
25.313	38.482
27.500	59.063
45.824	60.000
69.858	78.482
85.824	94.464
101.847	110.491
117.813	132.188
118.750	139.375
153.438	0.000

EXTREMA VALUES IN MILLIVOLTS

NETWORK: 10

1 MAX =	245	MIN =	-167
2 MAX =	245	MIN =	-166
3 MAX =	245	MIN =	-312
4 MAX =	200	MIN =	-312
5 MAX =	200	MIN =	-166
6 MAX =	200	MIN =	-167
7 MAX =	200	MIN =	-167
8 MAX =	199	MIN =	-315
9 MAX =	199	MIN =	-315
10 MAX =	245	MIN =	0

APPENDIX 2 - SAMPLE FOCAS RUN

```
focas

   Fiber Optic CAble Simulator FOCAS
        Revision  21 OCTOBER 86
r the input file name: e63e6.

FOLLOWING OUTPUT FILES WILL BE CREATED:

   e63e6.tg = time domain REGIS file
   e63e6.td = time domain data file

*****************************************************

   ! E6 E6 E6 E6 3 E6 E6 E6 E6  in NRZI  4b5b code
   !  E63E6.
   !  October 8, 1986  -  Ann Ewalt
   GEN PW=8  DEL=16  PER=720 TR=4.4  TF=7.
   GEN PW=8  DEL=56
   GEN PW=16 DEL=72
   GEN PW=8  DEL=96
   GEN PW=8  DEL=136
   GEN PW=16 DEL=152
   GEN PW=8  DEL=176
   GEN PW=8  DEL=216
   GEN PW=16 DEL=232
   GEN PW=8  DEL=256         !ngen=10
   GEN PW=8  DEL=296
   GEN PW=16 DEL=312
   GEN PW=16 DEL=344
   GEN PW=8  DEL=368
   GEN PW=32 DEL=384
   GEN PW=8  DEL=424
   GEN PW=8  DEL=448
   GEN PW=24 DEL=464
   GEN PW=8  DEL=496
   GEN PW=8  DEL=520         !ngen=20
   GEN PW=32 DEL=536
   GEN PW=8  DEL=576
   GEN PW=8  DEL=600
   GEN PW=32 DEL=616
   GEN PW=8  DEL=656
   GEN PW=16 DEL=680
   GEN PW=8  DEL=712         !ngen=27

   TEE R1=38.73 L1=15 C=0.04
   FIBER X=3.38 SO=.0000909 LO=1349 FI=1.127 AO=.74 LC=1291 FW=126
   .OUT V1=0
   .EYE TX=8 fs=1
*****************************************************
```

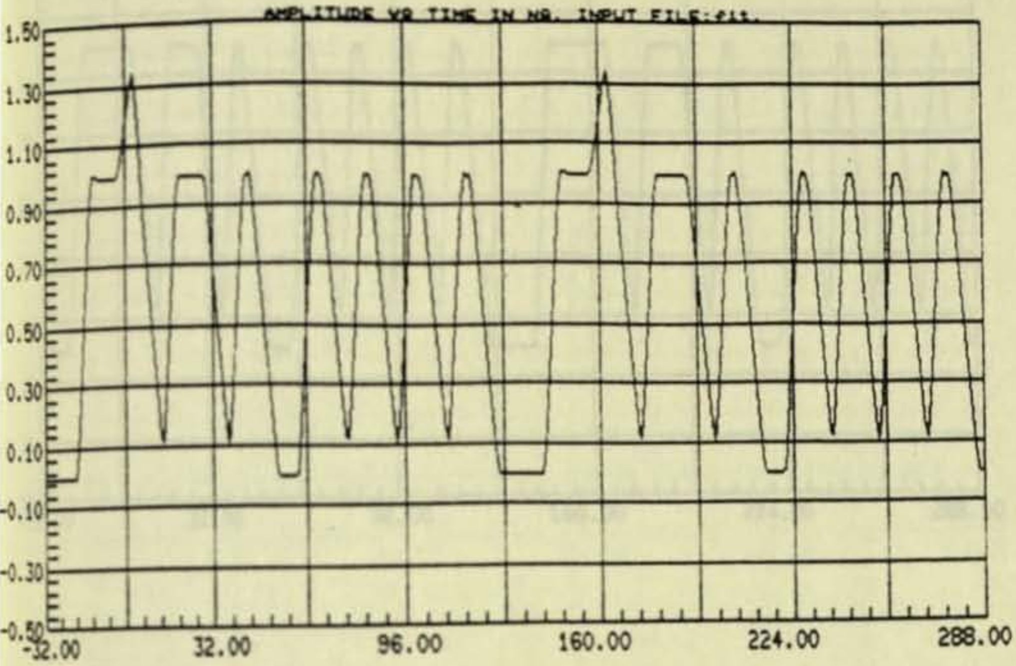
Sample FOCAS Run (cont.)

```
 FREQ. DOMAIN RESPONSE WILL NOT BE   CALCULATED  --  EYE PATTERN REQUESTED

 THERE ARE          1024 FREQ. TERMS TO COMPUTE

FOCAS IS ALIVE & WELL . . . freq term:  180
FOCAS IS ALIVE & WELL . . . freq term:  360
FOCAS IS ALIVE & WELL . . . freq term:  540
FOCAS IS ALIVE & WELL . . . freq term:  720
FOCAS IS ALIVE & WELL . . . freq term:  900

Number of frequency terms computed =          1024


CROSSOVER TIMING IN NANOSECONDS, INPUT FILE: e63e6.

NETWORK       29
VOLTAGE      0.000
DELAY        0.000

             1.592
             7.293
             2.015
             7.435

FORTRAN STOP
```

FIGURES

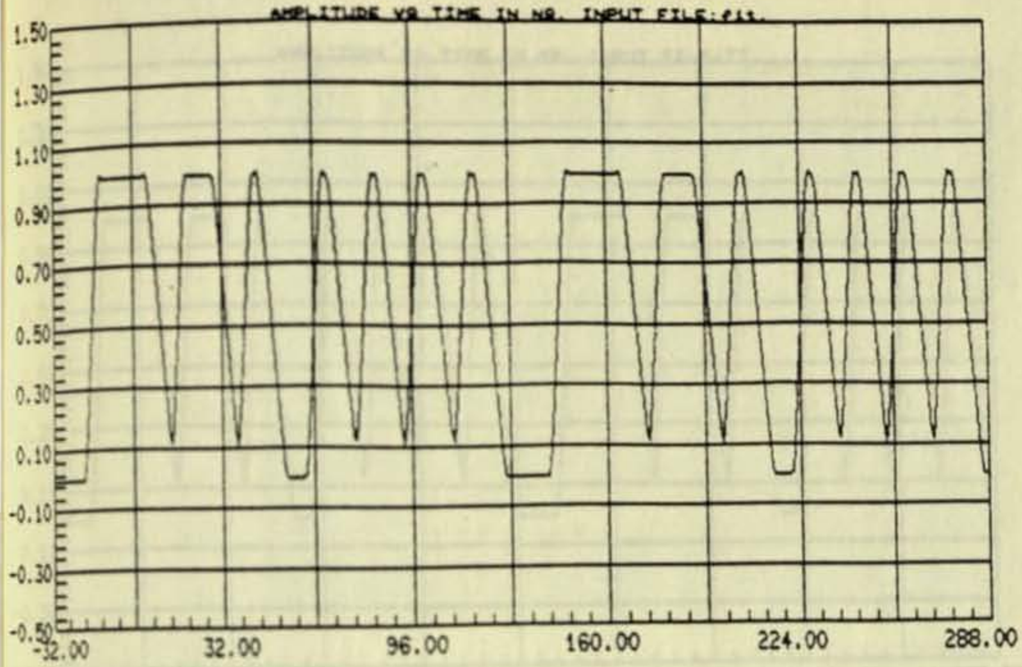
Sample FOCAS Run (cont.)

```
FREQ. DOMAIN RESPONSE WILL NOT BE   CALCULATED  --  EYE PATTERN REQUESTED

THERE ARE          1024 FREQ. TERMS TO COMPUTE

FOCAS IS ALIVE & WELL . . . freq term:  128
FOCAS IS ALIVE & WELL . . . freq term:  256
FOCAS IS ALIVE & WELL . . . freq term:  512
FOCAS IS ALIVE & WELL . . . freq term:  768
FOCAS IS ALIVE & WELL . . . freq term:  896

Number of frequency terms computed =        1024


CROSSOVER TIMING IN NANOSECONDS. INPUT [illegible]

NETWORK          [illegible]
VOLTAGE          0.050
DELAY            0.505

                 [illegible]
                 7.393
                 2.015
                 7.485

FORTRAN STOP
```



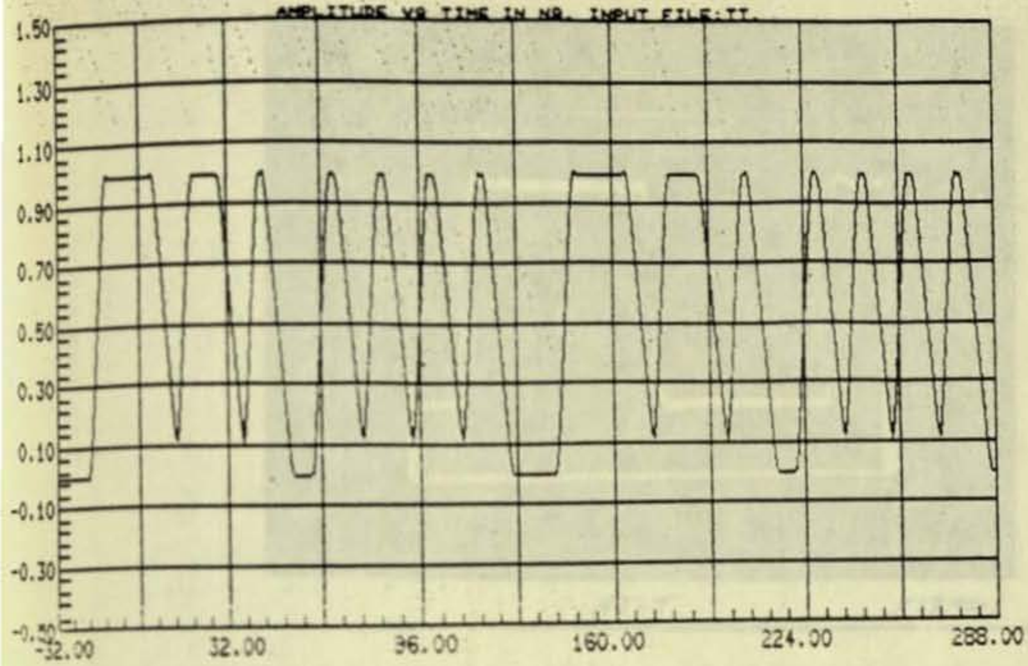

```
!SIMULATION OF 4 5b PATTERN        10110  10010  10101  10011
!
!  First and last pulse generator overlap to give overshoot
!  for the electronic case where voltage sources add
!
 GEN PW=8 PER=160 TR=4.4 TF=7
 GEN PW=16 DEL=16
 GEN PW=8 DEL=40
 GEN PW=8 DEL=64
 GEN PW=8 DEL=80
 GEN PW=8 DEL=96
 GEN PW=8 DEL=112
 GEN PW=16 DEL=144
.out
.END TX=320 DC=.5 FS=2
```

FIGURE 1. OVERSHOOT WITH LEADING & TRAILING ONE s



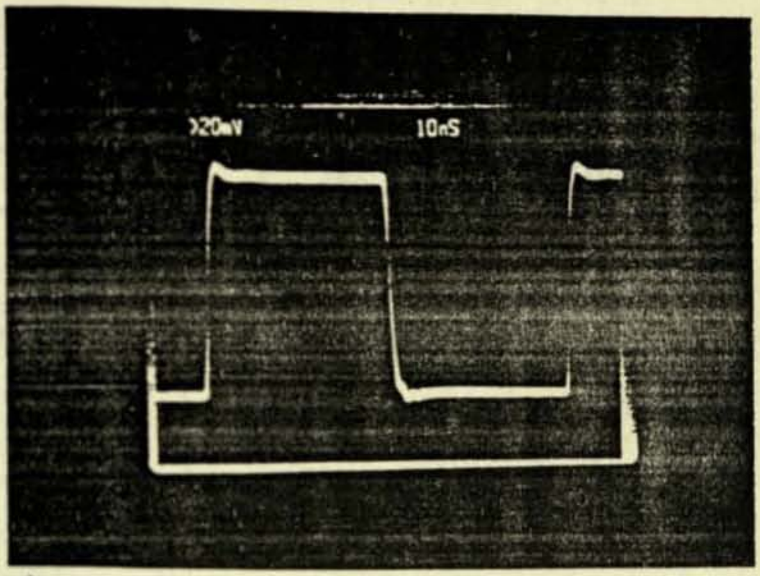

```
!SIMULATION OF 4 5b PATTERN
!
!  First and last pulse generator overlap to give overshoot
!  for the electronic case where voltage sources add, but
!  only result in a single wider pulse for the optical case.
!
 GEN PW=8 PER=160 TR=4.4 TF=7
 GEN PW=16 DEL=16
 GEN PW=8 DEL=40
 GEN PW=8 DEL=64
 GEN PW=8 DEL=80
 GEN PW=8 DEL=96
 GEN PW=8 DEL=112
 GEN PW=16 DEL=144
.out
.END TX=320 DC=.5 FS=2
```

FIGURE 2. OPTICAL SUPERPOSITION OF PULSES



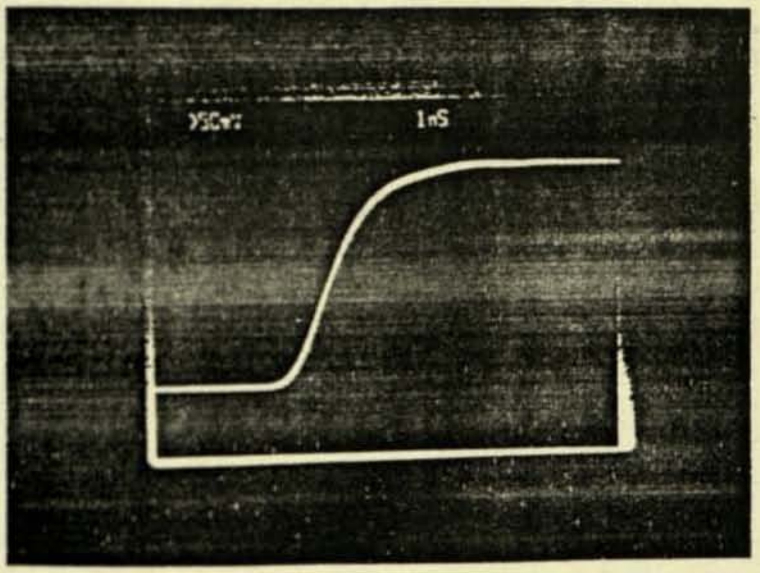

```
!SIMULATION OF 4 5b PATTERNS

  Model changed to elimate overlap of first and last
       generators - equivalent to automatic correction
  performed in FOCAS

GEN PW=16 DEL=16 PER=160 TR=4.4 TF=7.
GEN PW=8 DEL=40
GEN PW=8 DEL=64
GEN PW=8 DEL=80
GEN PW=8 DEL=96
GEN PW=8 DEL=112
GEN PW=24 DEL=144
.out v1=0
.END TX=320 DC=.5 FS=2
```

FIGURE 3. COMBINED GENERATORS (equivalent to Fig. 2)



AT+T pigtail

a) Single slope rising edge



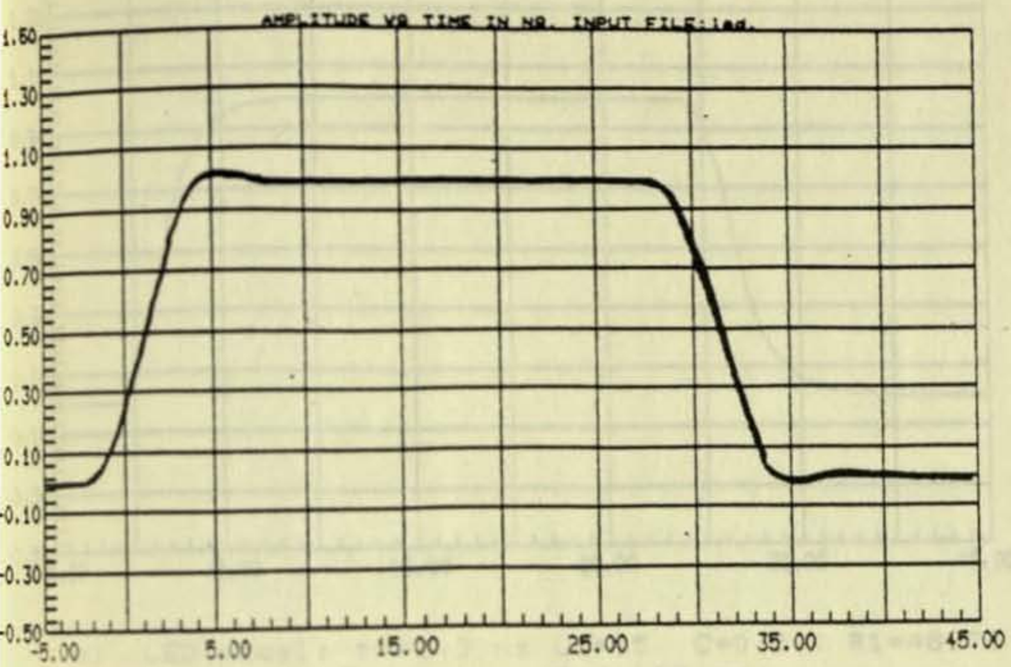
Sumitomo [illegible] HLS [illegible] Tr=2.0ns pigtail

b) Dual slope rising edge

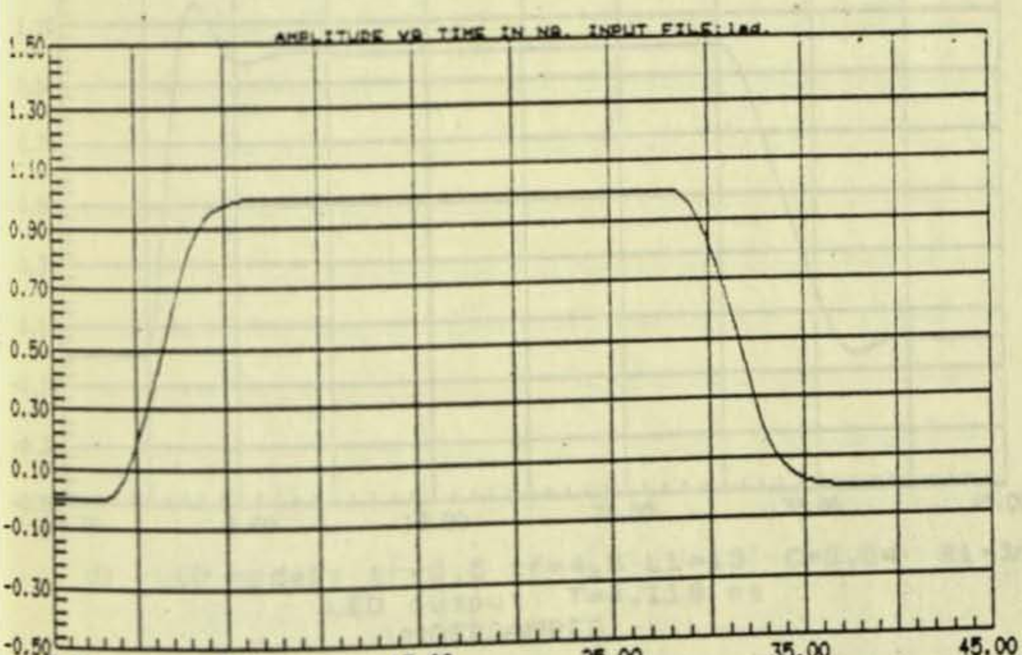
FIGURE 4

```
 ----------
|   #1     |---0-----
|   GEN    |        |
|          |---0-   |    ----------          ----------
 ----------      |  |-0---|   #3     |---0---|          |---0---
                 |  |     |   TEE    |       |  FIBER   |         <------>
 ----------      |  |-0---|          |---0---|          |---0---
|   #2     |---0-   |      ----------          ----------
|   GEN    |        |
|          |---0-   |
 ----------      |  |
     .           |  |
     .           |  |
     .           |  |
 ------------    |  |
| NGEN-th    |--0-- |
|            |      |
|   GEN      |--0---|
|------------|
```

FIGURE 5. BASIC SCHEMATIC



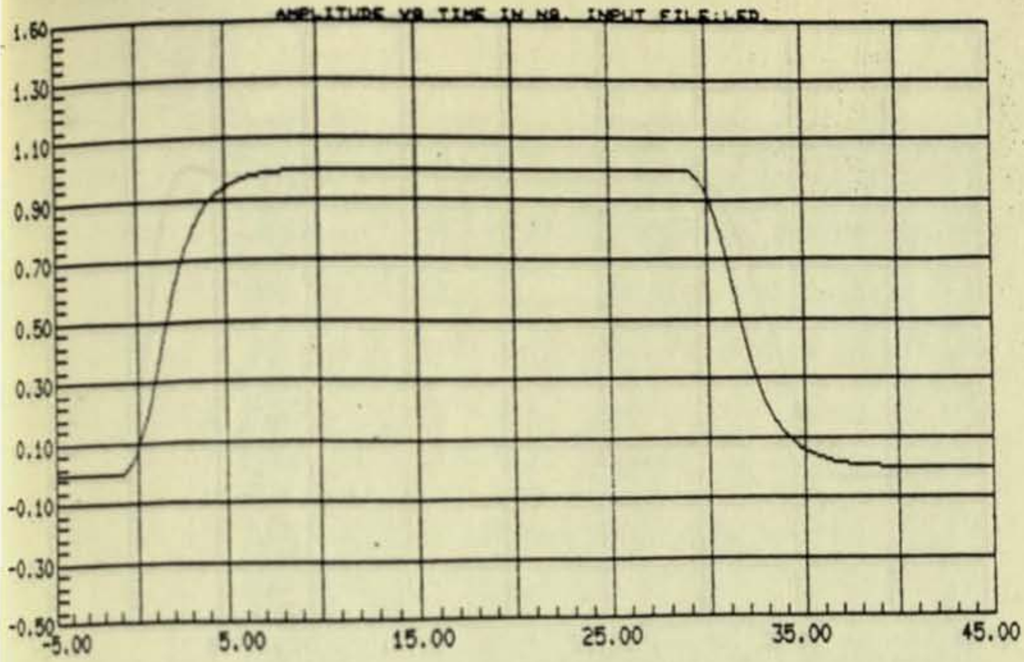
a) LED model: tr=3.95 ns L1=15 C=0.04 R1=28.73
LED output T=4.115 ns



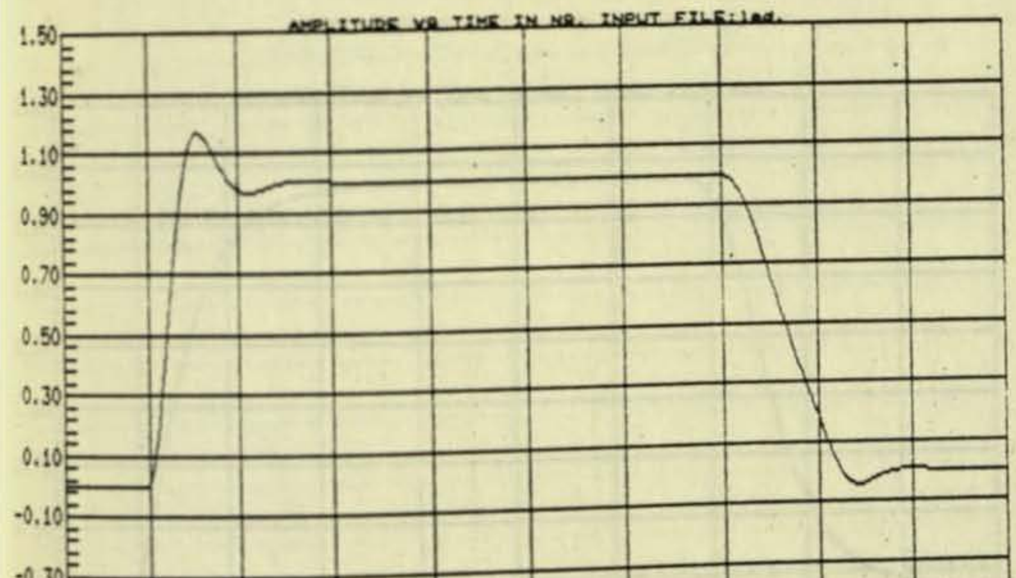
b) LED model: tr=3. 25 ns L1=15 C=0.04 R1=38.73
LED output T=4.115 ns

CRITICALLY DAMPED

FIGURE 6 LED MODEL BEHAVIORS

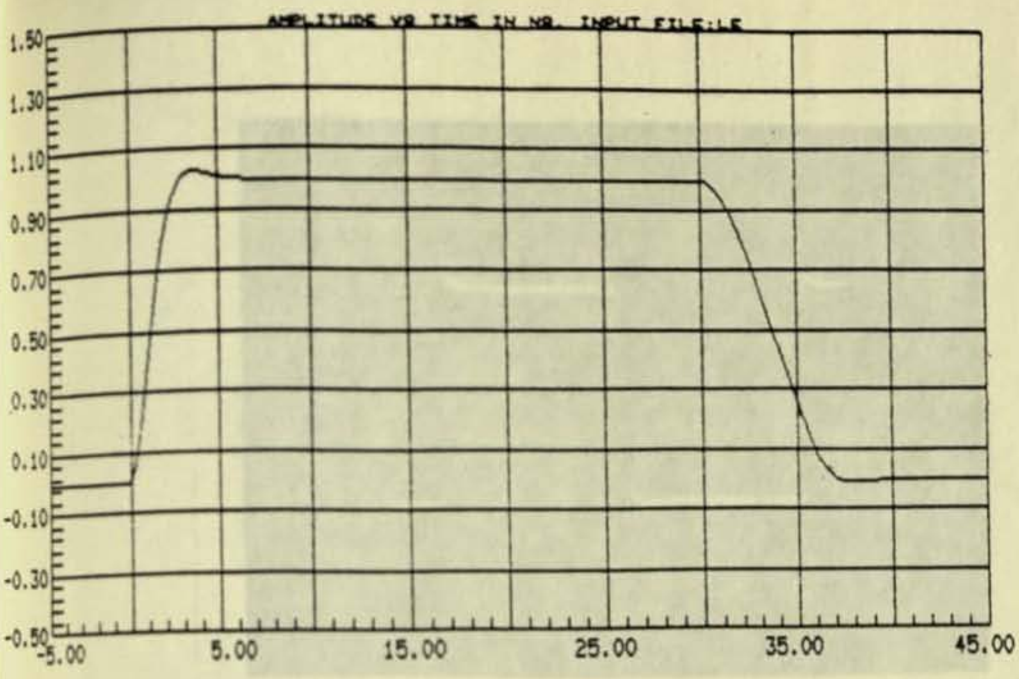


c) LED model: tr=1.9 ns L1=15 C=0.04 R1=48.73
LED output T=4.118 ns
OVERDAMPED

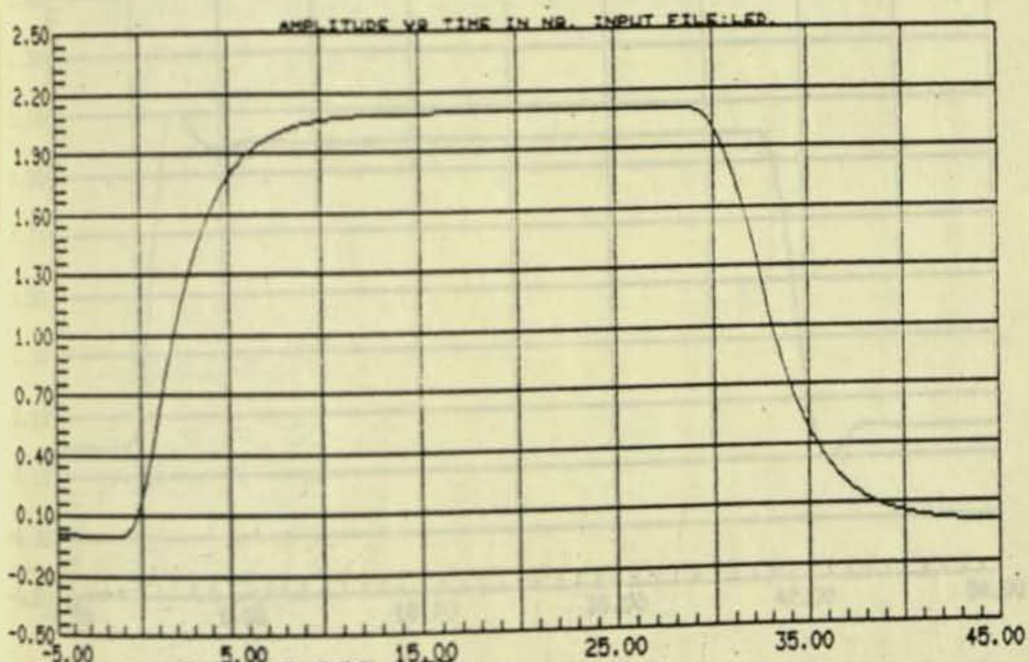


d) LED model: tr=0.5 tf=4.5 L1=15 C=0.04 R1=28.73
LED output T=4.118 ns
UNDERDAMPED

FIGURE 6. LED MODEL BEHAVIORS

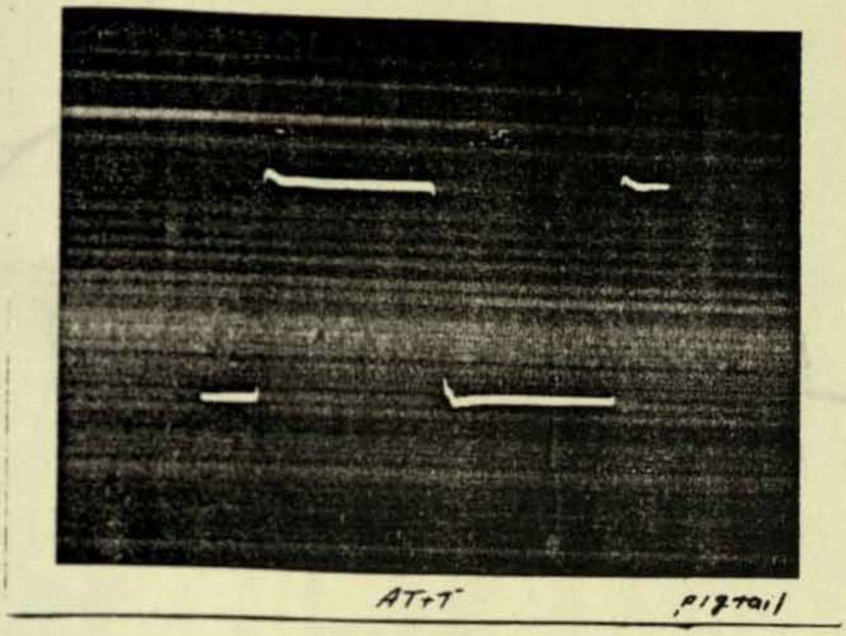


e) LED model: tr=0.5 tf=4.5 L1=15 c=0.04 R1=28.73
LED output: r=1.8ns f=4.6ns

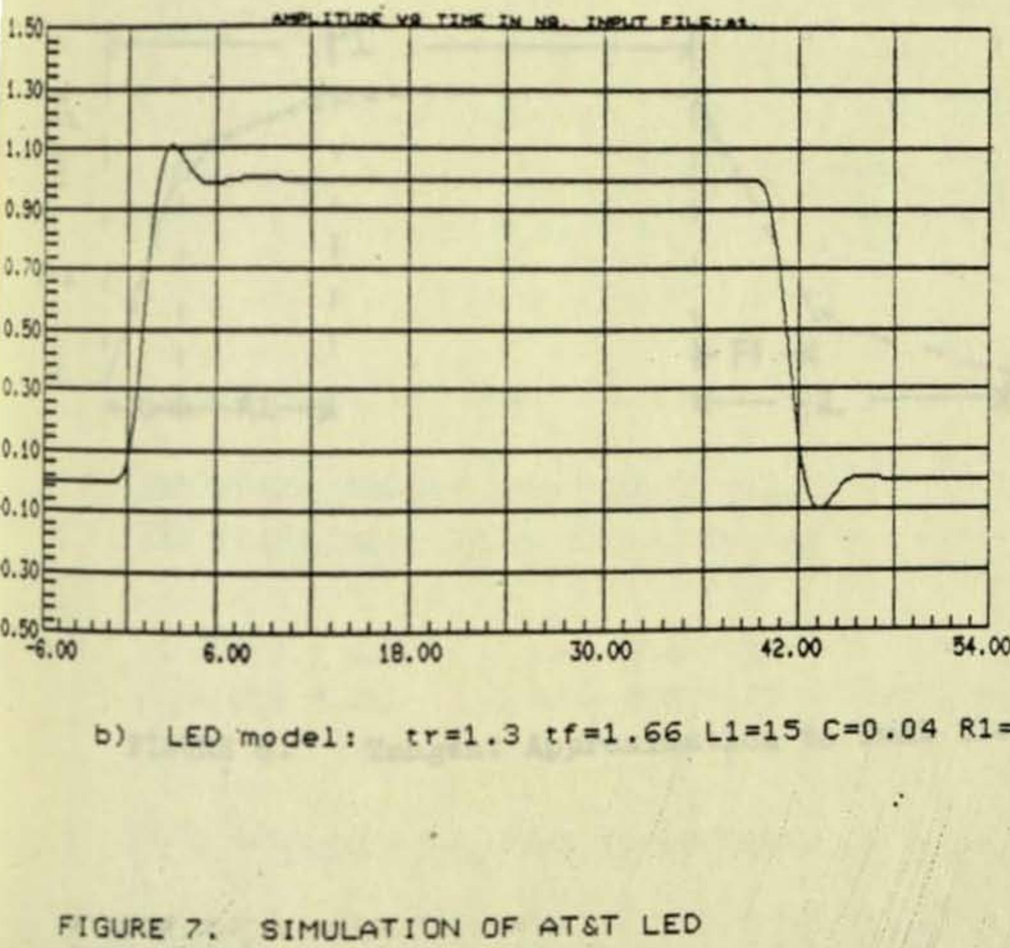


f) DUAL SLOPE LED
gen amp=1.8 pw=30 per=50 tr=1.7 tf=3
gen amp=.3 pw=30 per=50 tr=3.5 tf=5 del=2.
tee r1=38.73 c=0.0

FIGURE 6. LED MODEL BEHAVIORS



a) AT&T LED measurement



b) LED model: tr=1.3 tf=1.66 L1=15 C=0.04 R1=20.

FIGURE 7. SIMULATION OF AT&T LED

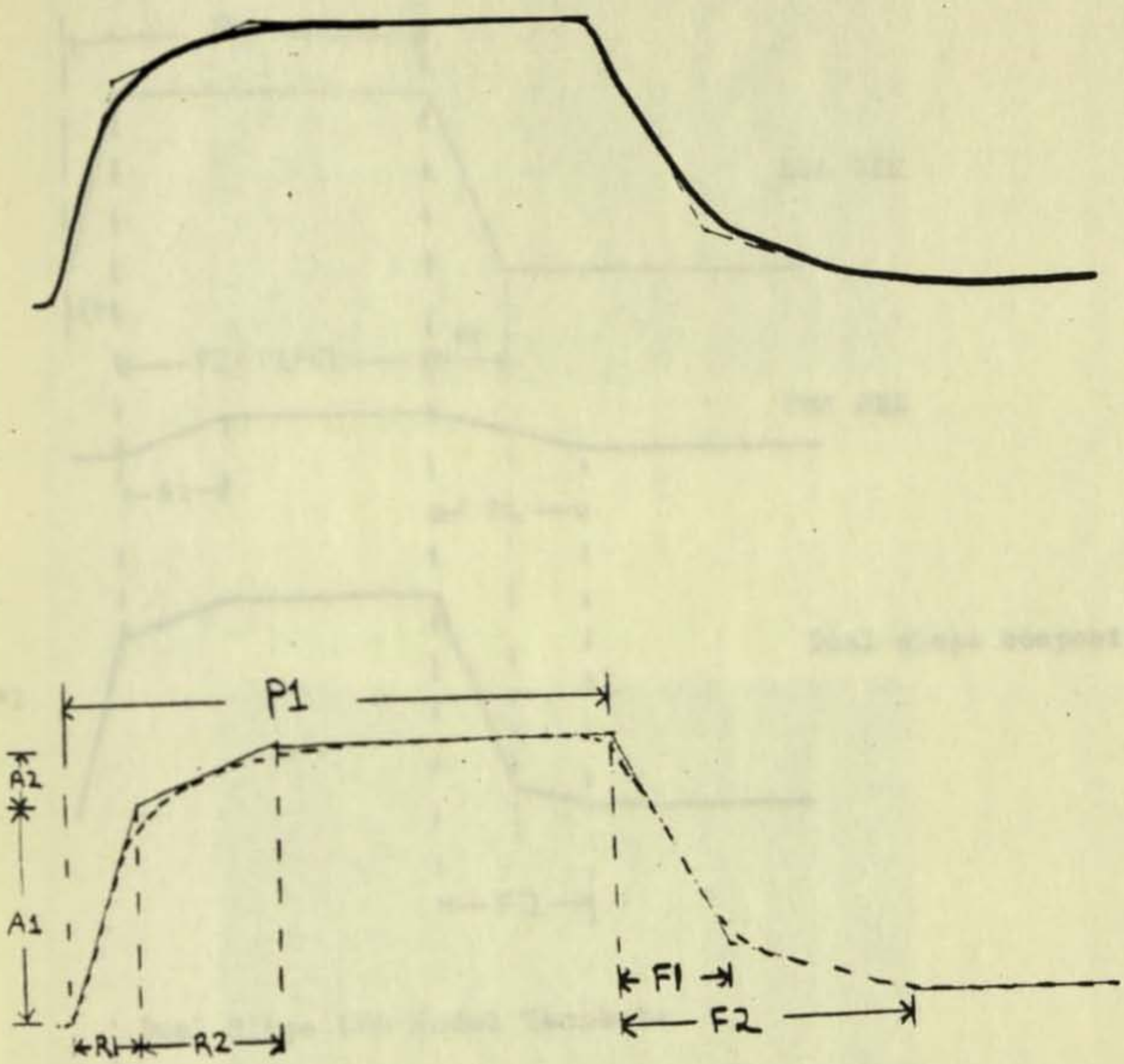
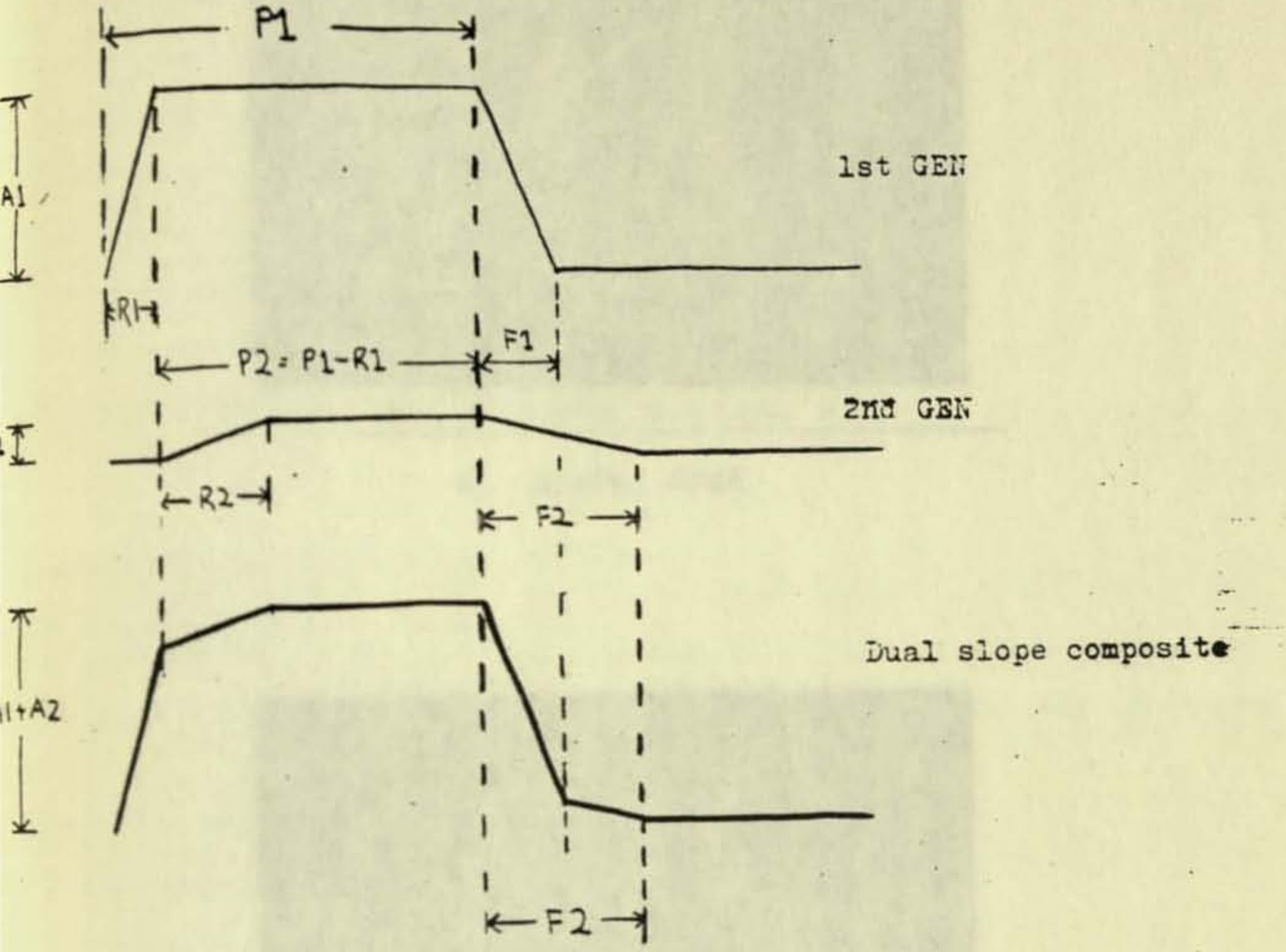


FIGURE 8. Tangent Approximation to Dual Slope Edge

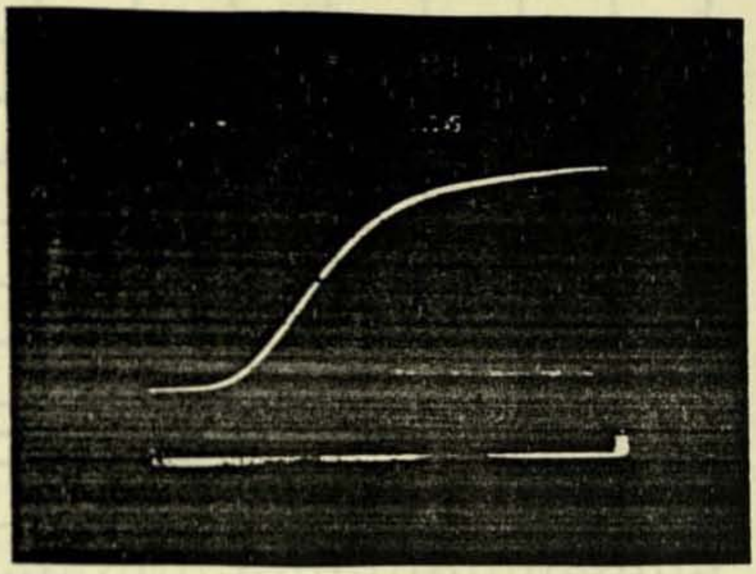



```
! Dual Slope LED Model Template
!
GEN PW=P1 PER=per TR=r1 TF=f1 AMP=A1
GEN PW=P2 TR=r2 TF=f2 AMP=A2 DEL=R1
```

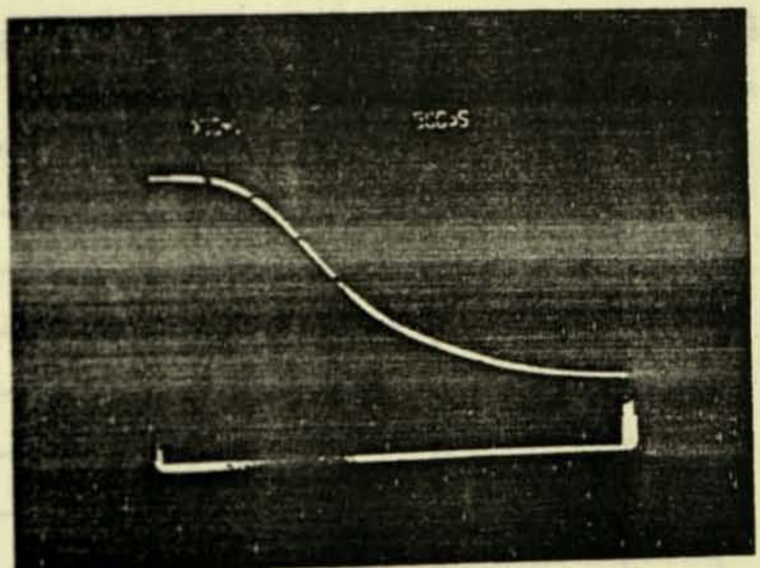
r1 = 0.8 * R1 r2 = 0.8 * R2

f1 = 0.8 * F1 f2 = 0.8 * F2 P2 = P1-R1

Figure 9. Dual Slope Model

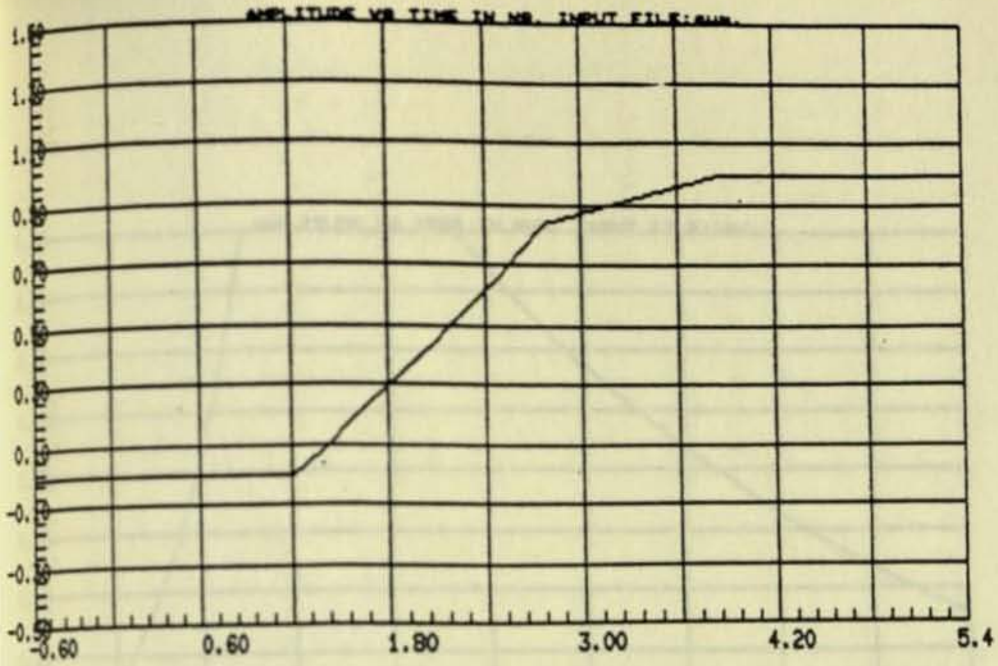


a) Rising Edge



b) Falling Edge

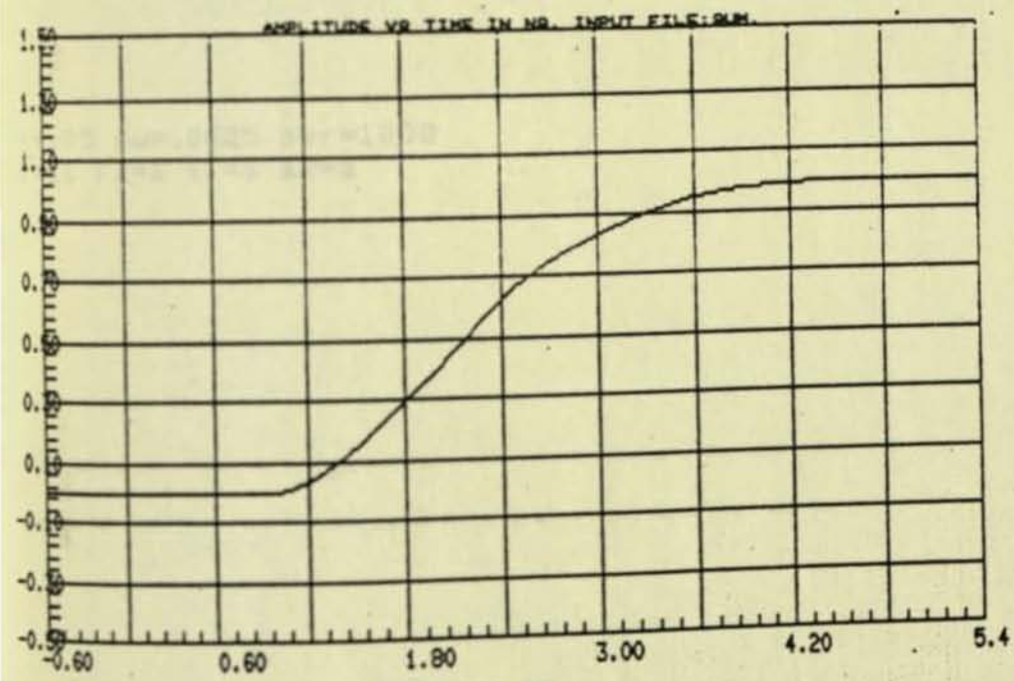
FIGURE 10. SUMITOMO OBSERVATIONS



a) Default Bandwidth on GEN's

IMULATION OF DUAL SLOPE SUMOTOMO LED

PW=40 PER=80 TR=1.2 TF=1.44 amp=.8
pw=40 per=80 tr=1.1 tf=2.8 amp=.2 del=1.2
to=78
tx=6 dc=.5 fs=2 !Scale adjusted to be comparable to that of Figure 10

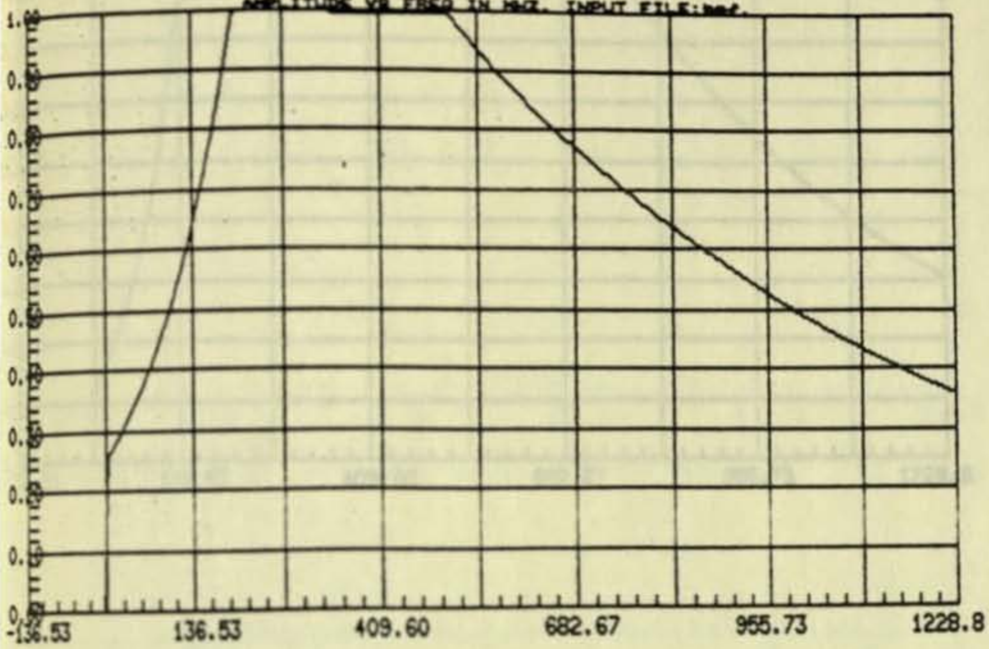


b) GEN Bandwidth = 400 MHz

SIMULATION OF DUAL SLOPE SUMOTOMO LED

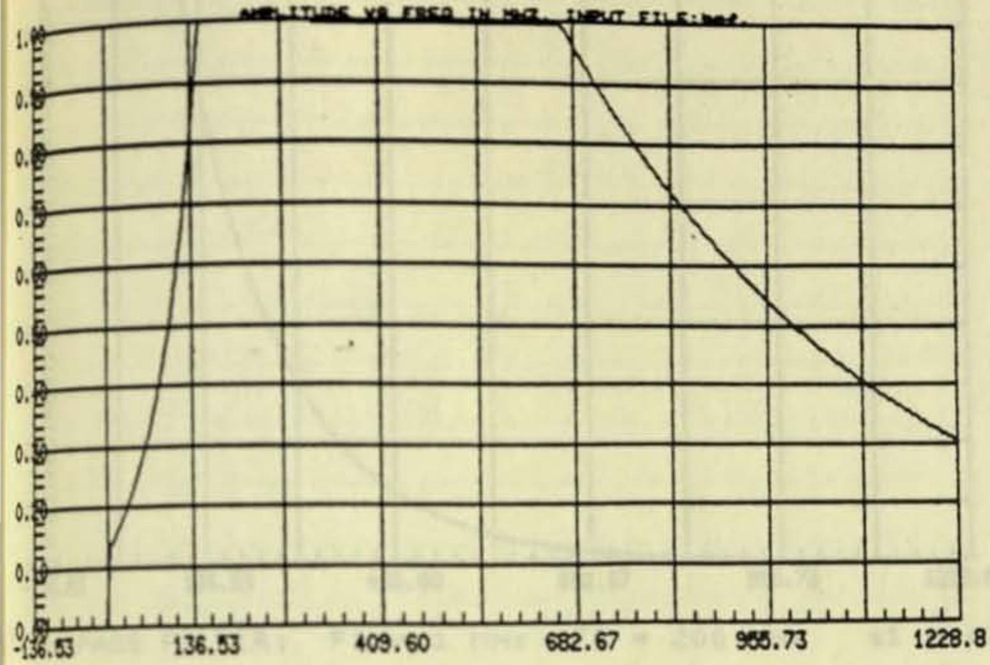
PW=40 PER=80 TR=1.2 TF=1.44 amp=.8 bw=.4
pw=40 per=80 tr=1.1 tf=2.8 amp=.2 del=1.2
t to=78
d tx=6 dc=.5 fs=2 !Scale adjusted to be comparable to that of Figure 10

FIGURE 11.



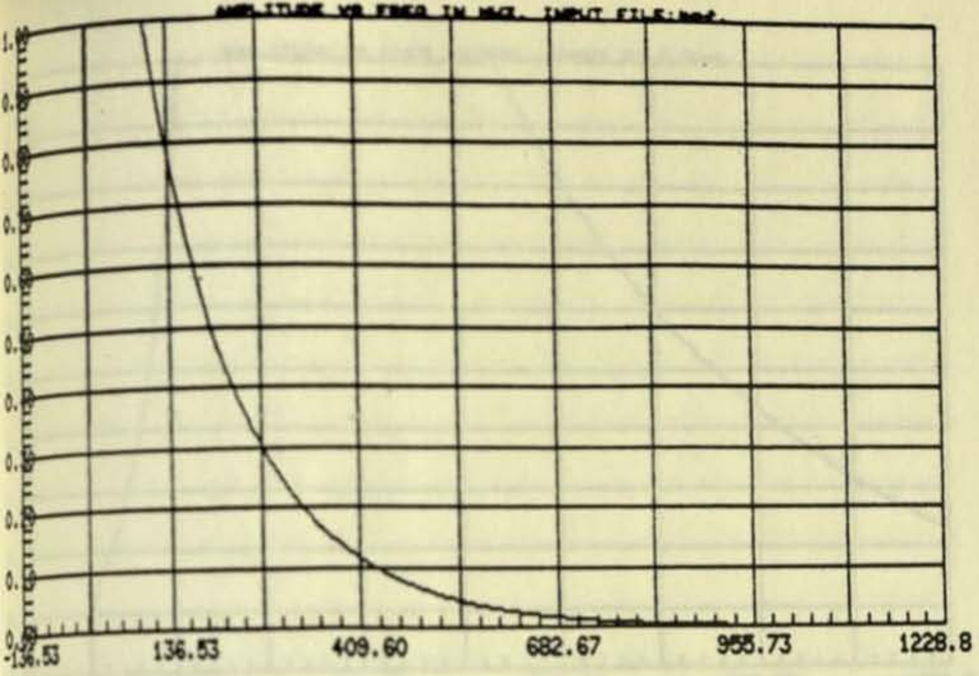
tr=.05 pw=.0625 per=1000
F1=.1 F2=1 s1=3 s2=3

FIGURE 12

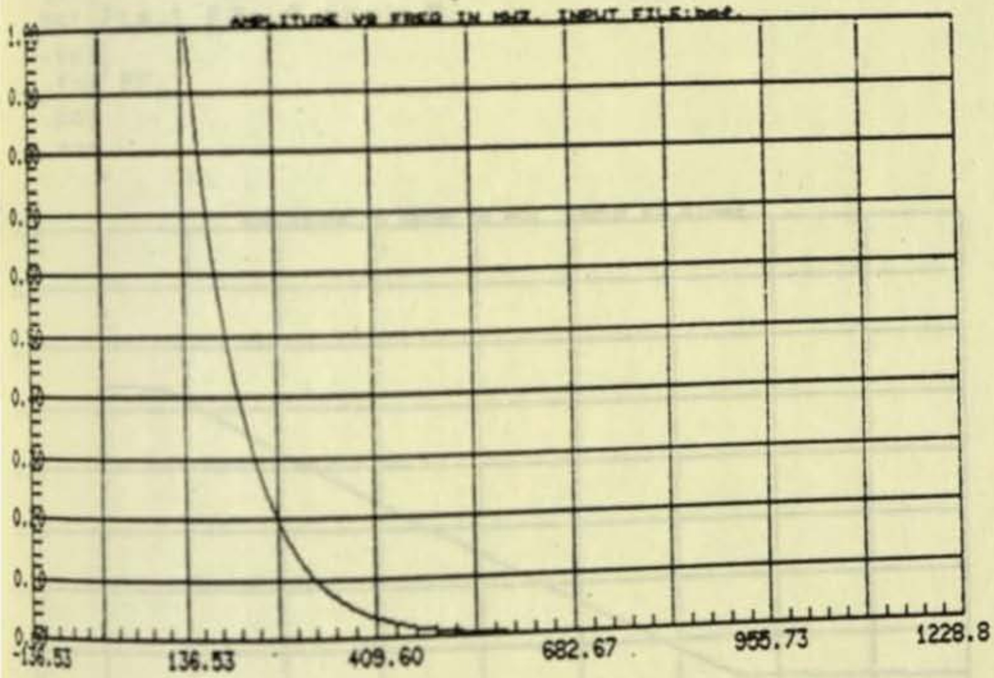


tr=.05 pw=.0625 per=1000
F1=.1 F2=1

FIGURE 13a

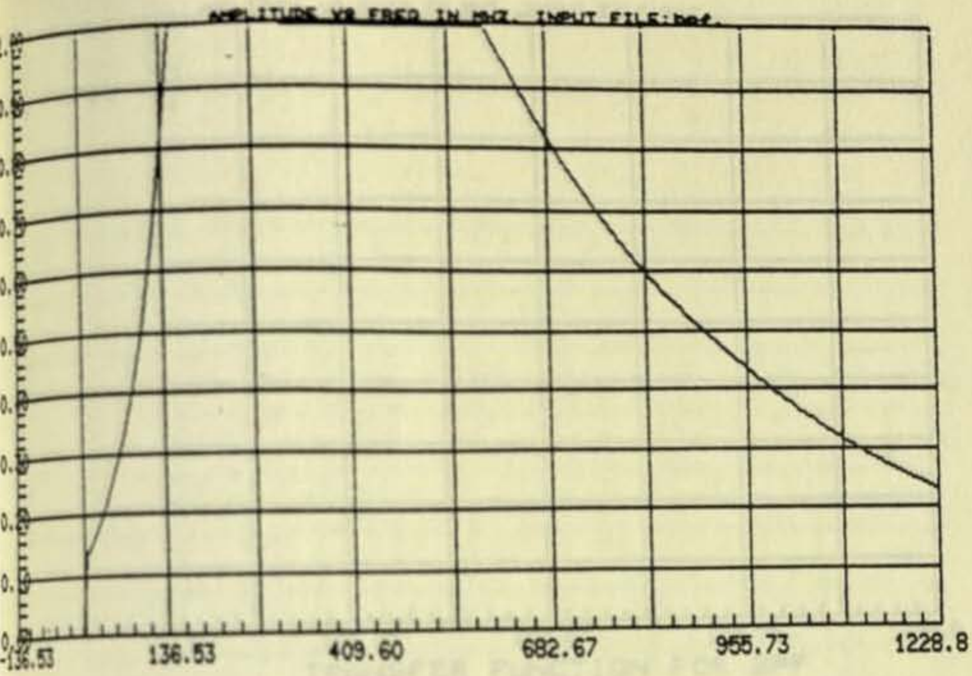


BANDPASS FILTER: F1 = 1 MHz F2 = 200 MHz s1 = s2 = 3 dB/octave



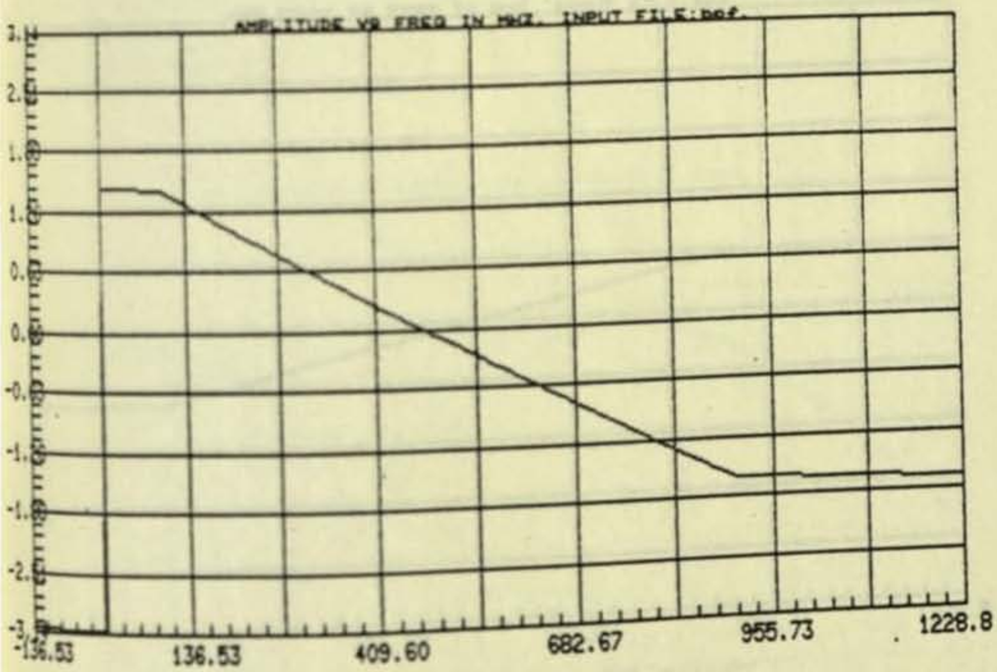
BANDPASS FILTER: F1 = 1 MHz F2 = 200 MHz s1 = s2 = 8 dB/octave

FIGURE 13



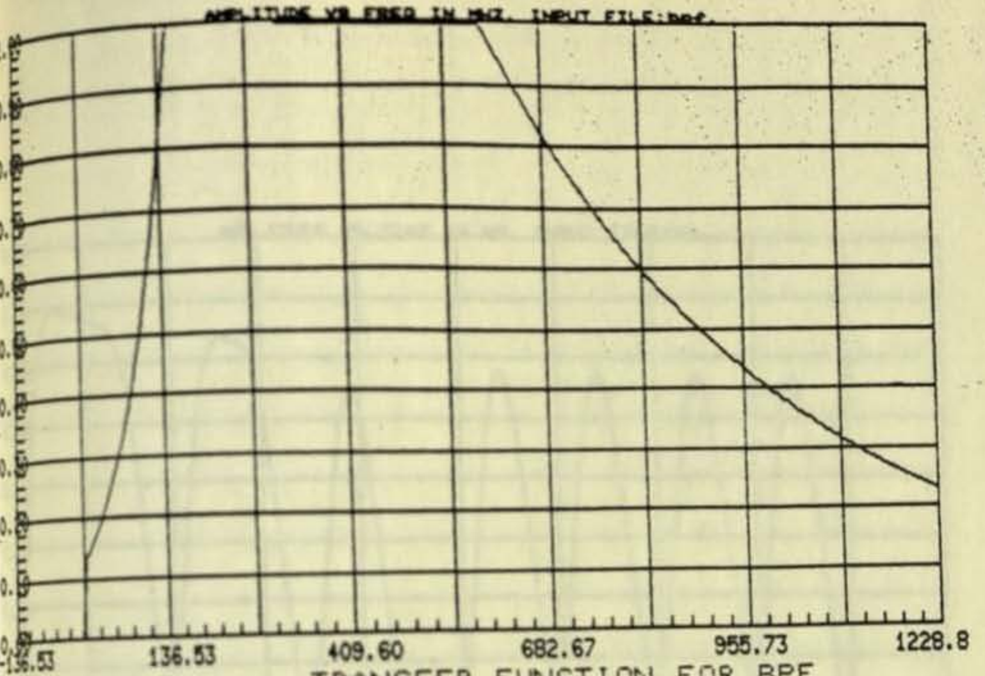
TRANSFER FUNCTION OF BPF

```
gen tr=.05 pw=.0625 per=1000
bpf F1=.1 F2=.9 ph=1.5
.out
.fdg FF
.pdg
.end
```



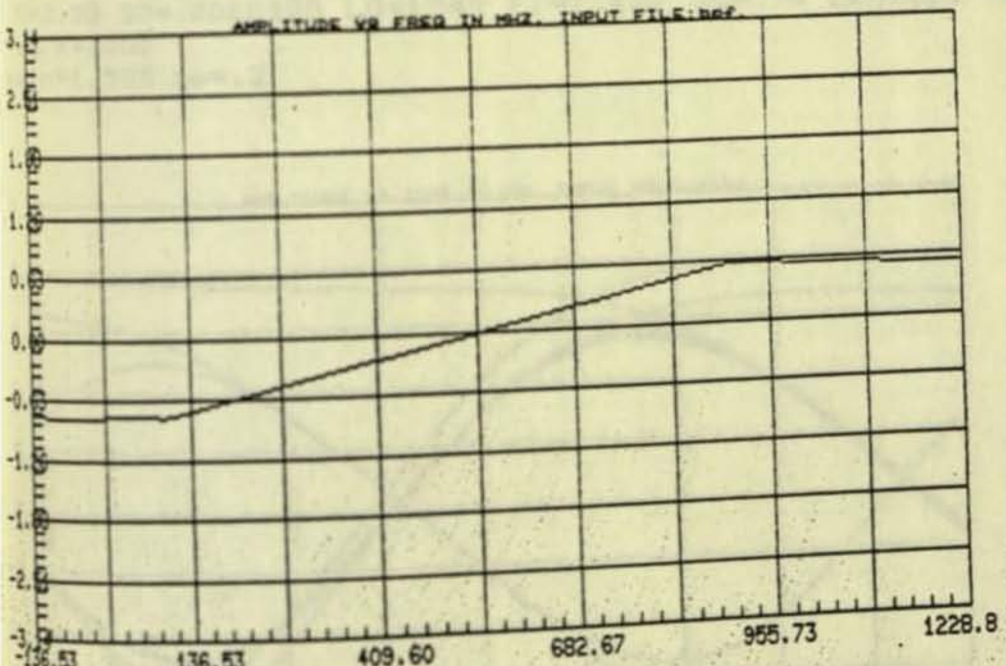
PHASE SHIFT FOR BPF

FIGURE 14a. BPF TRANSFER AND PHASE CHARACTERISTICS



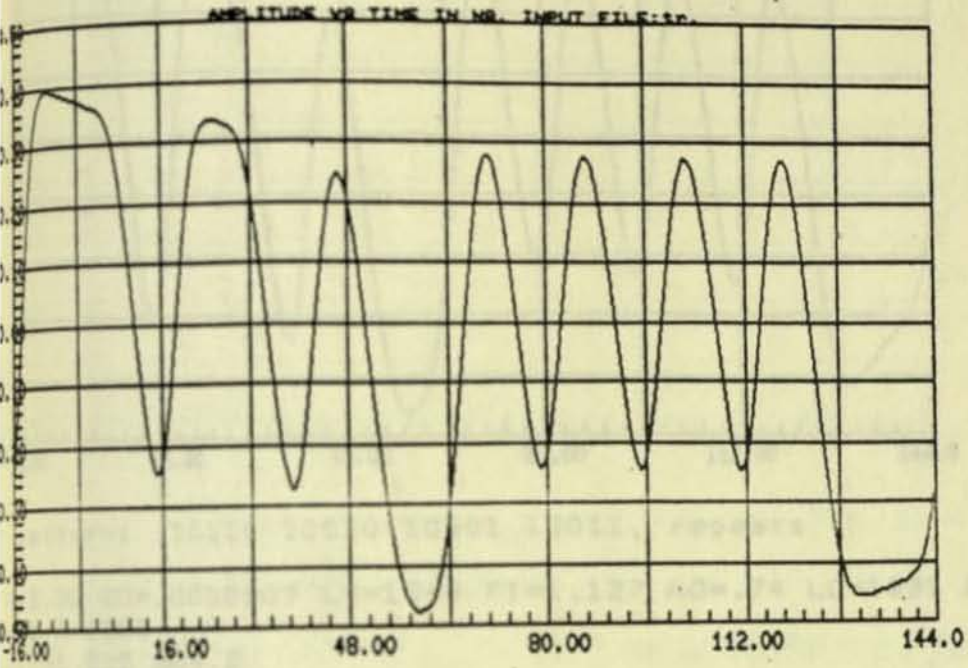
TRANSFER FUNCTION FOR BPF

```
gen tr=.05 pw=.0625 per=1000
bpf F1=.1 F2=.9 ph=-.785
.out
.fdg FF
.pdg
.end
```



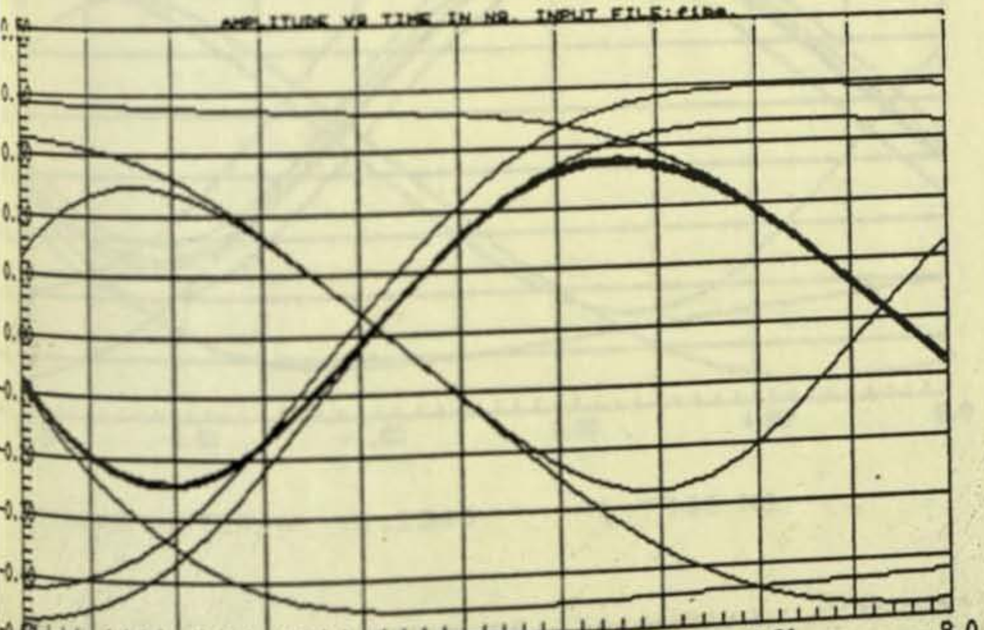
BPF PHASE SHIFT

FIGURE 14b. BPF TRANSFER AND PHASE CHARACTERISTICS



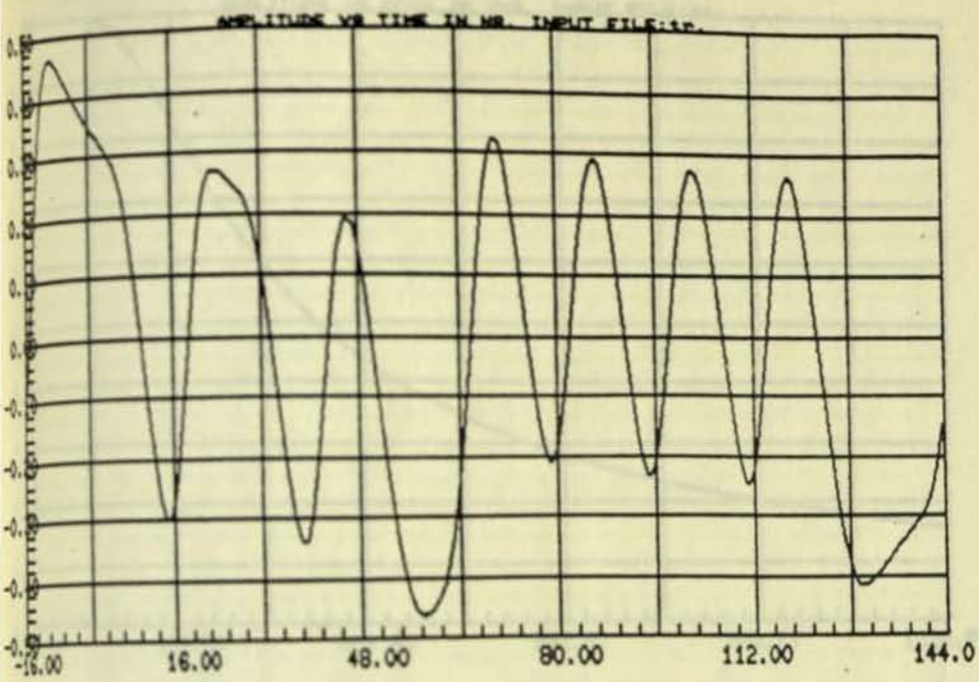
t pattern: 10110 10010 10101 10011, repeats

X=3.38 SO=.0000909 LO=1349 FI=1.127 AO=.74 LC=1291 FW=126
=.2 R=1000
gain=1.585 bw=.2



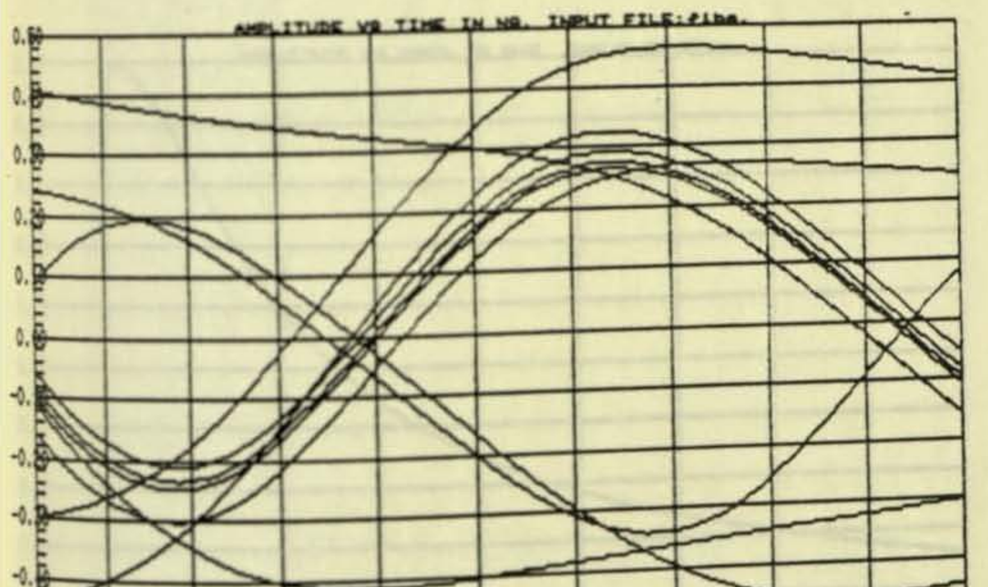
TIMING JITTER = 0.6051 0.3797 NS

FIGURE 15



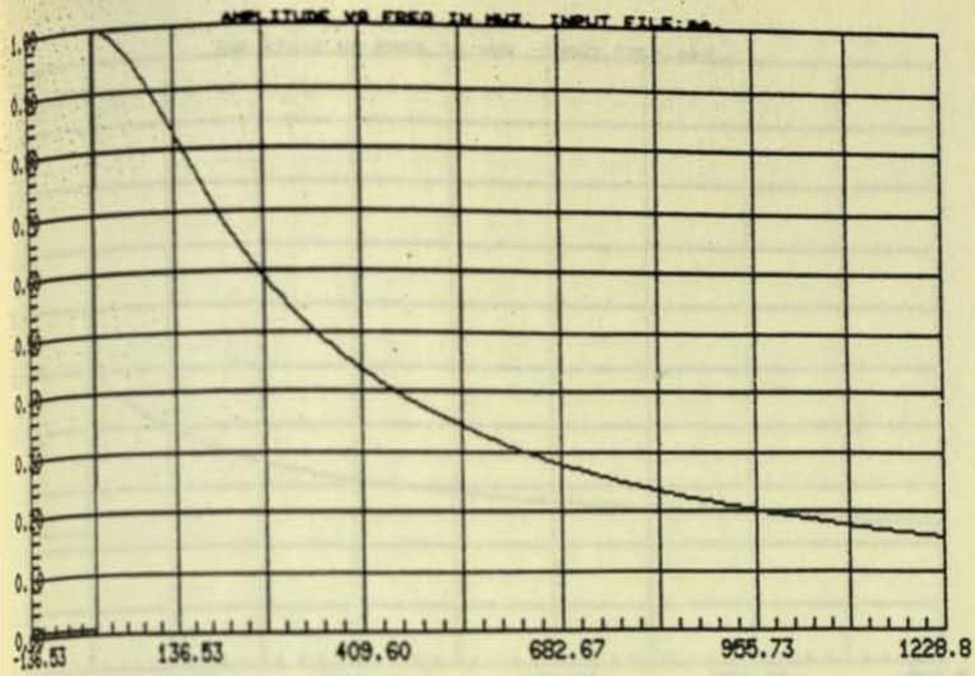
it pattern: 10110 10010 10101 10011, repeats

R X=3.38 SO=.0000909 LO=1349 FI=1.127 AO=.74 LC=1291 FW=126
C=.05 R=1000
gain=1.585 bw=.2



TIMING JITTER = 2.1549 1.7868 NS

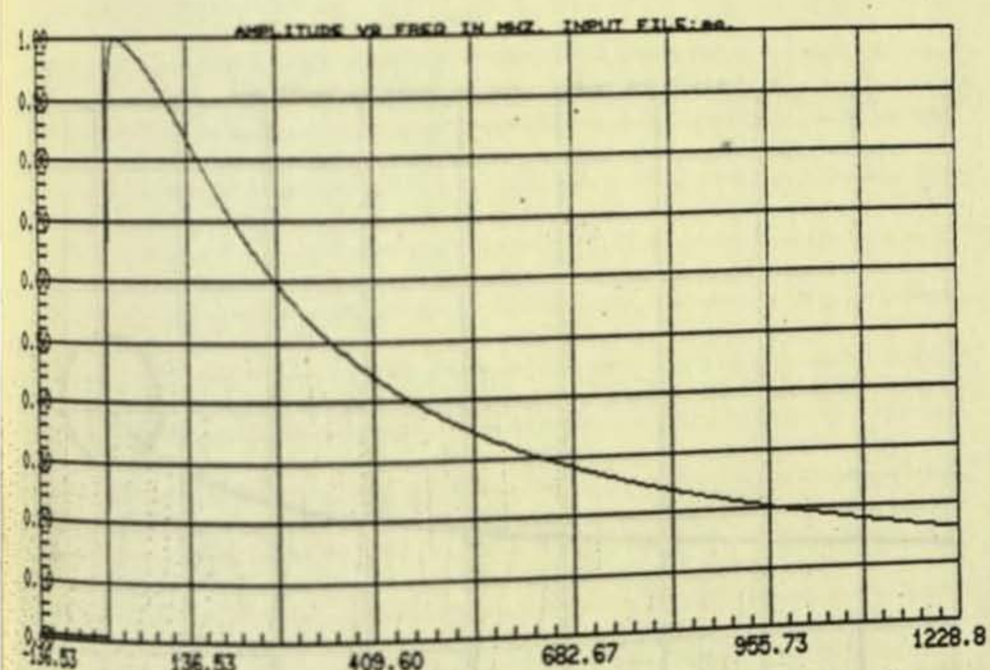
FIGURE 16



ODEL OF OPTICAL RCVR USING AC COUPLER & EAMP FOR GAIN

tr=.05 pw=.0625 per=1000 R=1000
C=.2 R=1000
GAIN=1.585 BW=.2

TJ = 0.605   0.308 ns

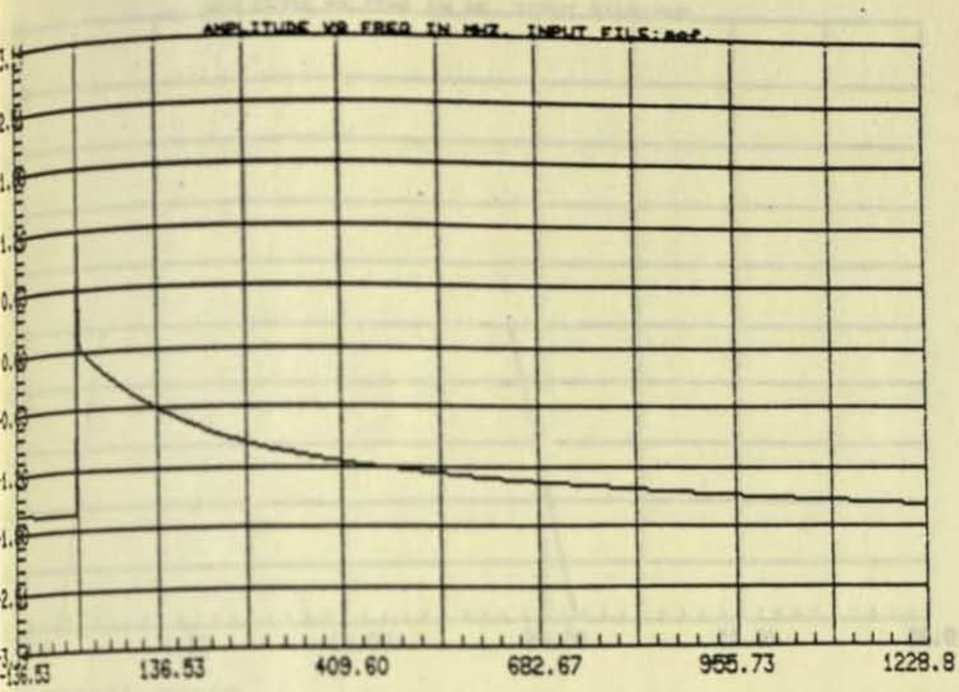


MODEL OF OPTICAL RCVR USING AC COUPLER & EAMP FOR GAIN

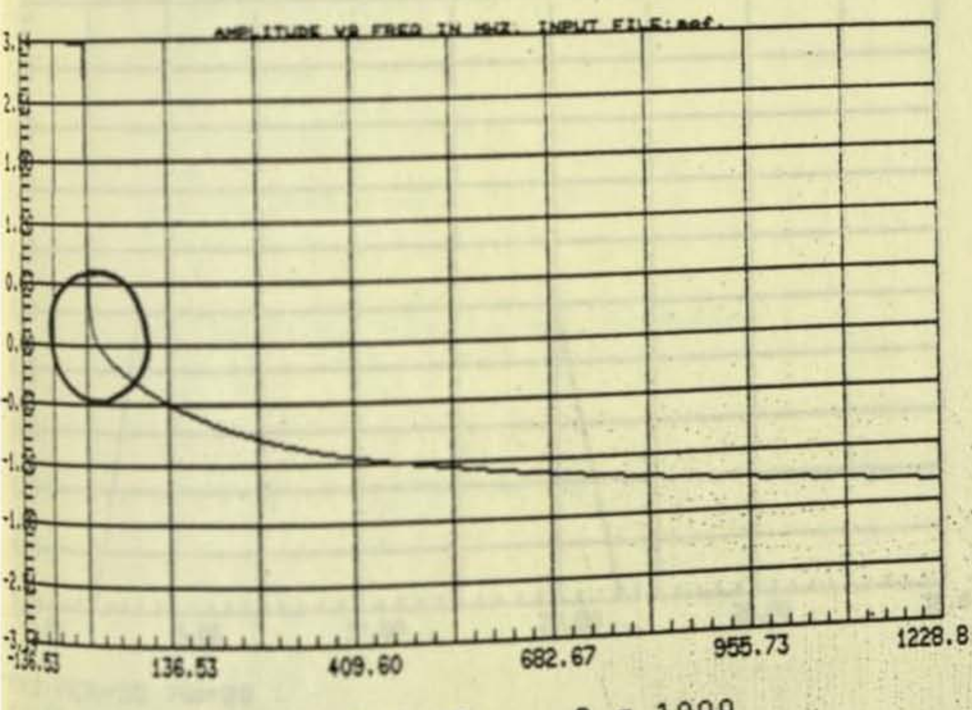
tr=.05 pw=.0625 per=1000 R=1000
C=.05 R=1000
GAIN=1.585 BW=.2

TJ = 2.15   1.79

FIGURE 17

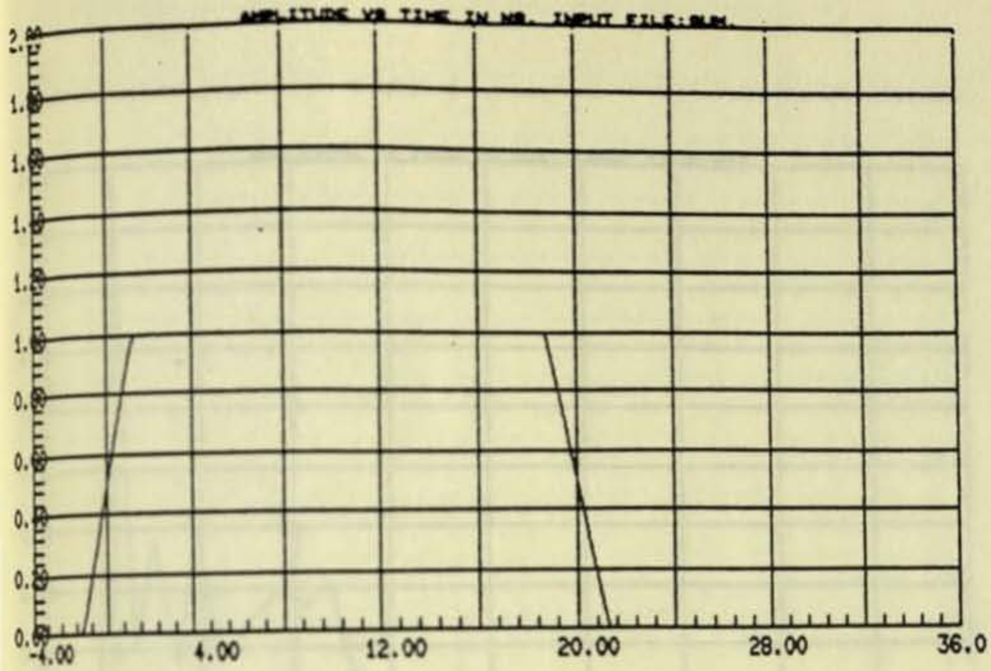


MODEL OF OPTICAL RCVR USING AC COUPLER & EAMP FOR GAIN
r=.05 pw=.0625 per=1000 amp=2 r=1000
=.2 r=1000
gain=1.585 bw=.2



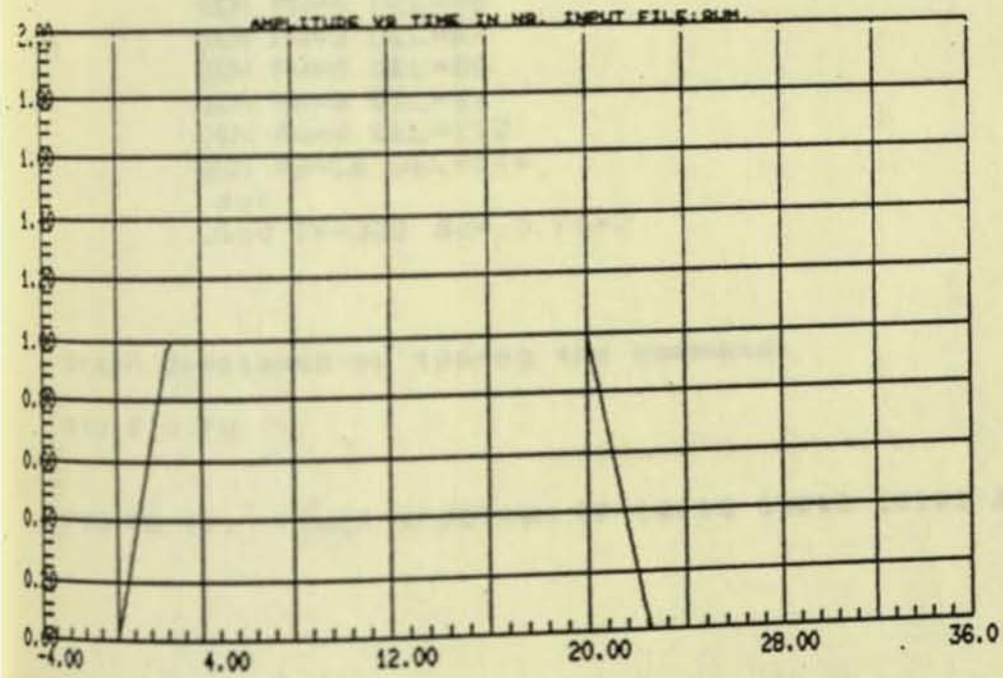
C = 0.05 R = 1000

FIGURE 18. PHASE SHIFT IN RADIANS VS. FREQUENCY IN MHZ



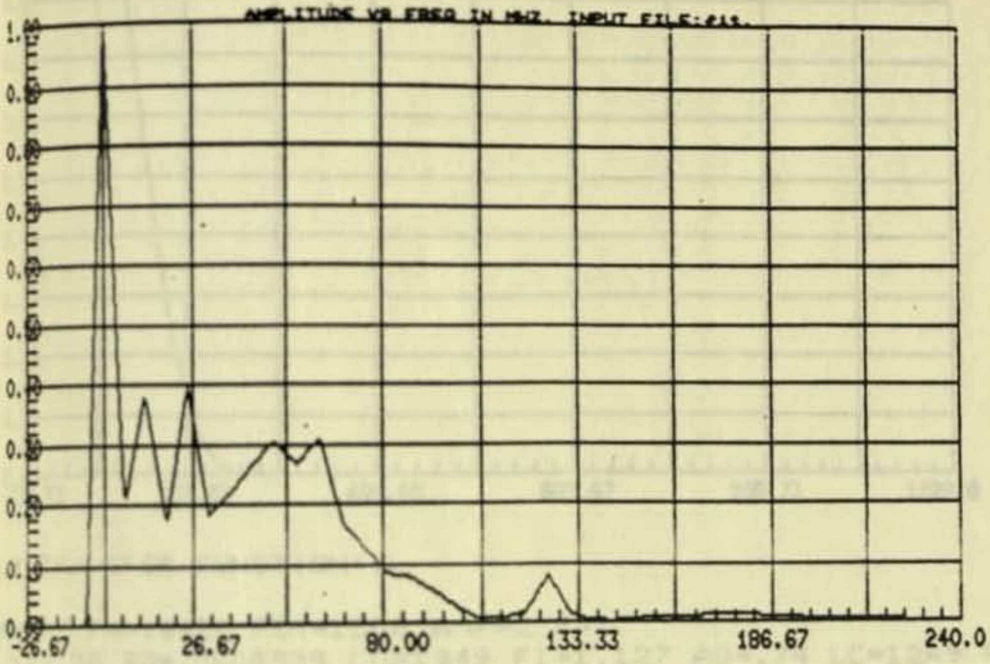
TR=2 PER=50 PW=20

TX=40



TR=2 PER=50 PW=20
T0=48.75
TX=40

FIGURE 19



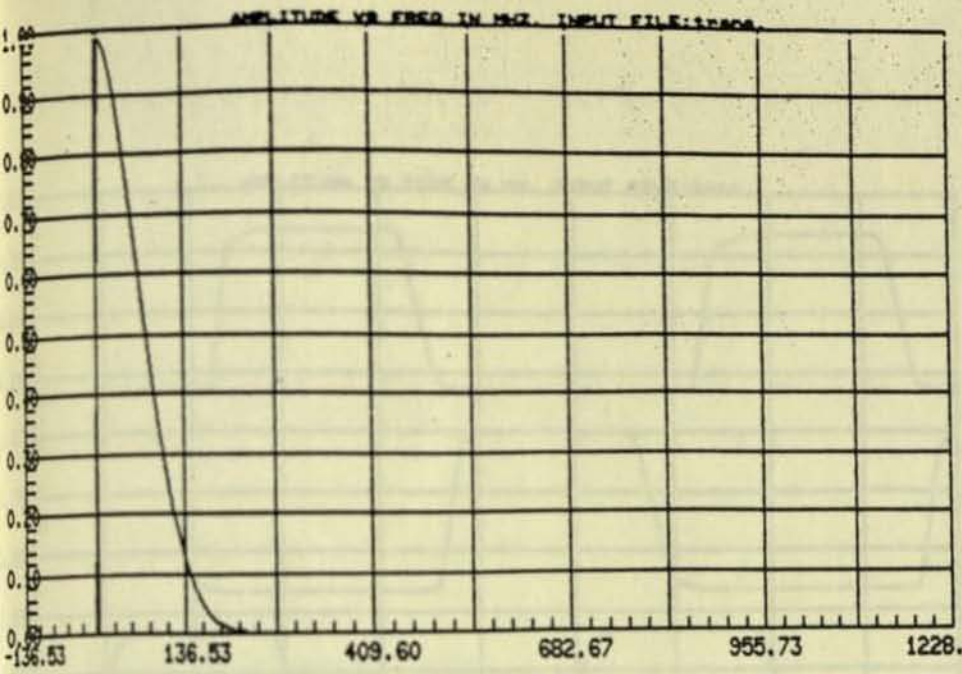
fit.fg for the model fit. below:

```
!SIMULATION OF 4 5b PATTERNS THRU 62.5/125 CABLE
GEN PW=8 PER=160 TR=4.4 TF=7
GEN PW=16 DEL=16
GEN PW=8 DEL=40
GEN PW=8 DEL=64
GEN PW=8 DEL=80
GEN PW=8 DEL=96
GEN PW=8 DEL=112
GEN PW=16 DEL=144
.out
.End TX=320 dc=.5 FS=2
```

Graph displayed by typing the command:

$ty fit.fg

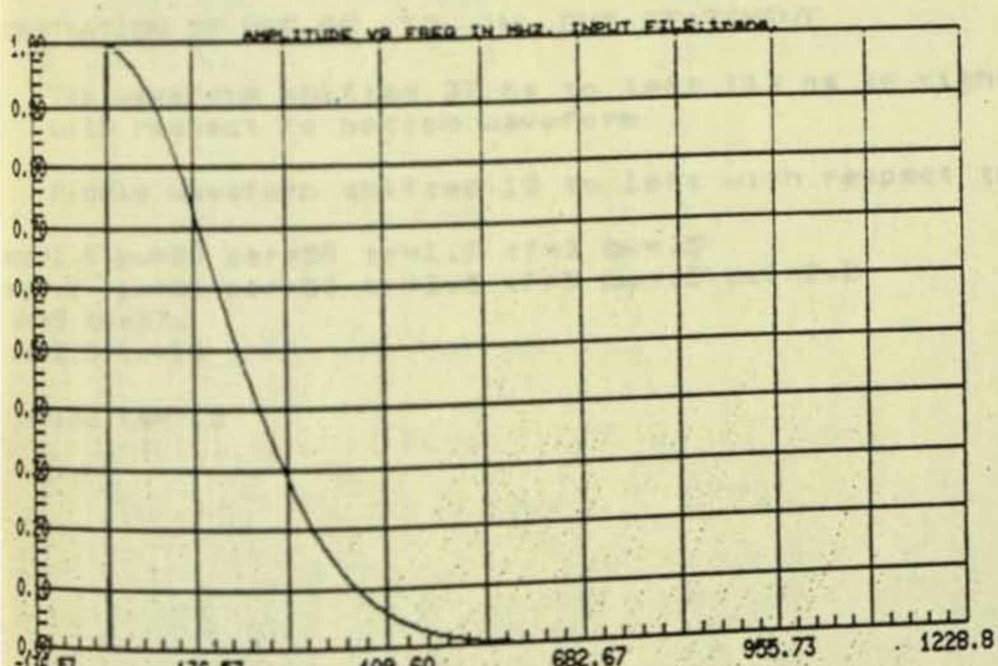
FIGURE 20. POWER SPECTRUM OF 10110 10010 10101 10011 PATTERN



LE TRANSFER FUNCTION's

R=.05 PW=.0625 PER=1000 AMP=2 R=1
X=3.38 SO=.0000909 LO=1349 FI=1.127 AO=.74 LC=1249 FW=126

TX=6 DC=.5 FS=3.

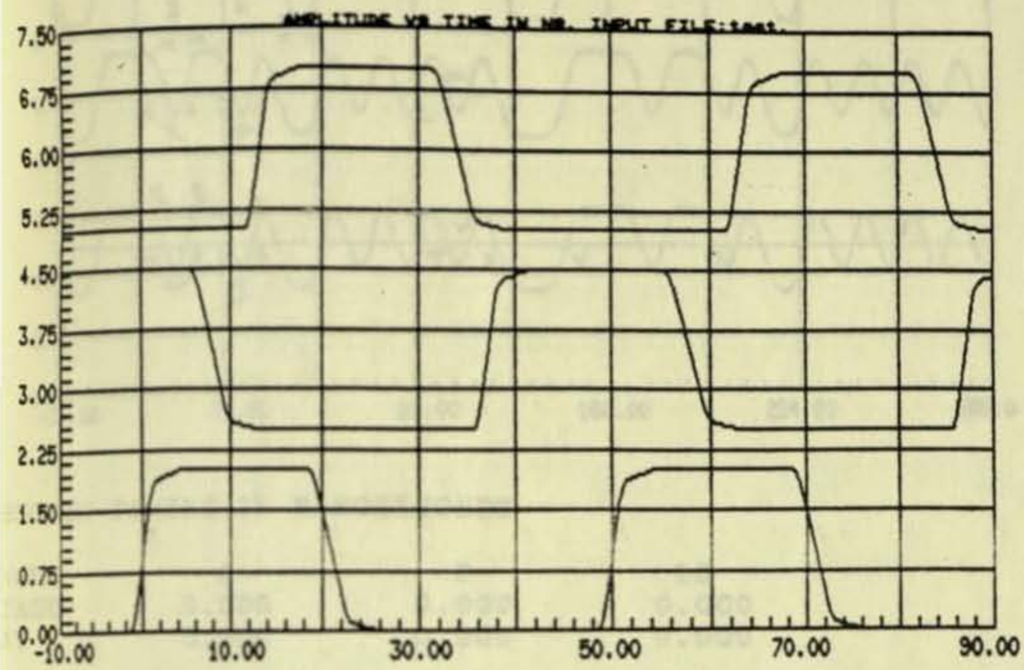


BLE TRANSFER FUNCTION's

TR=.05 PW=.0625 PER=1000 AMP=2 R=1
R X=3.38 SO=.0000909 LO=1249 FI=1.127 AO=.74 LC=1249 FW=126

TX=6 DC=.5 FS=3.

FIGURE 21. Variation in optical fiber bandwidth with (Lo-Lc)



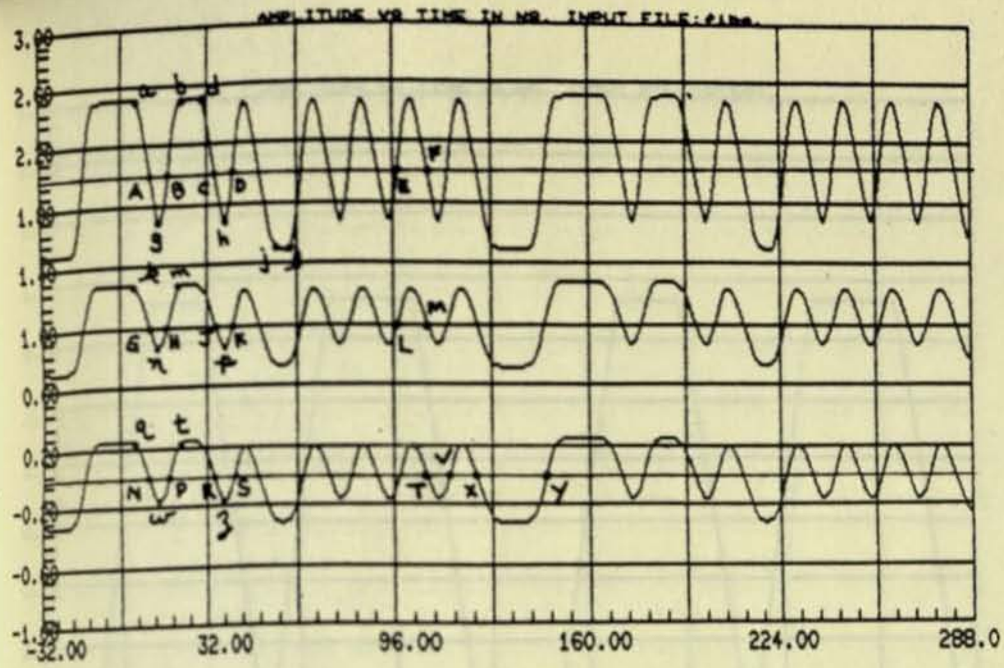
EMONSTRATION OF USE OF TO IN .OUT STATEMENT

Top waveform shifted 37 ns to left (13 ns to right) with respect to bottom waveform

Middle waveform shifted 13 to left with respect to bottom

```
 amp=1.8 pw=20 per=50 tr=1.7 tf=3 bw=.5
 amp=.2  pw=20 per=50 tr=3.5 tf=5 bw=.5 del=2.2
t dc=5 to=37.
t dc=2.5 to=13
t
d tx=100 fs=7.5
```

FIGURE 22. USE OF TO IN .OUT STATEMENT



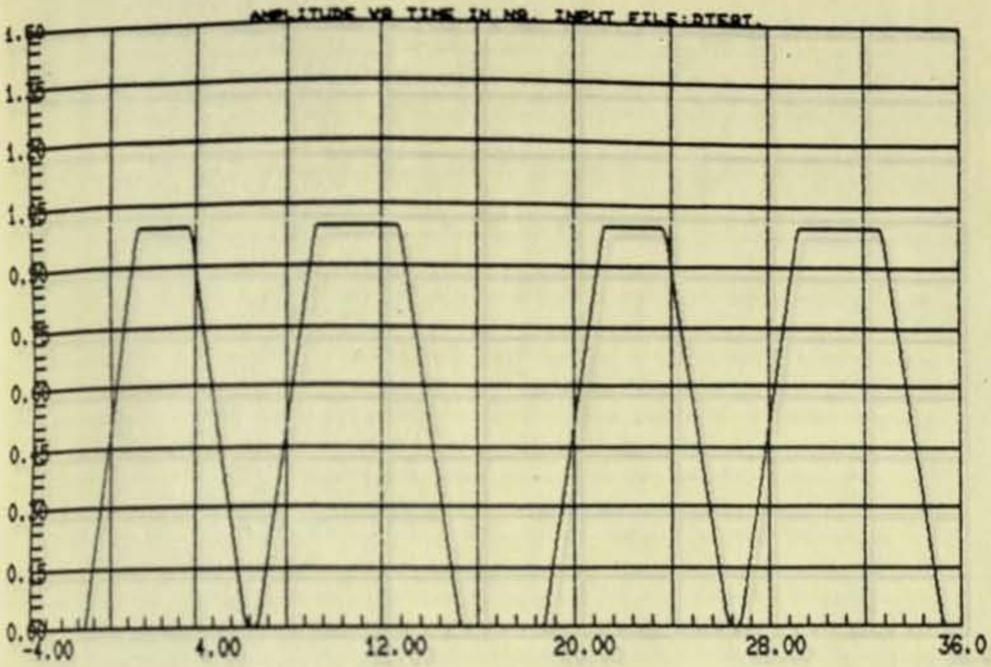
OSSOVER TIMING IN NANOSECONDS

TWORK	8	9	10
LTAGE	0.000	0.000	0.000
LAY	0.000	0.000	0.000
	11.167 A	11.181 G	10.625 N
	17.494 B	17.372 H	17.813 P
	35.165 C	35.176 J	34.609 R
	41.490 D	41.392 K	41.823 S
	51.167	51.163	50.608
	65.527	65.508	65.913
	75.165	75.174	74.609
	81.490	81.392	81.823
	91.167	91.181	90.625
	97.494 E	97.372 L	97.813
	107.178 F	107.188 M	106.602 T
	113.488	113.381	113.821 V
	123.171	123.160	122.604 X
	145.527	145.508	145.913 Y

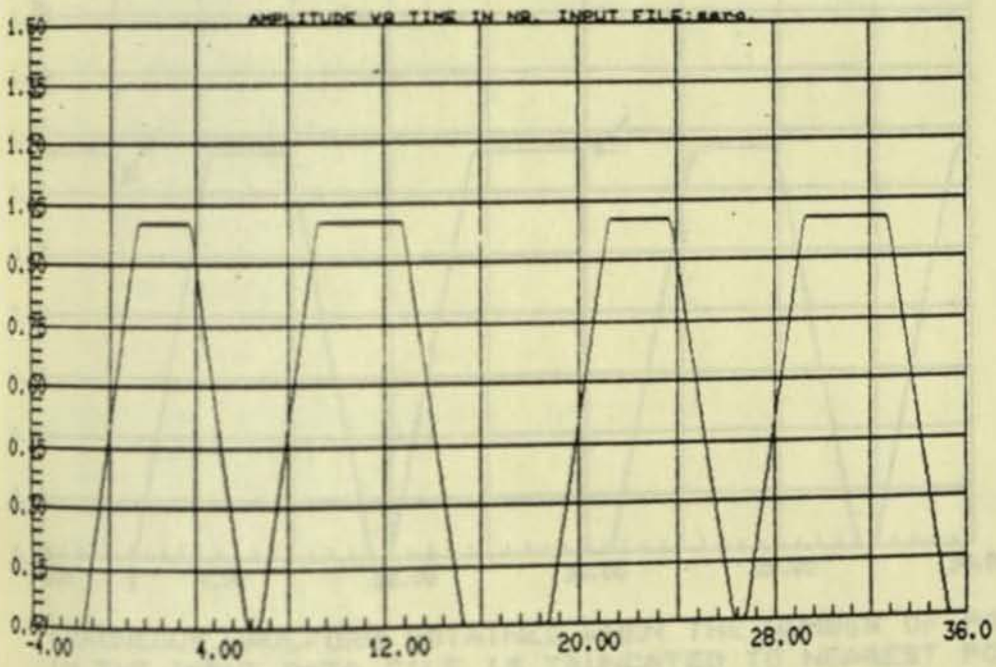
XIMA AND MINIMA TIMING IN NANOSECONDS

TWORK	8		9		10	
LAY	0.000		0.000		0.000	
	MAX	MIN	MAX	MIN	MAX	MIN
	5.625 a	14.570 g	4.219 k	14.453 n	4.219 q	14.453 w
	23.203 b	38.568 h	23.828 m	38.359 p	23.828 t	38.359 z
	29.688 d	58.047 j	27.969	58.203	27.969	58.203
	45.859	61.563 ℓ	45.703	59.844	45.703	59.844
	69.766	78.568	69.766	78.359	69.766	78.359
	85.859	94.570	85.703	94.453	85.703	94.453
	101.797	110.599	101.797	110.391	101.797	110.391
	117.734	130.078	117.734	130.391	117.734	130.391
	151.172	141.563	151.797	139.844	151.797	139.844

FIGURE 23. USE of DV in .OUT

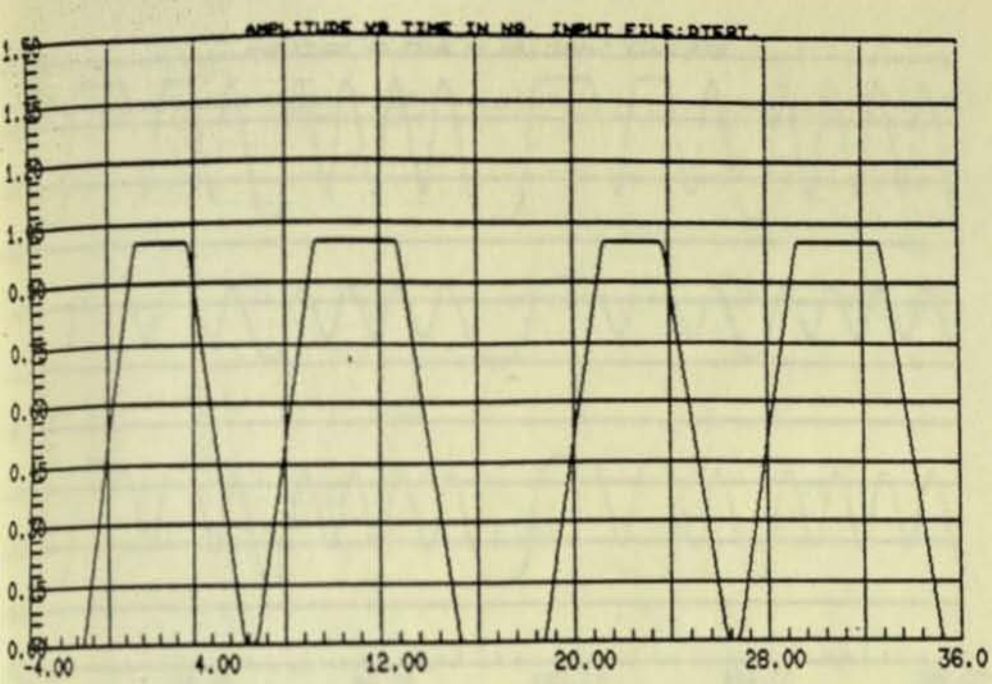


TWO PERIODS OF ORIGINAL WAVEFORM

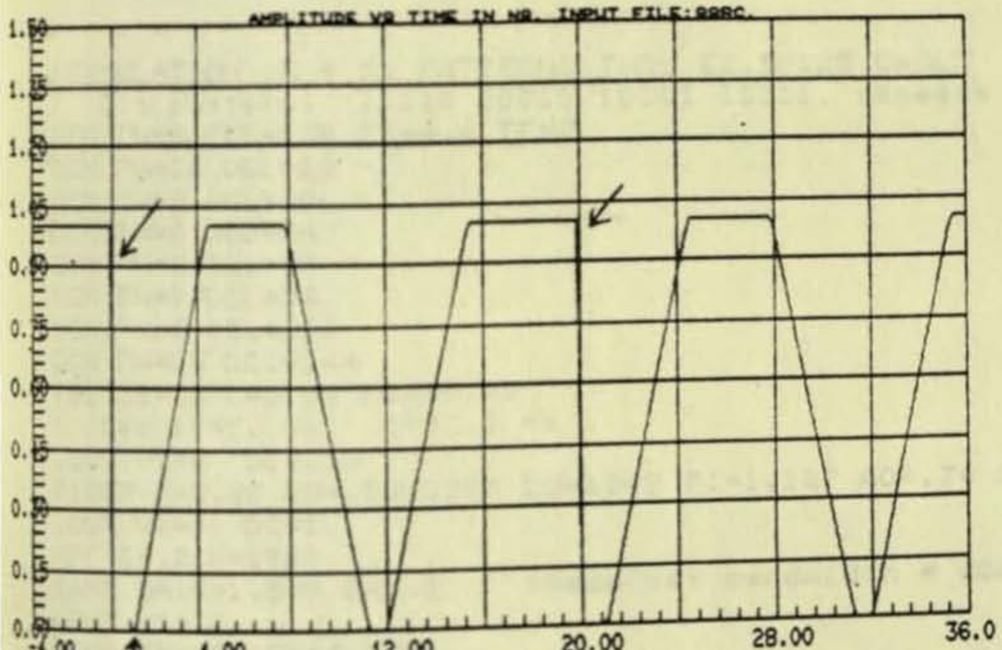


TIME DOMAIN OUTPUT FROM USING SRC MODEL WITH SOURCE.DTA
CONTAING 256 POINTS OVER A SINGLE PERIOD OF TOP WAVEFORM

FIGURE 24. SRC OUTPUT FOR NT = 256

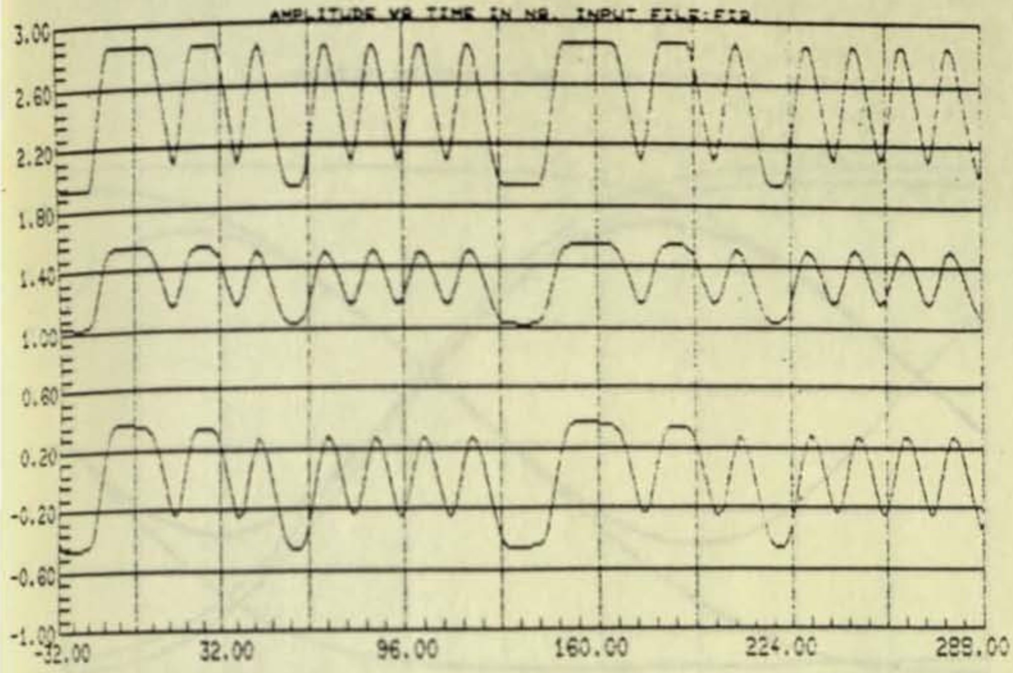


ORIGINAL WAVEFORM - 2 PERIODS



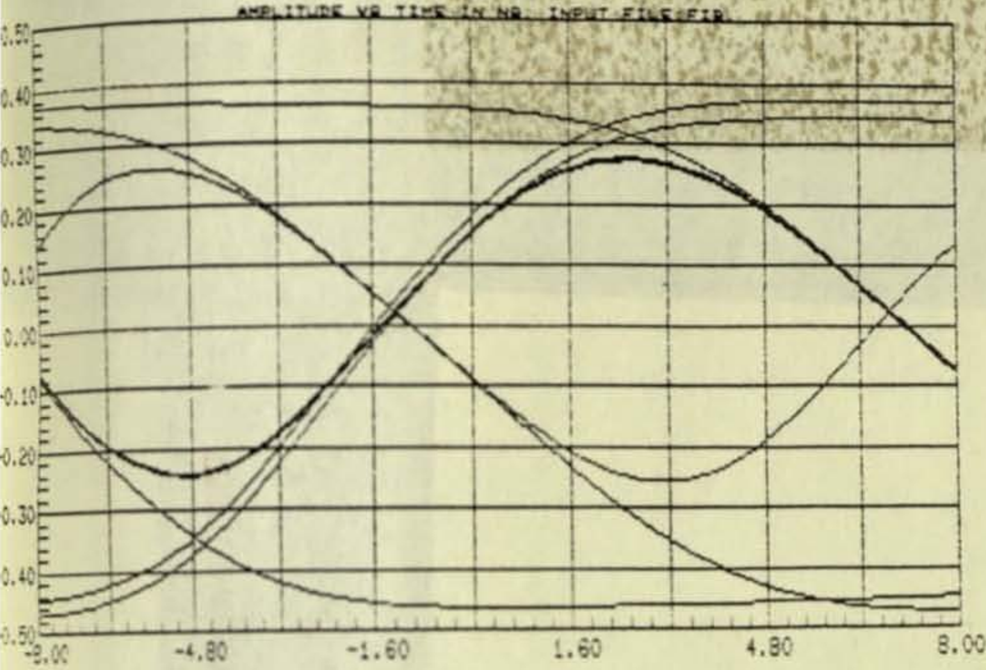
ERRONEOUS WAVEFORM OBTAINED WHEN THE NUMBER OF POINTS IN THE INPUT DATA FILE IS TRUNCATED TO NEAREST POWER OF 2 - (350 equally spaced points of above waveform) truncated to 256 points as required for FFT analysis

FIGURE 25. SRC OUTPUT - NT ROUNDED TO POWER OF 2




```
!SIMULATION OF 4 5b PATTERNS THRU 62.5/125 CABLE
!  Bit pattern:  10110 10010 10101 10011, repeats
GEN PW=8 PER=160 TR=4.4 TF=7
GEN PW=16 DEL=16
GEN PW=8 DEL=40
GEN PW=8 DEL=64
GEN PW=8 DEL=80
GEN PW=8 DEL=96
GEN PW=8 DEL=112
GEN PW=16 DEL=144
TEE L1=15 C=0.04 R1=38.73
!  Led tr=5. ns   tf=7.3 ns
.OUT V1=0  DC=1.9
FIBER X=3.38 SO=.0000909 LO=1349 FI=1.127 AO=.74 LC=1291 FW=120
.OUT V1=0. DC=1.
HPF C=.2 R=1000
EAMP GAIN=1.585 BW=.2     !Receiver bandwidth = 200 Mhz
.OUT V1= 0
.END TX=320 FS=4 DC=1
```

FIGURE 26. EXAMPLE 1




```
!SIMULATION OF 4 5b PATTERNS THRU 62.5/125 CABLE.
!  Bit pattern:  10110 10010 10101 10011, repeats
GEN PW=8 PER=160 TR=4.4 TF=7
GEN PW=16 DEL=16
GEN PW=8 DEL=40
GEN PW=8 DEL=64
GEN PW=8 DEL=80
GEN PW=8 DEL=96
GEN PW=8 DEL=112
GEN PW=16 DEL=144
TEE L1=15 C=0.04 R1=38.73
!  Led tr=5. ns    tf=7.3 ns
FIBER X=3.38 SO=.0000909 LO=1349 FI=1.127 AO=.74 LC=1291 FW=126
HPF C=.2 R=1000
EAMP GAIN=1.585 BW=.2     !Receiver bandwidth = 200 Mhz
.OUT V1= 0
.EYE TX=8 DC=.5 FS=1
```

FIGURE 27. EYE PATTERN

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