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TIME DOMAIN AND FREQUENCY DOMAIN MEASUREMENT TECHNIQUES

by

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DEPARTMENT OF ELECTRICAL AND CONTROL ENGINEERING

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SUMMARY

The principles underlying two distinct approaches to the measurement of electrical network characteristics over a wide frequency range are outlined, together with brief descriptions of currently available test systems which cover the range 0.1 - 4GHZ.

The two techniques are assessed in terms of their ultimate capabilities with regard to accuracy, speed of measurement and costs.

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1. Introduction

At a given frequency a linear one-port network is fully characterized by the magnitude and phase angle of any one of the following quantities: reflection coefficient (ρ), admittance (Y), impedance (Z). Similarly, the transmission and reflection properties of a linear two-port network at a given frequency are completely determined by the specification of any one of the well-known parameter sets, such as scattering parameters (s_{ij}), admittance parameters (y_{ij}), impedance (z_{ij}) or hybrid (h_{ij}) parameters.

Complete experimental characterization of linear networks over a range of frequencies involves, therefore, the determination either of one, or of four, complex quantities as functions of frequency. If behaviour over a wide range of frequencies is to be specified then sufficient information on the frequency variation of each quantity must be obtained to permit prediction of that quantity for any point on the frequency scale.

At the present time two distinct experimental methods are available for the determination of one-port and two-port parameters of electrical networks, including active devices, at frequencies within the range 100 - 4000 MHZ. These methods are conveniently described as 'Frequency Domain' and 'Time Domain' techniques.

In Frequency domain procedures, which include the conventional methods for loss and phase measurement, the system behaviour is measured at each separate frequency by the application of a sinusoidal signal of that frequency.

In contrast to this approach, Time Domain methods involve the simultaneous measurement of system behaviour at all frequencies within the frequency range by a single procedure which consists of the subjection of the test network to a pulse or step signal, and the recording of its response to this non-sinusoidal time-dependent excitation. The input signal is chosen to contain Fourier components covering the complete frequency range of interest. The desired characteristic parameters, for any frequency, are then obtained by Fourier analyses of input pulses, and of reflected and transmitted signals.

The present Note contains a preliminary, though general, evaluation of the two techniques, and a comparison between them in terms of accuracy, complexity of equipment, convenience of use, and cost.

In any overall assessment of this kind, account must be taken of the fact that, while complete instrumentation systems for Frequency Domain techniques, and for 'Time Domain Reflectometry' have been commercially available for several years, the quantitative Time Domain techniques considered here represent a more recent development. Data on their use are based, so far, upon laboratory experience.

2. Description of basic techniques

2.1 Frequency domain measurements

All frequency domain methods involve the determination of the magnitude and phase of the desired network parameters from driving point reflectance and transmission coefficients measured under conditions of single frequency excitation. Each measurement results in the collection of information reflated to the behaviour of the system at a single frequency. If data over a band of frequencies are to be ascertained, then a number of measurements at different frequencies must be carried out. This can be done manually, or by automatically stepped or swept signal sources and detectors.

While earlier instruments intended for frequency domain measurements, such as the General Radio 1607A bridge, were designed for the direct determination of open/closed port parameters (e.g. z, y or h), the difficulties and inaccuracies inherent in the achievement of effective short-circuit and open-circuit conditions over the VHF-UHF range have led to a recent shift in emphasis towards finite termination parameters, and, in particular, towards the use of the scattering ('s') parameter set. This group of parameters, which comprises the complex reflection and transmission coefficients presented by the network under test when it is embedded in a transmission line system of known characteristic impedance, is well adapted to wide band measurement procedures since it obviates the need for frequency dependent adjustments of the measuring system. This made possible the introduction of efficient stepped and swept frequency techniques of measurement which permit the collection of data over a wide frequency band in a minimum of time. Simultaneously, however, s-parameter techniques, involving the separation of incident and reflected signals, made necessary the introduction of directional couplers into the measuring system, thereby incurring penalties with respect to both convenience and accuracy of measurement. These arise from the frequency dependent tracking errors of the couplers, and the limited band over which a particular directional coupler will operate satisfactorily. If the effects of coupler errors are to be eliminated from the final results, these errors must be obtained for each frequency of interest from separate calibration runs, stored and subsequently used to correct the raw data obtained.

2.2 Time domain methods

Time domain methods utilize recent advances in sampling oscilloscope techniques which have made it possible to obtain, and record with good precision, pulse shapes of time varying signals whose frequency spectra extend into the 4 - 12 GHz region. The information collected may be used in several ways to define the behaviour of the system under investigation over a wide frequency band. The earliest and now widely used form of Time Domain analysis is represented by 'Time Domain Reflectometry' ('TDR') in which qualitative information relating to a complex reflection coefficient is obtained by visual analysis of the shape of the reflected pulse, generated if a fast-rise pulse is allowed to be incident upon the reflecting system.

A significant further development of time domain methods consists of quantitative time domain analysis, or 'Time Domain Spectroscopy', ('TDS') The feasibility of this technique was shown by F. Davis and the writer in 1965.

TDS methods represent an advance over conventional TDR techniques in several respects:

(1) Quantiative information is derived from the time domain signals by suitable Fourier conversion techniques.

(2) The analysis includes transmitted as well as reflected signals, thereby permitting complete one-port and two-port specifications. The Fourier components of the time signals are related in a direct manner to the scattering parameters, from which any other parameter set can be computed.

(3) The effects of source pulse shape and transmission system degradations can be eliminated from the final results.

A unique advantage possessed by all Time Domain methods over Frequency Domain techniques lies in the possibility of identifying particular components of the reflected pulse and of attributing them to specific and exactly localized line mismatches. This facility provides the opportunity to distinguish between the reflection pattern set up by the component under test, and spurious reflections arising from the unavoidable shortcomings of the transmission line system used to carry out the measurements. Provided only that the time delay separating the two pulses lies within the resolving power of the system, such separation should always be possible.

This advantage, which TDS in particular, enjoys over corresponding FD methods, is of considerable significance in any assessment of the two methods. As will be shown below it offers possibilities of attaining a very high degree of accuracy. Moreover, it enables TDS to be used under conditions which include, of necessity, mismatches between measurement system, contact region and active region of network under test, such as conditions arising when 'on slice' measurements on integrated circuits are involved.

3. Description of current systems

3.1 FD Methods

3.1.1 The Hewlett Packard Network Analyzer

The Hewlett-Packard Network Analyzer, which was introduced in the United States towards the end of 1967, probably represents the most comprehensive instrument for FD measurements which is currently being marketed. It makes use of sampling techniques to generate low frequency replicas of signals lying in the 110 MHz - 12.4 GHz range. By simultaneous conversion of a reference and a test signal, the amplitude ratio and phase difference of the two signals is obtained. These may be displayed on a meter, x-y recorder, or in Smith chart form on a polar display oscilloscope. For measurements over a wide frequency range swept frequency generators with synchronised detectors enable amplitude ratio and phase to be displayed virtually instantaneously once the system has been set up and standardised.

The two test modes, namely transmission measurements and reflection measurements are obtained by the arrangements shown in Fig. 1.

3.1.2 The Rohde and Schwartz Z-g Diagraphs

These instruments, which have been available for a number of years permit the measurement of reflection and transmission coefficients over the range 30-420 MHz (type ZDU) and 300-2500 MHz (Type ZDD). Open/closed port termination conditions are provided. The amplitude ratio and phase difference are displayed on a Smith chart type scale, standardised to unit reflection coefficient. Phase indication is obtained by manual balancing. As indicated in Fig. 2, here also use has to be made of directional couplers to separate incident from reflected signals. Heterodyning methods are used to obtain amplitude and phase correct replicas of the VHF signals.

3.1.3 Bell Telephone Laboratories Test Set 5-250 MHz (2)

This equipment, although not commercially available, is of interest in indicating how high accuracy can be achieved in FD measurements under laboratory conditions. Moreover, it demonstrates a technique for avoiding the use of directional couplers in reflectivity measurements. The high accuracy is achieved, however, at the cost of relatively complicated operation and the loss of wideband swept frequency capabilities as indicated in Fig. 3. The amplitude ratio and phase difference are measured by continuous comparison between the path containing the network under test and paths containing attenuator standards and phase standards. Through adjustment of these two standards for null balance readings are obtained. By paying special attention to the design of the standards and of the transmission line system, and utilizing continuous comparisons by means of 'sample and hold' techniques, the designers achieved maximum inaccuracies of 0.1 db and 0.5° over the entire frequency range. Reflection coefficient measurement is carried out by means of a shunt insertion method. This avoids the need for directional couplers but makes it necessary to use line transformers for impedances which are significantly higher than the characteristic impedance of the system.

3.2 TDS: Practical Systems

It has already been stated that, at the time of writing, complete TDS Systems, (as distinct from instruments for TDR), are not available commercially. However, several versions of an experimental TDS system have been constructed at Cranfield during the period 1965-68, and another such system, based upon a Cranfield design, has recently been constructed in an industrial computer research laboratory. In all cases, these systems were assembled almost entirely from commercially available components, so that it is possible to make performance predictions for similar arrangements.

A design for a typical TDS system is illustrated in schematic form in Fig. 4. It can be seen that, unlike FD methods, which require different system components for reflection and transmission measurements, TDS methods utilise one basic arrangement for both. To change from reflection to transmission evaluation merely requires a change in the test probe location, or, for a 2-channel sampling system, a change from one channel to the other.

The first significant difference between FD and TDS methods concerns standardization. In both techniques this involves the use of 'short circuit' and 'through line' standards. However, since TDS involves simultaneous (though implicit) measurement of the amplitudes of all component frequencies, a single operation will provide a complete set of reflection reference data, while a second operation will provide all data for a transmission reference. With suitable system design it becomes possible to utilize the same set of data for both transmission and reflection measurement standardization.

The accuracy achievable in TDS systems will be discussed below.

4. FD Measurements: Source of Error

4.1 Transmission measurements

In FD transmission measurement methods the signal from the source is divided into two components one of which is sent down the reference line, while the other passes through the test channel. The amplitude ratio and phase difference of the signals are then measured by heterodyne or sampling methods. Standardization involves the insertion of a reference standard in the test line and adjustment of reference line to yield a given amplitude ratio and zero phase difference. For highest accuracy, standardization must be carried out at each frequency of measurement, involving a two-step procedure at each frequency.

Errors will arise from shortcomings of the transmission line system, from mismatches at power divider and measuring terminals and from errors in the phase and amplitude measuring system. In general, these errors will be dependent upon signal amplitude.

Figures quoted for worst case accuracy of transmission measurements on the Hewlett-Packard Network Analyzer and Transmission Test Unit are of the order ± 0.3 db, ±5° for measurements of total transmission factor, and ± 0.26 db, ± 3.3° for incremental measurements involving the use of similar networks in reference and test channel. These accuracies are achieved under conditions which permit swept frequency mode of operation. In contrast, the higher accuracies quoted for the Bell Laboratories Test Set imply conditions of operation which preclude this mode.

4.2 Reflection Measurements

The major difference between FD transmission and FD reflection measurement techniques (excluding the use of shunt insertion measurements, which are not adapted to wideband/swept frequency methods) consists in the use of directional couplers to separate the incident from the reflected signal. The measurement procedure is again essentially a two-step method in which the reflection of the test device is compared to that of a short circuit standard against which the system has been calibrated.

The introduction of directional couplers adds a further source of error to the other sources present, since coupler tracking inaccuracies are unavoidable. Typical tracking errors, quoted for the Hewlett-Packard 8741A and 8742A test units amount to ± 0.5 db amplitude error, ± 3° phase error (0.11 - 2.0 GHz) and ± 5° phase error (2.0 - 12.4 GHz). The uncertainty involved in reflection coefficient magnitude is related to the value of the reflection coefficient and lies between ± 0.01 for $\rho \approx 0$ and $0.11 < f < 1$GHz, and ± 0.043 for $\rho \approx 1$ and $8 < f < 12.4$GHz. In the absence of correction procedure this implies, for example, a ± 5% impedance uncertainty in the measurement of 100 ohms at 1 GHz.

The effects of coupler directivity errors can be eliminated by the use of standardising procedures. For measurements at a few spot frequencies this can be done manually. However, if results over a frequency range are to be corrected then it becomes convenient to use on-line computing facilities to store the correction terms for each of a large number of frequencies and to evaluate the corrected amplitudes and phases of the test device reflection coefficient. This facility is available in the Hewlett-Packard Automatic Network Analyzer. Once a computer forms part of the measurement system, its function need not be restricted, of course, to that of storing and calibrating out error data, but it may be used for parameter conversion, data storage, display and print out control and similar functions.

5. TDS Measurements: Sources of Error

The following factors will be of major influence upon the performance of a TDS System:

(1) Quality of transmission line system
(2) Time scale accuracy of sampling oscilloscope
(3) Amplitude accuracy of sampling oscilloscope

With respect to (1) it appears that the use of commercially available co-axial transmission lines, such as the GR 874 series imposes no significant accuracy limitation over the range 0 - 3 GHz, provided the system is designed to eliminate line loss effects as will be described below. For higher frequency ranges it may be necessary to use higher quality lines and fittings, such as the GR 900 series.

Under the heading of time scale accuracy one must consider time scale non-linearities, time scale calibration accuracy and time jitter. To consider a specific case let it be assumed that the amplitude of the time signal is to be measured at intervals of 0.1 n sec., corresponding to a frequency cut-off of 5 GHz. For a ± 5% time scale uncertainty between samples time jitter must not exceed ± 5 p sec. This represents $\frac{1}{2}$ the quoted maximum value for the Hewlett Packard 1425A time base system. If X - Y recording is used, an averaging effect will tend to reduce the magnitude of this jitter.

A series of practical tests in which one port reflection coefficients of certain co-axial standards and of test networks were measured on two TDS systems in different locations and the results compared with FD measurements (which included first order corrections for directional coupler errors), indicated that overall agreement between the three sets of measurements to ± 5% in both amplitude and phase were readily achievable over the range 0 - 1 GHz. Recent work at Cranfield established low frequency noise in the sampling system vertical amplifier (Hewlett-Packard, 1411A) as a major source of error, and in later tests, in which this cause had been eliminated, reproducibility of results was found to be of the order of ± 0.3% over the range 0 - 1.5 GHz, ± 1% from 1.5 to 2.0 GHz and ± 2% from 2.0 to 3.5 GHz. Under the same conditions the reflection coefficient of a 200 ohm co-axial standard ($\rho = 0.6$) was obtained to an accuracy of ± 0.5% over the range 0 - 0.8 GHz. Examples of lineprinter output and plots of these results are given in Appendix B.

Amplitude errors may arise not only from inaccuracies of the vertical amplifier systems of the oscilloscope and X - Y recorder used to record the signal, but also from errors in taking sample amplitudes from the pulse trace. It can be shown that the presence of amplitude errors will result in the superposition of amplitude and phase errors which vary periodically with frequency, upon the amplitude and phase spectra. In the tests referred above, it was found that this type of error could be kept at insigificant levels for both manual and semi-automatic (Benson-Lehner table)?conversion of data, for frequencies up to 1 GHz. It should be borne in mind that relative rather than absolute information on pulse amplitude is required since it is the ratio of Fourier components which results from the computation.

In summary of this section one can say that the present accuracy limits for measurement of passive networks over the range 0 - 1 GHz will lie in the region of ± 1%, or better, for amplitude measurements, ± 5% for phase measurements, while for active devices, which impose signal level limitations, the accuracy limits will be somewhat broader, probably typically ± 5%. These limitations arise not from the measurement system as such, but from the shortcomings of present day sampling oscilloscopes and from the relatively simple methods used, so far, for deriving digital information from analogue signals.

With the use of more elaborate methods of signal processing, such as smoothing and signal averaging, it is estimated that an improvement by a factor of 10 in accuracy should be readily achievable at the cost of some increase either in equipment complexity or computer usage. Extension of the frequency range over which high accuracies can be achieved will also be relatively easy. In assessing the ultimate accuracies which TDS systems should be capable of achievement, perhaps the most significant factor is the time separation of reflections from different parts of the measurement system. This feature offers at one and the same time a high degree of immunity from the effects of transmission line shortcomings and obviates the need for the use of directional couplers. This latter point is particularly important, since coupler characteristics are one of the biggest error sources in FD techniques. Only TDS can offer s-parameter measurement without the use of directional couplers.*

6. Conclusions

The preceding discussion regarding the performance of TD and TDS technique based instrumentation leads to the following conclusions:

1. Present-day TDS techniques, utilizing a fast pulse generator, sampling oscilloscope, X-Y recorder and off-line computing facilities can yield accuracies of the same order as those achieved by the most complex commercially available FD network analyzer sets, which include on-line computing techniques.

2. With further developments, such as more accurate data conversion by means of on-line techniques, an improvement in precision of TDS systems can be brought about, which is likely to go beyond that achievable in FD systems. This prediction is based upon the ability of TDS, mentioned above, to eliminate the effects of mismatch reflections and to obviate the need for directional couplers.

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*Recent work at Cranfield has led to the conclusion that it will be feasible, by proper choice of transmission line lengths to achieve optimum time segregation of mismatch reflections and compensation of line losses, to reduce spurious reflection effects below 1% even though individual components of the system may have reflection coefficients as high as 50%.

3. Even the simplest TDS system offers a degree of wide band facility equal to or greater than that provided by the most complex FD swept frequency measuring apparatus. The superiority of the TDS method derives from (i) absence of frequency limitations other than the spectral limit of pulse generator and sampling oscilloscope so that, with present-day sampling heads 0-4 GHz, or 0-12.4 GHz can be covered, (ii) possibility of submitting the same data to further Fourier analyses, so that information relating to any frequency within the range can be obtained at any time without further experimentation.

4. The ability to separate desired and unwanted reflections makes TDS techniques superior to FD ones as a means for measuring integrated circuit components through probe measurements on the slice.

5. While TDS as here discussed is essentially a method for the measurement of linear network parameters, the experimental equipment can be used, with an increase in pulse amplitude, for measurements on non-linear devices in the switching mode, to provide data on rise and fall times, delays and other large signal data. In cases where such information is required, in addition to small signal parameters, any FD system will have to be complemented by a separate pulse system, while both facilities are contained in the TDS apparatus.

6. At the present time, TDS equipment, in spite of its greater versatility, compares favourably in cost with most FD systems as indicated in Appendix A.

It seems evident, from these considerations, that a strong case exists for the rapid further development of TDS techniques with a view to producing an instrument which could form a superior alternative to FD equipment.

References

1. F. Davis, H.W. Loeb
Time domain measurements for transistor and network characterization up to 1 GC - Proc. IEEE 53, 1649-50, October, 1965.

2. D. Leed, F. Kummer
A loss and phase set for measuring transistor parameters and two-port networks between 5 and 250 Mc. JSTJ 40, 841-884.

3.
Network analysis at microwave frequencies - Hewlett Packard Applic. Note 92.

Appendix A

Comparison of cost estimates for FD and TDS systems

1. FD system

1.1 Non-automatic network analyzer (Hewlett Packard)

Note: This equipment permits single frequency measurements and swept frequency oscilloscopic displays of amplitude and phase of transmission and reflection coefficient, but does not provide for automatic range changing, storage of calibration data, and error corrections as carried out by the 'Automatic Network Analyzer'. Such functions could be provided, off-line, by any general purpose digital computer with suitable software.

		Cost to nearest £10 (May 68 Price List + 2% for US imported eqpt.)
(i)	Network Analyzer (8410A) + Harmonic Converter (8411A)	1970
(ii)	Phase Gain Indicator (8413A)	390
	(alternative, or complementary, Polar Display Unit (8414A))	(450)
(iii)	Transmission Test Unit (8740A) (0.11 - 12.4 GHz)	590
(iv)	Reflection Test Unit (8741A) (0.11 - 2 GHz)	680
	(Reflection Test Unit (8742A) 2.0 - 12.4 GHz)	(680)
(v)	Sweep Oscillator (8690A)	660
	RF units for above:	
	(8699A) 0.11 - 4 GHz	1410
	(8693A 4 - 8 GHz)	(730)
	(8694A 8 - 12 GHz)	(730)
(vi)	Test Fixtures etc.	300
	Total cost for 0.11 - 2 GHz equipment	6000
	Additional cost to cover 2.0 - 4 GHz range	680
	Additional cost to cover 4 - 12.4 GHz range	1460
	Total system cost 0.11 - 12.4 GHz	8140

1.2 Automatic Network Analyzer (Hewlett-Packard)

This comprises, in addition to above, a 2115 digital computer, analog to digital conversion, automatic range switching etc. It offers the facilities described in section 4. U.S. Price (Spring 1968).

Basic System (0.11 - 2 GHz)	$81,000
(0.11 - 12.4 GHz)	$97,200

2. TDS System

2.1 0 - 4 GHz

(i)	Sampling Oscilloscope	£	£
	Hewlett Packard 140A	246	
	+ 1411A	370	
	+ 1432A	528	
	+ 1424A	633	1800
(ii)	Pulse Generator 213B (100 p sec)		120
(iii)	Co-axial lines and fittings		600
(iv)	General purpose X - Y recorder		300
(v)	Use of computer		—
			2820

2.2 Extension of above system to 0 - 12.4 GHz

(i)	1431A sampler unit (in place of 1432A)	1600
(ii)	20 p sec pulse generator	350
	additional cost:	1950
	total cost	4800

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REFLECTED PULSE = DATASET NO.  5 /  TDR 1408 GMY 1/10/68 10/20 GREEN
REFERENCE PULSE = DATASET NO.  1 /  TDR 1401  GMY 1/10/68 5/20   WN5


                        TABLE OF ONE-PORT NETWORK REFLECTION COEFFICIENTS

  FREQ                RHO           Y*          Y(MHO)          Z*          Z(OHM)          VSWR

   0.000      X   51.117E-02    32.347E-02    64.695E-04    30.914E-01    15.457E 01        3.0914
              Y   00.000E-02    00.000E-02    00.000E-02    00.000E-02    00.000E-02

              R   51.117E-02    32.347E-02    64.695E-04    30.914E-01    15.457E 01
              Ø    0.00          0.00          0.00          0.00          0.00
  50.000      X   50.745E-02    32.673E-02    65.347E-04    30.605E-01    15.302E 01        3.0606
              Y   19.623E-05   -17.271E-05   -34.542E-07    16.178E-04    80.890E-03

              R   50.745E-02    32.673E-02    65.347E-04    30.605E-01    15.302E 01
              Ø    0.02         -0.03         -0.03          0.03          0.03
 100.000      X   49.663E-02    33.632E-02    67.265E-04    29.730E-01    14.865E 01        2.9733
              Y   32.051E-04   -28.618E-04   -57.237E-06    25.298E-03    12.649E-01

              R   49.664E-02    33.633E-02    67.267E-04    29.731E-01    14.865E 01
              Ø    0.37         -0.49         -0.49          0.49          0.49
 150.000      X   47.980E-02    35.144E-02    70.289E-04    28.426E-01    14.213E 01        2.8458
              Y   11.951E-03   -10.914E-03   -21.829E-05    88.282E-03    44.141E-01

              R   47.994E-02    35.161E-02    70.323E-04    28.440E-01    14.220E 01
              Ø    1.43         -1.78         -1.78          1.78          1.78


 200.000      X   45.918E-02    37.007E-02    74.014E-04    26.872E-01    13.436E 01        2.7046
              Y   29.370E-03   -27.576E-03   -55.152E-05    20.024E-02    10.012E 00

              R   46.012E-02    37.109E-02    74.219E-04    26.947E-01    13.473E 01
              Ø    3.66         -4.26         -4.26          4.26          4.26
 250.000      X   43.851E-02    38.807E-02    77.613E-04    25.244E-01    12.622E 01        2.5863
              Y   57.951E-03   -55.918E-03   -11.183E-04    36.375E-02    18.188E 00

              R   44.232E-02    39.207E-02    78.415E-04    25.505E-01    12.752E 01
              Ø    7.53         -8.20         -8.20          8.20          8.20
 300.000      X   42.309E-02    39.863E-02    79.726E-04    23.677E-01    11.838E 01        2.5367
              Y   98.914E-03   -97.214E-03   -19.443E-04    57.742E-02    28.871E 00

              R   43.450E-02    41.031E-02    82.063E-04    24.371E-01    12.185E 01
              Ø   13.16        -13.71        -13.71         13.71         13.71
 350.000      X   41.938E-02    39.324E-02    78.649E-04    22.258E-01    11.129E 01        2.6089
              Y   15.120E-02   -14.841E-02   -29.683E-04    84.008E-02    42.004E 00

              R   44.581E-02    42.032E-02    84.064E-04    23.791E-01    11.895E 01
              Ø   19.83        -20.68        -20.68         20.68         20.68


 400.000      X   43.394E-02    36.529E-02    73.058E-04    21.034E-01    10.517E 01        2.8638
              Y   21.065E-02   -20.056E-02   -40.113E-04    11.549E-01    57.745E 00

              R   48.236E-02    41.673E-02    83.346E-04    23.996E-01    11.998E 01
              Ø   25.89        -28.77        -28.77         28.77         28.77
 450.000      X   47.168E-02    31.479E-02    62.959E-04    20.025E-01    10.012E 01        3.3802
              Y   26.980E-02   -24.104E-02   -48.209E-04    15.333E-01    76.668E 00

              R   54.339E-02    39.648E-02    79.297E-04    25.221E-01    12.610E 01
              Ø   29.77        -37.44        -37.44         37.44         37.44
 500.000      X   53.415E-02    24.970E-02    49.941E-04    19.243E-01    96.214E 00        4.2913
              Y   31.873E-02   -25.963E-02   -51.927E-04    20.008E-01    10.004E 01

              R   62.202E-02    36.023E-02    72.046E-04    27.760E-01    13.880E 01
              Ø   30.82        -46.12        -46.12         46.12         46.12
 550.000      X   61.827E-02    18.160E-02    36.321E-04    18.700E-01    93.504E 00        5.8708
              Y   34.682E-02   -25.324E-02   -50.648E-04    26.077E-01    13.038E 01

              R   70.891E-02    31.162E-02    62.325E-04    32.089E-01    16.044E 01
              Ø   29.29        -54.35        -54.35         54.35         54.35
```

```
 600.000    X   71.620E-02    12.003E-02    24.007E-04    18.417E-01    92.088E 00
            Y   34.524E-02   -22.531E-02   -45.062E-04    34.570E-01    17.285E 01        8.7594

            R   79.507E-02    25.529E-02    51.059E-04    39.170E-01    19.585E 01
            Ø    25.74       -61.95        -61.95          61.95         61.95

 650.000    X   81.650E-02    70.021E-03    14.004E-04    18.393E-01    91.965E 00
            Y   30.916E-02   -18.211E-02   -36.423E-04    47.837E-01    23.918E 01       14.7572

            R   87.307E-02    19.511E-02    39.022E-04    51.251E-01    25.626E 01
            Ø    20.74       -68.97        -68.97          68.97         68.97

 700.000    X   90.645E-02    32.810E-03    65.621E-05    18.362E-01    91.812E 00
            Y   23.919E-02   -12.958E-02   -25.916E-04    72.521E-01    36.260E 01       30.9903

            R   93.748E-02    13.367E-02    26.734E-04    74.809E-01    37.404E 01
            Ø    14.78       -75.79        -75.79          75.79         75.79

 750.000    X   97.469E-02    76.477E-04    15.295E-05    14.530E-01    72.651E 00
            Y   14.138E-02   -72.144E-03   -14.428E-04    13.707E 00    68.535E 01      131.4380

            R   98.489E-02    72.548E-03    14.509E-04    13.783E 00    68.919E 01
            Ø     8.25       -83.95        -83.95          83.95         83.95


 800.000    X   10.135E-01   -68.999E-04   -13.799E-05   -32.539E 00   -16.270E 02
            Y   25.999E-03   -12.823E-03   -25.646E-05    60.474E 00    30.237E 02     -144.9534

            R   10.138E-01    14.561E-03    29.123E-05    68.673E 00    34.336E 02
            Ø     1.47      -118.28       -118.28         118.28        118.28

 850.000    X   10.204E-01   -12.281E-03   -24.563E-05   -53.635E-01   -26.817E 01
            Y  -94.605E-03    46.249E-03    92.498E-05   -20.197E 00   -10.098E 02      -81.5970

            R   10.248E-01    47.852E-03    95.704E-05    20.897E 00    10.448E 02
            Ø    -5.30       104.87        104.87        -104.87       -104.87

 900.000    X   99.804E-02   -98.009E-04   -19.602E-05   -91.014E-02   -45.507E 00
            Y  -20.845E-02    10.330E-02    20.661E-04   -95.934E-01   -47.967E 01     -103.1196

            R   10.195E-01    10.377E-02    20.754E-04    96.365E-01    48.182E 01
            Ø   -11.80        95.42         95.42         -95.42        -95.42

 950.000    X   95.355E-02   -76.487E-05   -15.297E-06   -31.189E-03   -15.594E-01
            Y  -30.615E-02    15.659E-02    31.319E-04   -63.855E-01   -31.927E 01    -1339.4645

            R   10.014E-01    15.660E-02    31.320E-04    63.856E-01    31.928E 01
            Ø   -17.80        90.28         90.28         -90.28        -90.28


1000.000    X   89.687E-02    13.184E-03    26.368E-05    31.468E-02    15.734E 00
            Y  -38.242E-02    20.426E-02    40.852E-04   -48.753E-01   -24.376E 01       79.0123

            R   97.500E-02    20.468E-02    40.937E-04    48.854E-01    24.427E 01
            Ø   -23.09        86.31         86.31         -86.31        -86.31

1050.000    X   83.859E-02    29.698E-03    59.397E-05    48.928E-02    24.464E 00
            Y  -43.670E-02    24.457E-02    48.914E-04   -40.293E-01   -20.146E 01       35.6873

            R   94.548E-02    24.637E-02    49.274E-04    40.589E-01    20.294E 01
            Ø   -27.51        83.08         83.08         -83.08        -83.08

1100.000    X   78.774E-02    45.586E-03    91.173E-05    58.032E-02    29.016E 00
            Y  -47.283E-02    27.654E-02    55.308E-04   -35.204E-01   -17.602E 01       23.6170

            R   91.875E-02    28.027E-02    56.055E-04    35.679E-01    17.839E 01
            Ø   -30.97        80.64         80.64         -80.64        -80.64

1150.000    X   75.012E-02    57.257E-03    11.451E-04    61.110E-02    30.555E 00
            Y  -49.774E-02    30.069E-02    60.138E-04   -32.092E-01   -16.046E 01       19.0490

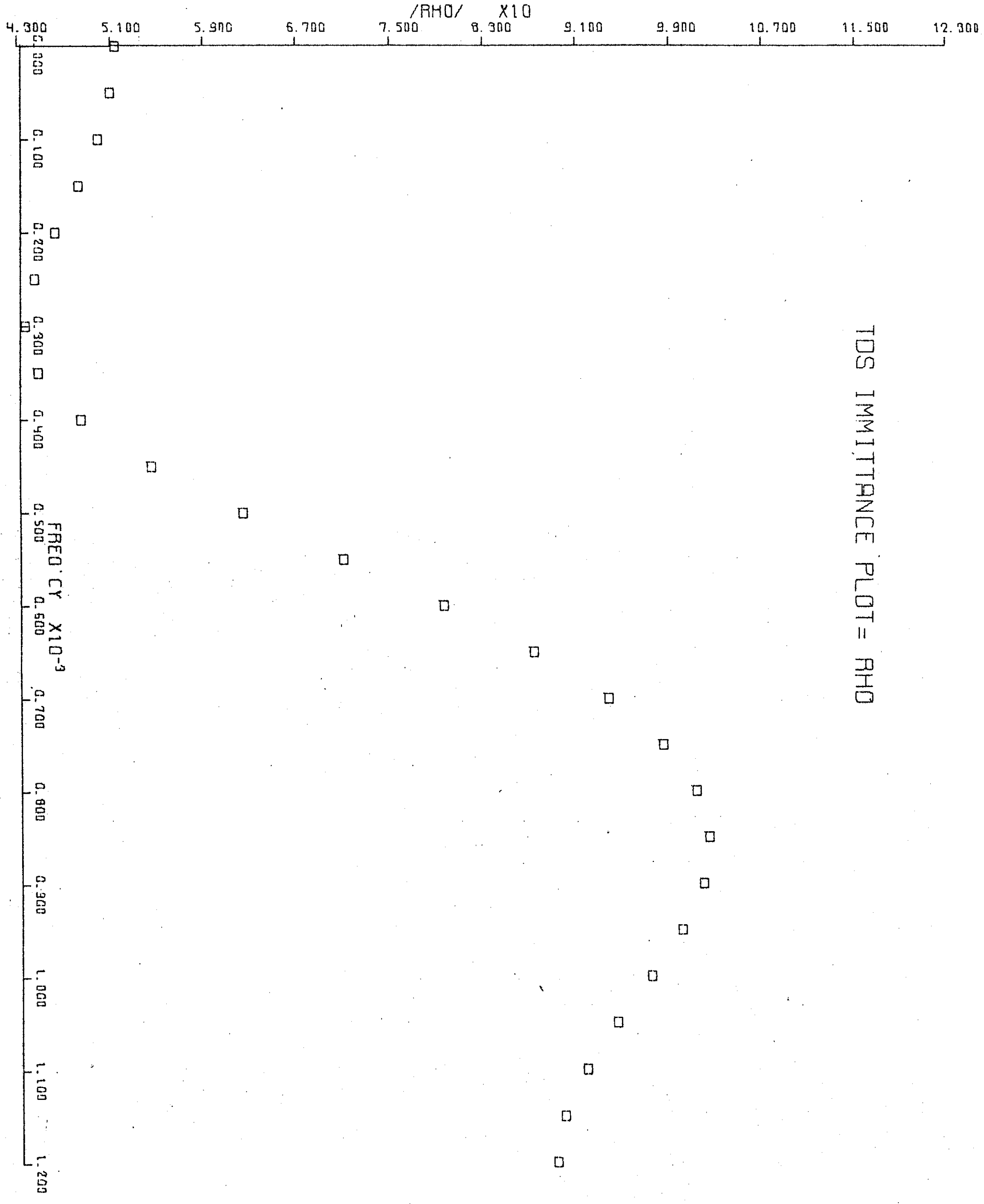
            R   90.024E-02    30.609E-02    61.219E-04    32.669E-01    16.334E 01
            Ø   -33.57        79.22         79.22         -79.22        -79.22


1200.000    X   72.728E-02    61.821E-03    12.364E-04    58.416E-02    29.208E 00
            Y  -51.954E-02    31.938E-02    63.876E-04   -30.179E-01   -15.089E 01       17.8314

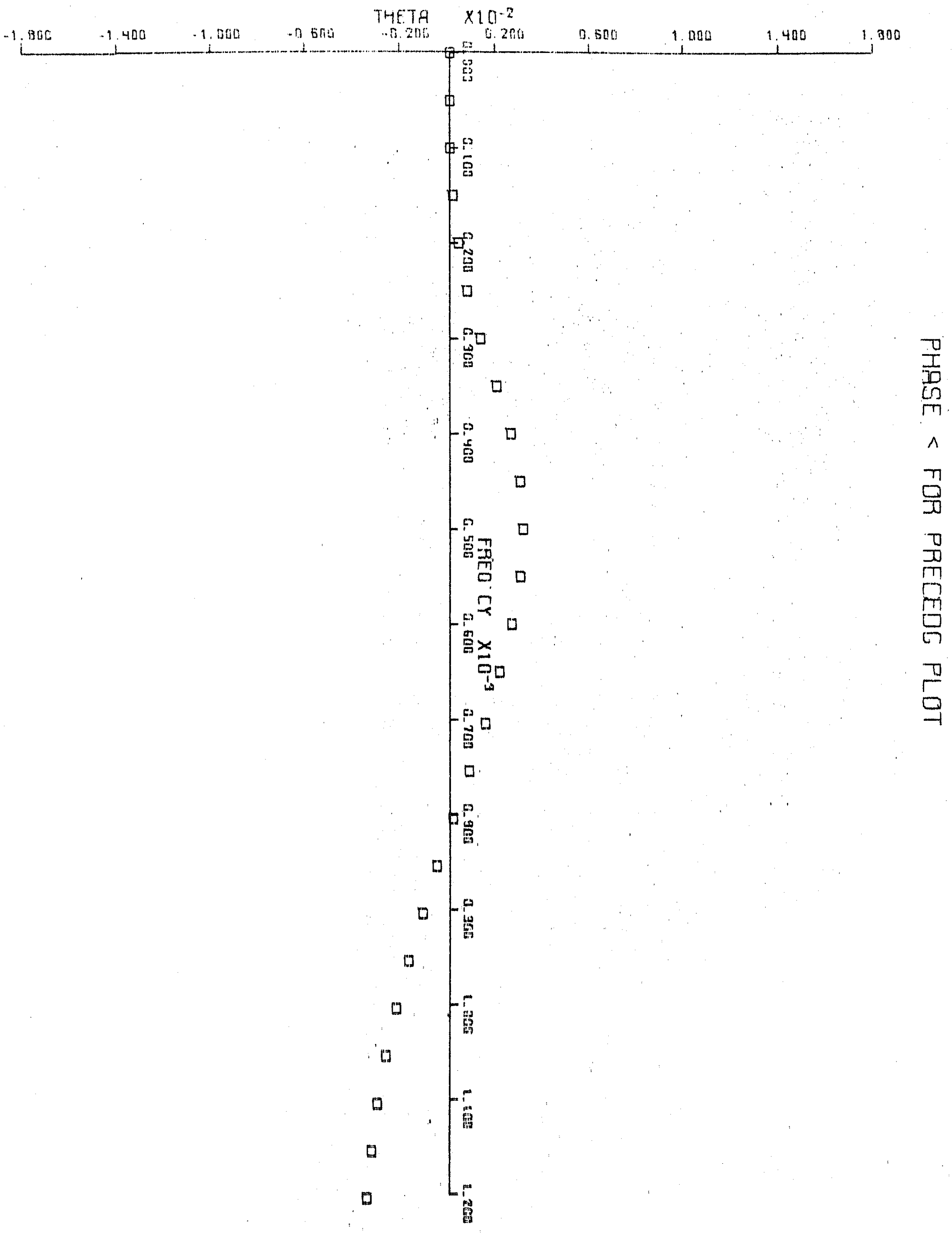
            R   89.379E-02    32.531E-02    65.062E-04    30.739E-01    15.369E 01
            Ø   -35.54        79.05         79.05         -79.05        -79.05
```

RE-RUN OF GMY DATA 1400 - .. ON EOIC. ARBITRARY TIME ZERO. IHWL - 13 DE 68!

TDR 1408 GMY 1/10/68 10/20 GREEN



APPENDIX B 2 cont.



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          FOURIER ANALYSIS       QUASI SPECTRA          TDR 1403  GMY 1/10/68 5/20  W200           13/11/68

             COLUMNS 4,5 ARE SPECTRUM REFERRED TO TDR 1406  GMY 1/10/68 5/20  W200

             COLUMNS 6,7 ARE SPECTRUM REFERRED TO TDR 1407  GMY 1/10/68 10/20  W05

    MHZ        AMPLITUDE     PHASE       AMPLITUDE     PHASE       AMPLITUDE     PHASE

      0          43.0000       0.0          0.9977       0.0          0.5850       0.0
    100          42.7030    -108.5          0.9984      -0.6          0.5920     126.5
    200          41.8996     143.2          0.9997      -1.2          0.6002    -108.3
    300          40.8139      35.5          1.0001      -1.9          0.5945      17.0
    400          39.7069     -71.6          0.9985      -2.6          0.5936     143.5
    500          38.7597    -178.4          0.9958      -3.1          0.5978     -90.7
    600          38.0050      74.8          0.9942      -3.6          0.5945      35.4
    700          37.3476     -32.3          0.9957      -3.9          0.5968     162.3
    800          36.6474    -139.6          0.9998      -4.4          0.6106     -71.7
    900          35.8002     112.9          1.0044      -5.1          0.6049      52.9
   1000          34.7711       5.3          1.0066      -6.0          0.5883    -179.4
   1100          33.5840    -102.4          1.0047      -7.0          0.6133     -52.1
   1200          32.2935     150.1          0.9992      -7.8          0.6065      70.8
   1300          30.9641      42.8          0.9920      -8.4          0.5695    -160.9
   1400          29.6620     -64.4          0.9852      -8.9          0.6005     -32.3
   1500          28.4473    -171.5          0.9799      -9.2          0.5989      89.2
   1600          27.3572      81.4          0.9769      -9.4          0.5450    -142.6
   1700          26.3869     -25.8          0.9768      -9.7          0.5830     -12.1
   1800          25.4863    -133.3          0.9797     -10.1          0.6057     106.4
   1900          24.5814     118.9          0.9845     -10.6          0.5158    -126.6
   2000          23.6111      10.7          0.9886     -11.6          0.5552       7.5
   2100          22.5526     -97.7          0.9883     -12.8          0.6188     123.4
   2200          21.4223     153.9          0.9811     -14.0          0.5017    -111.5
   2300          20.2532      45.5          0.9680     -15.1          0.5382      24.4
   2400          19.0711     -63.0          0.9525     -15.8          0.6255     139.5
   2500          17.8850    -171.5          0.9388     -16.2          0.4943     -97.8
   2600          16.6981      80.0          0.9289     -16.4          0.5015      39.8
   2700          15.5203     -28.6          0.9222     -16.6          0.6218     159.9
   2800          14.3643    -137.4          0.9178     -16.9          0.5075     -82.2
   2900          13.2214     113.5          0.9158     -17.1          0.4941      56.6
   3000          12.0418       3.9          0.9181     -17.4          0.6459     175.6
   3100          10.7439    -106.5          0.9259     -18.1          0.4736     -67.2
   3200           9.2590     142.7          0.9363     -19.6          0.4695      78.4
   3300           7.5849      32.2          0.9389     -22.4          0.7385    -170.2
   3400           5.8221     -76.6          0.9098     -26.8          0.4030     -56.7
   3500           4.1850     179.4          0.8181     -30.9          0.3870      99.9
   3600           2.9863      84.2          0.6854     -29.3          0.6676    -164.5
   3700           2.4675      -3.7          0.6205     -19.9          0.2780     -28.6
   3800           2.3978     -95.4          0.6454     -12.5          0.3372     128.5
   3900           2.3172     166.7          0.6676     -10.9          0.4541    -125.0
   4000           2.0900      69.5          0.6306      -9.4          0.2765       2.8
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          FOURIER ANALYSIS       QUASI SPECTRA          TDR 1404 GMY  1/10/68 5/20   WN5           13/11/68

             COLUMNS 4,5 ARE SPECTRUM REFERRED TO TDR 1401  GMY 1/10/68 5/20   WN5

             COLUMNS 6,7 ARE SPECTRUM REFERRED TO TDR 1402  GMY 1/10/68 5/20   W05

    MHZ        AMPLITUDE     PHASE       AMPLITUDE     PHASE       AMPLITUDE     PHASE

      0          71.5000    -180.0          0.9986       0.0          0.9986    -180.0
    100          71.0545      69.7          0.9986       0.6          0.9983    -179.6
    200          69.8453     -40.2          0.9987       1.3          0.9980    -179.1
    300          68.1975    -149.7          0.9994       1.9          0.9985    -178.6
    400          66.4887     101.2          1.0009       2.6          1.0002    -178.1
    500          64.9865      -7.6          1.0026       3.2          1.0024    -177.7
    600          63.7590    -116.3          1.0036       3.8          1.0036    -177.3
    700          62.6987     134.8          1.0035       4.4          1.0033    -176.9
    800          61.6217      25.6          1.0028       5.1          1.0024    -176.4
    900          60.3634     -83.8          1.0025       5.8          1.0026    -175.9
   1000          58.8272     166.6          1.0031       6.6          1.0045    -175.3
   1100          56.9980      57.0          1.0041       7.3          1.0069    -174.8
   1200          54.9450     -52.4          1.0043       7.9          1.0074    -174.4
   1300          52.8134    -161.7          1.0029       8.6          1.0046    -173.9
   1400          50.7871      89.3          1.0004       9.3          0.9997    -173.3
   1500          49.0110     -19.5          0.9981      10.2          0.9965    -172.3
   1600          47.5090    -128.4          0.9975      11.1          0.9985    -171.3
   1700          46.1617     122.4          0.9982      11.9          1.0053    -170.4
   1800          44.7796      12.9          0.9986      12.6          1.0128    -169.8
   1900          43.2239     -96.9          0.9977      13.4          1.0157    -169.6
   2000          41.4907     153.4          0.9961      14.2          1.0116    -169.4
   2100          39.6984      43.8          0.9963      15.1          1.0032    -168.8
   2200          37.9893     -65.7          1.0012      16.1          0.9966    -167.9
   2300          36.4155    -175.3          1.0109      16.9          0.9962    -166.9
   2400          34.8999      74.8          1.0219      17.3          1.0019    -166.0
   2500          33.3045     -35.5          1.0288      17.3          1.0087    -165.7
   2600          31.5374    -146.1          1.0277      17.2          1.0110    -165.6
   2700          29.6041     103.1          1.0197      17.4          1.0068    -165.5
   2800          27.5658      -7.9          1.0103      18.1          1.0000    -165.1
   2900          25.4464    -119.2          1.0050      19.2          0.9966    -164.4
   3000          23.1762     129.0          1.0063      20.3          1.0006    -163.6
   3100          20.6310      16.7          1.0119      21.4          1.0112    -163.1
   3200          17.7435     -95.5          1.0164      22.3          1.0230    -163.1
   3300          14.6094     153.3          1.0151      23.3          1.0286    -163.3
   3400          11.5381      45.0          1.0091      25.1          1.0226    -163.4
   3500           9.0272     -58.3          1.0174      28.5          1.0120    -162.2
   3600           7.5695    -156.4          1.0819      32.3          1.0290    -159.4
   3700           7.1697     105.7          1.2061      32.8          1.0949    -157.6
   3800           7.2264       3.3          1.3061      29.2          1.1755    -158.1
   3900           7.1825    -102.9          1.3355      24.8          1.2394    -159.9
   4000           6.8839     150.1          1.3183      21.6          1.2852    -162.1
```
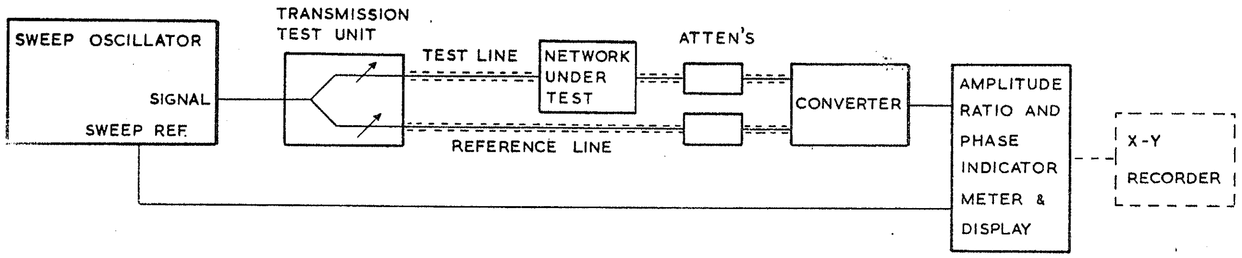

(a) TRANSMISSION MEASUREMENTS



(b) REFLECTION MEASUREMENTS

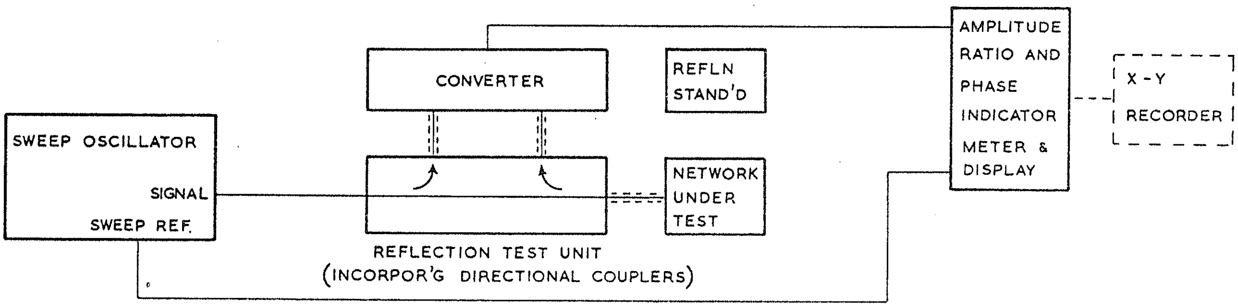
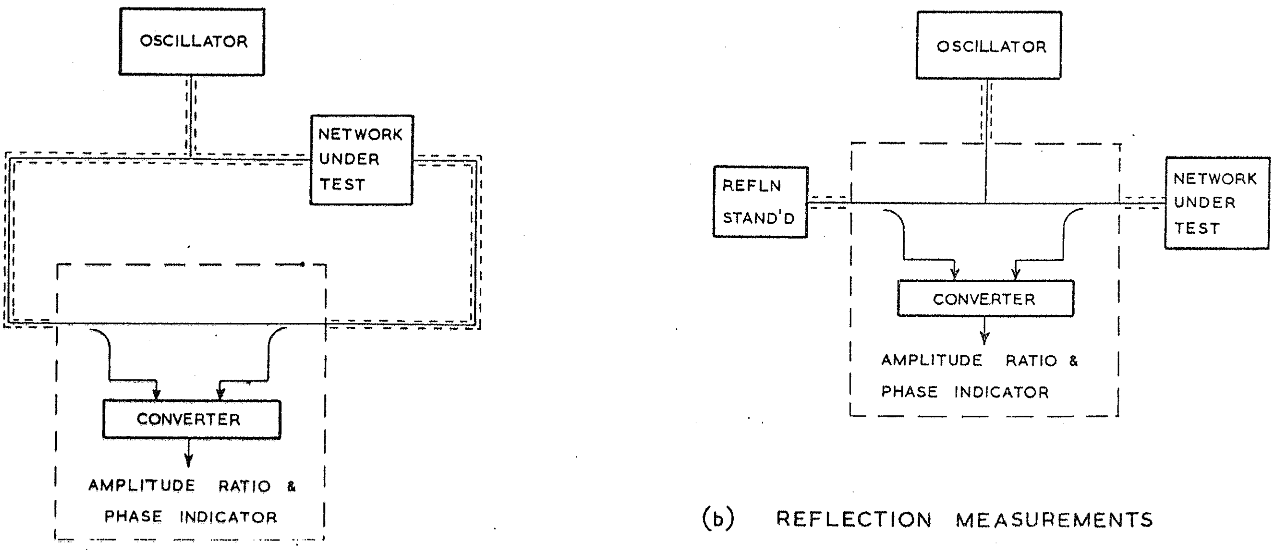


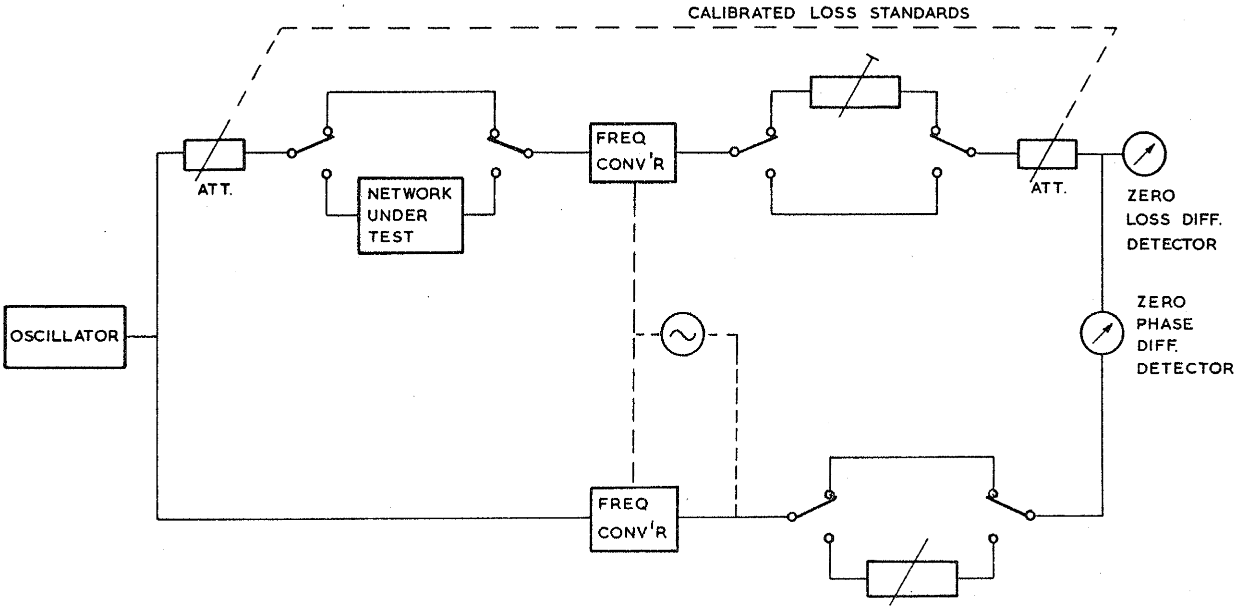
FIG. 1. EXPERIMENTAL ARRANGEMENT FOR F.D. TRANSMISSION AND REFLECTION MEASUREMENTS BASED UPON THE HEWLETT PACKARD NETWORK ANALYZER.



(b) REFLECTION MEASUREMENTS

(a) TRANSMISSION MEASUREMENTS

FIG. 2. EXPERIMENTAL ARRANGEMENT FOR TRANSMISSION AND REFLECTION MEASUREMENTS BASED UPON Z - G DIAGRAPHS.



ALL SWITCHES OPERATE SYNCHRONOUSLY AT 60 Hz

FIG. 3. SIMPLIFIED BLOCK DIAGRAM OF B.T.L. LOSS AND PHASE MEASURING SET

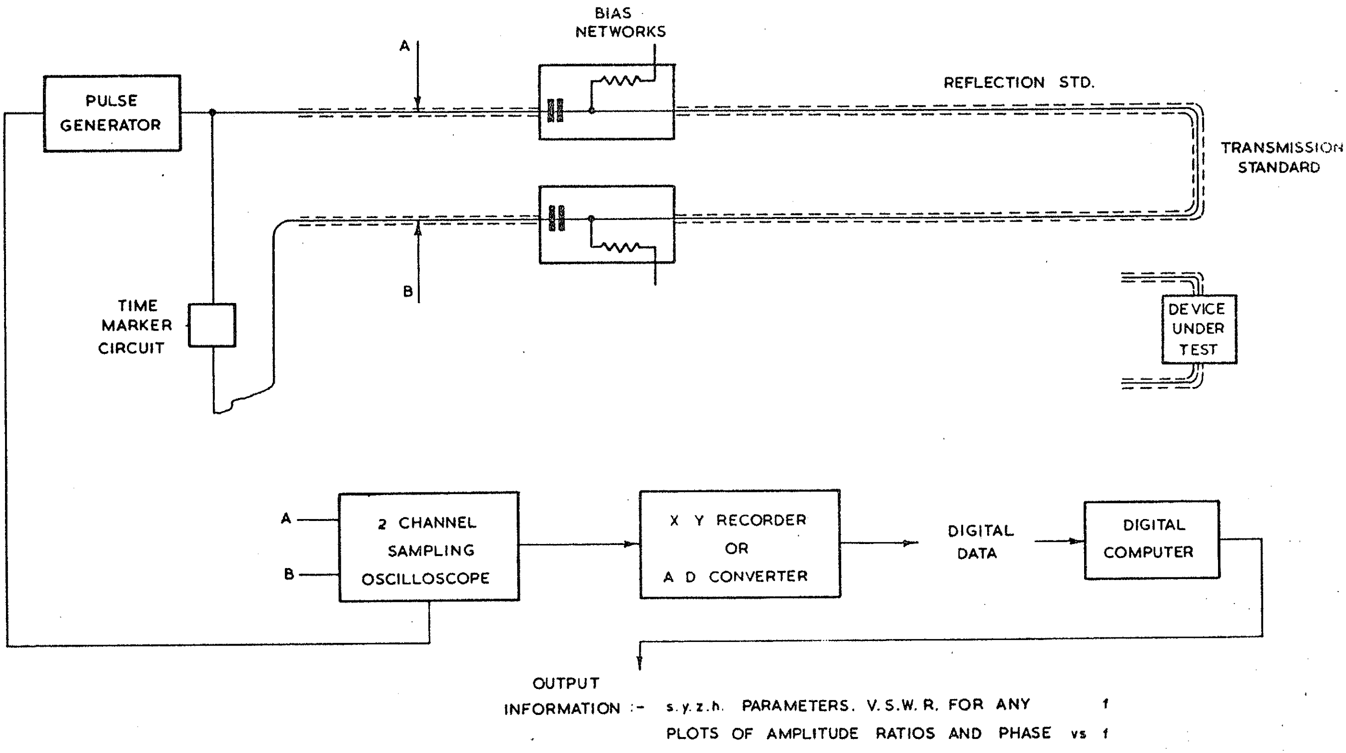


FIG.4. BLOCK DIAGRAM OF T.D.S. SET.