**AFRL-SN-RS-TR-2006-44**
**In-House Final Report**
**February 2006**

# MODULE EVALUATION

*APPROVED FOR PUBLIC RELEASE; DISTRIBUTION UNLIMITED.*

**AIR FORCE RESEARCH LABORATORY**
**SENSORS DIRECTORATE**
**ROME RESEARCH SITE**
**ROME, NEW YORK**

Although this report references limited and classified documents (*), listed on pages 4, 14, 41 & 90, no limited information or classified information has been extracted.

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This report describes the research performed to develop and demonstrate various testing methodologies for the evaluation and characterization of Transmit/Receive (T/R) modules for phased array radars. Discussed are techniques for characterizing T/R modules in transmit and receive modes under ideal and emulated operation environments. Further, techniques for life testing these modules are discussed. Data from the evaluation of typical T/R modules is provided to show the capabilities of these techniques and the characteristics of T/R modules developed during the early and mid 1980's. Data provided shows the performance in terms of gain and phase for both transmit and receive, as well as the receive noise figure. Further, data showing how modules degrade as a function of time and temperature is provided.

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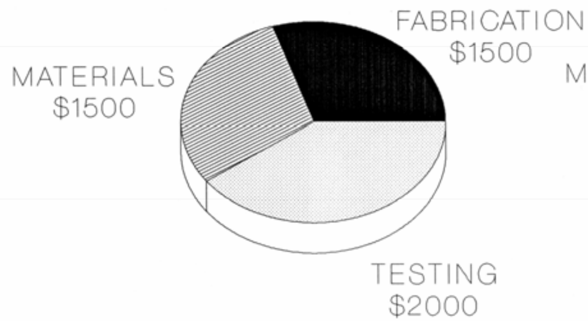
# 1.0 INTRODUCTION

Since the late 1970's, the Sensor's Directorate of the Air Force Research Laboratory (a.k.a. Rome Laboratory (RL) from 1991-1997 and Rome Air Development Center (RADC) from 1950 to 1990), and other agencies have been developing Monolithic Microwave Integrated Circuit (MMIC) technology for use within Transmit/Receive (T/R) modules for phased array radars. The impetus for using MMIC technology in T/R modules is to reduce the cost, size and weight and to increase the performance and reliability over what can be achieved utilizing other technologies. By judiciously formulating a testing methodology that utilizes the right type of testing at a critical location within the fabrication process, a major cost savings with an increase in performance and reliability can be achieved. Table 1.1 illustrates a documented example where such a methodology had an impact on the cost of a T/R module. The module is from the Module Validation (MODVAL) contract with Raytheon in which over 250 T/R modules at X band were fabricated. Note the percentage of testing cost and the impact of adding on-wafer pulsed RF testing would have had to the total per module cost. By putting more test up front (and screening out bad power amplifiers), the amount of rework was significantly decreased and the overall cost per good module was almost cut in half.

To provide for a continual and progressive development of the more cost effective testing methods for T/R modules, RL initiated an in-house program in 1980 entitled "Module Evaluation". Its purpose was two fold, (1) to develop and demonstrate novel testing techniques for T/R modules, and (2) to determine the performance capabilities of specific T/R modules and their sub-components. Over the eleven year life of the effort, various testing techniques were developed and evaluated. The demonstration vehicles for validating those techniques were T/R modules, deliverables from research and development contracts.

MODVAL MODULE COST
(QTY OF 250 MODULES)

ACTUAL COST




PROJECTED COST
WITH ON-WAFER TEST

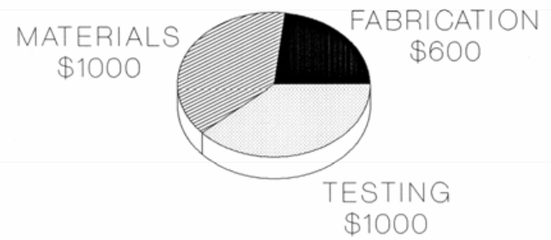



**FIGURE 1.1.1 - MODVAL T/R MODULE COST BREAK-OUT**

# 2.0 TEST SYSTEM DESCRIPTION

The test system developed is actually a number of test systems tied together and collocated within the same facility. These systems include the following:

Pulsed Power Test System (MEL-2)
Long Term Performance Test System (MELTS)
Pulsed Phase Measurement System

Each of these systems meets a need that was not previously addressed by industry. All are computer controlled using a Motorola 68000 computer with Basic as the operating system. The specific instrument controllers are Hewlett Packard 9000 Series 200 and 300 computers utilizing HPBasic/WS operating systems versions 4.0 and 5.0 respectively.

## *2.1 PULSED POWER TEST SYSTEM (MEL-2)*

Experience from the Pave Paws radar development showed that testing under actual radar operating conditions was needed to insure that T/R modules actually perform as designed when placed within an operational system. When Pave Paws was first turned on, a significant portion of the hybrid T/R modules burned out. The modules had been tested as good using CW small signal measurement equipment. However, when first operated in the actual system, the modules tended to burn up due to the complex impedance caused by their operation under pulsed conditions. Pulse testing had not performed on these modules because there was no commercial Automatic Test Equipment (ATE) capable of subjecting a Device Under Test (DUT) to a pulsed power waveform to measure their performance. The solution included a survey of the possible testing techniques and the development and demonstration of the most promising technique. A list of the surveyed techniques with their most prevalent assets and drawbacks is presented in Table 2.1.1. The technique chosen as the most promising involved the phase discriminator.

The first pulsed power ATE system developed became commonly known as MEL (short for Module Evaluation Lab). It was split into two subsystems; the Automatic Pulsed Measurement System (APMS) and the Noise Figure Measurement System (NFMS). A block diagram of this early test system is presented in Figure 2.1.1. This system was not fully automated and had limitations in operating frequency. It was highly reconfigurable by manually changing the microwave plumbing and could be set up to do a variety of experiments. Its full capabilities were outlined in RADC-TR-83-21 “Monolithic Amplifier Evaluation” by Edward J. Jones, RADC/OCTP. A picture of this early system is shown in Figure 2.1.2.

The latest version of MEL is MEL-2, the second generation module evaluation system. It is also split into two subsystems, APMS and NFMS. MEL-2 is fully automated and incorporates all of the advances identified during the development of MEL. A block

diagram of MEL-2 is depicted in Figure 2.1.3 and a list of its specification is presented in Table 2.1.2. The system is constructed with the capability to operate from 1 to 12 GHz in both transmit and receive. Detailed information is presented in RADC-TR-89-225 * "Module Evaluation Lab (MEL-2 Report)" by Atlantic Research Corporation. A picture of MEL-2 is shown in Figure 2.1.4.

| | Modified ANA | Four Port | Six Port | Digital Detection |
|---|---|---|---|---|
| Cost | **Total $180K W/o ANA $20K** | **$95K** | **$130K** | **$180K** |
| Frequency Range | **45 MHz to 110 GHz** | **1 GHz to 18 GHz** | **1 GHz to 110 GHz** | **500 MHz to 18 GHz** |
| Pulse Width | **>200 usec** | **>1 usec** | **Power Meter >500 msec Diode > 1 usec** | **> 1 usec** |
| Speed | **1 sec** | **50 msec** | **Power Meter 4 sec Diode 0.5 sec** | **100 msec** |
| Intra-pulse Measurement | **NO** | **Yes** | **Yes, but not with Power Meter sensors** | **Yes** |
| Amplitude Accuracy | **± 0.1 dB** | **< 1 dB peak w/o correction < 0.5 dB corrected** | **Power Meter < 0.03 dB Diode < 0.3 dB** | **± 0.06 dB RMS** |
| Amplitude Repeatability | **< 0.04 dB** | **< 0.5 dB** | **< 0.003 dB** | |
| Phase Accuracy | **± 0.15 deg** | **< 7 deg peak w/o correction 0.67 deg RMS 1.0 deg peak corrected** | **Limited sensor & Calc** | **± 0.3 deg RMS** |
| Phase Repeatability | **< 0.1 deg** | **< 0.4 deg** | **Dependent on Amplitude Repeatability** | |
| Notes | **No Warranty Own Service** | **Temp Control Required 20 dB Dynamic Range** | **Temp Control Required 60 dB Dynamic Range** | **Not Yet Built** |

* Table Compiled in 1987

TABLE 2.1.1 - SURVEYED TESTING TECHNIQUES

* RADC-TR-89-225 is Distribution limited to DOD and Their Contractors - Export Control

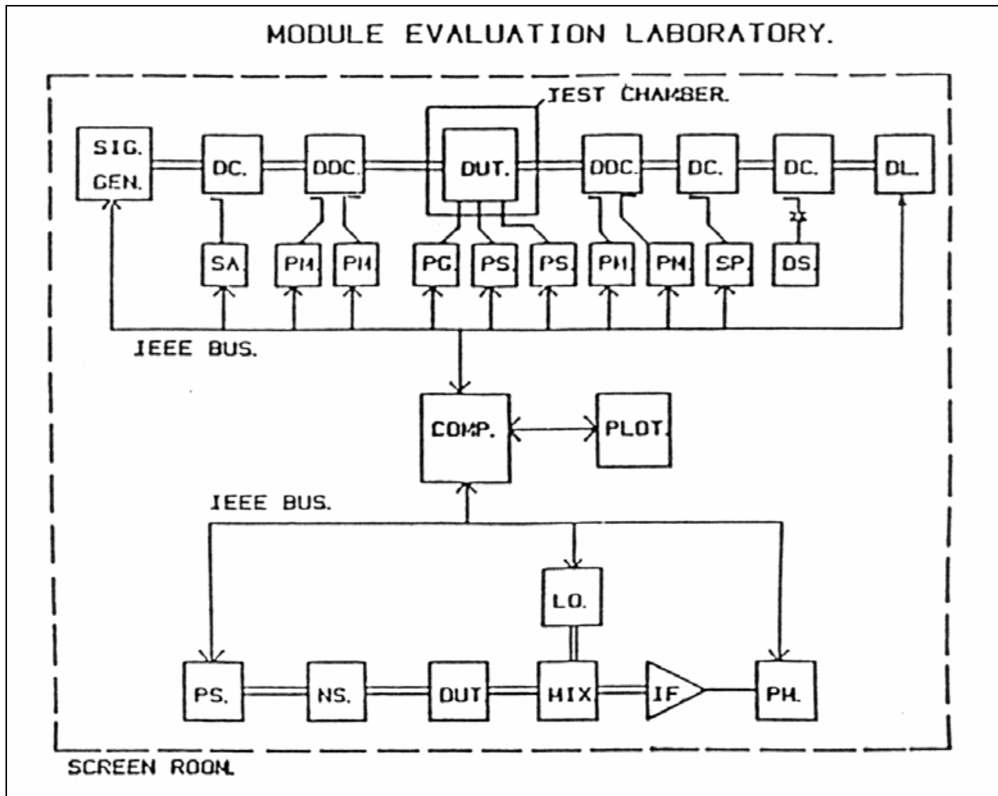



FIGURE 2.1.1 - BLOCK DIAGRAM OF MEL

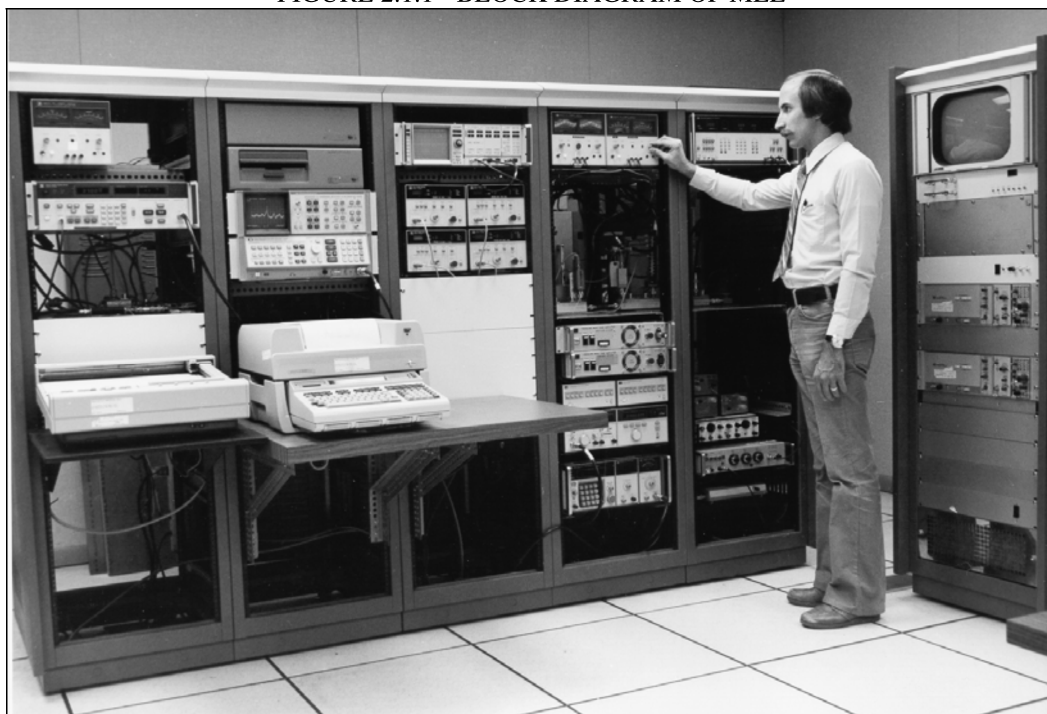


FIGURE 2.1.2 - EARLY PICTURE OF MEL

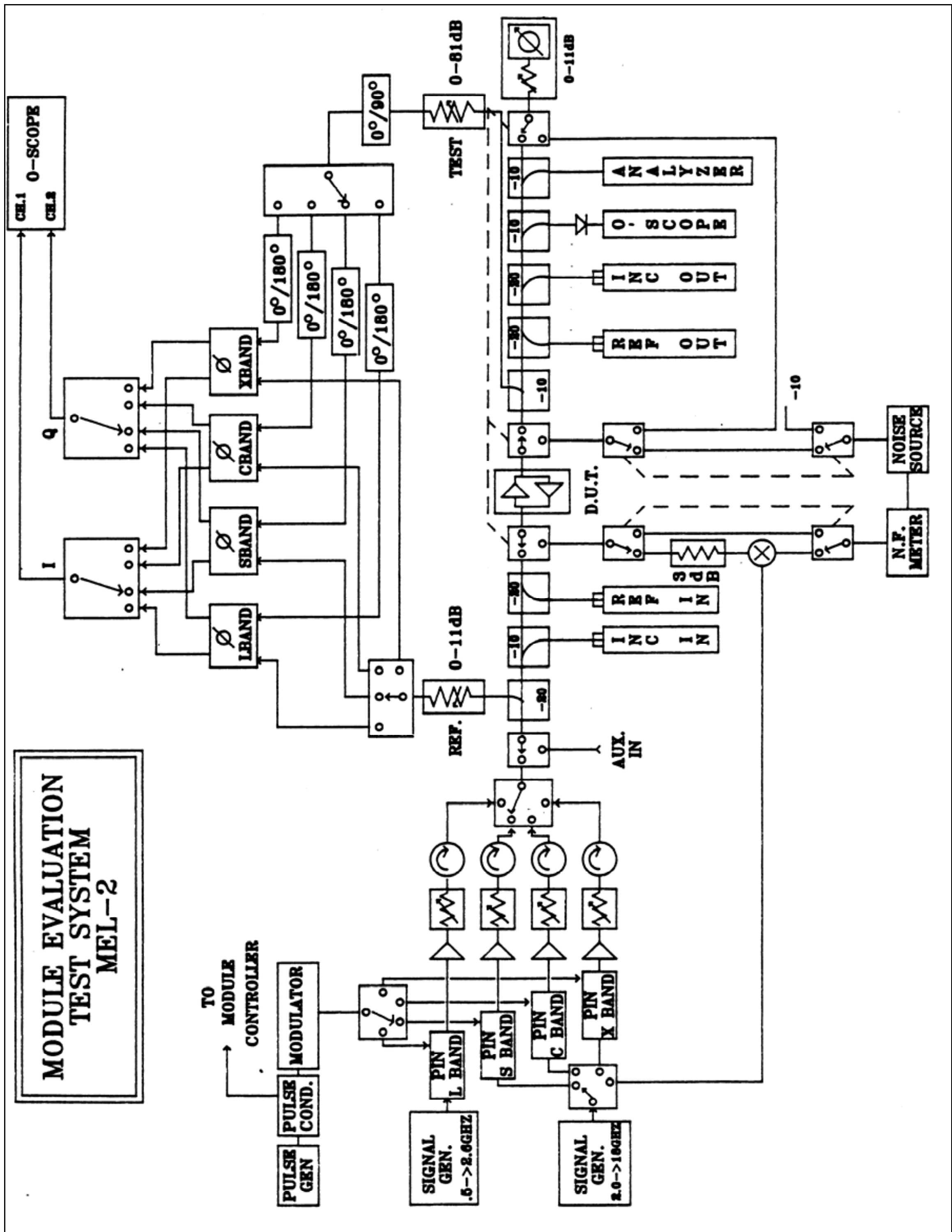



FIGURE 2.1.3 – BLOCK DIAGRAM OF MEL-2

MEL-2 System Specifications

Electrical Characteristics

Operating Mode

1. Remote - Computer controlled for measurement sequence
2. Local - Used primarily for troubleshooting or specialized test

Interface - IEEE 488/HPIB
Nominal Measurement Time - 10 sec./data pt.
DC Bias Control 0 - 60 V
0 - 12 A

Primary Power

| | |
|---|---|
| Voltage | 120 Vac ± 10% |
| Number of Breakers | Four at 20 A Each |
| Frequency | 50/60 Hz |
| System Power | 4800 W (maximum) |
| System Controller and Peripherals | 1000 W (maximum) |

Service Conditions

| | |
|---|---|
| Operation | Continuous |
| Temperature | $0^{\circ}$ - $+55^{\circ}$ C |

Physical Characteristics

Dimensions

Height - 71"
Width - 112"
Depth - 33"

Approximate weight - 1800 lbs. (Controller not included)

Environmental

Temperature

| | |
|---|---|
| No Load | $-30^{\circ}$ to $30^{\circ}$ C |
| 5 Watt Load | $-20^{\circ}$ to $30^{\circ}$ C |

Low Temperature Cycle Time from Ambient - 30 minutes

| | |
|---|---|
| Source | Thermoelectric Modules |
| Cooling | Forced Air |
| Accuracy | $\pm 1^{\circ}$ C |

TABLE 2.1.2 – MEL-2 SPECIFICATION (page 1 of 2)

Noise Figure Measurement

Frequency Range

Fundamental* 10 to 1500 MHz

* Extended Range is accomplished by mixing techniques, see H.P. 8970A Noise Figure Operating and Service Manual.

Nominal Operating Input Power + 10dBm

| | |
|---|---|
| Dynamic Range | 30 dB |
| Resolution | 0.01 dB |

R.F. Transmit/Receive

Frequency Range — 1.0 to 12.0 GHz (Four Bands)

Maximum Drive Power
[Average Power at 1dB Compression Point]
- L-Band - 20 dBm
- S-Band - 18 dBm
- C-Band - 17 dBm
- X-Band - 10 dBm

Dynamic Range (All Bands)

| | |
|---|---|
| From nominal setting -20dBm | ±6 dB |

Modulation

| | |
|---|---|
| Pulse Width | 1 us (minimum) |
| Duty Cycle | 50% (maximum) |

Pulse Repetition Frequency 1 kHz - 10 MHz

Dynamic Load

| | |
|---|---|
| VSWR (Nominal) Load/Source | 1.2:1 to 3.0:1 |
| Phase | $0^\circ$ to $360^\circ$ in $90^\circ$ steps |

Accuracy (Rms - Midband Dynamic Range)

| | |
|---|---|
| Phase | 1.0 deg |
| Amplitude | <0.5 dB |

Repeatability (Rms - Midband Dynamic Range)

| | |
|---|---|
| Phase | 0.5 deg |
| Amplitude | 0.2 dB |

TABLE 2.1.2 – MEL-2 SPECIFICATION (page 2 of 2)

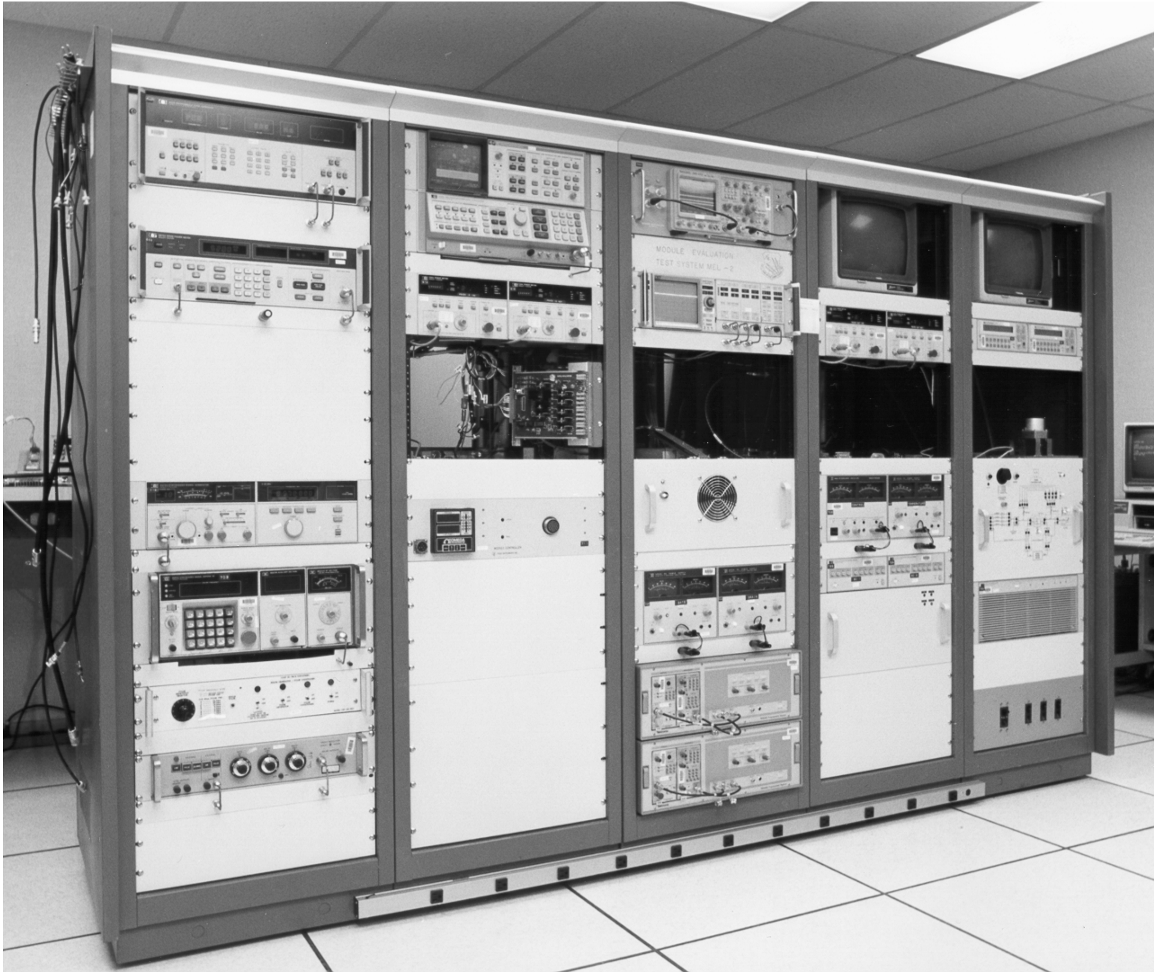



FIGURE 2.1.4 – PICTURE OF MEL-2

### 2.1.1 PHASE DISCRIMINATOR CIRCUIT

The heart of both MEL and MEL-2 is the use of the phase discriminator to measure the complex (amplitude and phase) transfer function of the DUT. This device takes a reference and test signal (signal sampled prior to and after the DUT respectively) as input and provides an I (in-phase) and Q (quadrature) signal as output. The I and Q voltage signals are then digitized and the computer calculates the DUT's transfer function. The specific phase discriminators used in MEL-2 are made by Anaren (models 2A0755, 2A0756, 2A0757, 2A0758) and operate over an octave bandwidth; L Band 1-2 GHz, S Band 2-4 GHz, C Band 4-8 GHz and X Band 8-12.4 GHz.

The phase discriminator is a direct conversion device that converts the microwave signal directly to base band video using quadrature couplers and diode detectors. The four voltages that are the output of the diode detectors are combined in a video amplifier section to form the I and Q signals. A block diagram of this setup is shown in Figure 2.1.5. A picture of a Phase Discriminator is shown in Figure 2.1.6. With a given test and reference signal with amplitudes A and B respectively and with a phase difference of $\theta$, the following voltages would be the output of an ideal set of diode detectors:

$V_1 = (A^2+B^2) + 2AB \cos\theta$
$V_2 = (A^2+B^2) - 2AB \cos\theta$
$V_3 = (A^2+B^2) + 2AB \sin\theta$
$V_4 = (A^2+B^2) - 2AB \sin\theta$

The video section then converts these four voltages to I and Q voltage signals by performing the following math functions.

$I = V_1 - V_2 = 4AB \cos\theta$
$Q = V_3 - V_4 = 4AB \sin\theta$

With these two equations, the amplitude and phase transfer function of the DUT can be calculated. With the added priori knowledge of the input power to the device, the output power can also be calculated. Unfortunately, there is no such thing as an ideal phase discriminator. The "real" version has errors and limitations. To correct for these errors, a technique developed by Atlantic Research Corporation is utilized. This technique utilizes measured and calculated coefficients in a matrix that is accessed during the measurement process. The formula to model these errors are as follows:

$I/B^2 = L_1 + L_2 + L_3R \cos\theta + L_4R \sin\theta$
$Q/B^2 = H_1 + H_2 + H_3R \cos\theta + H_4R \sin\theta$

Where:
A = DUT output signal amplitude
B = DUT input signal amplitude
R = A/B
$\theta$ = DUT input to output relative phase
L = modeling coefficients for I channel
H = modeling coefficients for Q channel

Details of this technique are described in two papers presented to the Automated RF Techniques Group at the Spring 86 and Spring 87 conferences. The papers were "Coherent (I/Q) Detector Performance Under Extended Drive Signal Conditions" and "Application of Phase Discriminator Error Model to Pulsed RF Measurement System Calibration" respectively.

Because of the use of non-linear devices (diodes) as the voltage detectors, various distortions occur during the measurements. Two sources of distortions are most common; 1) providing to much or to little power to the input of the phase discriminators (operating the diode in the non-linear range), and 2) providing a unbalanced set of inputs. In figure 2.1.7, these non-linear effects are illustrated. The potential resultant phase errors are illustrated in figure 2.1.8.

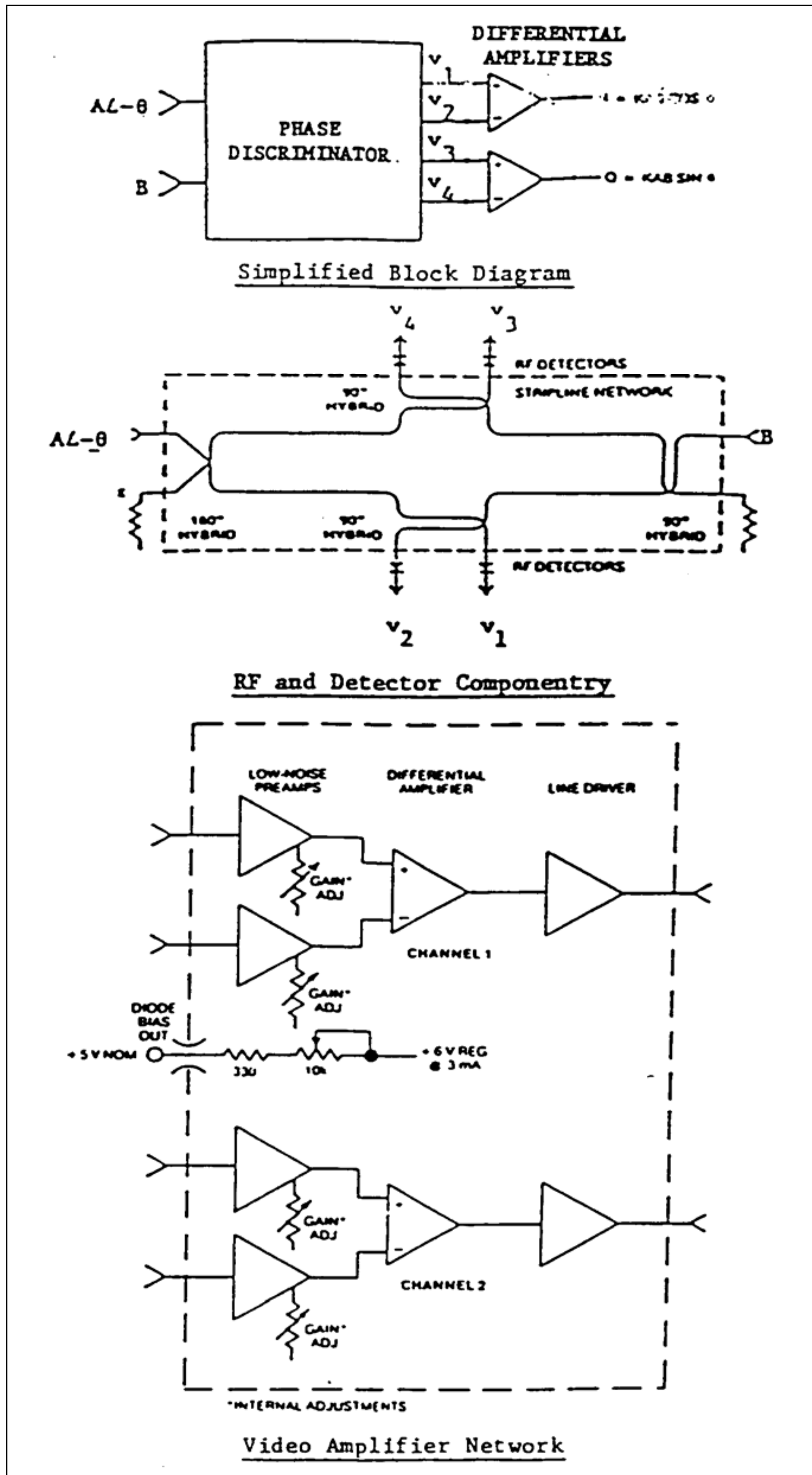



FIGURE 2.1.5 - BLOCK DIAGRAM OF PHASE DISCRIMINATOR

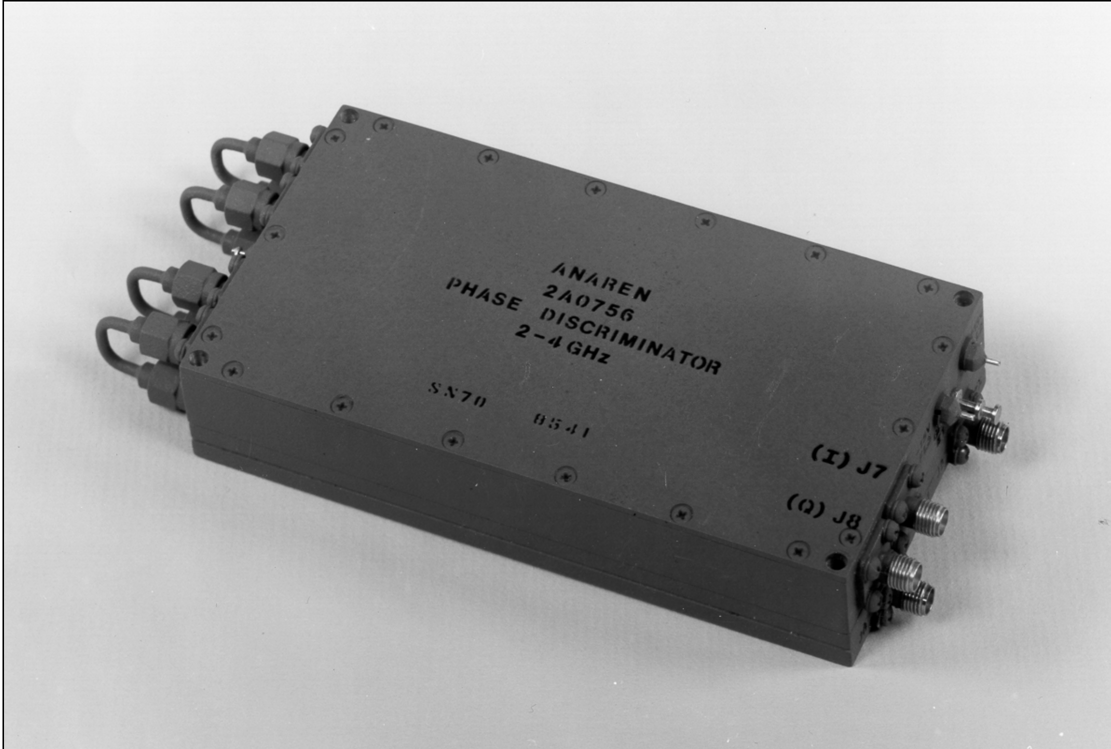


FIGURE 2.1.6 - PICTURE OF A PHASE DISCRIMINATOR

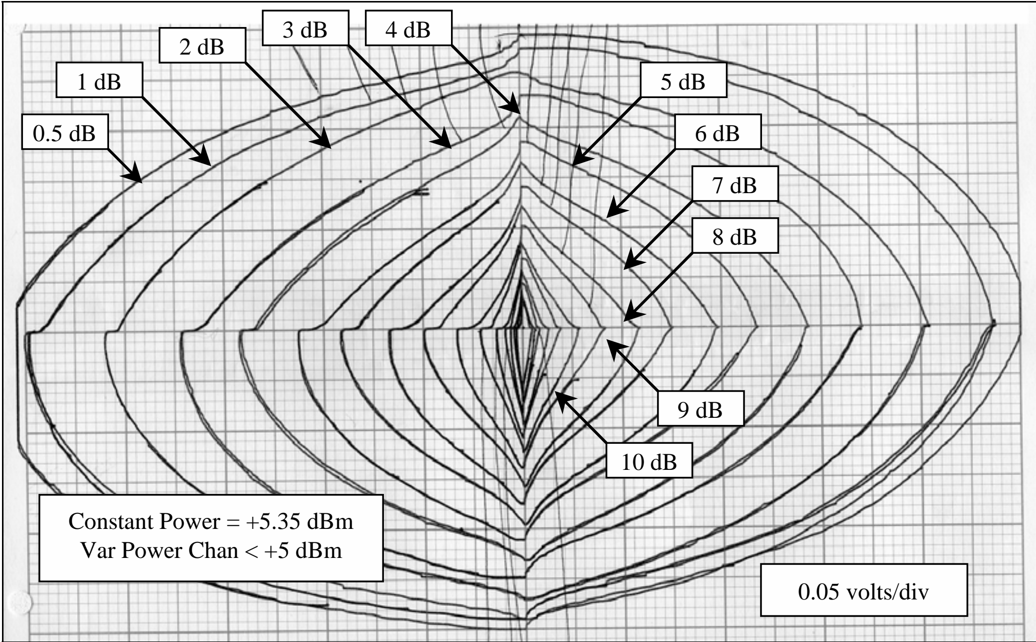


FIGURE 2.1.7 – VOLTAGE OUTPUTS VERSE POWER INPUTS

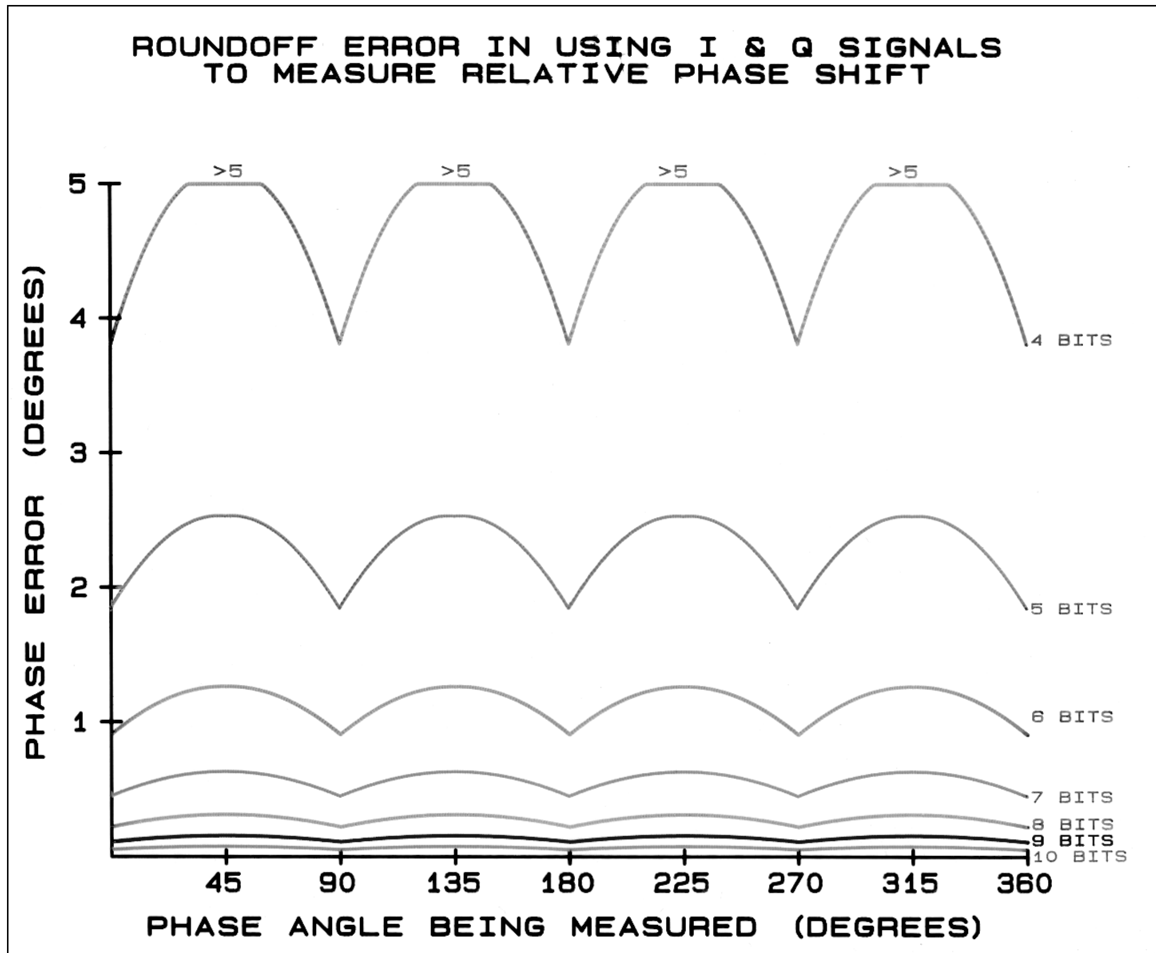



FIGURE 2.1.8 – MEASURED PHASE ERROR RESULTING FROM ROUNDOFF ERRORS

## 2.1.2 RADAR SYSTEM EMULATION

One of the important points to remember is that the reason for testing in a pulsed mode is to determine how the DUTs will operate in a fielded system. What better way to determine that operation, than to operate the devices as they would be operated in such a system. To accomplish this operation, the system has been configured to provide the electrical and mechanical environment that the DUT is projected to see in a fielded system. The environments include various parameters in the dimensions of temperature, atmospheric pressure, load VSWR (Voltage Standing Wave Ratio), basis voltages, microwave excitation (waveform and drive level), and DUT state control. All of which, except the temperature and atmospheric pressure environments, are computer controlled.

### *2.1.2.1 TEMPERATURE AND ATMOSPHERIC PRESSURE*

The temperature and atmospheric pressure environment is controlled manually using various methods. All methods involve the addition of a special apparatus that must be inserted into the basic MEL-2 configuration for the specific experiment. Available equipment includes a thermal plate, an oven, and a space chamber.

A picture of the Thermal Plate is shown in Figure 2.1.9. The plate will be replacing the nitrogen bath technique described in Section 3.3.4. A combination of liquid nitrogen and heating coils are embedded within the base plate to maintain the proper temperature. Also, the thick baseplate allows for holes to be drilled and tapped to mount DUTs.

Figure 2.1.8 shows a picture of the space chamber. The chamber has two access ports that can provide DC, RF, and gas/liquid interface points to experiments within. Also, shown in the picture is the first item that was tested. Four "dummy" MODVAL T/R modules were placed in an emulated space environment to test a new heat removal technique. That experiment is fully documented in RADC-TR-90-56* entitled "Transmit/Receive Module Thermal Dissipation Measurements".

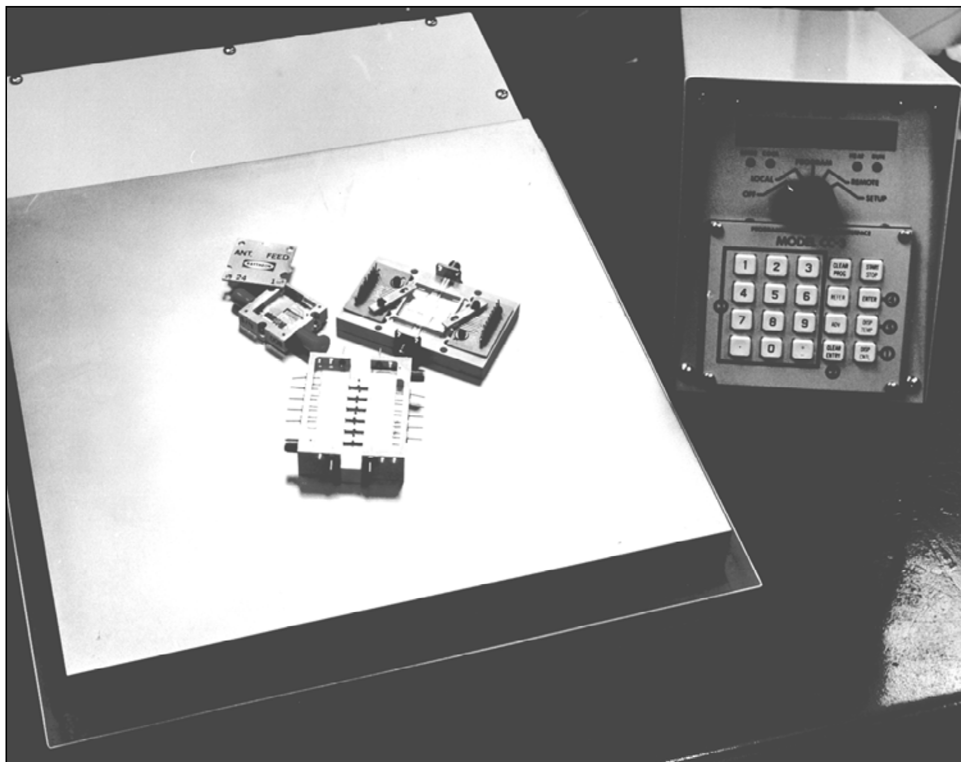



FIGURE 2.1.9 – PICTURE OF THERMAL PLATE

* RADC-TR-90-56 is Distribution limited to U.S. Government and Their Contractors - Export Controlled.

FIGURE 2.1.10 – SPACE CHAMBER WITH THERMAL TEST FIXTURE

### *2.1.2.2 LOAD VSWR*

To provide a variable complex load on the antenna port of the DUT, a dynamic load was developed and implemented. This load provides VSWRs from 1.2:1 to 3.0:1 to emulate the load that a T/R module would experience in a phase array while it is electronically scanned off bore sight. The apparent VSWR that a DUT would see in an actual system is the signal coupled into its antenna element from an adjacent element that is electrically not one half wave length away in phase (due to phase shifter settings needed to scan the beam). This effect is called mutual coupling. In MEL-2 this VSWR is emulated by reflecting a proportionate amount of the DUT's signal back into itself. The device that performs this function is called a dynamic load and is made up of a programmable attenuator, a coaxial phase shifter and a short circuit. Figure 2.1.11 provides a pictorial representation of this circuit. Note that the programmable attenuator sets the diameter for the VSWR circle on the Smith chart and the coaxial phase shifter moves the complex impedance around that circle. A picture of the phase shifter with a stepper motor mounted on it is shown in Figure 3.1.12.

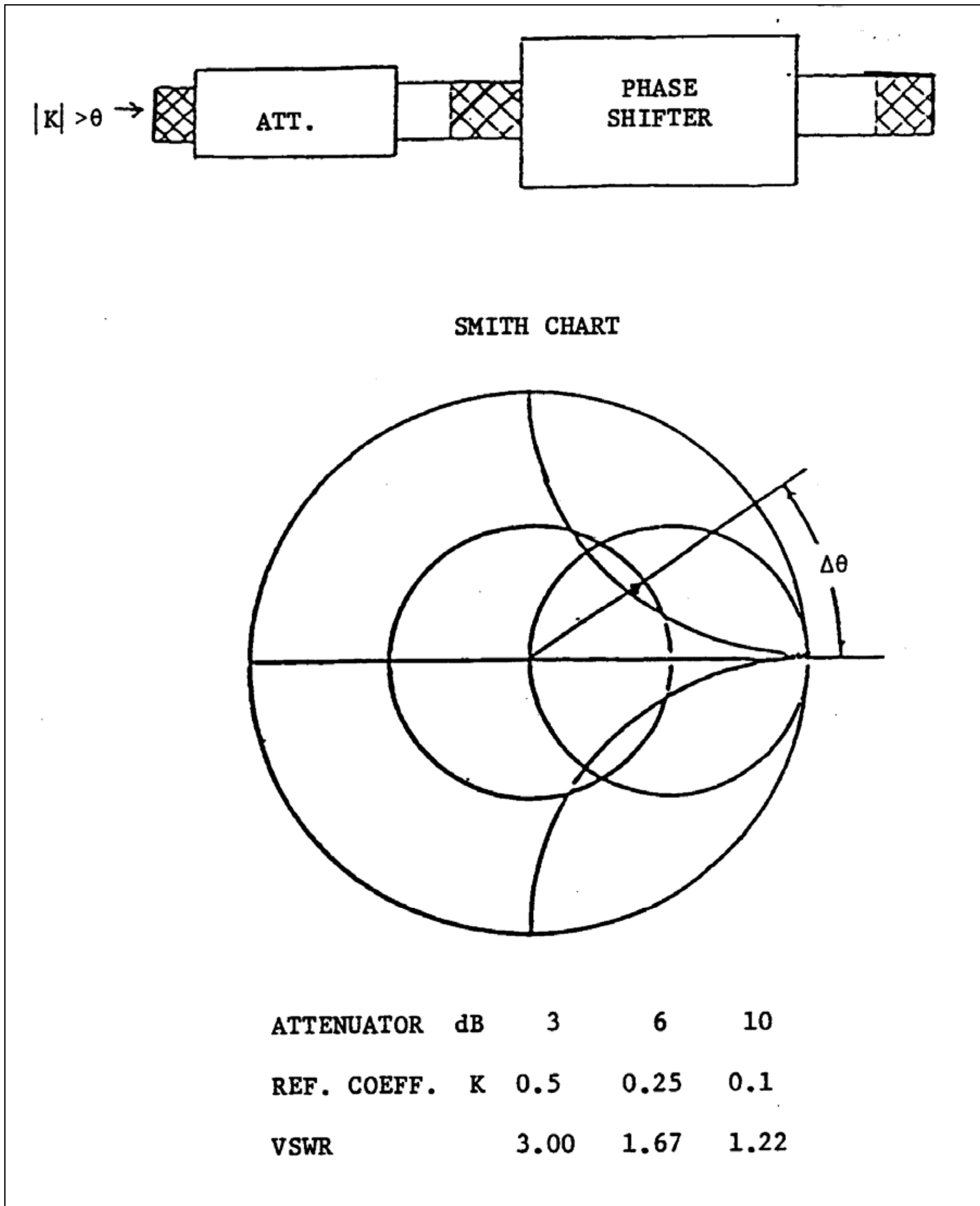



FIGURE 2.1.11 – DYNAMIC LOAD CIRCUIT

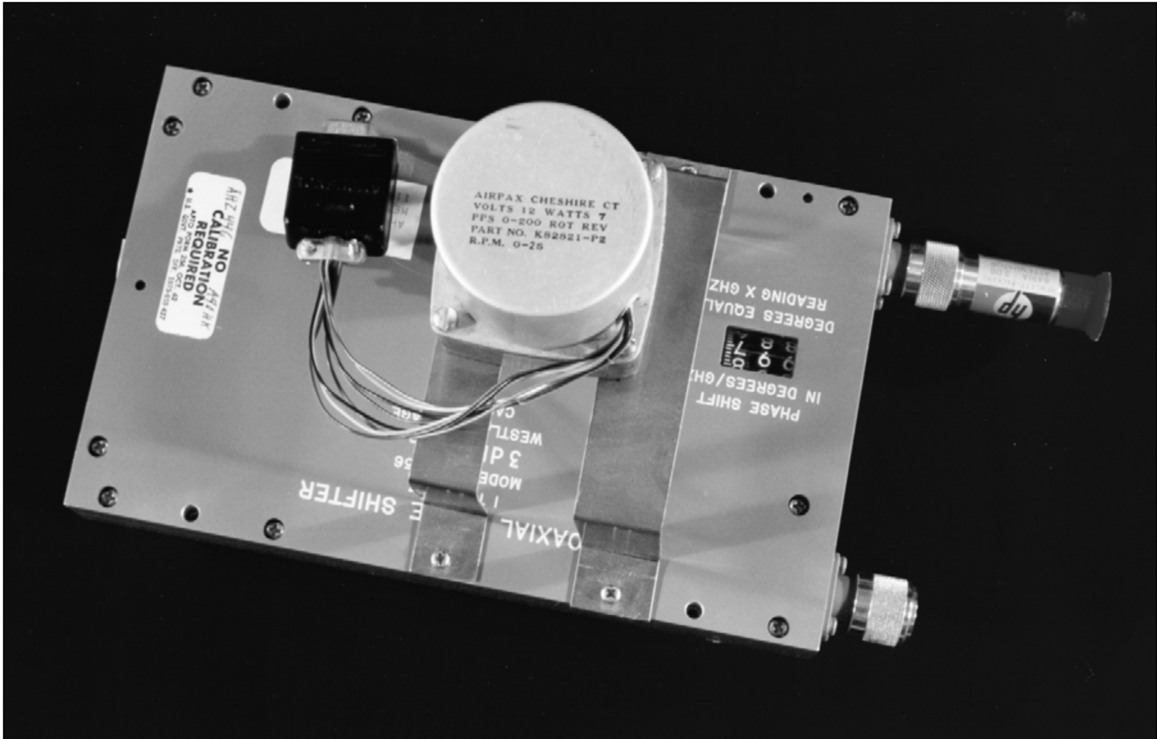


FIGURE 2.1.12 – DYNAMIC LOAD WITH STEPPER MOTOR CONTROLLED PHASE SHIFTER

### *2.1.2.3 BIAS VOLTAGES*

The test system has individual control, via the computer, to adjust up to 4 different bias voltages. Generally these supplies will be used to provide a negative gate bias, a positive drain bias, a negative control circuit bias, and an additional miscellaneous voltage. Each power supply is controlled by the computer via the IEEE-488 bus, commonly known as HP-IB, as well as having a capability to be manually set. Each power supply provides 200 watts of DC with a maximum capability of up to 60 volts or 12 amps.

The current system configuration has the capability of testing a DUT under brown out conditions (reduced bias voltages) and under voltage stress conditions (increased voltages). In addition, provisions have been made to subdivide the four basic voltages to support special purpose regulation, current monitoring and bias switching (i.e., drain pulsing). An example of such a special regulator board is the one presented in Figure 2.1.13. This board provided up to 8 different regulated biases; four positive and four negative. It was specifically designed for use as a regulator board in life testing T/R modules at S Band and C Band, but was later adapted to test C Band power amplifiers as well.

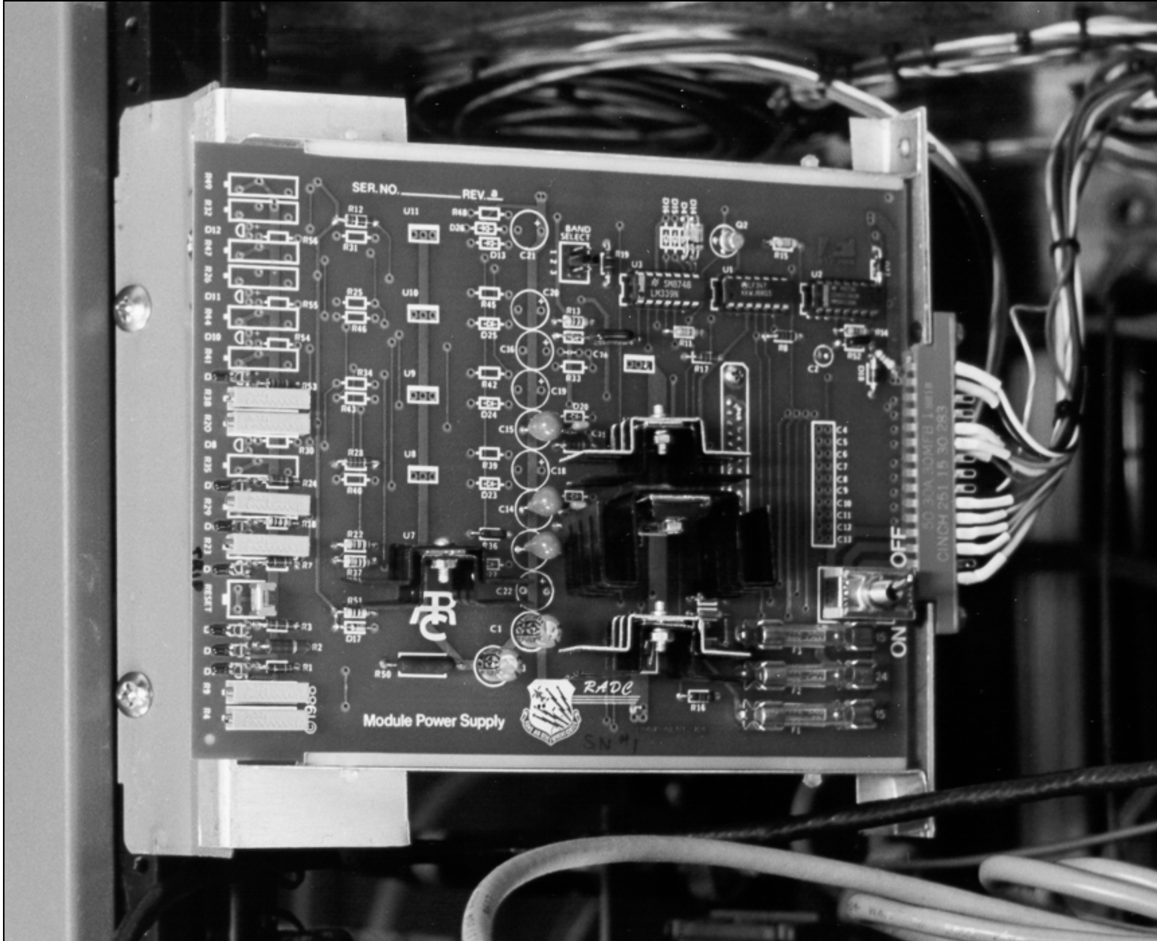



FIGURE 2.1.13 – DC BIAS BOARD FOR S & C BAND DUTS

### *2.1.2.4 MICROWAVE EXCITATION*

The test system has the capability of providing discrete frequency and complex waveforms. In all cases, the drive power, pulse width and duty cycle can be varied. The waveform can be controlled using either manual controls or the computer commands. The most common waveform for characterization of a DUT is a discrete frequency pulsed waveform with a constant pulse width, duty cycle and power level at set frequency points across the measurement bandwidth.

To provide a LFM (Linear Frequency Modulation) waveform, there are two exciters available at S Band - one built by RCA in the late 1970's and another built in-house during the mid 1980's. The RCA exciter is described in the "Operation and Maintenance Manual for the Wideband Waveform Generator and Signal Processor" (not published). A highlight of its operational capabilities is presented in Table 2.1.3 and a picture of it being used in an experiment is shown in Figure 2.1.14. The LFM generator built in-house is described as an appendix in the "Module Evaluation Lab (MEL-2 Report)" previously mentioned. This in-house built LFM generator was collocated with a circuit called a pulse conditioner. The pulse conditioner was designed to take the test system

master clock pulse and provide two output pulses called drain enable and RF enable. The purpose of such conditioning is to provide a pulse within a pulse. It is occasionally desirable to have one of the pulses to encompass the other pulse by a given amount of time (i.e. 10 usec or so). An example is shown in Figure 2.1.15. The RF is then pulsed using the RF pulse enable to drive a PIN diode switch. Both of the generators utilize a VCO (Voltage Controlled Oscillator) driven by a saw tooth waveform to create the LFM. A picture of this box is shown in Figure 2.1.16.

For complex waveforms, there is an AWS (Arbitrary Waveform Synthesizer) available. The AWS allows the user to define the waveform via a mathematical description, which is then fed into memory by the computer controller. Then, through repetitive scanning of the memory, the waveform is generated via a D/A converter.

| Characteristic | Description |
|---|---|
| Wideband Waveform Output | Linear FM up chirp |
| Pulsewidth | 48 ± 0.1 microseconds |
| Sweep Bandwidth (3 dB) | 300 MHz, minimum |
| Center Frequency | 3,300 MHz |
| Output Level | +10 dBm, minimum |
| Pulse-to-Pulse Phase Coherence | ≤ 3 degrees RMS with respect to cw reference |
| Pulse Jitter | ≤ 100 picoseconds RMS |
| Time Sidelobes | -37 dB peak for ± 0.2 μs window<br>-32 dB peak for ± 0.8 μs window |
| Pulse Rate | 7.8125 to 2,000 Hz in 256 steps or as designated in remote mode |
| Sweep Rate | 6.25 MHz per microsecond |
| Pulse Pair Spacing | 10 to 3,000 microseconds in 0.1 μs steps |
| Impedance | 50 ohms |
| VSWR | 1.5:1, maximum |
| Spurious Output | 60 dB, minimum |
| Correlation Reference Output | Linear FM up chirp |
| Pulsewidth | 51.2 ± 0.1 microseconds |
| Bandwidth | 320 MHz, minimum |
| Center Frequency | 3820 MHz |
| Output Level | +10 dBm, nominal |
| Impedance | 50 ohms |
| VSWR | 1.3:1, maximum |

TABLE 2.1.3 – WIDEBAND WAVEFORM GENERATOR CAPABILITIES

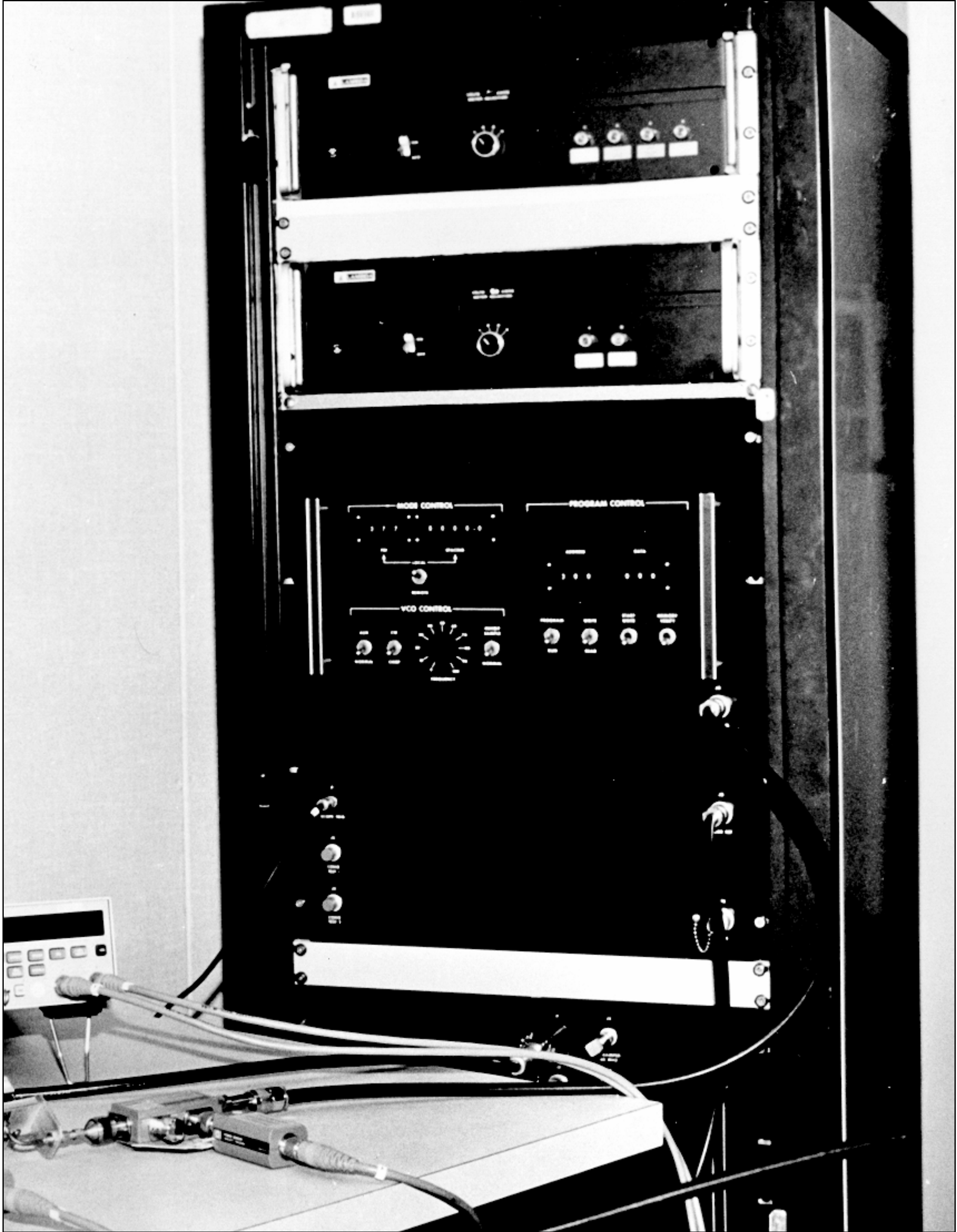



FIGURE 2.1.14 – WIDEBAND WAVEFORM GENERATOR

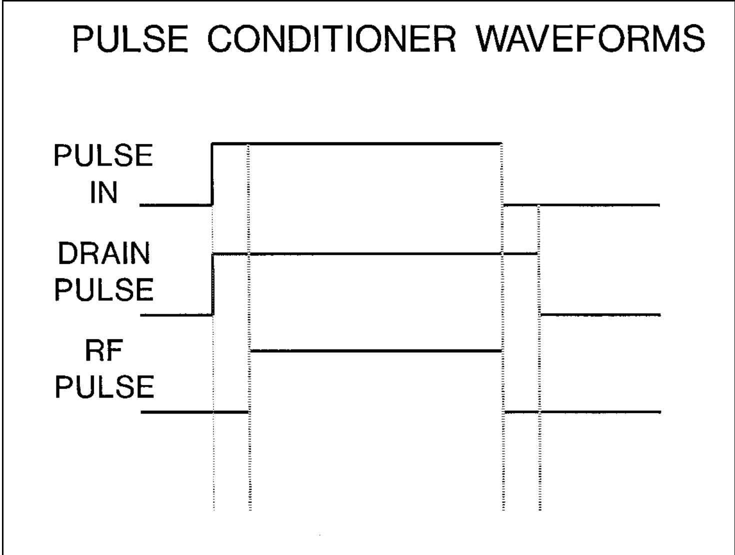



FIGURE 2.1.15 – PULSE CONDITIONER WAVEFORM

FIGURE 2.1.16 – PULSE CONDITIONER & LFM WAVEFORM GENERATOR

### *2.1.2.5 DUT STATE CONTROL*

The DUTs that were tested tended to require very complex control schemes in order to be fully characterized. As such, specialized controllers need to be developed for each type of DUT. An example of such a controller is one developed in-house to control the GE C

Band module.  This module has a CMOS beam steering controller built-in that accepts digital commands that are transmitted to the module using a frequency shift keying (FSK) modulation technique.  To create FSK commands, a circuit was fabricated that continually dumped commands that had been previously stored on an EEPROM.  A picture of this apparatus is shown in Figure 2.1.15.

Other controllers include the manual controller built to control simpler modules.  A good example of this type of controller is shown in Figure 2.1.16.  It was no more than a box with a voltage regulator, a drain switch for automatically toggling the drain bias, and toggle switches for changing the phase shifter settings.

FIGURE 2.1.17 – C BAND MODULE CONTROLLER

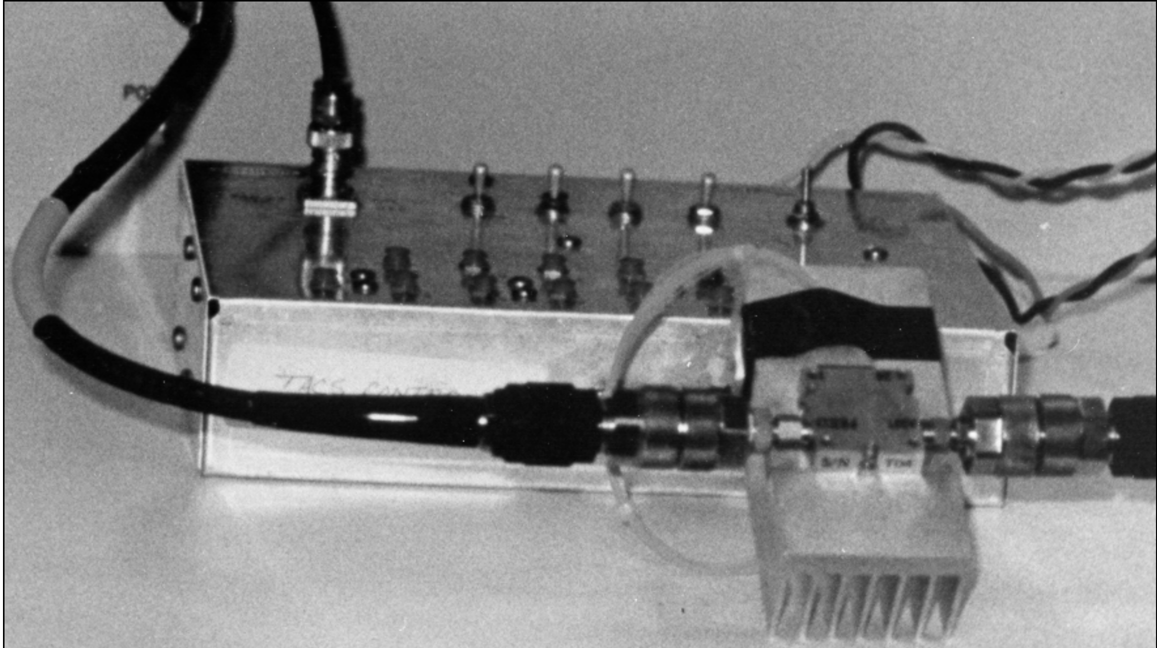


FIGURE 2.1.18 – L BAND MODULE CONTROLLER

## *2.2 LONG TERM PERFORMANCE TEST SYSTEM (MELTS)*

This system is designed to operate a number of devices simultaneously for long periods of time under specified conditions. It is used to perform the second of three tests that a DUT undergoes when being subjected to life testing. The first and third tests involve the characterization of the DUT on the large signal pulsed test system (MEL-2).

The details of MELTS and how it operates is the subject of a unpublished RADC technical (see bibliography). The test system is designed to operate T/R modules and sub-components under both DC only and RF operating conditions within an emulated radar environment. Performance data of the devices under test are continuously monitored and recorded for later evaluation. The control of the test system is fully automated using a Hewlett Packard series 200 computer (HP 9836). A picture of the first version of the life test system is shown in Figure 2.2.1. A picture of version 2, with greater testing capabilities is shown in figure 2.2.2 with a corresponding block diagram presented in Figure 2.2.3.

FIGURE 2.2.1 – LONG TERM PERFORMANCE TEST SYSTEM VERSION 1

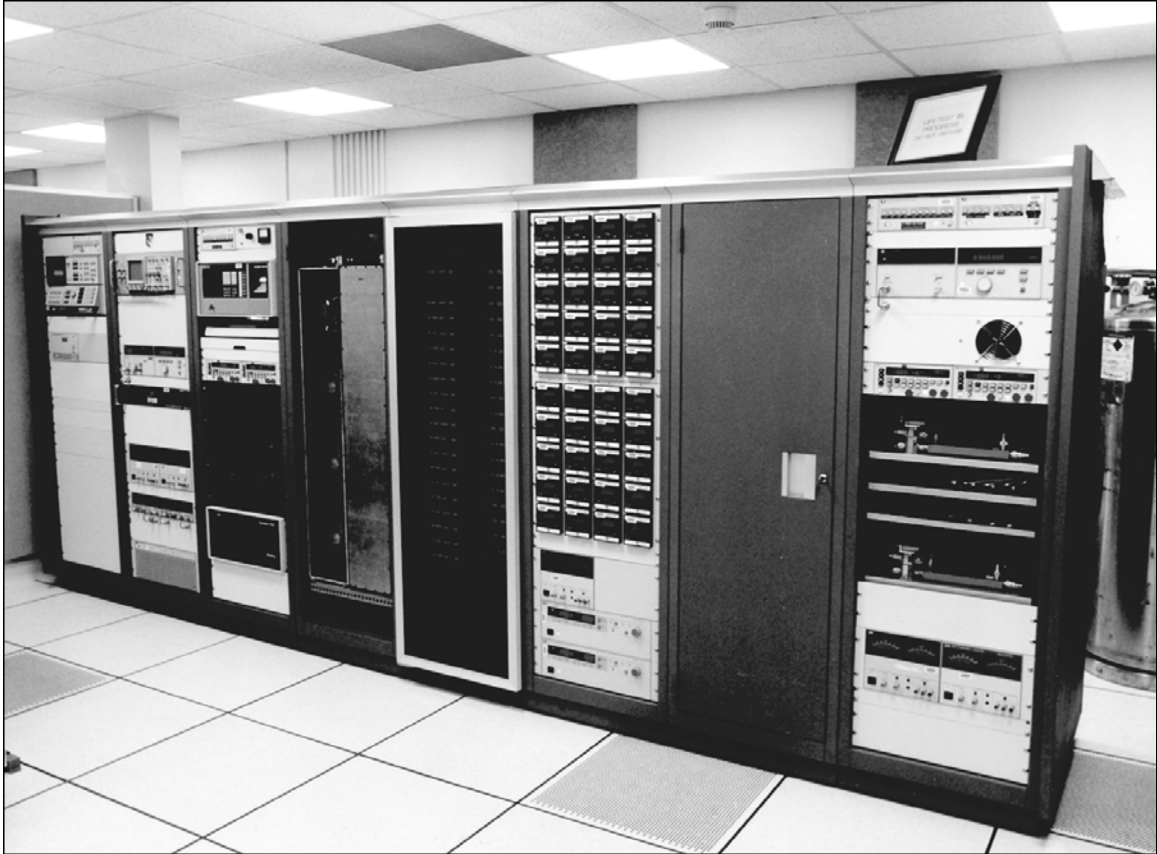


FIGURE 2.2.2 - LONG TERM PERFORMANCE TEST SYSTEM VERSION 1

Version 2 of MELTS, the last version to be used for testing devices, was configured to test up to 40 devices. A maximum of 20 of these could be tested under microwave operating conditions. Hardware limitations constrained the microwave testing to a maximum of ten wide band (S through X Band) and a maximum of ten C band devices. The first test conducted (using version 1 of the system) had 20 C Band modules (10 DC and 10 RF) and 20 S Band modules (10 DC and 10 RF). Table 2.2.1 shows the specific capabilities of version 2 of the system, which was being utilized as part of the DARPA MIMIC program to test the reliability of MMICs and T/R modules. This configuration was a compromise between the desire to constantly monitor the performance of each device and the expense involved in capital equipment. The DUTs were exercised in both transmit and receive modes, including operating the phase shifter bits during transmit mode. A diagram indicating the timing of this exercising is shown in Figure 2.2.4. Measurements were at regular intervals to determine how various operating parameters changed as a function of time (i.e., 4 months, 9 months, 1 year, etc.). The parameters monitored included the drain current, the gate current, the base plate temperature, and the microwave gain of the DUT.

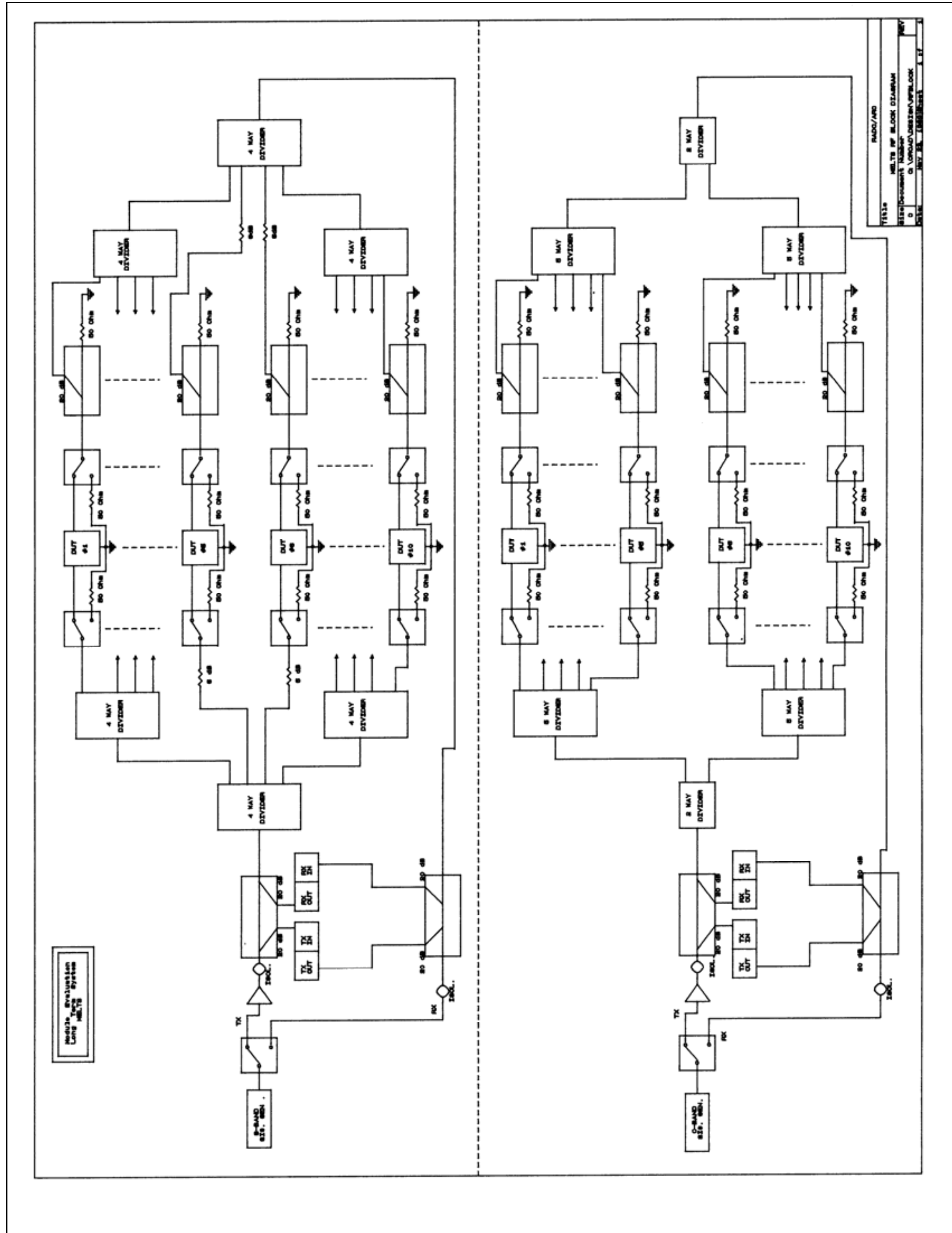


FIGURE 2.2.3 – BLOCK DIAGRAM OF LONG TERM PERFORMANCE TEST SYSTEM VERSION 2

1. Electrical Characteristics

a. Operating Mode

1. Remote - Fully automated controlled operating sequence and data acquisition.

2. Local - Used primarily for trouble shooting or system verification

b. Interface

1. IEEE 488

2. RS-232

c. Primary Power

| | |
|---|---|
| Voltage | 120 VAC ±10% |
| Frequency | 50/60 Hz |
| System Power | 6500 watts (maximum) |
| System Controller and Peripherals | 800 watts (maximum) |
| Service Conditions: | |
| Operation | Continuous |
| Temperature | 0° to +55° C |

2. Physical Characteristics

a. Dimensions

| | |
|---|---|
| Height | 71" |
| Width | 112" |
| Depth | 33" |

TABLE 2.2.1 – LONG TERM PERFORMANCE TEST SYSTEM VERSION 2 SPECIFICATIONS (PAGE 1 OF 2)

b. Approximate Weight 1900 lbs.

(controller not included)

c. Maximum Test Article Quantities

40 modules total

1. 20 S-band

10 RF applied

10 No RF applied

2. 20 C-band

10 RF applied

10 No RF applied

3. Operational Characteristics

a. Frequency Range

2.0 to 6.2 GHz

b. Average Drive Power

Tx mode 0 dBm

Rx mode -25 dBm

c. Drive Modulation

CW only

d. Power Meter Accuracy

<0.1 dB

Repeatability < Accuracy specification (see 438A manual, Part# 0438-90015)

e. Autodata Accuracy

Voltage/Current ± 0.005% of Reading

Temperature < 0.5° C

Repeatability ±0.002% of full scale

Scan time for 140 channels → 11 seconds

TABLE 2.2.1 – LONG TERM PERFORMANCE TEST SYSTEM VERSION 2 SPECIFICATIONS (PAGE 2 OF 2)

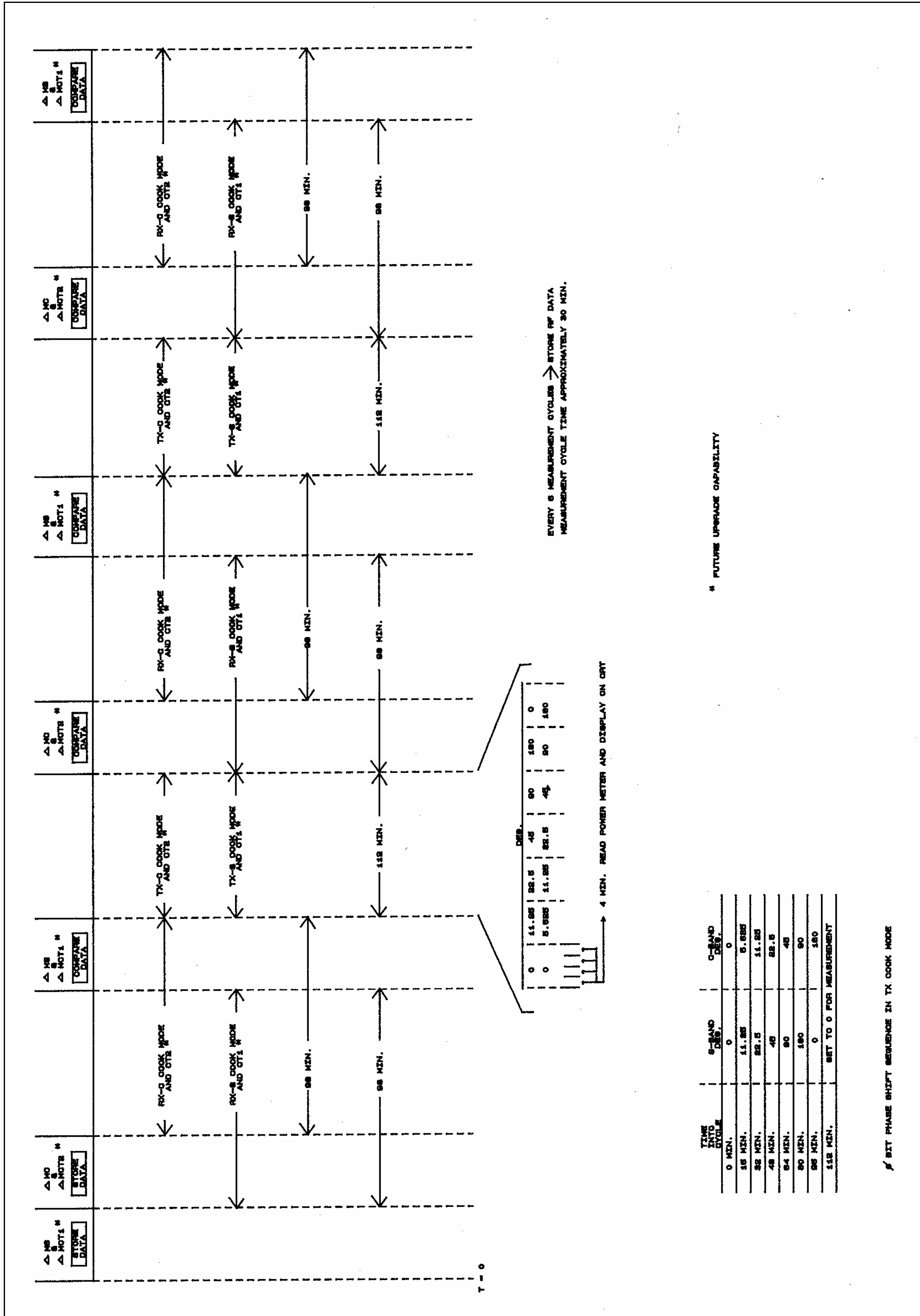


FIGURE 2.2.LIFE TEST SYSTEM TIMING DIAGRAM

### 2.2.1 DATA ACQUISITION AND CONTROL

The control of the test system is fully automated using a Hewlett Packard series 200 computer (HP 9836). The operating system used was HP Basic 4.0. A picture of the computer is shown in figure 2.2.5. A typical screen showing the status of the devices being tested is shown in figure 2.2.6. Performance data of the devices under test are continuously monitored and recorded for later evaluation. HP-IB interface boards in the 9836 were used to control and collect data from the various instruments within the system. A data logger, shown in figure 2.2.7, was used to collect temperature data. A multi-programmer was used to command the temperature controllers. The data that is acquired and recorded by this test system is the following:

DUT gain in dB (microwave only case)
Frequency of signal (microwave only case)
DUT drain bias current
DUT gate bias current
DUT base plate temperature
Date/Time of measurement
DUT operating state

Each record of data is stored on hard disc and is then copied periodically to tape for analysis. Data, although acquired regularly (every four hours), is only recorded on disc every 24 hours, or when a test parameter has changed significantly.

FIGURE 2.2.5 - LIFE TEST SYSTEM CONTROLLER

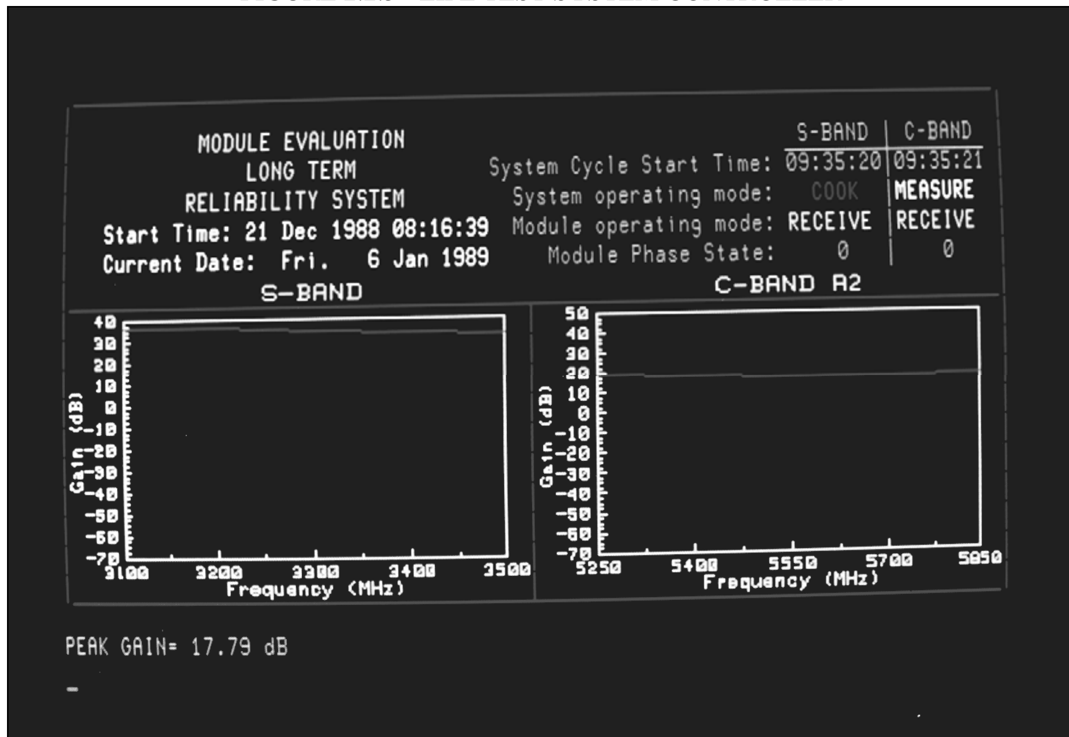



FIGURE 2.2.6 – TYPICAL LIFE TEST SYSTEM DISPLAY

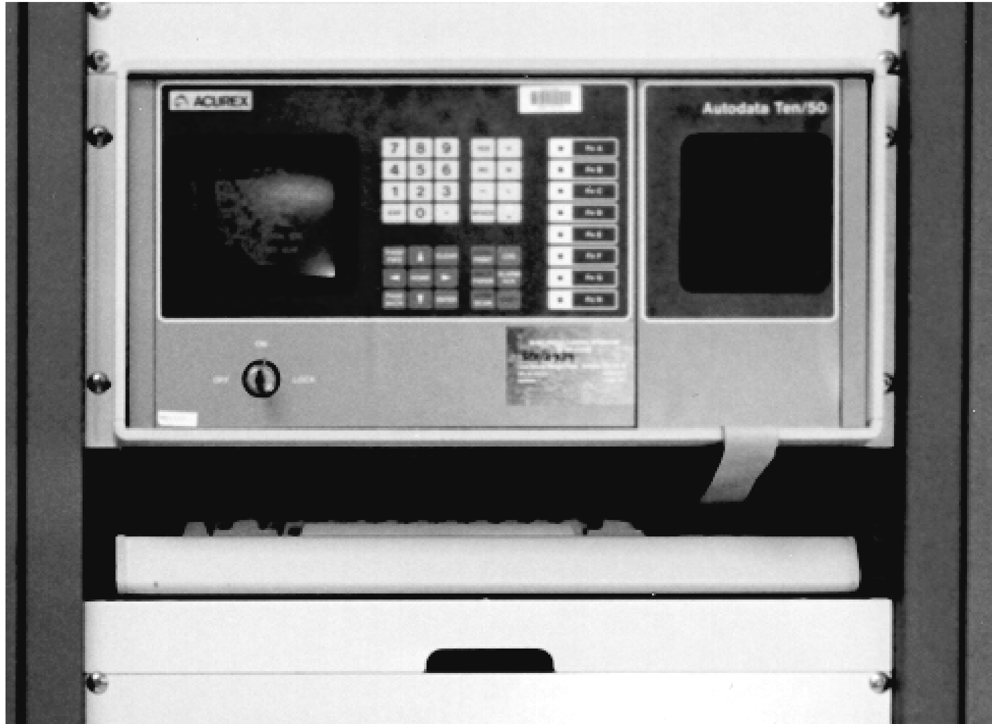



FIGURE 2.2.7 – DATA LOGGER

### 2.2.2 ENVIRONMENTAL CONDITIONS

The test system was configured to emulate a radar system. The various electrical and environmental conditions could be varied to correspond to conditions that would be experienced in an actual phased array radar system. For the purpose of most tests, which are generally reliability driven, a majority of the conditions were maintained in a constant and benign condition.

In the first version of the test system, the only environmental condition allowed to vary was the temperature. The module's base plate temperature was maintained by limiting the use of convection cooling and/or forced air ventilation. In addition, four resistors were incorporated within the thermal chamber (made from Styrofoam construction insulation) to allow for additional heat to be inserted. This heating technique provided a 25 degree Centigrade variation between the coolest and warmest periods (4 hour temperature cycling). The exact temperature level was dependent on the individual module's efficiency and output power level. Data on the module temperature variations are presented in Section 3.2. A picture of version one's test chamber is shown in Figure 2.2.8.

FIGURE 2.2.8 – LIFE TEST VERSION 1 DUT TEST CHAMBER

The second version of the test system only allowed the temperature to be the environmental condition to vary as well. However, this time the temperature was more precisely controlled and the DUT was subjected to a dry nitrogen atmosphere. The module's base plate temperature was maintained by heating the copper baseplate with an electric heating element as shown in figure 2.2.9. This heating element was controlled by a temperature controller that monitored the copper blocks temperature with a thermal couple. A picture of version two's test chamber is shown in Figure 2.2.10.

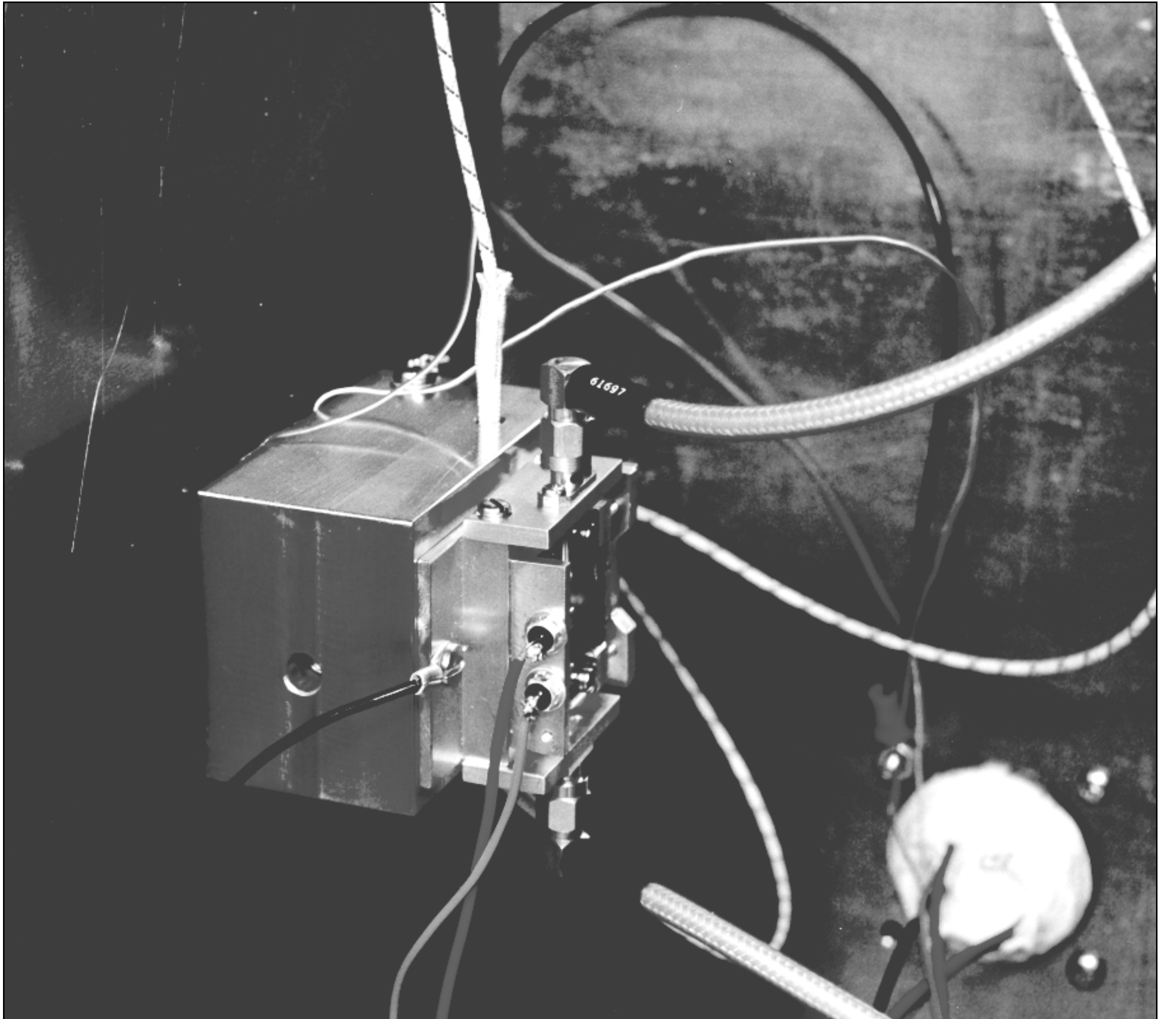


FIGURE 2.2.9 – DUT LIFE TEST FIXTURE MOUNTED ON COPPER BLOCK

Figure 2.2.10 - LIFE TEST VERSION 2 DUT TEST CHAMBER

## *2.3 PULSED PHASE MEASUREMENT SYSTEM*

To provide a means of measuring intra pulse and inter pulse phase and amplitude stability, the pulsed phase measurement system was developed. This system attaches to MEL-2 in place of the digital sampling scope which takes an average across many pulses. In this system, the I and Q signals are simultaneously processed through an A/D converter by using two transient digitizers (Tektronics 7912) with a 500 MHz bandwidth. A picture of this system is shown in Figure 2.3.1.This configuration is shown in Figure 2.3.2 and is described in detail in a paper entitled "Computer Controlled Pulse Power Measurement System" by M. Little and L. L. Stevens.

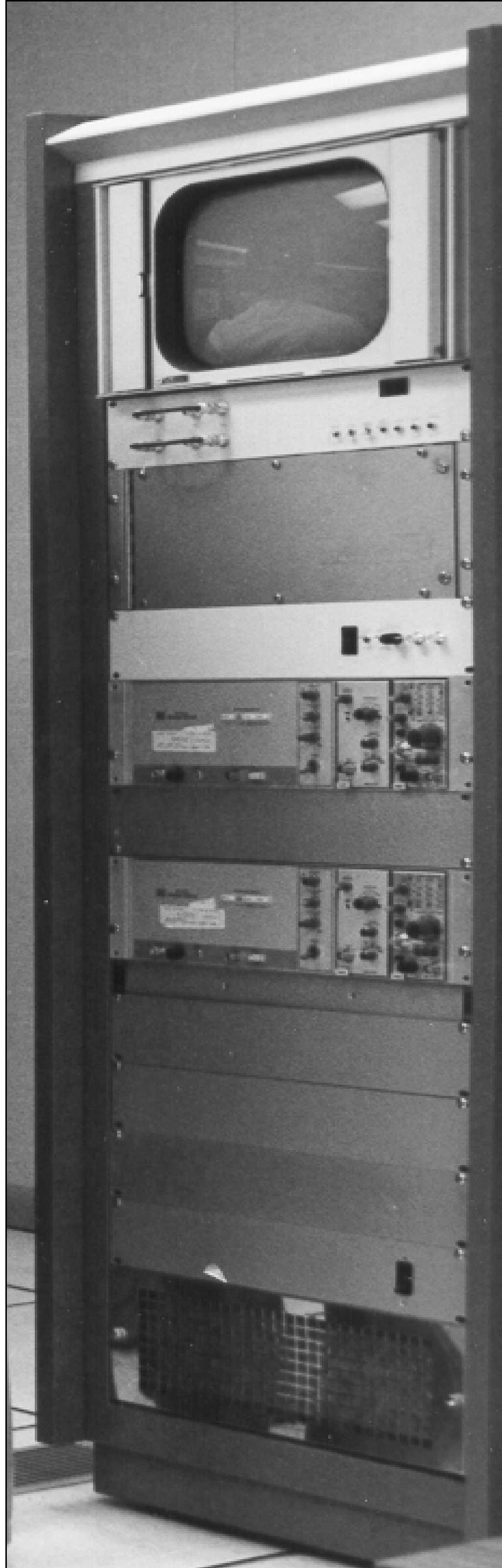


FIGURE 2.3.1 – PULSED PHASE MEASUREMENT SYSTEM

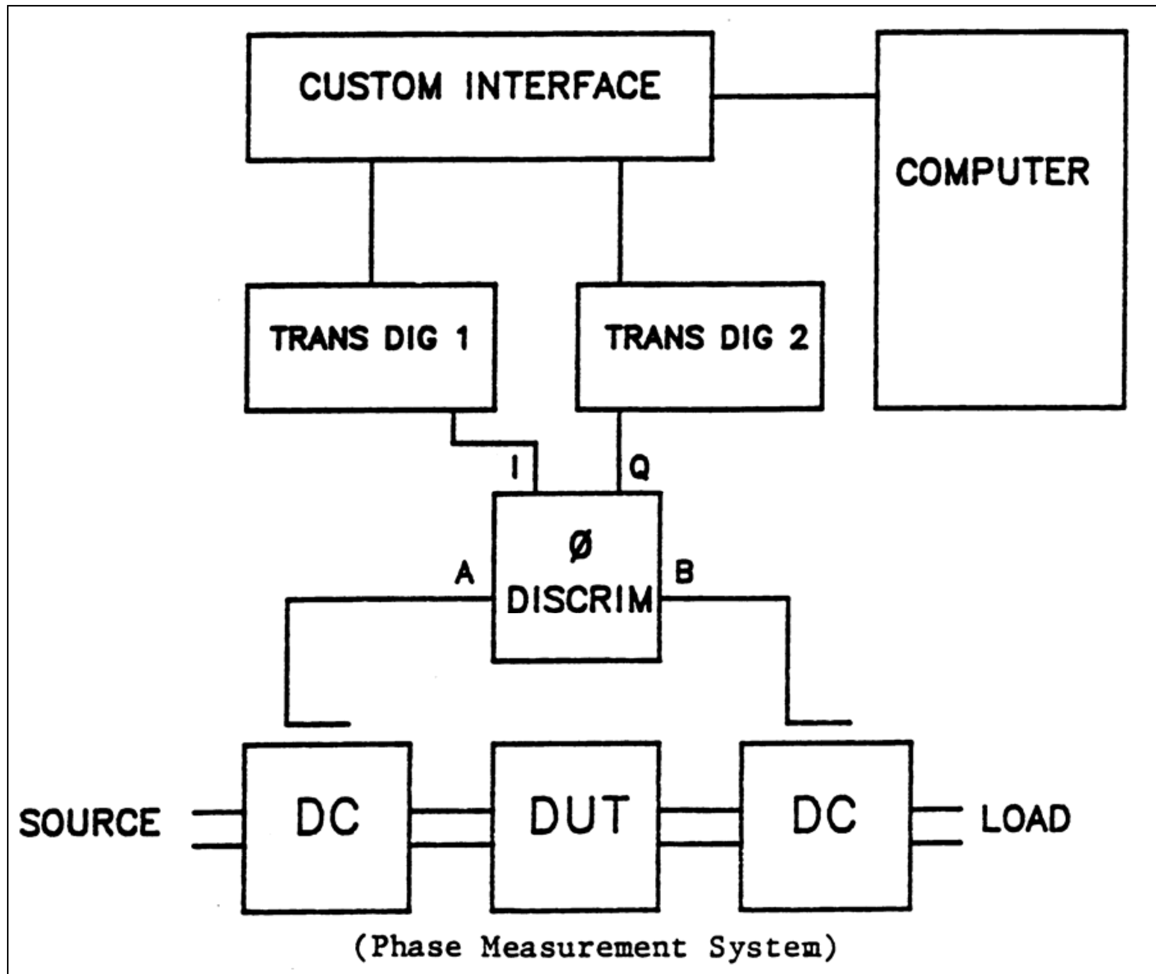



FIGURE 2.3.2 – PULSED PHASE MEASUREMENT SYSTEM DIAGRAM

The system uses one digitizer to capture the I signal and the second digitizer to capture the Q signal. The video I and Q signals are fed into the digitizer which acts as an array of sample and holds an A/D converter through the use of scan converters. A scan converter is a cathode ray tube with both a write gun and a read gun. The write gun scans a beam of electrons across an array of diodes; thus, discharging those diodes. The read gun then scans the diodes array charging those diodes which had been previously discharged. The charging of the diodes creates a current flow which identifies those diodes as having been written on.

Depending on the number of samples per pulse desired and the duty cycle of the waveform, the one-shot digitization can incorporate from a fraction of a pulse to multiple pulses. The number of samples is limited to 500. The actual measurement limitations are caused by the phase discriminator which has a rise time limit and by the capacitive coupling of the video amplifier. The discriminator rise time is on the order of 35 nsec (see figure 2.3.3); thus limiting the pulse width to greater than 100 nsec. The capacitive coupling limits the pulse width to less than 1 msec. The A/D converter uses 8 bits; thus not becoming the limiting factor in the accuracy of the measurement (limitations are caused by phase discriminator).

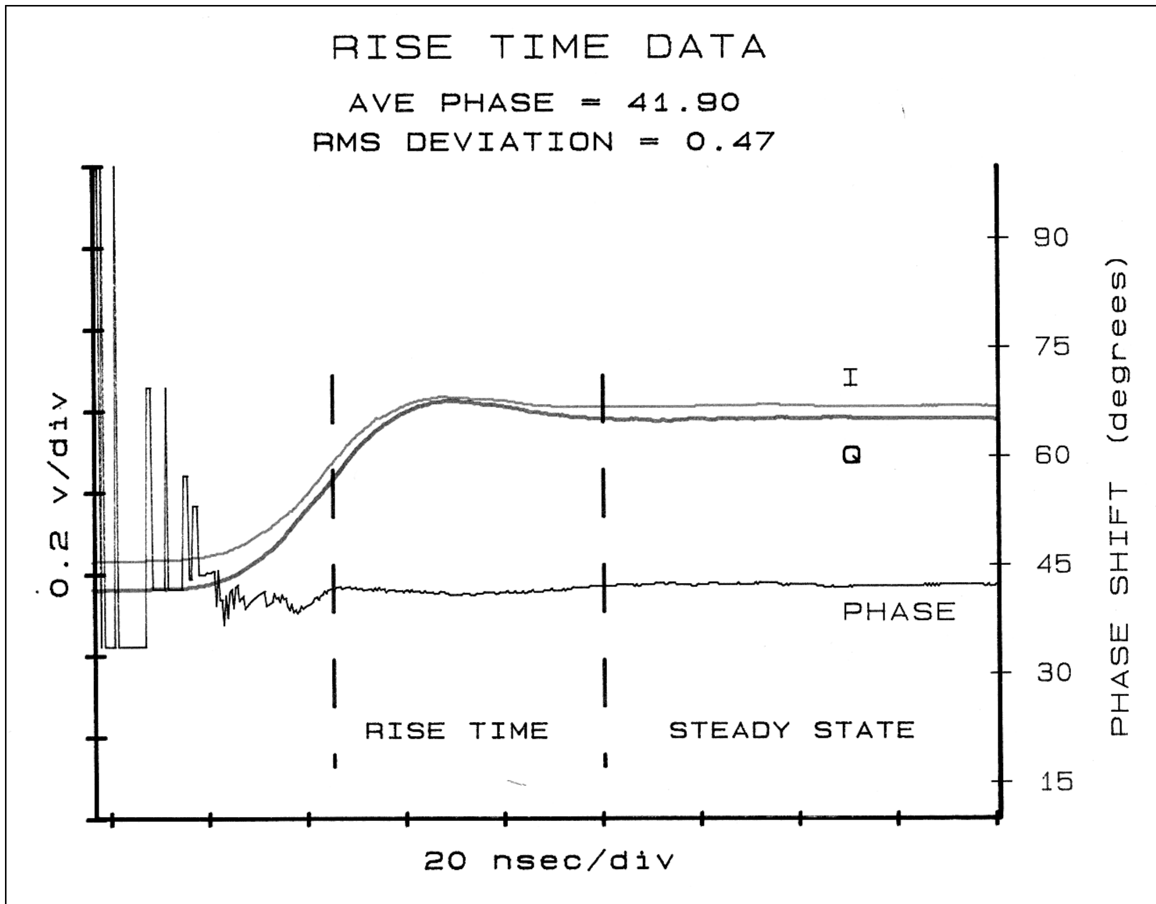



FIGURE 2.3.3 – PULSE MEASUREMENT SYSTEM RISE TIME DATA

# 3.0 EXPERIMENTS/RESULTS

As an aid to evaluating the testing techniques developed and to keep track of the characteristics and capabilities of the components and T/R modules being developed, various tests were performed. This section provides the major achievements and highlights the data acquired in conducting those tests.

## *3.1 EARLY L & S BAND MODULES (CHARACTERIZATION)*

These modules were the deliverables from a set of efforts, started in 1978. A selection of these modules is shown in Figure 3.1.1. Some experiments were performed on these modules and on their individual circuits. The early work was done at L band using Silicon-on-Sapphire (SoS) technology. Later work was performed at both L and S bands using GaAs technology. SoS technology was abandoned due to its high loss and low gain in the active circuits. This was especially true with the power amplifier circuits. * The results of the SoS T/R module experiments have been reported previously in RADC-TR-84-34 and will not be discussed here.

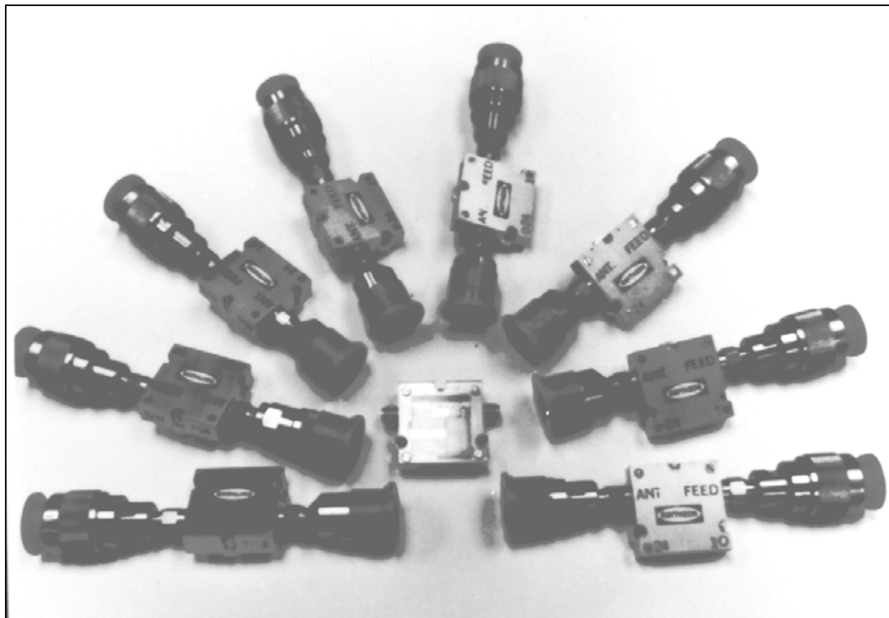



FIGURE 3.1.1 – EARLY L & S BAND MODULES

The test that will be covered by this report were conducted on S band GaAs T/R modules. Some of these modules had a added final power amplifier providing 10 Watts of output power. Some of the phase data taken shows the effects of an extra length of cable the test channel of the phase discriminator. This cable caused an increase in the measured phase length of the DUT. The data is, however, provided as a reference of the advances that have been achieved in both MMIC T/R modules and in measurement technology. These measurements were made on the earlier version of MEL. A picture of one of these modules is shown in Figure 3.1.2 during room temperature testing.

* RADC-TR-84-34 is Distribution CONTROLLED; DOD CONTROLLED

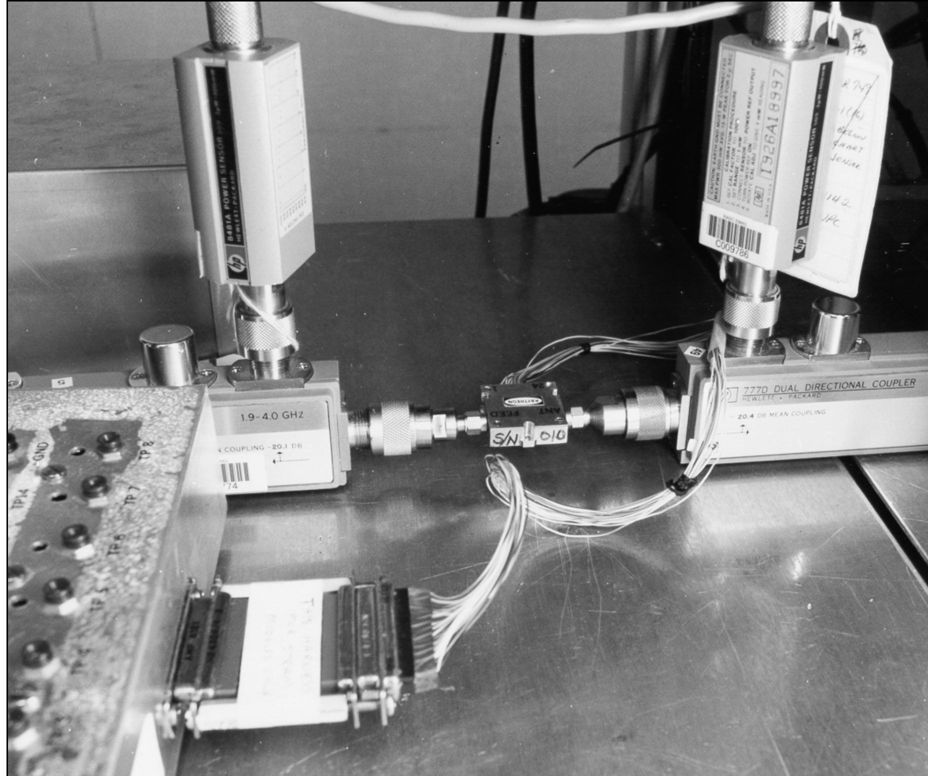


FIGURE 3.1.2 – EARLY S BAND MODULE UNDER TEST

### 3.1.1 TEST RESULTS

One of the more significant tests was the parametric test conducted on the receiver. The receiver parametric test involved independently varying the temperature, the gate bias and the source mismatch and observing the changes in noise figure and small signal gain. The first results shown were conducted at -20 degrees centigrade. Note that adjusting the gate bias had little effect on the noise figure and provided only small variations in the gain. In all cases not involving device failure or measurement error, the gain and noise figure curves retained their shape. The gain change was proportional to the magnitude of the negative voltage of the gate bias (see Figure 3.1.3). The same measurements conducted at zero degrees centigrade yielded a definite gate bias sensitivity (see Figure 3.1.4). Note that one measurement is significantly different than the other two. This was caused by a bad DC/Control connector. The subminiature connector was subject to many failures during the testing program. Test varying the temperature of a module indicated that gain changes inversely proportional and noise figure changes proportional with temperature change. The measurements were taken every 20 degrees centigrade from +40 to -20. The data is shown in Figure 3.1.5. The source mismatch test was performed using a directional coupler to isolate the noise source from the source mismatch. Figure 3.1.6 provides the data that resulted. A block diagram of this unique test setup is shown in Figure 3.1.7.

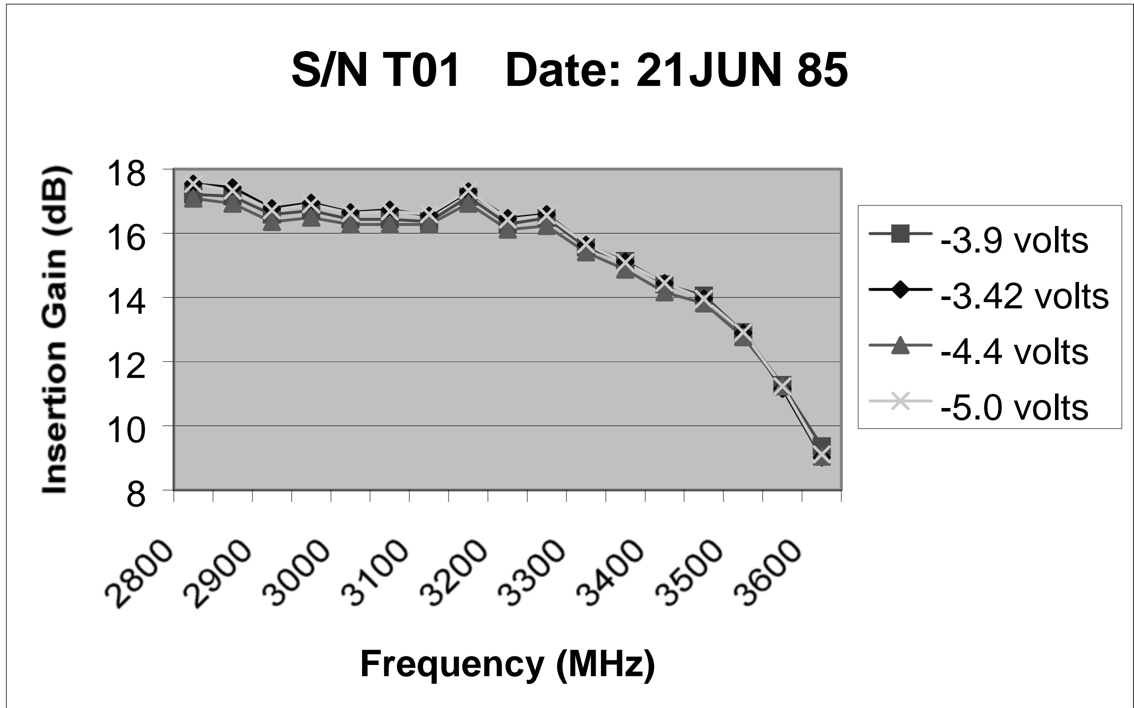



FIGURE 3.1.3 (A) – GAIN VERSUS GATE VOLTAGE

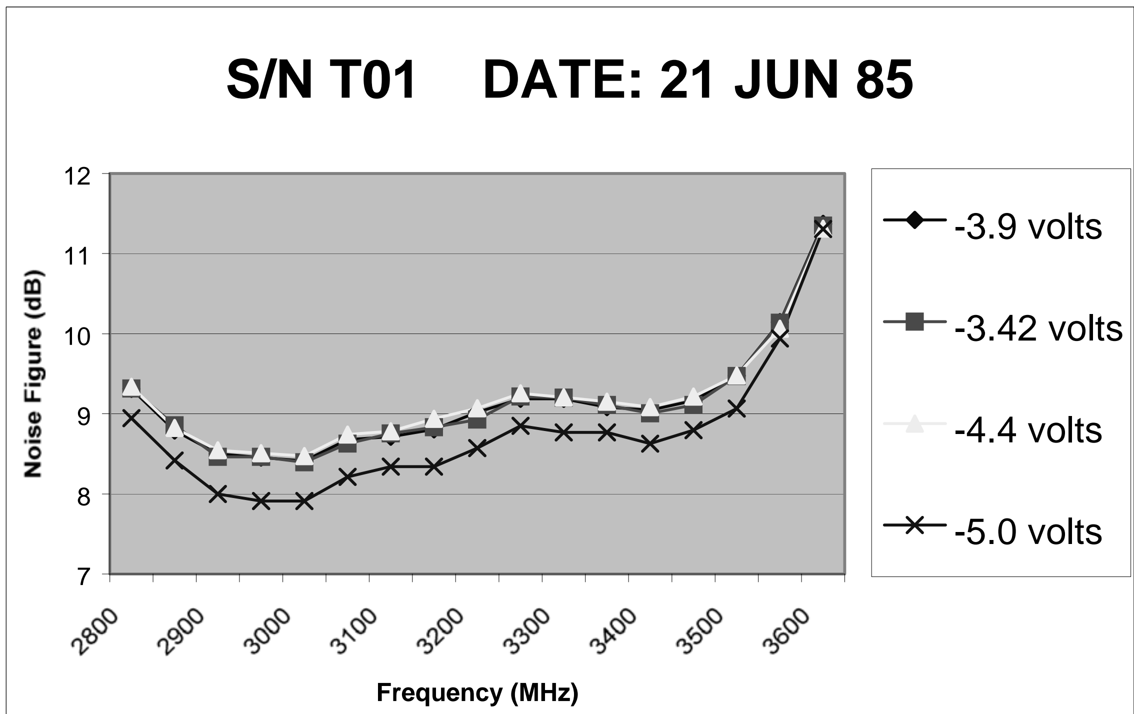



FIGURE 3.1.3 (B) – NOISE FIGURE VERSUS GATE VOLTAGE

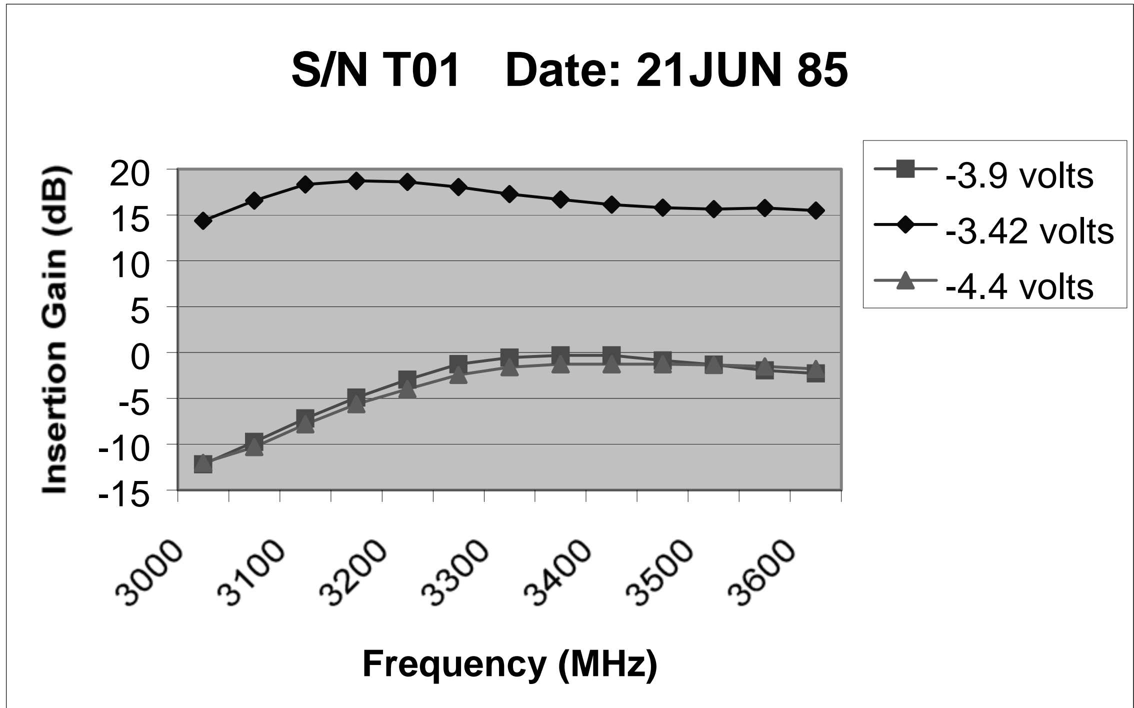



FIGURE 3.1.4 (A) – GAIN VERSUS GATE VOLTAGE (0 DEGREE C)

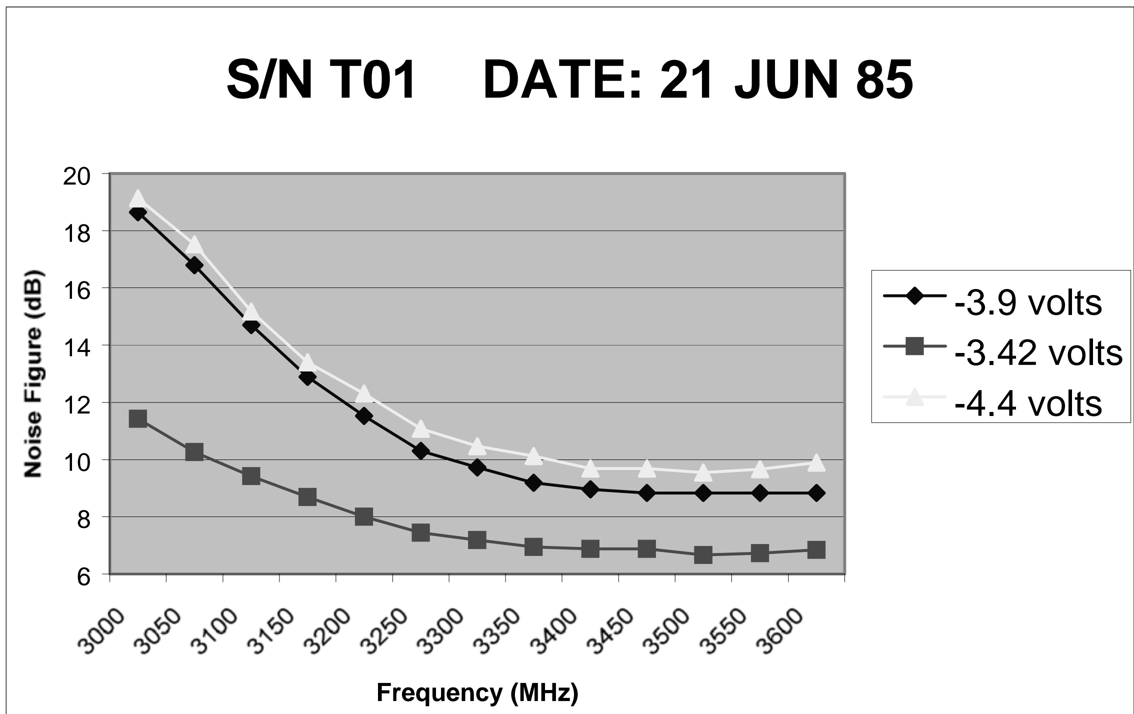



FIGURE 3.1.4 (B) – NOISE FIGURE VERSUS GATE VOLTAGE (0 DEGREE C)

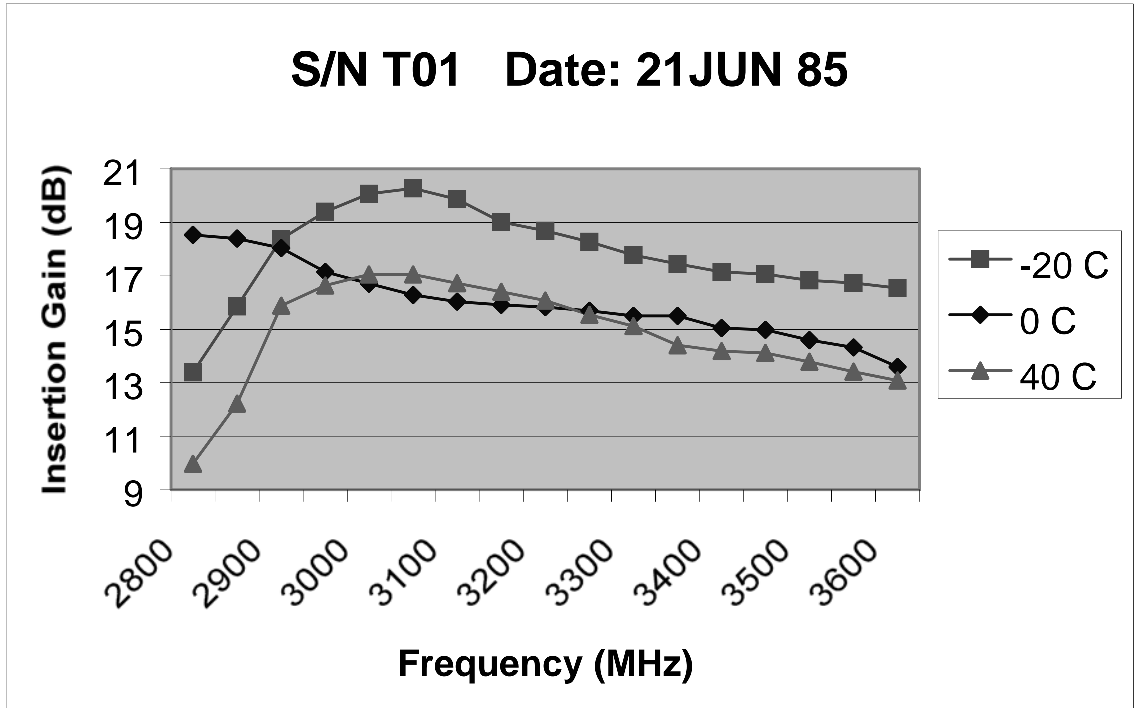



FIGURE 3.1.5 (A) – GAIN VERSUS TEMPERATURE

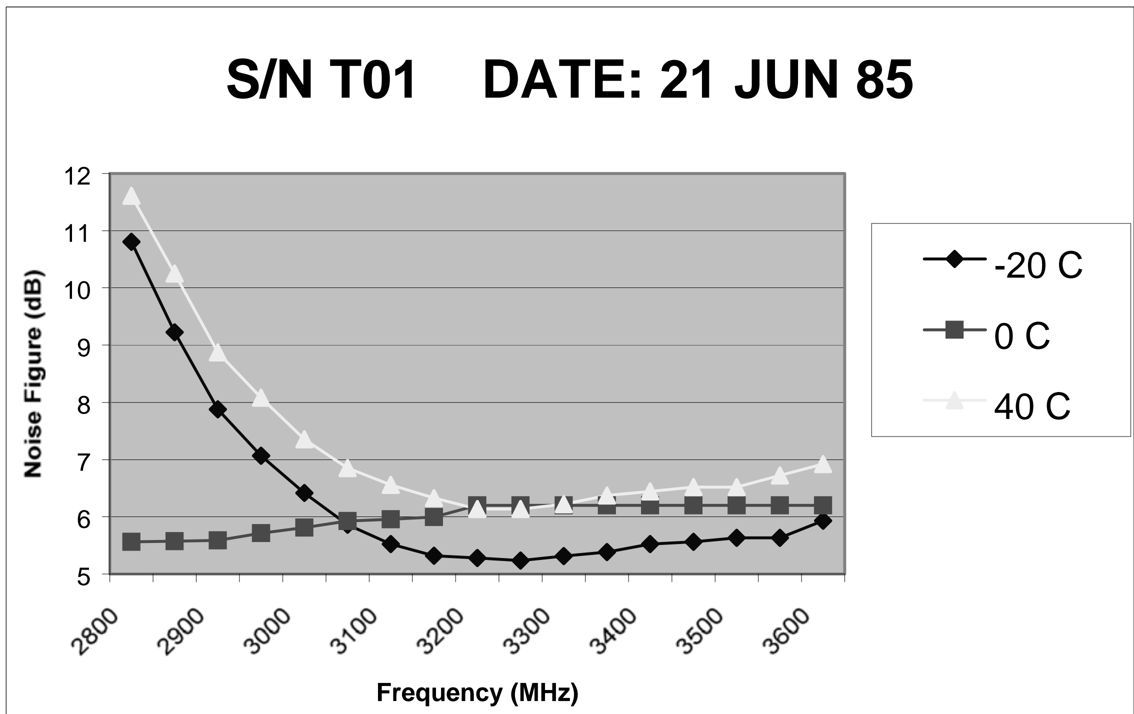



FIGURE 3.1.5 (B) – NOISE FIGURE VERSUS TEMPERATURE

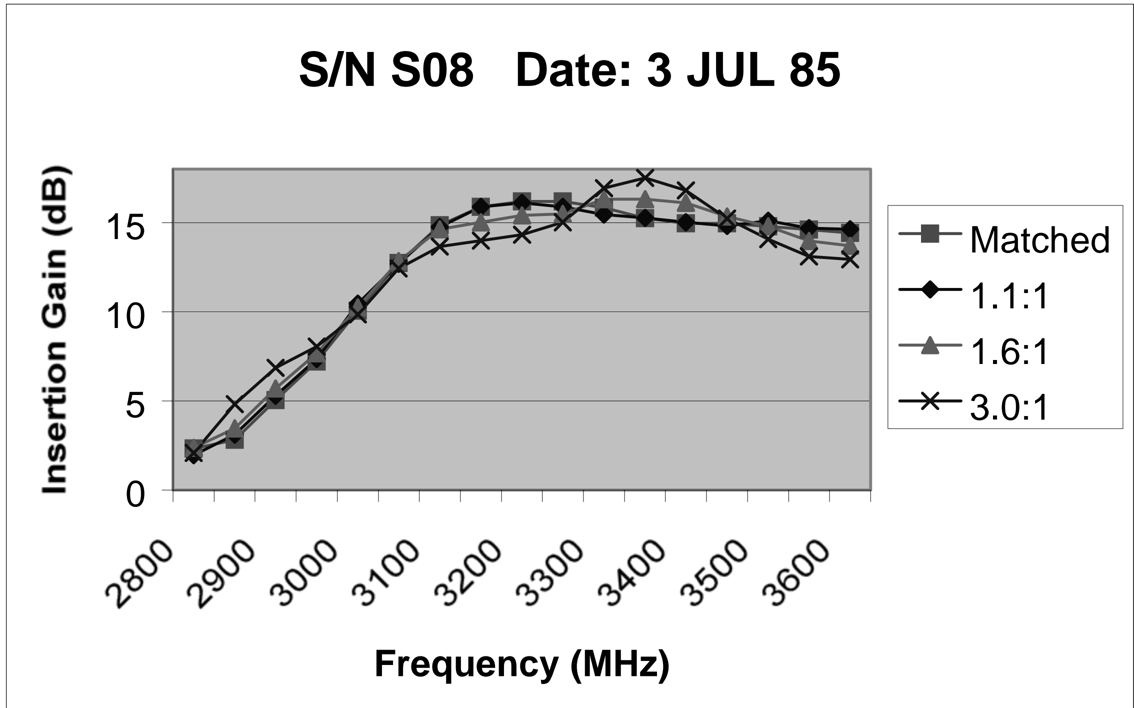



FIGURE 3.1.6 (A) – GAIN VERSUS SOURCE MISMATCH

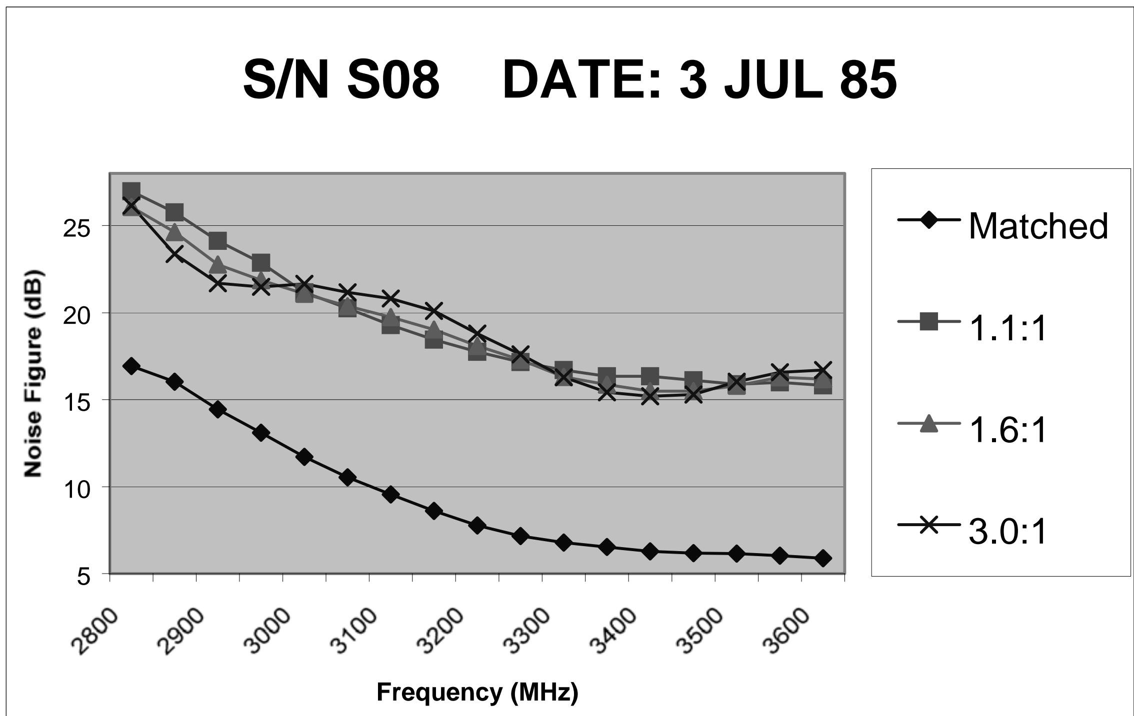



FIGURE 3.1.6 (B) – NOISE FIGURE VERSUS SOURCE MISMATCH

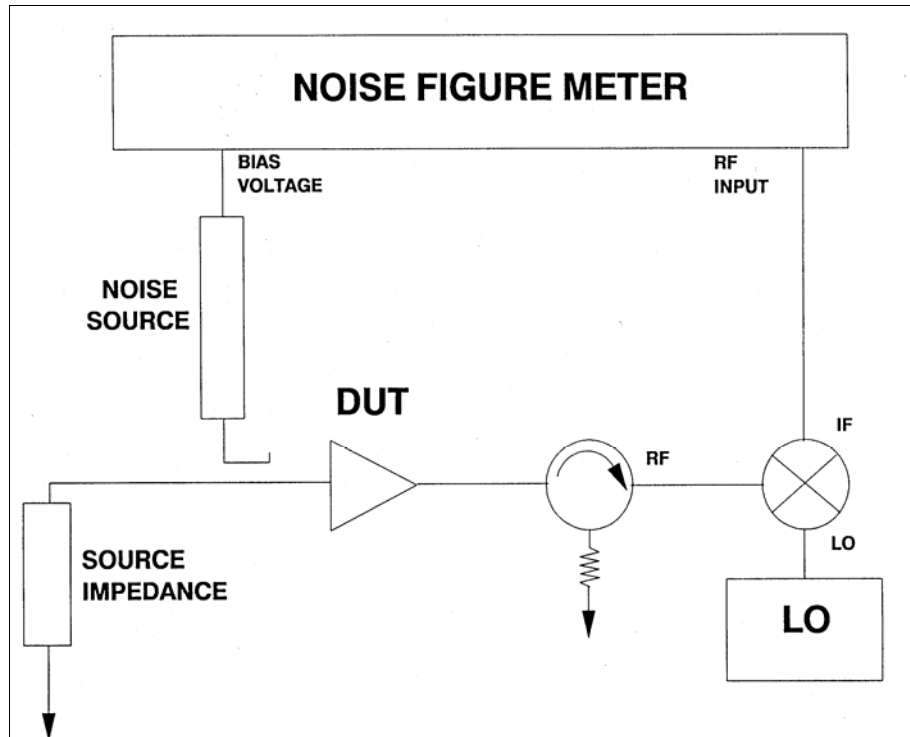


FIGURE 3.1.7 – SOURCE MISMATCH BLOCK DIAGRAM

Pulsed transmit tests were also conducted on both the lower and higher power modules. These tests were conducted at room temperature (20 degrees Centigrade) and within an oven/refrigerator at -20, 0 and 40 degrees Centigrade. Gain, phase and phase linearity data for modules serial numbers S09 through S12 and T01 through T04 are presented in Figures 3.1.8 through 3.1.15. Note that the phase data for these modules taken at non-room temperatures includes the extra electrical length mentioned earlier. This is due to the additional cabling needed to place the DUT in the temperature test chamber. All of these measurements were taken with nominal drive levels and bias voltages. To demonstrate the effect the phase shifter has on gain, data on modules T01 and T02 is provided comparing all phase bits off with all phase bits on (Figure 3.1.16 and 3.1.17). Figure 3.1.18 shows the effect changes in the pulse width will have on performance. Module to module tracking for the lower power modules is shown in Figure 3.1.19 and for the four higher power modules in Figure 3.1.20.

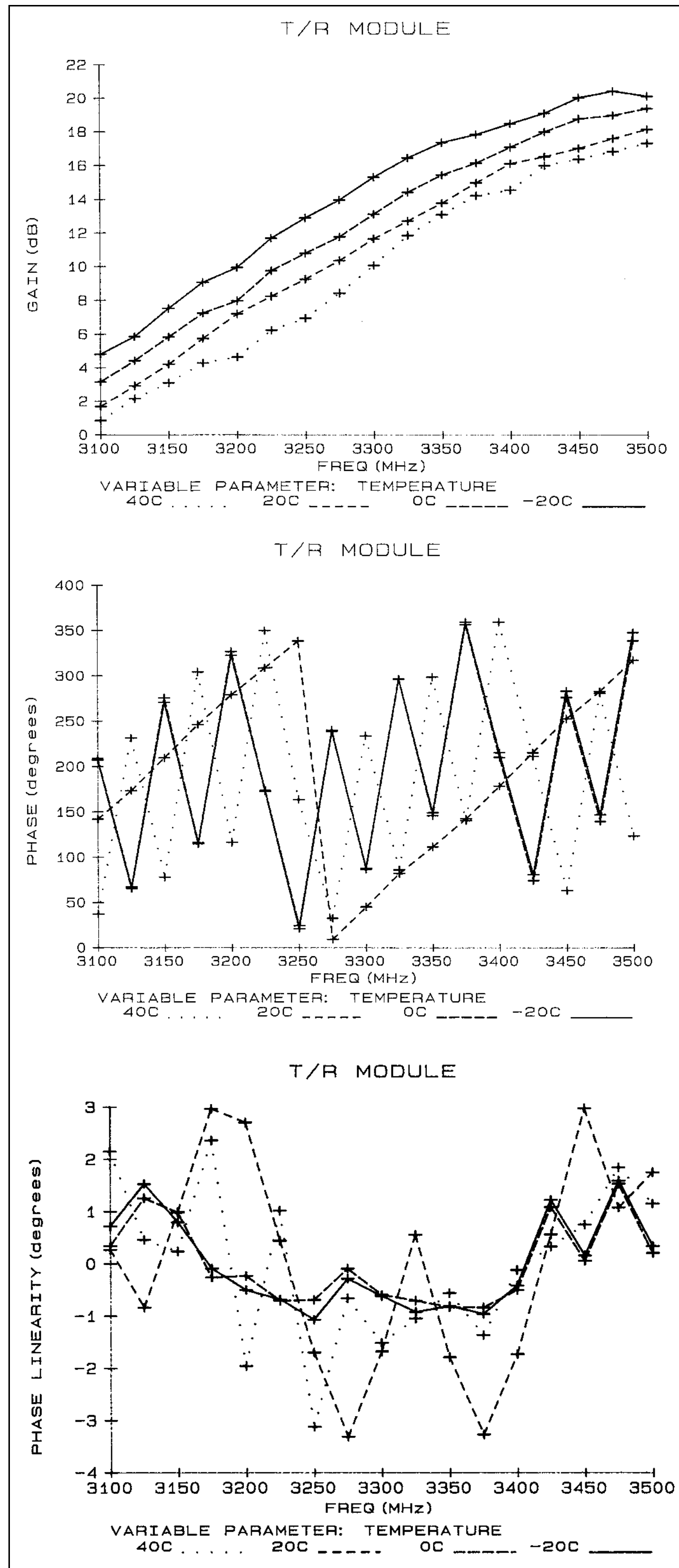


FIGURE 3.1.8 – S09 GAIN, PHASE & PHASE LINEARITY DATA

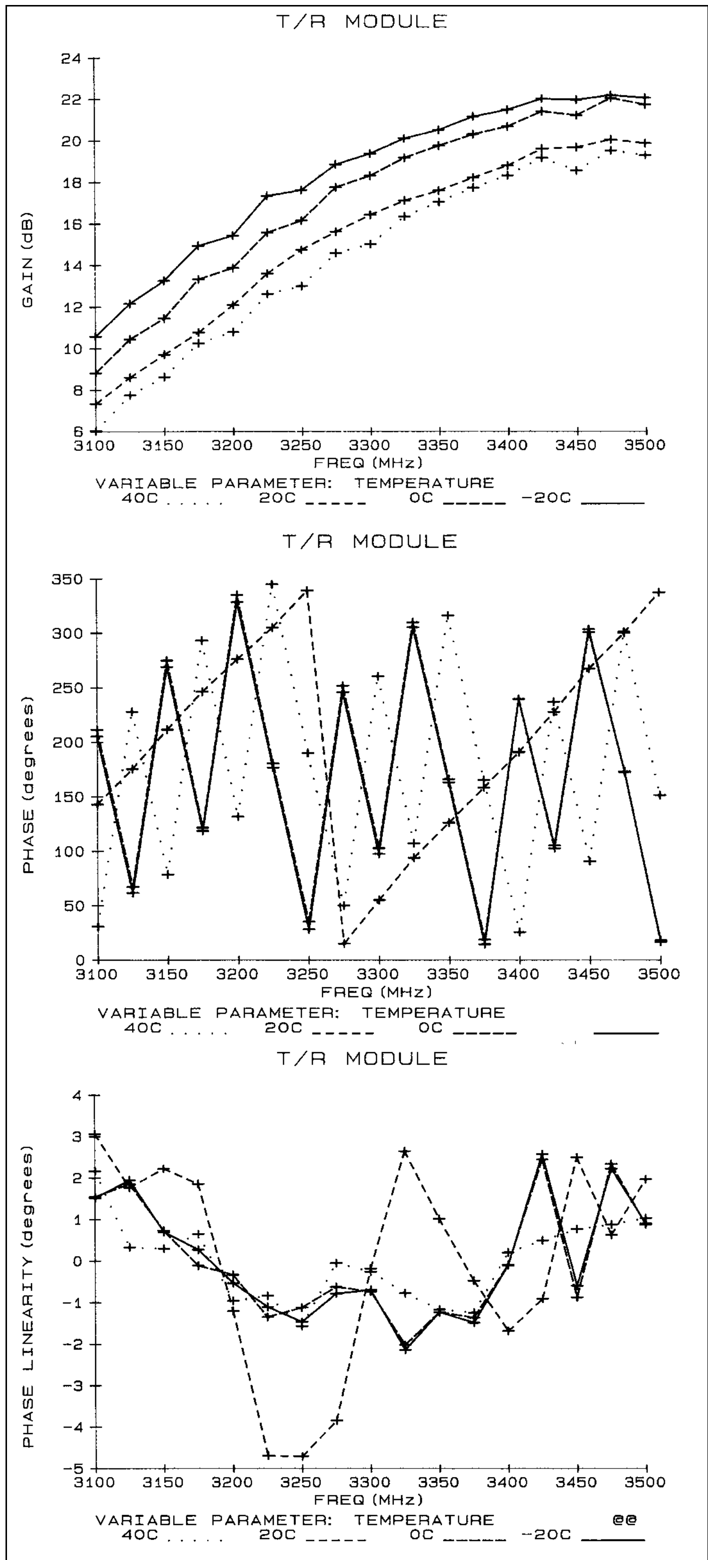



FIGURE 3.1.9 – S10 GAIN, PHASE & PHASE LINEARITY DATA

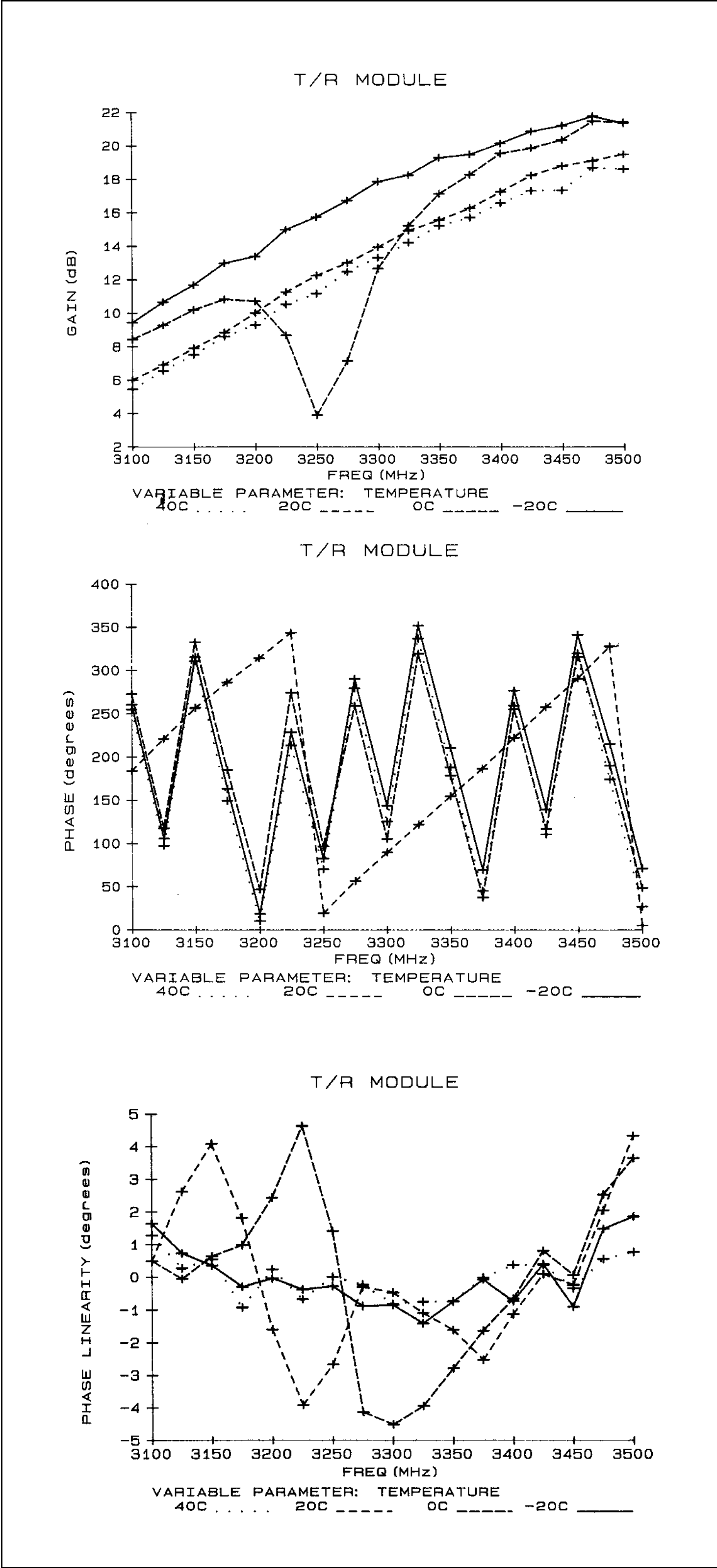



FIGURE 3.1.10 – S11 GAIN, PHASE & PHASE LINEARITY DATA

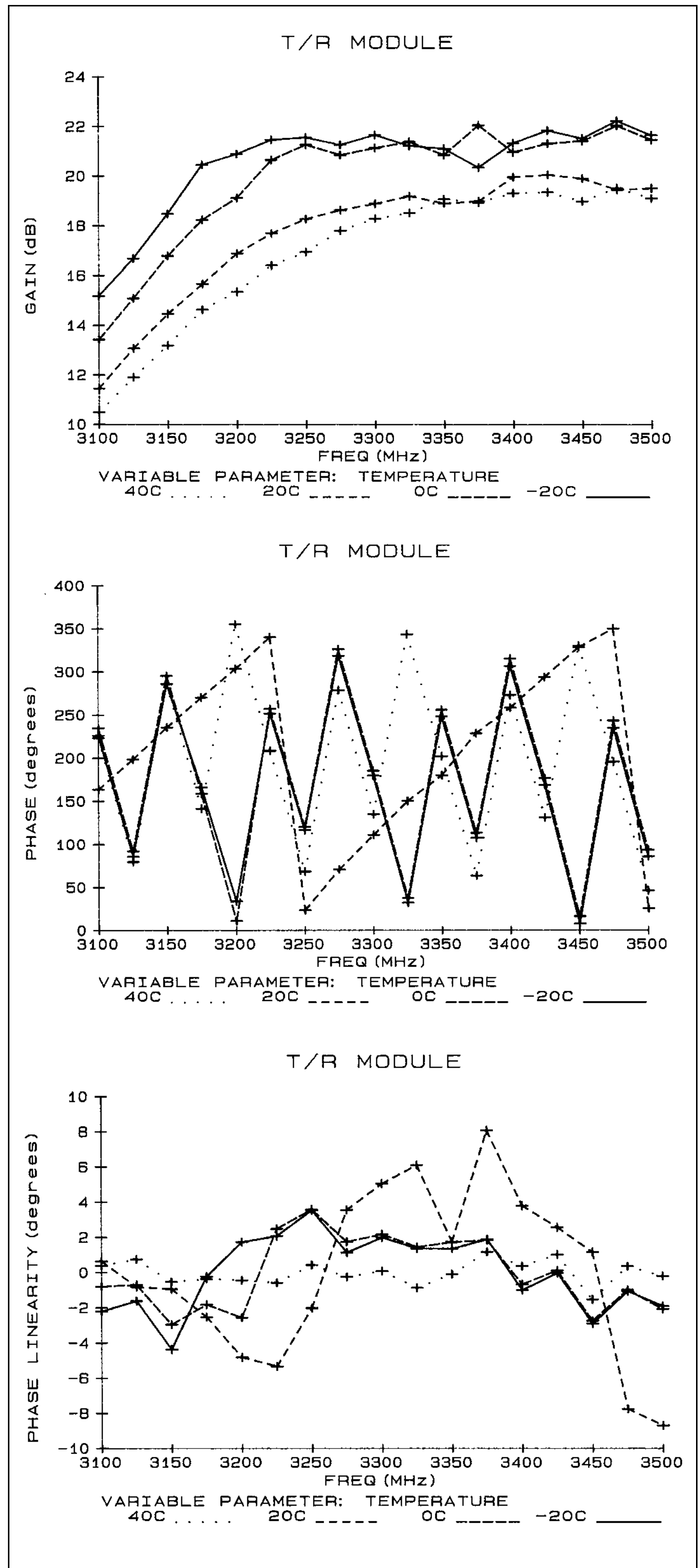


FIGURE 3.1.11 – S12 GAIN, PHASE & PHASE LINEARITY

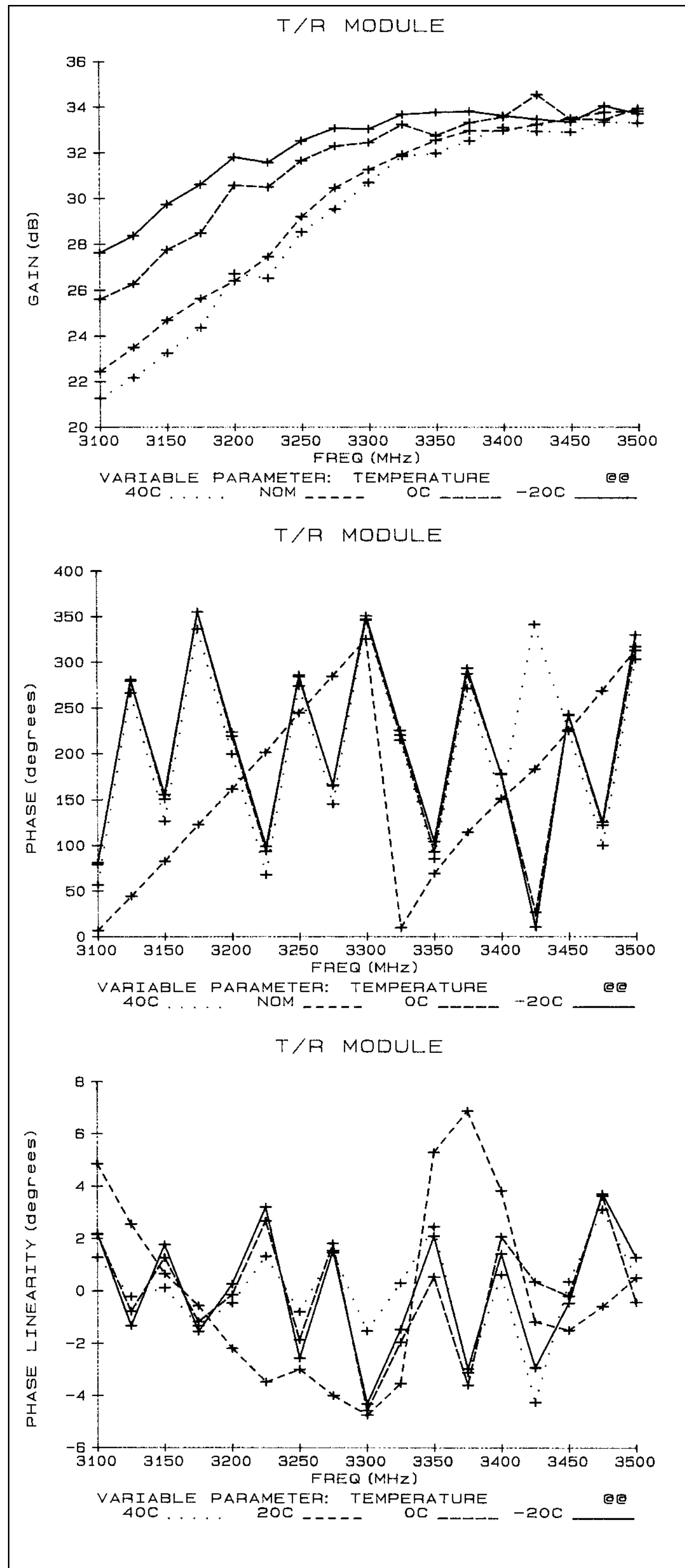



FIGURE 3.1.12 – T01 GAIN, PHASE & PHASE LINEARITY

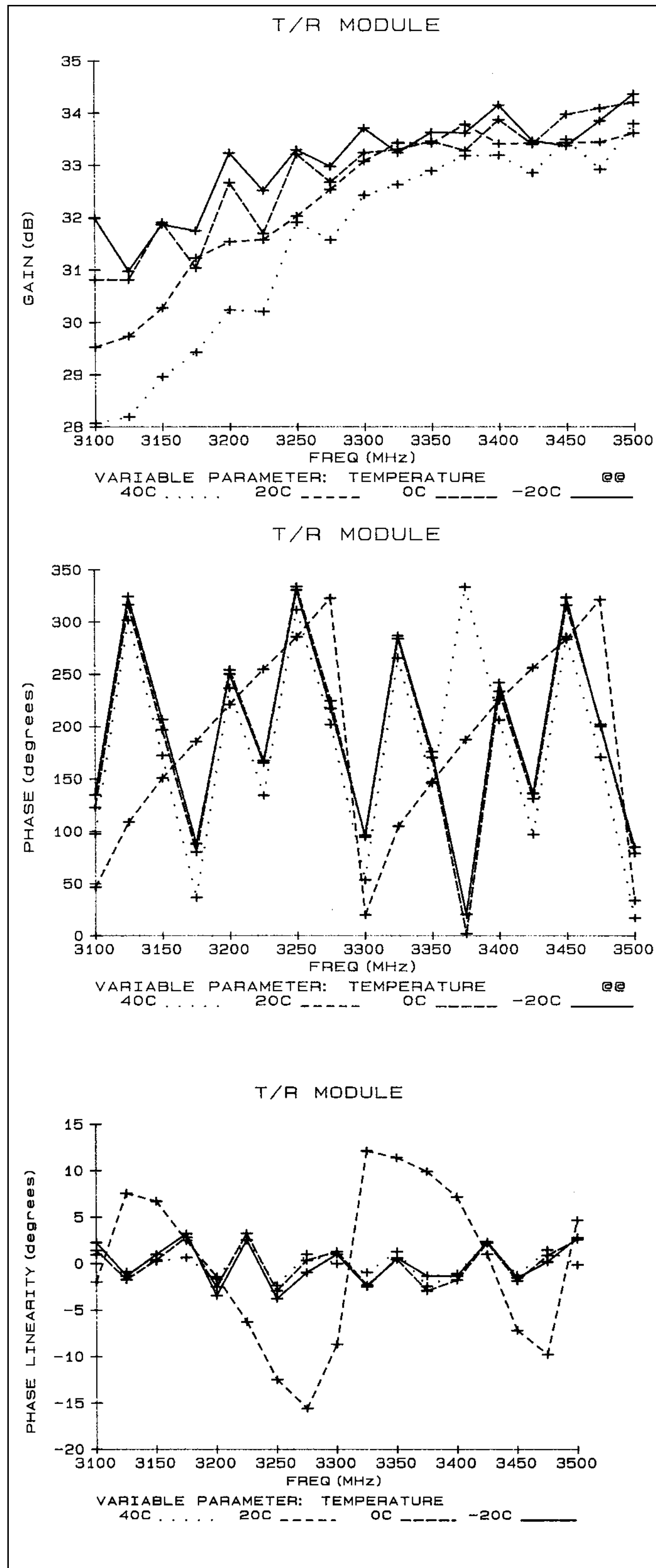



FIGURE 3.1.13 – T02 – GAIN, PHASE & PHASE LINEARITY

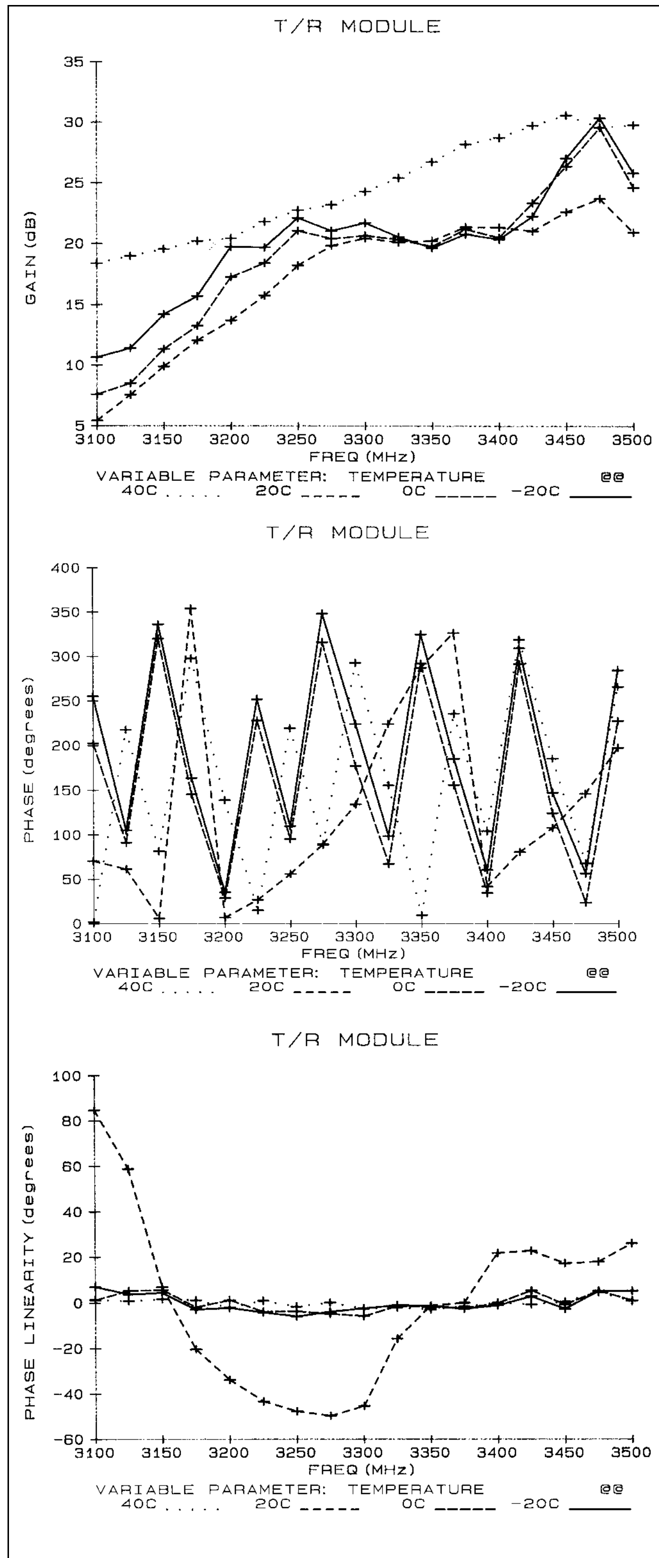



FIGURE 3.1.14 – GAIN, PHASE & PHASE LINEARITY DATA

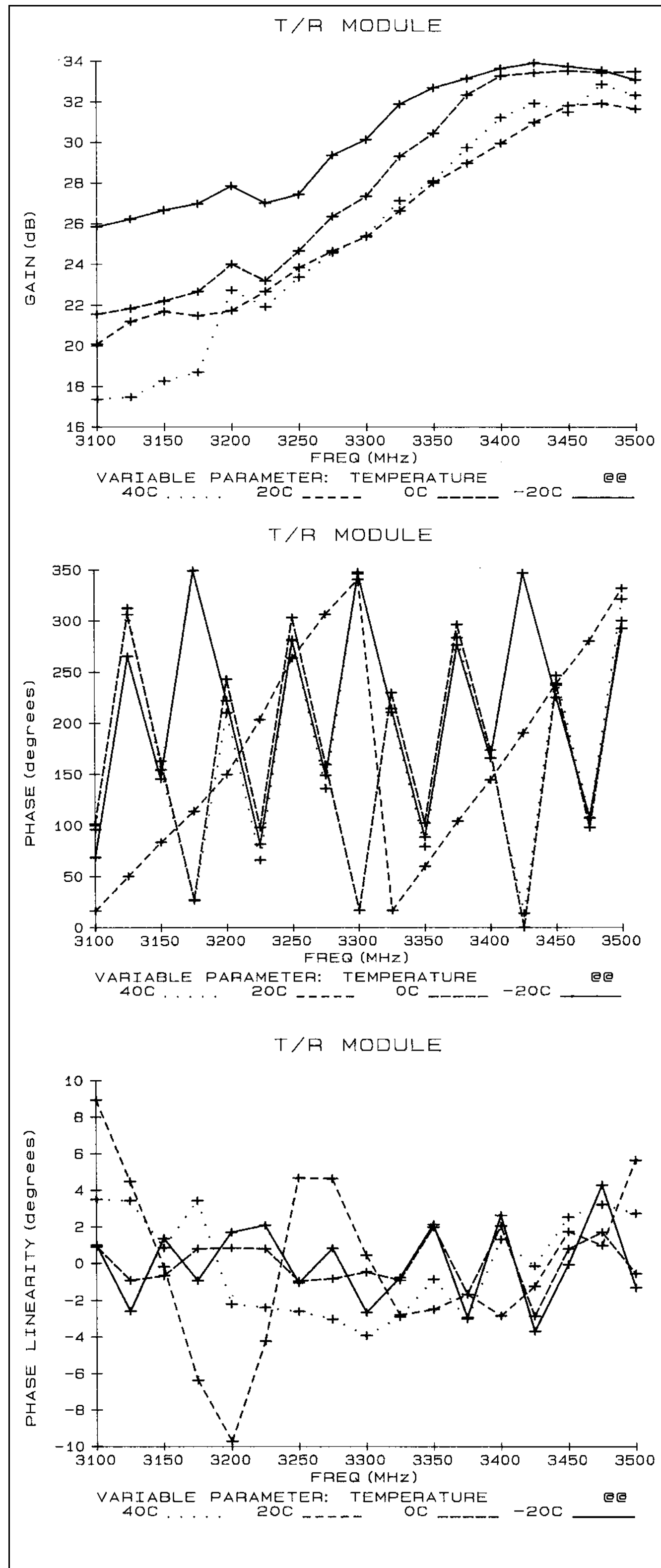


FIGURE 3.1.15 – T04 GAIN, PHASE & PHASE LINEARITY DATA

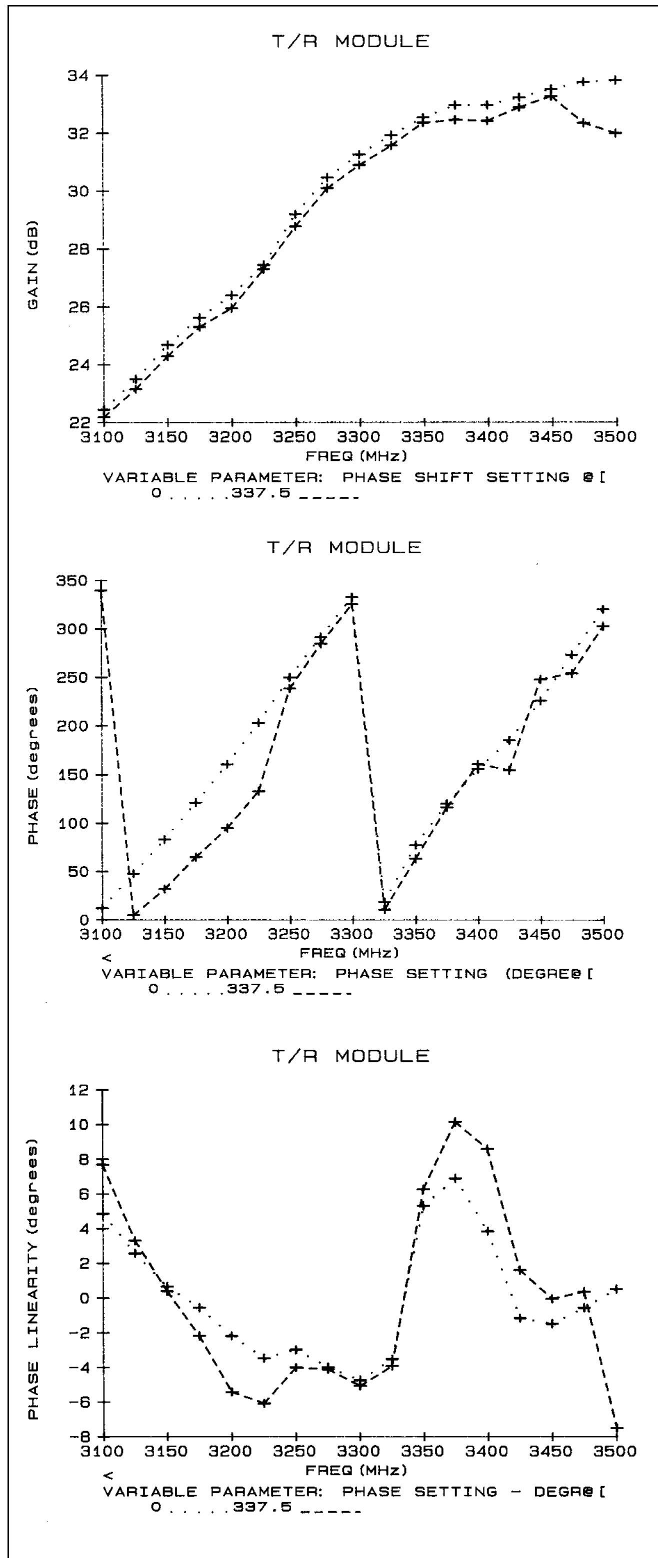


FIGURE 3.1.16 – T01 PHASE SHIFTER SETTING SENSITIVITY DATA

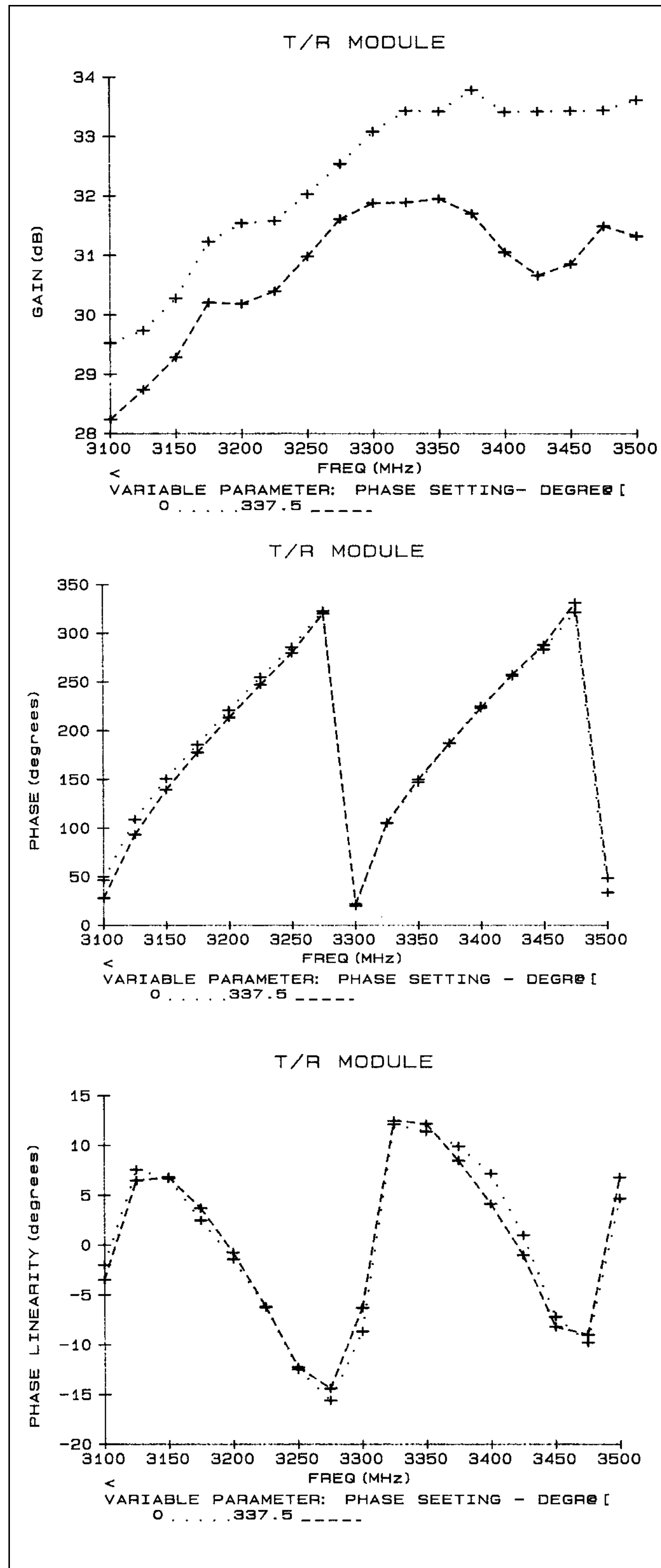



FIGURE 3.1.17 – TO2 PHASE SHIFTER SETTING SENSITIVITY DATA

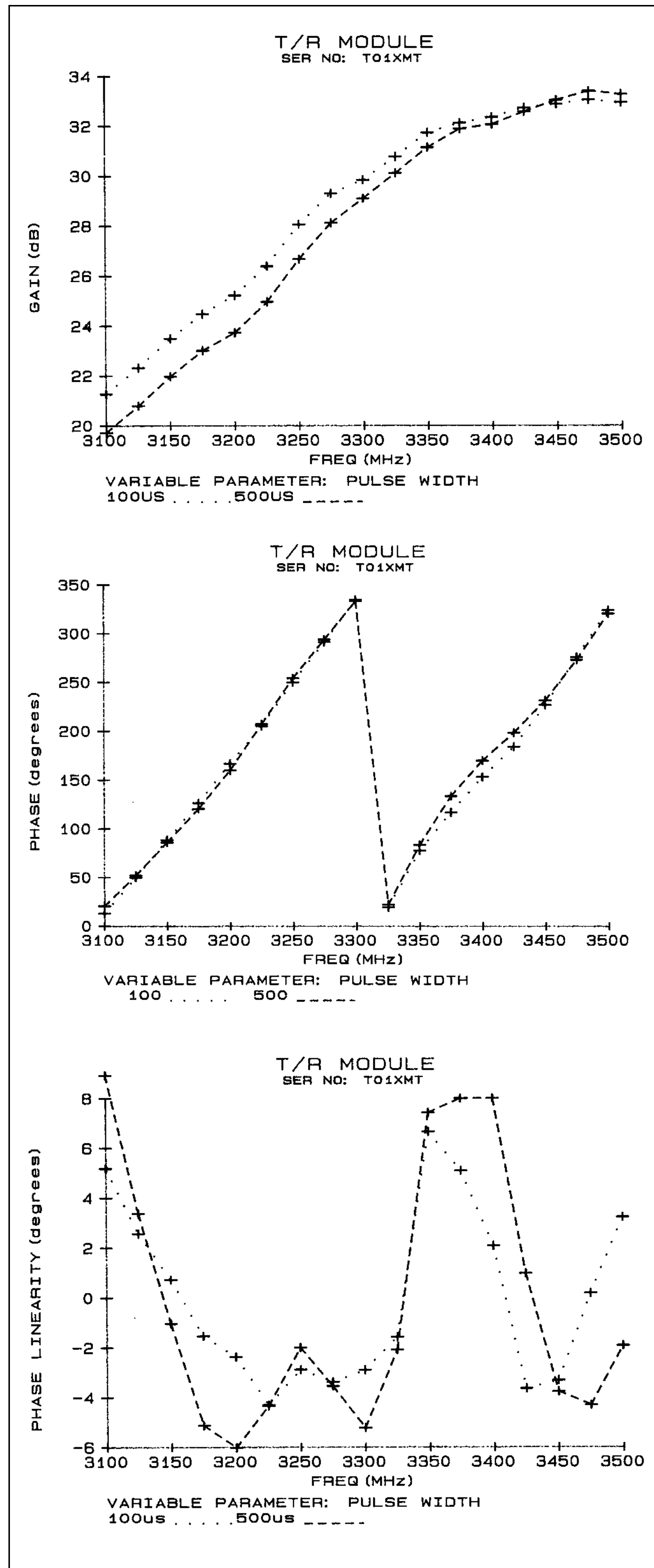



FIGURE 3.1.18T01 PULSE WIDTH SENSITIVITY DATA

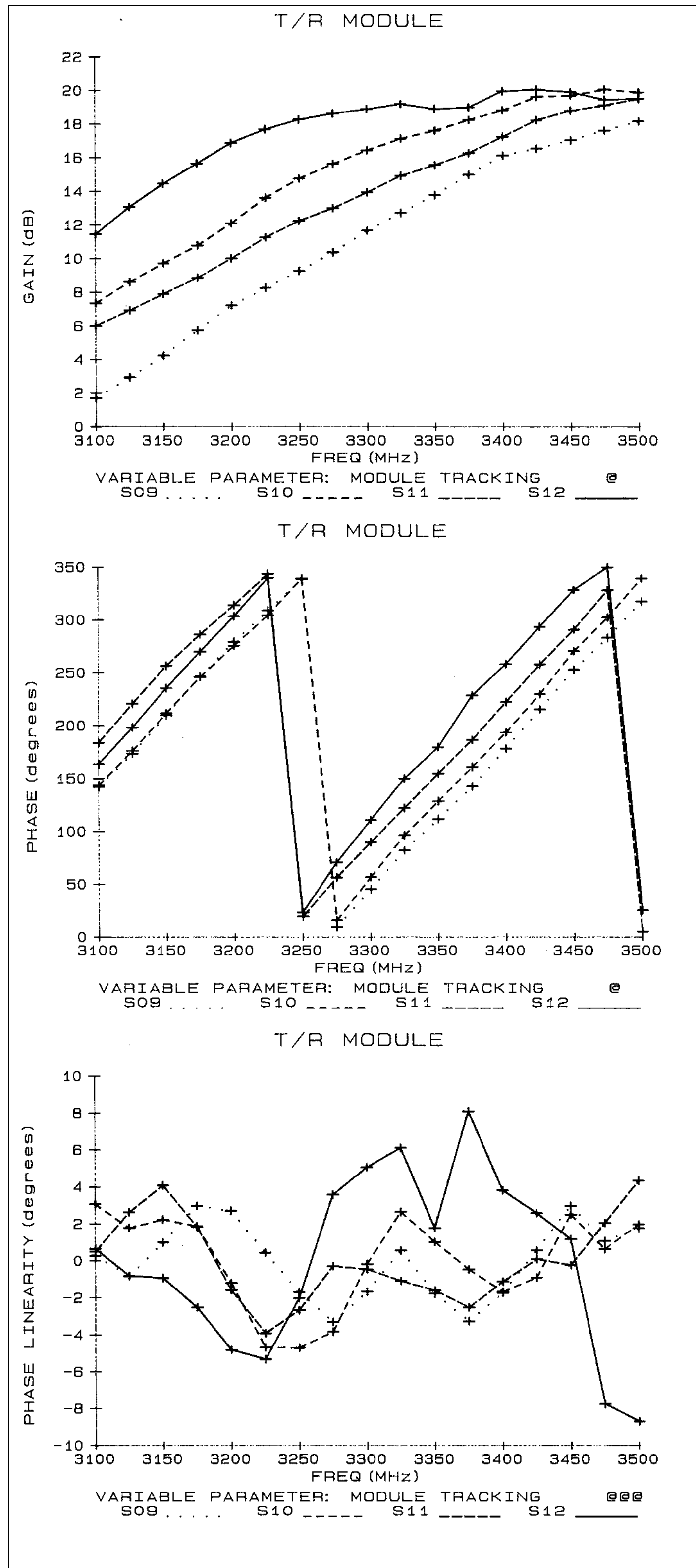



FIGURE 3.1.19 – LOW POWER S BAND MODULE TO MODULE TRACKING DATA

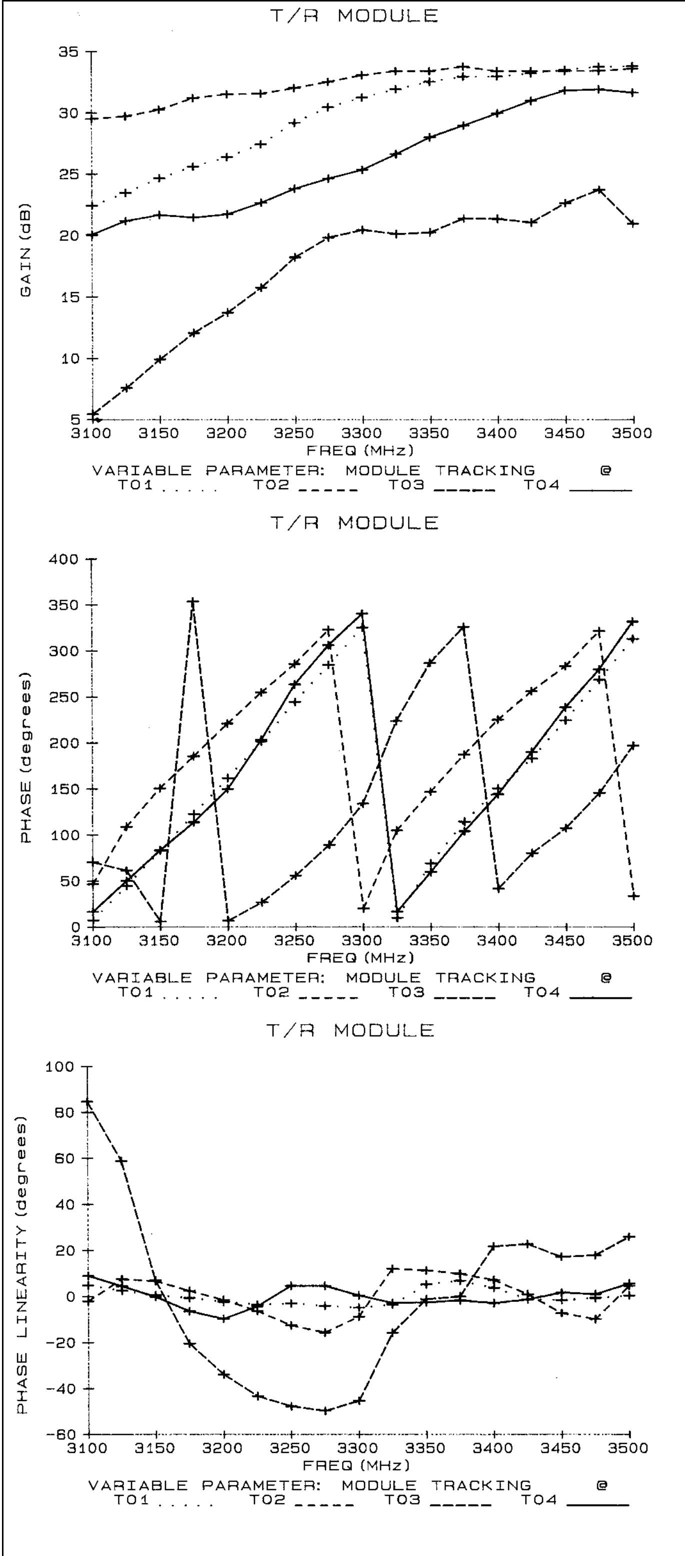



FIGURE 3.1.20 – HIGH POWER S BAND MODULE TO MODULE TRACKING DATA

## 3.2 C BAND MODULES

A group of C Band T/R modules that were developed under a contract with RADC were subjected to a variety of test, also. The most significant of these tests was a life test. In fact, these devices were the first subjected to life testing within the MELTS system. One hundred of these modules were manufactured, of which 20 were placed under life test at RADC and 29 were life tested by the contractor. Additional modules were expended in other performance and reliability tests and are reported on elsewhere.

### 3.2.1 MODULE DESCRIPTION

The microwave circuits of these modules are predominately of GaAs technology in the form of Monolithic Microwave Integrated Circuits (MMIC). The only variation was in the discrete power amplifier which is an IMFET (Internally Matched Field Effect Transistor). A picture of the module is shown in Figure 3.2.1. Notice that the right half of the 10.5 inch module is the microwave portion and the left half is the controller portion.

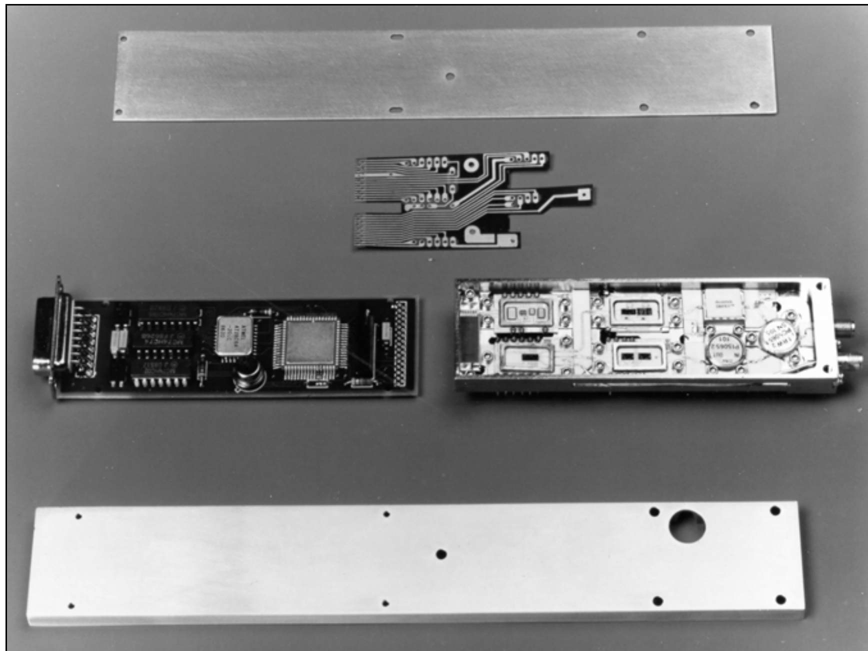


FIGURE 3.2.1 – C BAND T/R MODULE (EXPLODED VIEW)

The block diagram shown in Figure 3.2.2 shows the architecture of this module. Notice that the module consists of a two chip power amplifier driver, the IMFET power amplifier, a three chip LNA section that has gain control and a multi-bit phase shifter. The controller is a custom CMOS processor with some TTL “glue” logic and an EEPROM look-up table for performance correction factors. The power conditioning is limited to HEXFET switching of the drain bias. This module operates from 8 power supply voltages as noted in Table 3.2.1. Typical module performance parameters are presented in Table 3.2.2.

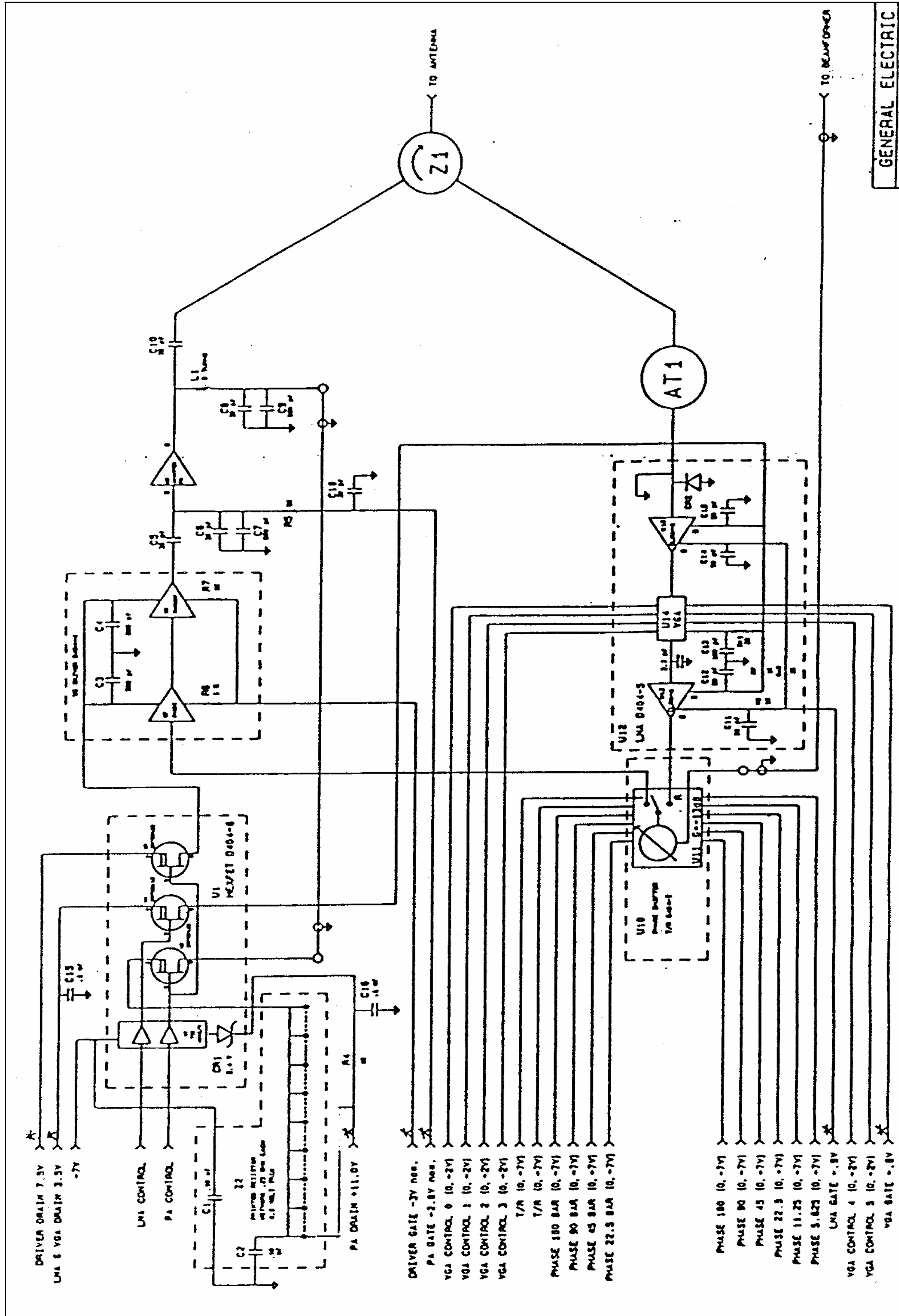


FIGURE 3.2.2 – C BAND T/R MODULE SCHEMATIC DIAGRAM

| | |
|---|---|
| Power Amplifier Drain Voltage | +14.0 Volts |
| Driver Amplifier Drain Voltage | + 9.0 Volts |
| Receiver Amplifier Drain Voltage | + 5.0 Volts |
| Power Amplifier Gate Voltage | - 7.0 Volts |
| Driver Amplifier Gate Voltage | - 6.0 Volts |
| Low Noise Amplifier Gate Voltage | - 2.0 Volts |
| Logic Voltage | - 8.0 Volts |
| Controller Voltage (MSC) | - 7.5 Volts |

TABLE 3.2.1 – TYPICAL BIAS VOLTAGES

| | |
|---|---|
| TRANSMIT MODE | |
| POWER OUTPUT | 2 WATTS AVE, 10 WATTS PEAK |
| GAIN | 20 dB +/- 1 dB |
| FREQUENCY RANGE | 5.25 TO 5.85 GHz |
| PHASE SHIFT BITS | 6 BITS +/- 3 DEGREES RMS |
| RECEIVE MODE | |
| GAIN | 25 dB +/- 1 dB |
| FREQUENCY RANGE | 5.25 TO 5.85 GHz |
| PHASE SHIFT BITS | 6 BITS +/- 3 DEGREES RMS |

TABLE 3.2.2 - TYPICAL MODULE PERFORMANCE PARAMETERS

### 3.2.2 LIFE TEST CONDITIONS

This module placed some major mechanical constraints on the test conditions. These included a built-in heat-sink and degradation temperatures of various components. The components with the lowest performance degradation temperature were the circulator, the dielectric, and the epoxy mounting of the power amplifier driver. The circulator's performance will theoretically permanently degrade at about 100 degrees Centigrade and the dielectric and epoxy will each degrade at about 125 degrees Centigrade. Later tests proved that the circulator could actually handle a far greater temperature without any significant performance impact. During the life test, the epoxy mounting caused the driver to operate at a failure point when the channel temperature was above 125 degrees Centigrade. Further failures occurred because there was a lack of strain relief between the individual component packages; causing conductor failure during temperature cycling.

The only electrical constraints that were placed on the test by this module were in the area of bias voltages for both the drain and gates. The transmit chain had a tendency to operate in the unstable region at the settings supplied by the manufacturer (an example of this is shown in Figure 3.2.3). Note that the module oscillated even when no RF was applied. These DC settings were selected by the contractor to achieve the maximum RF output power as measured by a CW power meter with no effort to maintain a good spectrum response. During the pretest characterization, the bias voltages used to achieve the maximum stable output power were determined. Table 3.2.3 provides the manufacturer suggested bias settings and the bias settings that were used to achieve stable operation.

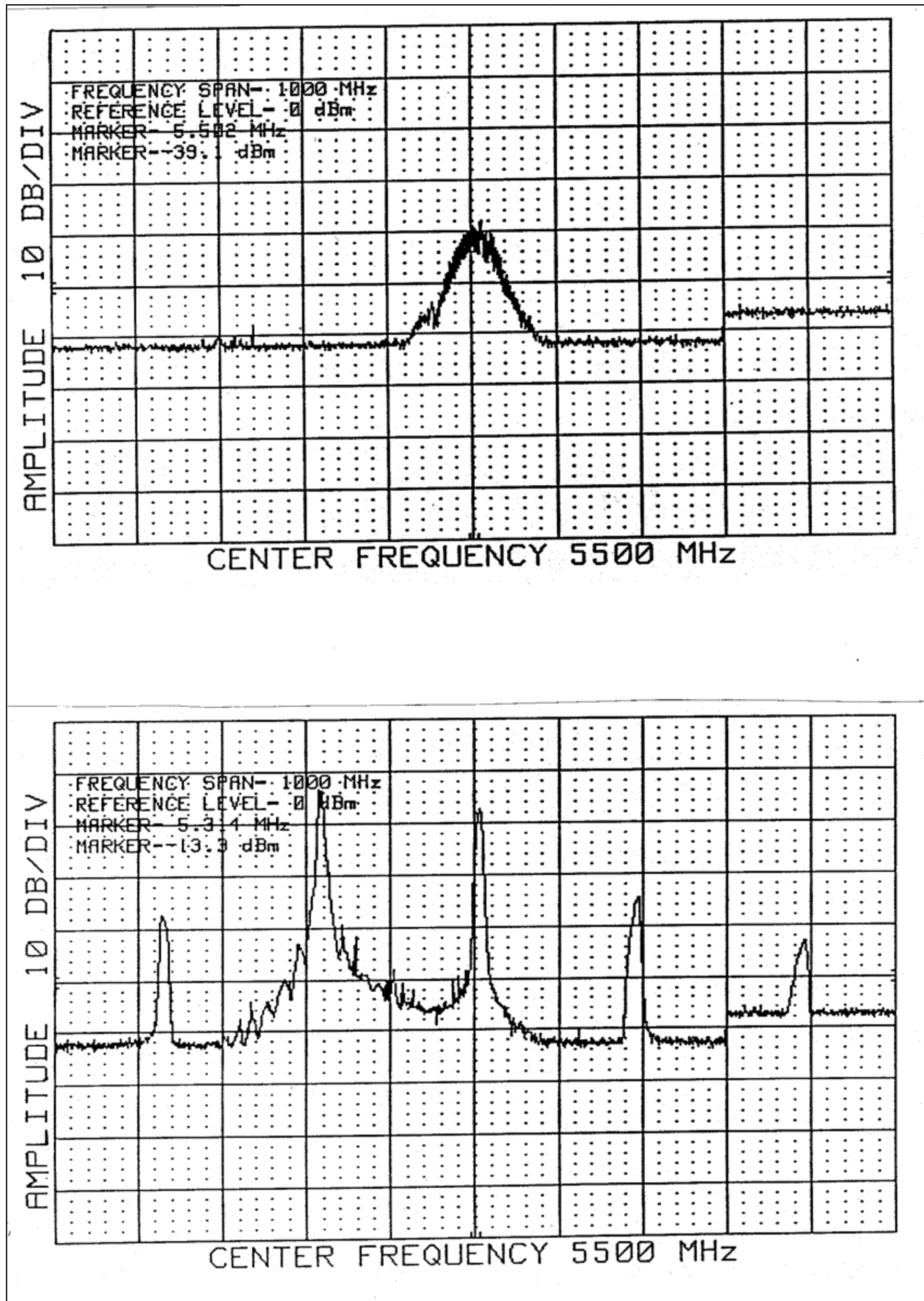



FIGURE 3.2.3 - C BAND T/R MODULE SPECTRUM OUTPUT WITHOUT RF INPUT (UPPER) AND WITH RF INPUT (LOWER)

Stable operation was deemed necessary for this test in order to eliminate as many unknown operating conditions as possible. Oscillations within the amplifier circuits could cause unique heating effects and initiate undesired failure mechanisms. The

drawback to reducing the bias to a stable operating point was that the channel temperatures would then be lower during the test; thus, increasing the time to failure. The channel temperature is a function of the base plate temperature and the DC power dissipated within the circuit. The actual channel temperatures were calculated based on data from IR measurements taken on discrete circuits and calculations made during finite element analysis.

| LOCATION | SERIAL NO. | PA (Contractor) | PA (MELTS) | DRV (Contractor) | DRV (MELTS) |
|---|---|---|---|---|---|
| **CA1** | 058 | +11.0 VOLTS | +10.3 VOLTS | + 7.5 VOLTS | + 3.64 VOLTS |
| **CB1** | 085 | +11.0 VOLTS | +10.13 VOLTS | + 7.5 VOLTS | + 3.10 VOLTS |
| **CC1** | 006 | +11.0 VOLTS | +10.81 VOLTS | + 7.5 VOLTS | + 3.40 VOLTS |
| **CD1** | 033 | +11.0 VOLTS | +110.06 VOLTS | + 7.5 VOLTS | + 7.54 VOLTS |
| **CE1** | 032 | +11.0 VOLTS | + 7.02 VOLTS | + 7.5 VOLTS | + 4.23 VOLTS |
| **CA2** | 065 | +11.0 VOLTS | +11.03 VOLTS | + 7.5 VOLTS | + 7.53 VOLTS |
| **CB2** | 057 | +11.0 VOLTS | + 9.49 VOLTS | + 7.5 VOLTS | + 4.01 VOLTS |
| **CC2** | 118 | +11.0 VOLTS | + 7.19 VOLTS | + 7.5 VOLTS | + 3.52 VOLTS |
| **CD2** | 056 | +11.0 VOLTS | +11.07 VOLTS | + 8.0 VOLTS | + 4.24 VOLTS |
| **CE2** | 063 | +11.0 VOLTS | +11.08 VOLTS | + 7.5 VOLTS | + 7.55 VOLTS |
| **CA4** | 070 | +11.0 VOLTS | + 6.91 VOLTS | + 8.0 VOLTS | + 4.60 VOLTS |
| **CB4** | 042 | +11.0 VOLTS | + 7.17 VOLTS | + 7.5 VOLTS | + 3.31 VOLTS |
| **CC4** | 017 | +11.0 VOLTS | + 8.74 VOLTS | + 7.5 VOLTS | + 3.35 VOLTS |
| **CD4** | 022 | +11.0 VOLTS | + 6.48 VOLTS | + 7.5 VOLTS | + 3.16 VOLTS |
| **CE4** | 084 | +11.0 VOLTS | +11.08 VOLTS | + 8.5 VOLT S | + 8.56 VOLTS |
| **CA3** | 089 | +11.0 VOLTS | + 7.61 VOLTS | + 7.5 VOLTS | + 3.13 VOLTS |
| **CB3** | 040 | +11.0 VOLTS | + 6.96 VOLTS | + 8.5 VOLT S | + 3.71 VOLTS |
| **CC3** | 044 | +11.0 VOLTS | +12.83 VOLTS | + 7.5 VOLTS | + 3.41 VOLTS |
| **CD3** | 039 | +11.0 VOLTS | + 7.52 VOLTS | + 7.0 VOLTS | + 3.71 VOLTS |
| **CE3** | 073 | +11.0 VOLTS | + 7.06 VOLTS | + 7.5 VOLTS | + 3.25 VOLTS |

TABLE 3.2.3 - ACTUAL BIAS SETTINGS FOR C BAND T/R MODULES

This initial test was designed to validate the test system and to provide some early reliability data on components. The rationale used to select the parameters for this test included: (1) consideration of the module's specification and known operating capability, (2) minimizing the impact of test system reliability and performance, (3) predicted time required to achieve module failure, and (4) adequacy of data to be acquired for reliability and performance evaluation.

To limit the effect that pulsing the drain voltage has on the system power supplies, the 20 modules were pulsed at 20 percent duty in five groups of four modules. These groups were staggered so that the current draw on the main power supplies would be relatively constant. The pulse width of each group was 100 microseconds long. Test results from this initial life test run indicated that the power supplies had sufficient capacity to negate the need for such staggering during subsequent test.

To acquire a reasonable amount of data in a cost effective manner, while not significantly prolonging the test, a specific test sequence was employed. This test sequence provided that the modules be subjected to 112 minutes of a cook mode while operating in the transmit mode. At the end of the transmit cook mode, the modules are then individually exercised through a measurement mode that lasts for approximately 30 minutes. The sequence then culminates in a 98 minute receive cook mode. Each cycle is 240 minutes

long and there are 6 cycles per day. An illustration of this sequence was shown earlier in Figure 2.2.4. To limit the quantity of data to reasonable levels, it was determined that data would be stored only every 24 hours, unless a significant change occurred in the drain current or the module gain. An arbitrary limit was defined to determine if a module's performance had degraded to the point where it should be considered a dead module. When a module reached that defined death level, it was either tested till a catastrophic failure occurred, or removed from test for detailed analysis. The exact course of action was determined on an individual case based on that module's historical data. The drain current and module microwave gain were defined as the parameters to watch as indicators of performance change.

The base plate temperature that each module was operated at was determined as a function of the DC power input, the module's efficiency, its cooling efficiency, and the ambient temperature of the surrounding environment. Ideally, the modules would all be operating at the same base plate temperature. Such consistency would theoretically lead to the channels all operating at the same temperature. Because the bias voltages for the modules are all set at different levels, and the module efficiency does not track from module to module, each module has a different amount of DC power being dissipated; thus, a different base plate temperature. Table 3.2.4 provides the base plate temperatures that the modules were operating at when the testing began. Figure 3.2.4 shows how these modules were mounted in the test chamber, note the large wattage resistors that were used to raise the ambient temperature in the test chamber.

FIGURE 3.2.4 – C BAND T/R MODULES IN LIFE TEST CHAMBER (LEFT SIDE)

| MODULE | TRANSMIT TEMP |
|---|---|
| CA1 | 54.8°C |
| CB1 | 65.3°C |
| CC1 | 70.5°C |
| CD1 | 75.2°C |
| CE1 | 68.5°C |
| CA2 | 72.1°C |
| CB2 | 60.4°C |
| CC2 | 65.2°C |
| CD2 | 75.0°C |
| CE2 | 72.0°C |
| CA4 | 59.6°C |
| CB4 | 58.5°C |
| CC4 | 54.5°C |
| CD4 | 50.7°C |
| CE4 | 64.7°C |
| CA3 | 49.6°C |
| CB3 | 54.3°C |
| CC3 | 56.1°C |
| CD3 | 47.1°C |
| CE3 | 50.3°C |
| ABIENT AIR TEMPERATURE | 45.0°C |

TABLE 3.2.4 - C BAND BASE PLATE TEMPERATURES

During the course of the test, various events occurred. These events are of two types: (1) test system related, and (2) DUT related. The test system related events provided information on how the structure and operation of the test system needed improvement and/or change, as well as information on the test environment. The DUT related events provided information on how the modules fared in performance and reliability within the test system environment. Table 3.2.5 provides a log of these events. It is important to note the interaction between system level and module level events (i.e., a test system failure can cause a premature module failure, module failures can change the thermal environment and effect power supply loading, etc). Although complicating the test results, these events did not invalidate the results. The event log entries helped in determining what was happening. Further, test system failure that caused a module failure would be a valid emulation of a radar system failure that would cause modules in the array to fail. Analysis of such a failure could lead to modules with a lower susceptibility to radar system "glitches".

| DATE /TIME | EVENT |
| --- | --- |
| 21 DEC 88/0816 | SYSTEM TURN-ON |
| 13 JAN 89/0830 | SYSTEM DOWN FOR SOFTWARE MODIFICATION |
| 13 JAN 89/1500 | SYSTEM RESTARTED |
| 13 JAN 89//2128 | SYSTEM HUNGUP IN RCVR COOK |
| 16 JAN 89/1031 | SYSTEM RESTARTED |
| 19 JAN 89 | TAPPED ON RF SWITCHES 1A1813 & 1A88 AFTER FIRST MEASUREMENT FREQUENCY & GAIN INCREASED APROX. 8dB (STICKY SWITCHES ?) |
| 19 JAN 89/1600 | CHANGED XMTR POWER SENSOR FROM MEDIUM POWER TO LOW POWER |
| 20 JAN 89/1500 | MODULE CE2 IS OSCILATING IN RCVR MODE |
| 23 JAN 89/1330 | MODULE CC2 IS OSCILATING IN RCVR MODE; STICKY RF SWITCH IS CAUSE OF CC4 LOW RCVR GAIN |
| 30 JAN 89/2235 | SYSTEM HUNGUP WHEN PRINTER RAN OUT OF PAPER |
| 31 JAN 89/0935 | SYSTEM WAS RESTARTED |
| 3 FEB 89/2055 | SYSTEM HUNGUP IN RCVR COOK MODE; CAUSED BY POWER METER NOT ZEROING PROPERLY |
| 6 FEB 89/1000 | ZEROED POWER METER & RESTARTED SYSTEM |
| 6 FEB 89/2336 | SYSTEM HUNGUP IN RCVR COOK MODE; CAUSED BY POWER METER NOT ZEROING PROPERLY |
| 7 FEB 89/1000 | ZEROED POWER METER & RESTARTED SYSTEM |
| 7 FEB 89/2300 | SYSTEM HUNGUP IN RCVR COOK MODE; CAUSED BY POWER METER NOT ZEROING PROPERLY |
| 8 FEB 89/1000 | ZEROED POWER METER & RESTARTED SYSTEM; REPLACED POWER METER |
| 8 FEB 89/1800 | SYSTEM HUNGUP IN RCVR COOK MODE; CAUSED BY S BAND SYNTHESIZER EQUIPMENT FAILURE |
| 9 FEB 89/1300 | FAILED SYNTHESIZER REPLACED; SOFTWARE MODIFIED |
| 10 FEB 89/1340 | RESTARTED SYSTEM |
| 10 FEB 89/1430 | SYSTEM PAUSED FOR CODE MODIFICATION |
| 10 FEB 89/1559 | SYSTEM RESTARTED |
| 13 FEB 89/1720 | SYSTEM HUNGUP IN RCVR COOK MODE |
| 14 FEB 89/0930 | SYSTEM RESTARTED WITH CLEAR I/O |
| 16 FEB 89/0358 | SYSTEM HUNGUP IN RCVR COOK MODE; PRINTER OUT OF PAPER |
| 16 FEB 89/1031 | SYSTEM RESTARTED |
| 17 FEB 89/0845 | POWER SUPPLY BOARD CC3 CURRENT SENSE TRIPPED; RESET BOARD |
| 17 FEB 89/1015 | POWER SUPPLY BOARD CC3 CURRENT SENSE TRIPPED; NOT RESET |
| 21 FEB 89/0950 | POWER SUPPLY BOARD CC3 RESET |
| 21 FEB 89/1135 | POWER SUPPLY BOARD CC3 CURRENT SENSE TRIPPED; NOT RESET |
| 4 MAR 89 | SYSTEM HUNGUP; CAUSE PRINTER OUT OF PAPER |
| 6 MAR 89/0923 | SYSTEM RESTARTED |
| 9 MAR 89 | SYSTEM HUNGUP; CAUSE PRINTER OUT OF PAPER |
| 10 MAR 89/0907 | SYSTEM RESTARTED |
| 13 MAR 89/0201 | SYSTEM HUNGUP; CAUSE PRINTER OUT OF PAPER |
| 13 MAR 89/0921 | SYSTEM RESTARTED |
| 15 MAR 89/1130 | ROOM TEMPERATURE IS AT 82°C |
| 27 MAR 89/1600 | ROOM AIR CONDITIONER CONTINUES TO MALFUNCTION; ROOM TEMPERATURE IS AT 85°C |
| 7 APR 89/0900 | SWITCH DRIVER FAILED; ALL MEASUREMENTS BECAME COMPOSITES |
| 11 APR 89/2200 | SYSTEM HUNGUP; CAUSE PRINTER OUT OF PAPER |
| 12 APR 89/1500 | SYSTEM RESTARTED; SWITCH DRIVER FIXED |
| 17 APR 89/1645 | REMOVED MODULES CA1, CC3, CB4, CE4, CE2 FROM TEST |
| 19 APR 89/1145 | SYSTEM HALTED IN RCVR COOK MODE; SOFTWARE UPDATE INSTALLED |
| 20 APR 89/1215 | RESTARTED SYSTEM |

| | |
|---|---|
| 21 APR 89/0400 | SYSTEM HUNGUP IN RCVR COOK MODE; CAUSE WAS TAPE BACK UP |
| 21 APR 89/0945 | SYSTEM RESTARTED |
| 28 APR 89/0100 | SYSTEM HUNGUP; SOFTWARE ERROR, REPAIRED |
| 28 APR 89/0955 | SYSTEM RESTARTED |
| 10 MAY 89/1226 | SYSTEM HUNGUP IN RCVR COOK MODE; CAUSE SOFTWARE ERROR |
| 10 MAY 89/1430 | SYSTEM RESTARTED |
| 11 MAY 89/0900 | SYSTEM HALTED FOR SOFTWARE MODIFICATIONS |
| 11 MAY 89/1000 | SYSTEM RESTARTED |
| 12 MAY 89/0331 | SYSTEM HUNGUP IN RCVR COOK MODE; CAUSE IS TAPE BACKUP |
| 12 MAY 89/0915 | SYSTEM RESTARTED |
| 16 MAY 89/1545 | SYSTEM HUNGUP IN XMTR MESURE MODE; CAUSED BY MAINTANCE |
| 16 MAY 89/1615 | SYSTEM RESTARTED |
| 19 MAY 89/0830 | SYSTEM HUNGUP; CAUSED BY SOFTWARE ERROR |
| 19 MAY 89/0932 | SYSTEM RESTARTED |
| 18 MAY 89/1930 | AIR CONDITIONING FAILED |
| 19 MAY 89/0930 | ROOM TEMPERATURE AT 80°C |
| 19 MAY 89/1510 | ROOM TEMPERATURE AT 88°C |
| 19 MAY 89/1532 | SYSTEM SHUTDOWN DUE TO ROOM TEMPERATURE |
| 6 JUN 89/0830 | SYSTEM RESTARTED |
| 6 JUN 89/1000 | RESET SYSTEM CLOCK |
| 12 JUN 89/1116 | OPENED CHAMBER DOOR FOR THREE MINUTES FOR TOUR |
| 20 JUN 89/1012 | SYSEM HALTED TO INSTALL S BAND MODULES |
| 22 JUN 89/1630 | SYSTEM RESTARTED |
| 23 JUN 89/1005 | SYSTEM HUNGUP; CAUSED BY TAPE BACKUP |
| 23 JUN 89/1015 | SYSTEM RESTARTED |
| 24 JUN 89/1750 | SYSTEM HUNGUP; AC POWER LOW VOLTAGE CHANGED EQUIPMENT ADRESSES |
| 26 JUN 89/1000 | SYSTEM RESTARTED; ADRESSES RESET |
| 28 JUN 89/1000 | SYSTEM HALTED; ADDITIONAL S BAND MODULES INSTALLED |
| 29 JUN 89/1540 | SYSTEM RESTARTED |
| 30 JUN 89/0919 | SYSTEM HUNGUP; CAUSED BY TAPE BACKUP |
| 30 JUN 89/0920 | SYSTEM RESTARTED |
| 14 JUL 89/1630 | SYSTEM HALTED; PLANNED POWER OUTAGE |
| 17 JUL 89/1326 | SYSTEM RESTARTED |
| 21 JUL 89/0350 | SYSTEM HUNGUP; CAUSED BY TAPE BACKUP |
| 21 JUL 89/0912 | SYSTEM RESTARTED |
| 24 JUL 89/1700 | SYSTEM HUNGUP; CAUSED BY POWER METER FAILURE |
| 26 JUL 89/1010 | SYSTEM RESTARED |
| 4 AUG 89/1310 | SYSTEM HUNGUP; CAUSED BY TAPE BACKUP |
| 4 AUG 89/1310 | SYSTEM RESTARTED |
| 13 AUG 89/0700 | SYSTEM HALTED BY POWER OUTAGE |
| 14 AUG 89/1000 | SYSTEM RESTARTED |
| 22 AUG 89/1600 | SYSTEM HALTED; CAUSED BY PLANNED POWER OUTAGE |
| 25 AUG 89/1145 | SYSTEM RESTARTED |
| 5 SEP 89/1630 | SYSTEM HALTED; CAUSED BY PLANNED POWER OUTAGE |
| 16 SEP 89/1430 | SYSTEM RESTARTED |
| 16 SEP 89/1733 | SYSTEM HALTED; CAUSED BY UNANOUNCED POWER OUTAGE |
| 17 SEP 89/1400 | SYSTEM RESTARTED |
| 1 NOV 89/0915 | SYSTEM HALTED; CAUSED BY TEST TERMINATED |

TABLE 3.2.5 - LIFE TEST LOG OF EVENTS

### 3.2.3 LIFE TEST RESULTS

A composite of data from all 20 C band modules, as measured on MEL-2 prior to MELTS testing, is presented in Figures 3.2.5 (RF module transmit gain, phase, gain linearity, phase linearity), 3.2.6 (RF module receive gain, phase, gain linearity, phase linearity), 3.2.7 (DC module transmit gain, phase, gain linearity, phase linearity), 3.2.8 (DC module receive gain, phase, gain linearity, phase linearity). The data is divided into two sets, the RF modules are those that were subjected to microwave excitation during the life test, and the DC modules are those that did not receive any excitation during life test (DC only). The microwave gain for the RF modules shows a wide spread between about 15 dB of gain to nearly 40 dB of gain, for a spread of about 25 dB. The DC modules exhibit a similar 25 dB spread starting from 5 dB of gain to a top end at just over 30 dB of gain. This data was measured after the transmit gate and drain bias voltages had been adjusted for stable operation. The phase data shows a wide spread of actual phase differences from module to module. Note that more of the DC modules than the RF modules match in phase across the band. This could be caused by numerous reasons including: (1) manufacturing tolerances, (2) connector tolerances, (3) load line differences due to the wide spread of bias settings, or (4) amplifier saturation. The most likely is a difference in load lines. The modules that are bunched together in gain are also the modules that are bunched together in phase. Note that the phase and gain linearity still at a reasonable level even with the inadequate module-to-module tracking. Individual plots for each module are presented in Appendix C.

In Figure 3.2.9, transmit and receive gain data taken during MELTS testing is presented in composite form. The figures shows the transmit and receive gain versus time at the center frequency of 5550 MHz, and the transmit and receive gain versus frequency at one point in time part way through the test. The date and time for each is noted. Note that data is presented only from the RF excited modules. The data that was recorded for the DC modules was corrupted during testing and could not be recovered. In the RF data presented, the gain is perturbed in steps, predominately in a downward direction. Each step is an indication of a major change in the module’s performance. The upwards steps indicate that the module either became unstable, the problem somehow improved, or a test system failure occurred. The downward steps indicate that the module either became stable again, or experienced a partial or complete failure. Because the modules did not have a temperature controller to maintain a constant temperature, these modules were susceptible to the temperature variations of the room. Daily variations in the gain of these modules are due to the daily fluctuation in room temperature. Further, as noted in the module data, there is also a seasonal temperature effect that varies the daily average. Sample room temperature data is shown in Figures 3.2.10 & 3.2.11. Individual plots for each module are presented in Appendix C.

Five modules were removed from testing during the latter half of April 89 (see events chart - Table 3.2.6). Three of these modules had received microwave excitation and two were tested under DC only conditions. The remaining modules were removed from test at the beginning of November 89. Upon removal from life testing, each module was

retested on MEL-2 (referred to as phase three). A composite of the phase three module performance is presented in Figures 3.2.12, 3.2.13, 3.2.14 & 3.2.15. Note that each module has a different level of degradation. Individual plots for each module are presented in Appendix C.

The modules were then subjected to a post mortem to determine the cause for the significant changes in performance. The root cause was not failures on the part of the MMICs. The failures are attributed to the specific packaging technique employed.

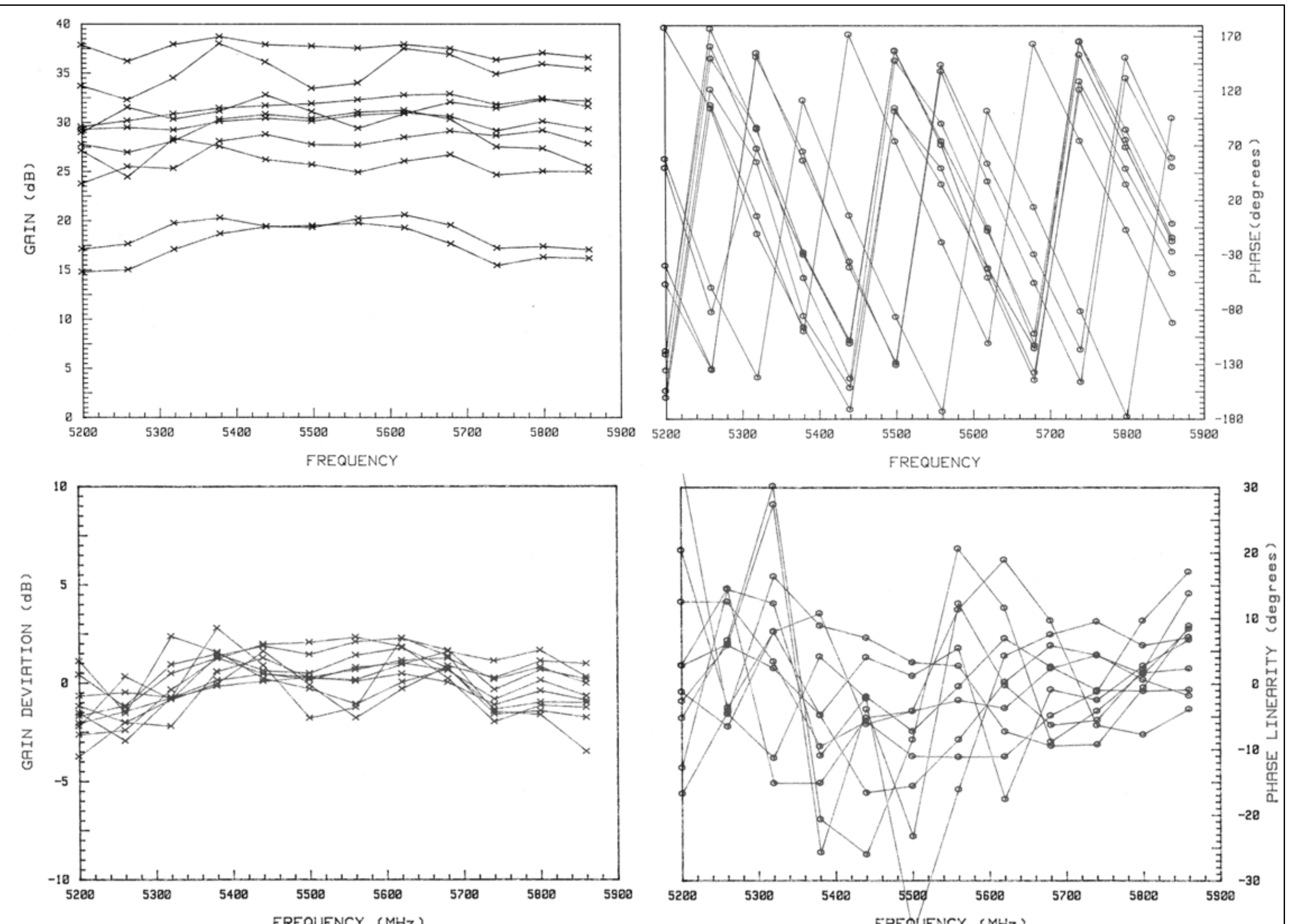


FIGURE 3.2.5 – C BAND T/R MODULE PHASE 1 RF TRANSMIT COMPOSITE DATA

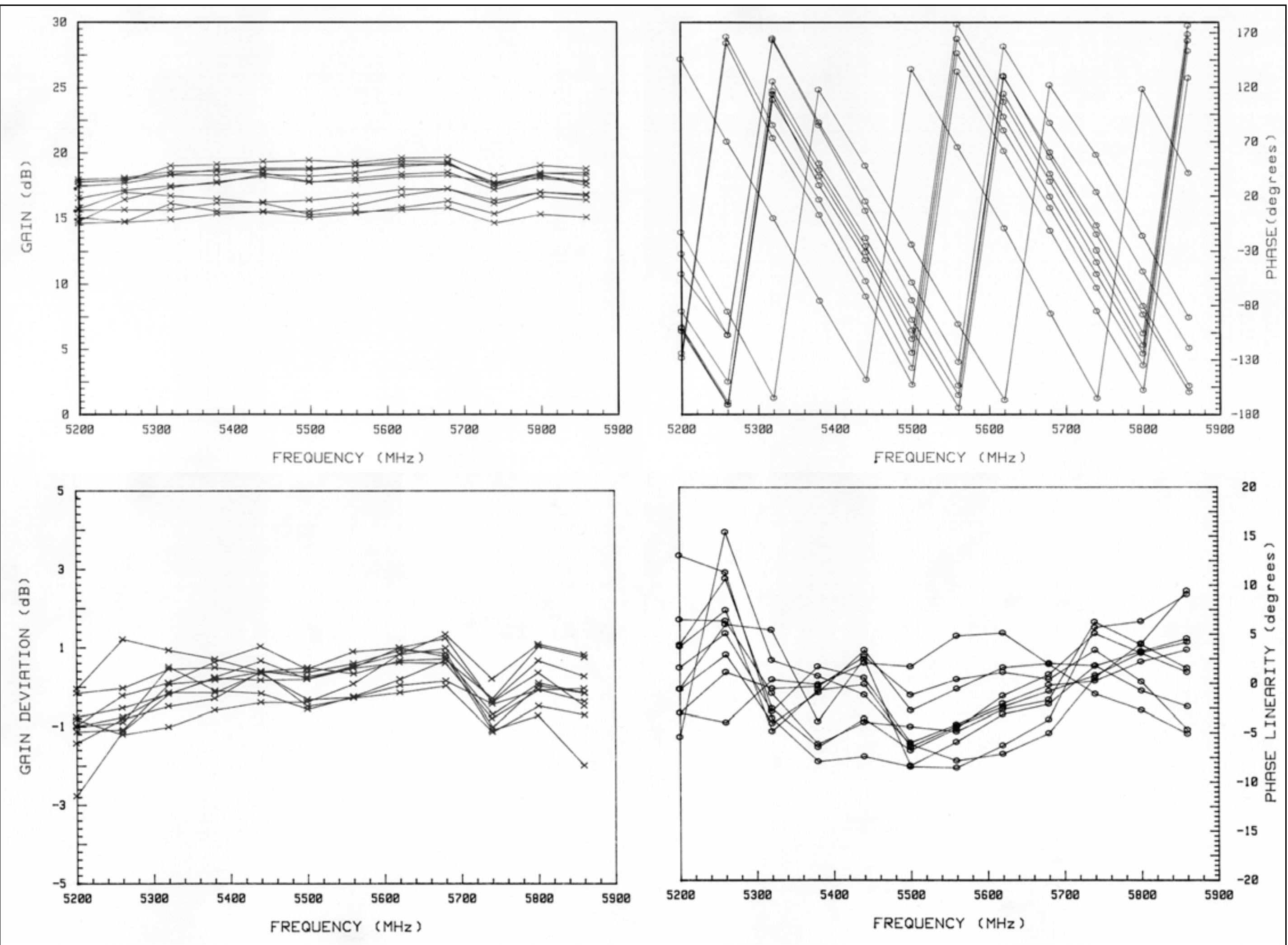



FIGURE 3.2.6 - C BAND T/R MODULE PHASE 1 RF RECEIVE COMPOSITE DATA

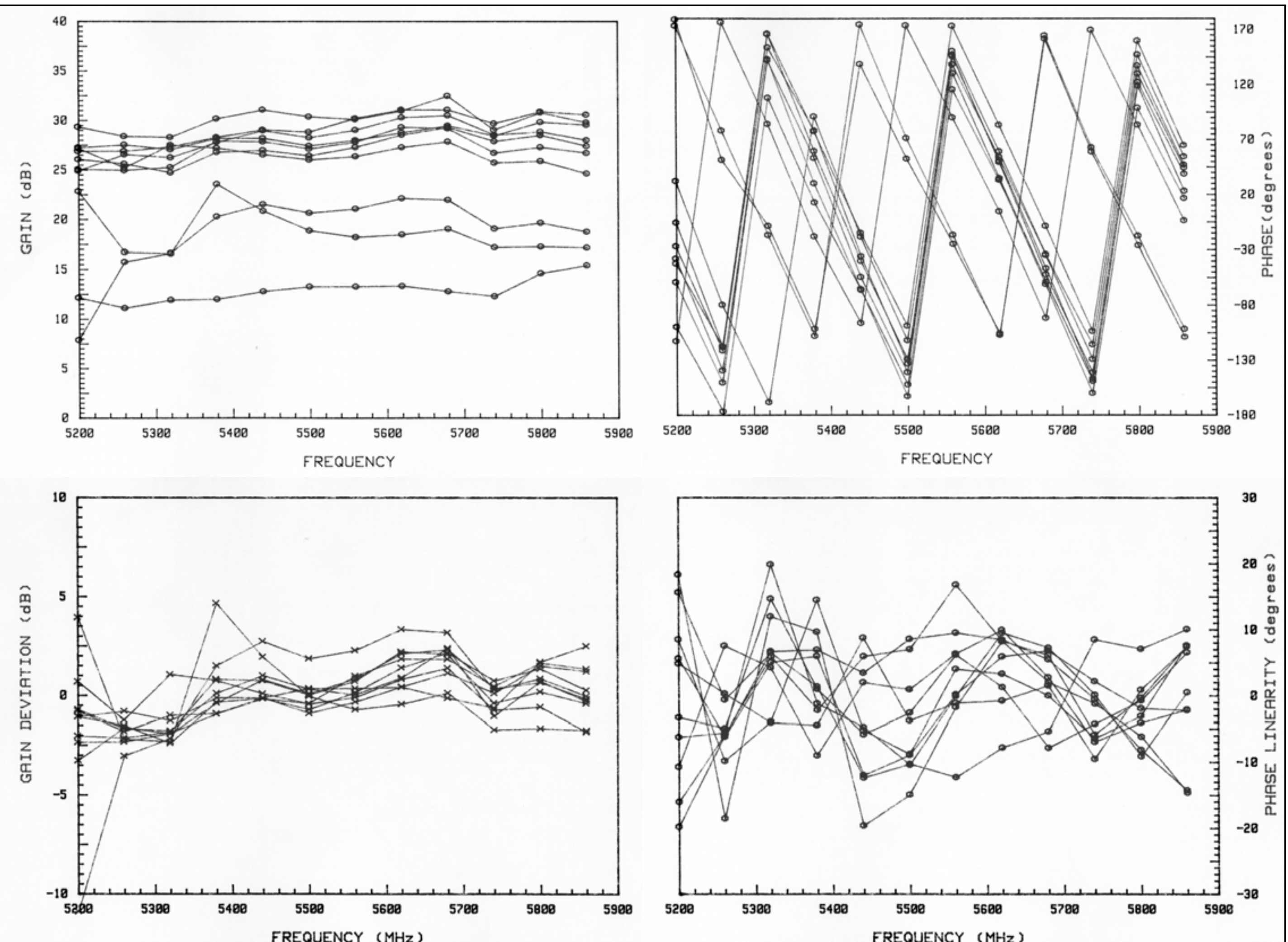



FIGURE 3.2.7 - C BAND T/R MODULE PHASE 1 DC TRANSMIT COMPOSITE DATA

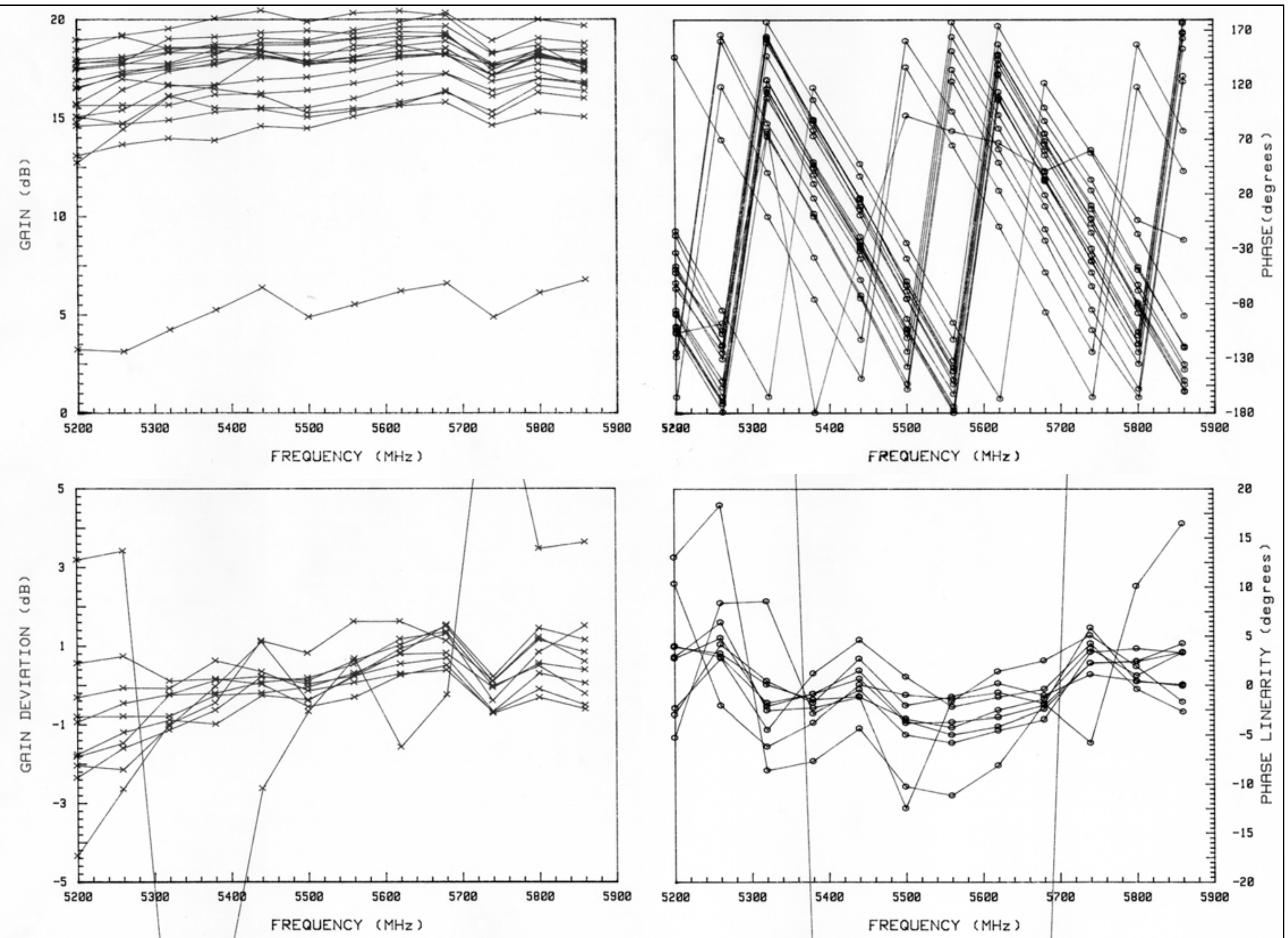



FIGURE 3.2.8 - C BAND T/R MODULE PHASE 1 DC RECEIVE COMPOSITE DATA

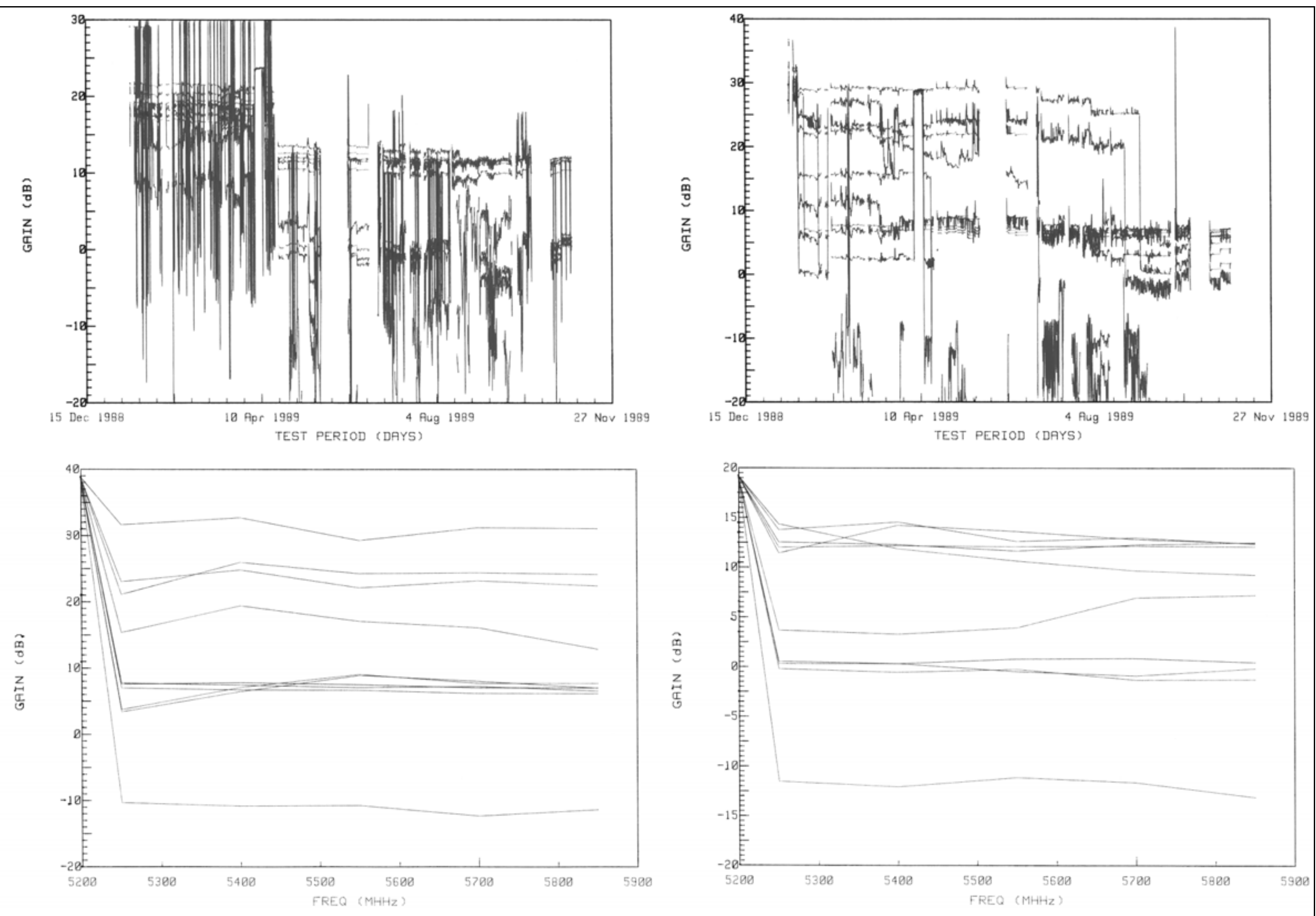



FIGURE 3.2.9 – C BAND COMPOSITE LIFE TEST

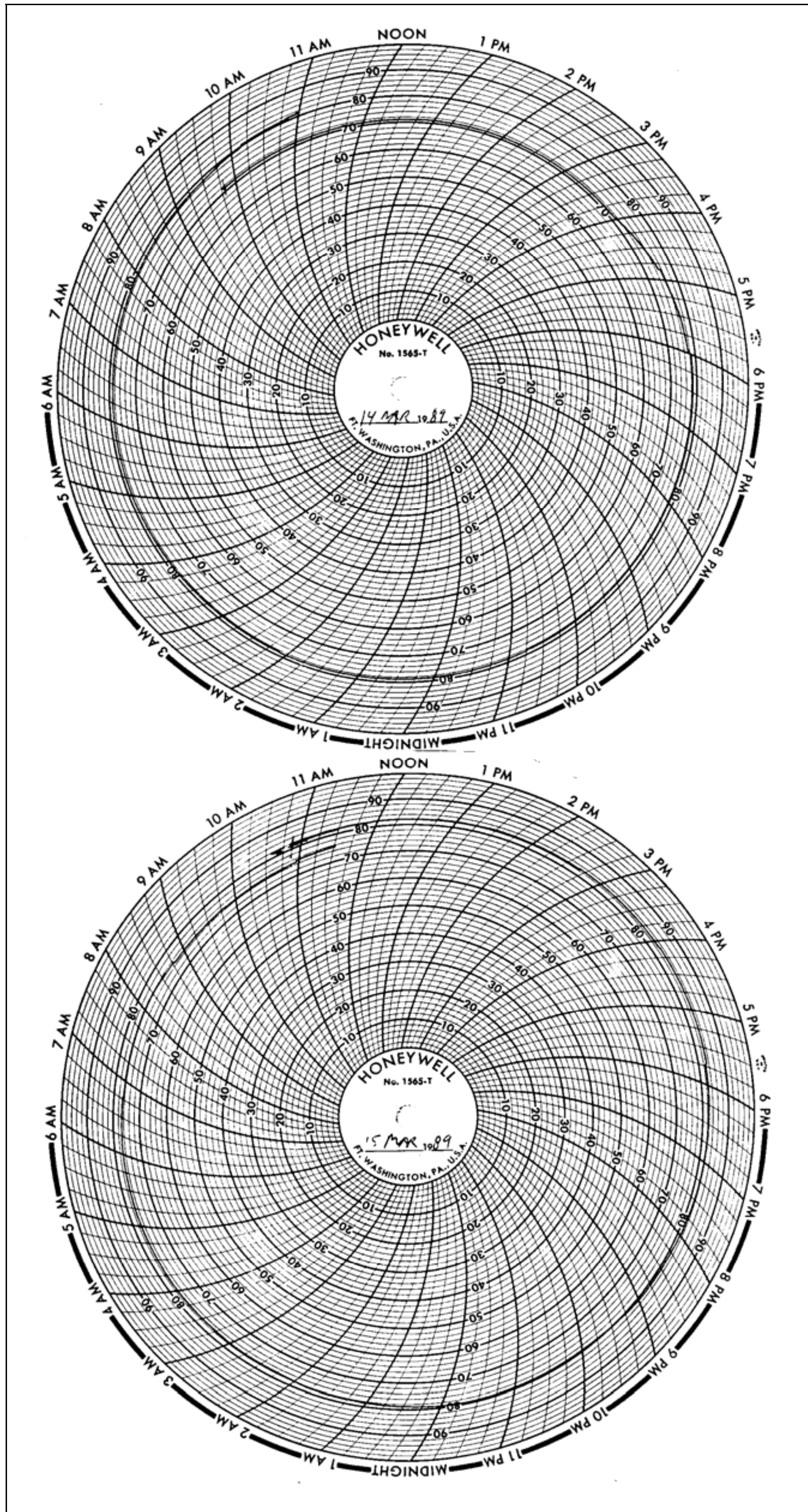



FIGURE 3.2.10 – ROOM TEMPERATURE 14 & 15 MARCH 1989

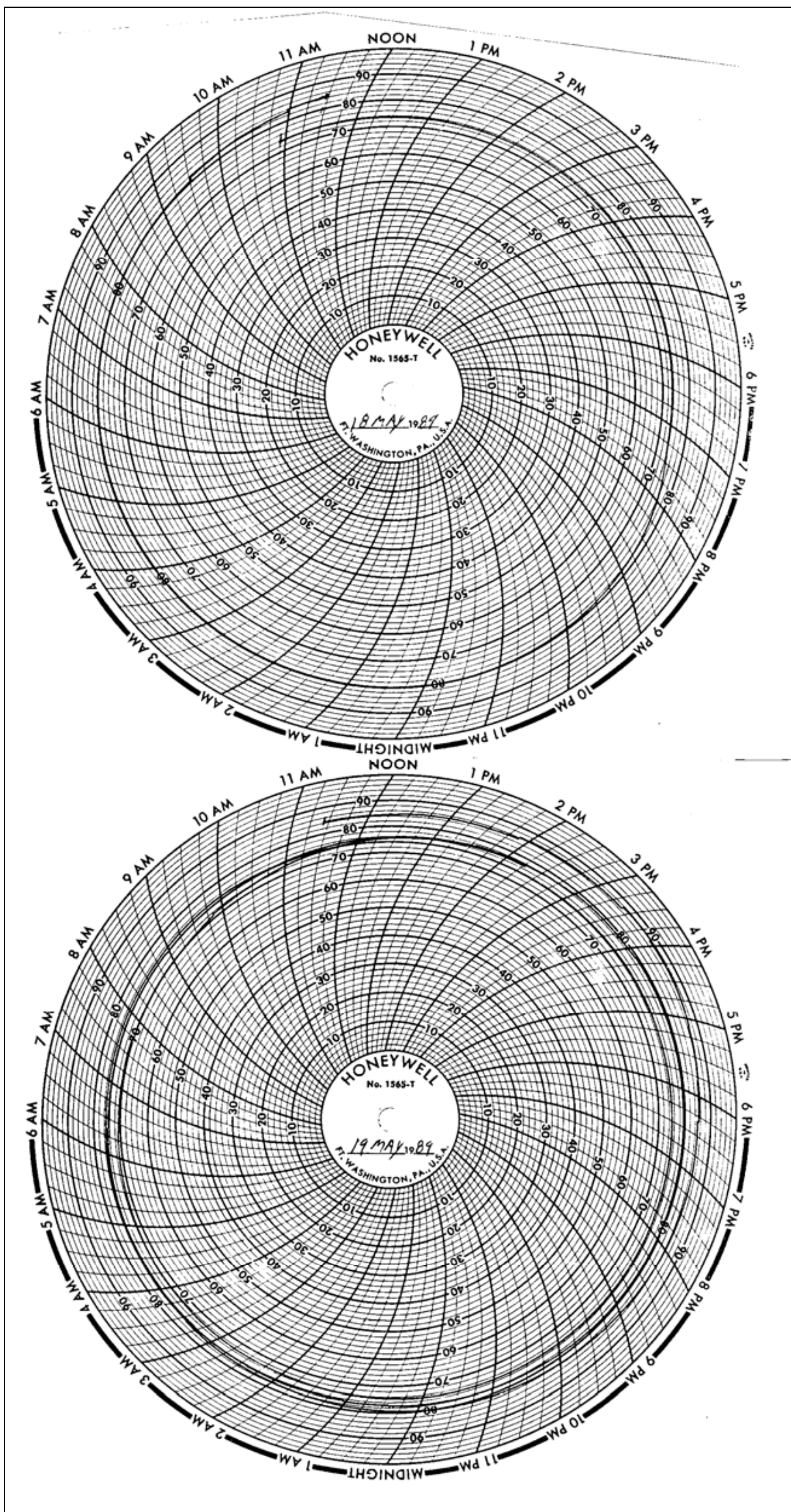



FIGURE 3.2.11 – ROOM TEMPERATURE 18 & 19 MAY 1989

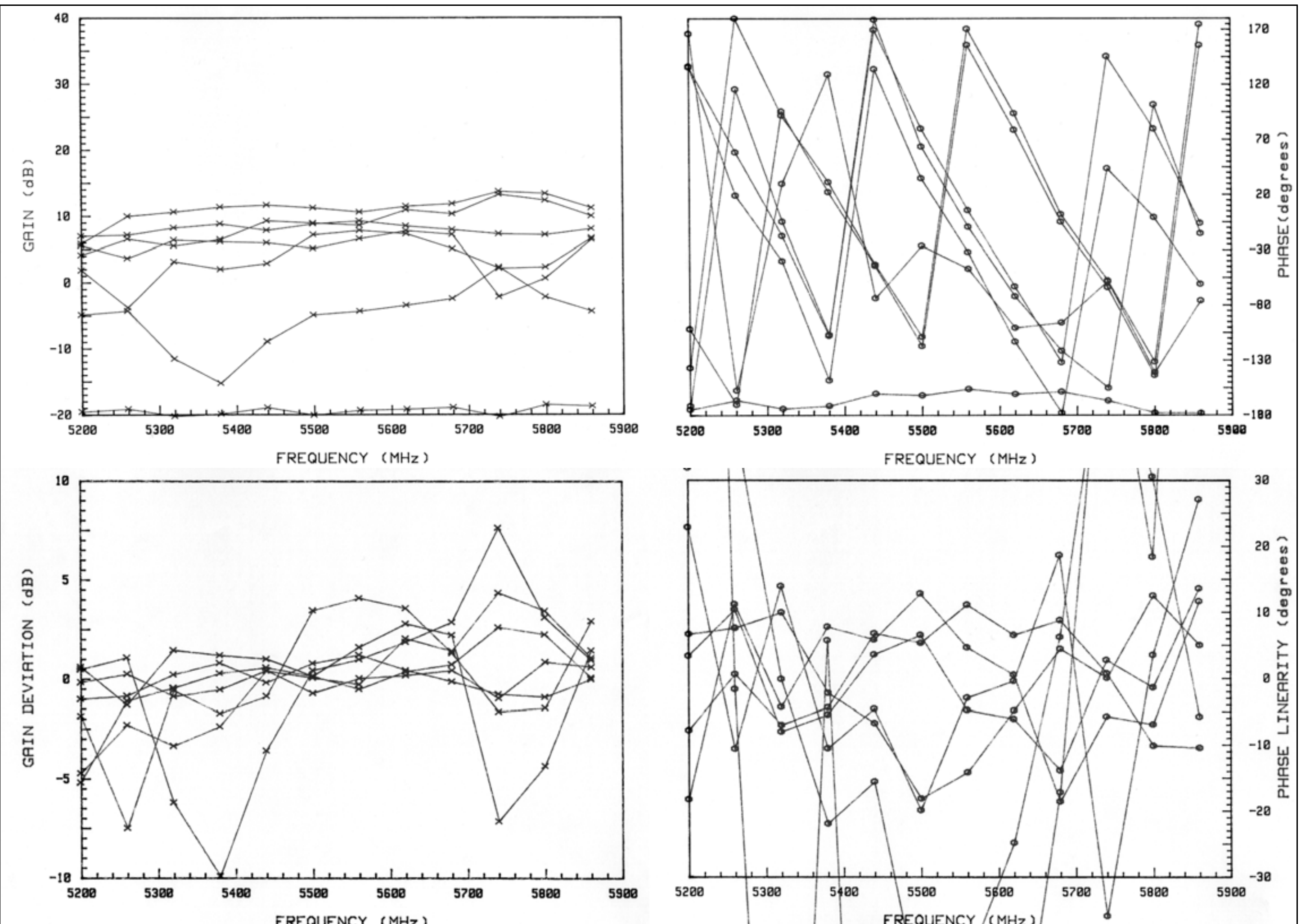



FIGURE 3.2.12 - C-BAND T/R MODULE PHASE III RF TRANSMIT COMPOSITE DATA

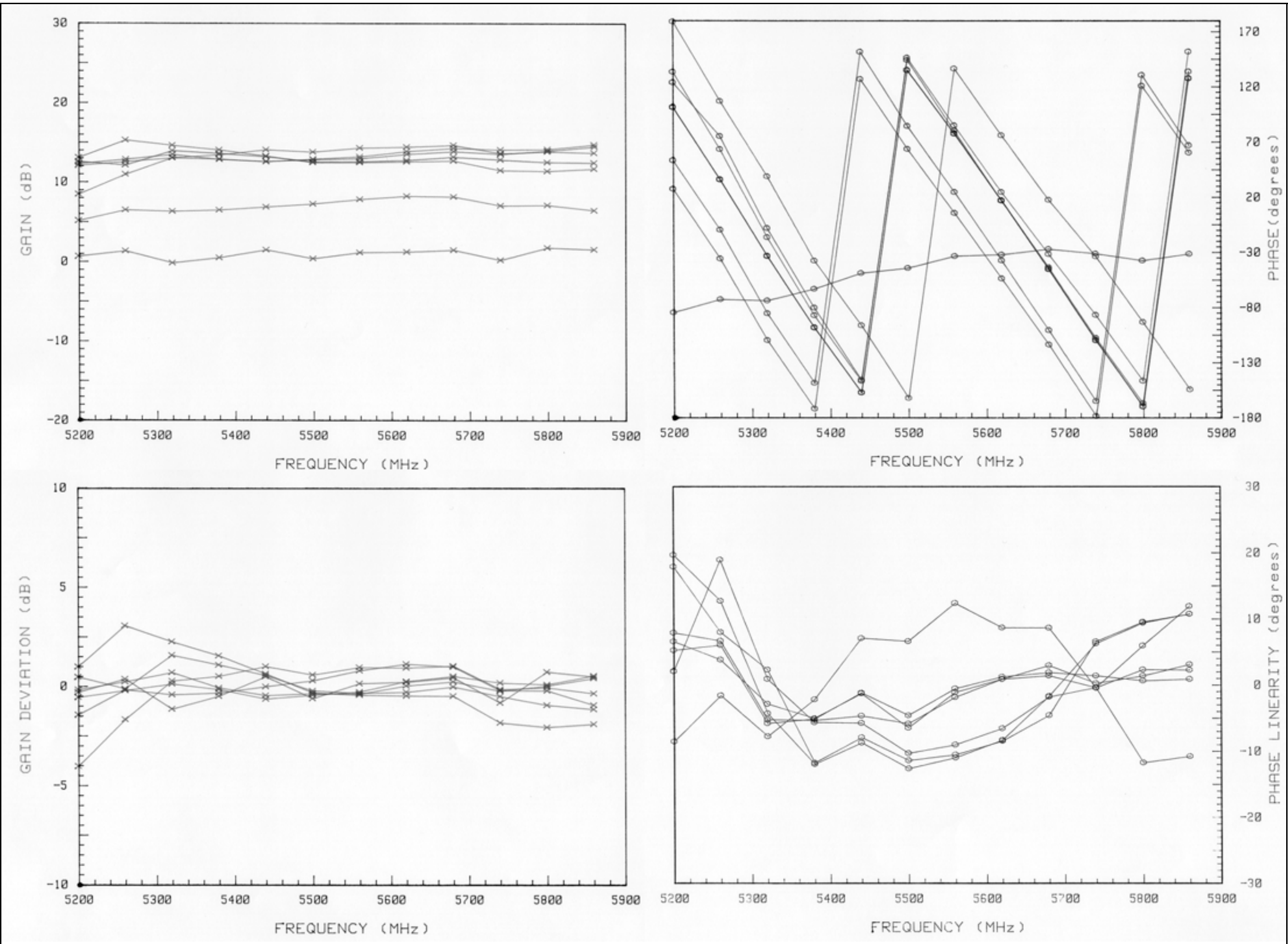



FIGURE 3.2.13 - C-BAND T/R MODULE PHASE III RF RECEIVER COMPOSITE DATA

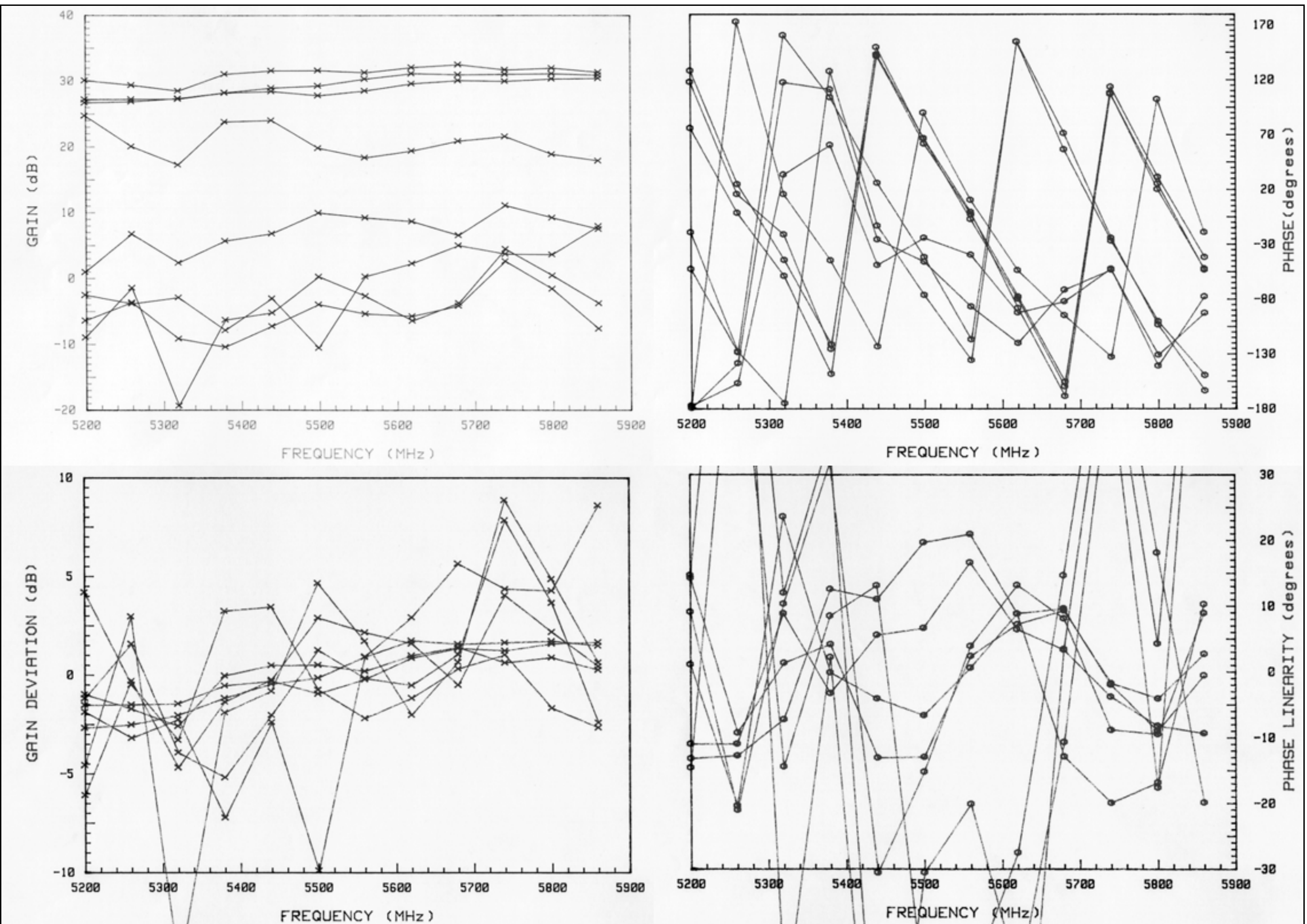



FIGURE 3.2.14 - C-BAND T/R MODULE PHASE III DC TRANSMIT COMPOSITE DATA

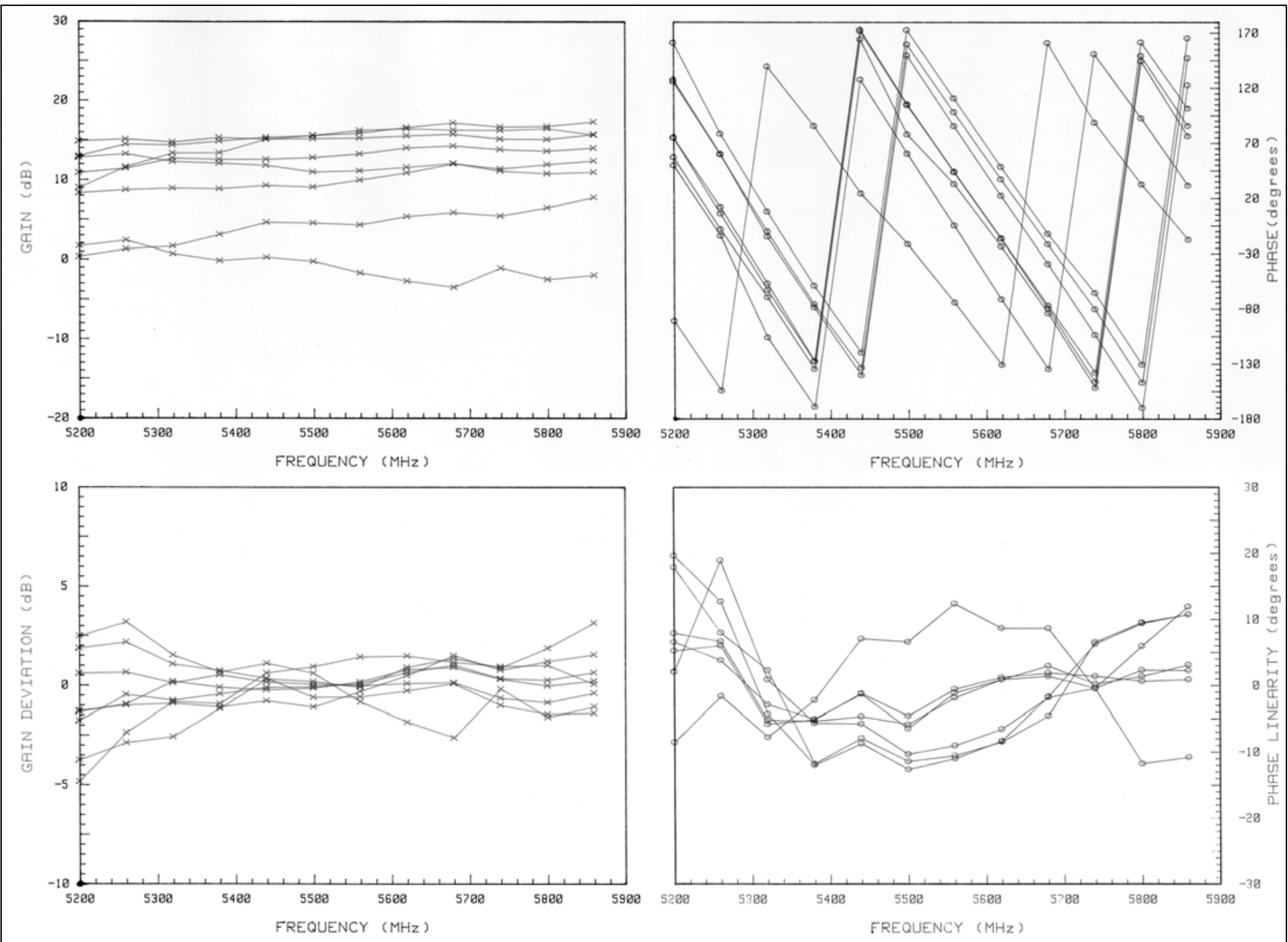



FIGURE 3.2.15 - C-BAND T/R MODULE PHASE III DC RECEIVER COMPOSITE DATA

## 3.3 S-BAND MODULES

These devices were subjected to a variety of test. The test discussed here are the temperature test that were conducted to determine their temperature related characteristics.

### 3.3.1 MODULE DESCRIPTION

The microwave circuits of these modules are of GaAs technology in the form of Monolithic Microwave Integrated Circuits (MMIC). This module was configured into two different packages. Both packages have identical electronics; thus, allowing data from one configuration to provide information on the reliability and performance of the other. The module configuration tested is shown in Figure 3.3.1 (with a close up of the microwave components). This package was the chosen for life testing due to its flat base plate surface's ability to mount onto the thermal heat sink. Notice that the module consists of a MMIC section, a circulator and a control section. This module operates from 3 power supply voltages.

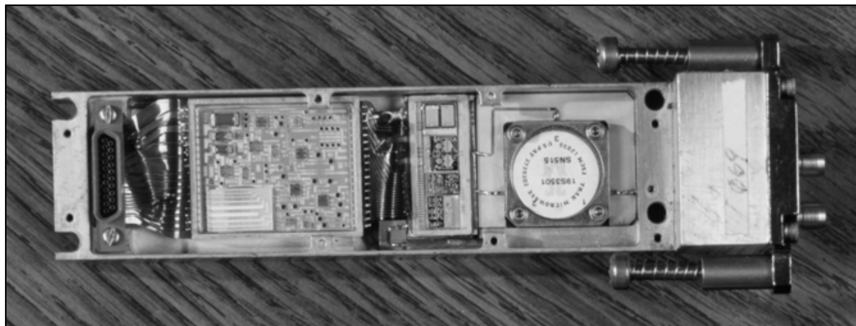


FIGURE 3.3.1 – S-BAND T/R MODULE

### 3.3.2 TEMPERATURE TEST

Tests were conducted on these modules across a large temperature differential to determine how temperature affects various operating characteristics. These tests included operation during temperature cycling from room temperature down to liquid nitrogen temperatures (-197 degrees Centigrade).

A liquid nitrogen bath, commonly referred to as the "beer cooler" bath, was constructed to enable the cooling of modules down to cryogenic temperatures. The devices were securely attached to a vertically oriented copper plate and suspended over the cold bath. By adjusting the height of the table supporting the bath, the extent to which the copper plate is immersed in the coolant is varied, hence controlling the temperature of the module. A picture of this setup is shown in Figure 3.3.2.

Figure 3.3.2 – “BEER COOLER” BATH TEMPERATURE TEST

Acquisition of the data required to characterize the module is accomplished by utilizing the MEL-2 test system to automatically measure pulsed RF and noise figure. Both small signal CW and pulse power transmit/receive testing enable the gain, noise figure, and phase data to be obtained during programmed temperature variation.

Temperature is measured using thermocouples judiciously attached to locations within the device itself. Thus, the performance of an operating module is continually monitored as a function of temperature, down to as low as that of liquid nitrogen, almost 200 degrees below zero Centigrade.

Figure 3.3.3 features the transmit performance of one of the S-Band modules as it is cooled. Note that the cooling initially improves the gain, albeit at a rate of 0.5 DB/10$^{o}$C. Gain peaks at about -70$^{o}$C and declines upon further cooling. Although gain fluctuations are not evident, the frequency spectra (not shown) revealed oscillations.

Small signal CW measurements of the T/R module are portrayed in Figure 3.3.4, highlighting the classical inverse relation between gain and noise as temperature falls. On cooling, gain and noise figure improved -170$^{o}$C, whereupon activity precipitously collapses and the module ceases operation. This shutdown is “forgiving”, activity resumes unaltered upon warming.

Tracking the individual temperatures of the MMIC chip and controller in pulse receive mode points to the controller as being responsible for this “freeze-out”. Close inspection (Figure 3.3.5) shows that while the MMIC chip is at liquid nitrogen temperature, it is the warming of the controller that turns the module on.
To validate that this phenomenon really exist, a total of 5 modules were tested. A plot of the module to module tracking of transmit gain is shown in Figure 3.3.6.

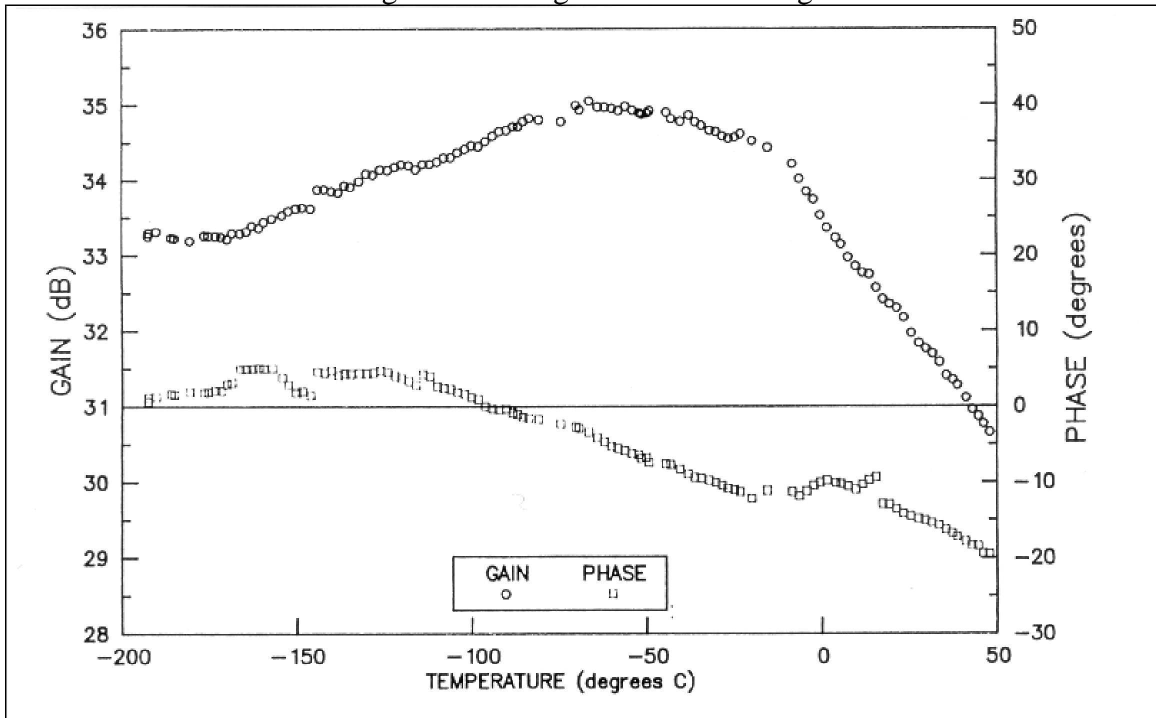


FIGURE 3.3.3 – S-BAND MODULE TRANSMIT GAIN & PHASE VS TEMPERATURE

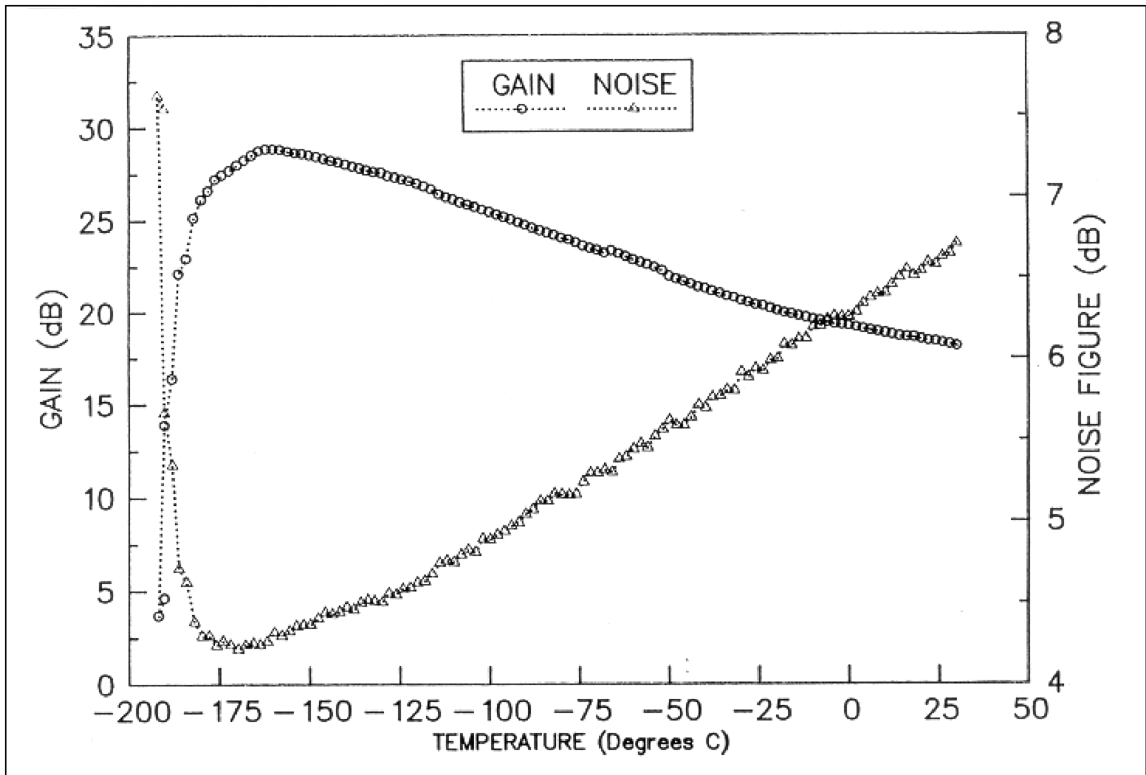



FIGURE 3.3.4 – S-BAND MODULE SMALL SIGNAL CW GAIN & NOISE FIGURE VS TEMPERATURE

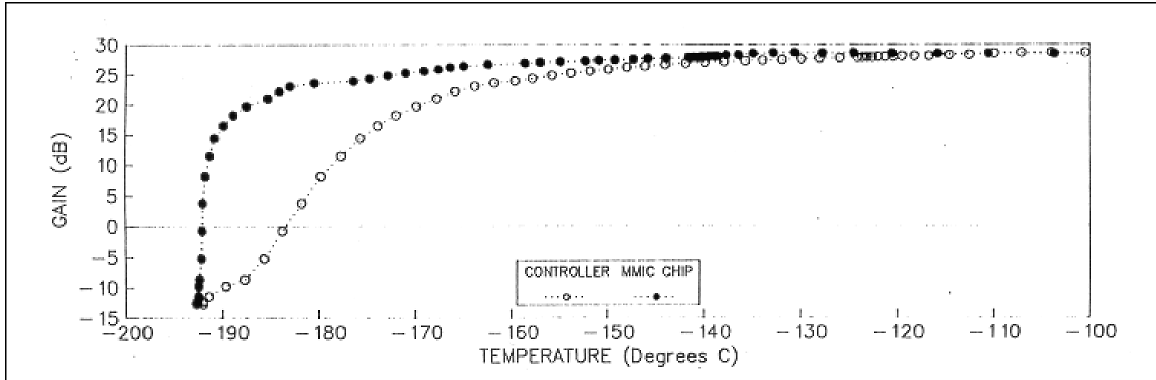



FIGURE 3.3.5 – S-BAND MODULE RECEIVE “FREEZE-OUT” MMIC CHIP AND CONTROLLER TEMPERATURES VS GAIN

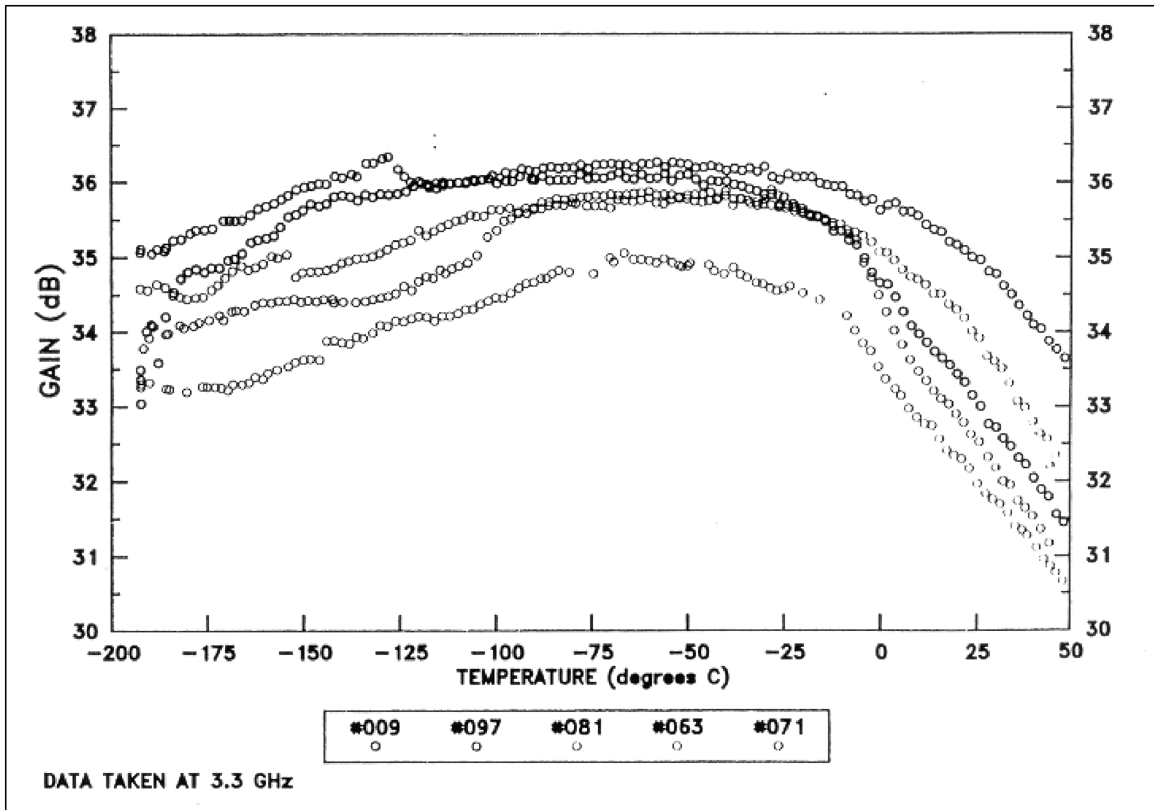


FIGURE 3.3.6 – S-BAND MODULE TRANSMIT GAIN MODULE TO MODULE TRACKING VS TEMPERATURE

# 4.0 CONCLUSIONS

The testing methodologies developed and demonstrated as part of this effort have made a significant impact on T/R module technology development. One of the more significant examples is the impact that this work had on convincing the Automated Network Analyzer manufacturers to develop a pulsed version of their product (Hewlett Packard and Wiltron). These products are now used widely by the various T/R module fabricators in their engineering development and on the manufacturing lines. The impact is on the cost and performance of the modules is consistent with the cost projections described back in introduction of this document. The savings was so significant that it has enabled the transition of this technology into the commercial arena. Specifically, T/R modules are a key component of the phased array antenna on the Iridium Satellite.

A significant byproduct of developing these testing methodologies is the testing that was conducted as part of their demonstration. Information of the characteristics of T/R modules and there performance under various operating conditions were evaluated and feed back to the various module developers for design and fabrication technique modifications. Examples of this are as follows:

1. The C band life test data showed that packaging can be a grater reliability issue than the devices are. Specifically, in fabricating a T/R module that must meet both the high performance and reliability requirements a trade-off must be made between how much packaging is used and the probability that a bad component will require some rework.

2. The early L-Band and S-Band modules showed that the interfacing, specifically the connectors can have a great impact on the performance and reliability of the module. Here the DC and Control connectors failed causing a significant change in performance. These failures were a function of the multiple connections that had to be made and the large temperature variations that the modules were subjected to.

3. At very low temperatures (i.e., -197 degrees Centigrade) GaAs devices continue to increase in performance, while silicon devices stop performing. Cryogenic performance yields insight into the underlying physics of module operation. The achieved results complement and extend previous research. This emphasis the need to keep in mine the various environments that the modules will be subjected to when designing and testing. Designing for performance at ambient temperatures and other conditions may not provide the best system performance. Further, the interaction of various technologies, with good individual performance needs to be evaluated as a complete system as well.

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# GLOSSARY

ARFTG - Automatic Radio Frequency Techniques Group which is a professional organization, an affiliate of the IEEE's Microwave Theory and Techniques Society, that specializes in automated methods of measuring RF performance of various devices.

DARPA - Defense Advanced Research Project Agency.

EEPROM - Electrically Erasable Programmable Read Only Memory.

FSK - Frequency Shift Keying modulation.

GHz - Gigahertz.

IEEE - Institute of Electrical and Electronic Engineers which is an international professional organization.

IMFET - Internally Matched Field Effect Transistor

KHz - kilohertz.

LFM - Linear Frequency Modulation.

MEL - Module Evaluation Laboratory, a name given to both the facility that all of the module testing has occurred during the last decade and the primary characterization system that operates in that lab.

MELTS - Module Evaluation Life Test System which is the common name for the Long Term Performance Test System, a system designed to subject DUTs to a consistent set of operating environments over a long period of time while continuously monitoring and recording data on their performance.

MHz - megahertz.

MIMIC - Microwave and Millimeter wave Integrated Circuit program sponsored by DARPA to develop MMIC foundry technology. The program is phased; Phase 0 - concept exploration, Phase 1 - Foundry & Demonstration Vehicle development, Phase 2 - Foundry & Brassboard demonstration, Phase 3 - Supporting Technology development.

MMIC - Monolithic Microwave Integrated Circuit, the technology of building microwave circuits on a single substrate (i.e. GaAs, Si, etc) using integrated circuit techniques.

MODVAL - MODule VALidation was a RADC contract with Raytheon and Texas Instruments to develop X Band modules for a Space Defense Initiative (SDI) mid course discriminating radar.

RF - Radio Frequency.

RL - Rome Laboratory (Formerly Rome Air Development Center (RADC)), is Air Force Material Command (AFMC) laboratory with the mission of $C^3I$.

VCO - Voltage Controlled Oscillator.

# APPENDIX A – C-BAND MODULE DATA

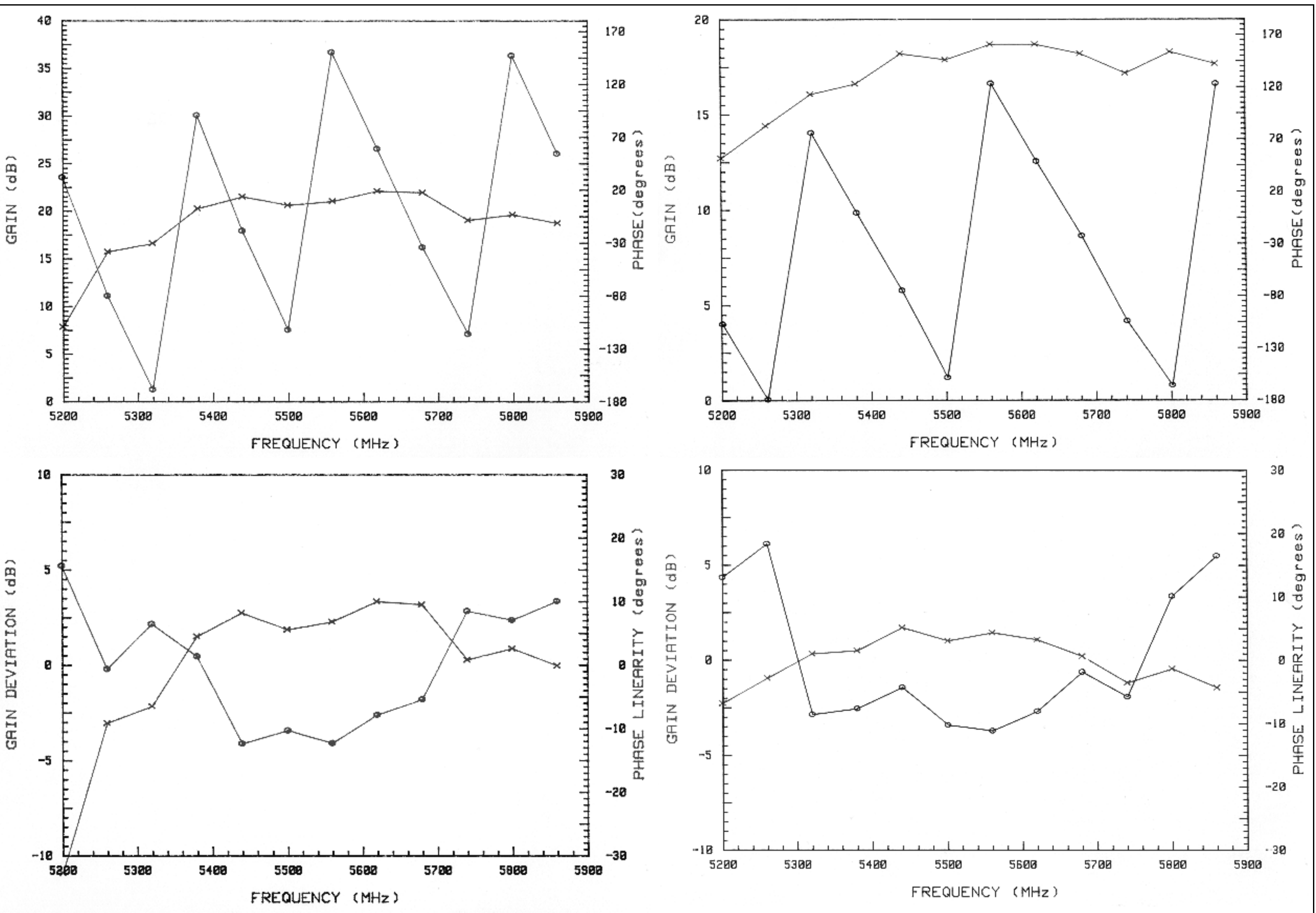


FIGURE A.2 - PHASE 1 TESTING C-BAND MODULE SN006 (LEFT) TRANSMIT & (RIGHT) RECEIVE

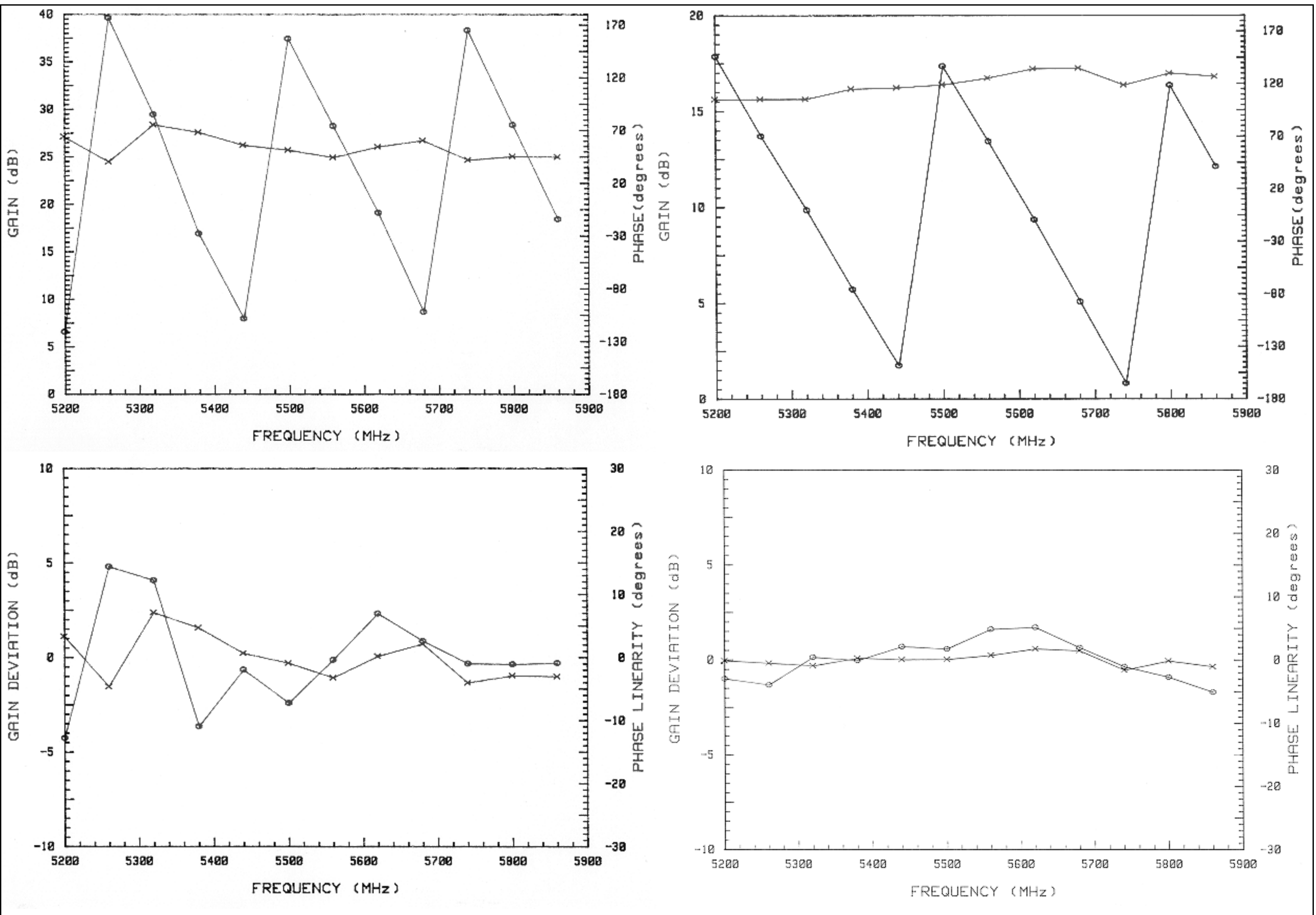


FIGURE A.3 - PHASE 1 TESTING C-BAND MODULE SN017 (LEFT) TRANSMIT & (RIGHT) RECEIVE

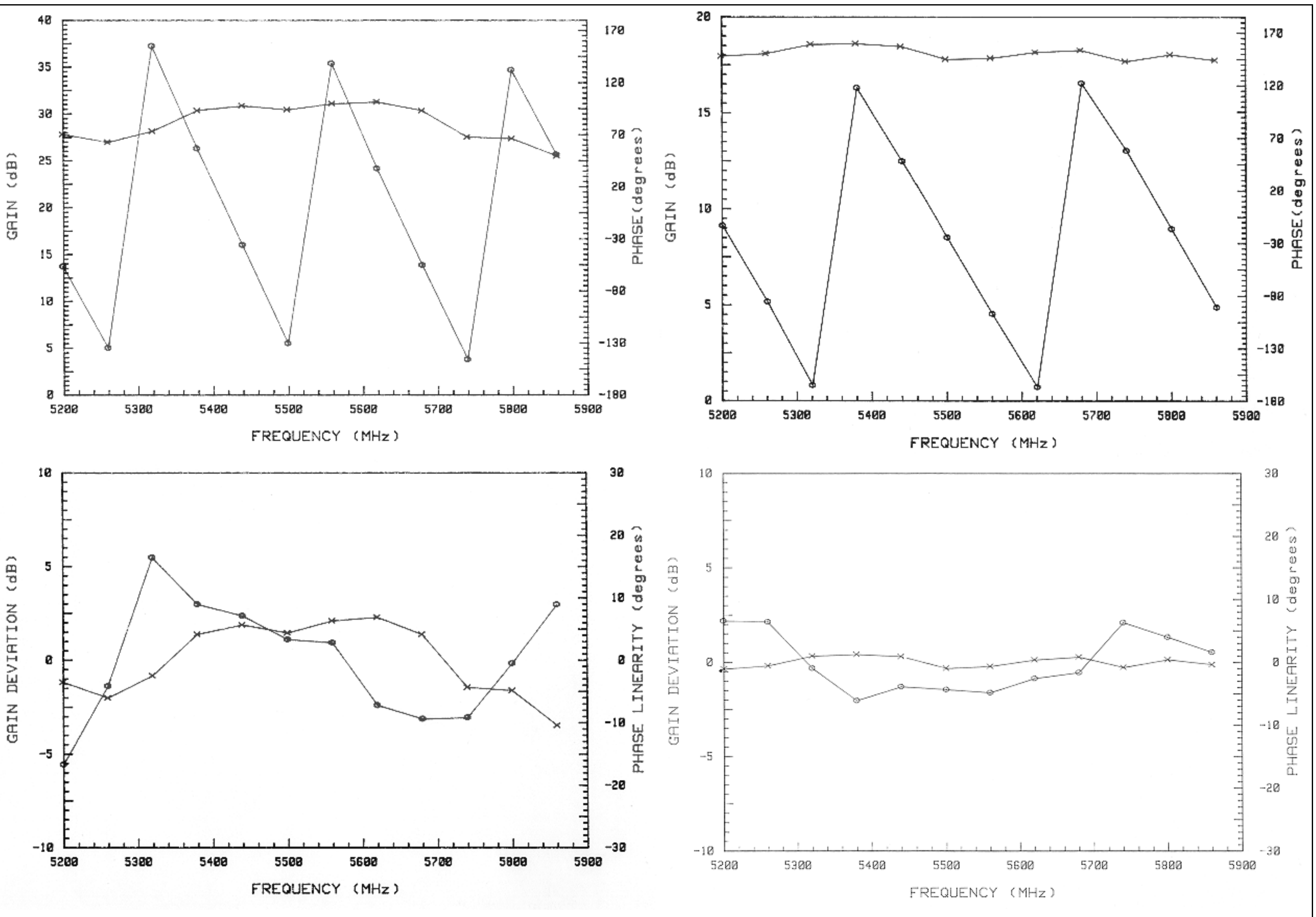


FIGURE A.4 - PHASE 1 TESTING C-BAND MODULE SN022 (LEFT) TRANSMIT & (RIGHT) RECEIVE

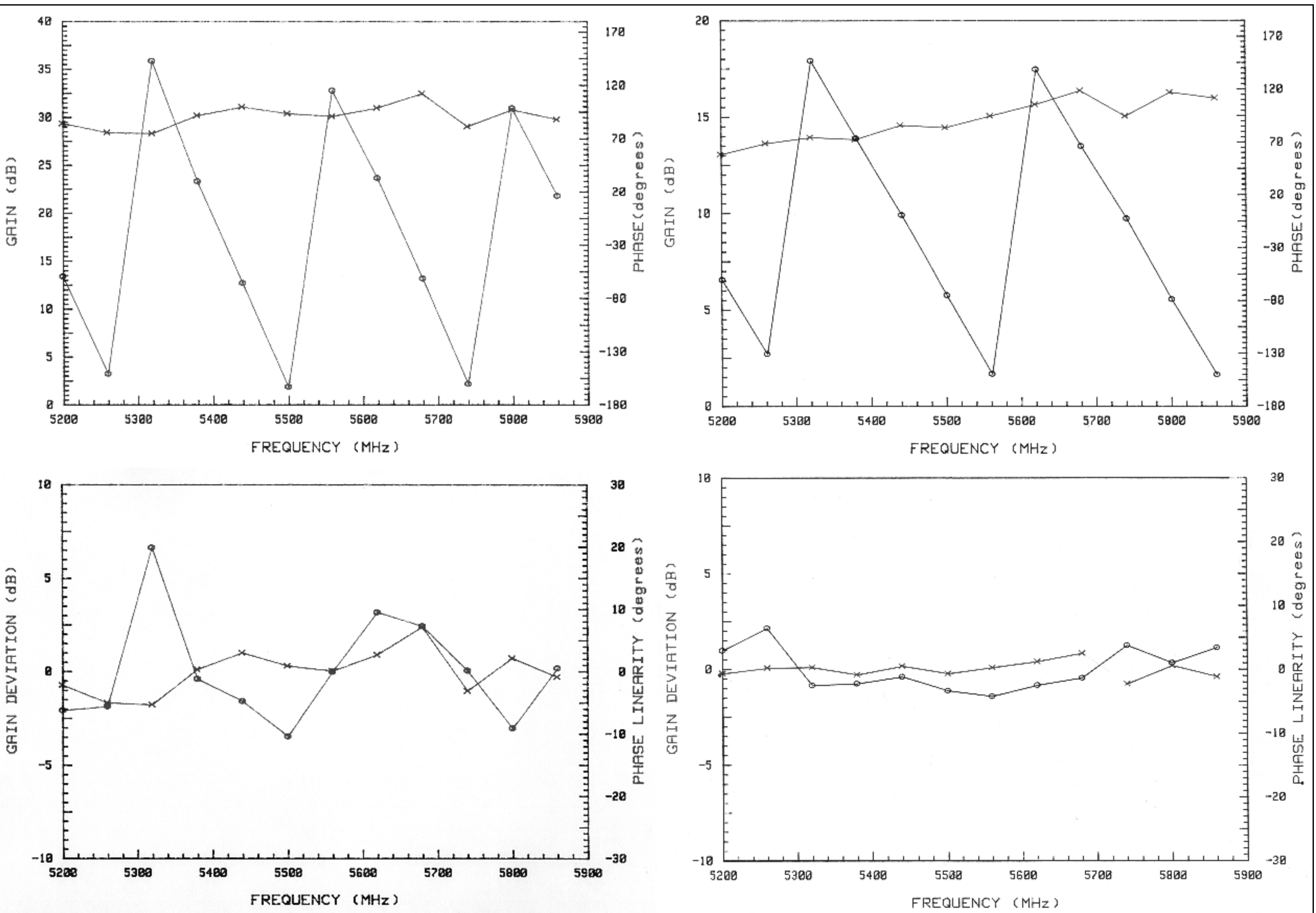


FIGURE A.5 - PHASE 1 TESTING C-BAND MODULE SN032 (LEFT) TRANSMIT & (RIGHT) RECEIVE

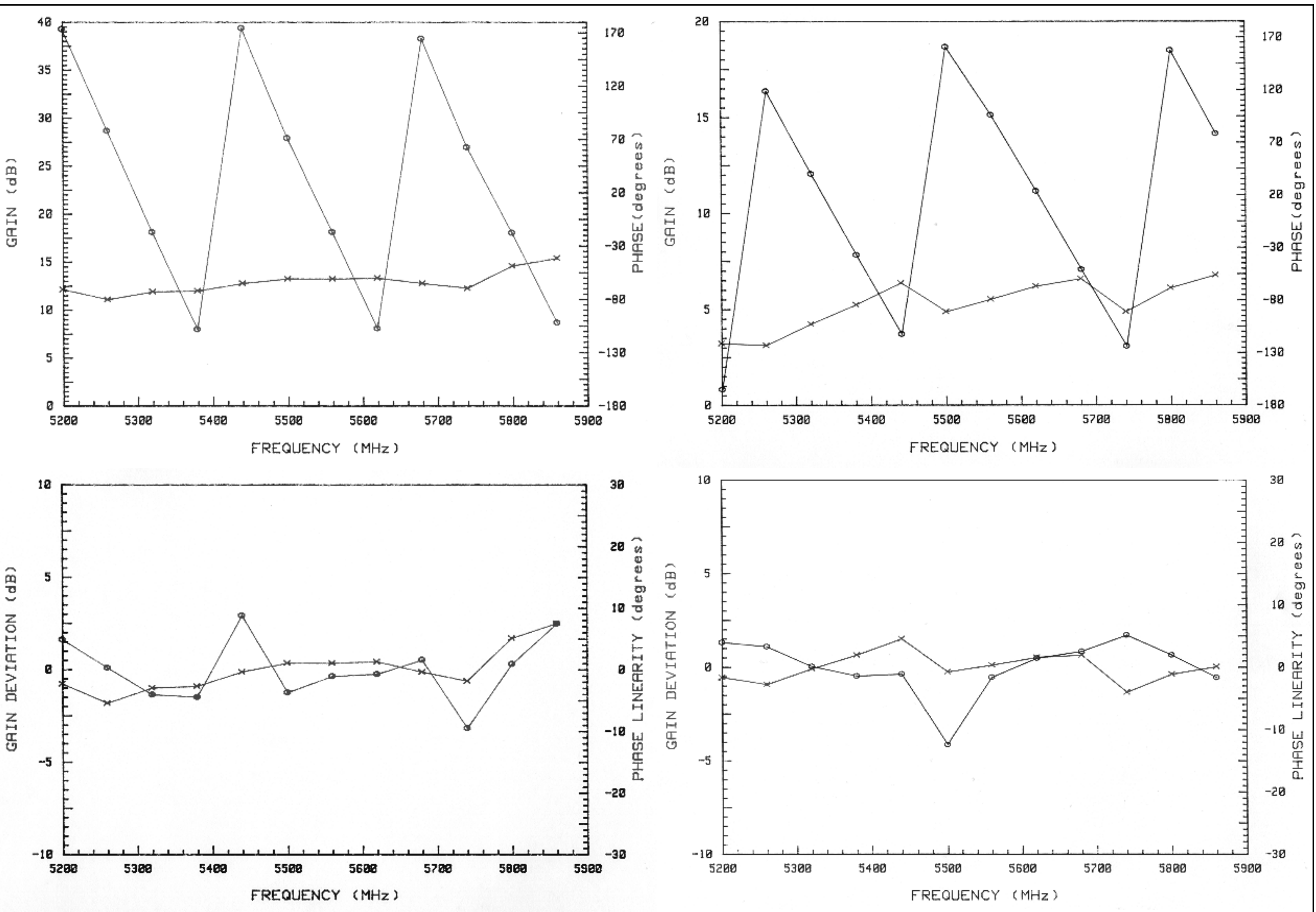


FIGURE A.6 - PHASE 1 TESTING C-BAND MODULE SN033 (LEFT) TRANSMIT & (RIGHT) RECEIVE

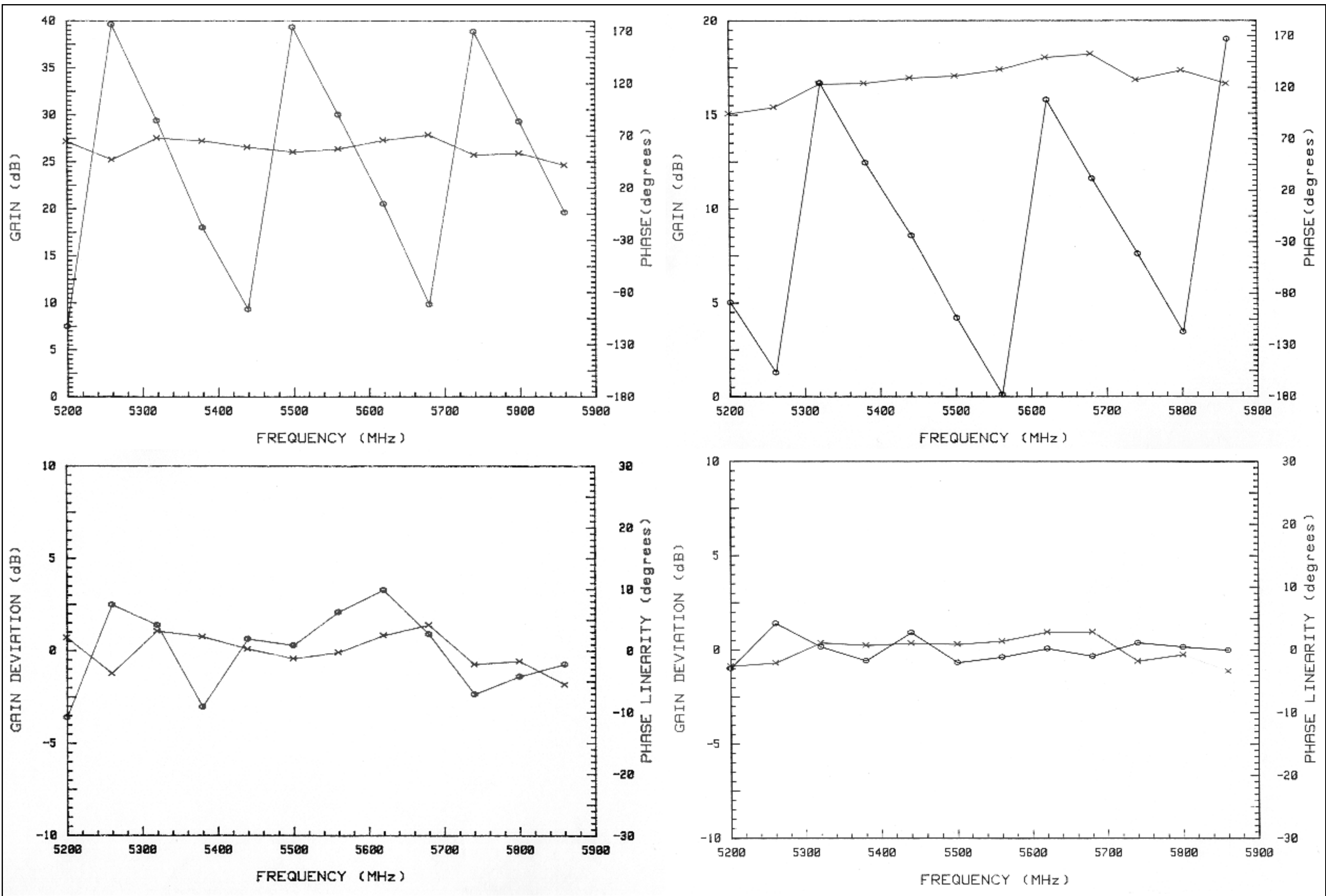

FIGURE A.7 - PHASE 1 TESTING C-BAND MODULE SN039 (LEFT) TRANSMIT & (RIGHT) RECEIVE

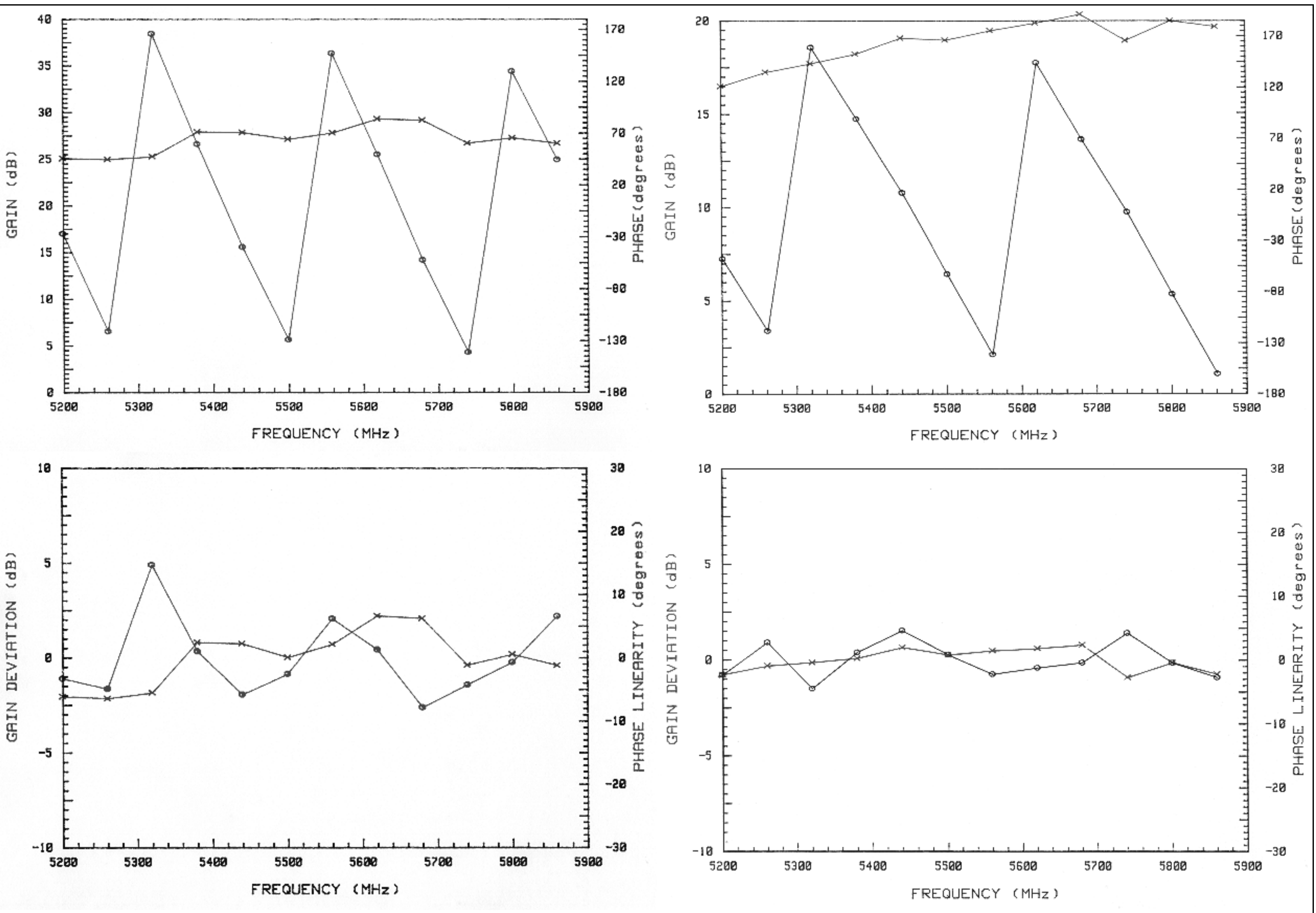

FIGURE A.8 - PHASE 1 TESTING C-BAND MODULE SN040 (LEFT) TRANSMIT & (RIGHT) RECEIVE

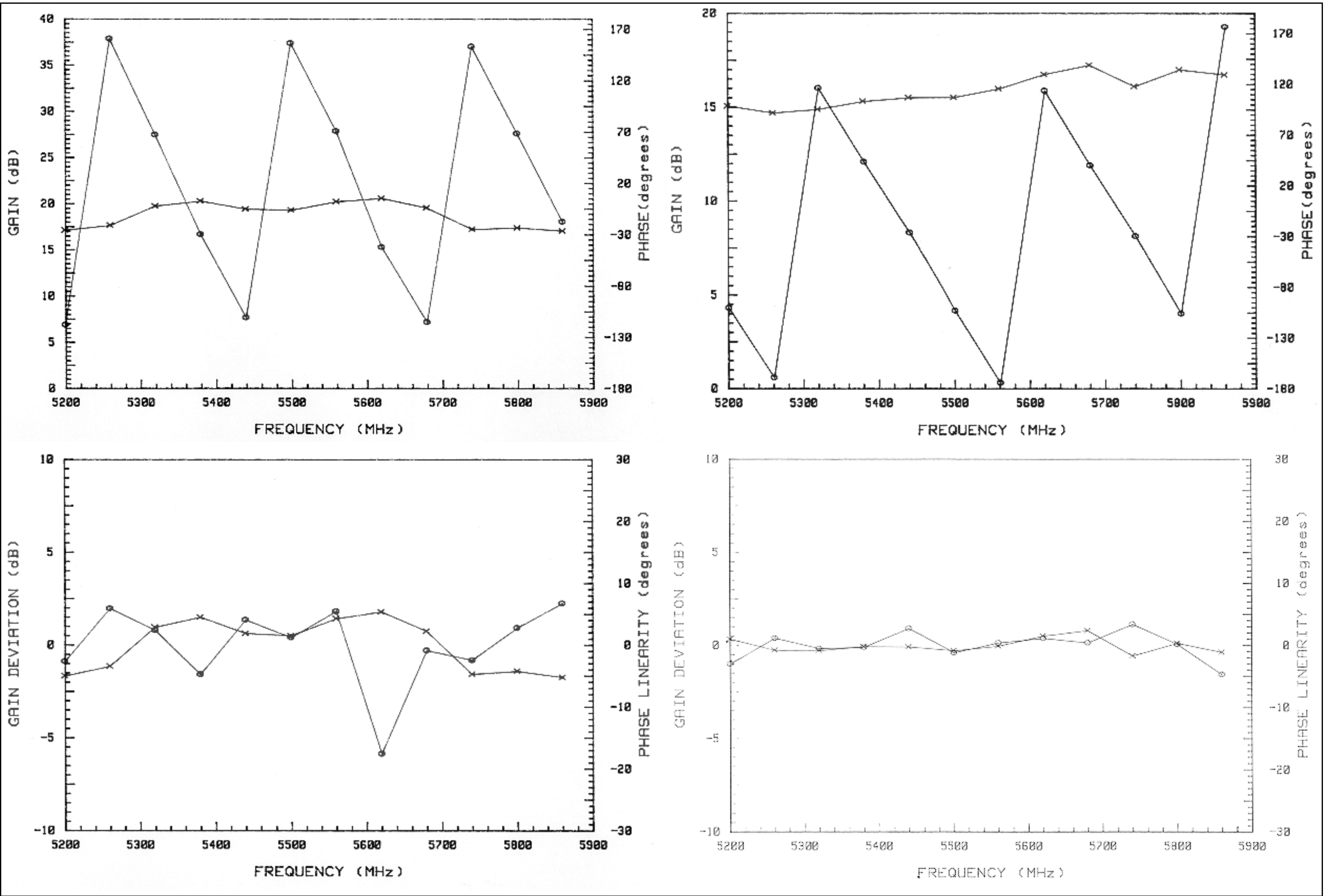


FIGURE A.9 - PHASE 1 TESTING C-BAND MODULE SN042 (LEFT) TRANSMIT & (RIGHT) RECEIVE

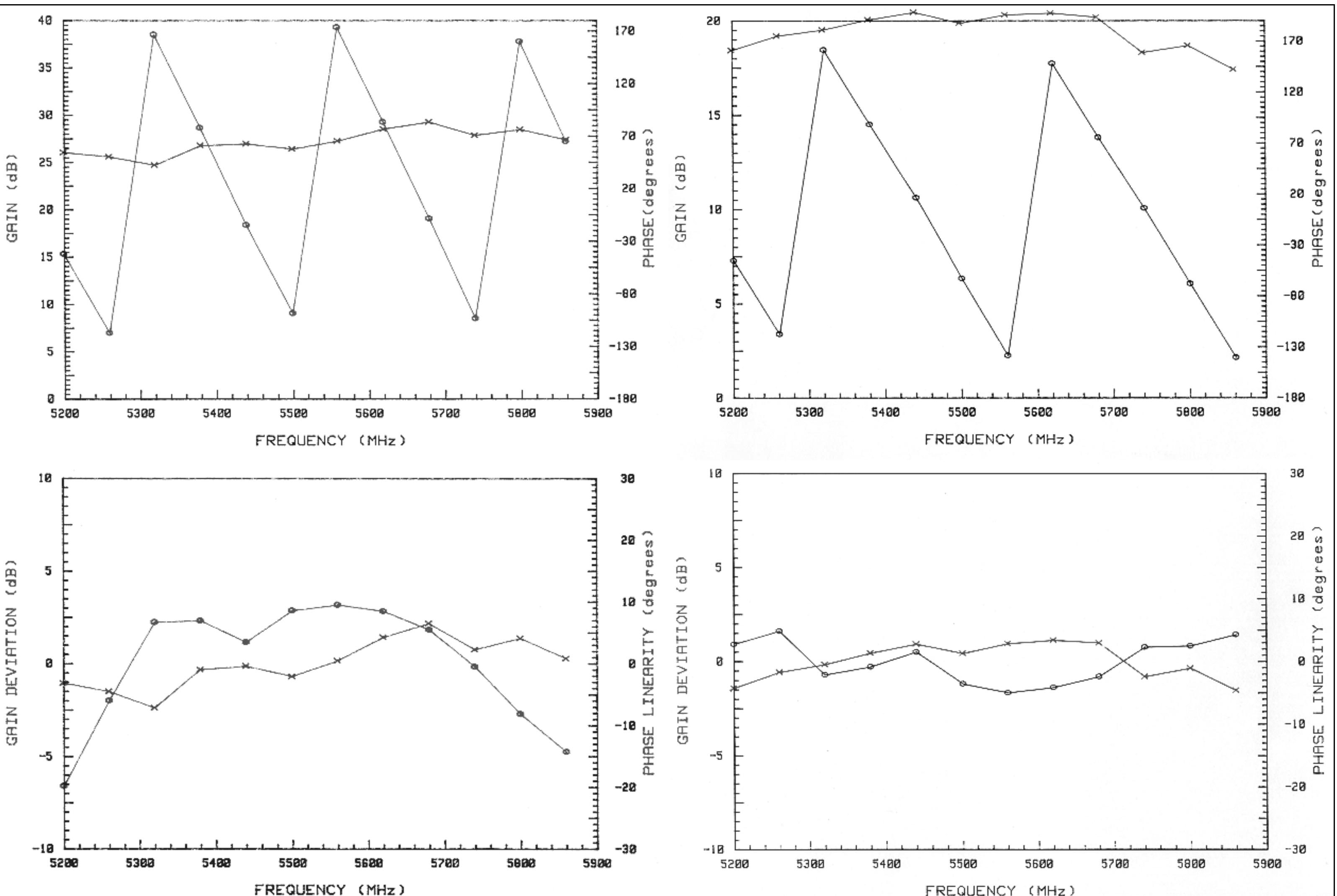


FIGURE A.10 - PHASE 1 TESTING C-BAND MODULE SN044 (LEFT) TRANSMIT & (RIGHT) RECEIVE

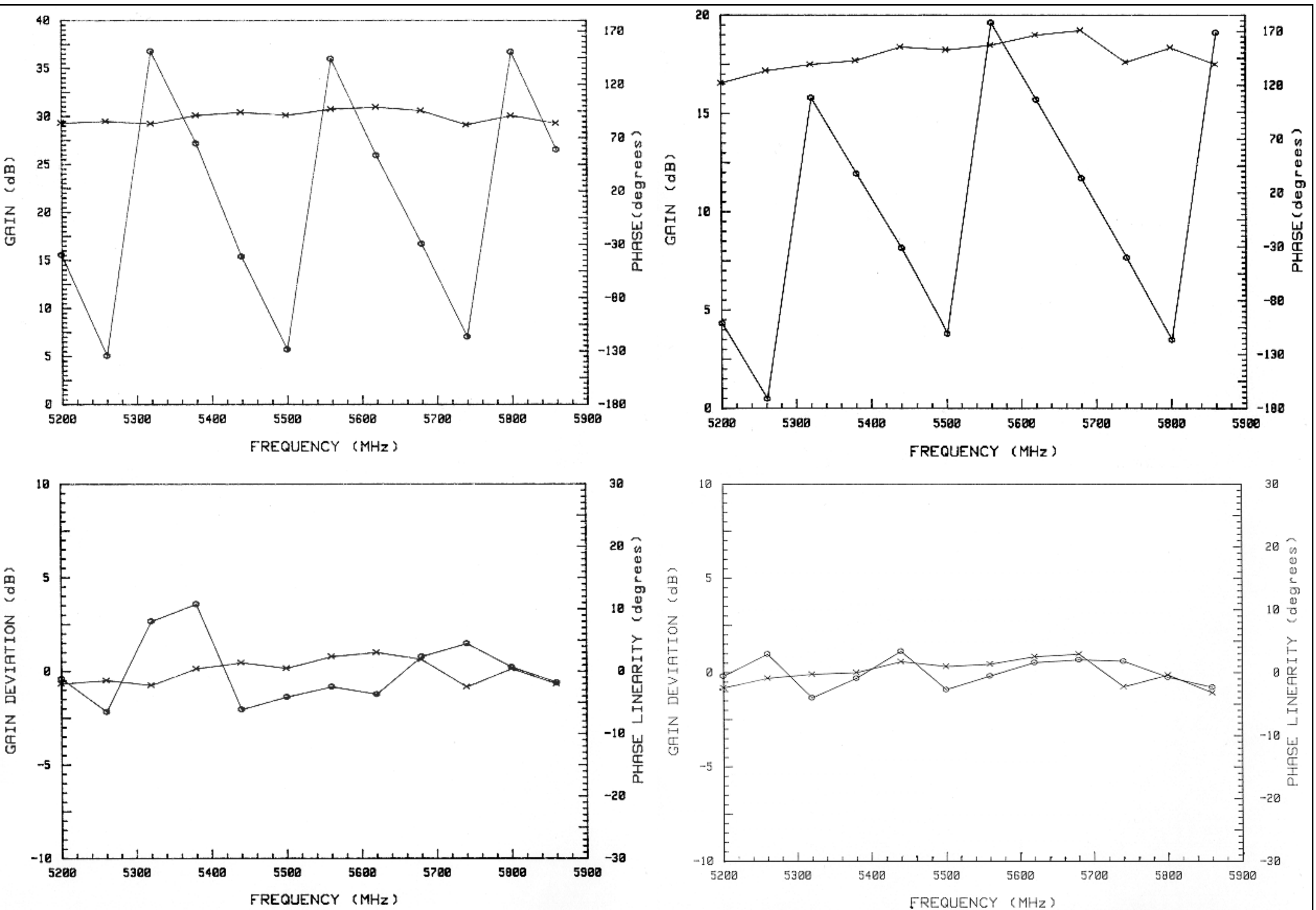


FIGURE A.11 - PHASE 1 TESTING C-BAND MODULE SN056 (LEFT) TRANSMIT & (RIGHT) RECEIVE

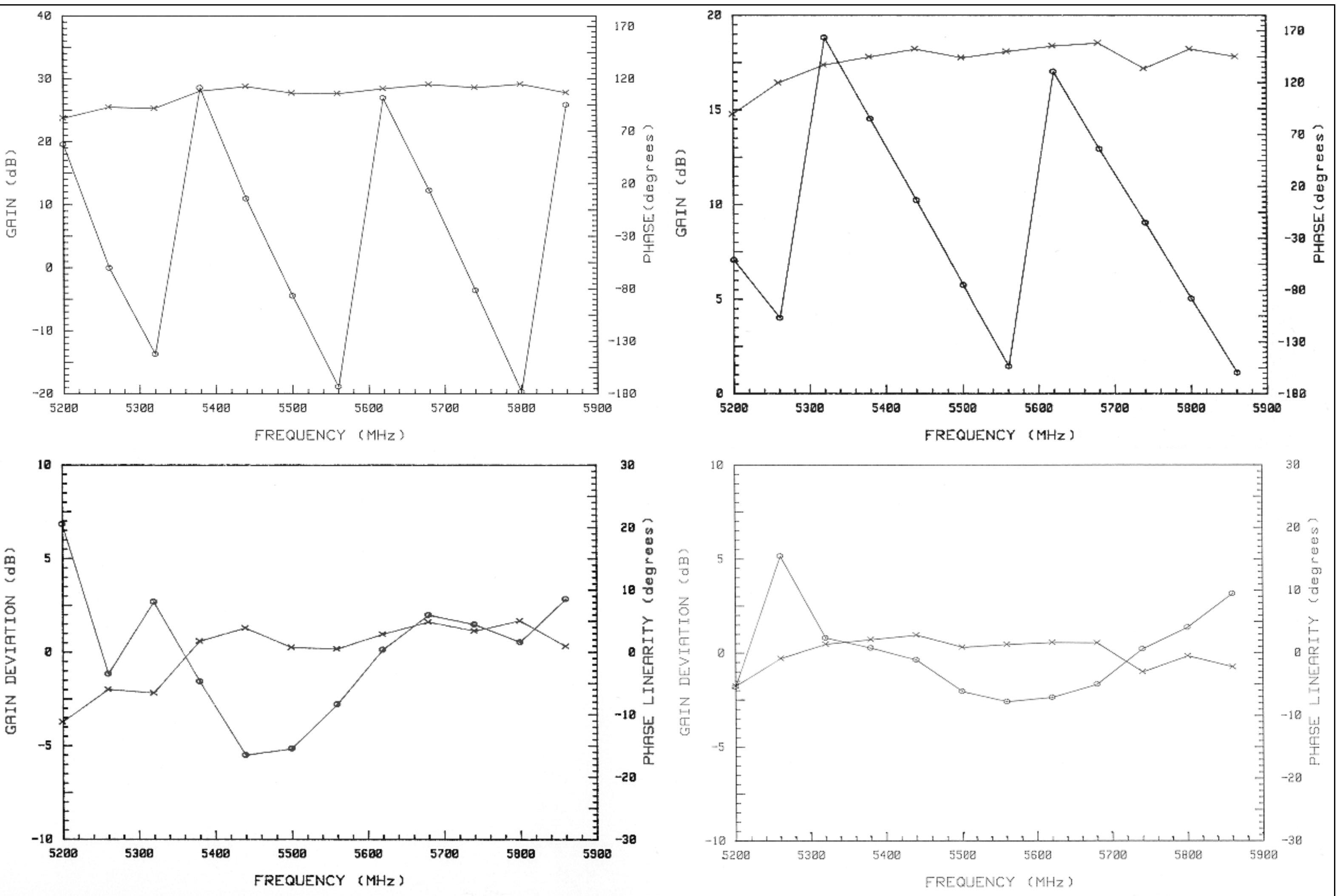


FIGURE A.12 - PHASE 1 TESTING C-BAND MODULE SN057 (LEFT) TRANSMIT & (RIGHT) RECEIVE

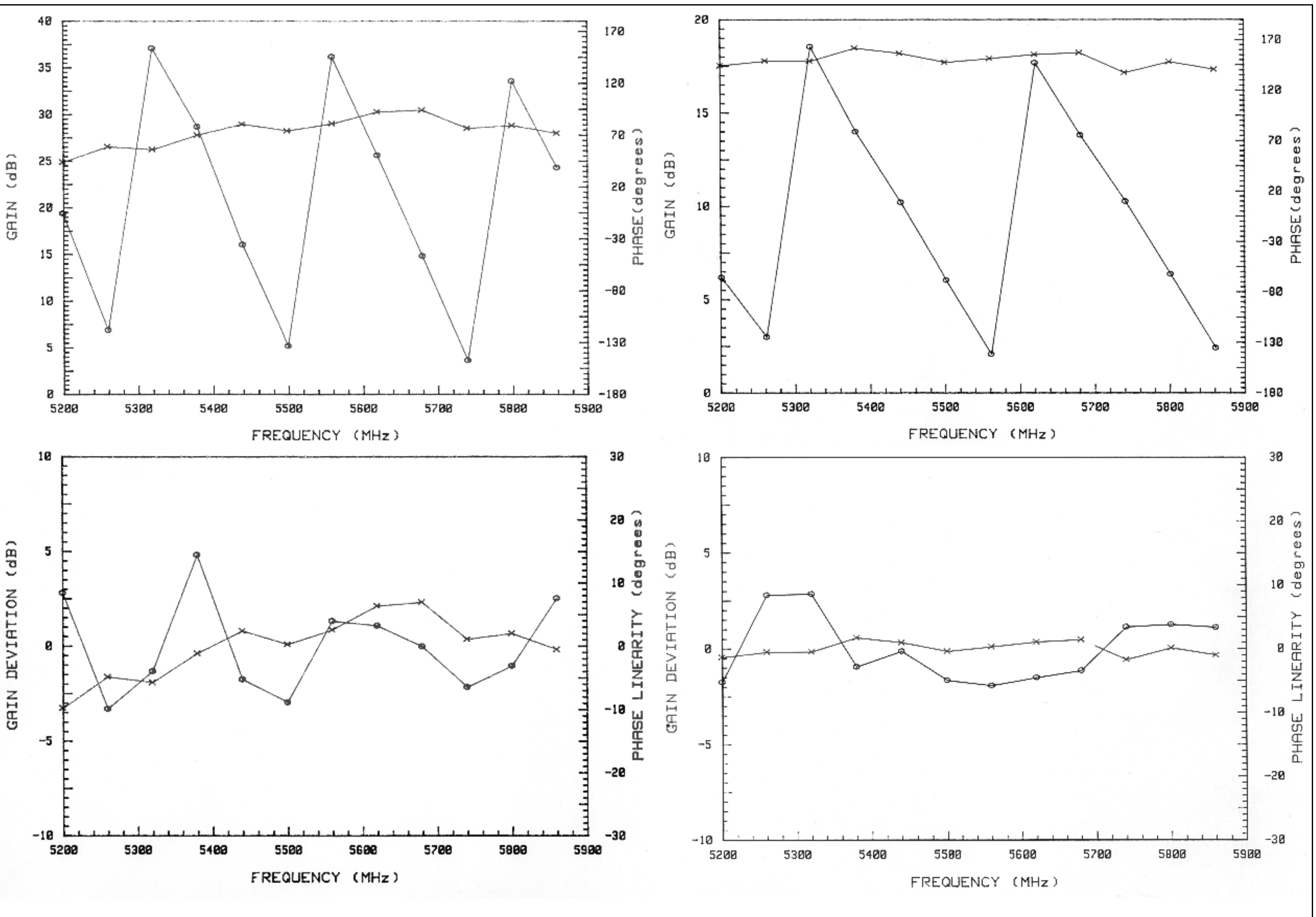


FIGURE A.13 - PHASE 1 TESTING C-BAND MODULE SN058 (LEFT) TRANSMIT & (RIGHT) RECEIVE

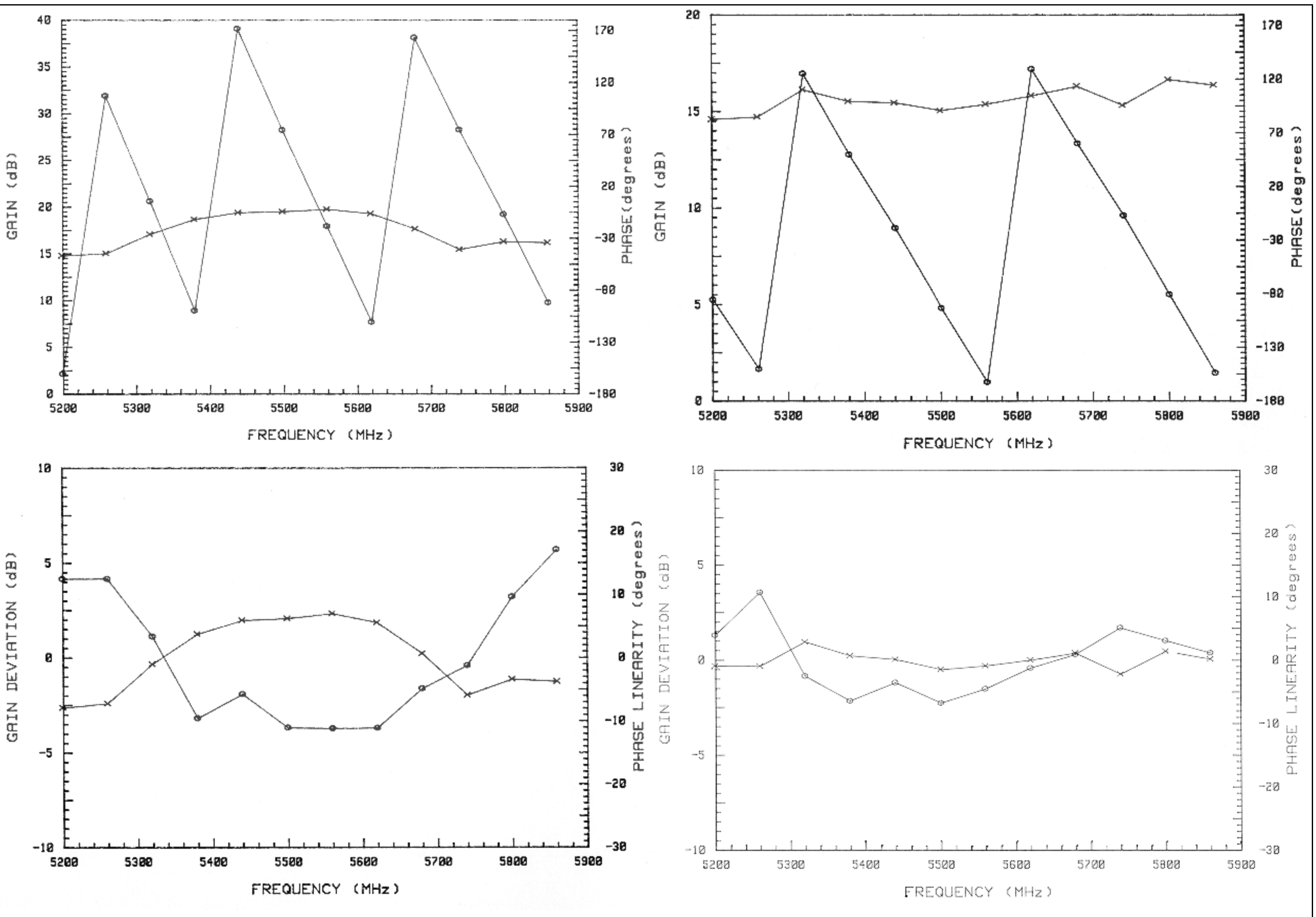


FIGURE A.14 - PHASE 1 TESTING C-BAND MODULE SN063 (LEFT) TRANSMIT & (RIGHT) RECEIVE

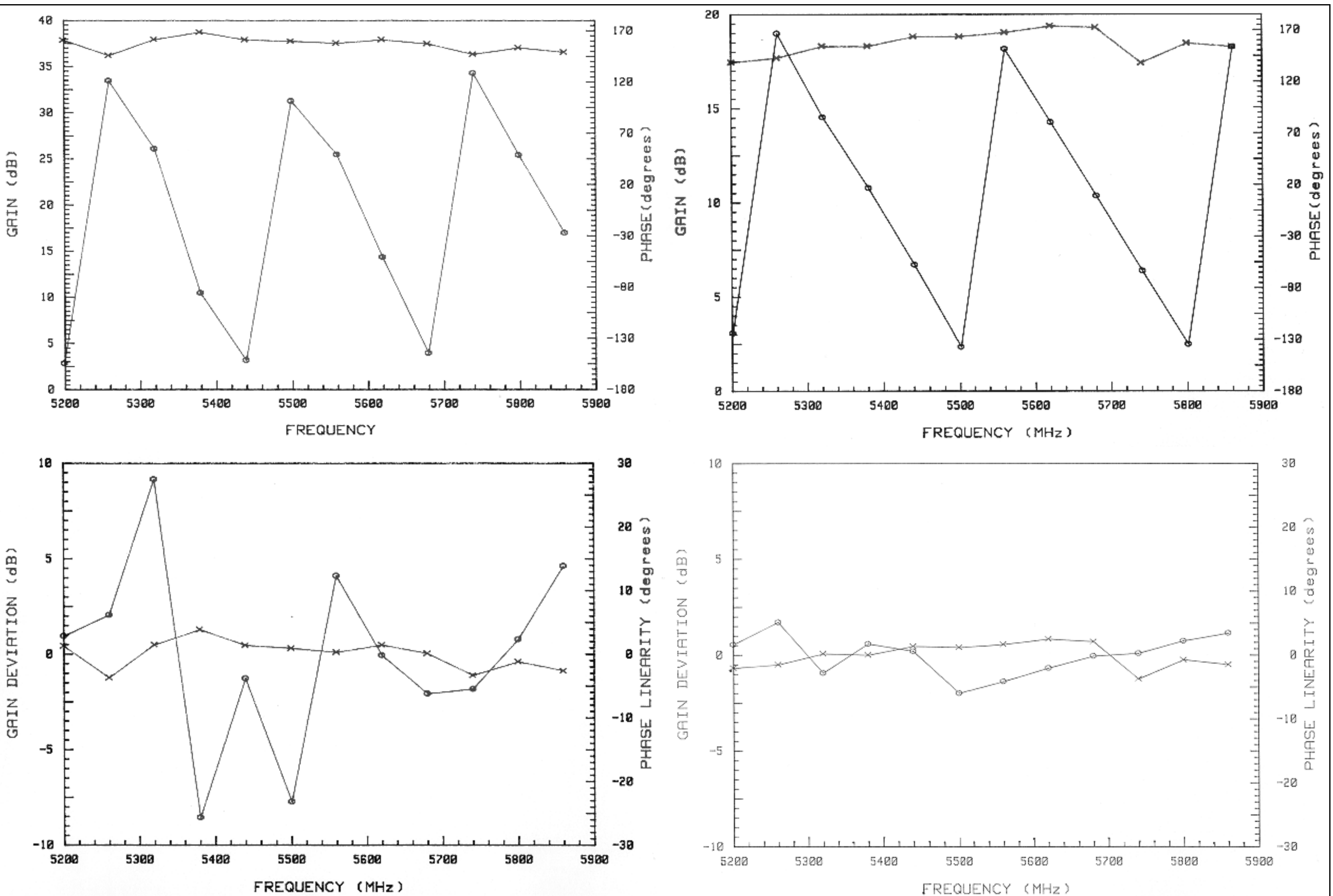


FIGURE A.15 - PHASE 1 TESTING C-BAND MODULE SN065 (LEFT) TRANSMIT & (RIGHT) RECEIVE

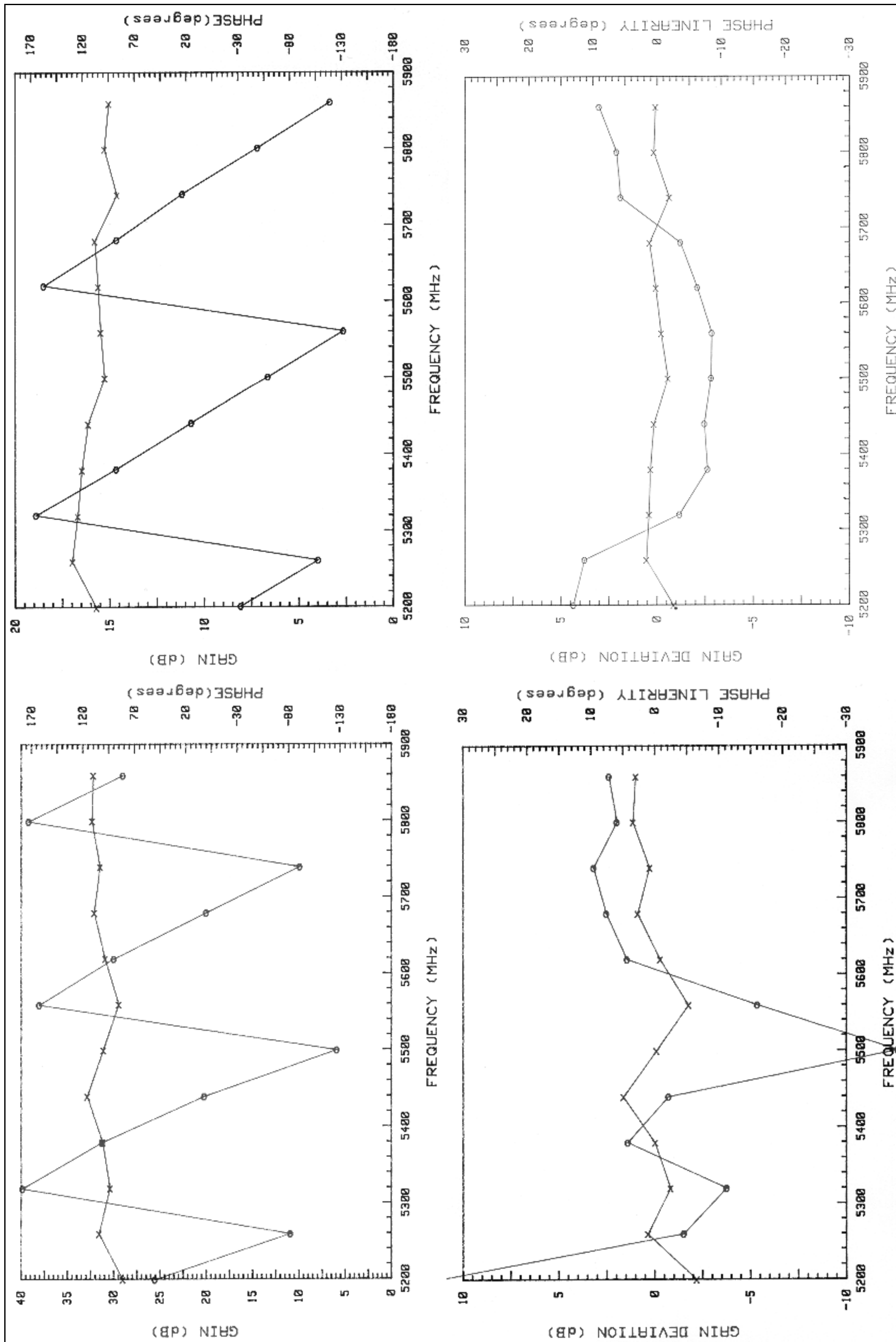


FIGURE A.16 - PHASE 1 TESTING C-BAND MODULE SN070 (LEFT) TRANSMIT & (RIGHT) RECEIVE

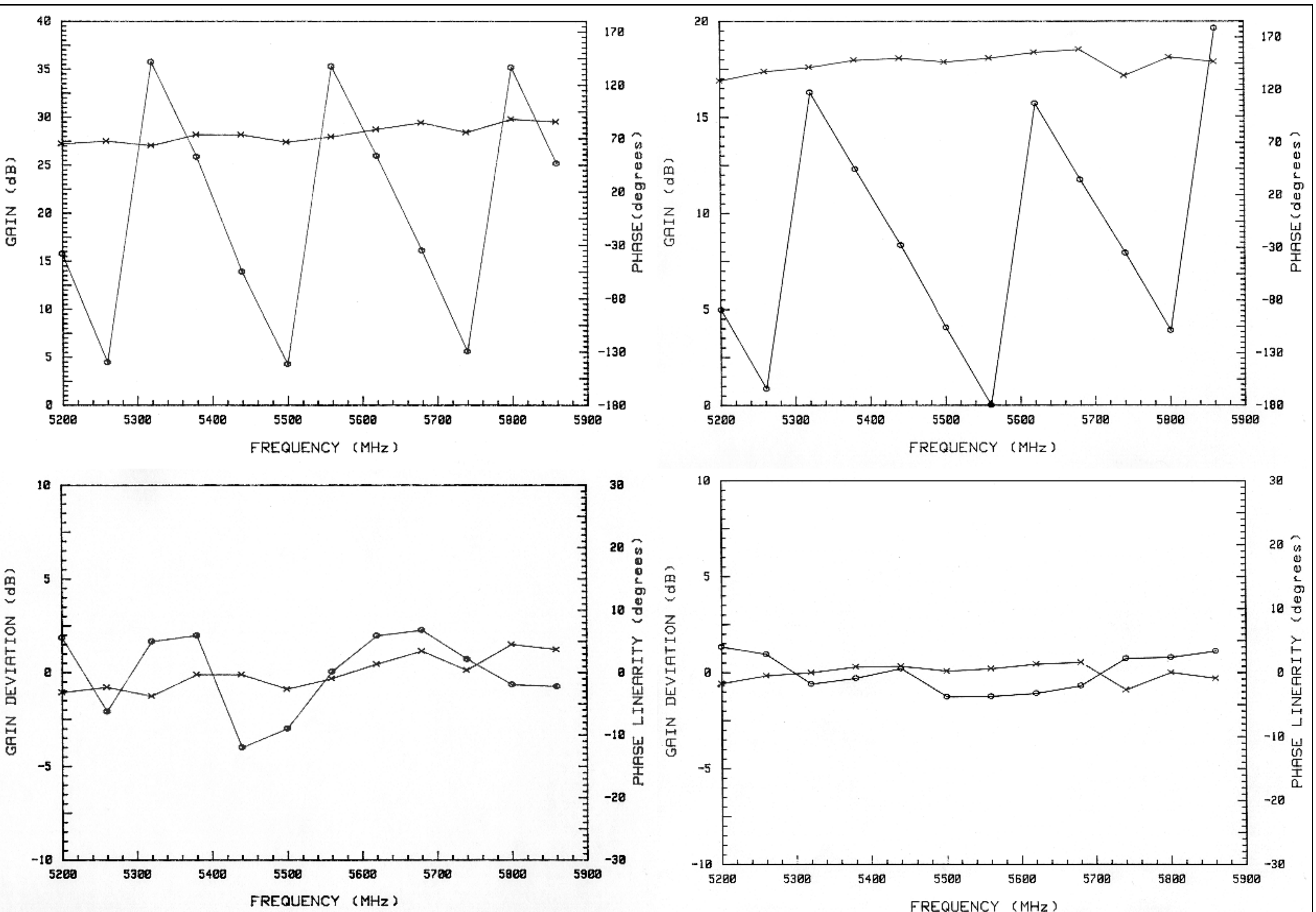


FIGURE A.17 - PHASE 1 TESTING C-BAND MODULE SN073 (LEFT) TRANSMIT & (RIGHT) RECEIVE

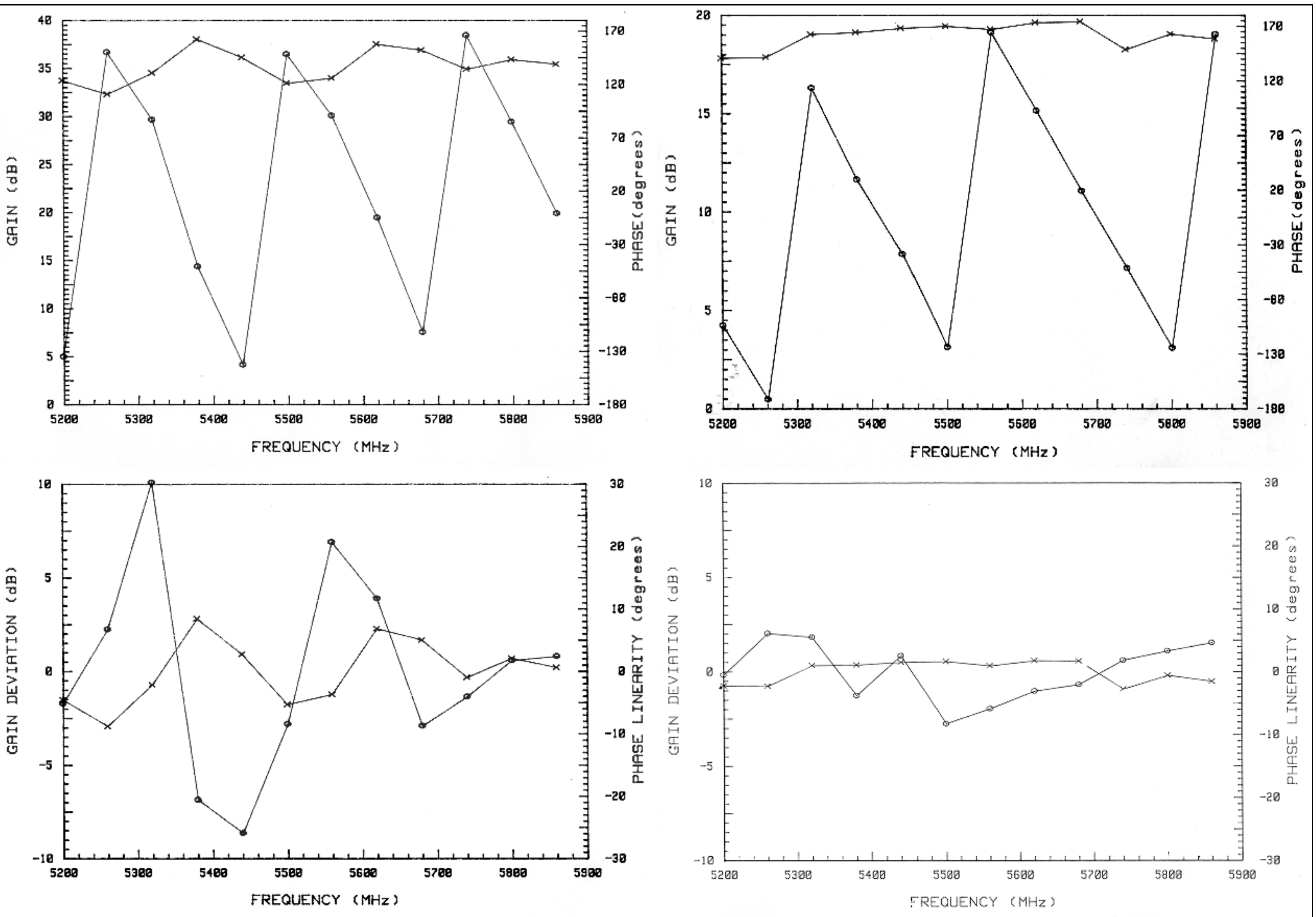


FIGURE A.18 - PHASE 1 TESTING C-BAND MODULE SN084 (LEFT) TRANSMIT & (RIGHT) RECEIVE

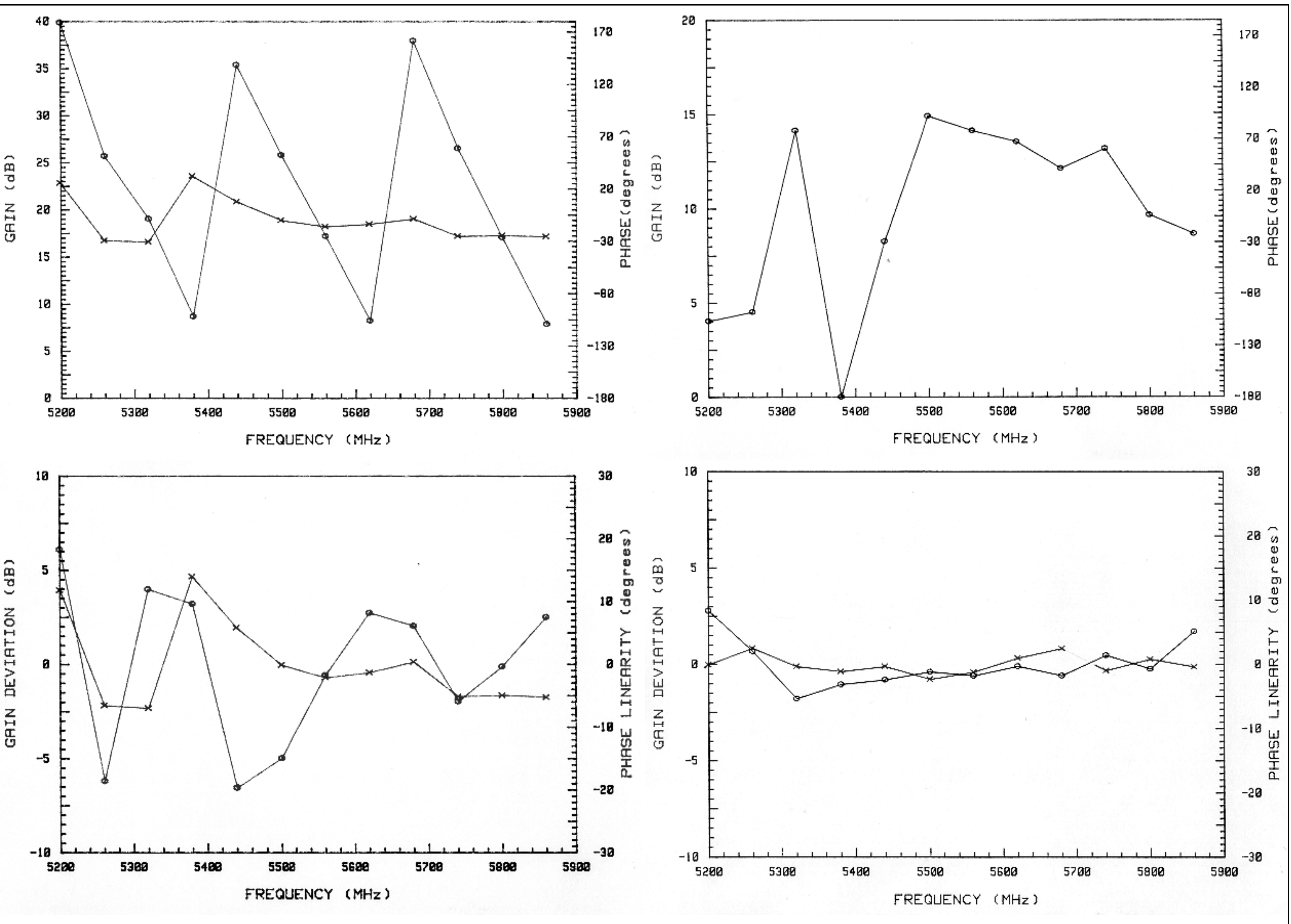


FIGURE A.19 - PHASE 1 TESTING C-BAND MODULE SN085 (LEFT) TRANSMIT & (RIGHT) RECEIVE

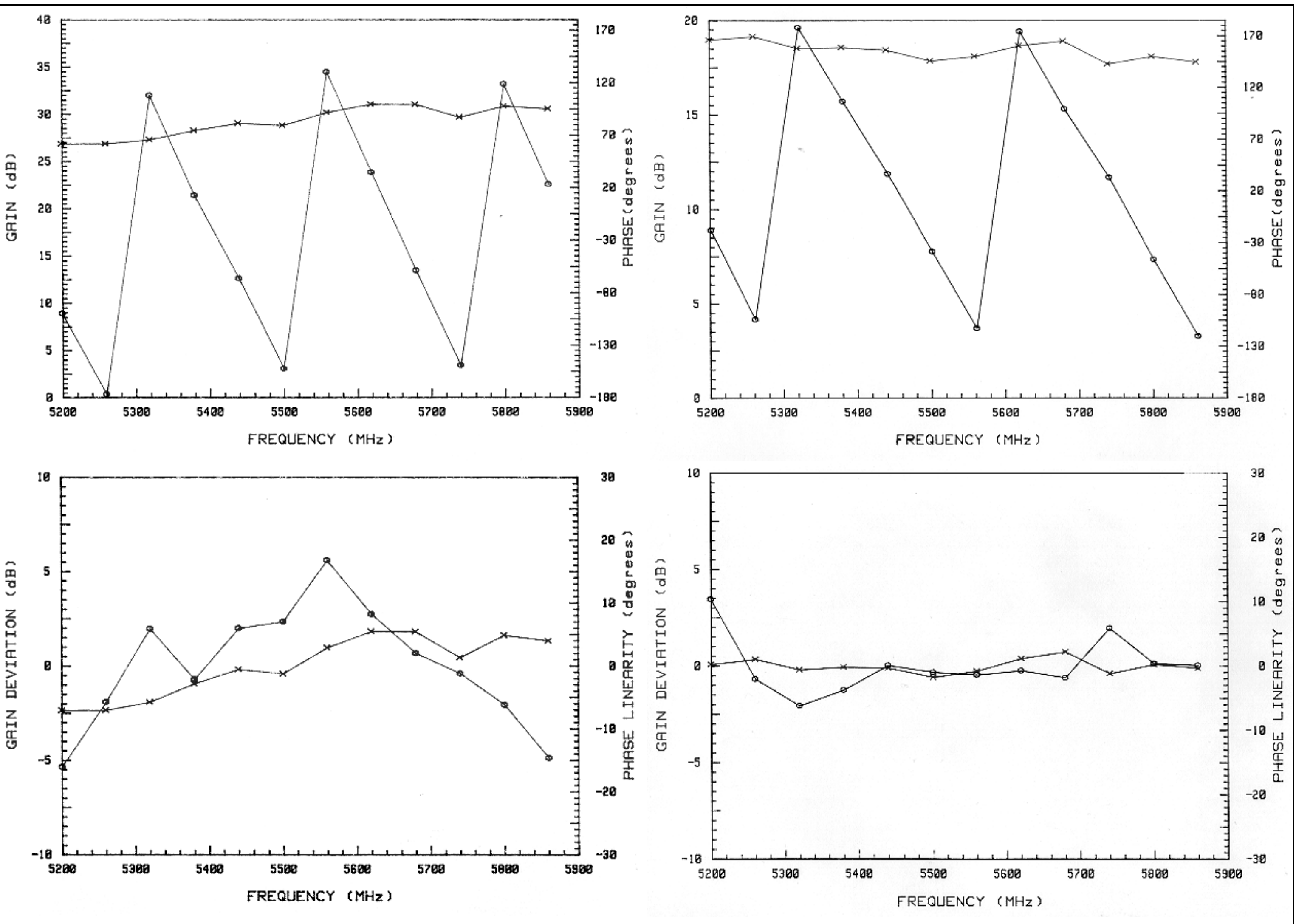


FIGURE A.20 - PHASE 1 TESTING C-BAND MODULE SN089 (LEFT) TRANSMIT & (RIGHT) RECEIVE

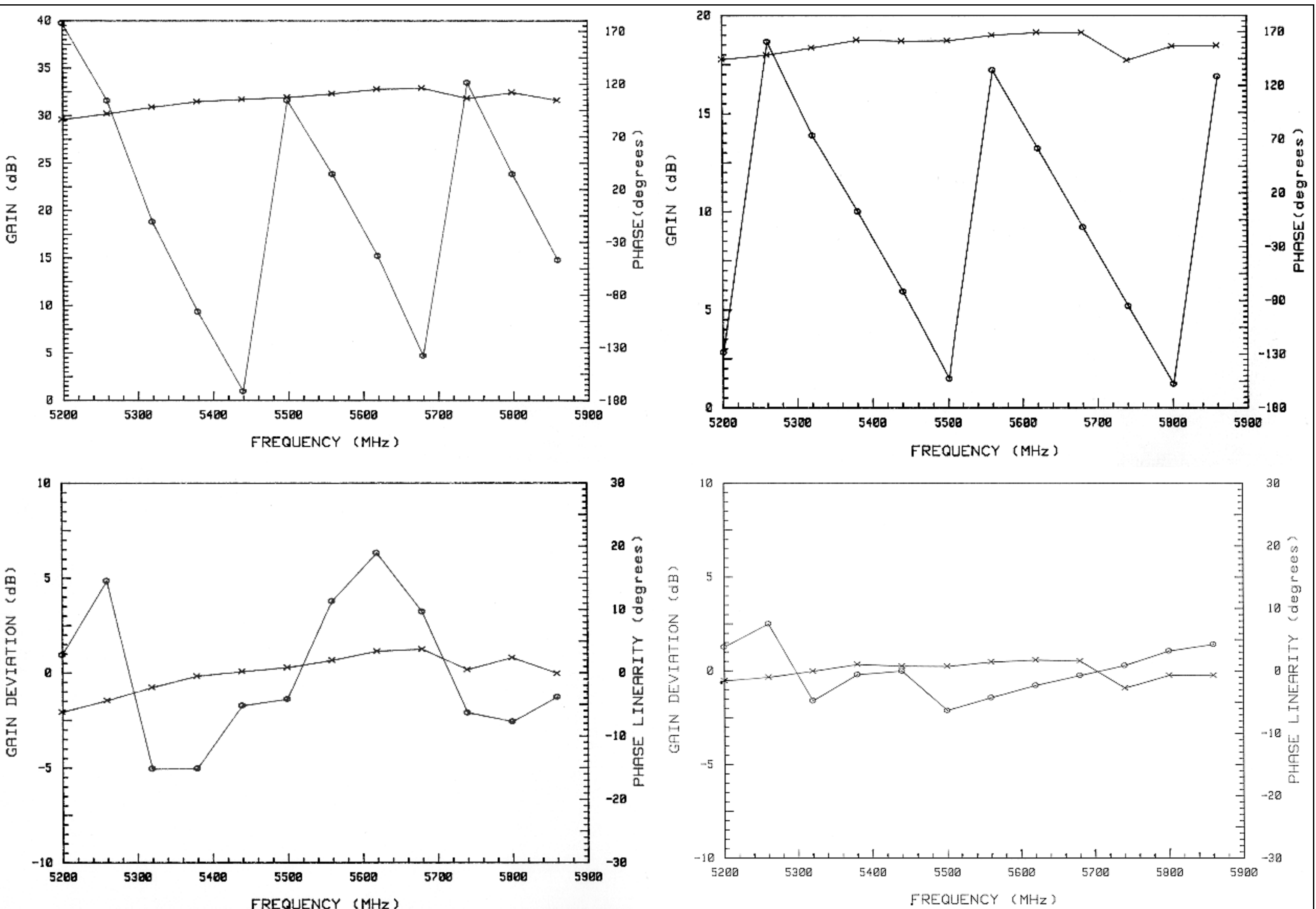


FIGURE A.21 - PHASE 1 TESTING C-BAND MODULE SN118 (LEFT) TRANSMIT & (RIGHT) RECEIVE

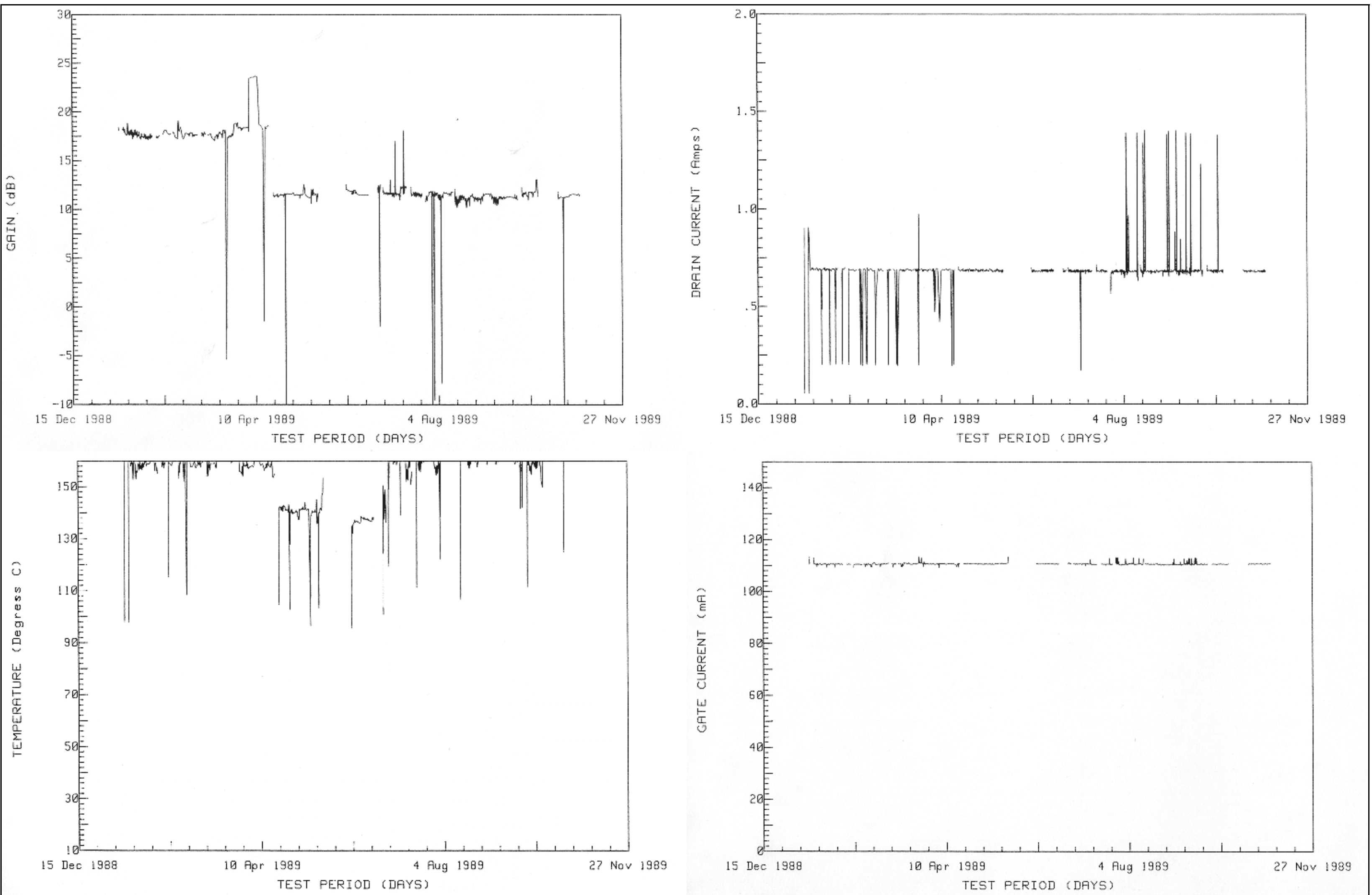

FIGURE A.21 – PHASE 2 TESTING DEVICE CA2

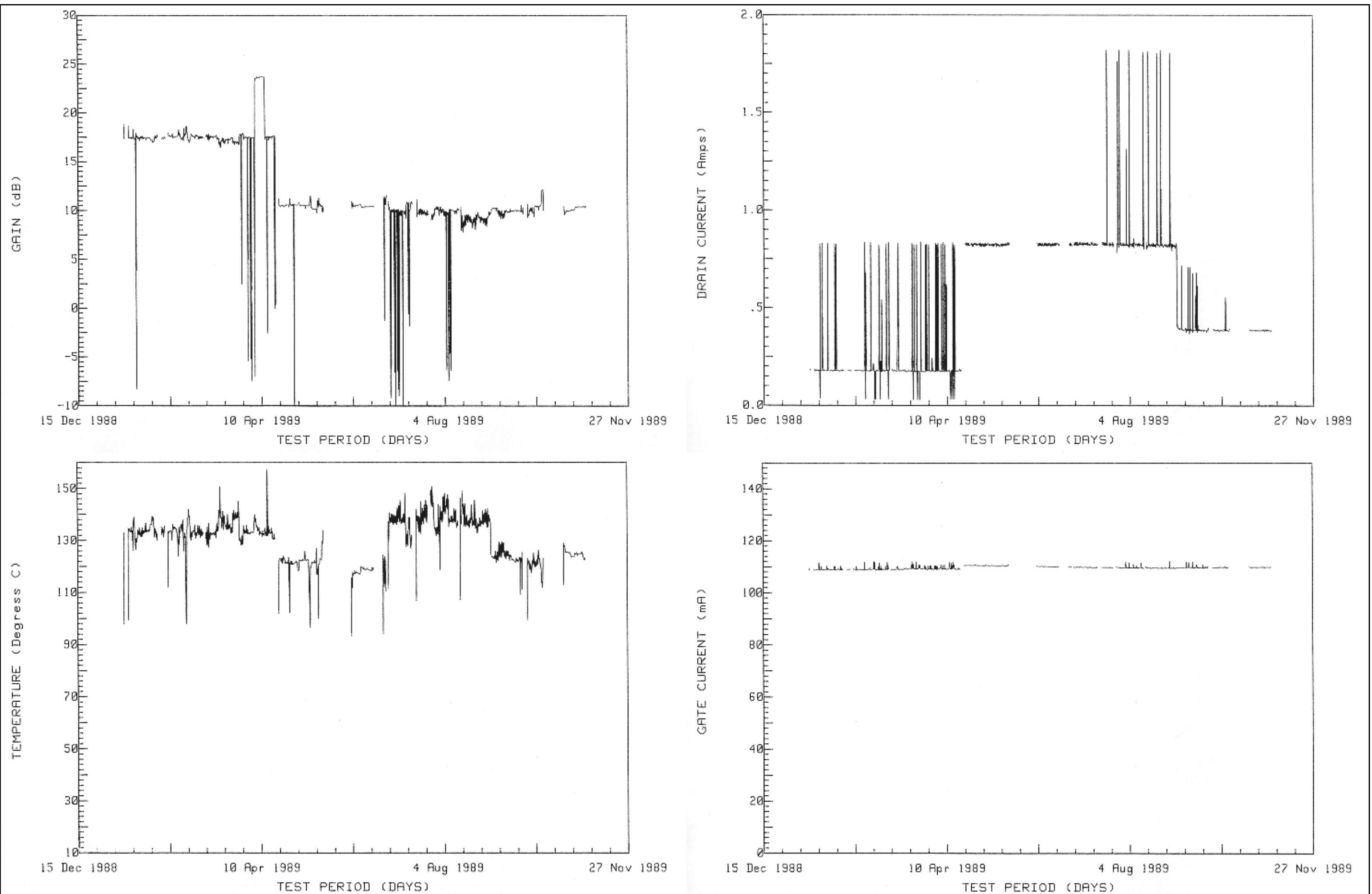


FIGURE A.22 – PHASE 2 TESTING DEVICE CA4

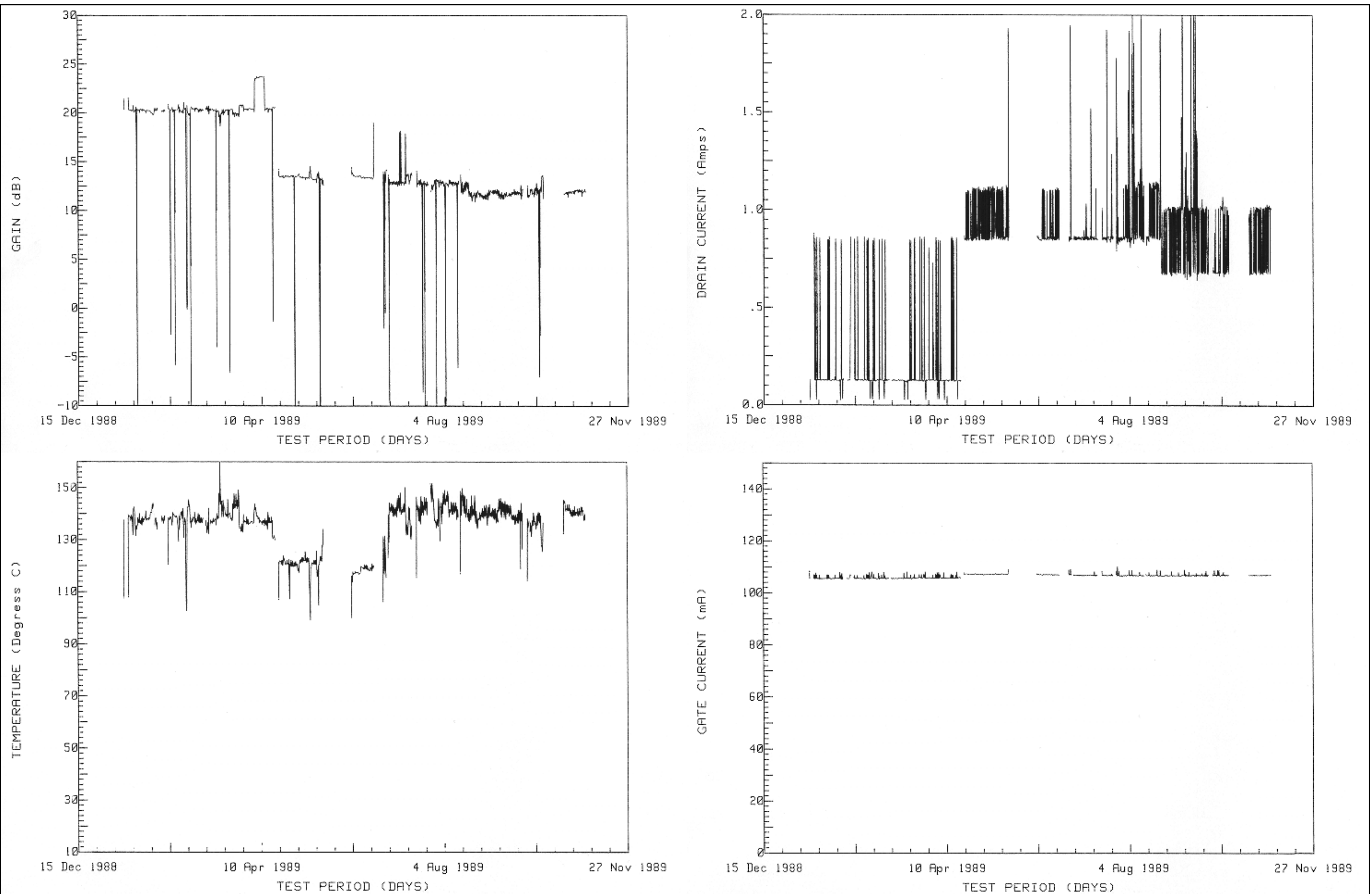


FIGURE A.23 – PHASE 2 TESTING DEVICE CB2

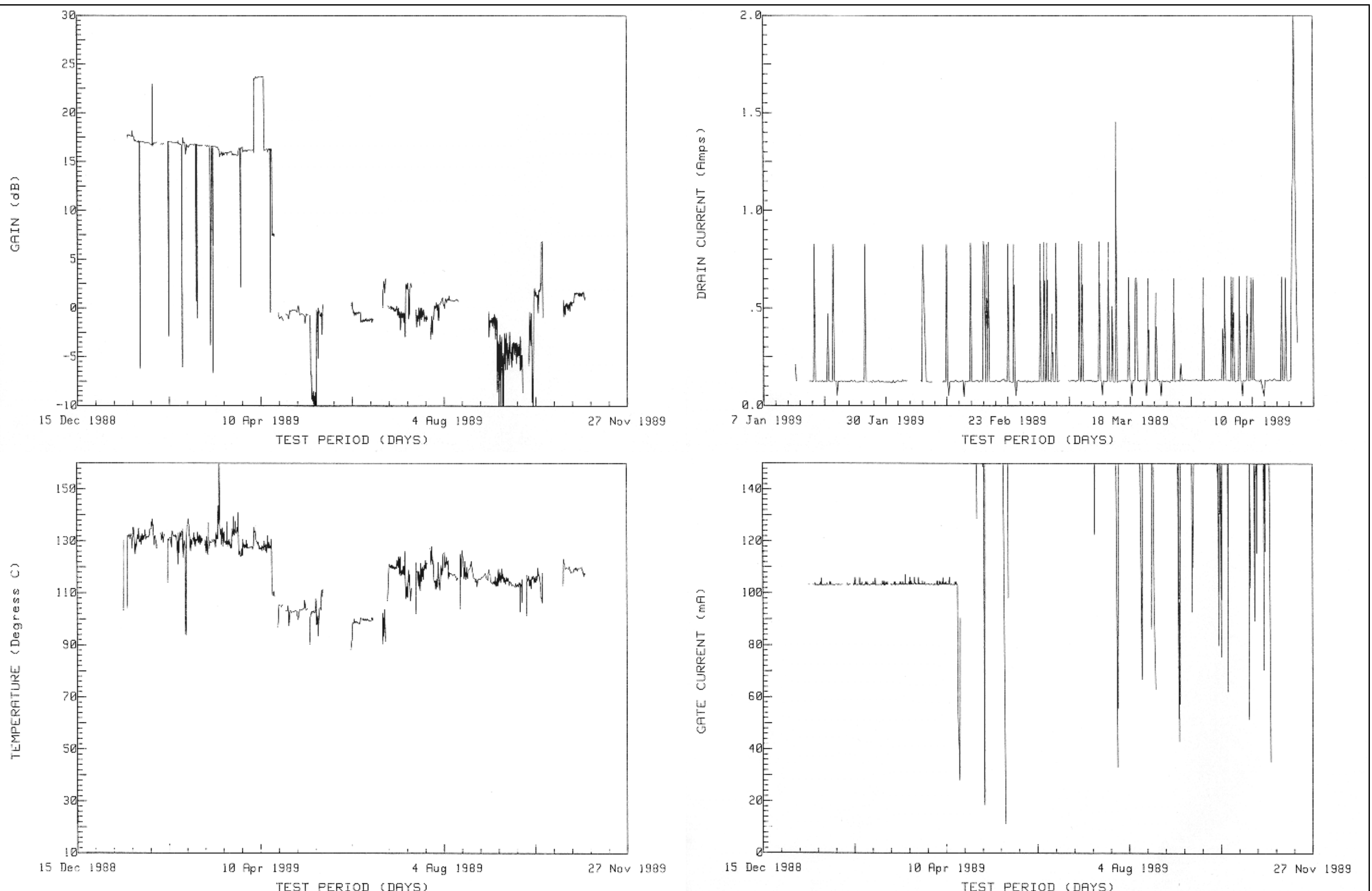


FIGURE A.24 – PHASE 2 TESTING DEVICE CB4

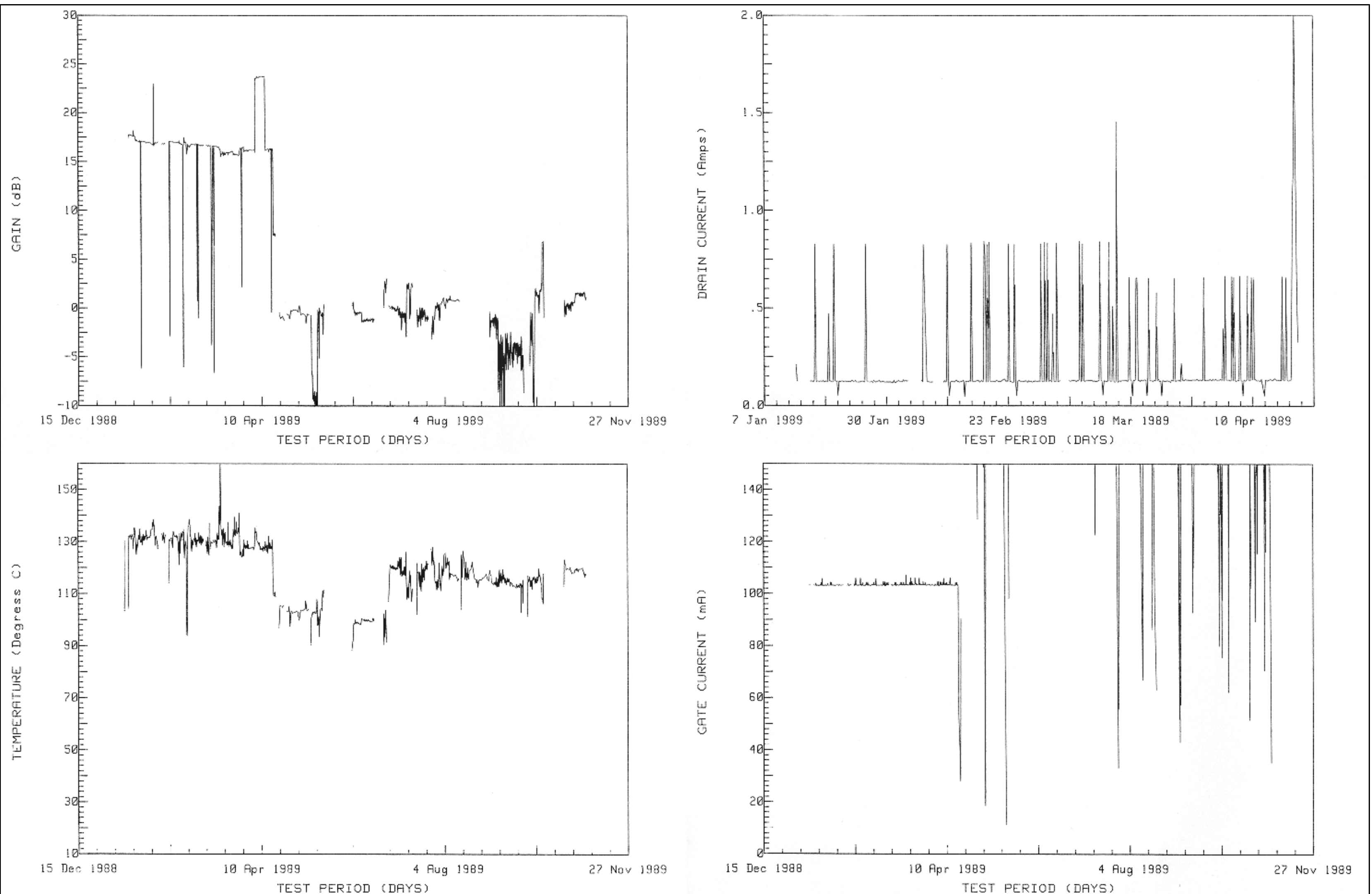


FIGURE A.24 – PHASE 2 TESTING DEVICE CB4

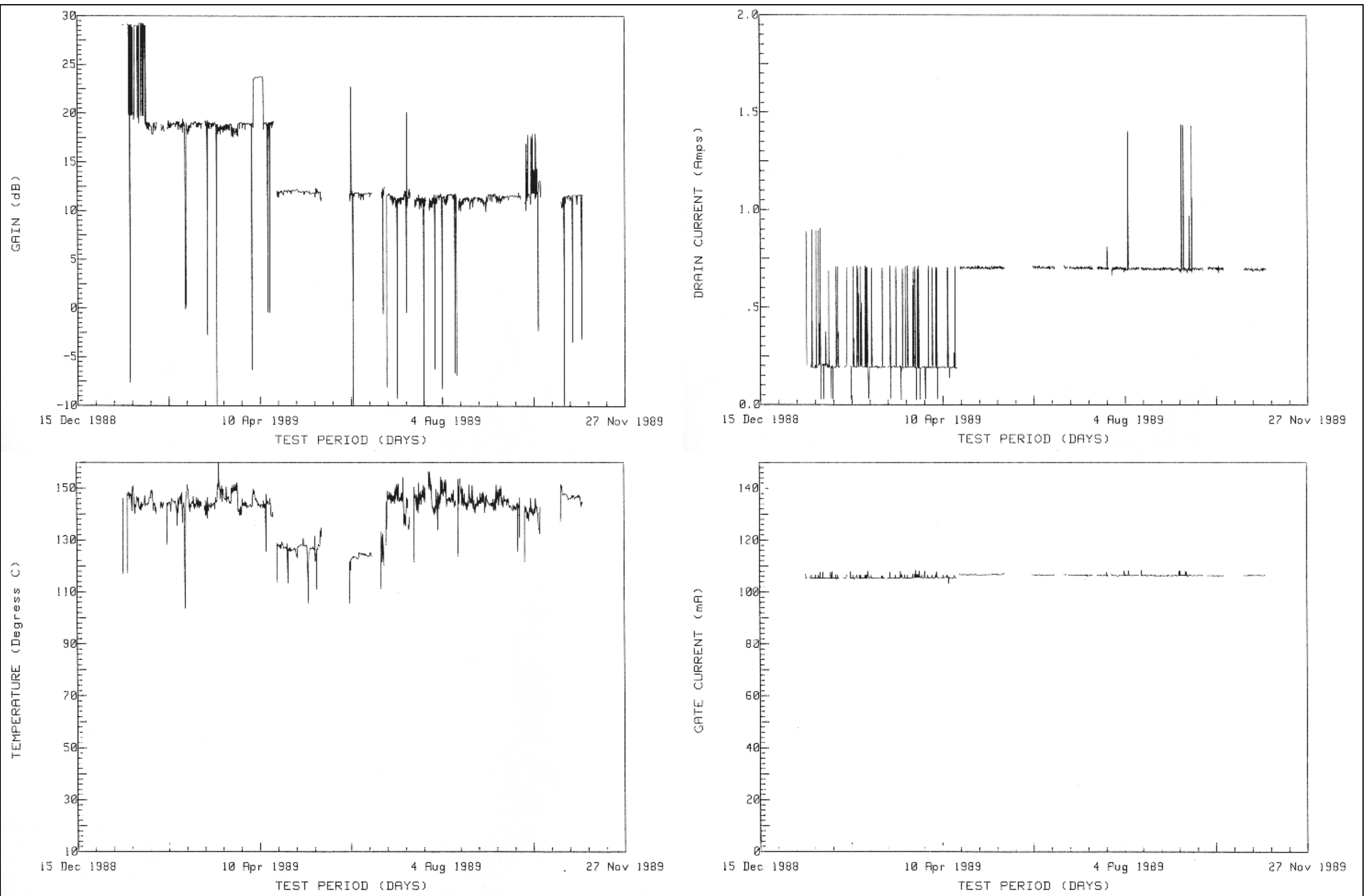


FIGURE A.25 – PHASE 2 TESTING DEVICE CC2

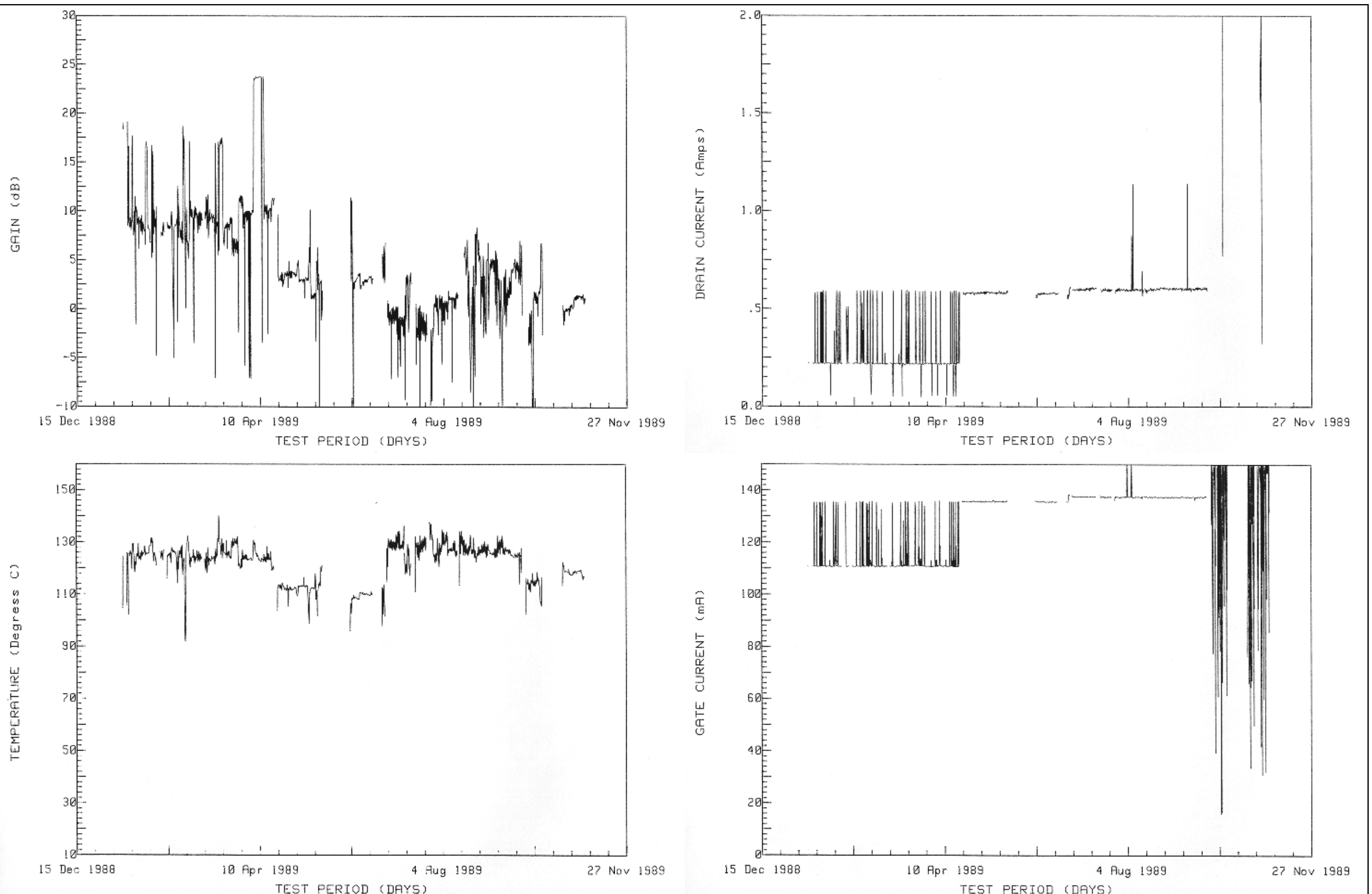


FIGURE A.26 – PHASE 2 TESTING DEVICE CC4

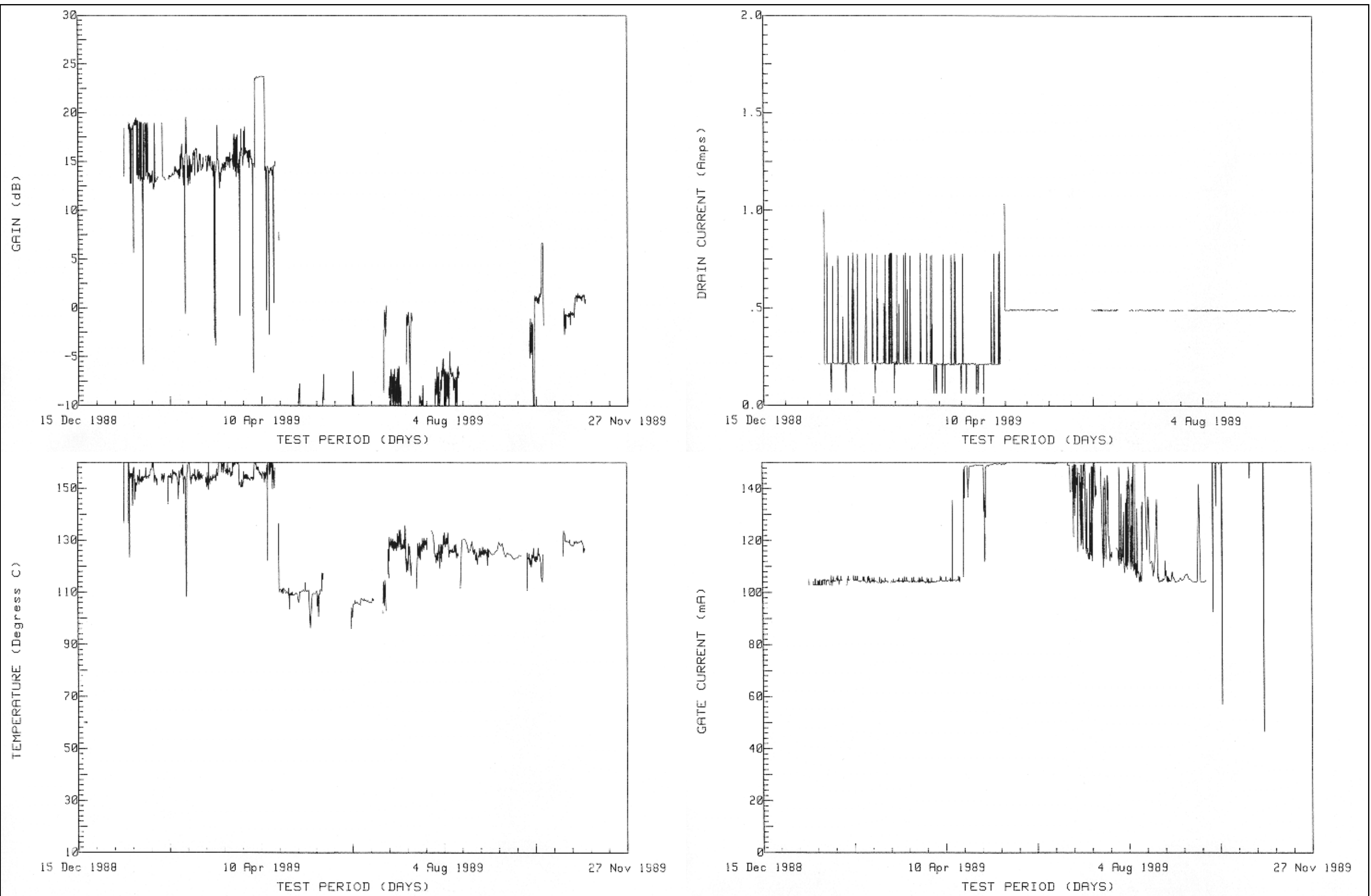


FIGURE A.27 – PHASE 2 TESTING DEVICE CD2

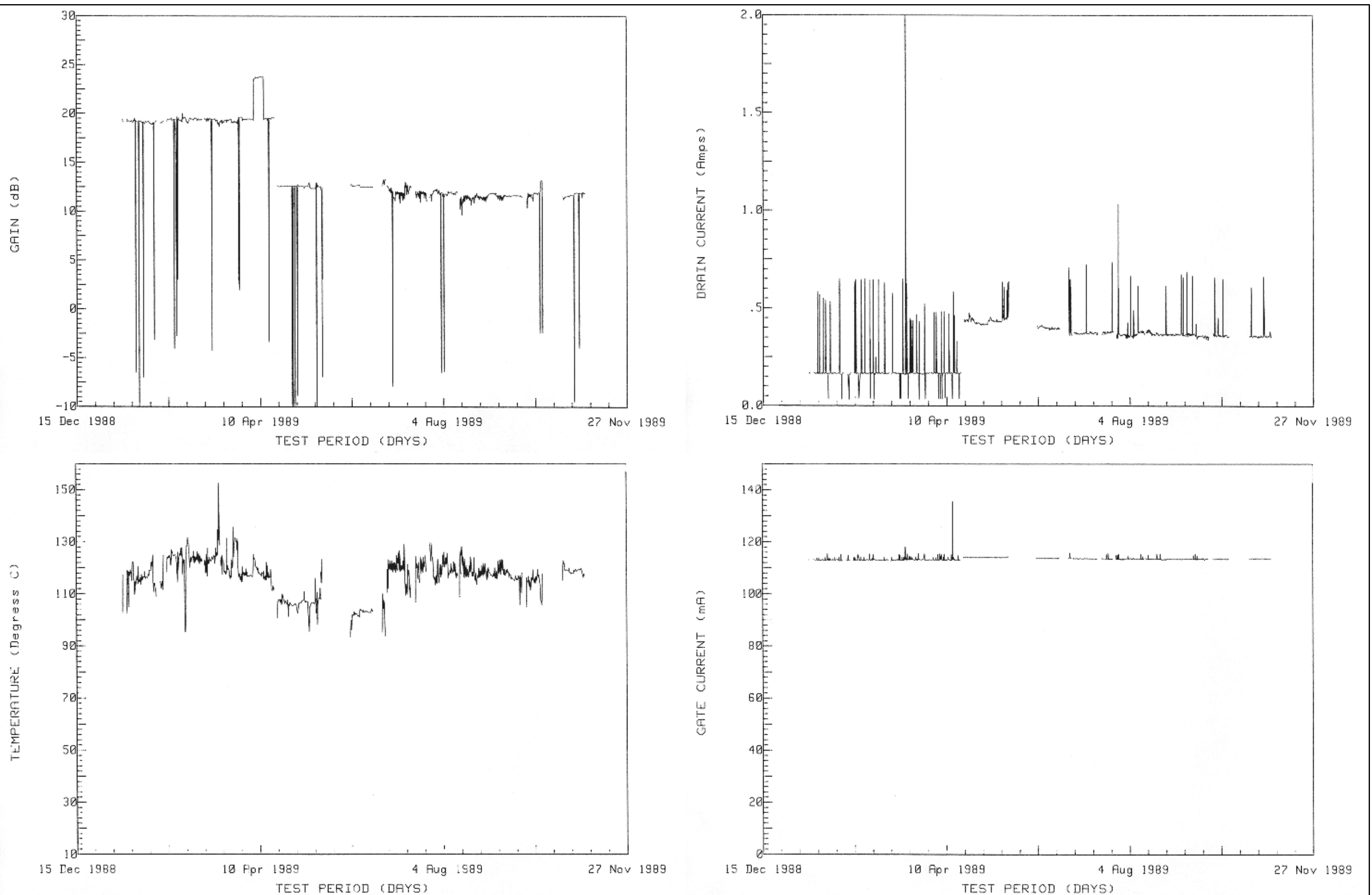


FIGURE A.28 – PHASE 2 TESTING DEVICE CD4

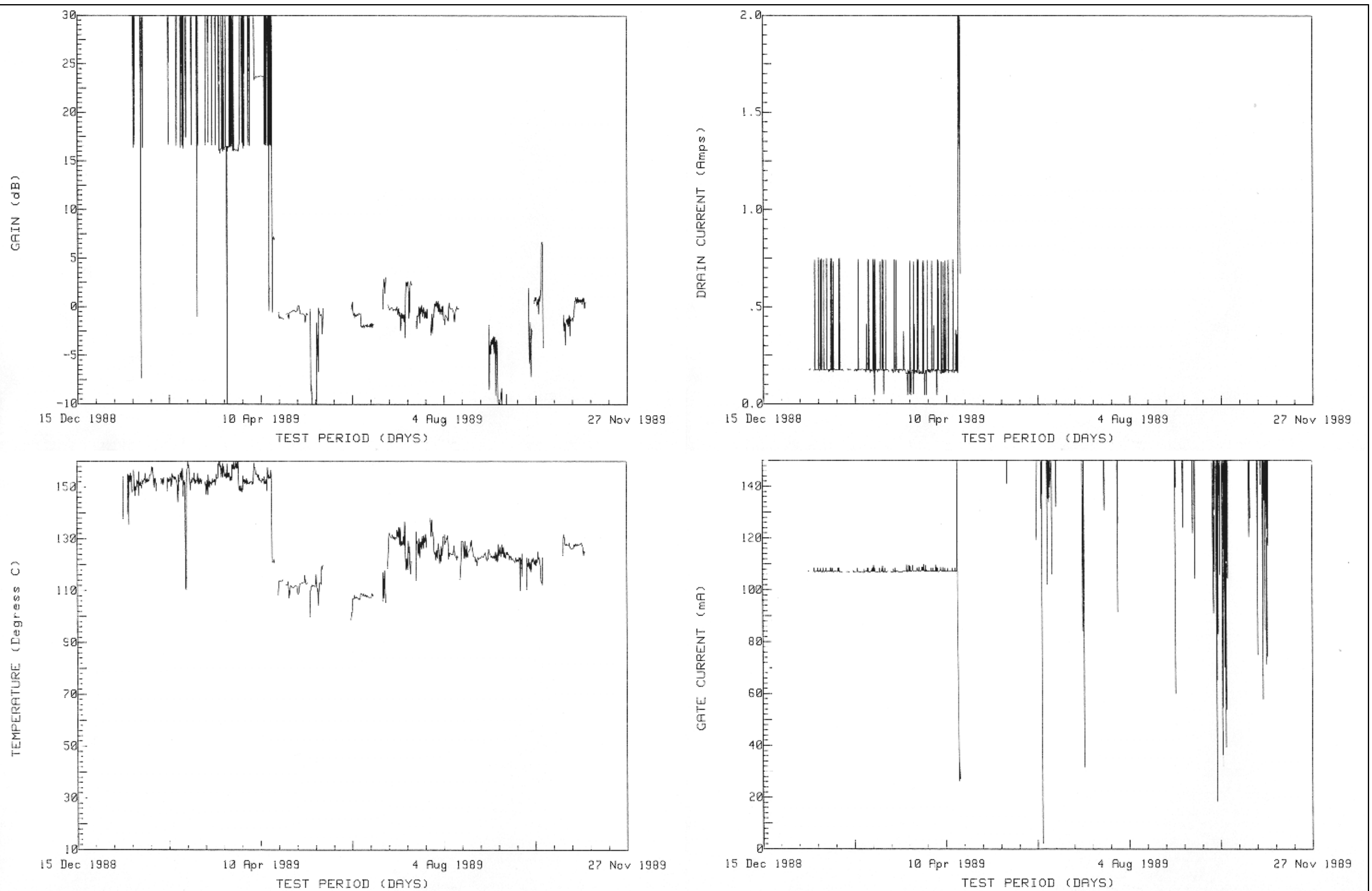


FIGURE A.29 – PHASE 2 TESTING DEVICE CE2

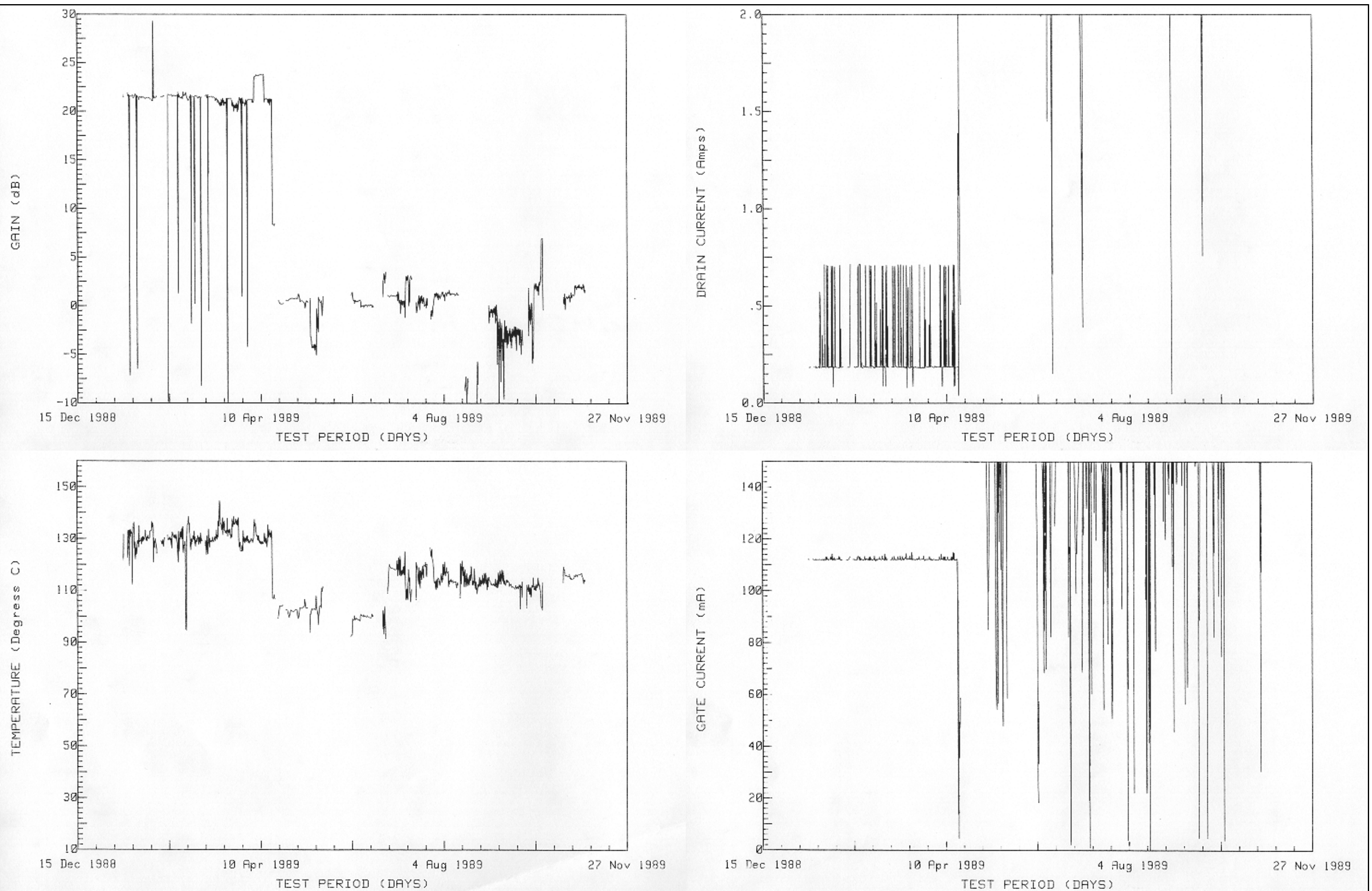


FIGURE A.30 – PHASE 2 TESTING DEVICE CE4

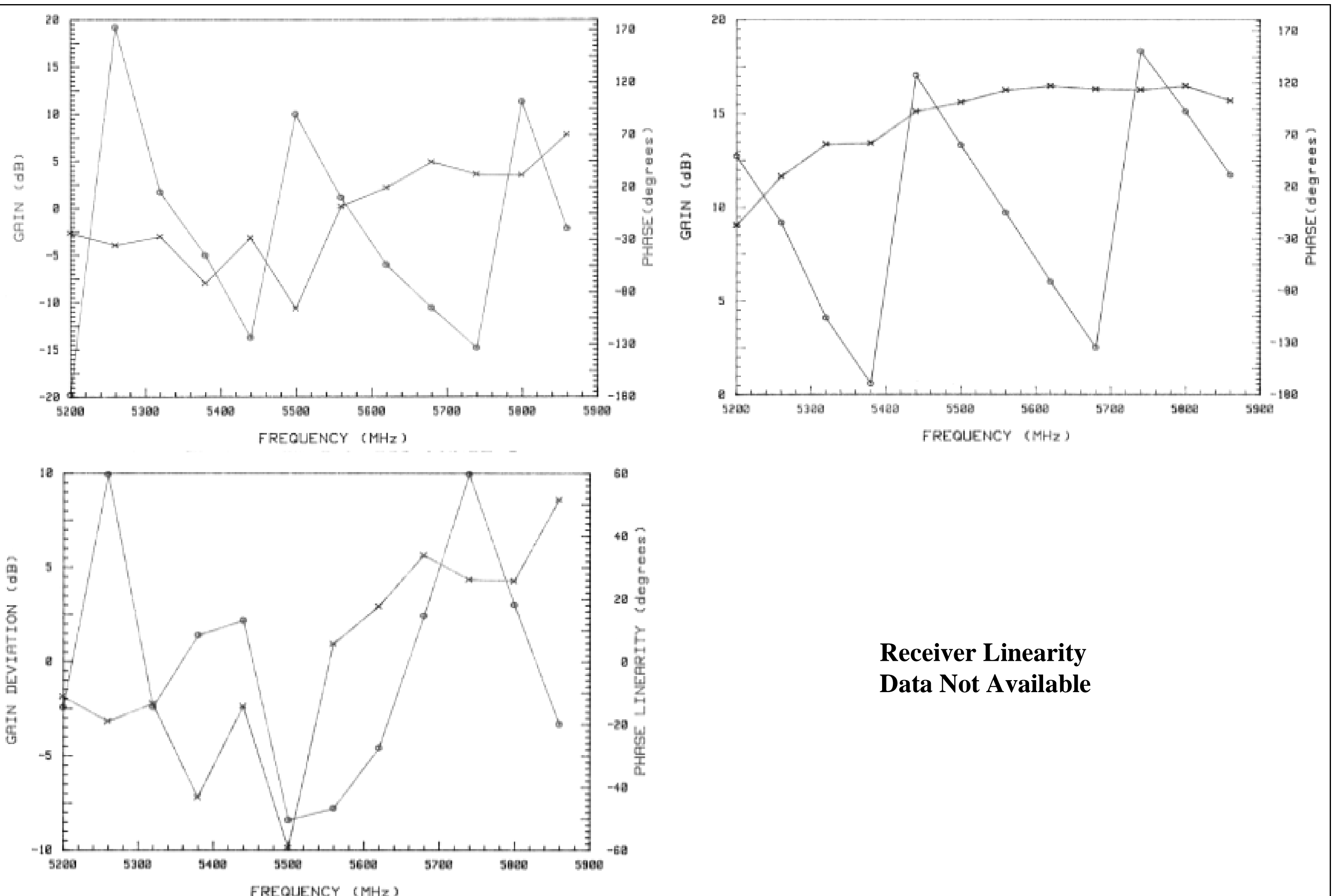


FIGURE A.31 - PHASE 3 TESTING C-BAND MODULE SN006 (LEFT) TRANSMIT & (RIGHT) RECEIVE

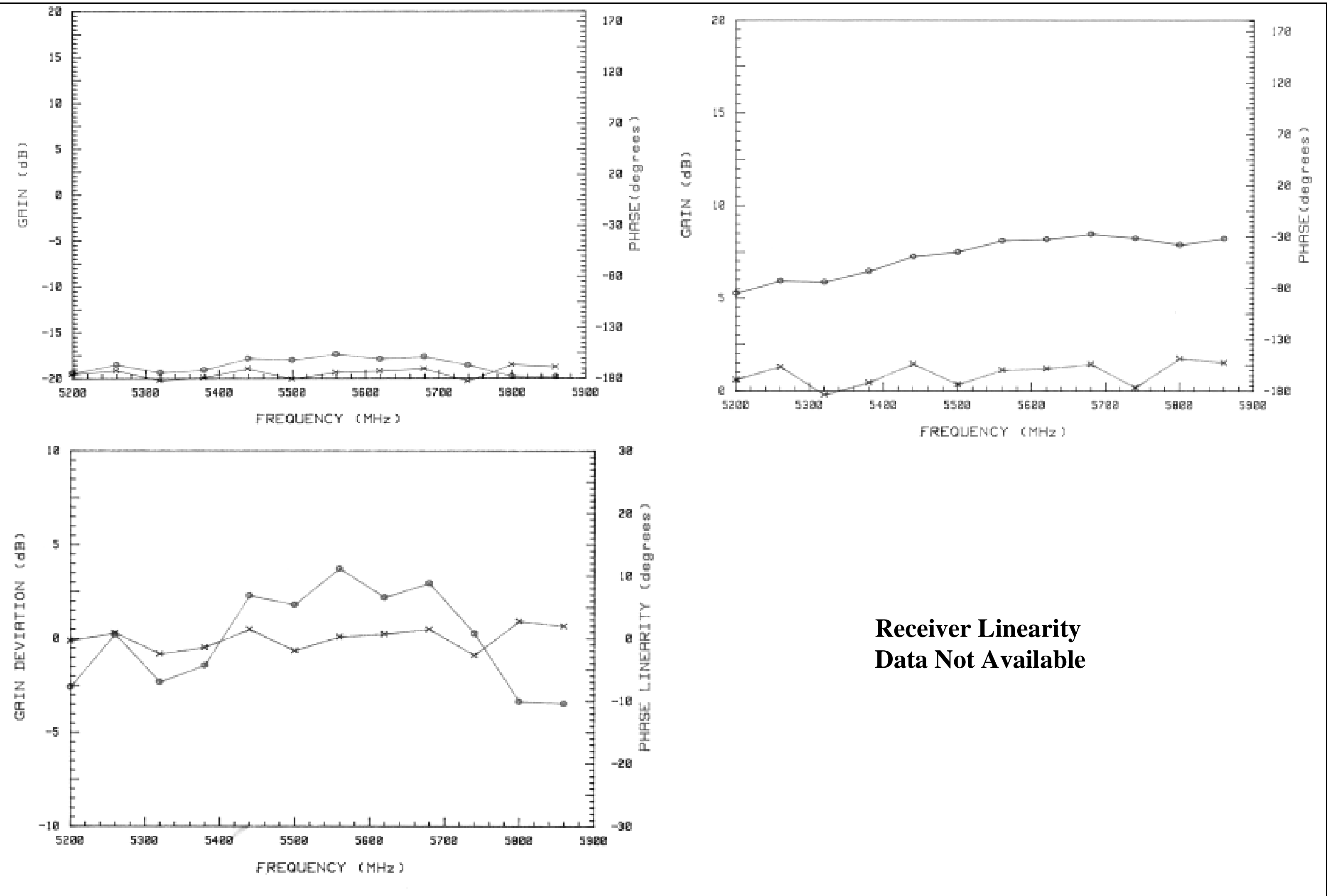


FIGURE A.32 - PHASE 3 TESTING C-BAND MODULE SN017 (LEFT) TRANSMIT & (RIGHT) RECEIVE

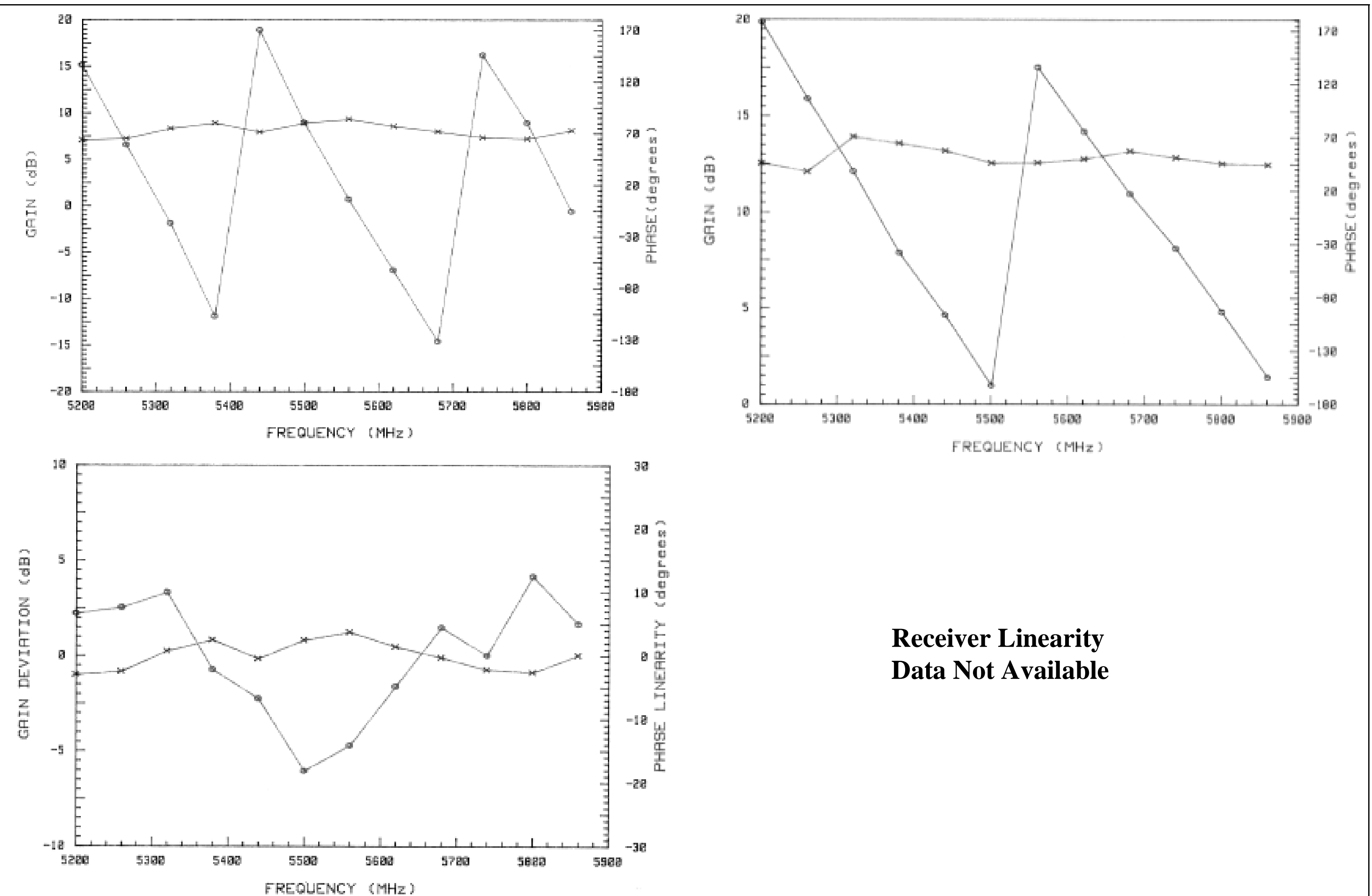


FIGURE A. 33 - PHASE 3 TESTING C-BAND MODULE SN022 (LEFT) TRANSMIT & (RIGHT) RECEIVE

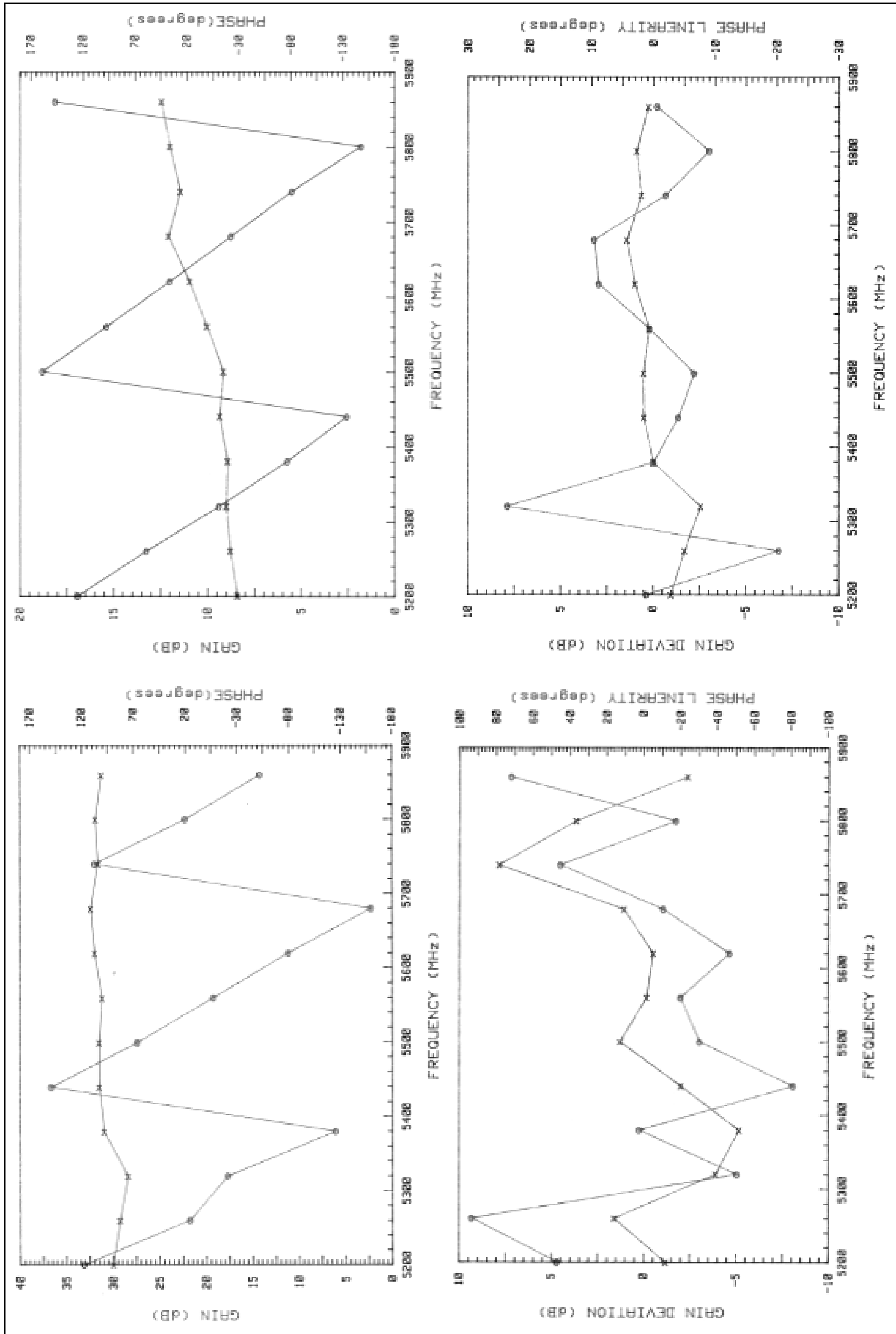


FIGURE A.34 - PHASE 3 TESTING C-BAND MODULE SN032 (LEFT) TRANSMIT & (RIGHT) RECEIVE

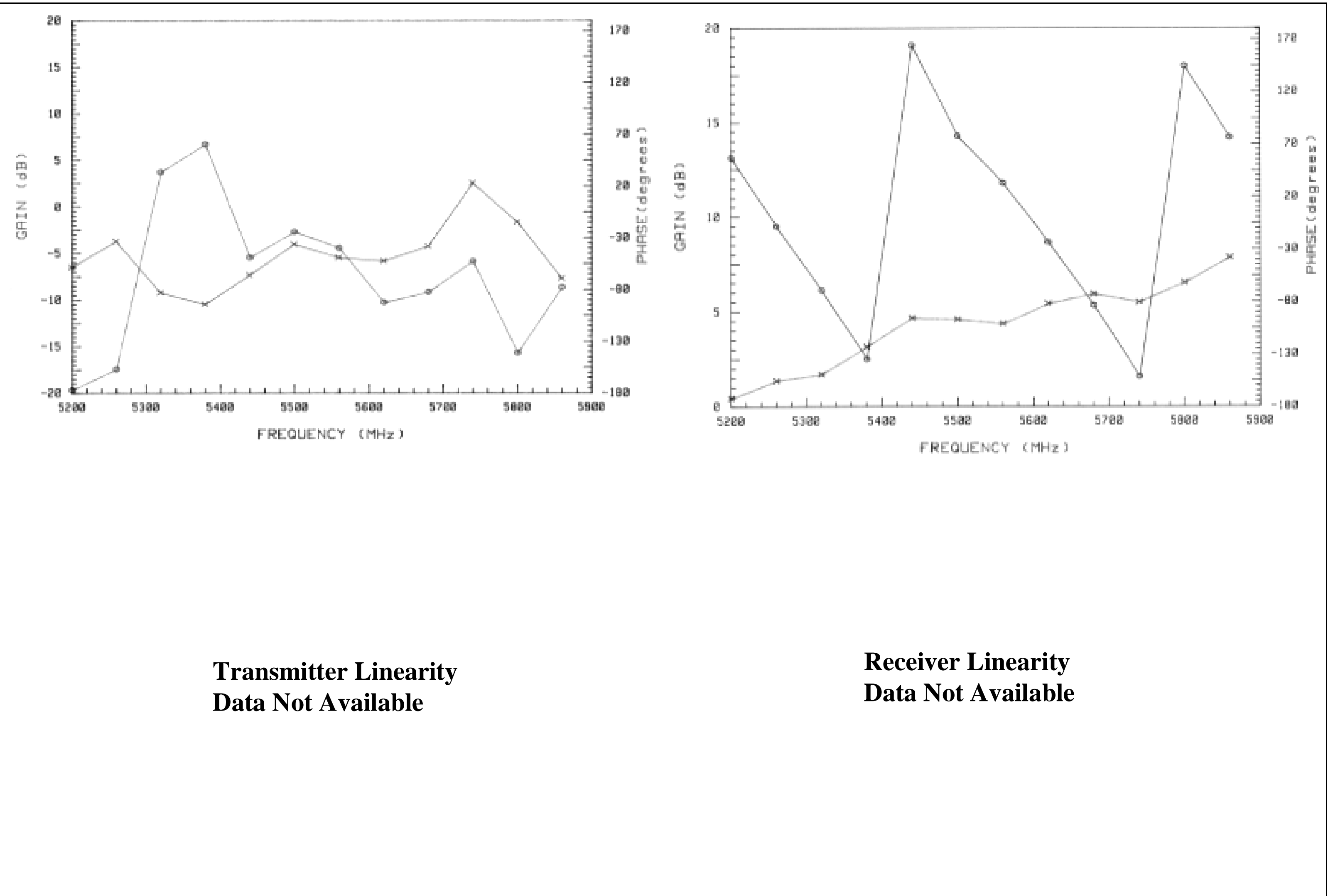


FIGURE A.35 - PHASE 3 TESTING C-BAND MODULE SN033 (LEFT) TRANSMIT & (RIGHT) RECEIVE

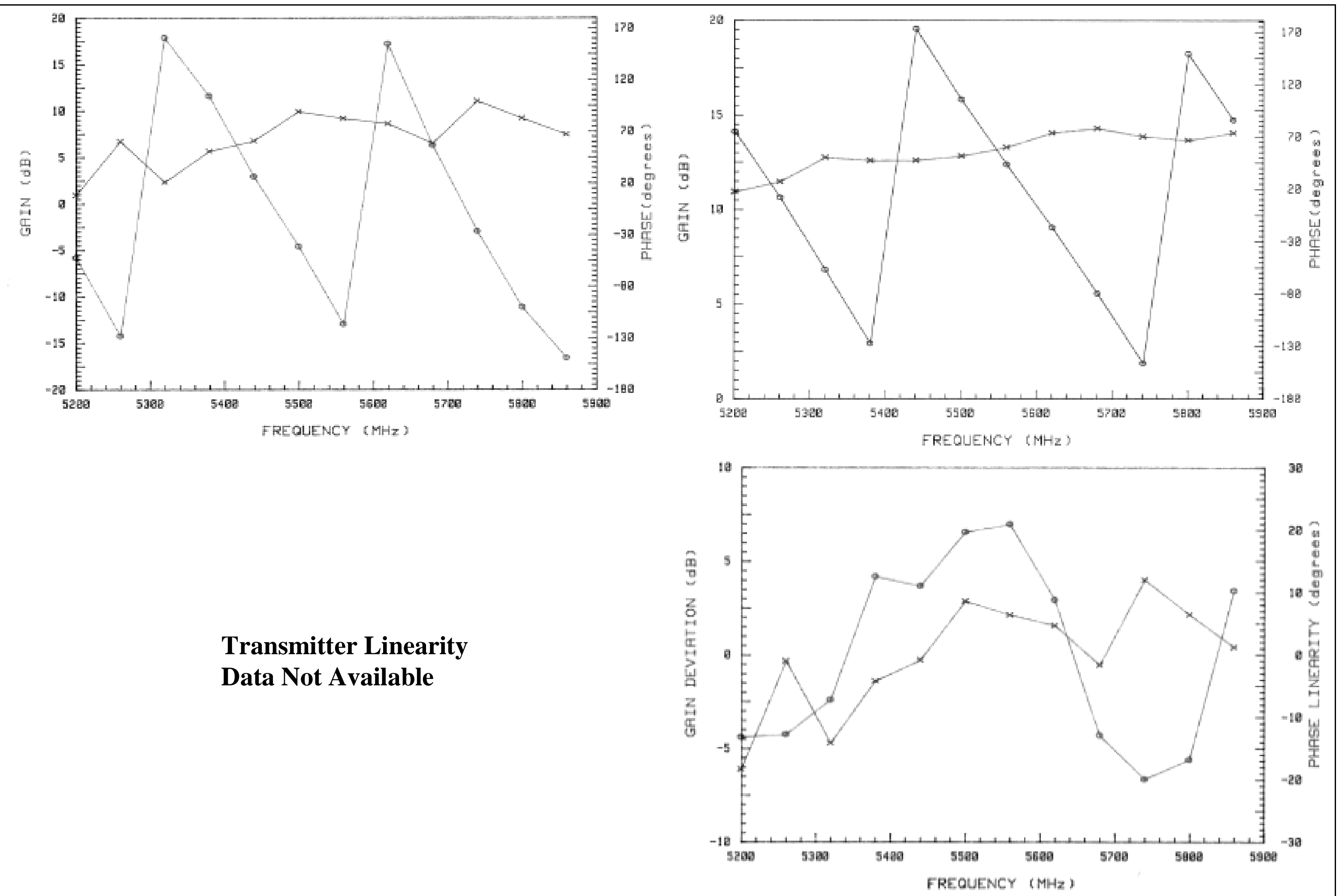


FIGURE A.36 - PHASE 3 TESTING C-BAND MODULE SN039 (LEFT) TRANSMIT & (RIGHT) RECEIVE

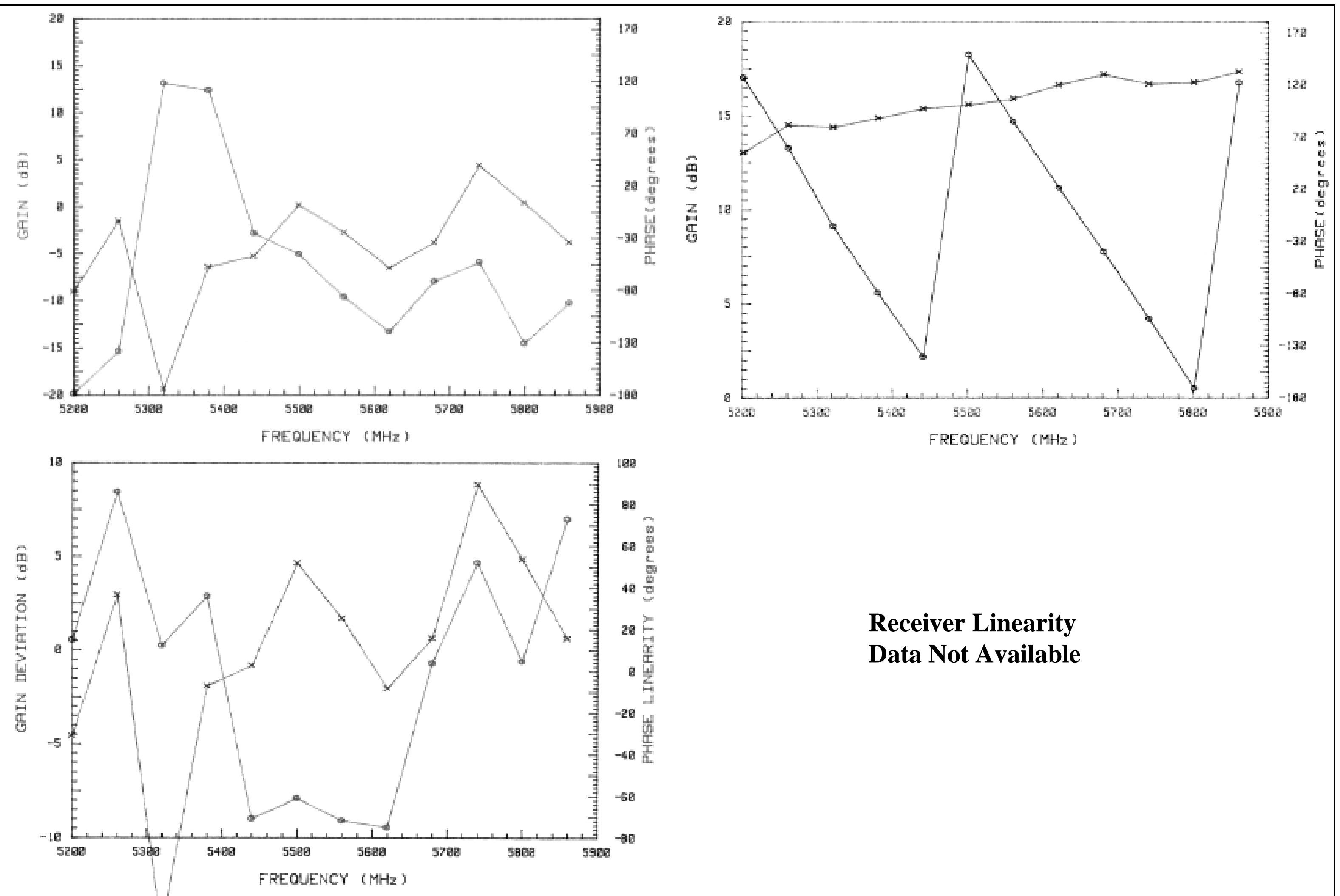


FIGURE A.37 - PHASE 3 TESTING C-BAND MODULE SN040 (LEFT) TRANSMIT & (RIGHT) RECEIVE

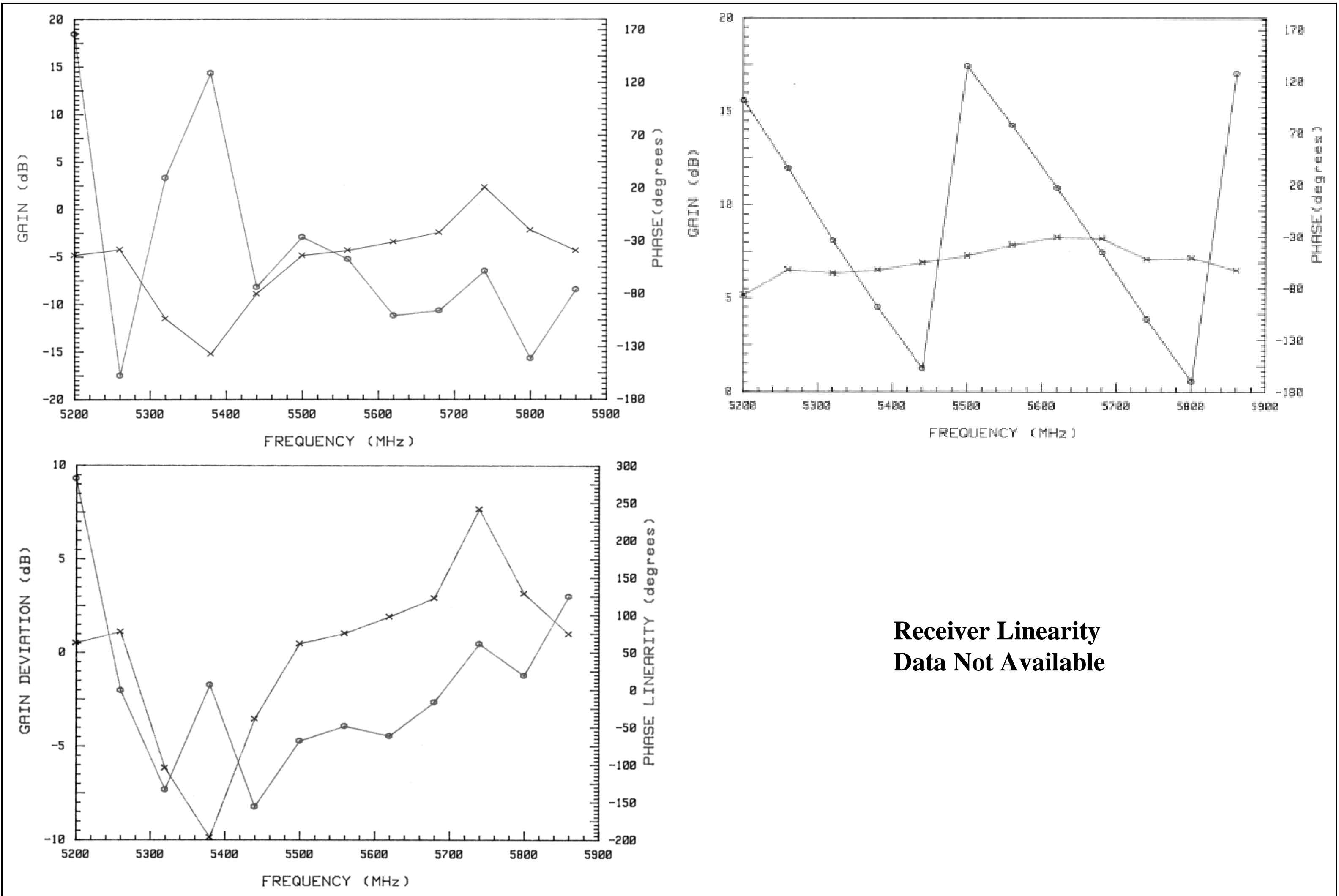


FIGURE A.38 - PHASE 3 TESTING C-BAND MODULE SN056 (LEFT) TRANSMIT & (RIGHT) RECEIVE

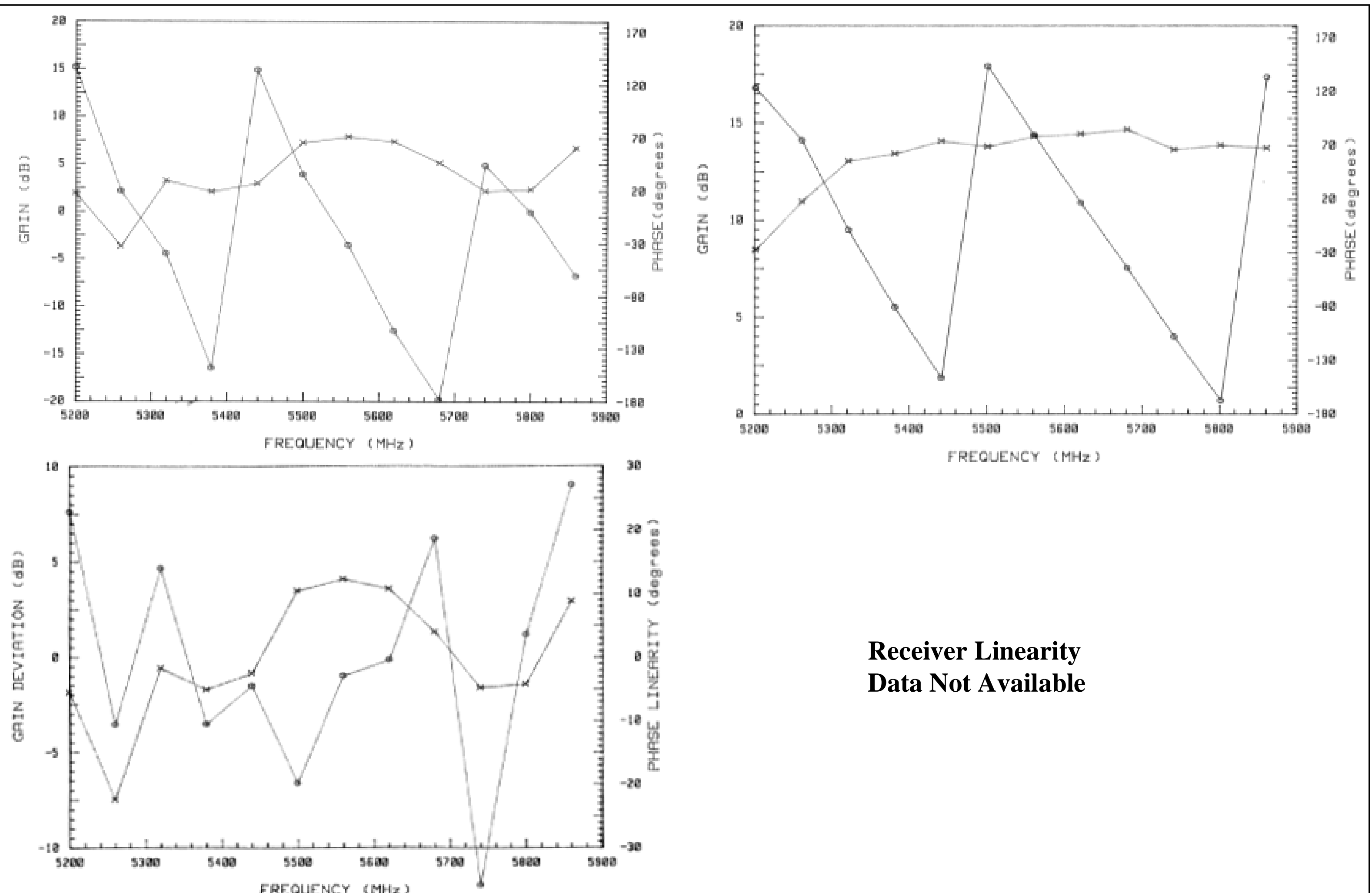


FIGURE A.39 - PHASE 3 TESTING C-BAND MODULE SN057 (LEFT) TRANSMIT & (RIGHT) RECEIVE

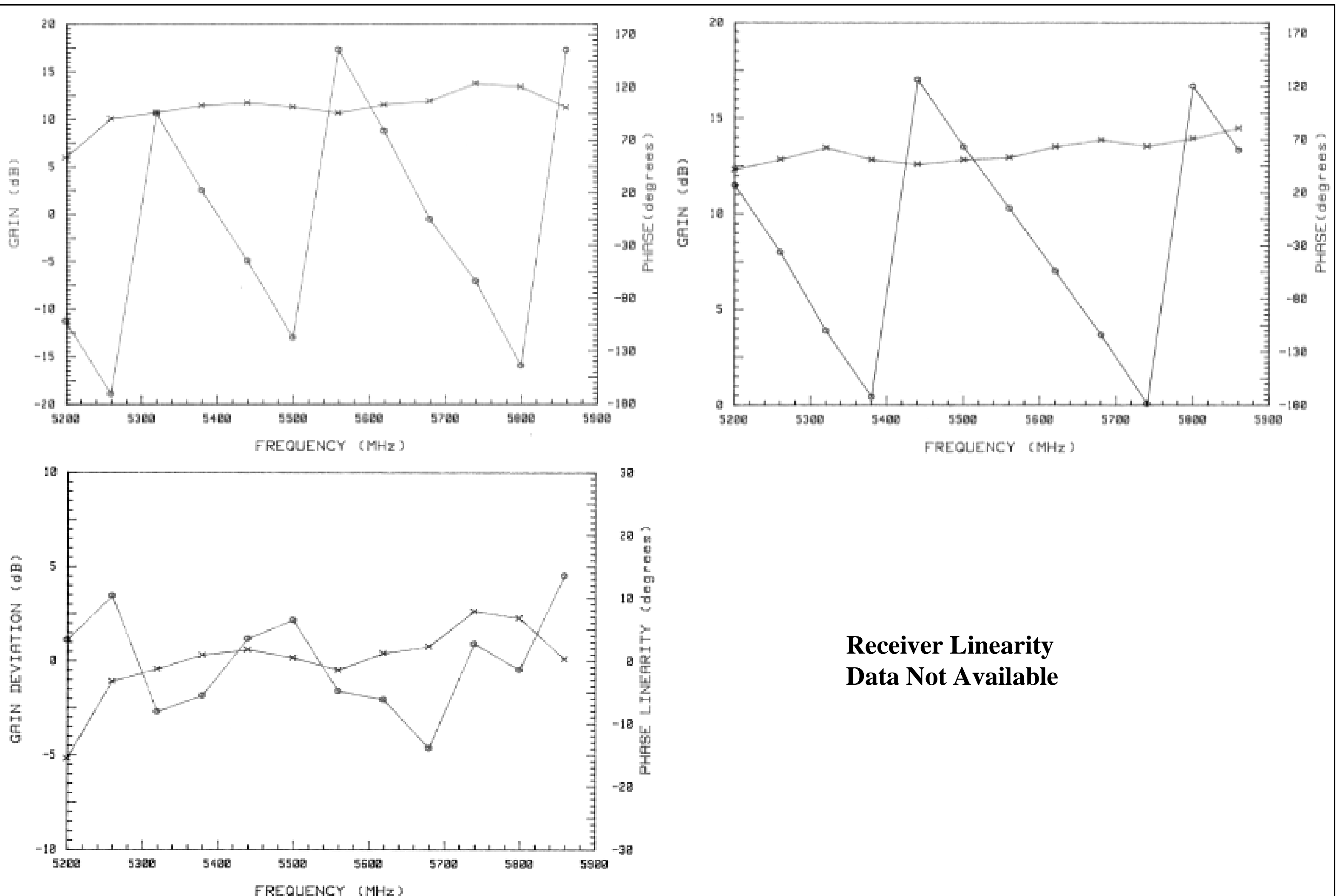


FIGURE A.40 - PHASE 3 TESTING C-BAND MODULE SN065 (LEFT) TRANSMIT & (RIGHT) RECEIVE

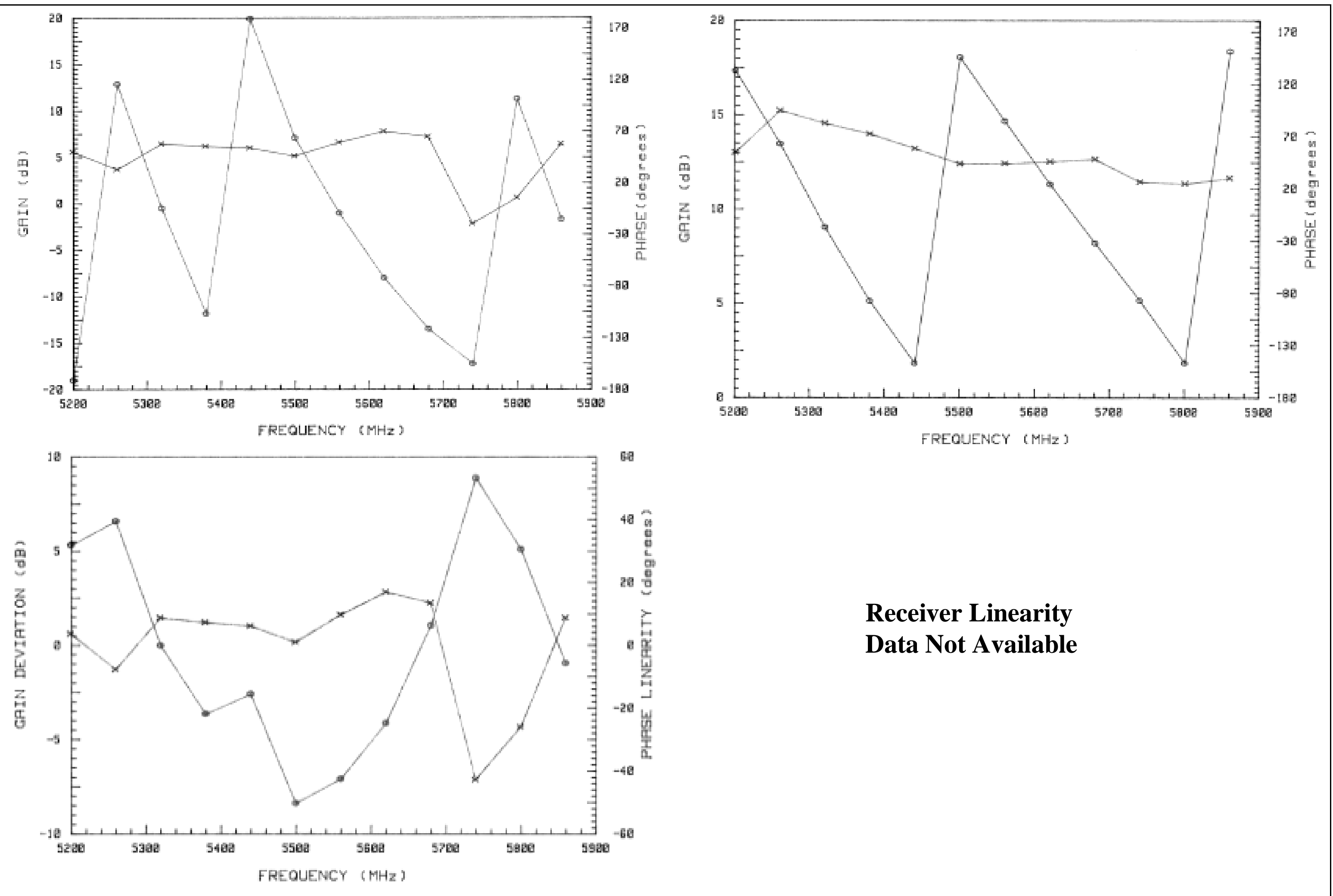


FIGURE A.41 - PHASE 3 TESTING C-BAND MODULE SN070 (LEFT) TRANSMIT & (RIGHT) RECEIVE

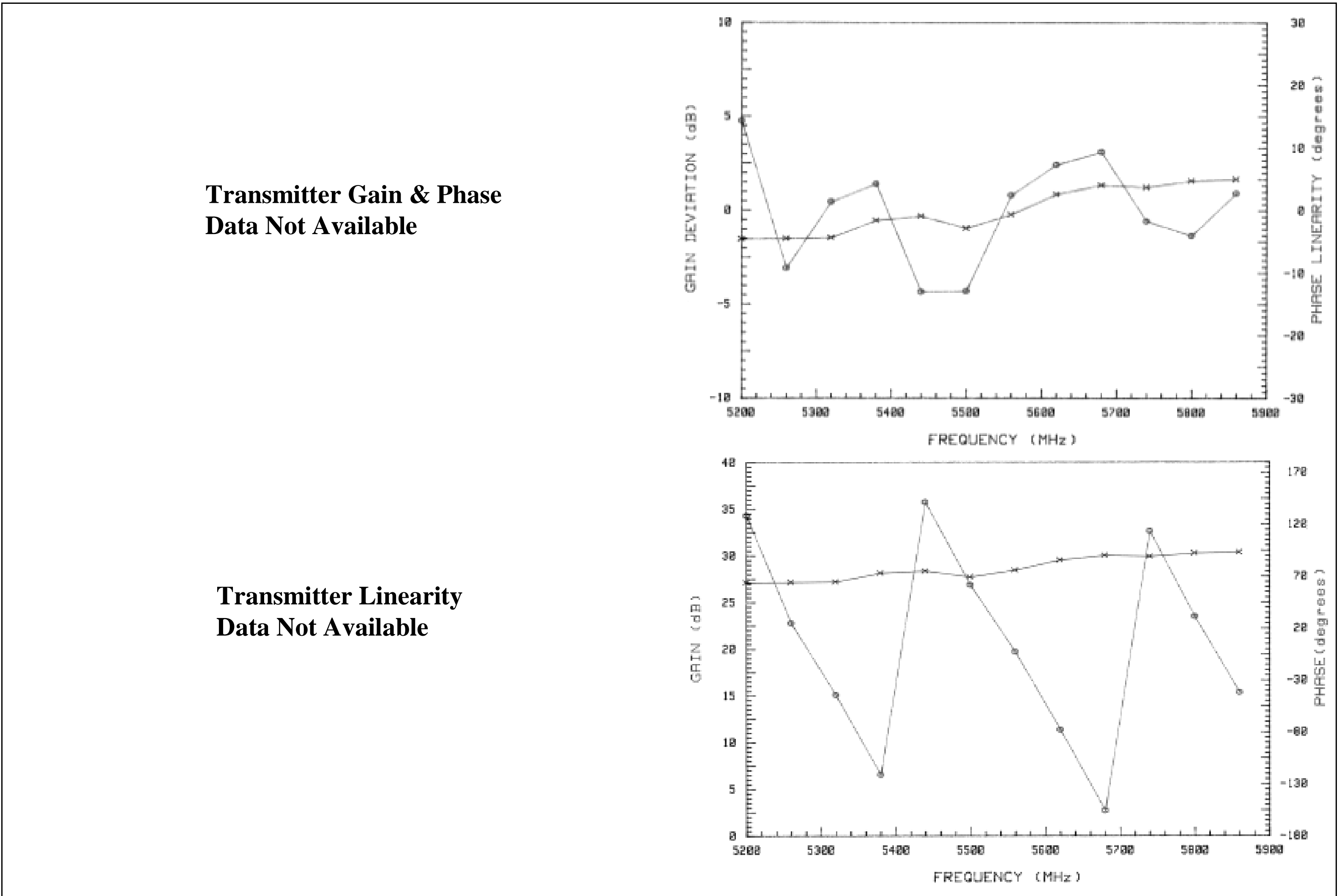


FIGURE A.42 - PHASE 3 TESTING C-BAND MODULE SN073 (LEFT) TRANSMIT & (RIGHT) RECEIVE

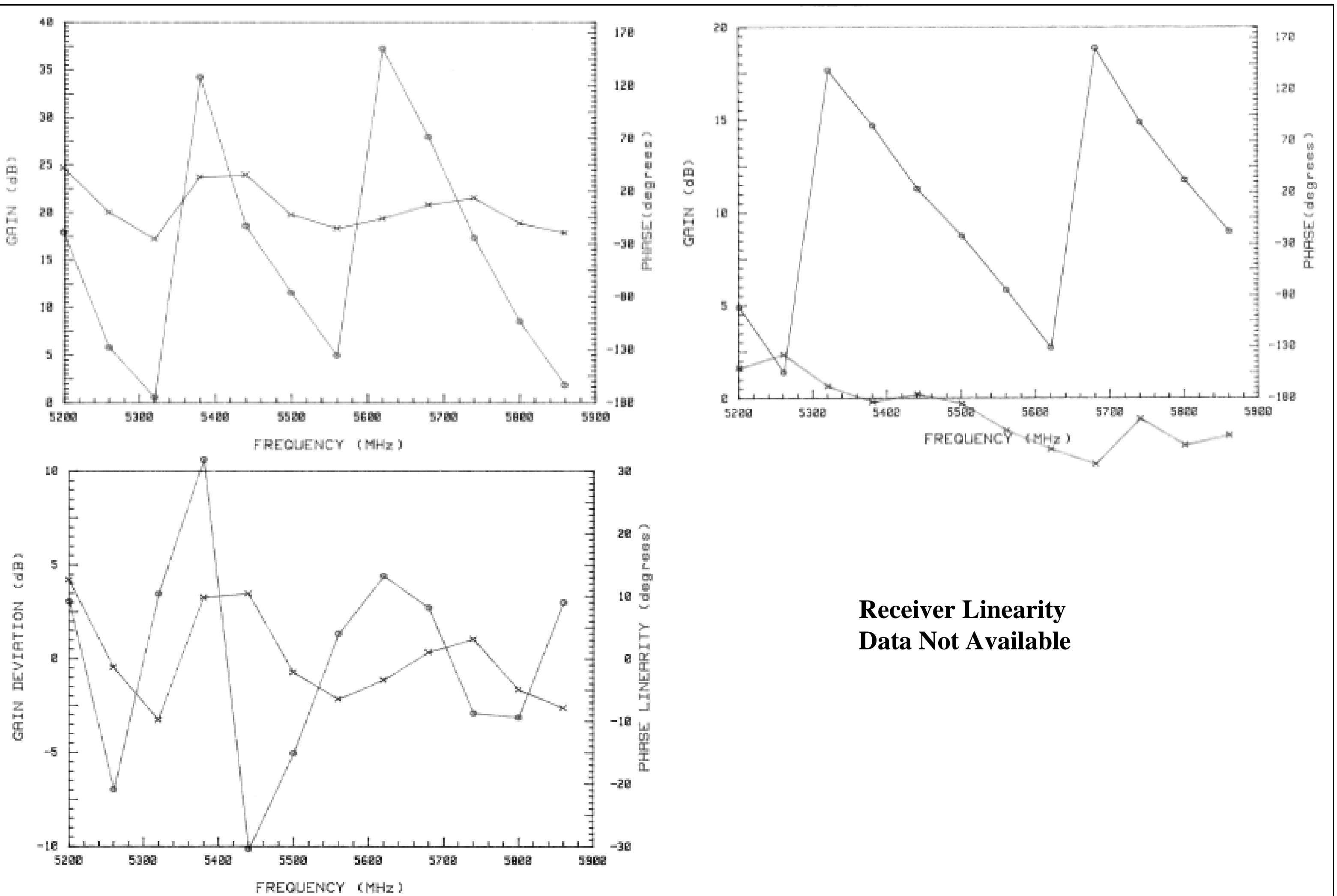


FIGURE A.43 - PHASE 3 TESTING C-BAND MODULE SN085 (LEFT) TRANSMIT & (RIGHT) RECEIVE

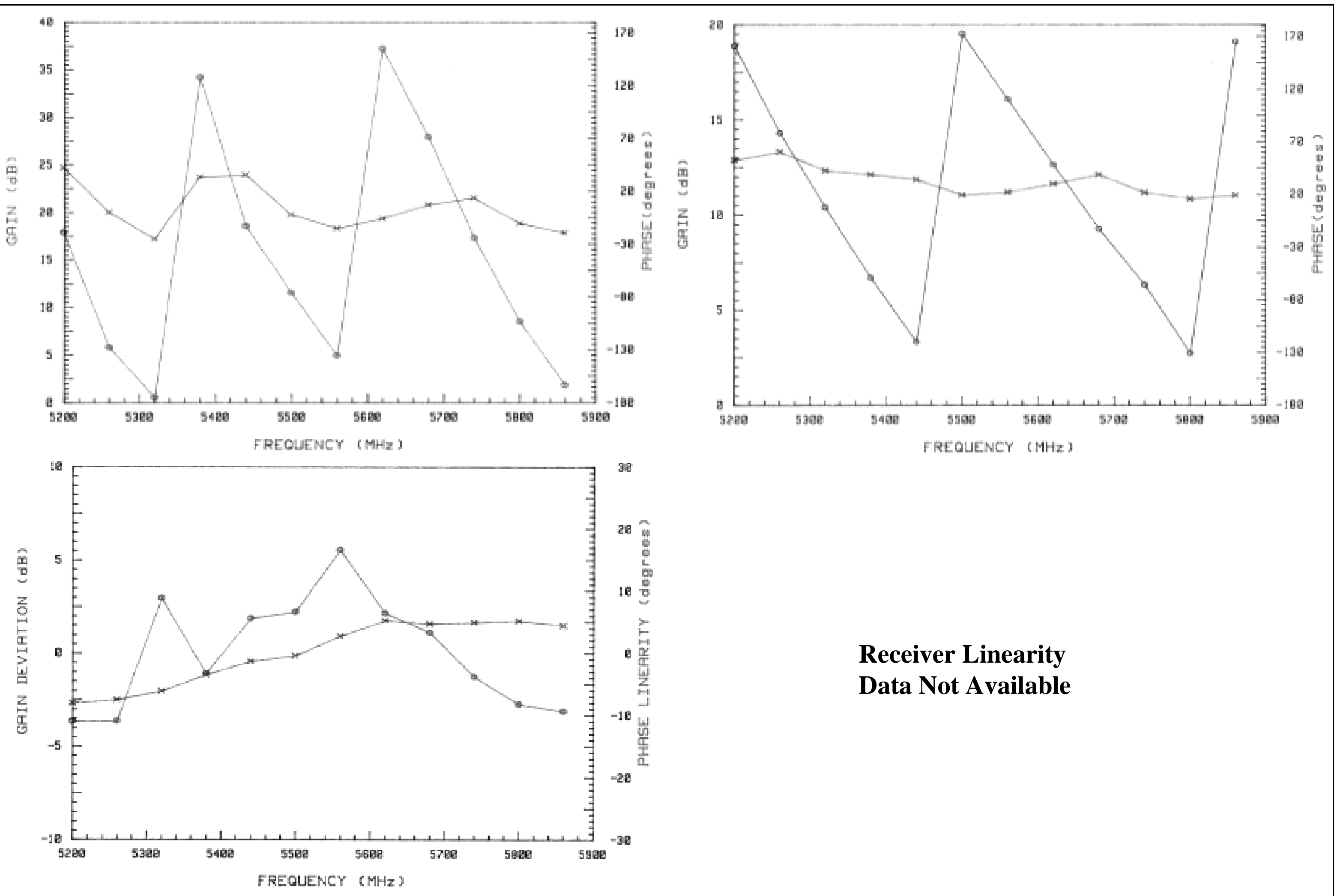


FIGURE A.44 - PHASE 3 TESTING C-BAND MODULE SN089 (LEFT) TRANSMIT & (RIGHT) RECEIVE

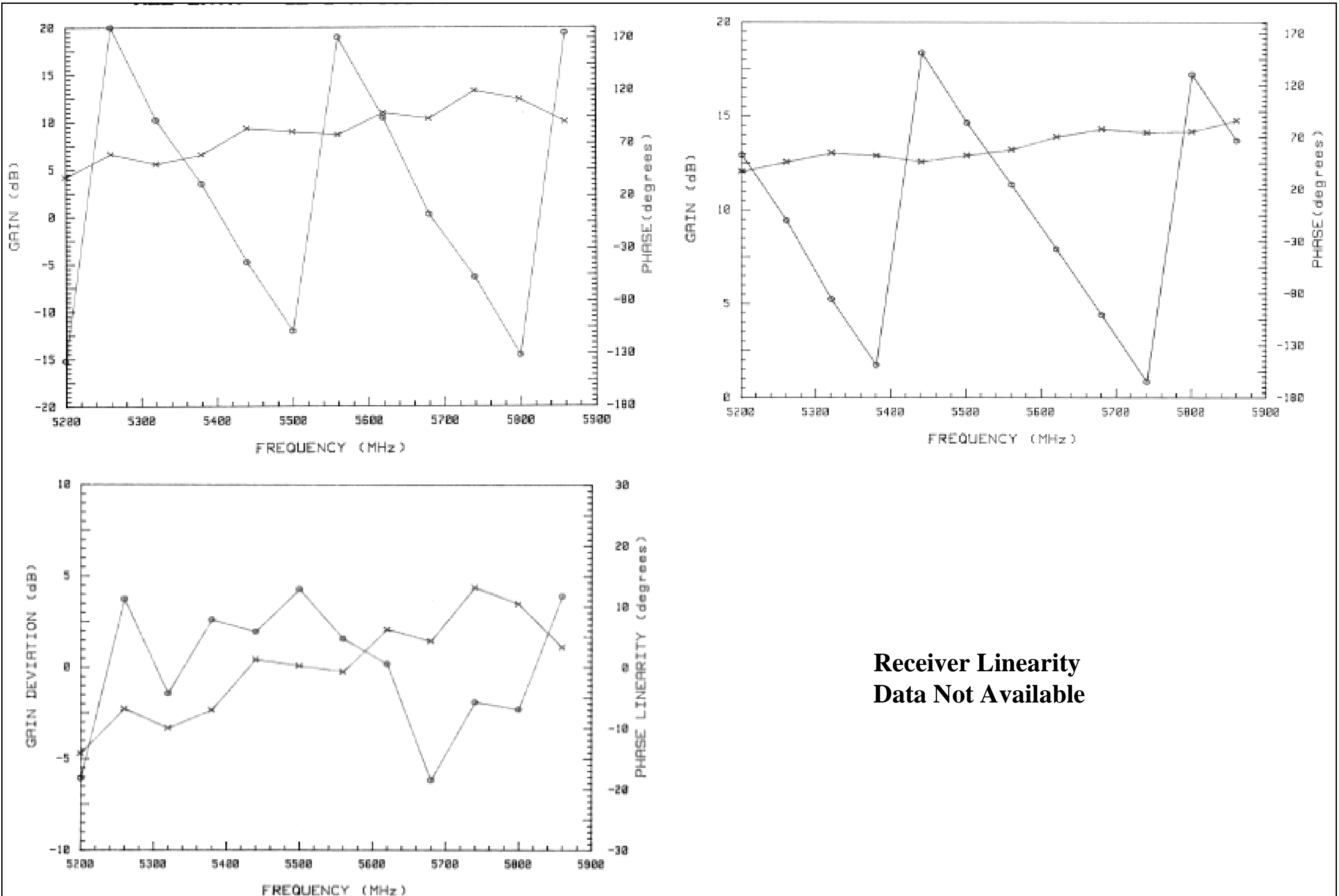


FIGURE A.45 - Phase 3 TESTING C-BAND MODULE SN118 (left) Transmit & (RIGHT) Receive