A Study of Intermodulation Interference

Due to Non-linearities in Metallic Structures

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ABSTRACT

Intermodulation products are spurious frequency components generated when two or more signals mix in devices with non-linear characteristics. In multi-frequency communications environments such as communal antenna sites, intermodulation products generated by active devices (transmitters and receivers) and passive components (metallic contacts and conductors) can cause serious radio interference. The interference caused by passive intermodulation products is a well known phenomenon and is sometimes called the 'rusty-bolt' effect.

This study is directed towards the characterisation, detection and location of external passive intermodulation interference sources at land mobile radio sites used by the UK Emergency Services. The thesis describes the development of computer-controlled passive intermodulation product measurement facilities. The laboratory and field measurement work investigates the parameters related to the generation of intermodulation products. The measurements concentrate on the lower order products and results are given for combined input powers of up to 63 W at 150 MHz. The types of test conditions and samples used are similar to a typical radio site environment.

A review of previous investigations related to passive intermodulation is presented. The various non-linear mechanisms at metallic contacts are described and the most dominant one is identified. Some analytical techniques for predicting intermodulation signals are considered and the theoretical results based on a power series model are compared with measurement results.

The basic principles of detecting and locating non-linear metallic contacts are explained. Experimental studies of audio and radio frequency detection techniques are conducted and strategies for detecting and locating external passive intermodulation interference sources are outlined.

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CHAPTER 1

Introduction

1.1 Harmonic and Intermodulation Product Generation

The work reported in this thesis is concerned with the study of radio frequency interference (RFI) caused by passive intermodulation products (PIMP) at multi-frequency land mobile radio sites [1]. In this section, the definition of harmonic and intermodulation products and an example of the generation of these products are presented. The project objective, scope of work and project approach are described in Sections 1.2 and 1.3.

Harmonic and intermodulation products are spurious signals due to the mixing of signals in non-linear active and passive components. In multi-frequency communications environments and systems, severe interference problems can occur if products fall into the passband of operating receivers. The magnitudes and frequencies of these products are related to the transfer function of the non-linear component and the magnitudes and frequencies of the injected signals. The extent of system degradation from non-linearly generated spurious signals is related to the levels of the interference signals and the relative susceptibility of the receivers.

To illustrate the generation of harmonic and intermodulation products, consider a simplified case where a non-linear passive component is excited by two unmodulated signals.

i.e.
$$V_{in} = V_1\cos(2\pi f_1 t) + V_2\cos(2\pi f_2 t) \tag{1.1}$$

where V_{in} is the input voltage, V_1 and V_2 are the amplitudes and f_1 and f_2 are the fundamental frequencies of the two signals. An n^{th} order power series as shown in equation (1.2) may be used to represent the transfer function of the non-linear component [2, 3].

i.e. $$V_{out} = K_1 V_{in} + K_2 V_{in}^2 + K_3 V_{in}^3 + \ldots\ldots \quad (1.2)$$

where V_{out} is the output voltage, K_1, K_2 and K_3 are the coefficients which depend upon the properties of the non-linear component.

Substituting equation (1.1) into (1.2) and solving gives the spectrum of V_{out}. Intermodulation and harmonic products are generated at frequencies described by the equations (1.3) and (1.4) respectively.

i.e. $$f(intermodulation) = mf_1 \pm nf_2 \quad (1.3)$$

and $$f(harmonic) = mf_1 \ \& \ nf_2 \quad (1.4)$$

where m and n are integers, either zero, positive or negative. The sum (|m| + |n|) defines the order of the intermodulation product.

The spectrum of V_{out}, shown in Fig. 1.1, consists of the two fundamental signals as well as some of the newly generated harmonic and intermodulation signals. A linear component produces no such additional frequency products. Generally, amplitudes of the intermodulation products fall off with increased order and lower order products are more likely to cause interference.

So far only a simple two-frequency case is considered. In multi-frequency environments, the interference problems can be much more serious. This is due to the co-location of many non-linear components and the large difference between some of the transmit and receive signal levels. Intermodulation interference (IMI) is not generally experienced from the even order products as they usually fall well outside of the receive bands. Many of the odd order products can also be discounted

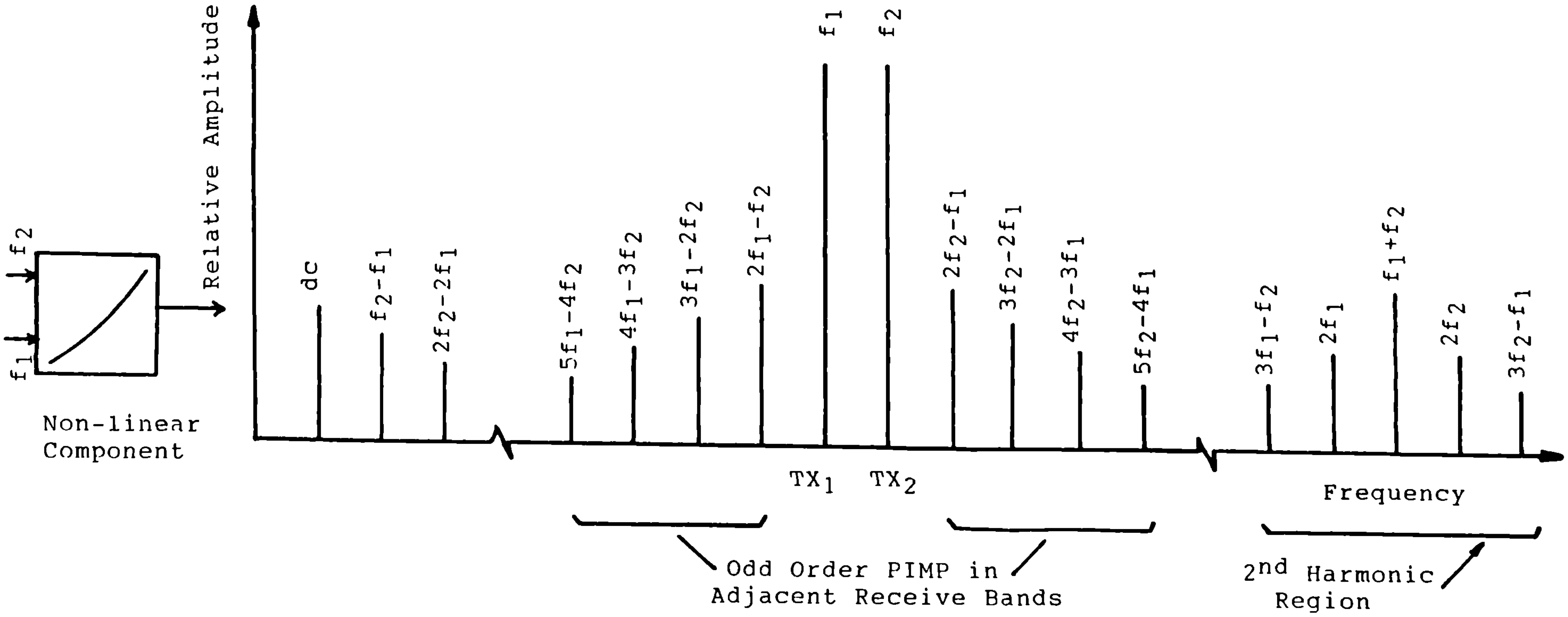

Fig. 1.1 Output Spectrum of a Non-linear Component

for the same reason. Only those odd order products, especially the lower order ones that fall into the receive bands may cause IMI. The number of intermodulation products increases very rapidly with the increase in number of transmissions [3, 4]. This is illustrated in Fig. 1.2 which shows the relationship between the number of channels and the number of odd order intermodulation products [3].

1.2 Project Objective and Scope of Work

Passive intermodulation interference can cause serious problem and its significance at the UK Home Office's radio sites has been discussed by Fudge [5]. Over the years, engineers from the Home Office have conducted several laboratory and field tests [5, 6] to study this problem and devise methods to overcome it. However, due to lack of manpower, their studies were incomplete and three UK Universities (Southampton, City and Kent) were contracted to continue the work. The work conducted at Southampton University [7] was mainly concerned with the development of algorithms to predict the intermodulation frequency spectra. The work at City University [8] was concentrated on the development of chemical agents to suppress the interference caused by rusty contacts. In Sections 2.4.7 and 5.1, there are more discussions of the studies carried out by these two Universities and the Home Office.

The work reported in this thesis is based on one of the above projects sponsored by the Directorate of Telecommunications of the UK Home Office. Its main objective was to conduct experimental and theoretical investigations into the characteristics of PIMP generated by the passive non-linearities in radio towers and nearby metallic structures (the so called 'rusty-bolt' effect). The work was directed towards the development of techniques and detectors which would allow

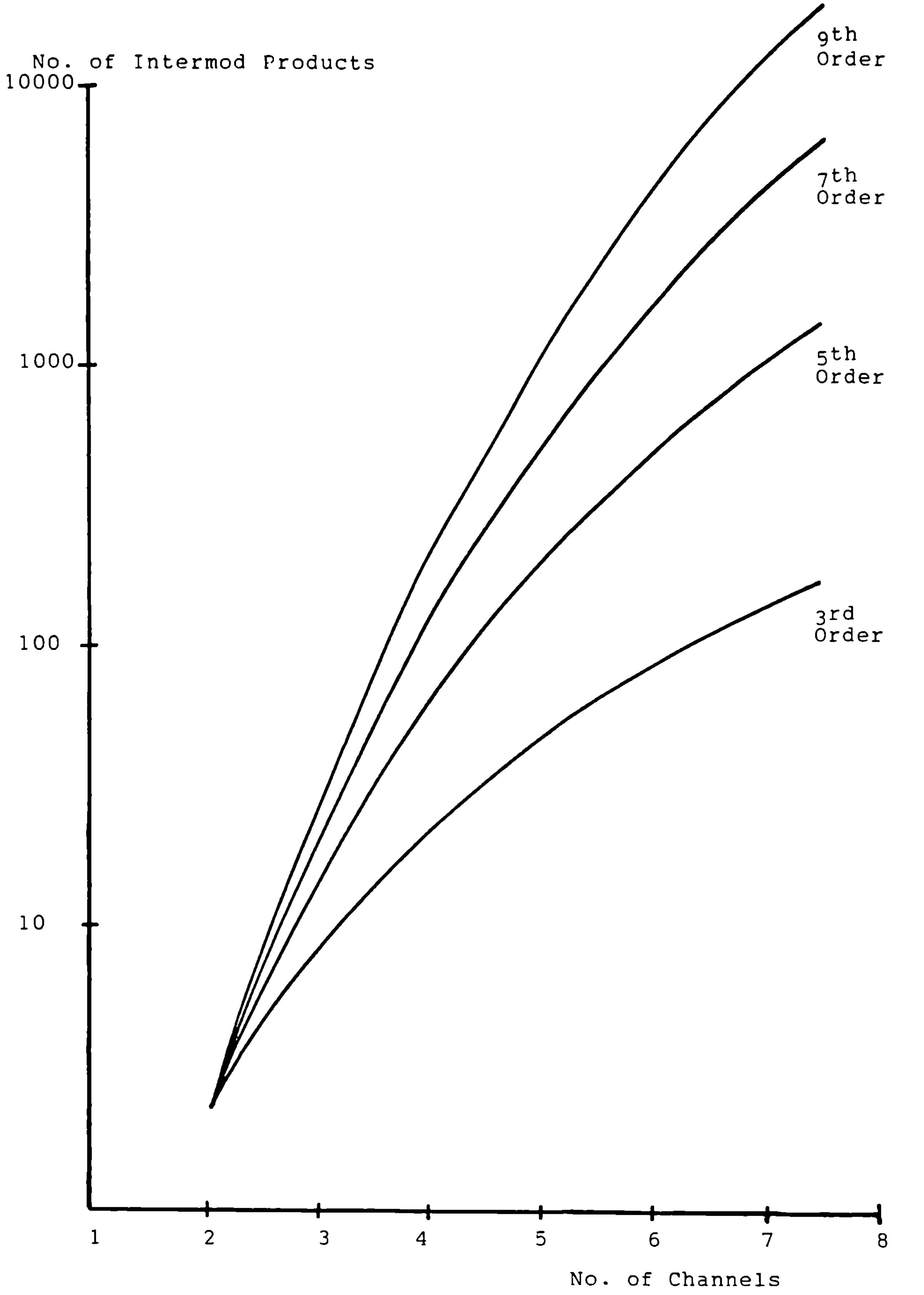

Fig. 1.2 Number of In-Band Intermod Products

field personnel to locate passive non-linearities capable of creating IMI. The study was made with particular reference to land mobile radio sites used by the UK Emergency Services and one of these sites is shown in Fig. 1.3. The laboratory and field investigations were confined to the high band VHF (143-167 MHz) of the frequency spectrum which is being used by the UK Emergency Services.

The project consists of two main topics, the laboratory and field studies of the characteristics of PIMP and passive non-linearities, and the detection and location of passive IMI sources.

The scope of work involved the following areas.

(1) A detailed literature study on topics related to PIMP and passive IMI.

(2) The design and development of PIMP measurement systems.

(3) The laboratory and field studies of the characteristics of PIMP and passive non-linearities.

(4) The analysis of passive non-linearities.

(5) The feasibility study of PIMP detection techniques and detectors.

(6) The design, development and evaluation of PIMP detection techniques and detectors.

1.3 Project Approach

A detailed literature review has been carried out to study the various approaches in investigating the passive IMI problems. The review revealed that there are basically two approaches, the theoretical approach and the experimental approach.

In the theoretical approach, a theoretical model based on the electron tunneling theory or non-linear circuit theory is built. This model is then verified by

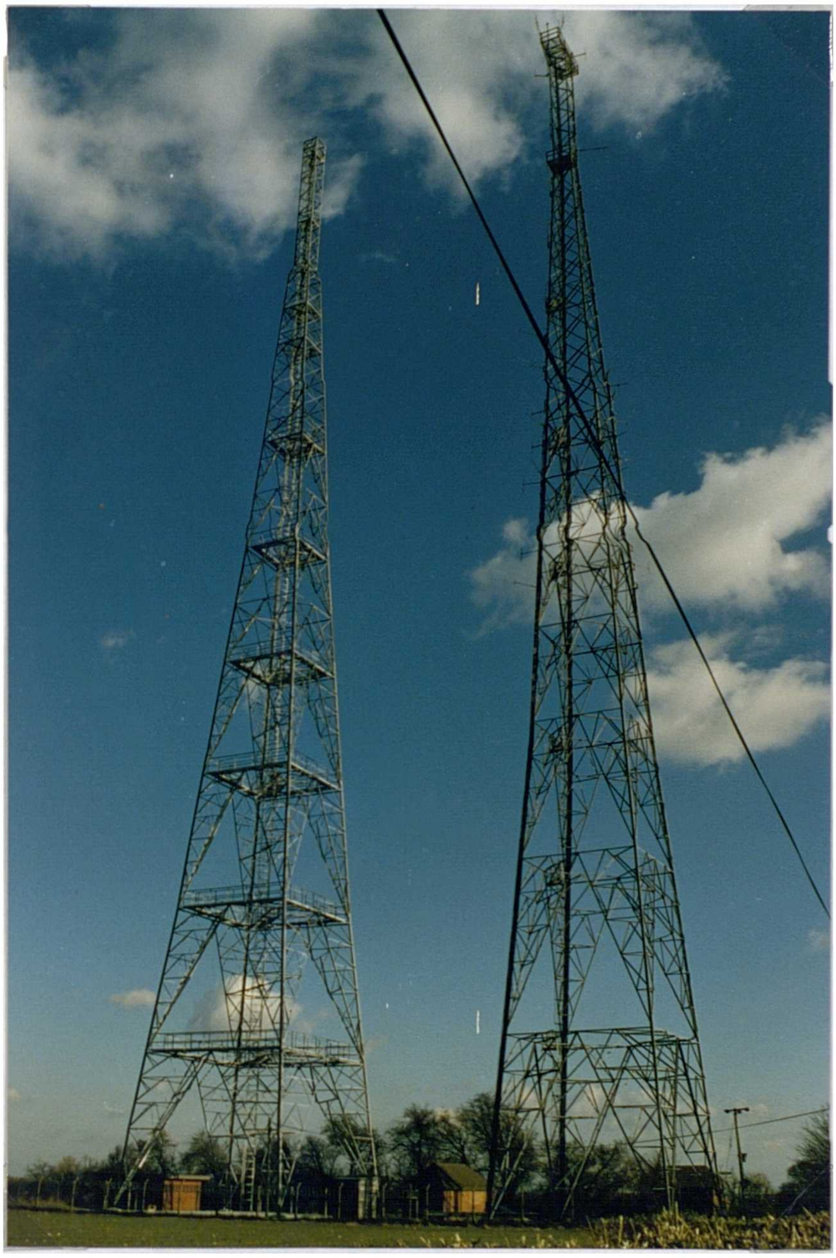

Fig. 1.3 Typical Home Office Land Mobile Radio Site

experiments performed on specially fabricated test samples. Bond et al. [9] and Higa [10] used this approach to study the PIMP generation in aluminium structures. They developed models based on the electron tunneling theory and verified them by measuring the characteristics of laboratory fabricated test samples. Some researchers develop non-linear models with lumped circuit elements such as resistors, capacitors and diodes, etc. These models are then used to simulate the 'rusty bolt' effect [11, 12]. Generally the theoretical approach either studies the microscopic mechanisms at metallic contacts or produces simulation models for predicting the level of intermodulation signals.

In the experimental approach, many commercially available components and laboratory constructed test samples are measured. The measurement results are then used to model the behaviour of PIMP as functions of various test parameters. These include the types of materials and joints, degrees of corrosion, surface conditions, input power, contact area and environmental factors, etc. This approach has been widely used by researchers and typical examples are projects conducted at the Massachusetts Institute of Technology [13], US Navy [14, 15], Georgia Institute of Technology [16, 17], University of Sheffield [18-21], University of Southampton [22, 23], Plessey [24, 25] and ERA Technology [26].

The study of approaches concluded that the experimental approach is more suitable for a project which requires practical solutions. It provides information which can be used to identify the potential IMI sources and predict the PIMP levels. It was therefore decided that this approach should be used.

Based on the experimental approach, a two-line investigation consisting of laboratory studies and field trials at a simulated radio site has been conducted. The laboratory work has been mainly based on the observations of controlled experiments. The field trials have been concerned with the characterisation and detection of passive non-linearities in a simulated radio site environment. Theoretical work has been given a lower priority than the experimental work due to the practical nature of the project.

1.4 Thesis Presentation

Most of the materials presented in this thesis are based on the seven papers [27-33] published by the author during the course of the research. The thesis is divided into eight chapters.

Chapter 1 begins with a simple example of how harmonic and intermodulation products are generated. The definition of these products is given, and the project objective, scope of work and project approach are defined. A brief comparison of the two approaches in investigating the passive IMI problems and the reasons for choosing the experimental approach are given.

Chapter 2 describes the types, causes and minimisation of IMI. A review of previous studies related to passive intermodulation in multi-frequency communications environments and systems is given [30].

Chapter 3 is concerned with the setting up of a laboratory PIMP measurement system. The system design, system hardware and software are described. The system performance and suggestions for improving the system performance are presented [29, 31].

Chapter 4 describes the laboratory measurement of PIMP. The types of test samples used and the relationships between the PIMP levels and various test parameters are presented. Conclusions are drawn with regard to the potential IMI sources [28, 29, 32].

Chapter 5 is concerned with the field measurement of PIMP. The function and design of the measurement system, test site, measurement method and test results are described. The field measurement results are also compared with the laboratory measurement results [33].

Chapter 6 begins with a description of the various mechanisms responsible for the generation of passive harmonic and intermodulation products. A brief review of various techniques used for analysing non-linearities is presented and a comparison of the theoretical and experimental results is given [32].

Chapter 7 is concerned with the detection and location of external passive IMI sources [27]. The causes of passive IMI and the basic principles of exciting, detecting and locating passive IMI sources are described. These and the experimental studies of detection techniques lead to the development of various detection strategies.

Chapter 8 concludes the research work. The research results based on experimental and theoretical studies are summarised and the suggestions for future work are made.

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CHAPTER 2

Intermodulation Interference At Radio Sites

2.1 Introduction

This chapter begins with a description of the types, causes and minimisation of intermodulation interference at radio sites. A review of previous studies related to passive intermodulation in multi-frequency communications environments and systems is presented.

2.1.1 Radio Interference

Due to the ever-growing number of radio users, increasing number of collocated radio systems and limited channels available for radio communications, radio frequency interference (RFI) has increased gradually and become a major factor to consider in design, operation and maintenance of radio communications systems. The RFI problems have been increasing at such a fast rate that it is no longer easy to operate radio equipment in an interference free environment. However, radio systems and equipment still have to be designed and operated in such a way that the interference level is kept to minimum.

The various types of interference generally can be classified as co-channel or off-frequency [1]. Co-channel interference includes transmitter noise, transmitter spurious and harmonics, transmitter intermodulation, atmospheric noise and device radiation, etc. Off-frequency interference refers to receiver selectivity, receiver desensitization, receiver spurious response and receiver intermodulation. To identify whether a particular type of interference is co-channel or off-frequency, specific test procedures and equipment are usually required.

2.1.2 Intermodulation Interference

One of the most common interference problems at a communal radio site is intermodulation interference (IMI). Intermodulation becomes an interference problem when any of the intermodulation products (IMP) generated fall into the passband of operating receivers. In a radio communications system, there are three areas where intermodulation can occur [2].

(1) The transmitter output stages, due to the non-linearity of the power amplifier circuits.

(2) The receiver input stages, due to the non-linearity of the mixer and radio frequency (RF) circuits.

(3) In metallic structures and contacts, including corroded and/or loose metallic contacts in cables, connectors, filters, antennas, tower and mast assemblies. This form of intermodulation is due to the non-linearities of materials and metallic contacts, and is popularly known as the 'rusty-bolt' effect.

When an investigation of IMI is undertaken, it is usually carried out in the above order as this is the most likely order of potential interference sources. A procedure for locating IMI sources at radio sites has been reported by Gourlay [3]. His paper explains the various tests for identifying the IMI sources and summarises the test procedures in a flow chart as shown in Appendix A. In the following sections (2.2-2.3), the causes and minimisation of intermodulation in transmitters, receivers and metallic structures are described briefly.

2.2 Active Intermodulation Interference

2.2.1 Transmitter Intermodulation

The likely place for transmitter intermodulation to occur is at a site where many transmitting antennas are located very close to each other. Mutual coupling exists between antenna systems resulting in RF signals feeding into the power amplifier circuits of other transmitters. Since most power amplifiers operate in class 'C' mode and are by nature non-linear, mixing between signals occurs and harmonic and intermodulation products are generated. These new products along with the fundamental carrier signals are then re-radiated via the antennas and may cause interference to adjacent systems. This process is shown in Fig. 2.1. Besides coupling between antennas, the mutual coupling can also occur due to the physical proximity of feeder cables and radio equipment. Any non-linear devices situated between the transmitter and antenna can also be the sources of transmitter intermodulation.

To reduce the transmitter intermodulation signal level, it is better to minimise the coupling between the antenna systems than to make the amplifier output stages more linear, as the latter will result in lower output efficiency. Proper layout of antennas can increase the isolation between transmitters. The isolation for horizontal and vertical separation at 150 MHz for a dipole antenna in vertical polarization is shown in Fig. 2.2 [4]. It can be seen that a vertical separation of approximately 3 meters between two dipole antennas can give an isolation of 40 dB as compared to 20 dB for the same separation in a horizontal plane.

Recent investigation of coupling between coaxial cables [5] has shown that the leakage from some coaxial cables can be quite high. Since most feeder cables are

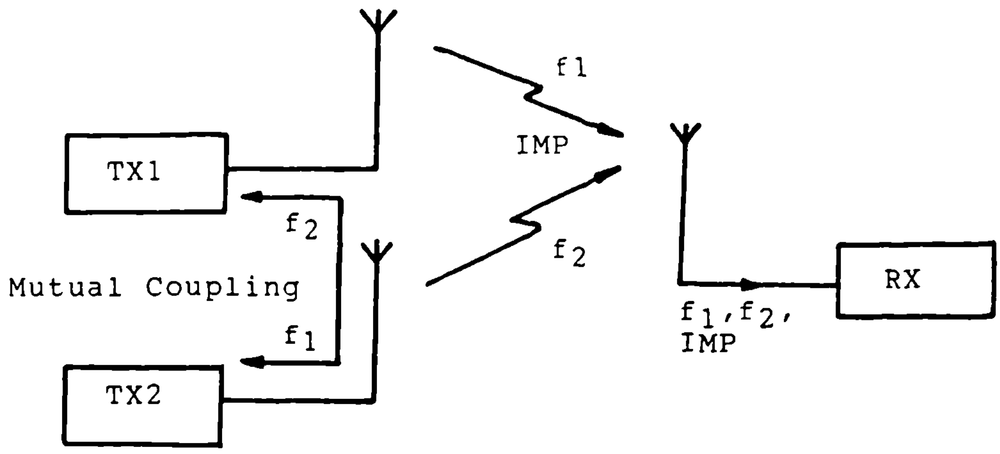


Fig. 2.1 Transmitter Intermodulation

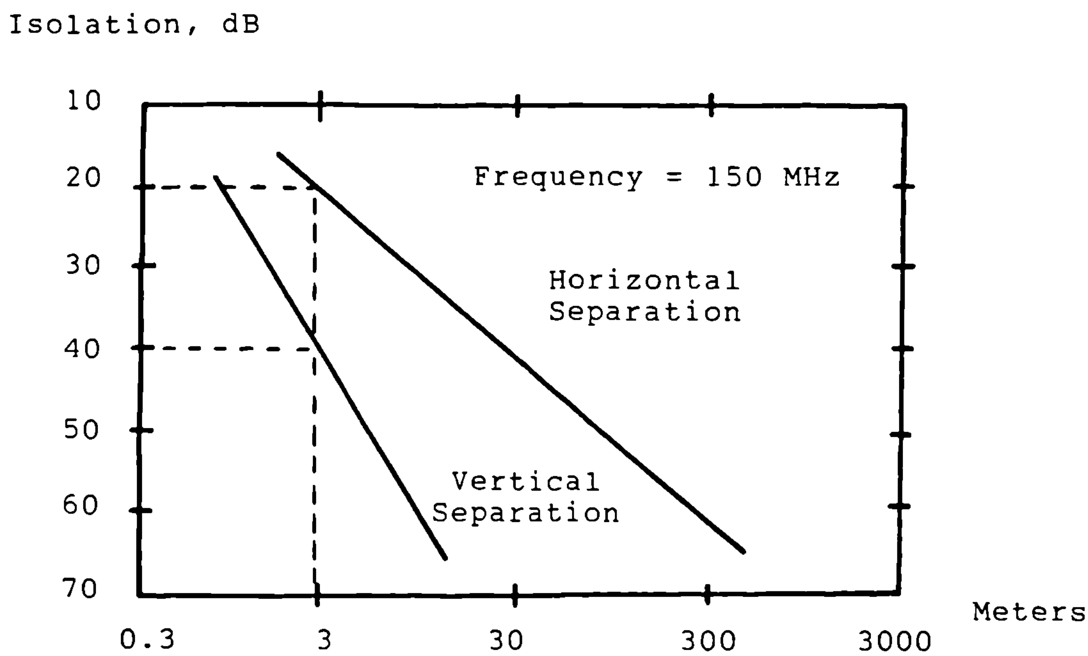


Fig. 2.2 Isolation of a Dipole Antenna

run side-by-side, there is obviously some mutual coupling between cables. To minimise such coupling, coaxial cables with good screening performance should be used, e.g. cables with solid outer conductor or double braid.

The transmitter intermodulation can be minimised by a variety of filtering techniques. Bandpass cavity and notch filters can be used between the transmitter and antenna to increase the system isolation. Isolation can also be achieved by incorporating a tuned isolator between the transmitter and antenna [6]. However, isolator is only useful in closely spaced channels (kHz), the widely separated channels will not benefit to the same degree. Under such circumstances, it may be necessary to consider a combination of isolator and bandpass filter to attenuate the unwanted signals entering the transmitter. The isolator itself may produce harmonic products due to the non-linear hysteresis effect of ferromagnetic materials [6]. To remove the harmonic products, a low pass filter is often used between the isolator and antenna. The ways of using isolators and filters to minimise transmitter intermodulation is illustrated in Fig. 2.3. In Chapter 3, there will be more descriptions of the characteristics and application of isolators in a passive intermodulation product measurement system.

2.2.2 Receiver Intermodulation

Receiver intermodulation occurs when two or more strong signals fall into the front end passband of operating receiver, shown in Fig. 2.4. These signals can drive the input stages of the receiver into non-linear mode and generate harmonic and intermodulation products. In order to minimise receiver intermodulation, the level of any signal likely to cause intermodulation must be reduced at the receiver input. This can be achieved by means of high-Q cavity filter, both of the bandpass

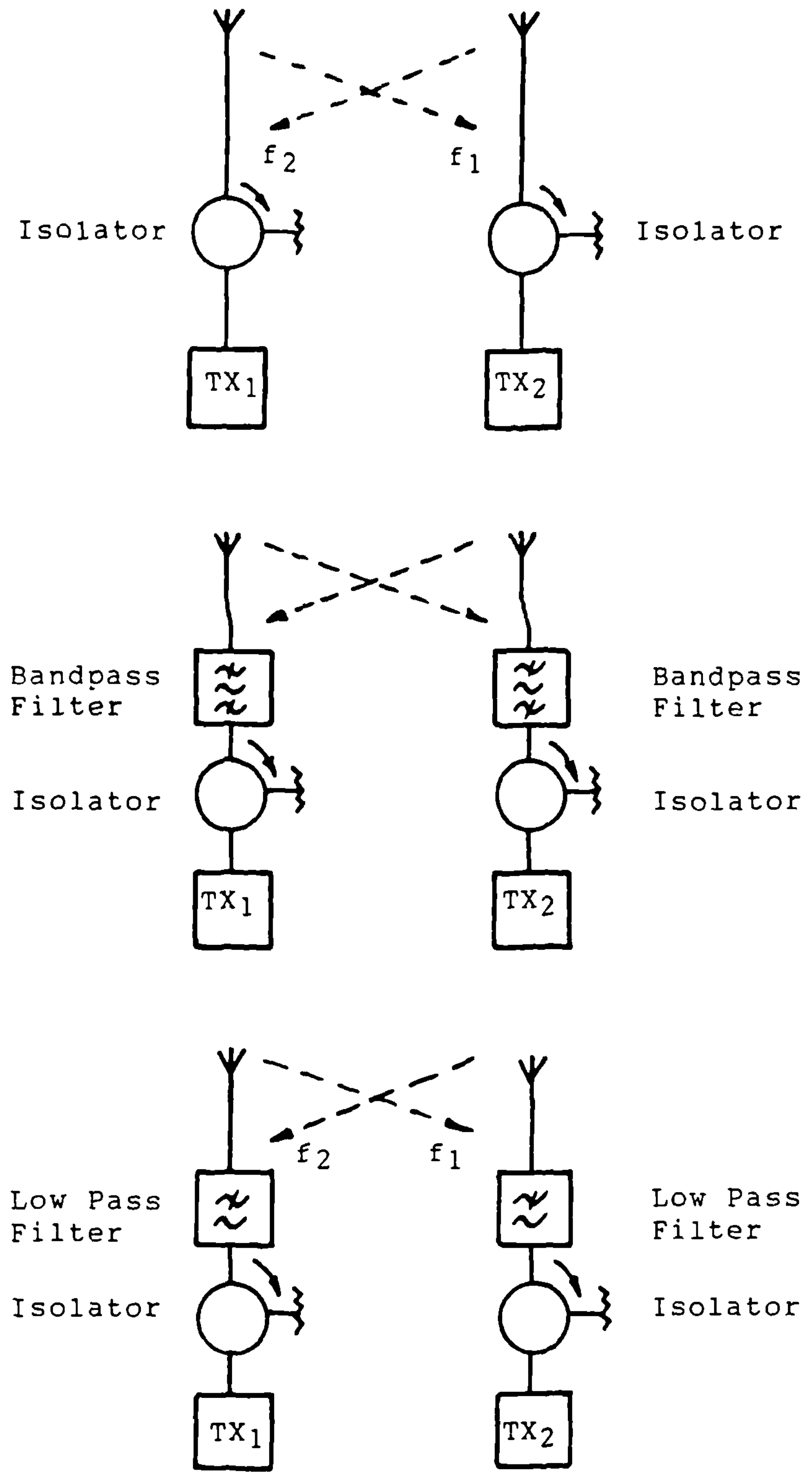


Fig. 2.3 Using Isolators and Cavity Filters to Minimise Transmitter Intermodulation

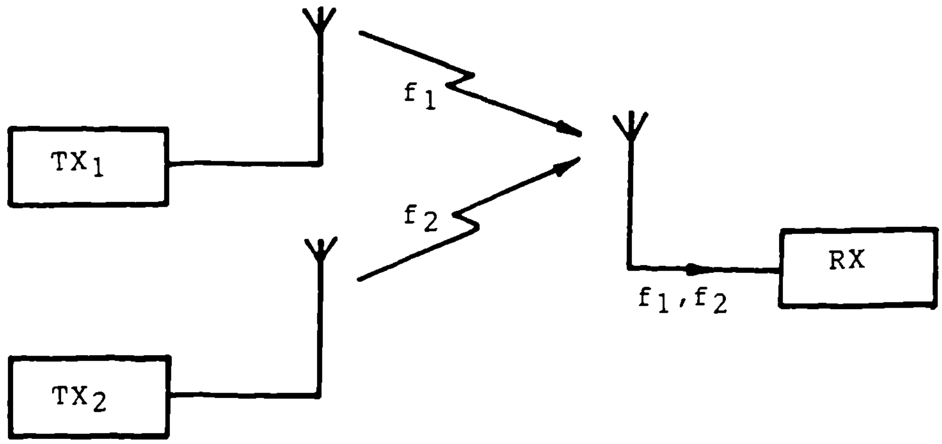
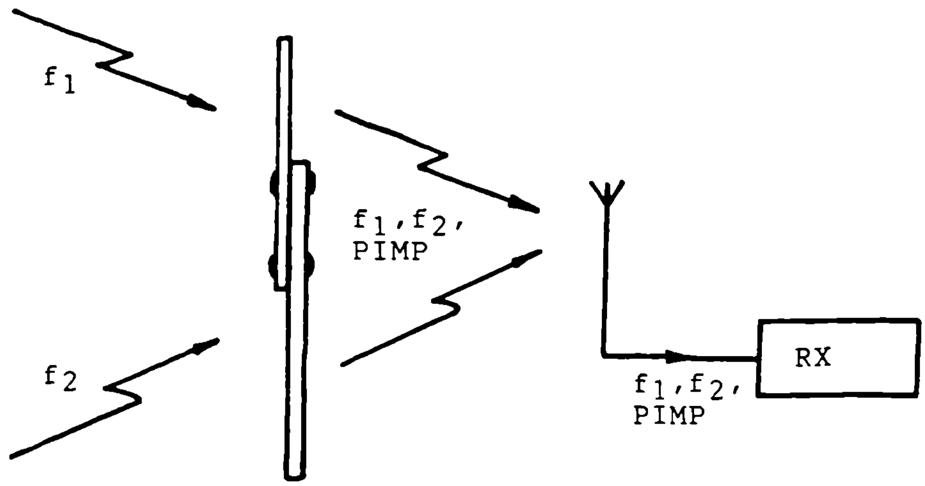


Fig. 2.4 Receiver Intermodulation



Non-linear Junction

Fig. 2.5 Passive Intermodulation

and notch type to attenuate the unwanted signals [7].

When filters are used between the receiver and antenna in the 150 MHz band, the bandpass filter is the best choice when an interfering frequency is at least 1.5 MHz from the receiver tuned frequency, and is particularly useful when there are many frequencies involved and/or the specific interference frequencies are not known. On the other hand, a notch filter is the preferred choice when the frequency separation is greater than approximately 200 kHz [4].

An attenuator connected to the input of the receiver may also be useful when the level of interference is low, and when a slight degradation in system performance is acceptable. Further protection against receiver intermodulation can be achieved by proper frequency planning, larger physical separation between the transmitters and receivers or a combination of both.

2.3 Passive Intermodulation Interference

2.3.1 Non-linear Junctions

Interference caused by non-linear metallic junctions is well known and has been widely reported [2-4] [7-11] [13-53]. It occurs in metals when currents flow through metallic junctions with non-linear current-voltage (I-V) characteristic. Harmonic and intermodulation products are generated at these junctions and they may be conducted and/or radiated by the metals themselves. This process is shown in Fig. 2.5. Non-linear junctions (NLJ) may be present in loose and/or corroded contacts in tower and mast structures, mounting components and feeders. The dc I-V responce curve of NLJ has been measured by several researchers and a typical I-V curve is shown in Fig. 2.6 [8].

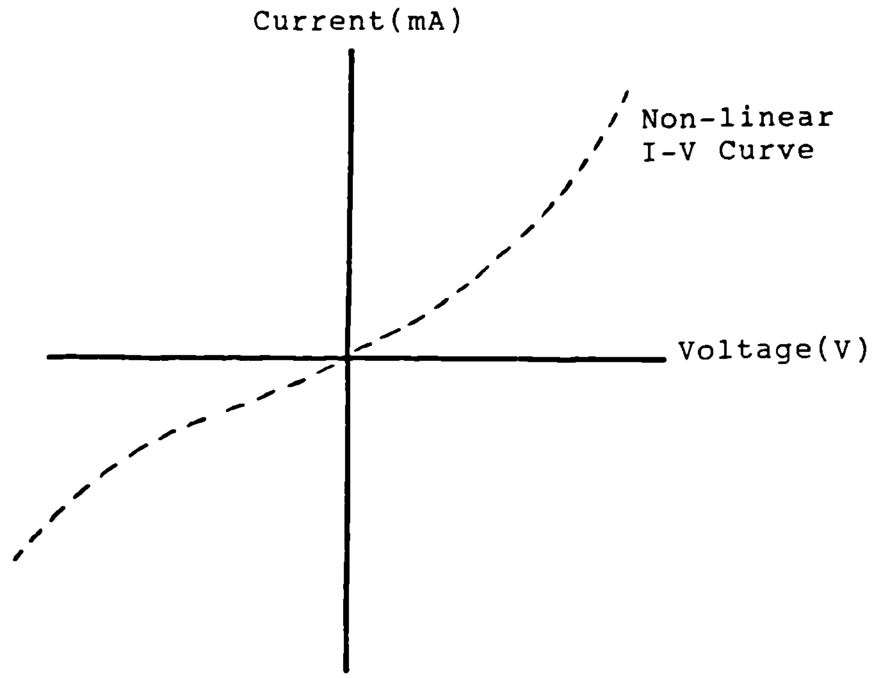


Fig. 2.6 Contact Non-linearity

Although the exact mechanisms responsible for the non-linear effect are not fully understood, the recent studies [14, 15] of passive IMI have suggested that the following causes may be responsible for PIMP generation: (i) Electron tunneling and semiconductor action through thin oxide layers separating metallic conductors at contacts. (ii) Microdischarge across voids and microcracks in metallic structures. (iii) Non-linearities associated with dirt, metal particles and carbonization on metal surfaces. (iv) High current densities at contacts and (v) Poor workmanship causing loose connections, cracks in metals and oxidisation at joints which in turn generate PIMP. In practice, the PIMP phenomenon may due to a combination of these mechanisms.

The complex mechanisms of contact non-linearity often make the prediction of PIMP level very difficult. However, experience has shown that the passive IMI level is usually lower than the active IMI level [3, 4]. The level of PIMP depends upon the transmitter signal levels, the amount of energy coupled to the non-linear component, the degree of non-linearity and the conducting and/or radiating efficiency of the non-linear component. At VHF mobile radio sites, because of the low transmitting power, passive IMI caused by the radio tower and surrounding metalwork is usually limited to the sites. However, at high power transmission sites, intermodulation signals may be detected over significant distances.

Filtering techniques as described in Section 2.2 (Active Intermodulation Interference) will not assist in minimising passive IMI. This problem is usually solved by cleaning and tightening the contacts or by-passing the contacts with short copper straps. These bonding straps must be welded or soldered at the contacts to avoid the formation of new non-linear joints. Care should also be taken to avoid resonance in these straps. Further reduction of PIMP level may be achieved by having adequate isolation between the transmitters and receivers, using PIMP free components, proper frequency planning and regular maintenance of radio sites.

2.3.2 Non-linear Materials

There are two different types of passive non-linearity exist in a radio communications environment [10, 11]. One is due to the contact non-linearity as described in Section 2.3.1 (Non-linear Junctions), and the other is due to the non-linear properties of materials. Typical examples of non-linear materials are ferromagnetic materials (e.g. mild steel and nickel) and graphite fibre (e.g. carbon fibre reinforced plastics or CFRP).

Ferromagnetic materials can generate significant level of PIMP when they are excited by two or more signals. The PIMP generation is due to the non-linear hysteresis or B-H characteristics of ferromagnetic materials [11]. The PIMP signal is stable with time and is usually stronger than that generated by a tight joint. Previous investigations have shown that components, cables and metallic structures which contain ferromagnetic materials can cause serious passive IMI to communications systems [11]. Graphite fibre is a light weight material which is commonly used for making reflector antennas. However, due to the non-linear resistivity of graphite, it can be a source of passive IMI [10, 12].

2.4 Previous Investigations of Passive Intermodulation

2.4.1 Introduction

Over the last forty years, there have been a lot of investigations of passive intermodulation in multi-frequency radio environments. To appreciate the scope of previous studies and the significance of present project, a brief review of previous investigations is presented in the following sections. This review is divided into six sections and each section is named either under a communications environment or radio components. It covers mainly the experimental aspect of the investigation, the theoretical aspect and the location of passive IMI sources are covered in Chapters 6 and 7 respectively.

2.4.2 Waveguide Components and Reflector Antennas

Microwave engineers often overlook the fact that many passive microwave components can generate significant levels of PIMP. One of the papers paying a lot of attention of this matter is the one published by Cox [13]. Cox's paper describes a measurement circuit to measure the 3^{rd}, 5^{th} and 7^{th} order intermodulation signals generated in waveguide components of a 6 GHz communications system. Tests were conducted on waveguide joints, flexible waveguides, isolators and circulators. The measurements revealed that loose waveguide joints and waveguide tuning screws can generate 3^{rd} order PIMP level as great as -25 dBm when using two 30 dBm transmitters. The sources of mixing products in the flexible waveguides were found to be mainly in the transitions between the flanged joints and flexible waveguides. In all cases observed, the loose metallic joints were found to generate erratic and high levels of intermodulation signals.

Detailed investigations of the generation of PIMP in feeds, filters and microwave components used in a multi-carrier system with high-power transmitters and low-noise receivers have been reported by Chapman et al. [14] and Rootsey et al. [15]. They developed a measurement set-up capable of delivering microwave power up to 10 kW and detecting intermodulation signals down to -140 dBm in the 8 GHz band. The PIMP levels were measured as functions of total input power, proportional power between carriers and waveguide current densities. The specific problems encountered in fabricating waveguide components and their relationships to intermodulation generation were studied. Specific emphasis was given to flanges, tuning devices, seams, materials and the degeneration of these components with time. They also studied the physical mechanisms responsible for the generation of PIMP at metallic contacts. The measurements revealed no correlation between the PIMP levels and materials used in feeds. However, the PIMP levels were related directly to how the metals were joined together, the quality of the mating surface finishes, the pressure at the junction, and the quality and cleanliness of the brazing or soldering process. A simple non-linear model was built and compared with experimental results. Guidelines for designing low PIMP microwave systems were suggested.

The recent work of Kumar [16] concentrates on the passive IMI problems in high-power satellite systems. Kumar's paper describes the causes of PIMP and summarises the design guidelines for minimising the generation of PIMP in RF components and systems.

Nuding [17] investigated the non-linearities of flange connections in transmission lines carrying high RF power. A test facility was developed to test flanges up to 1 kW in the 2 GHz band. Measurements revealed that with input power up to 500 W, the amplitudes of the 3^{rd} order PIMP vary according to the third power of the applied signal power. Above 500 W, the input and intermodulation relationship does not follow the same relationship. The main cause behind this disagreement was not explained.

In the 70's, Matos [18] published a short review paper on PIMP generation in waveguide joints, coaxial cables and circulators. Matos's paper summarises the investigations carried out by Young [11], Cox [13], Rootsey et al. [15], Bayrak and Benson [24], and Betts and Ebenezer [40].

Large reflector antennas are usually fabricated by assembling a large number of small aluminium panels onto a large structure. In NASA Deep Space Network antennas, the difference between the transmit and receive signal levels can be as large as 250 dB. Under such conditions, the intermodulation signals generated by aluminium joints can cause serious passive IMI. Higa [19] investigated this problem and gave a detailed discussion of the mechanisms responsible for the PIMP generation. He developed a model based on the electron-tunneling theory and performed laboratory experiments at around 2 GHz to support his model. His paper also describes the electron-tunneling phenomenon in terms of an antenna structure and analyses the antenna as a non-linear circuit element.

However, Higa's work was commented on by Guenzer [20] and there was a disagreement as to the correct form of tunneling equations used. In the late 70's, Bond, Guenzer and Carosella [21] investigated the generation of PIMP due to electron-tunneling through aluminium-oxide films on aluminium reflector antennas. Their paper describes the tunneling theory and the fabrication of thin film aluminium-oxide tunneling junctions. The current-voltage (I-V) and capacitance characteristics of these junctions were measured. A test facility was developed to measure the 3^{rd} order (290 MHz) intermodulation signal. The PIMP levels were correlated with the junction parameters and tunneling theory. Measurements revealed that oxide surfaces with implanted metallic ions are more conductive and linear than ordinary oxide surfaces.

The non-linearity of graphite fibre has been studied theoretically by some researchers [12]. In the 80's, Lee [10, 22] developed a VHF measurement system to characterise graphite fibre and other non-linear materials. A half-wavelength long coaxial line was designed to accommodate test sample which forms the inner conductor of the coaxial line. He concluded that graphite fibre generates high levels of intermodulation signals. At around the same time, Watson [42, 43] of Plessey also investigated the non-linearity of carbon fibre composite (CFC). He used an experimental set-up which is different from Lee's system [10, 22] and showed that jointless CFC materials are linear, but jointed CFC panels generate harmonic products.

2.4.3 Coaxial Cables, Connectors and RF Components

In the 60's, researchers at IIT Research Institute in Chicago studied the nonlinearities of cables, connectors, dummy loads and metals [23]. They discovered that ferromagnetic materials such as nickel and stainless steels generate harmonic and intermodulation products, and the product levels increase as a function of current density. Distributed loads such as long lengths of coaxial cable were found to be more linear than lumped loads.

In the 70's, several researchers in England studied the non-linear effects of cables, connectors and metals in the microwave bands [24-30]. First Bayrak and Benson [24] made a detailed experimental study of the non-linear effects at contacting surfaces between similar and dissimilar metals. An S-band experimental set-up was designed to measure the 3^{rd} and 5^{th} order intermodulation signals. Contact materials of commercial copper, brass, mild steel, aluminium alloy, stainless steel, nickel and electroplated contacts of gold, silver, copper and tin were studied under various test conditions. Test samples were fabricated in three different forms (i.e. surface, spherical and point) with different contact areas. They also carried out preliminary measurements on coaxial cables with various types of construction and a variety of coaxial and waveguide components. Bayrak's work was later continued by Sanli [25]. Sanli improved Bayrak's experimental set-up and tested samples with mechanically polished, electropolished and oxidized surfaces. Arazm's work [26] is similar to those carried out by Bayrak. He tested a variety of metals including some home-made steels at frequencies around 1.5 GHz. The 3^{rd} and 5^{th} order intermodulation signals were measured as functions of the types of metal, input power levels and axial force applied to the metallic contacts. Arazm's work was later extended by Sanli [27].

Amin and Benson [28, 29] measured the odd order PIMP levels of commercially available and specially constructed coaxial cables at L-, S- and C-band frequencies. The parameters studied include composition of braid materials, lengths of cable, types of inner conductor and braid construction, number of braids, braid filling factor, discontinuities and corrosion in the braids, fundamental frequencies and ambient temperature. They observed that the ambient temperature in the case of polythene dielectric cables and oxides on copper-wire braids affects considerably the generation of PIMP in a coaxial cable. The composition of the braid materials is by far the most important parameter in PIMP generation.

Martin of ERA [30] studied the PIMP generation in bulk materials, cables and connectors in the HF and UHF bands. He developed a simple test bench and investigated the effects of surface films, RF power, contact pressure, effect of frequency and ageing on PIMP generation. Problems in cables, connectors and structures were outlined and some suggestions were made as to how to reduce them. Many of the conclusions drawn by Martin are similar to those reported by researchers at the University of Sheffield [24-29].

Young's investigation [11] concentrates on the ferromagnetic non-linear effect in adaptors and connectors. He developed a low-noise VHF test set to characterise a large number of commercially available RF components. The non-linear effect of stainless steel, nickel plating and hermetic seal was studied. He also measured the PIMP levels as functions of the magnetic field strength, RF power and types of metals.

In the 80's, the passive IMI problem in cables and connectors was again studied. Shands, Woody and Denny of Georgia Tech [31, 32] tested 83 samples made from various coaxial cables, connectors and cable-connector combinations. Samples were measured at frequencies from 22 MHz to 450 MHz and at input power levels up to 126 W. Empirical models were developed as functions of various test parameters and then verified by measuring new samples.

A recent paper by Kellar [33] describes the measurement system, experiments and test results of corroded and loose connectors used in the cable television system. The results obtained are similar to those reported by Bayrak and Benson [24].

The investigations described so far have concentrated on coaxial cables, connectors and waveguide components. Gardiner et al. [34] investigated the PIMP generation in typical multicoupler components. Two areas have been identified as possible sources of passive IMI: (i) The aluminium interfaces at cavity walls. (ii) The bimetallic interfaces such as the helix or centre conductor to cavity wall, connectors to outer case, copper sheet to cavity walls, etc. A VHF measurement system was developed to compare the PIMP levels generated by specially made reference components and standard components. Measurements revealed that the standard components generate stronger intermodulation signals and could be the potential IMI sources at radio sites.

2.4.4 Ship Environment

One of the earliest papers on passive IMI in a ship environment was published by Blake [35]. He conducted field experiments in the VHF band on a wooden test tower and a naval vessel. Results revealed that the interference signals were generated at the tie plates and bolts of the wooden tower. These signals could also be reproduced by touching together any two pieces of corroded metal. The effect was found to be very strong if the length of metal was approximately a multiple of one half-wavelength. During the field trials, the footropes, pulley shackles and a loose aerial rod aboard the vessel were identified as principal interference sources.

Mason's paper [36] describes a method for measuring the spurious signals generated by a multiple HF system radiating from a common aerial aboard a ship. He observed that the residual PIMP level changed considerable from day to day. He associated these variations with the changes in atmospheric conditions and the unstable properties of non-linear contacts.

A large scale project which involved laboratory and field experiments and the development of passive IMI detection techniques on naval vessels was carried out by the US Navy in the late 60's [37-39]. It was concerned with the narrowband multiple-transmission communications system. Research efforts were directed towards an assessment of the relative intermodulation contribution of the two non-linear mechanisms. Results revealed that using the PIMP/input power relationship is not a reliable way to separate the contact non-linearity from the ferromagnetic non-linearity. Laboratory experiments showed that loose contacts generate much stronger and less stable PIMP signals than those generated by steel. Field trials indicated that ferromagnetic non-linearity probably accounts for a significant proportion of the residual PIMP level associated with the clean ship. In all cases observed, the most significant passive IMI sources located are the loose and/or corroded metallic joints [38, 39].

A paper by Betts and Ebenezer [40, 41] describes the set-up and results of a laboratory investigation in which steel samples were tested in the HF band with known field strength and orientation. Attention has been given to the PIMP level dependence upon surface preparation, which includes machined and polished, electro-deposited cadmium, cold sprayed zinc finishes, corroded and clean surfaces. A comparison of PIMP levels for various types of steel was made. The main purpose of the field trials was to determine whether the ship structure is a significant interference source, and the possibility of separating it from the contact non-linearity.

The recent work of Watson [42, 43] concentrates on the measurement of harmonic and intermodulation products generated by metallic and carbon fibre junctions in structures. His papers describe a 100 MHz to 8 GHz harmonic backscatter free space measurement system and a HF intermodulation detection system to characterise passive non-linearities. He also developed a laboratory waveguide test jig to measure the properties of non-linear junctions and materials. Measurements revealed that joined metallic objects such as lengths of rigging including shackles and eyebolts generate significant harmonic products, but the bulk and jointless materials generate no measurable harmonic products.

2.4.5 Aircraft Environment

The PIMP generated by aircraft passive components and structures have been operationally and experimentally shown to be large enough to degrade system performance. In a surveillance aircraft where high-power transmitters and sensitive receivers are collocated, the problem can be very serious [44, 45]. Shands and Woody have investigated the non-linearities of coaxial cables and connectors used on aircraft [31, 32]. Recently they have investigated the PIMP generated by aircraft structures [46]. Test samples which closely resemble the actual aircraft panel joints were constructed. The 3^{rd} order intermodulation signals were measured from 20 MHz to 1100 MHz with typical input power of 44 dBm. The relationships between the PIMP levels and various parameters such as vibration, temperature, pressure, input power, frequency, types of joint and metal, chemical treatments and sealants were studied. A model based on the experimental data was built to describe the PIMP behaviour as a function of some of these parameters.

2.4.6 Spacecraft Launching Site

In the 60's, the passive IMI problem was discovered at the NASA Kennedy Space Centre. Preliminary tests indicated that the IMI was created in the environment external to the space vehicle; namely the service structure and umbilical tower. Investigators from IIT Research Institute were called in to conduct theoretical and experimental investigations [47]. They studied the non-linear effect of steel and the behaviour of non-linear junctions at VHF frequencies. The paints used on the tower were also investigated. Results revealed that the paints are linear, however, steel generates high PIMP level and should not be used as a material for constructing antennas. The significant IMI sources located were found to be loose metallic contacts such as the metallic chains, bundles of armoured cables and sliding panels.

2.4.7 Land-Based Radio Sites

The IMI problem caused by the 'rusty-bolt' effect at land-based radio sites is very well known and has been widely reported [2-4] [7-9] [48-53]. However, the amount of serious investigation carried out in this area is less than that carried out in other areas (see Sections 2.4.2-2.4.4). In the mid 70's, Betts [49] explained the significance of the 'rusty-bolt' effect in mobile radio communications systems. A few years later, Betts and Debney [50] measured the 'rusty-bolt' effect at three VHF land mobile radio sites. Their measurements revealed that with typical transmitter level of 32 W, the intermodulation signals generated due to antennas, tower structures and surrounding metalwork are negligible. However, at higher transmitter power, 500 W, the 'rusty-bolt' contribution was measurable up to the 11^{th} order intermodulation.

At Bradford University, Mawjoud and Gardiner [8] measured the dc I-V characteristic of corroded metallic joints and modelled them as two back-to-back diodes with and without added resistance. They also carried out field measurement of a simulated corroded joint and the results agree to those reported by Sturton [9] and Shepherd [48].

The recent work at City University [51] concentrates on the development of chemical compounds to suppress the 'rusty-bolt' effect. A VHF laboratory measurement system and a remote control field data acquisition system have been developed to evaluate the performance of the chemical compounds. Samples such as gold, platinum, copper, steel and corroded steel were fabricated in the form of a small tube for laboratory test.

The UK Home Office [52, 53] also conducted laboratory and field investigations of the 'rusty-bolt' effect at land mobile radio sites. The field measurement [52] studied the relationships between the PIMP levels and the polarisation, transmitter configuration and audio impairment. The laboratory test [52] studied the PIMP and input power relationship, spectral density of PIMP and the audio impairment caused by PIMP. In all the laboratory measurements, tests were conducted without using any real samples, the passive non-linearity of the measurement system was used to simulate the 'rusty-bolt' effect.

2.5 Summary

There are two types of IMI in multi-frequency communications environments and systems. The active IMI is known to be a more serious problem but can be minimised by well developed techniques. However, the equally well known passive IMI problem can not be minimised by the same techniques. From the recent published literatures, it can be concluded that the passive IMI problem is increasing in many radio communications systems and there is no evidence that this problem has been solved.

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CHAPTER 3

Laboratory Measurement System

3.1 Introduction

Over the last thirty years, many laboratory and field measurement systems have been developed for the study of passive intermodulation [1-21]. Generally these systems can be classified into either non-radiating or radiating types. The former are suitable for investigating items such as non-linear materials, connectors, cables, filters and waveguide components. They are normally housed in a screened room or laboratory, terminated by a matched load and ideally no energy is radiated. On the other hand, the latter are suitable for investigating radiating structures such as antennas, feeds and large structural components, and are normally situated in an anechoic chamber or an open field test site. The non-radiating system is more widely used because the user has better control over the test parameters and environment. In contrast, the radiating system can be affected by the local signal environment. However, for certain tests a radiating system is essential.

Measurement systems can further be classified according to the test frequency, i.e. audio, microwave and radio.

(1) Audio frequency systems, for testing electronic components such as resistors, capacitors, diodes and audio connectors [1, 2].

(2) Microwave frequency systems, for testing microwave components such as waveguides, filters, antennas, coaxial cables and connectors [3-10].

(3) Radio frequency systems, for testing radio frequency components such as multicouplers, coaxial cables and connectors [11-21].

Although the configurations, components and test equipment of these systems are different from one another, the design is usually based on the two-frequency technique, that is two signals are used to excite the sample and the intermodulation signals generated are filtered and measured. In this chapter, the development of a high band VHF laboratory measurement system for characterising passive non-linearities in metallic structures is described. The system requirements, design considerations, system hardware and software, system performance and system improvement suggestions are presented.

3.2 System Requirements and Design

3.2.1 System Requirements

The function of a laboratory measurement system is to allow the study of various parameters that affect the generation of PIMP in metallic structures under a controlled environment. To set up such a system, the following requirements were identified.

(1) It should have the capability of testing a variety of structural components and metallic joints.

(2) It should have good linearity and low residual intermodulation level.

(3) It should have the capability of exciting the non-linearities in metallic structures and detecting the low level intermodulation signals.

(4) It should have the flexibility for performing a variety of tests and the capability of processing the test data.

(5) It should not cause interference to other systems.

(6) It should be designed in such a way that it is relatively easy to exchange

test samples.

(7) It should have a simple configuration and could be set up with standard equipment.

3.2.2 Signal Excitation and Detection

In this section, the various ways of exciting test samples and detecting intermodulation signals are considered. In a radio environment or system, the passive non-linearities in metals and materials are usually excited by energy coupled by conduction or radiation. The non-linearities in connectors, cables, antennas and components which form part of the conducting system are excited by conduction energy. However, the non-linearities in radio towers, support and mounting components which are situated in the vicinity of the transmitting antennas are normally excited by radiation energy.

Two ways of exciting the test samples have been considered. A test sample could either act as a parasitic element or form part of a conducting system, which makes it an active element. Betts and Ebenezer [11] have developed a HF measurement system which could excite a small test sample both as an active element (parallel-line excitation) and a parasitic element (solenoid excitation). Since this project was concerned mainly with the study of non-linearities in structural components, it was considered appropriate to excite the test sample as a parasitic element. However, there are two problems associated with this method. First, it requires high power to excite a large test sample and this may exceed the power rating of some equipment, such as the amplifiers, cavity filters and isolators. Second, the immersion of a large test sample in the excitation field changes the field pattern and magnitude and this could complicate the system design.

A study concerning the various ways of exciting a test sample concluded that the intermodulation signals are independent of the excitation methods [11]. It was therefore decided that the simple and widely used active method [1-9] [11-21] would be used. The signal detection method is related to signal excitation method. If a test sample is excited by radiation energy, a probe or antenna is usually used to detect the radiated intermodulation signals [11]. However, if a test sample is excited by conduction energy, the detection could be done by line connection at the output of the test sample [1-9] [12-21]. In our system, a 20 dB coupler, three cavity filters and a test receiver were connected as shown in Fig. 3.1 to detect the 3^{rd} order intermodulation signal.

3.2.3 System Design

Passive intermodulation product measurement systems can be designed in many ways [1-21]. The system configuration depends upon the system requirements and equipment used. The measurement system developed by the author was constrained by the availability of equipment, time and funds. Equipment such as the signal generators, power amplifiers, isolators, cavity filters, power meters and dummy loads were borrowed from the UK Home Office. The test receiver and computer system were specially purchased for the project. Other components such as the couplers, test chamber, new power meter and distributed loads were either purchased or built during the setting up of the system.

Most of the systems developed by other researchers suffered from limitations in terms of measurement flexibility, sensitivity and the capability of handling a variety of test samples [1-21]. The system developed by the author, as described in the following sections, was intended to minimise these limitations and meet the

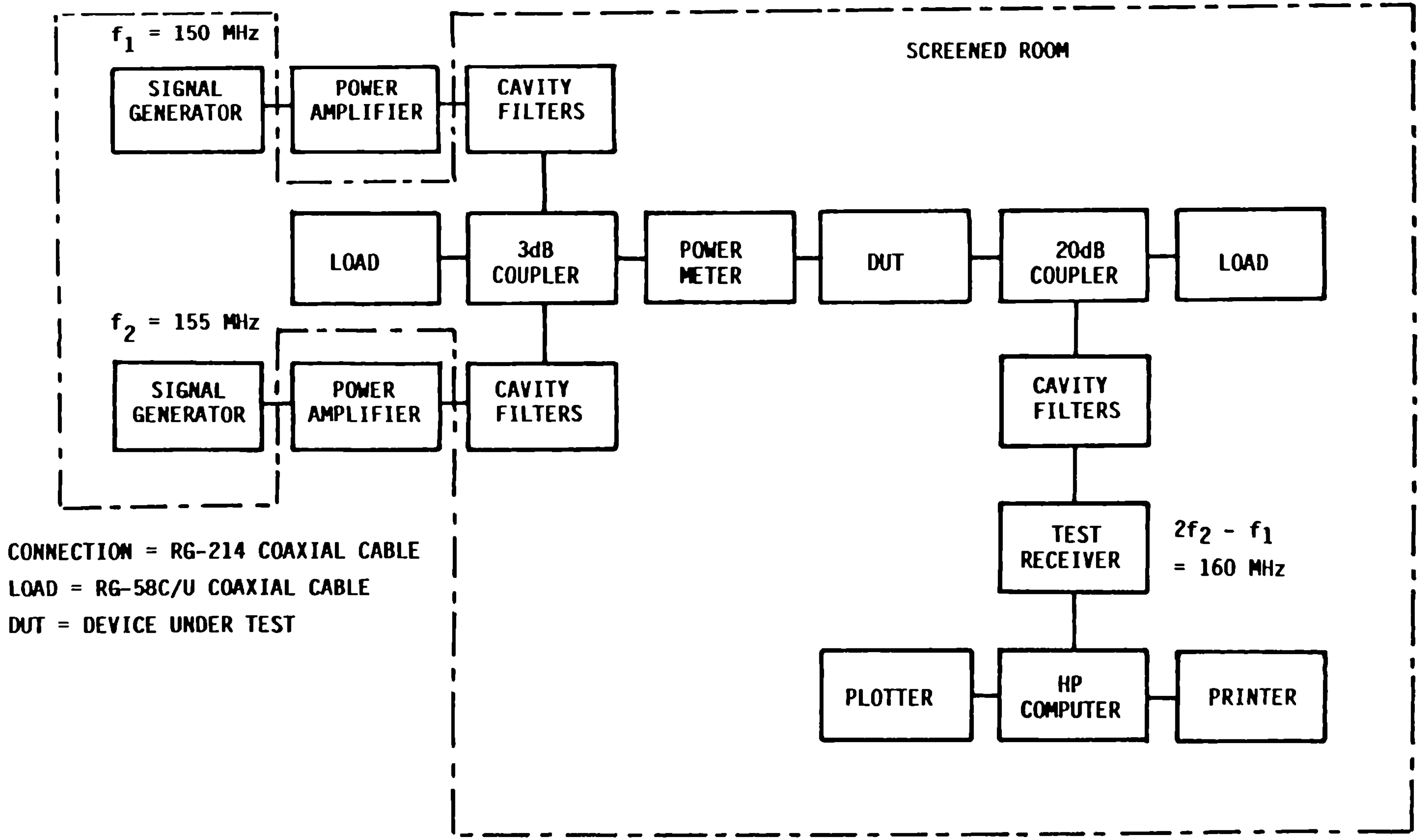


Fig. 3.1 Block Diagram of PIMP Measurement System

stated requirements. The main practical feature of it, besides the computer-controlled facilities, is its capability of handling a variety of test samples and its wide dynamic range.

The information described in this section has been published [22]. The block diagram of the measurement system is shown in Fig. 3.1. Two unmodulated signals (150 and 155 MHz) produced by synthesised signal generators were amplified by high-power linear amplifiers. Two high-Q bandpass cavity filters were used in each transmission arm to remove the unwanted signals and provide isolation between the two sources. A broadband (150-300 MHz) 3 dB coupler was used as a signal combiner, combining the two signals and providing an additional 30 dB isolation to the two sources. The combiner load was provided by a 300 meter length of RG-58C/U coaxial cable. The forward power, reflected power and Voltage Standing Wave Ratio (VSWR) were monitored by a through-line power meter. A broadband (150-300 MHz) 20 dB coupler with RG-58C/U coaxial cables as distributed loads was used as a signal sampler. Its functions were to sample the output signal, protect the receiver and terminate the forward and reflected power. The 3^{rd} order intermodulation signal (160 MHz) generated by the test sample was filtered by three high-Q bandpass cavity filters. For detection, a test receiver was used in preference to a spectrum analyser because of the need for good selectivity, sensitivity and dynamic range. The detailed discussion of the use of a test receiver for radio interference measurement is available in a recent publication [23]. Repetitive measurements were simplified by the use of a computer system to control the receiver and process the data. All components except the two high-power amplifiers were housed in a screened room to minimise radio interference. Double braid, silver plated RG-214U coaxial cables and silver plated N-type connectors were used for making connection cables. The number of connections was kept to minimum to minimise the generation of intermodulation signals. Care has been taken to ensure all the current paths were clean and free of ferromagnetic materials because dirty contacts and ferromagnetic materials can generate strong intermodulation signals [6, 19].

Two test chambers have been designed to accommodate a variety of test samples. The larger cylindrical chamber design is based on a half-wavelength transformer and can accommodate large structural components of up to 1 m long. The smaller chamber was internally dimensioned as a 50 ohm rectangular coaxial line for thin sheet samples. Both test chambers were designed to match the 50 ohm system impedance. Samples for test were soldered to the centres of the enclosed test chambers to avoid additional non-linear junctions.

3.3 System Hardware

The following sections describe the components used (see Fig. 3.2 – 3.6) for setting up a passive intermodulation product measurement system.

3.3.1 Signal Generators and Amplifiers

Two stable, clean and high power VHF signals were used to excite the test sample. The signal separation was chosen to be 5 MHz so that the comparison of system performance could be made with a system which has similar equipment and a 5 MHz signal separation [20]. The two transmit signals (150 and 155 MHz) and the 3^{rd} order intermodulation signal (160 MHz) were chosen to fall within the bandwidths of the two couplers (150-300MHz) and other equipment.

Two Marconi Instruments synthesised signal generators as shown in Fig. 3.2 were

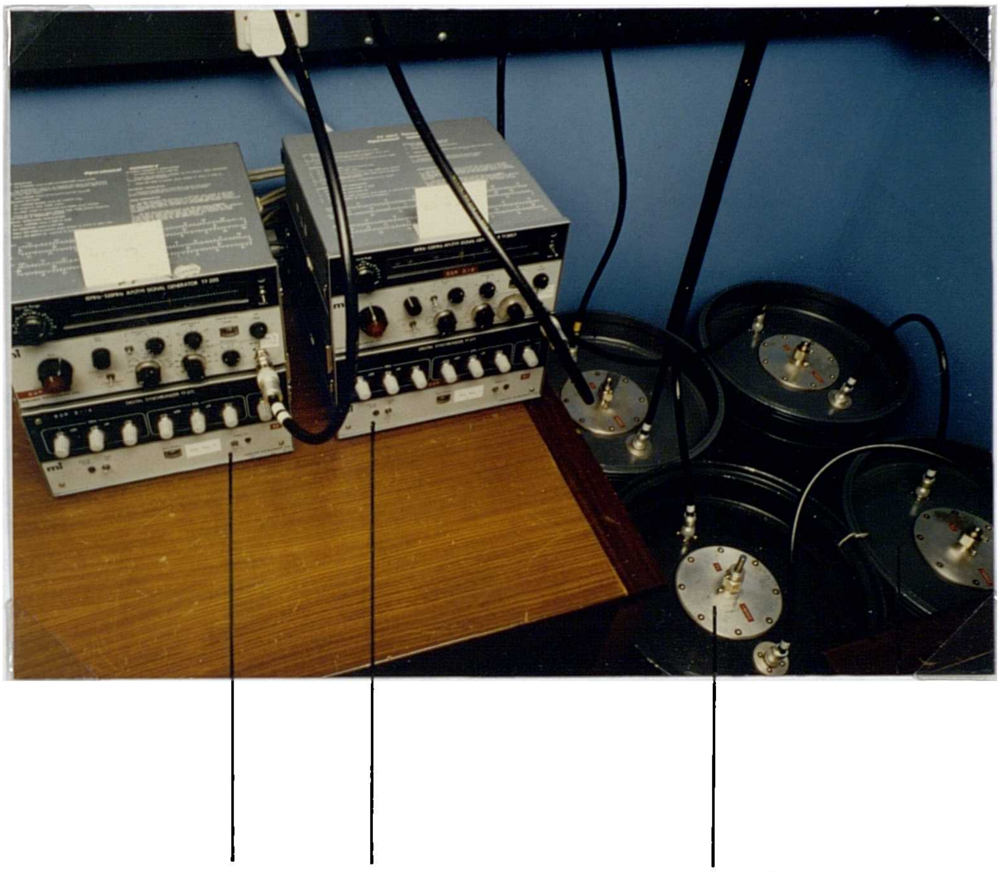


Fig. 3.2 Signal Generators and Cavity Filters

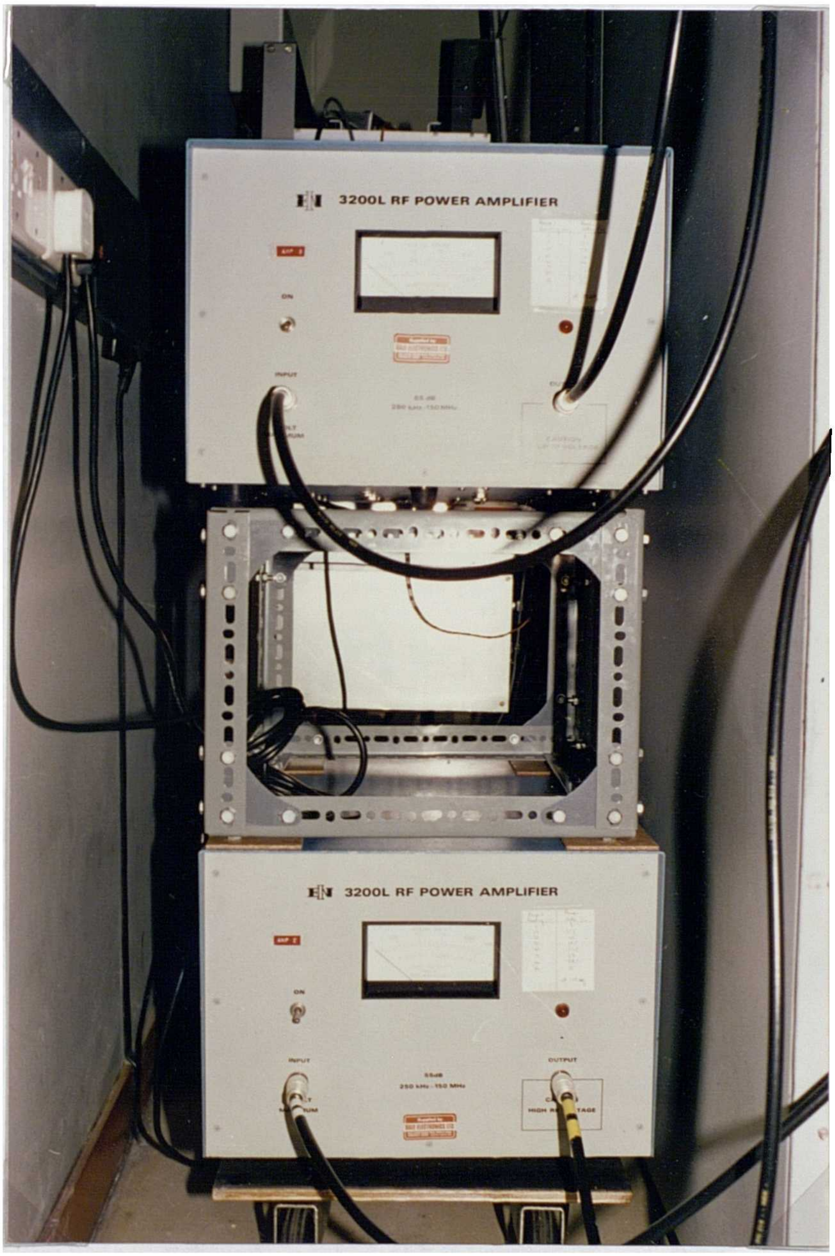


Fig. 3.3 Power Amplifiers

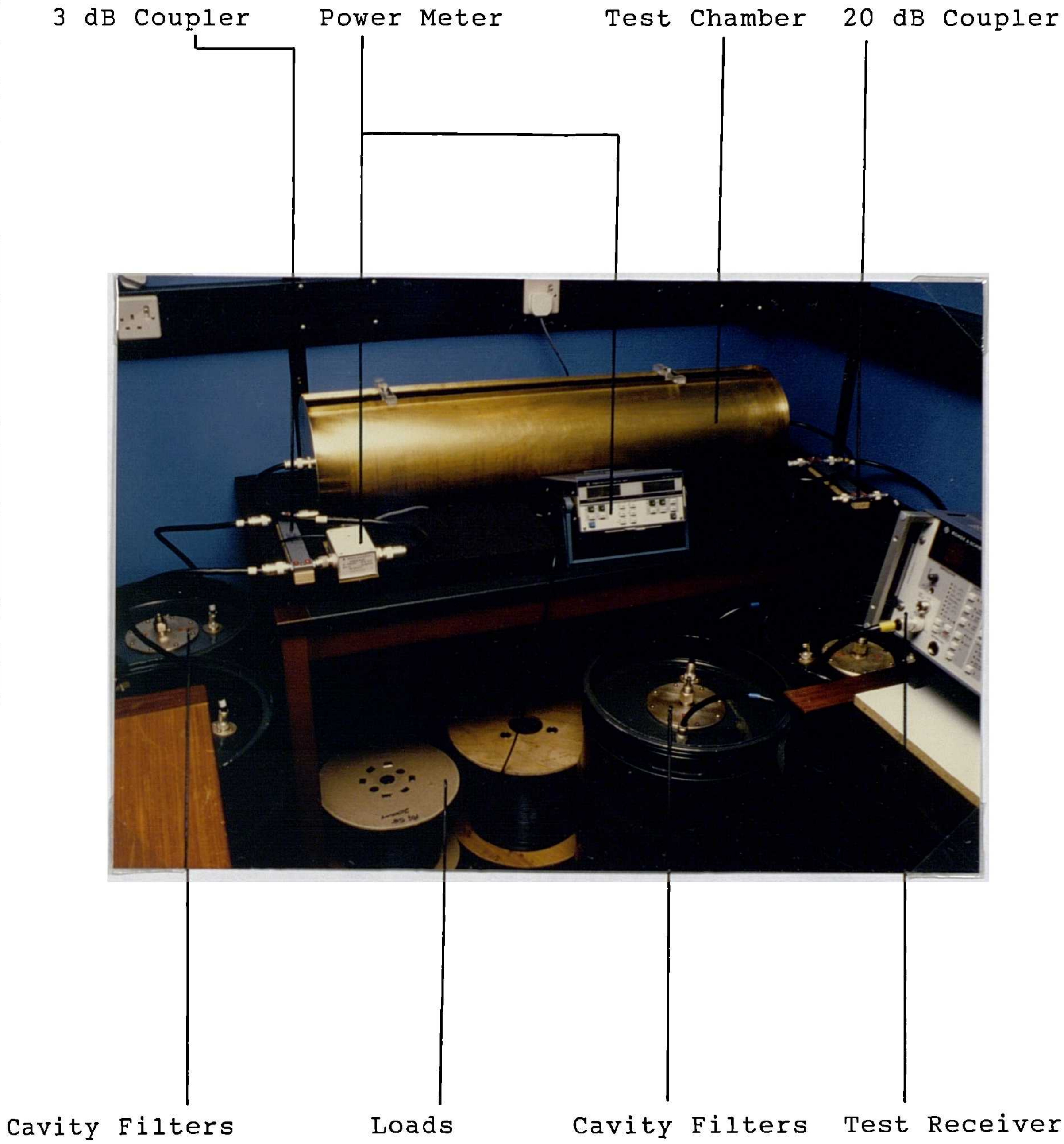


Fig. 3.4 PIMP Measurement System

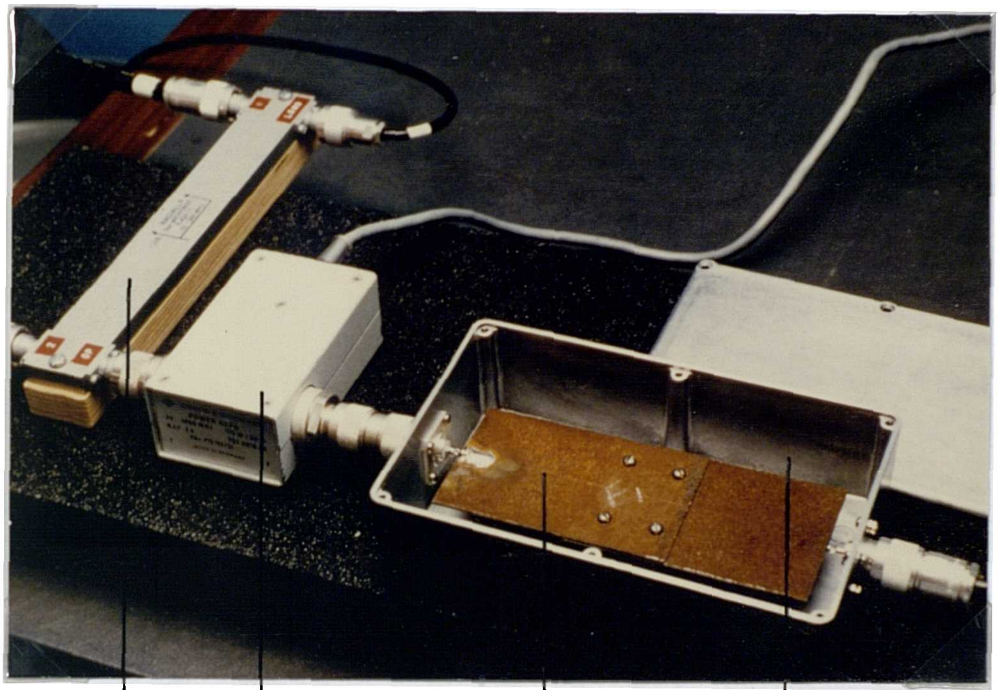


Fig. 3.5 50 Ohm Test Chamber

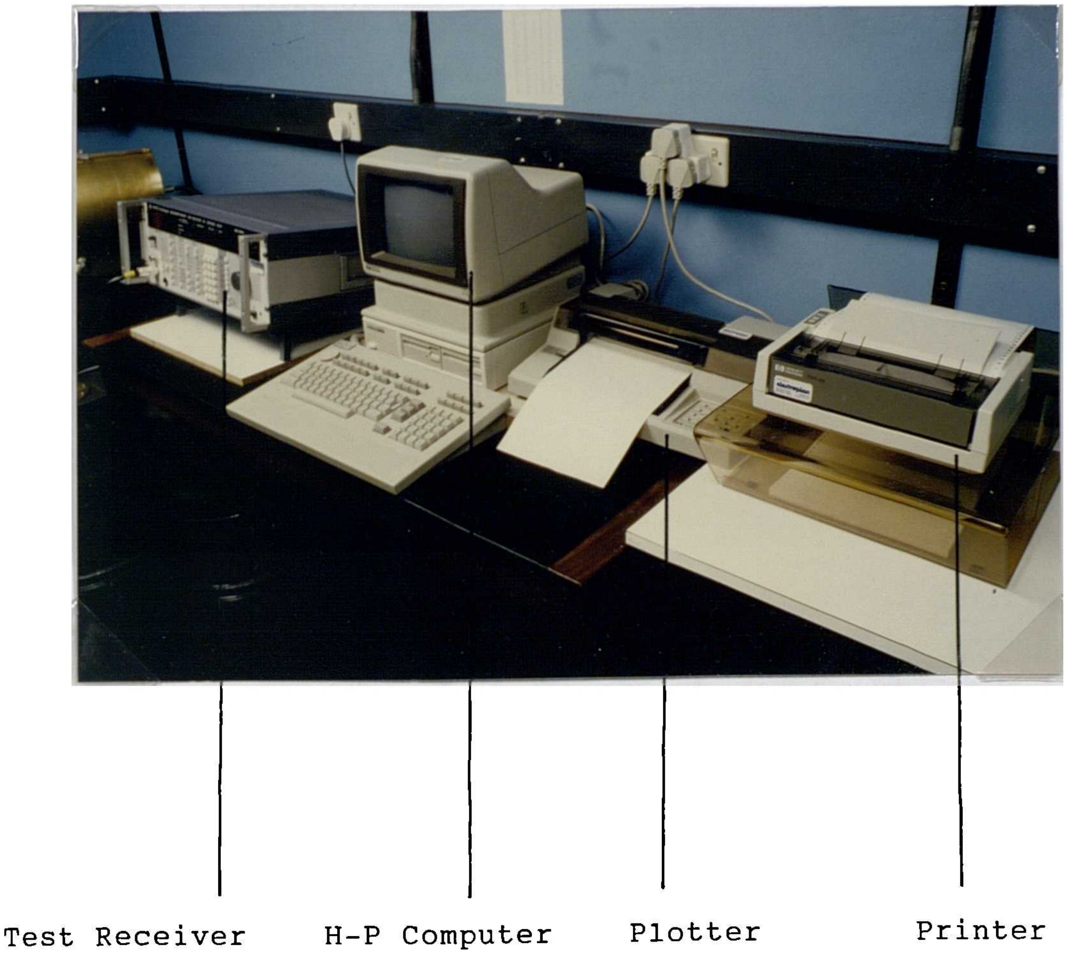


Fig. 3.6 Test Receiver and Computer

used to generate the two VHF signals. They are manually controlled instruments with tuning range of 10-520 MHz. The two ENI amplifiers situated outside of the screened room (see Fig. 3.3) were used to amplify the VHF signals. They are solid state high-power linear amplifiers and have a maximum output of 175 W. The frequency response is flat from 250 kHz to 150 MHz and the nominal gain is 55 dB. The spectrum of the two amplified signals with and without filtering were measured by the test receiver and the results are shown in Fig. 3.7 and 3.8. It is quite clear that a cleaner spectrum could be obtained when the two bandpass cavity filters were used in each transmission arm. Throughout the laboratory measurements, the two signal sources were used in the continuous wave (CW) mode. Since each cavity filter has a CW power rating of 100 W (50 dBm) and an insertion loss of approximately 1 dB, the combined power input to the sample was limited to 63 W (48 dBm).

3.3.2 Isolators

An isolator is a passive non-reciprocal three-port device commonly used for isolating signal sources, thus reducing transmitter intermodulation [24]. In the initial set-up, two 50 W isolators supplied by Clewave RF and Aerial Facilities Ltd (AFL) were used for signal isolation. The AFL and Celwave isolators were tuned to 150 and 154 MHz respectively. Their frequency responses, shown in Fig. 3.9, were measured by the two-port test facility of the test receiver. The off-tuned Celwave isolator has a slight edge over the tuned AFL isolator. The former attenuates the 155 MHz signal by 30 dB and the 150 MHz signal by 25 dB, and the latter attenuates the 150 MHz signal by 31 dB and the 155 MHz signal by 15 dB. After several tests, it was decided that the two isolators should not be used in the system because their CW power rating (50 W) limits the combined input power to the test

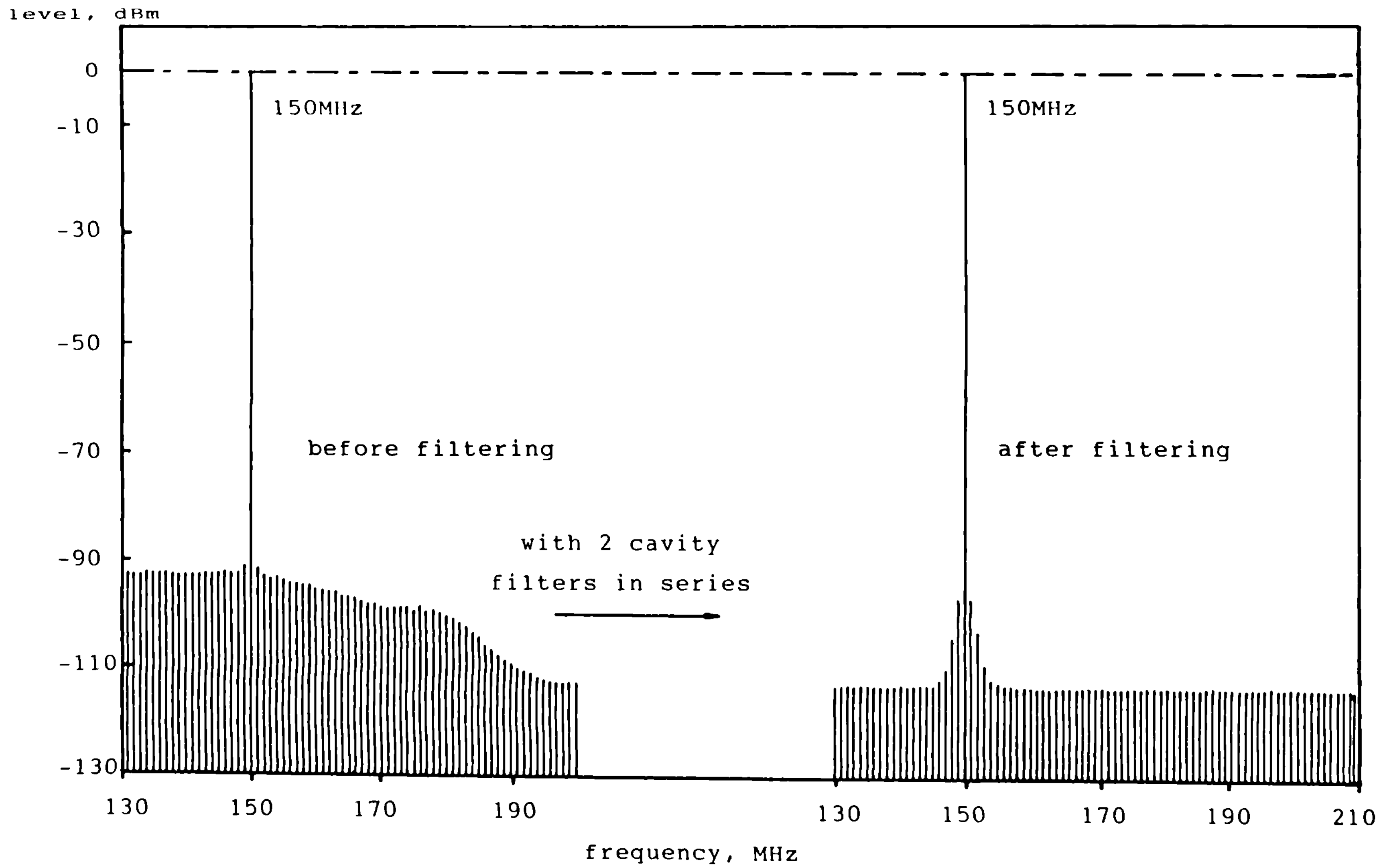


Fig. 3.7 Output Spectrum of Transmit Signal With and Without Filtering

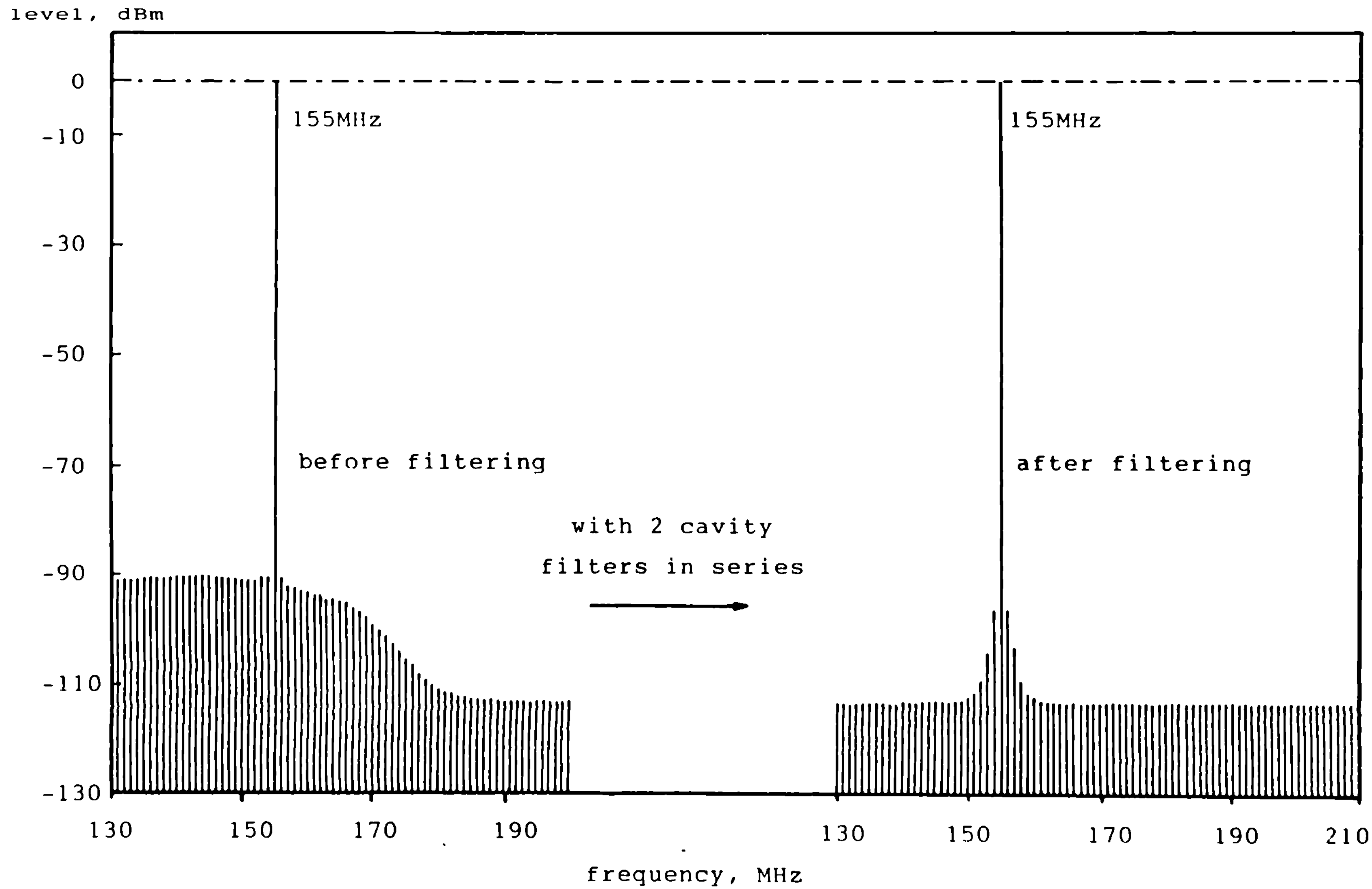


Fig. 3.8 Output Spectrum of Transmit Signal With and Without Filtering

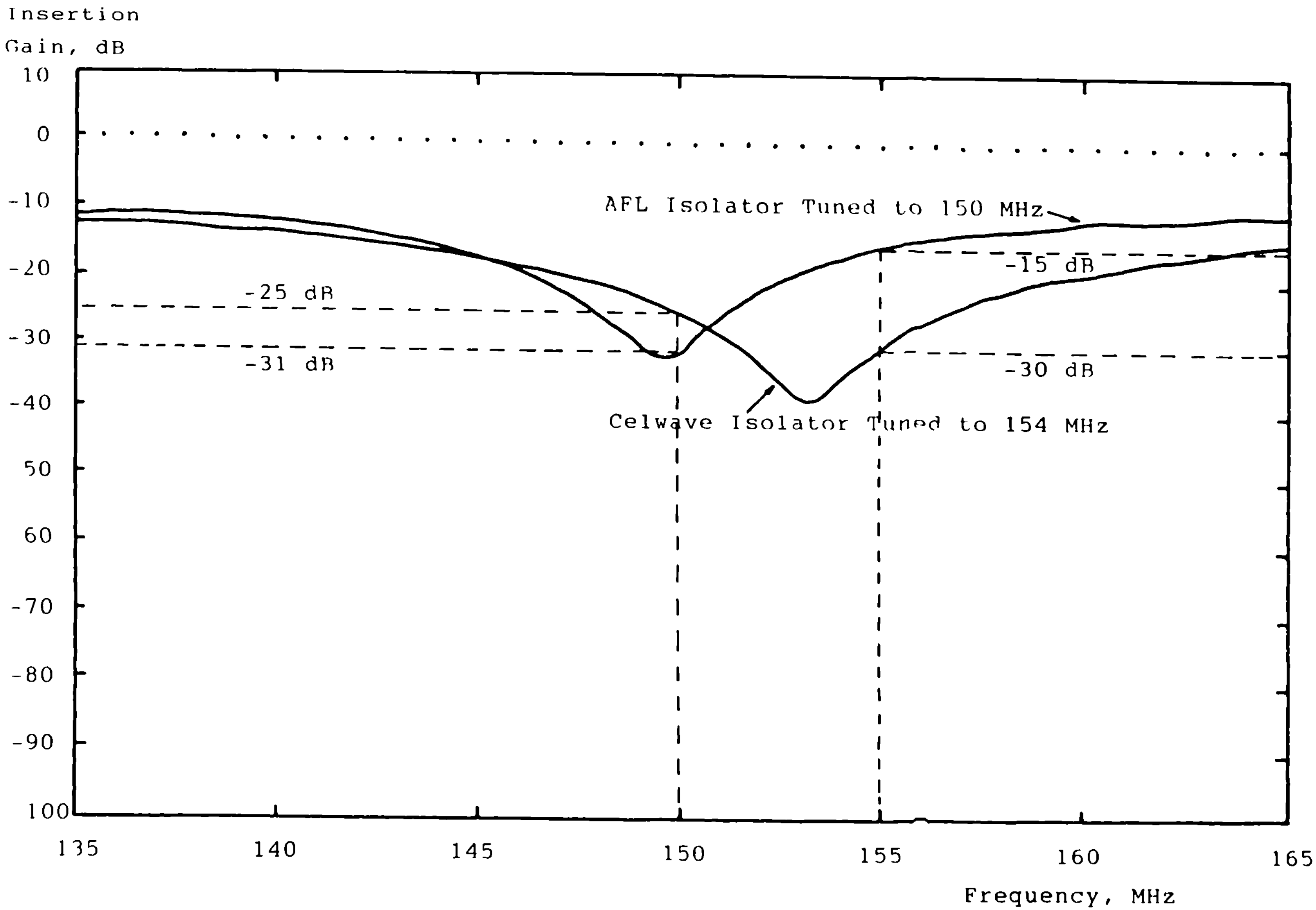


Fig. 3.9 Frequency Response of Isolators

chamber. There is a 2 dB insertion loss from the two cavity filters and cable connections in each transmission arm. This 2 dB loss reduces the maximum combined input power from 50 W (47 dBm) to 32 W (45 dBm). It was considered that this amount of power might not be sufficient to excite samples with weak non-linearities. Since a 3 dB coupler was used as a signal combiner, which added 30 dB to the 80 dB isolation provided by the two cavity filters (see Fig. 3.11). The combined 110 dB isolation was found to be sufficient to isolate the two signal sources. Without the two isolators, the maximum combined input power could reach 63 W (48 dBm). Also the isolator is made of non-linear ferromagnetic material which can generate harmonic and intermodulation products. This has been discussed in Section 2.2.1.

3.3.3 Cavity Filters

Cavity filters are extensively used in VHF and UHF mobile radio systems as part of transmitter combiners allowing for common antenna working. The design, characteristics and application of these filters have been described by Howson et al. [25-27]. The purpose of using cavity filters in the system was to isolate the two signal sources and filter the desired intermodulation signal. Seven high-Q cavity filters as shown in Fig. 3.2 and 3.4 were used. These AFL manufactured filters have aluminium cases and silvered plated copper telescopic centre conductors. The input and output ports are loop coupled into the cavity using N-type connectors. The frequency tuning is by mechanical means and the tuning range is 145-180 MHz. The unloaded Q is 11,000 and the insertion loss of each filter is approximately 1 dB [28].

All these filters had been used by the Home Office for years and were found to be very dirty. To set up a measurement system with low residual intermodulation level, all connectors and contacts of the filters should be clean and free of visable oxides. Any loose and oxidised contacts may increase the residual intermodulation level quite substantially [13]. A cleaning up exercise was therefore carried out and all the nickel plated bolts, nuts and washers found were replaced by zinc plated equivalents. The characteristics of these seven filters were then measured by the two-port test facility of the test receiver and the results showed that they have differences in insertion loss and frequency response. Further investigation revealed that it was due to variation in the sizes of the coupling loops. After a few tests, it was found that a loop size of approximately 4 cm in diameter gave a good performance in terms of insertion loss and Q-factor. Fourteen such coupling loops were therefore made to replace the old ones.

The best four filters were selected for the two transmission arms to give maximum signal isolation and minimum insertion loss. The remaining three filters were used for the less critical receive arm. Filters were connected together by quarter-wavelength long coaxial cables [26, 27]. The responses of a single filter, two and three filters in series were measured as shown in Fig. 3.10. The isolation between the two transmission arms with two filters in each arm is 80 dB, shown in Fig. 3.11. The receive filters were tuned to the 3^{rd} order intermodulation signal (160 MHz) and they attenuate the transmit signals (150 and 155 MHz) by 90 dB.

3.3.4 Power Combiner and Sampler

There are many ways of combining and sampling RF signals. Some of techniques used have been discussed by Wills [29], Gardiner and Mgombelo [30]. Ideally the signal combiner and sampler should satisfy the following conditions.

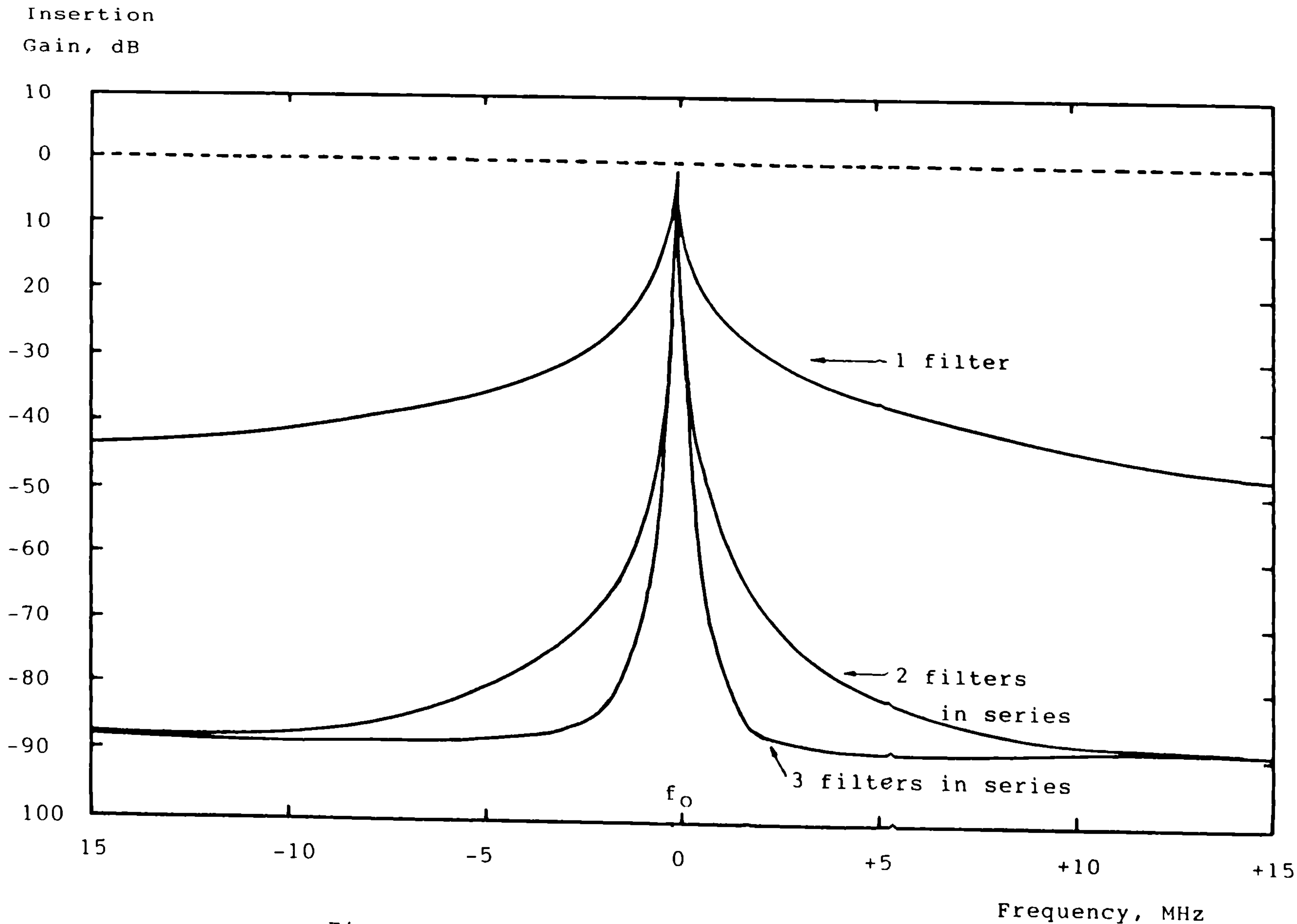


Fig. 3.10 Frequency Response of Cavity Filters

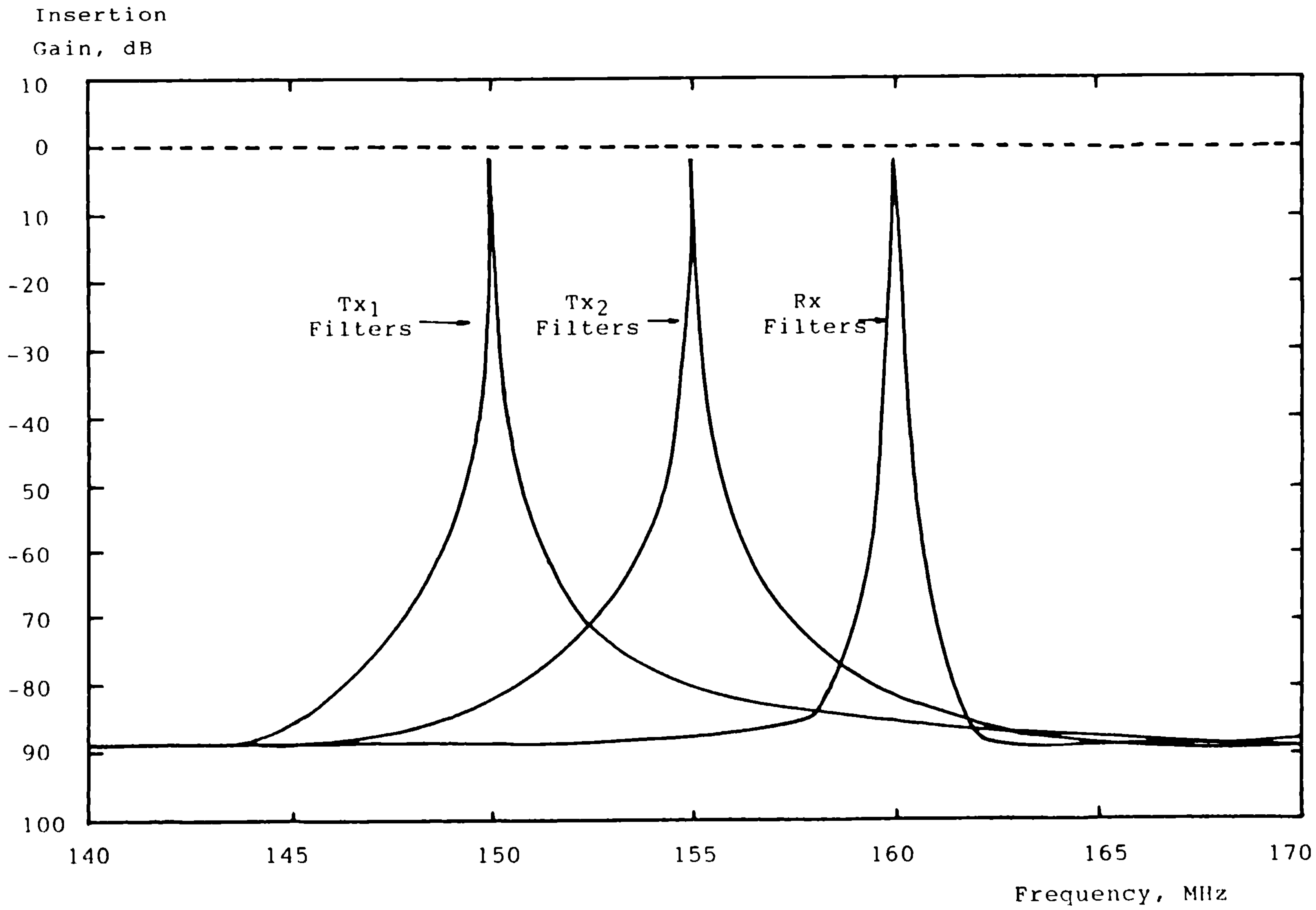


Fig. 3.11 Frequency Response of Cavity Filters

(1) Low insertion loss, e.g. less than 0.5 dB.

(2) High isolation between ports, e.g. greater than 20 dB.

(3) Low VSWR at ports, e.g. less than 1.25.

(4) Good linearity.

(5) Sufficient bandwidth.

(6) High power rating.

(7) Low cost.

In practice there is always a trade-off between these factors. Review of various measurement systems [1-21] revealed that there are three common ways of combining and sampling signals. The use of a T-piece and two quarter-wavelength coaxial cables. It is a simple and low cost method [13, 20, 21], however, the length of these cables is critical and a careful design is needed to provide maximum signal isolation. The use of duplexer, either one [12, 19] or two [15] has been reported, but it is not so widely used because of the higher cost involved. The use of directional couplers with various degrees of coupling [17, 18]. They provide good signal isolation and are broadband and available for many frequency bands. But there is always a 3 dB loss at the combiner.

In practice, the choice of method depends upon the test requirements. After evaluating the three different methods, it was decided that the two Radiall couplers, a 3 dB and a 20 dB, shown in Fig. 3.4 and 3.5 would be used for signal combining and sampling. They have a bandwidth of 150-300 MHz, VSWR of 1.15 and CW power rating of 500 W. These couplers were measured by the two-port test facility of the test receiver and the results, shown in Fig. 3.12-3.15, suggest

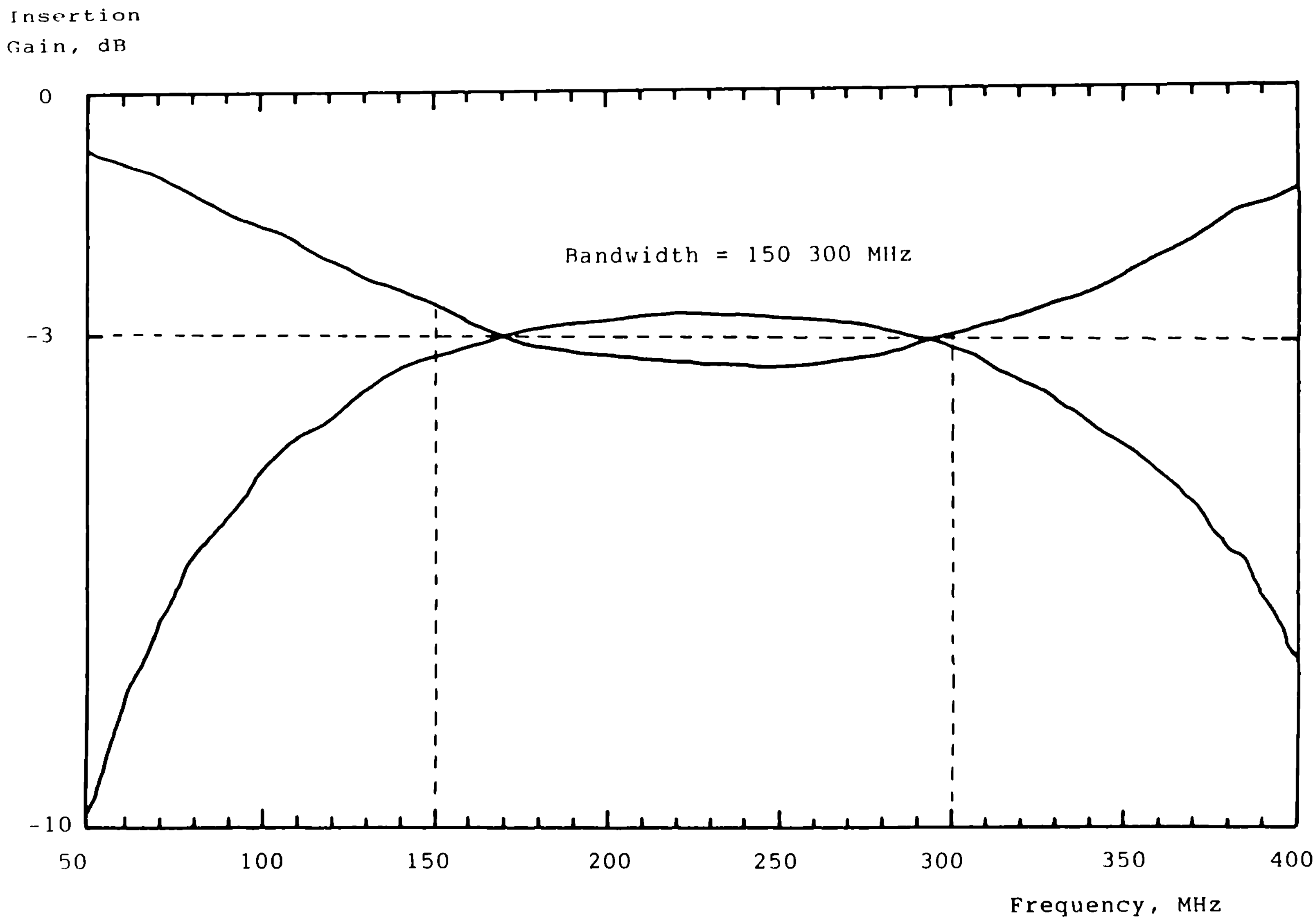


Fig. 3.12 Frequency Response of 3 dB Coupler

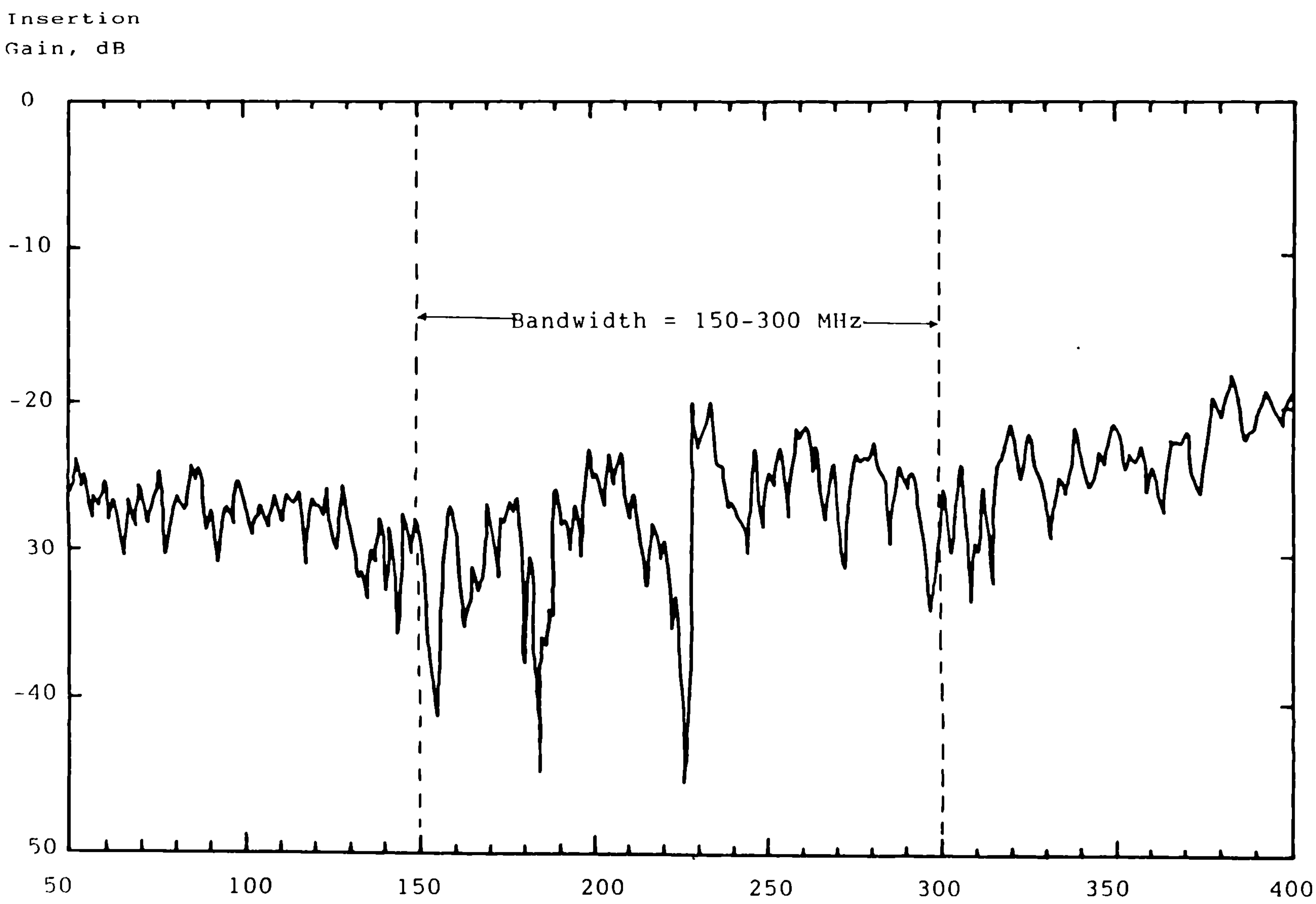


Fig. 3.13 Isolation of 3 dB Coupler

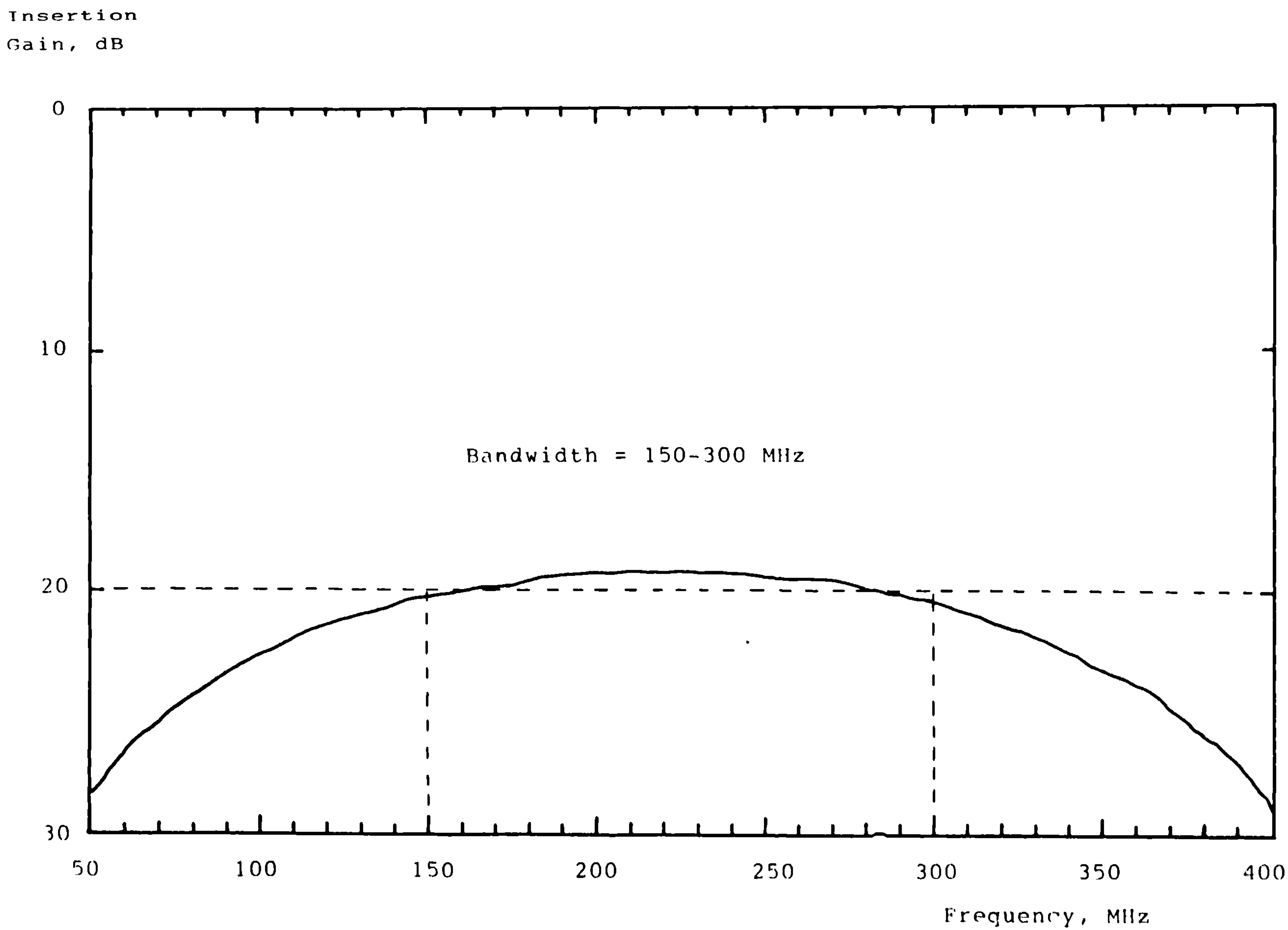


Fig. 3.14 Frequency Response of 20 dB Coupler

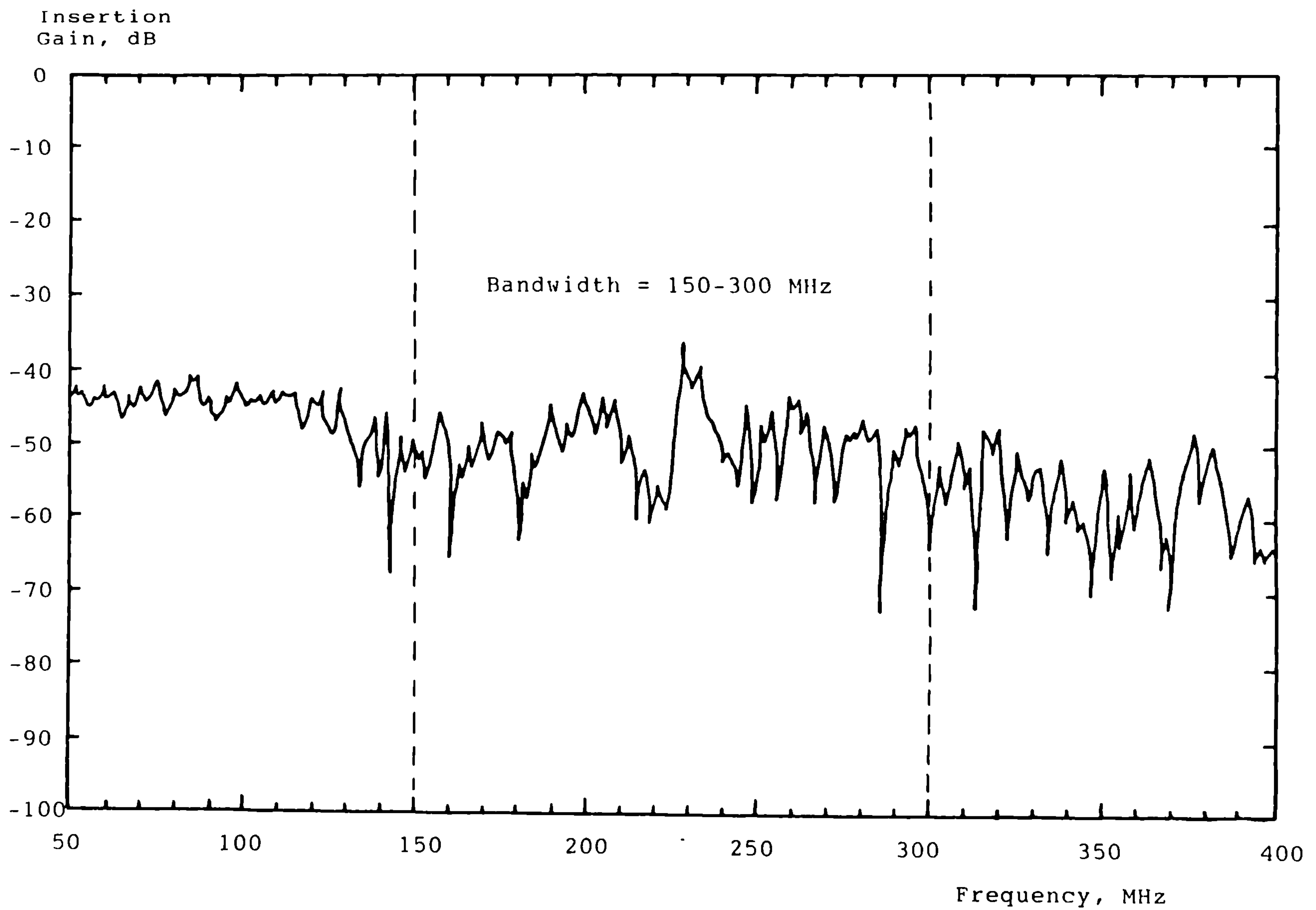


Fig. 3.15 Isolation of 20 dB Coupler

that they satisfy our test requirements.

3.3.5 Power Meters

A power meter is commonly used for monitoring the flow of power. In the initial set-up, three Bird through-line power meters were used. Two at the input of the 3 dB coupler and one at the input of the test chamber. Four new power elements with rating from 10 W to 100 W were used as sensors. However, tests showed that the total measurement error due to the error in sensing elements (5%) and meters (5-10%) was too high. It was decided that they should be replaced by more accurate power meters.

Further study suggested that one power meter connected to the input of the test chamber may be used. This configuration has the advantage of having fewer connections and reduced instrument error. A Rohde & Schwarz through-line power meter as shown in Fig. 3.4 and 3.5 was used. It has a bandwidth of 25-1000 MHz and a sensitivity of 50 mW – 100 W. It displays the forward and reflected power, VSWR, percentage of reflection, modulation depth, transmission and return loss. It also has an optional IEEE-488 interface bus facility for automated measurement.

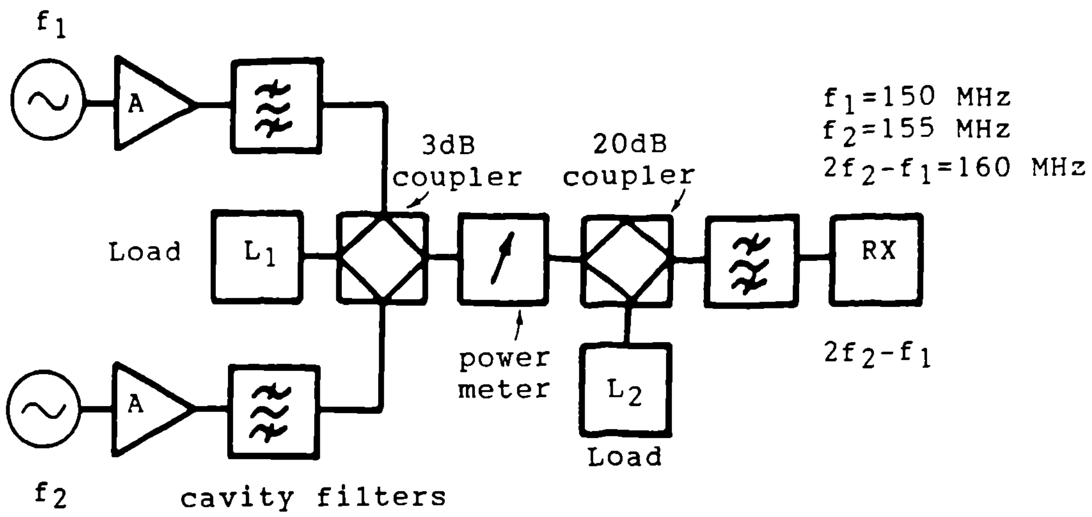
3.3.6 Dummy Loads

In non-radiating PIMP measurement systems, dummy loads are used to absorb the transmitted power. It is important that they should generate no significant PIMP. Commercially available dummy loads which are adequate for most applications, are not normally designed to meet the rigid linearity requirement of a PIMP measurement system. To select a linear distributed dummy load, there are a few factors that need to be considered: linearity, characteristic impedance, power handling capability, attenuation per unit length, weight, volume and cost. The linearity is the prime requirement as it is the main contributor to the residual intermodulation level. The characteristic impedance is another important requirement since it decides the matching of the load to the system. A high attenuation cable reduces the required length, but it gets heated up faster than a low attenuation cable.

Research on dummy loads suggested that distributed loads are generally more linear than lumped loads [32]. The RG-58C/U coaxial cable was chosen for its linearity, low cost and small volume [32]. Two reels of RG-58C/U coaxial cable with lengths of 200 m and 300 m were used. They were compared with two reels of 100 m length URM-67 coaxial cable and two commercial lumped loads. One of the lumped loads is a 25 W air-cooled type and the other is a 50 W oil-cooled type. The load linearity test set-up, combination of loads and test results are shown in Fig. 3.16 and 3.17. Test revealed that using RG-58C/U coaxial cables as loads provides the best result. Other combinations generated much higher PIMP levels and the two commercial lumped loads should not be used. In the actual set-up, three reels of RG-58C/U coaxial cable with lengths of 100 m, 200 m and 300 m were used. These cables attenuate the 150MHz signal by approximately 0.2 dB per meter.

3.3.7 Cables and Connectors

Research work has shown that connectors are usually the major source of passive IMI in cable-connector combinations [17, 19]. Any connectors with mechanical imperfections, such as slightly bent centre pins, or a ferromagnetic material content may generate high levels of intermodulation. The method of construction employed in joining the cables to connectors and the cleanliness of all the contact surfaces are also very critical.



No.	Load (L_1)	Load (L_2)
1.	RG-58C/U (200m)	RG-58C/U (300m)
2.	RG-58C/U (200m)	URM-67 (100m) and 50W Load (Bird)
3.	URM-67 (100m)	URM-67 (100m) and 50W Load (Bird)
4.	URM-67 (100m)	RG-58C/U (300m)
5.	URM-67 (100m) and 25W Load (AFL)	RG-58C/U (300m)
6.	URM-67 (100m) and 50W Load (Bird)	RG-58C/U (300m)

Fig. 3.16 Test Set-Up For Testing Dummy Loads

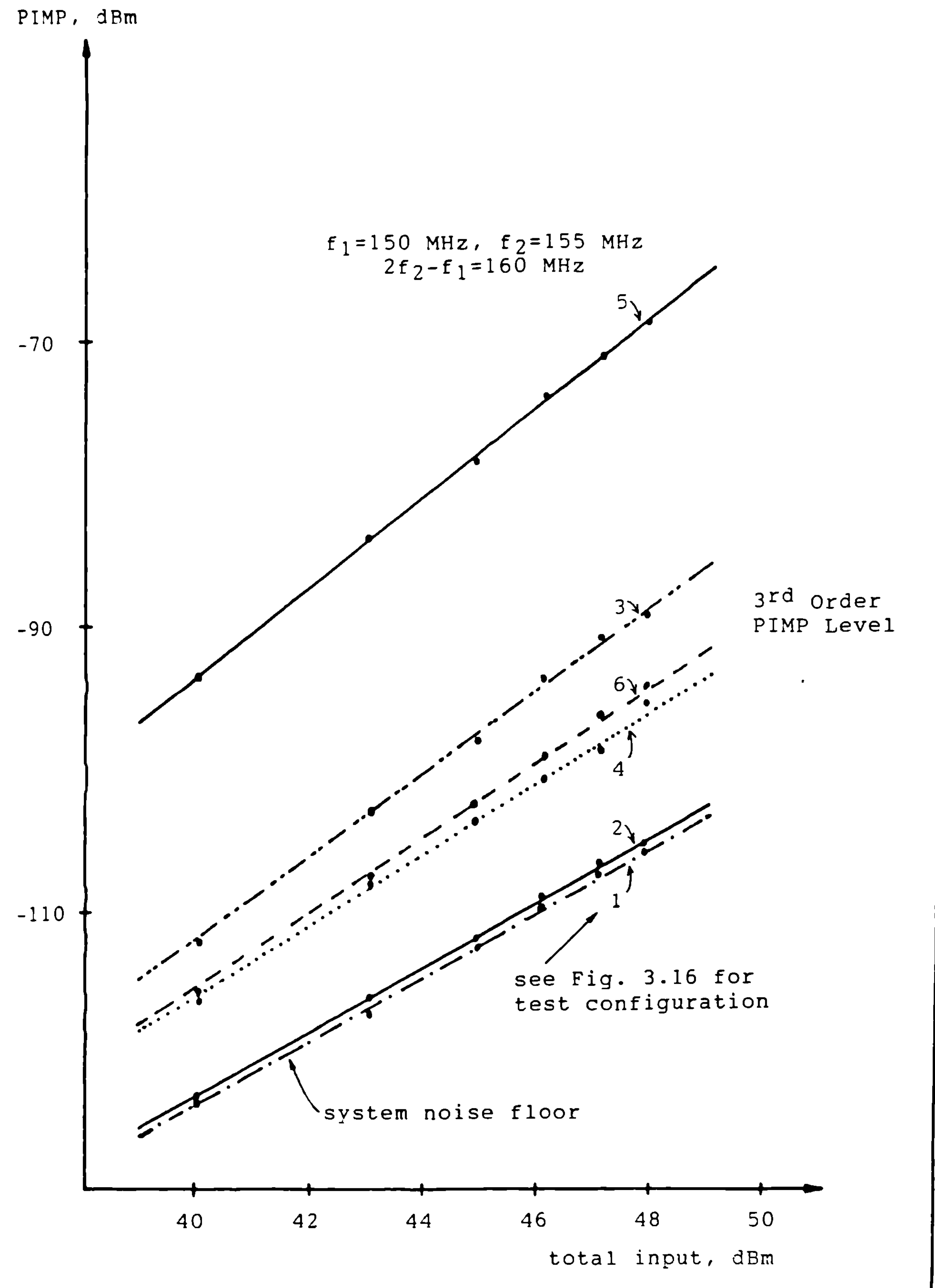


Fig. 3.17 Test Results of Linear Dummy Loads

Studies concerning the PIMP generation in coaxial cables and connectors have been conducted [7-9] [15-17] [19]. To keep the residual intermodulation level low, it is essential to choose the right type of cable and connector. Between the RG (of MIL-C-17) and URM (of BS2316) cables, the RG type was preferred due to its more rigid specification. The RG-214U coaxial cable with double braid, silver plated copper conductor was used because of its good linearity, screening performance and power handling capability [15, 17]. Since all the equipment except the two signal generators use N-type connectors, silver plated N-type connectors with RG-214U coaxial cables combination were used. Extra cable-connector combinations have been made to screen out any irregular one. Care has been taken to ensure the cable-connector combinations were properly constructed and all the contacts were tight and free of visable oxides and dirts.

3.3.8 Test Receiver and Computer System

The spectrum analyser is an instrument commonly used for intermodulation measurement [33]. However, a recent study of radio interference measurement instrument suggested that the test receiver is a better choice due to its good selectivity, sensitivity and dynamic range [23]. A Rohde & Schwarz programmable test receiver was therefore used for signal detection. It has a tuning range of 20-1300 MHz, sensitivity of -126 dBm and a two-port test facility. Besides intermodulation measurement, it was used to tune the cavity filters and measure the characteristics of couplers, test chambers and dummy loads.

The test receiver was used with an IF bandwidth of 7.5 kHz, a front end attenuation of 0 dB and a sensitivity of -126 dBm. It was controlled by a Hewlett-Packard microcomputer and the connections between the test receiver, microcomputer, printer and plotter were via the IEEE-488 bus. This set-up is shown in Fig. 3.6.

3.3.9 50 ohm Test Chamber

To study the non-linearities of passive components, test samples need to be tested under controlled environments. If they cannot be connected directly into the laboratory measurement system, then some kind of test chamber to accommodate the test sample is required. In this section, the main requirements for designing test chambers, the background of test chamber design, and the design of a 50 ohm test chamber are described.

One of the main requirements in test chamber design is impedance matching. A test chamber needs to be matched with the characteristic impedance of the measurement system. If it is not properly matched, the reflected power can damage the sensitive test equipment. Further, experience has shown that a Voltage Standing Wave Ratio (VSWR) of 1.5 at the input port of the test chamber can change the measured passive intermodulation product levels by as much as 10 dB [18]. Besides matching, a good linearity is essential. If a test chamber is made of non-linear materials or has non-linear joints, the intermodulation signals generated will mask the intermodulation signals produced by the test samples. In addition, the increase in residual intermodulation signals will in turn reduce the dynamic range of the measurement system. Other requirements such as having the flexibility to accommodate a variety of test samples, an access for exchanging test samples, and shielding facilities to minimise radio interference are all very important. However, in practice it is very difficult to design a single test chamber that meets all these requirements.

A detailed study of test chamber design was conducted and it revealed that there are three different designs. The first one, shown in Fig. 3.18(a), was designed by the researchers at City University [20]. It is a four-port test jig and was used for assessing the effectiveness of using chemical compounds to suppress the 'rusty-bolt' effect. The test samples, in a cylindrical form with dimensions of 4 cm in length and 8 mm in diameter, are joined to the test jig by screw connection. The test jig was made of brass and has a cover to provide the shielding. The second one, shown in Fig. 3.18(b), was designed by the researchers at Georgia Institute of Technology [18]. It is a two-port rectangular box and was used for measuring the intermodulation signals generated by aircraft structures at VHF and UHF. The test sample consists of three pieces of metal, two of which are 4.75 inches long by 1.5 inches wide while the third is 5.25 inches long by 1.5 inches wide. These metals are joined by two bolts and nuts to form a plate sample. The plate sample, supported by four Teflon spacers, is connected to the box by soldered joints. The 50 ohm characteristic impedance of the box is achieved by positioning the test sample at a right distance above the ground plane [18]. The matching performance and the dimensions of the box were not given. The third one, shown in Fig. 3.18(c), is a half-wavelength long two-port test chamber. It was designed by the researchers at Massachuseetts Institute of Technology [15] to measure the non-linearities of ferromagnetic materials and carbon fibres at 256.5 MHz. The design is based on a half-wavelength transformer and the test sample forms the centre conductor of the transmission line.

Of the three designs, the four-port test jig was considered as not suitable for the author's experiment because it cannot accommodate plate samples which are the most common type of joints at radio sites. Besides the joints between the test jig and samples are made by screw connection and they can generate intermodulation

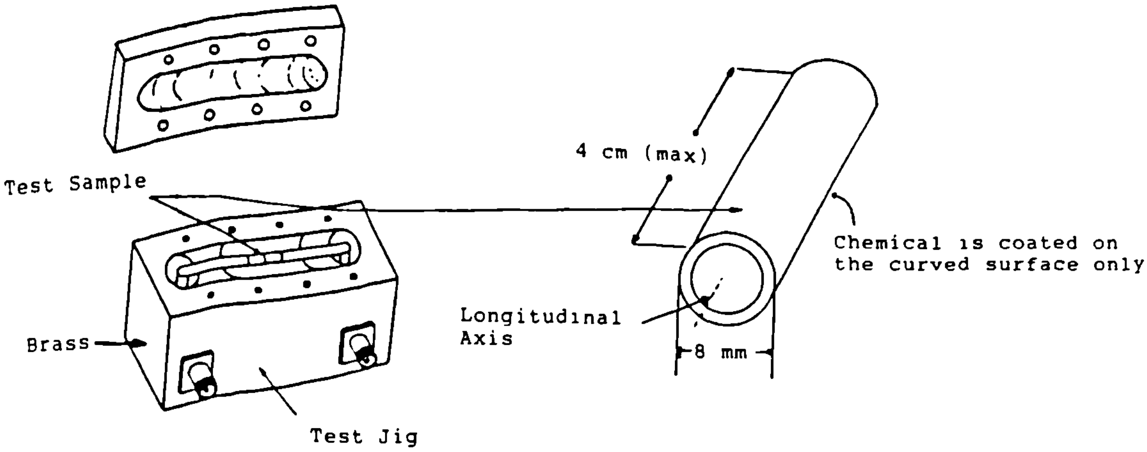


Fig. 3.18(a) A four-port test jig designed by researchers at City University. It was used to evaluate the effectiveness of using chemical compounds to suppress the 'rusty-bolt' effect at VHF (see reference no. 20)

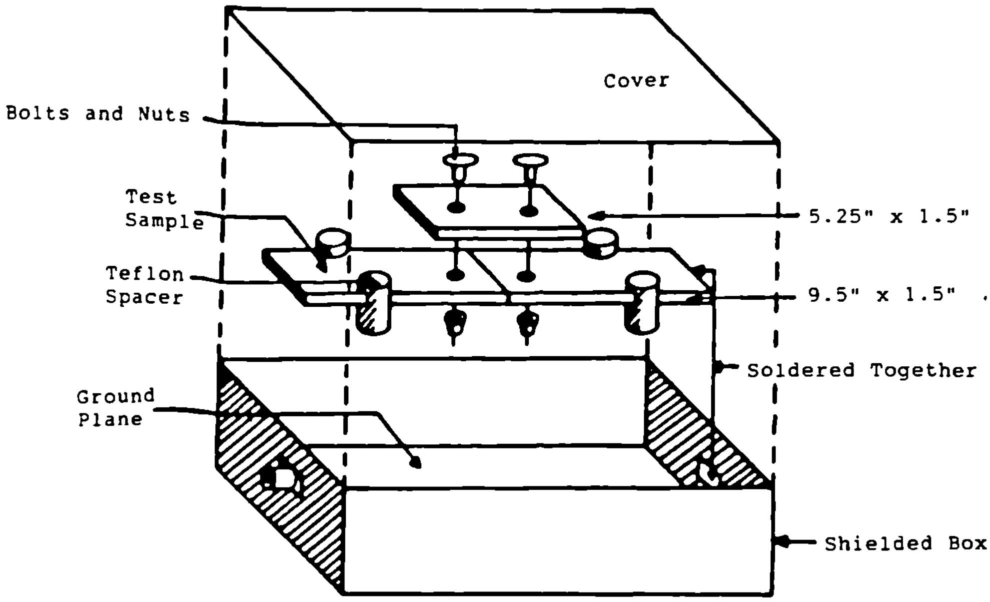


Fig. 3.18 b) A two-port test box designed by researchers at Georgia Institute of Technology. It was used to measure the passive intermodulation products generated by aircraft structures at UHF & VHF see reference no. 18)

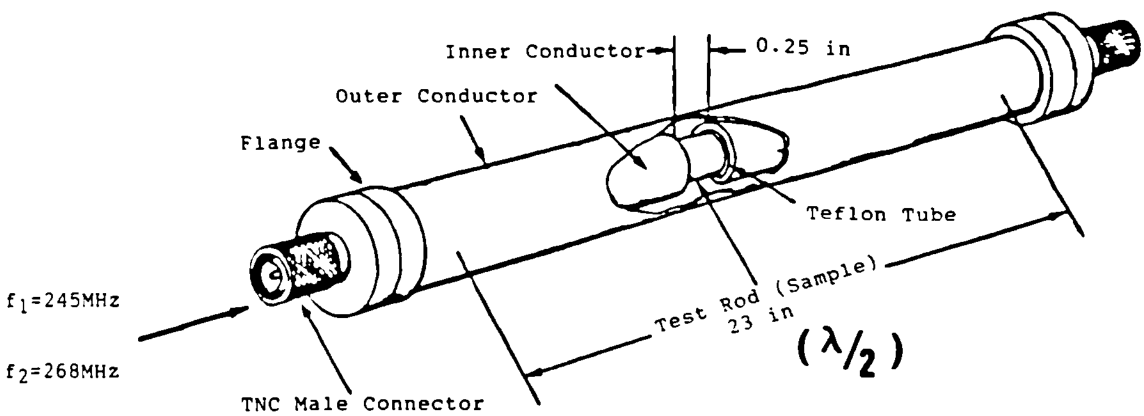


Fig. 3.18(c) A two-port half-wavelength long test tube designed by researchers at Massachusetts Institute of Technology. It was used to measure the passive nonlinearities of conducting materials at UHF & VHF see reference no. 15

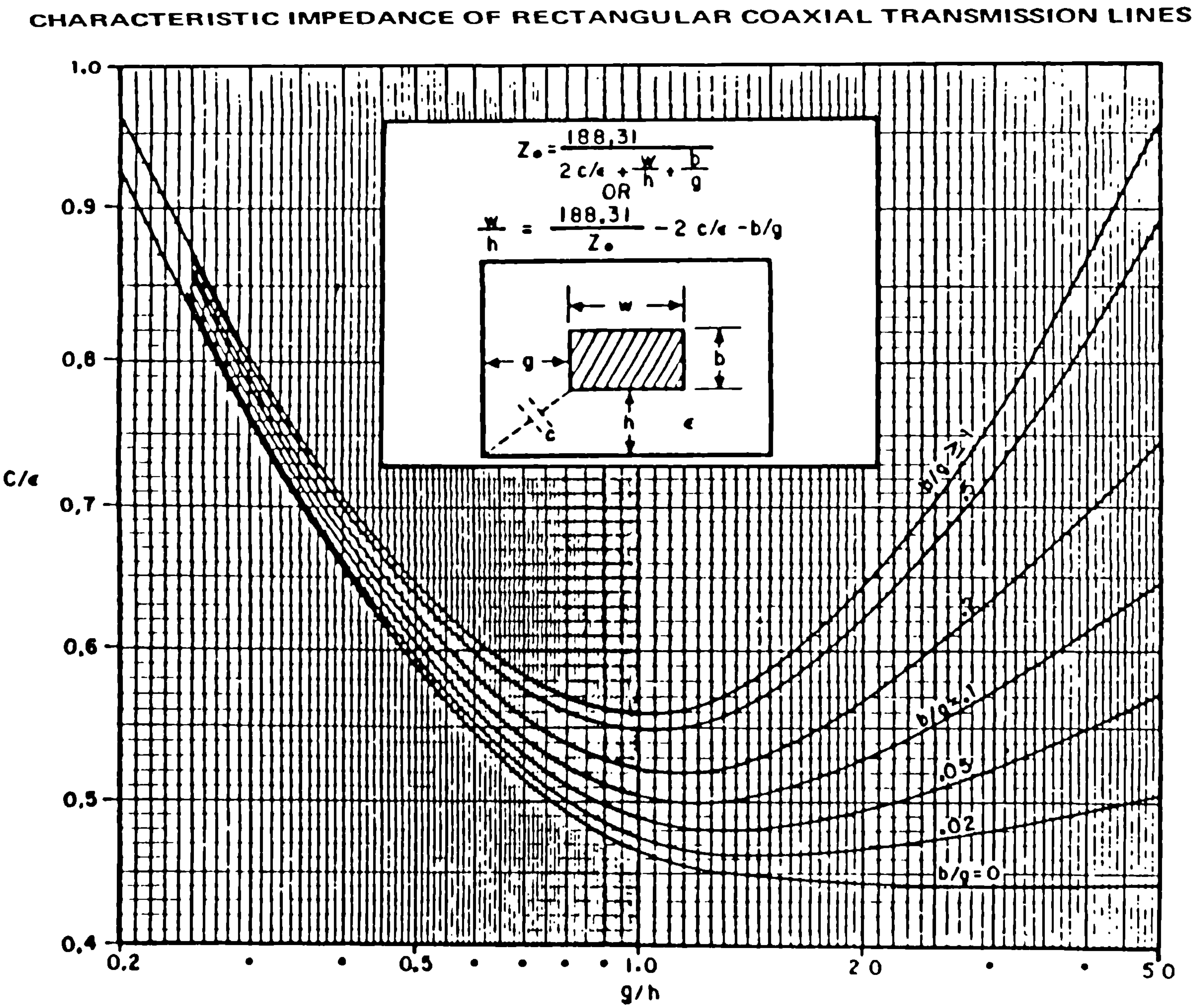
signals. The rectangular box is ideal for plate samples, but a better way to achieve the 50 ohm characteristic impedance is required. The half-wavelength test chamber design meets the matching requirement, however, certain design modifications are required before it can be used for large and irregular shaped structural components. Based on this design study, two test chambers were designed for experiments at 150 MHz. The design of a half-wavelength long test chamber is described in Section 3.3.10 and the design of a 50 ohm test chamber is described in the following paragraphs.

After further investigation of the rectangular box design, the author discovered that a formula for designing rectangular coaxial lines can be used to design a 50 ohm box. The design curve and formula, shown in Fig. 3.19, were taken from the Microwave Engineers's Handbook [34]. There are two design approaches, either design a box from a known sample size or design a sample from a known box. Since diecast boxes are available and it is easier to make a plate sample than a box, the latter approach was used. A medium size aluminium alloy diecast box with internal dimensions of 11.5 x 4.8 x 18.4 cm (width x height x length) was therefore chosen for the first design exercise. After a few calculations, it was discovered that a sample with dimensions of 6.5 x 0.2 x 15.8 cm (width x height x length) give a characteristic impedance of 48 ohm. This calculation is shown as follows:

Using information as shown in Fig. 3.19, when g = 2.5 cm, w = 6.5 cm, g/h = 1.087, h = 2.3 cm, b = 0.2 cm, b/g = 0.08

$$Zo = 188.31 / [(2 \times 0.5) + (6.5 / 2.3) + 0.08]$$

$$Zo = 48 \text{ ohm}$$



This graph was reproduced, with permission from the publisher Artech House, from the Microwave Engineers' Handbook, edited by Saad T S, Vol 1, pp. 98

Fig. 3.19 Design Curve and Formula For 50 ohm Test Chamber Design

The frequency response of the box, with a clean brass plate as test sample, was measured using the two-port test facility of the test receiver. The result, shown in Fig. 3.20, shows that it has an insertion loss of 0.5 dB from 50 to 500 MHz. The VSWR was measured with a through-line power meter and a typical value of 1.15 was achieved. To maintain a low VSWR, a smooth transition of energy at the sample and connector interface is essential. This can be achieved by ensuring that there are no gaps between the edges of the sample and the centre pins of the connectors. Since this design gave very satisfactory results and the sample is large enough to represent typical metallic joints, no modifications were made to the box or the dimensions of the plate samples. A picture of this box can be seen in Fig. 3.5.

3.3.10 Half-Wavelength Test Chamber

Many of the passive intermodulation interference sources are loose contacts embedded in large structures. To measure the intermodulation signals generated by such structures, a test chamber larger than the 50 ohm box is required. The use of a half-wavelength transformer [35] was discussed and two different designs were considered. The first one was a rectangular box with a top cover, and the second one was a jointless cylinder with an opening for accessing the test sample. Since linearity is the main requirement in this design, the first design was considered as less satisfactory because the contacts between the cover and the box may generate intermodulation signals.

Using the second design, a half-wavelength test chamber, shown in Fig. 3.4 and 3.21, was made. It was designed at the mean frequency (152.5 MHz) of the two test signals (150 MHz and 155 MHz). The test chamber was constructed with

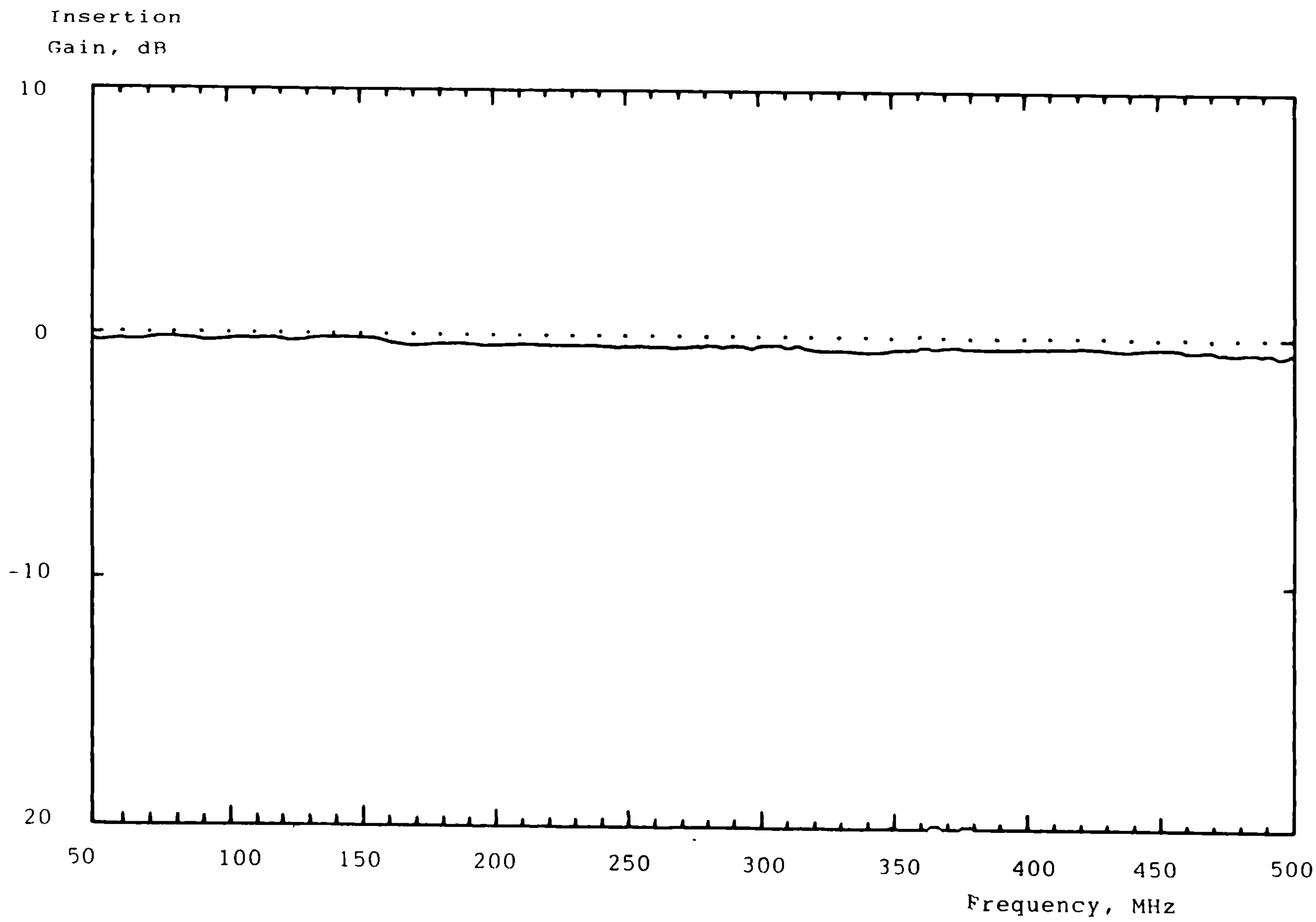


Fig. 3.20 Frequency Response of 50 ohm Test Chamber

brass plates and all the joints were soldered to minimise non-linear contacts. The diameter of the test chamber was chosen to be 24 cm so that it is large enough to accommodate structural components and not too difficult to construct. An opening of 1 m long and 8.5 cm wide was made along the side of the test chamber for accessing the sample. The length of the test chamber and sample were chosen to be 1 m and 0.98 m respectively to represent the average half-wavelength (0.984 m). The difference in length between the test chamber and sample is due to the presence of two centre pins (see Fig. 3.21). In practice it is very difficult to make a coaxial line exactly the same length as the calculated one because of the presence of connectors.

The performance of the test chamber was measured with test samples such as angle irons, tubes, rods and steel ropes. The frequency responses, measured with the two-port test facility of the test receiver, are shown in Fig. 3.22. The result shows that the insertion loss is approximately 1 dB at 150 MHz, 300 MHz and 450 MHz. At other frequencies, the inseriton loss is higher due to the mismatch of impedance. The matching performance was found to be a function of the sample size and the test frequencies. Like the 50 ohm test chamber, a smooth transition of energy at the sample and connector interface is essential. A typical VSWR of 1.2 or less was achieved in most tests. The RF leakage from the opening was measured with a loop probe and the test receiver, and was found to be insignificant. Since the test chamber performance was satisfactory, no further design modifications were made.

3.4 System Software

The test receiver was used to measure the following components and signals:

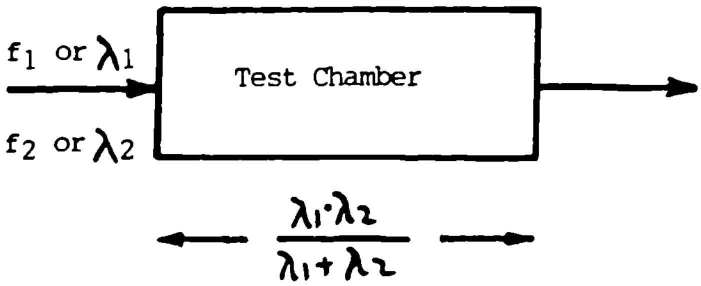
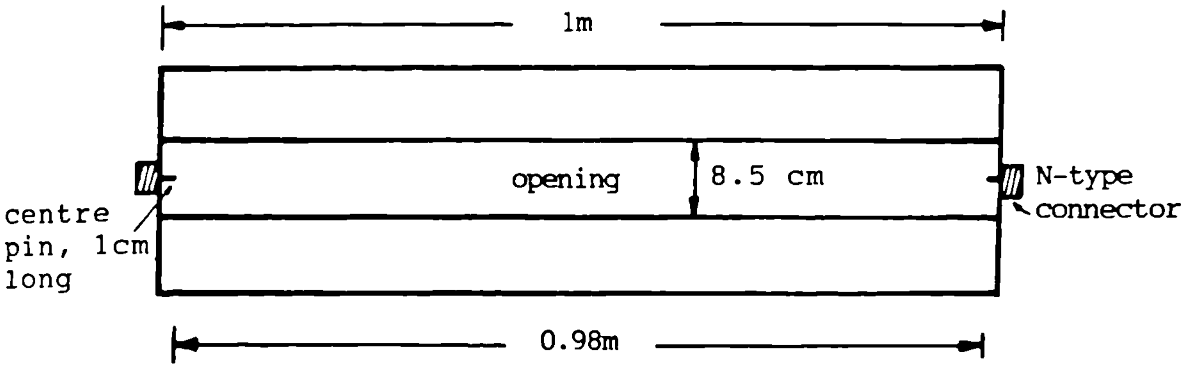
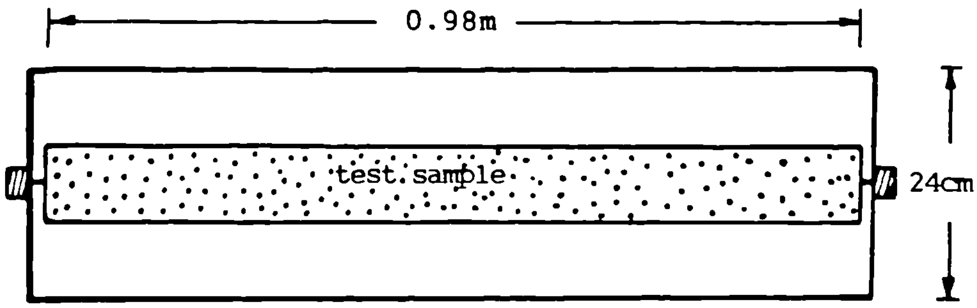


Fig. 3.21 Half-Wavelength Test Chamber



(Top View)



(Side View)

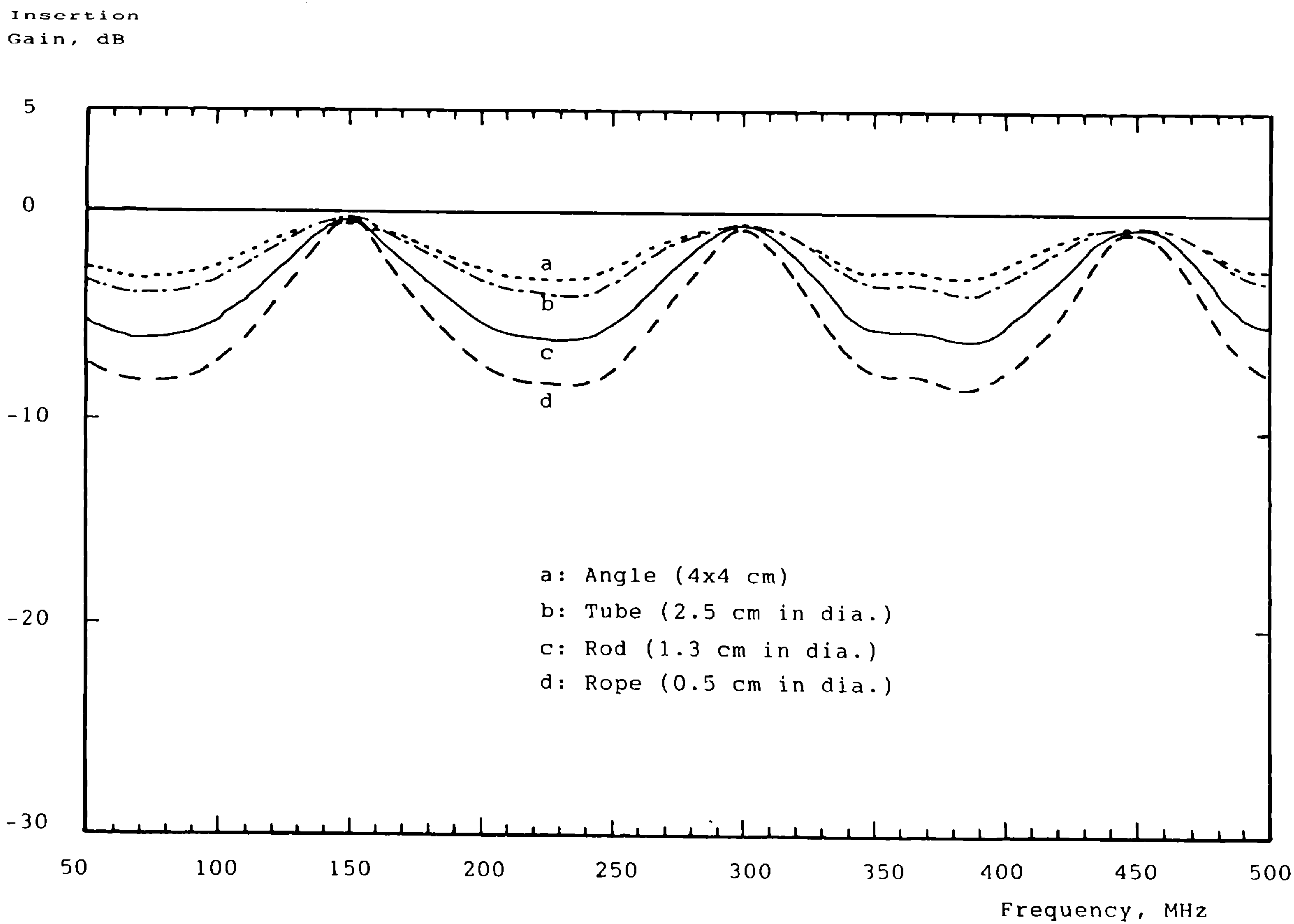


Fig. 3.22 Frequency Response of $\lambda/2$ Test Chamber

(1) The characteristics of couplers, cavity filters, dummy loads and test chambers.

(1) The harmonic and intermodulation signals.

Three main programs have been developed for the measurements. A general purpose program for measuring the properties of the two-port components, a program for measuring the mean value of an intermodulation signal at a fixed frequency over a period of time, and a program for measuring the RF spectrum. The listing of these programs are shown in Appendix B, C and D respectively.

3.5 System Performance

3.5.1 System Non-linearity and Dynamic Range

Since the system consists of connectors, cables, filters, couplers, instruments and metallic contacts, some of these components and contacts may generate intermodulation signals. If these signals are strong, the weak intermodulation signals generated by the test sample might be masked. A low residual intermodulation level is therefore essential. To assess the system performance and system noise floor, a test was conducted. The 3^{rd} order residual intermodulation signals were measured and compared with systems with similar configuration [18, 20]. The measurement was conducted without the test chambers and samples. The measurement setup used is identical to the one used for measuring dummy loads (see Fig. 3.16, configuration 1). The test receiver used has a sensitivity of -126 dBm, an IF bandwidth of 7.5 kHz, a front end attenuation of 0 dB and an operating range of 20 dB. The 3^{rd} order residual intermodulation signals, generated with equal input signals, set the system noise floor which is shown in the following table, Fig. 3.17 and Fig. 4.4-4.15. This system noise floor is lower than the system noise floor published earlier

[22] because the test receiver used during the earlier experiment has a sensitivity of -116 dBm, an IF bandwidth of 7.5 kHz, a front end attenuation of 10 dB and an operating range of 60 dB.

Systems	f_1(MHz)	f_2(MHz)	$2f_2$-f_1	Input(dBm)	3rd PIMP(dBm)	Dynamic Range
Ref. 18	250	225	200	44	-104	148 dB
Ref. 20	150	145	140	47	-100	147 dB
Ref. 22	150	155	160	44	-114	158 dB

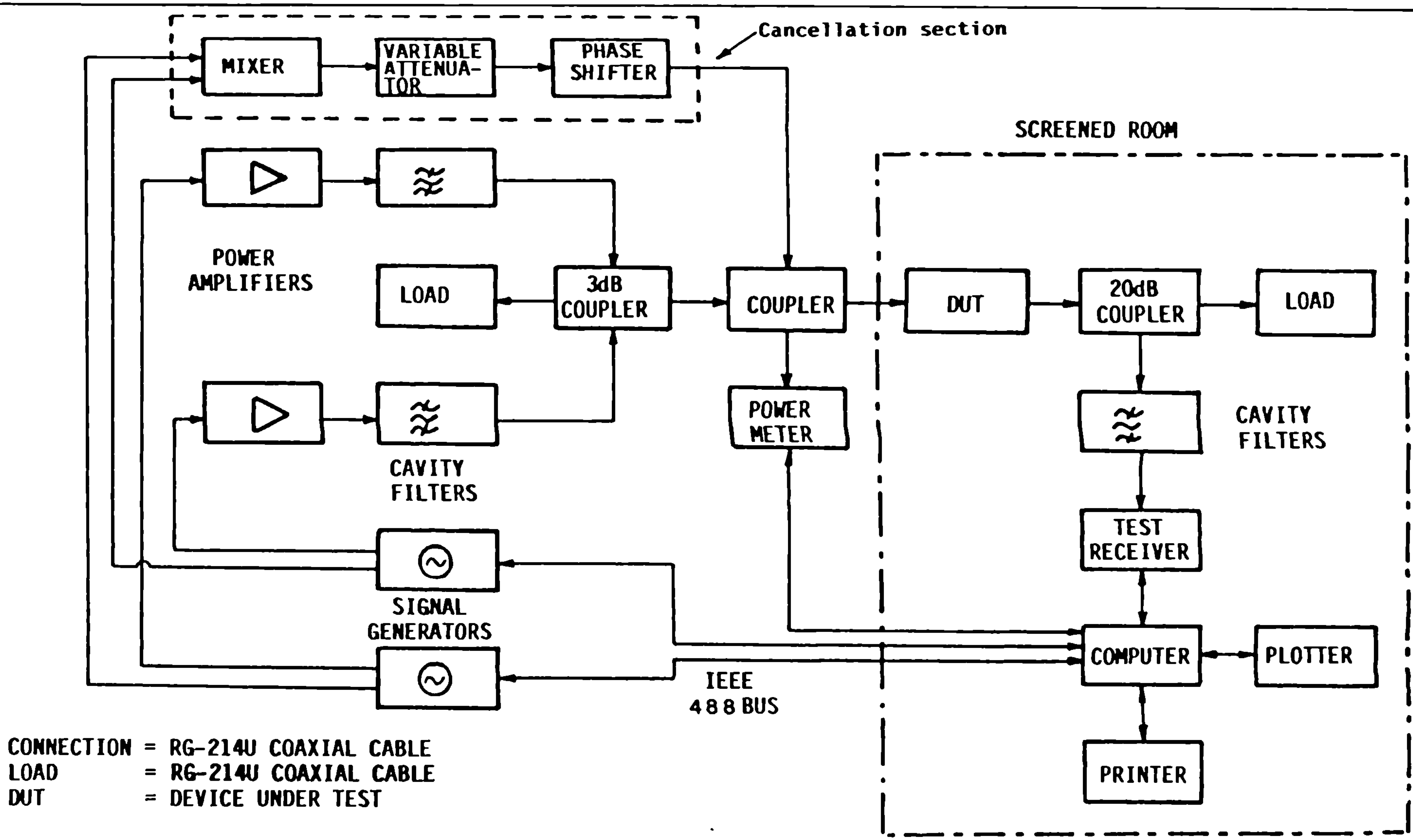
The system (Ref. 22) developed by the author can be seen to have a better performance than comparable systems. This is due to the careful choice of system configuration and equipment, and the cleanliness of components. However, this advantage is less important than consistent performance. In this latter aspect, it has shown excellent stability over a year of use. No attempt has been made to compare this system with other RF measurement systems as the latter have different configurations and operating frequencies.

3.5.2 Suggestions For Improvement

The laboratory system developed by the author has shown excellent performance over the period of use. However, the following improvements can be considered if time and development funds are available. Fig. 3.23 shows the block diagram of the proposed system which has been presented recently [36].

(1) Replace the RG-58C/U cable (dummy load) by RG-214U cable for its better screening and power handling specification.

(2) Replace the two signal generators and the power meter by programmable units thus providing a fully automatic system.



CONNECTION = RG-214U COAXIAL CABLE
LOAD = RG-214U COAXIAL CABLE
DUT = DEVICE UNDER TEST

Fig. 3.23 Block Diagram of Improved PIMP Measurement System

(3) Develop new programs for controlling a fully automatic system.

(4) Improve the isolation between high and low power equipment.

(5) Add a PIMP cancellation section, as suggested and implemented by Woody and Shands [17], to lower the residual intermodulation level. This employs a mixer to generate new intermodulation signals. The amplitude and phase of which are then varied and introduced back to cancell the residual intermodulation signal.

(6) An alternative to suggestion (5) is to add a notch filter, which is tuned to the residual intermodulation signal, at the input port of the test chamber. This suggestion is easier to implement than suggestion (5).

3.6 Summary

A computer-controlled low-noise measurement system has been developed for characterising passive non-linearities in metallic structures. This system can be used for testing a variety of metallic samples as well as connectors, coaxial cables and conducting materials at RF. The system requirements, development and performance have been described. Some suggestions for system improvement have been given. Performance tests showed that this system has met most of the stated requirements and has a better performance than comparable systems.

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CHAPTER 4

Characterisation of Non-linearities in Metallic Structures

4.1 Introduction

This chapter is mainly based on the three papers [1-3] published by the author during the course of the research. It presents the laboratory measurement results of an investigation into the parameters related to the generation of passive intermodulation products (PIMP) in small metallic plates and 1 meter long structural components. The relationships between the PIMP levels and the following test samples and conditions were studied.

(1) Types of metals, joints and corrosion in standardised plate samples.

(2) Types of metals, joints and corrosion in typical structural and support components.

(3) Tightness and looseness at joints, effect of vibration and presence of moisture.

(4) Input power.

The tests were conducted under controlled laboratory conditions in a screened room (see Fig. 3.4). The types of test conditions and samples used were limited to those that are typical of a land mobile radio site environment.

4.2 Test Procedures

The purpose of this section is to explain the basic test procedures for measuring intermodulation signals. To minimise measurement errors, test procedures have been standardised. The mean values from repetitive measurements were used because of the unstable nature of intermodulation signals generated by metallic contacts. Generally there are three basic, sequential steps. First calibrate the test receiver, then put the sample in the test chamber, set the input power level and measure the intermodulation signal level. The PIMP measurements were conducted over a period of approximately six months during 1987 and 1988.

To avoid the creation of non-linear contacts, soldered joints between the samples, connection wires and connectors were used. Non-rigid samples were held in tension during test, and regular checks were carried out to ensure that all connections were clean and tight.

Tests were conducted with equal power from both signal sources and the combined input power was varied from 10 W to 63 W, with a step size of 10 W. Vibration and moisture tests were conducted on a number of samples to study the behaviour of PIMP levels in relation to environmental changes. Vibration was introduced by placing a small vibrator (an air pump) on top of the test chamber. This had the desired effect of vibrating the sample. To ensure the vibration does not loosen the connections, checks were carried out regularly. For the moisture test, the sample was first tested dry, then wetted by tap water and tested again. At each input level (e.g. when the combined input power level was set at 20 W), the 3^{rd} order PIMP levels were measured over a period of one minute and at a sampling interval of one second. The mean value of the PIMP levels was calculated by the computer. In most tests an average of fifteen measurements were done on each sample at each input level. In all tests, the test receiver was set at an IF bandwidth of 7.5 kHz (narrowest) and an operating range of 20 dB. These are recommendated settings [4] for measuring intermodulation signals.

4.3 Test Samples

4.3.1 Samples and Materials

A variety of test samples which closely resemble the typical metallic joints at a radio site were made. These samples can be divided into two types, small metallic plates with dimensions of 6.5×0.2×15.8 cm, and 1 m long structural components incorporating a variety of fixtures. Some of these test samples are shown in Fig. 4.1-4.3.

A total of 89 such samples have been tested and the numbers and types of samples used are summarised in Table 4.1. The materials used were mild steel, hot dip galvanised mild steel, zinc electroplated mild steel, copper and aluminium. All metal corrosion was due to natural oxidisation and clean samples were either made with new or naturally weathered materials. Clean samples here refer to samples without visible rust. The weathered materials are galvanised light duty angle irons and they have been exposed to weather at an antenna site for many years. In the following paragraphs, there are more details about the types of test samples used.

4.3.2 Small Metallic Plates

The 47 plate samples made can be classified into two types, with joint and without joint. They were used to study the intermodulation signals generated by ferromagnetic and non-ferromagnetic metals, and at joints with different degrees of corrosion. Initially salt water was used to create rusty plates and joints, but the rust created on the metal surfaces was found to be too soft and could be removed easily. It was considered that unstable rusty samples were not suitable for repetitive intermodulation measurements. It was then decided that the natural oxidised rusty metals with evenly corroded surfaces should be used for preparing samples.

Samples : Small Plates

Configuration | Materials/Samples

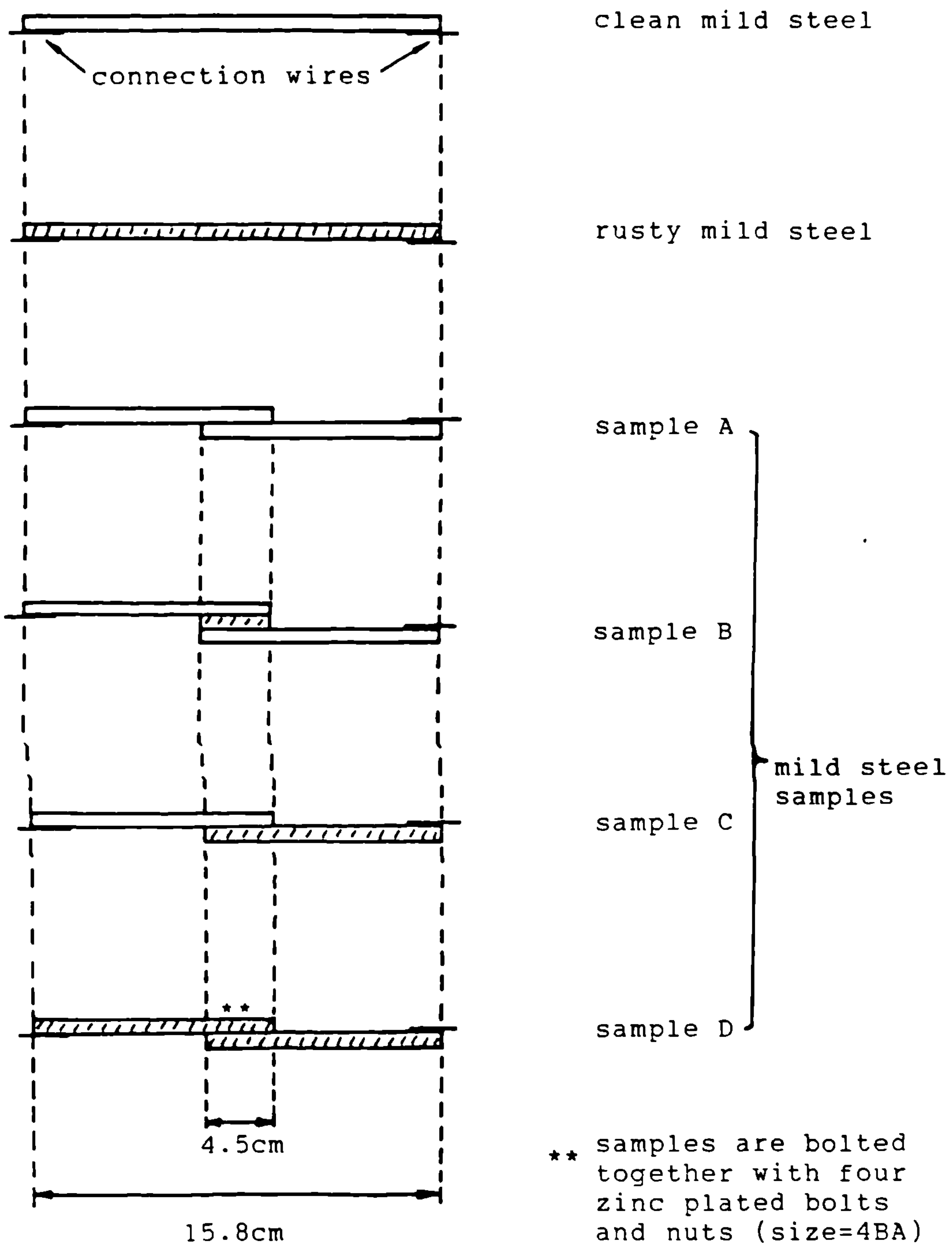

Fig. 4.1 Small Metallic Plates

Samples : Small Plates

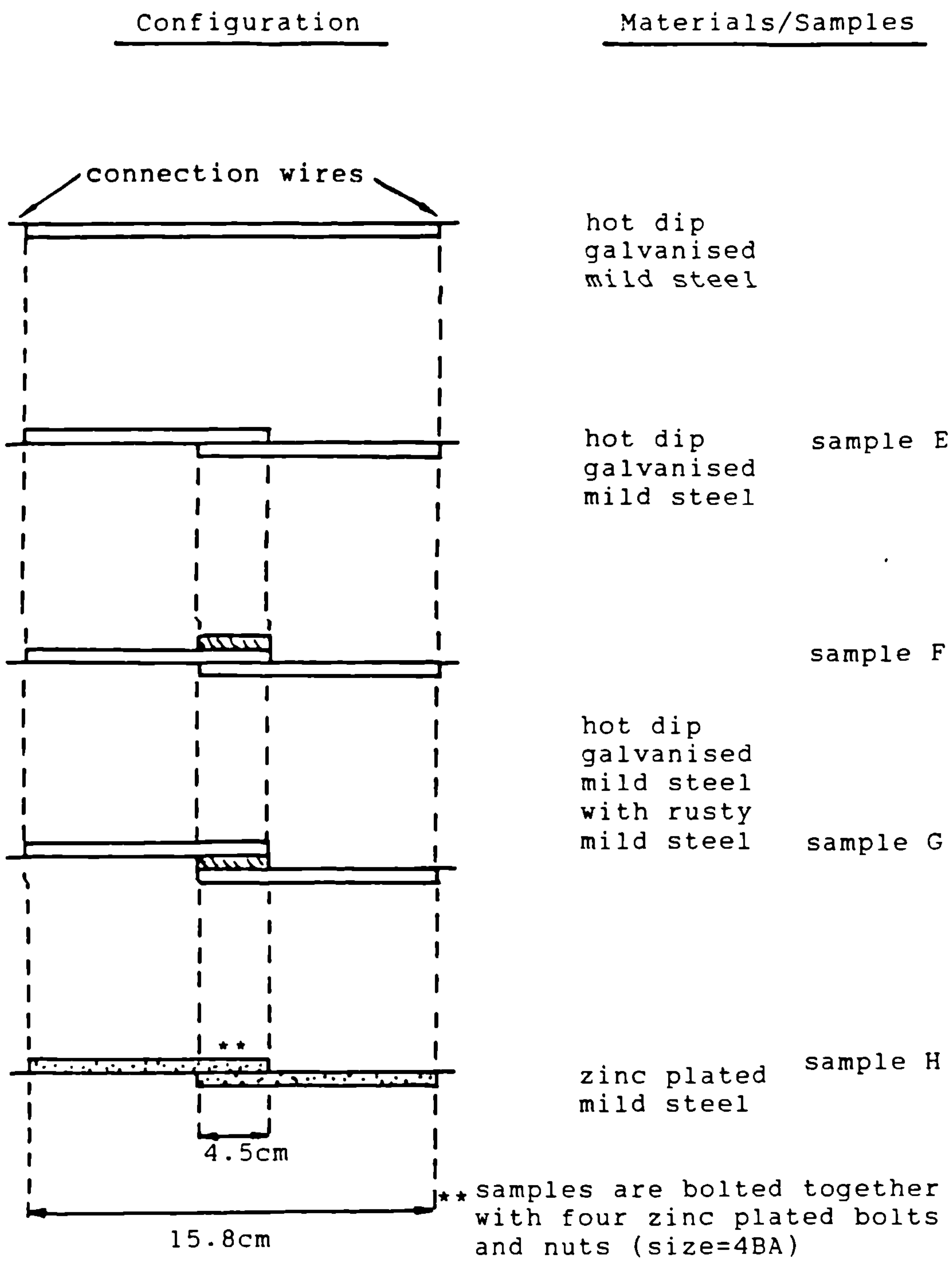

Fig. 4.2 Small Metallic Plates

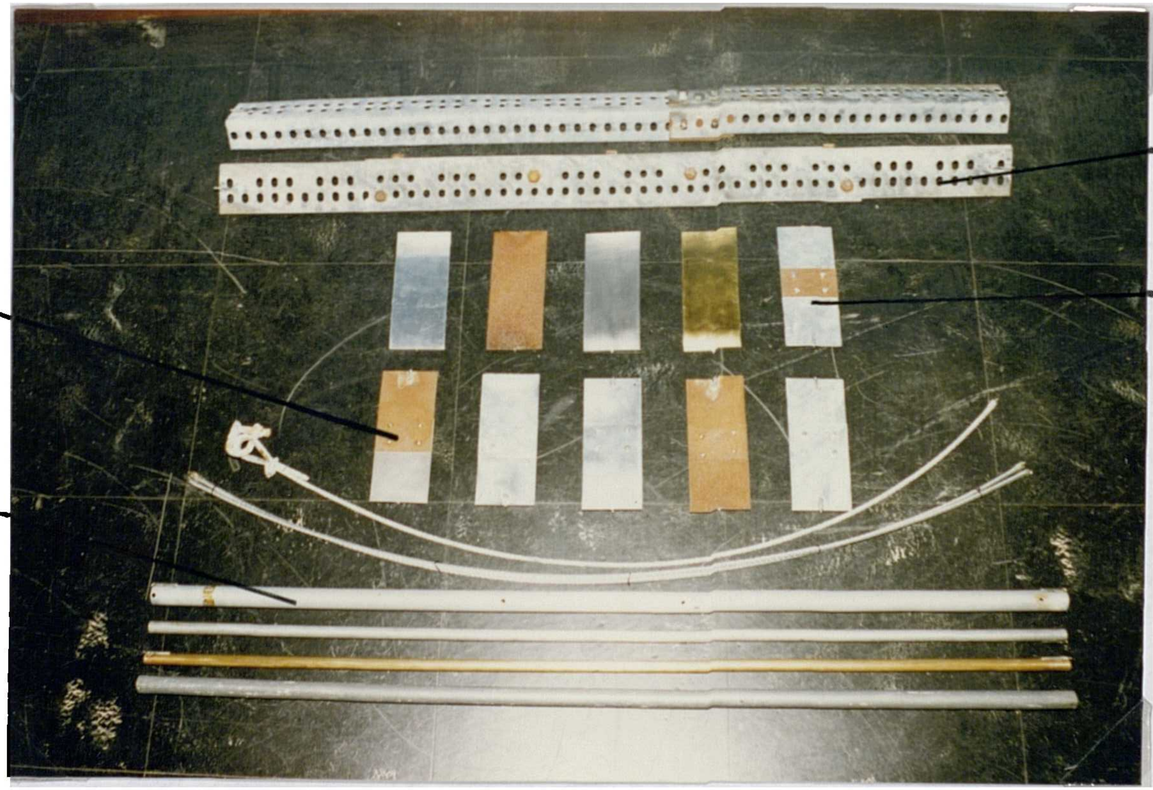

Fig. 4.3 Test samples

	Jointless Samples	Samples With Tight Joint	Samples With Loose Joint
Small Metallic Plates	- Aluminium (3) - Copper (3) - Mild Steel (3) - Hot Dip Galvanised Mild Steel (3) - Rusty Mild Steel (3)	- Sample A (4) - Sample B (4) - Sample C (4) - Sample D (4) - Sample E (4) - Sample F (4) - Sample G (4) - Sample H (4) see Fig.4.1 and Fig.4.2	—
1 m Long Metallic Samples	- Aluminium Rod (2) - Copper Rod (2) - Mild Steel Rod (2) - Aluminium Tube (2) - Copper Tube (2) - Mild Steel Tube (2) - Galvanised Mild Steel Tube (2) - Mild Steel Angle Iron (2) - Galvanised Mild Steel Angle Iron (2) - Galvanised Mild Steel Rope (2) - Rusty Mild Steel Rope (2)	- Angle Iron With Rusty Plate at Joint (2) - Angle Iron With Rusty Bolts and Nuts (2) - Angle Iron (2) - Aluminium Tube With Rusty Bolts and Nuts (2)	- Angle Iron (2) - Mild Steel Chain (2) - Rusty Galvanised Rope With Shackle & Thimble (2) - Aluminium Tube With Rusty Bolts and Nuts (2) - Rusty Mild Steel Chain (2) - Galvanised Rope With Shackle & Thimble (2)

Note : No. in bracket = No. of samples tested
Total no. of samples = 89

Table 4.1 Test Samples

All plate samples were prepared at the University mechanical workshop. The jointed samples were first cleaned with soapy water to remove the grease and then bolted together with four size 4BA zinc plated bolts and nuts (see Fig. 4.3). The zinc coating (hot dip and electroplated) of samples was done by professional platers. The hot dip galvanised samples were prepared according to British Standard BS 729 [5] which is the standard used for zinc coating tower and mast components.

4.3.3 Large Structural Components

Some of the components similar to those commonly used for constructing antennas, radio towers and masts were chosen for measurements. They are light duty angle irons, metal tubes and rods, metal chains, steel ropes and steel ropes with shackles and thimbles. Most of these samples were prepared with new or weathered metals at the University mechanical workshop. The weathered metals with and without rusty bolts and nuts were obtained from an antenna site. Evenly corroded small rusty plate was sandwiched at the angle iron joint to simulate a corroded joint.

4.4 Relationships Between Input and PIMP Levels

The following sections describe the relationships between combined input power and 3^{rd} order PIMP levels. The measurement results are shown in Fig. 4.4-4.15, and the input and PIMP levels shown in these figures were measured at the power meter and test receiver respectively.

4.4.1 Jointless Metallic Plates

The aim of this test was to compare the 3^{rd} order intermodulation signals generated by jointless bulk metals with clean or rusty surfaces. The metals tested were copper, aluminium, hot dip galvanised mild steel, mild steel and rusty mild steel, and the result is shown in Fig. 4.4. As expected the lowest level of intermodulation signal was generated when non-ferromagnetic metals, copper and aluminium, were used as samples. This signal is mainly due to the PIMP generated by the measurement system. The next lowest level of intermodulation signal was generated by hot dip galvanised mild steel. Because of its thick layer of zinc coating, very little RF current is conducted by the mild steel, as a result the contribution from the non-linear hysteresis effect is insignificant. Mild steel plate generates high level of intermodulation signal because of the non-linear hysteresis effect, and it becomes noisier when the surfaces are rusty. A rusty surface can be seen as a surface with many small non-linear contacts and they generate intermodulation signals when energised by RF currents.

4.4.2 Jointed Mild Steel Plates

The 3^{rd} order intermodulation signals generated by jointed mild steel samples with different types of rusty joints were measured and the result is shown in Fig. 4.5. All samples tested have tight joints and Fig. 4.1 shows the configuration of these samples. Sample D, a joint formed by two rusty plates, generates the highest level of intermodulation signal. It is about 7 dB above the PIMP level of a clean joint, sample A. Samples B and C are joints formed by a combination of clean and rusty plates and they have intermediate PIMP levels. The result suggests that the intermodulation signals were contributed by a combination of the non-linear hysteresis effect in mild steel, contact non-linearity at joints and rust on metal surfaces.

4.4.3 Jointed Galvanised Mild Steel Plates

Most of the metallic contacts found on a radio tower are hot dip galvanised mild

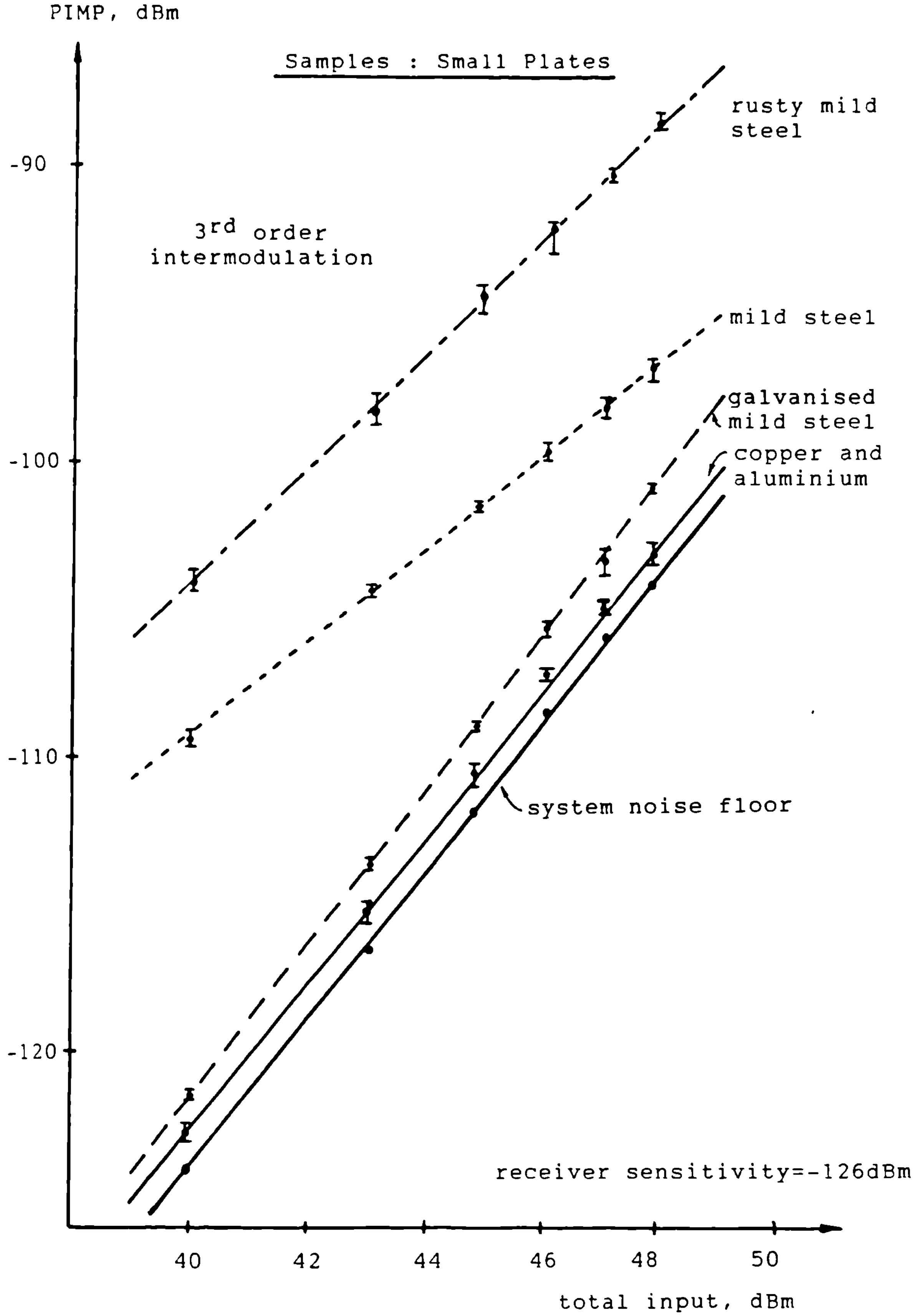

Fig. 4.4 Relationships Between PIMP and Input Levels For Jointless Samples

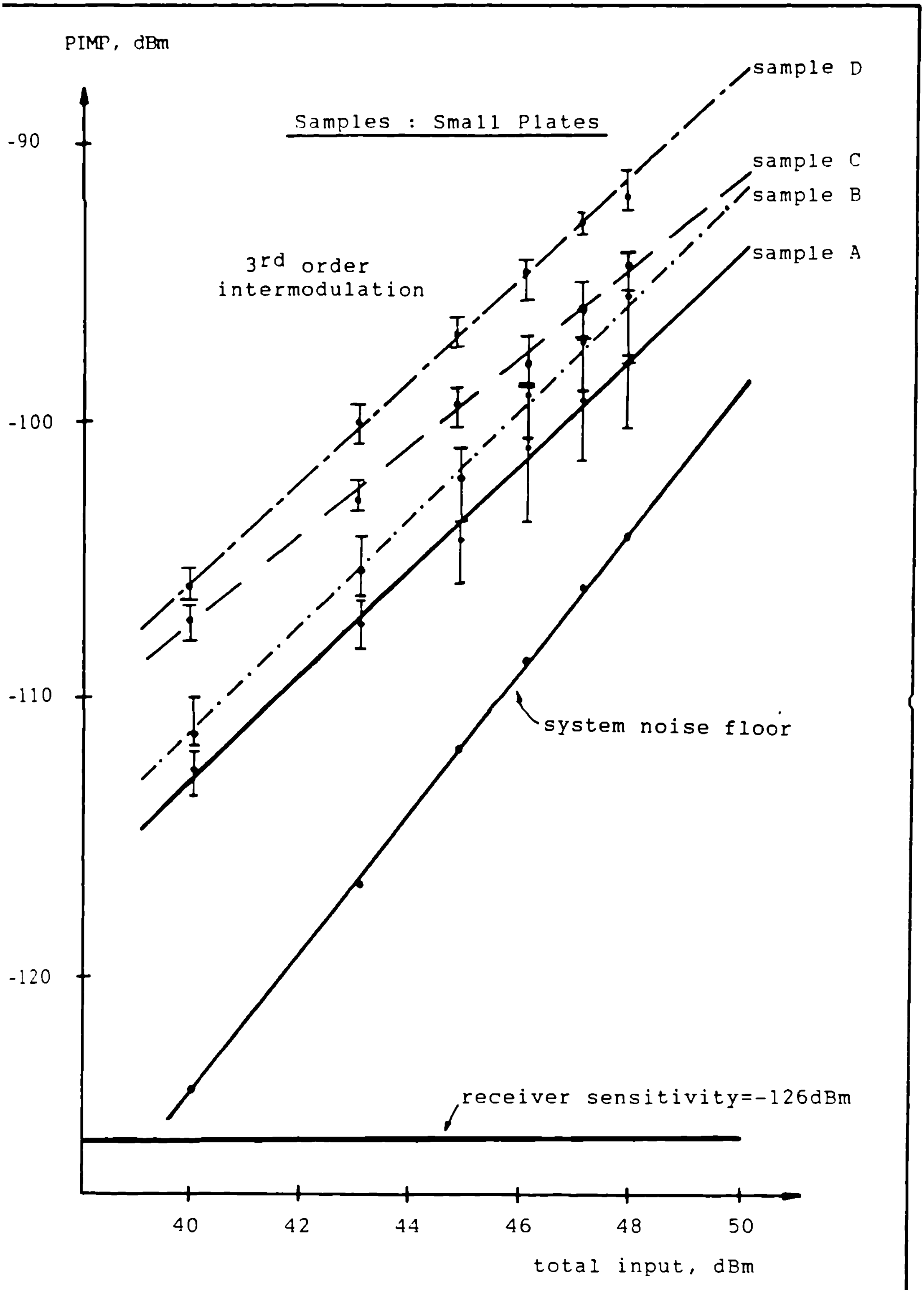

Fig. 4.5 Relationships Between PIMP and Input Levels For Jointed Samples

steel joint. In this section, the intermodulation signals generated by this type of joints are compared with those generated by galvanised mild steel plates and joints formed by zinc electroplated plates. The result as shown in Fig. 4.6 suggests that the jointless galvanised mild steel plate generates the lowest level of intermodulation signal, it is followed by a clean joint, sample E. Other samples such as samples F, G and H, shown in Fig. 4.2, are slightly noisier than sample E. This is due to the rust at joints and the hysteresis effect in mild steel. In zinc coated samples, the intermodulation signals are generated mainly at the joints. The zinc coating conducts most of the RF signals and the contribution from the non-linear hysteresis effect in mild steel is limited. Sample H is noisier than sample E because the former was electroplated and has a thinner layer of zinc coating than the hot dip galvanised sample, sample E.

4.4.4 Jointless Structural Components

This section presents the results of a series of measurements on 1 m long structural components. Samples used were jointless angle irons, tubes, rods and ropes. Results as shown in Fig. 4.7-4.10 suggest that hot dip galvanised mild steel and non-ferromagnetic metals generate very low levels of intermodulation signals. The difference of PIMP level between some mild steel and non-ferromagnetic samples can be as large as 35 dB. These tests conclude that the non-linear hysteresis effect in galvanised radio tower structures cannot be a dominant intermodulation interference source. However, ungalvanised mild steel structures can generate high levels of intermodulation signals. These results agree with those described in Section 4.4.1.

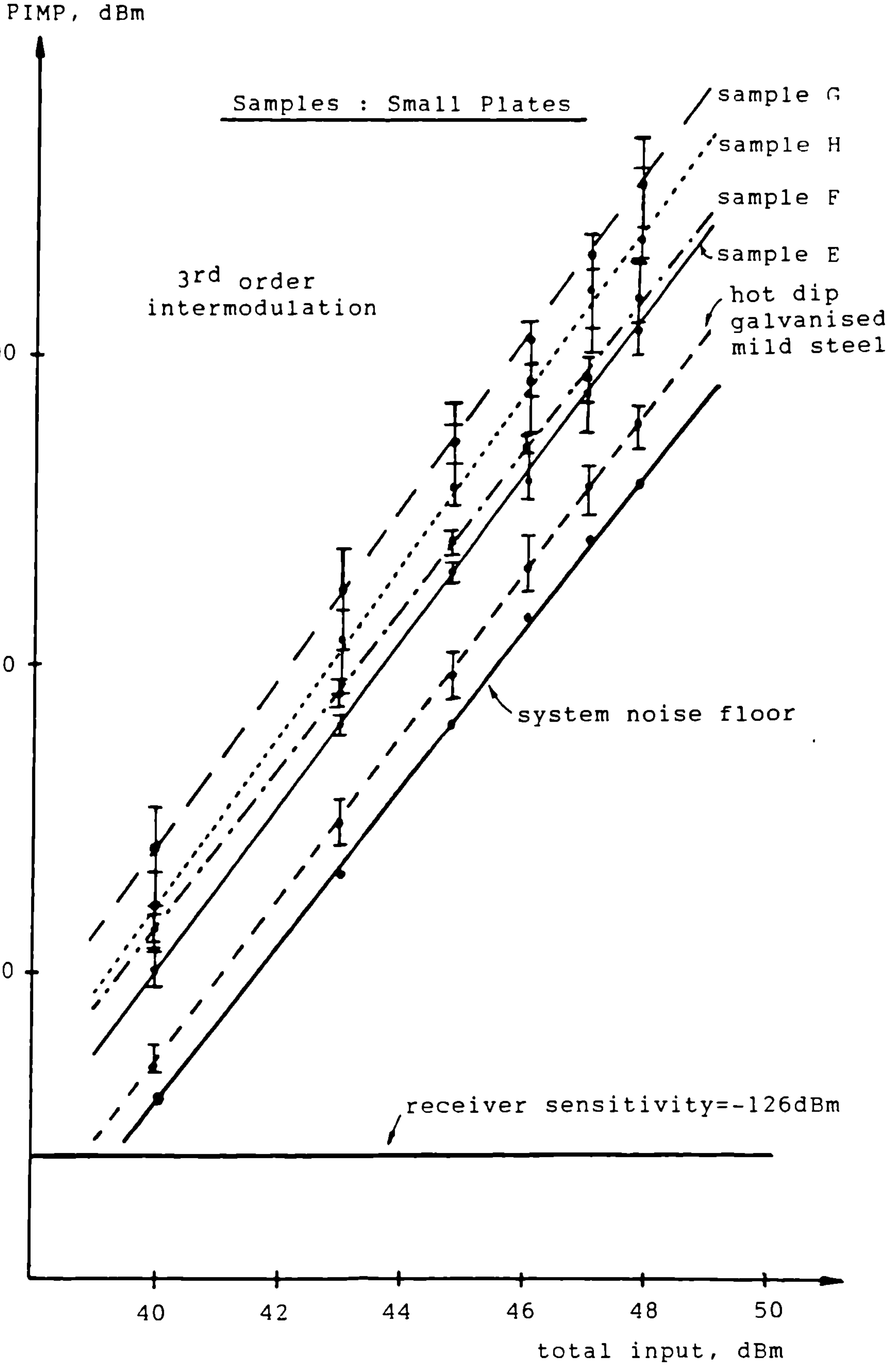

Fig. 4.6 Relationships Between PIMP and Input Levels For Jointed Samples

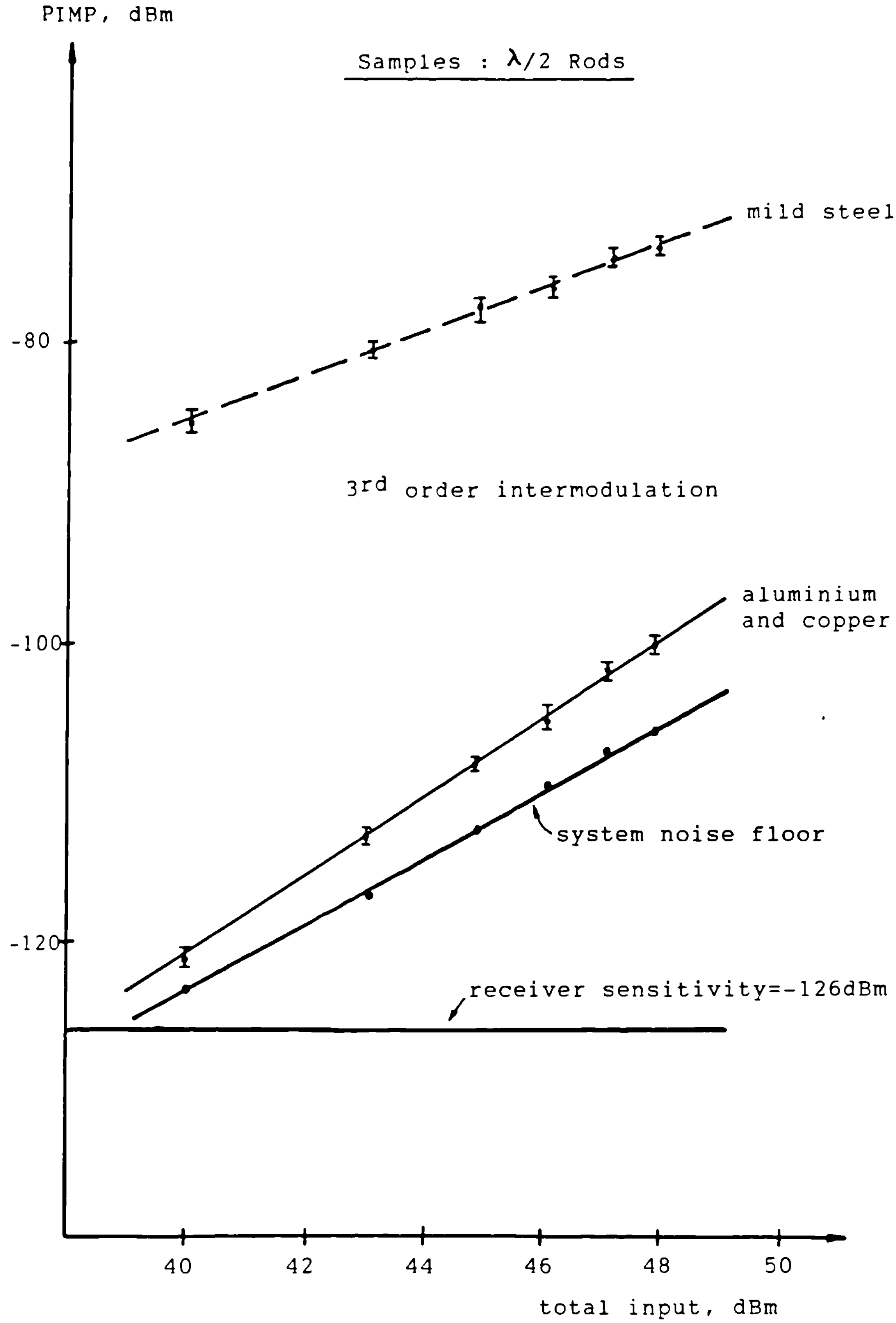

Fig. 4.7 Relationships Between PIMP and Input Levels For 1 m long Rods

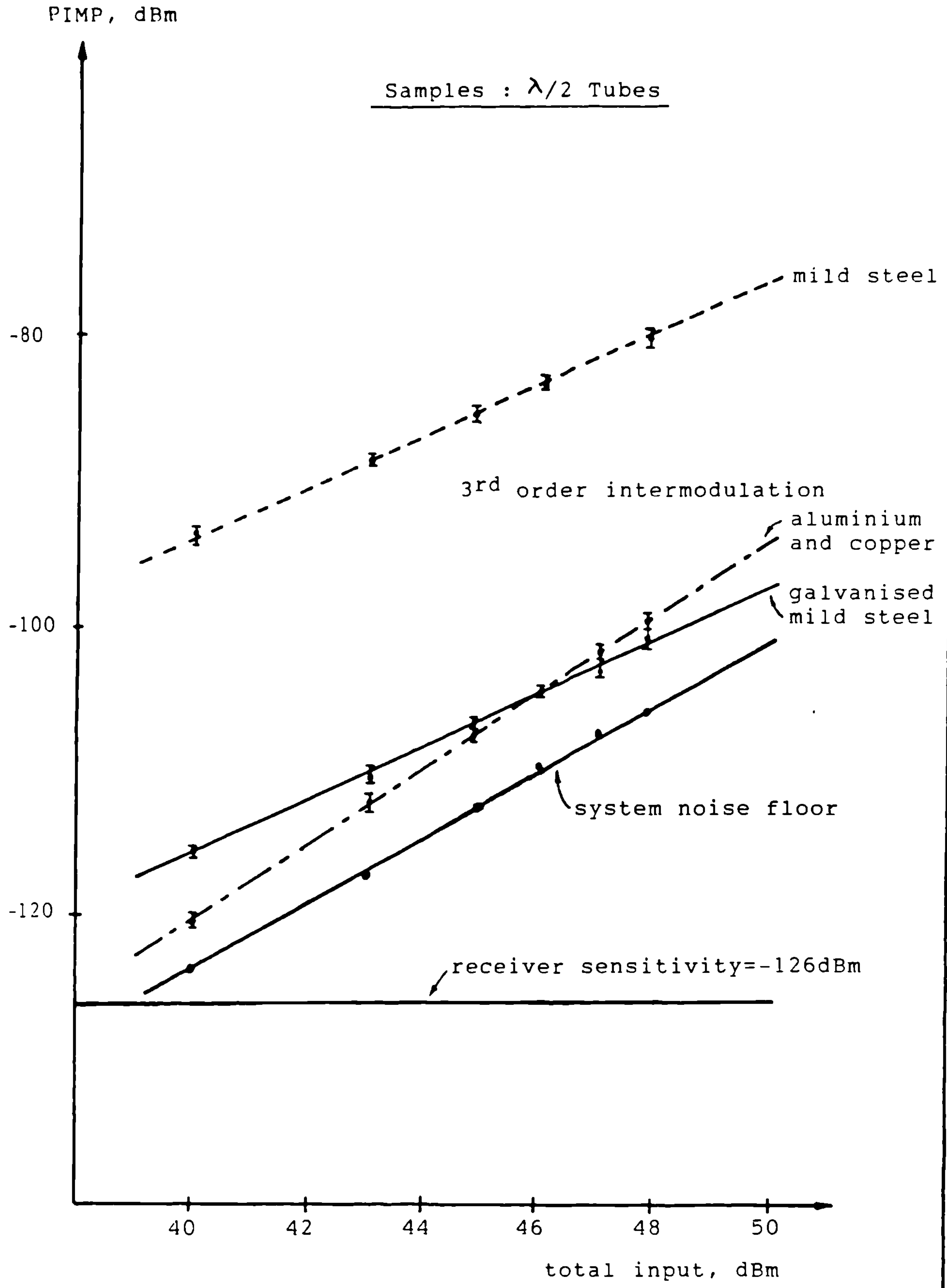

Fig. 4.8 Relationships Between PIMP and Input Levels For 1 m Long Tubes

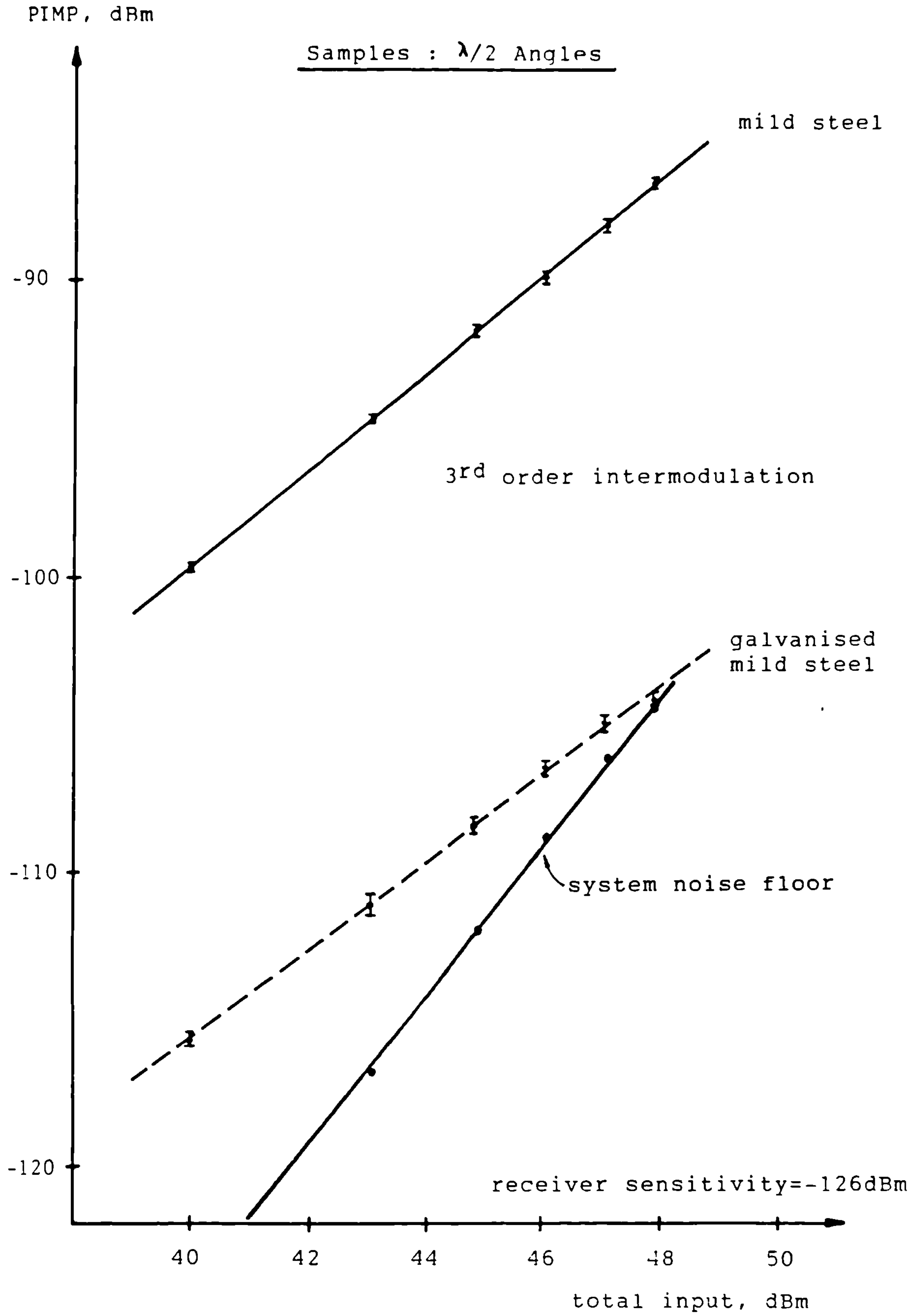

Fig. 4.9 Relationships Between PIMP and Input Levels For 1 m long Angle Irons

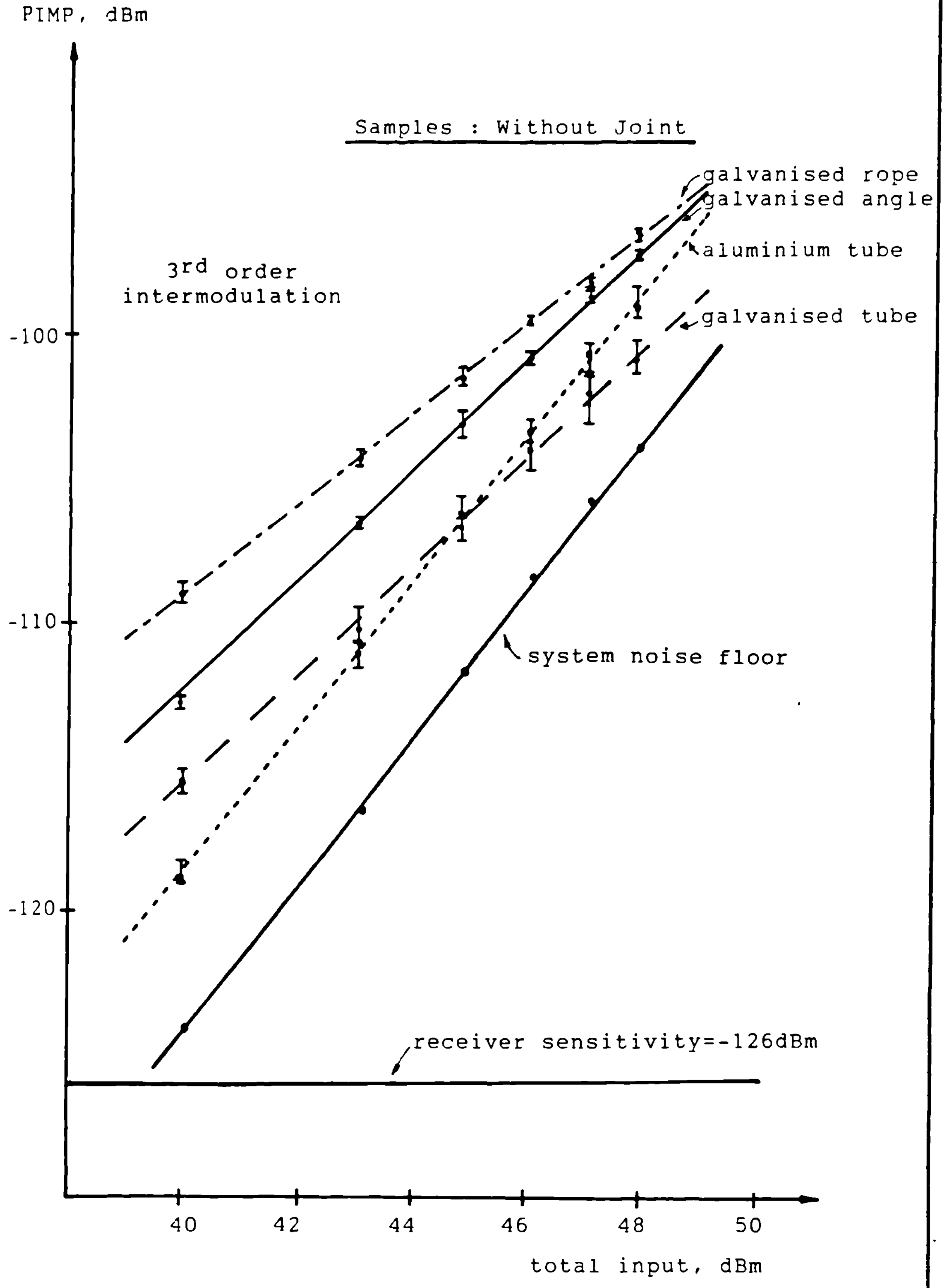

Fig. 4.10 Relationships Between PIMP and Input Levels For 1 m Long Jointless Samples

4.4.5 Jointed Structural Components

Some of the tower components, guy wires and chain-link fences have been reported as sources of intermodulation interference. Jointed samples similar to these types of components were made for intermodulation measurements. Samples used include 1 m long angle irons, mild steel chains and galvanised steel ropes with shackles and thimbles. Tests conducted include tightness, looseness and degrees of corrosion at the joints. Results as shown in Fig. 4.11-4.14 suggest that the rusty joint is not the worst offender, if the joint is tight the effect may actually be minimal. Components on a radio tower or mast, that have loose and/or small area mating surfaces, can generate much stronger intermodulation signals than those due to corrosion alone. This explains why most of the passive intermodulation interference sources located are loose metallic joints.

4.4.6 Aluminium Antenna Structure

A wide range of small metallic plates and large structural components have been tested and the results have been discussed. In this section, the measurement of a weathered aluminium antenna structure is described. The sample used is a Yagi antenna with corroded bolt and nut joints. The reflector elements of the Yagi antenna have been cut away and the sample is in the form of a 1 m long tube with four corroded joints. The sample was first measured with these four corroded joints, then measured with loosely tightened corroded joints and without joints. The result, shown in Fig. 4.15, suggests that loose joints generate higher PIMP levels than tight corroded joints, and the difference in PIMP levels between a jointless sample and a sample with tight corroded joints is less than 5 dB. This indication agrees with many test results obtained from other types of samples.

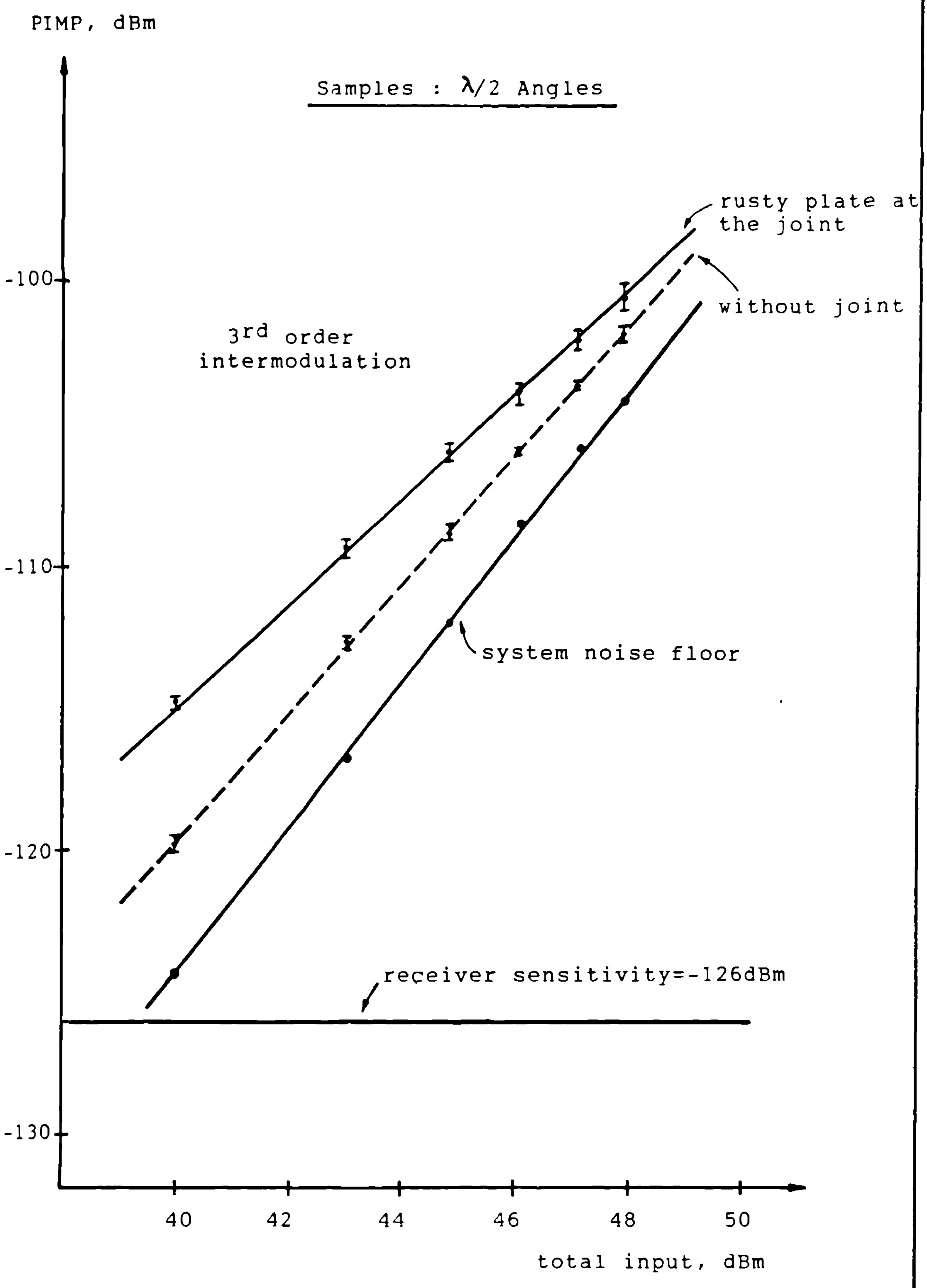

Fig. 4.11 Relationships Between PIMP and Input Levels For 1 m Long Angle Irons

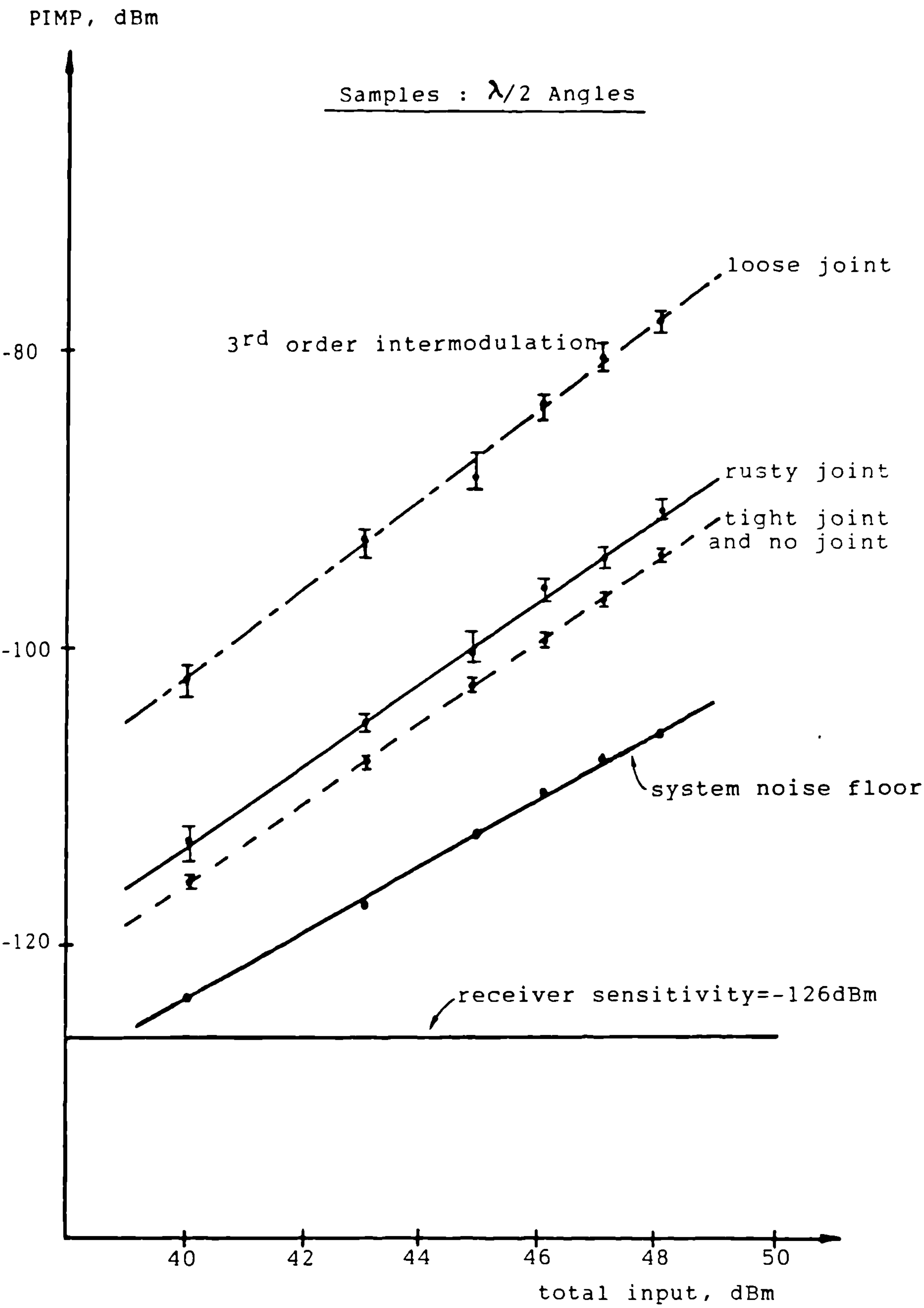

Fig. 4.12 Relationships Between PIMP and Input Levels For 1 m Long Angle Irons

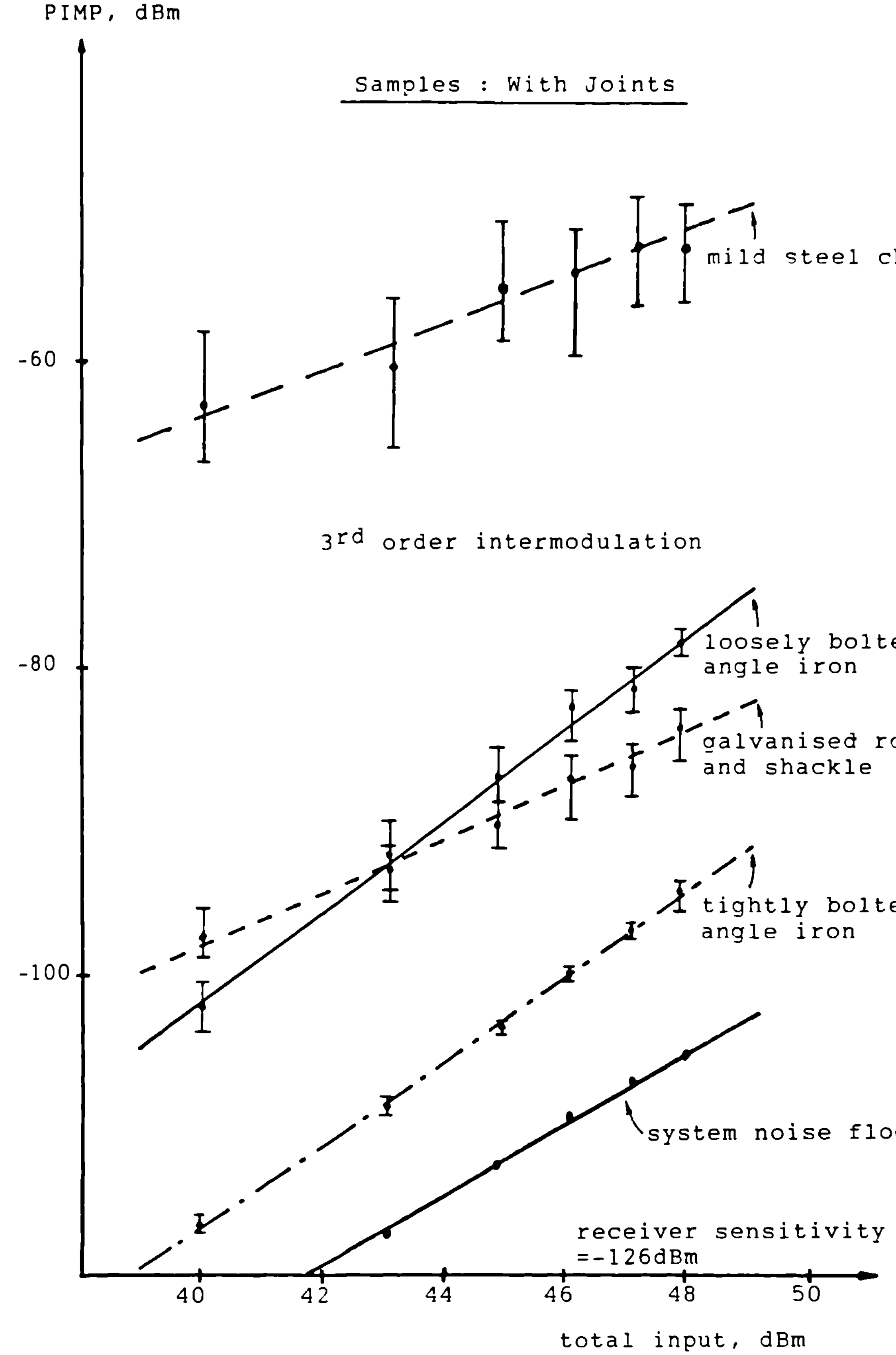

Fig. 4.13 Relationships Between PIMP and Input Levels For 1 m Long Jointed Samples

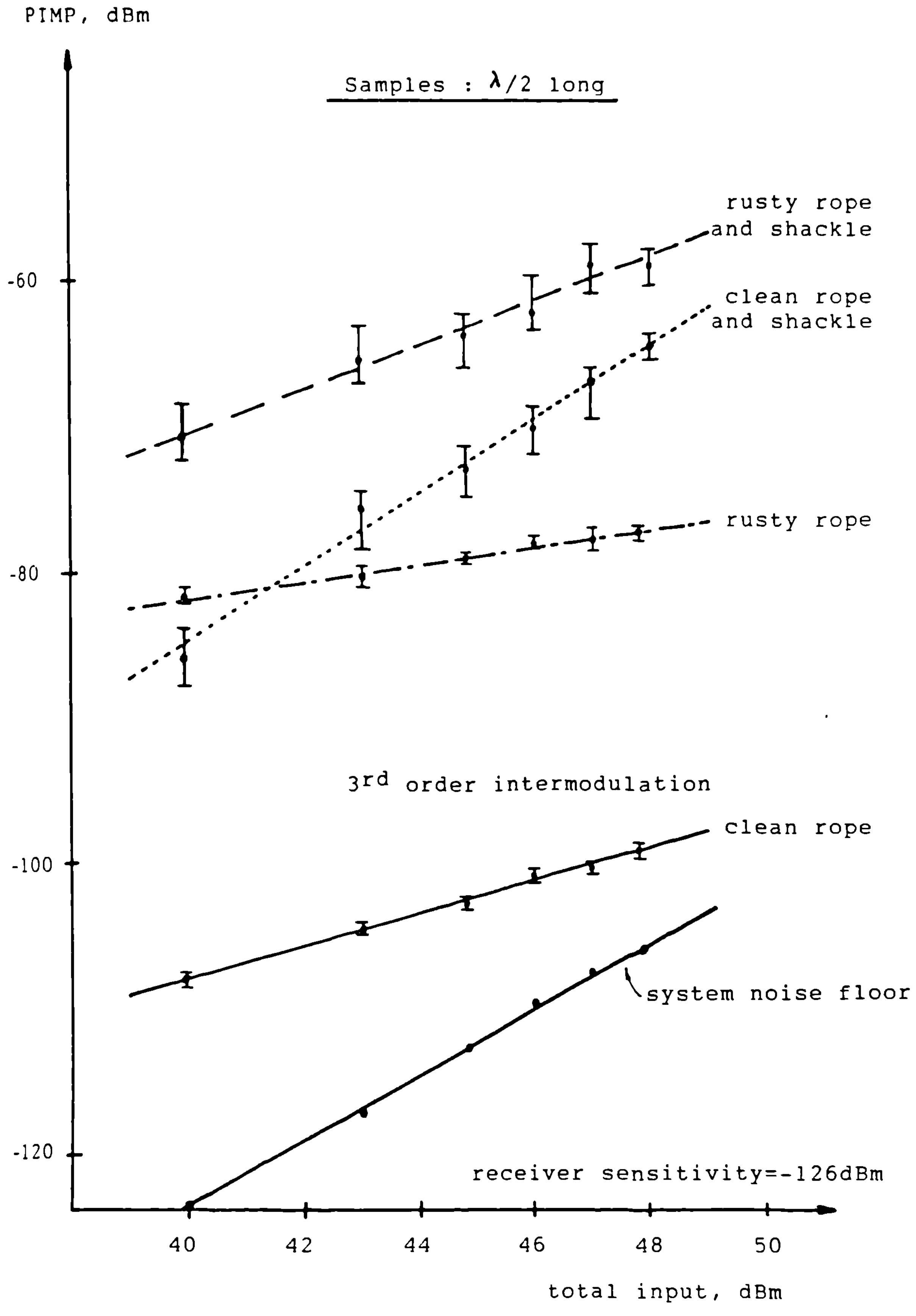

Fig. 4.14 Relationships Between PIMP and Input Levels For 1 m Long Jointed Samples

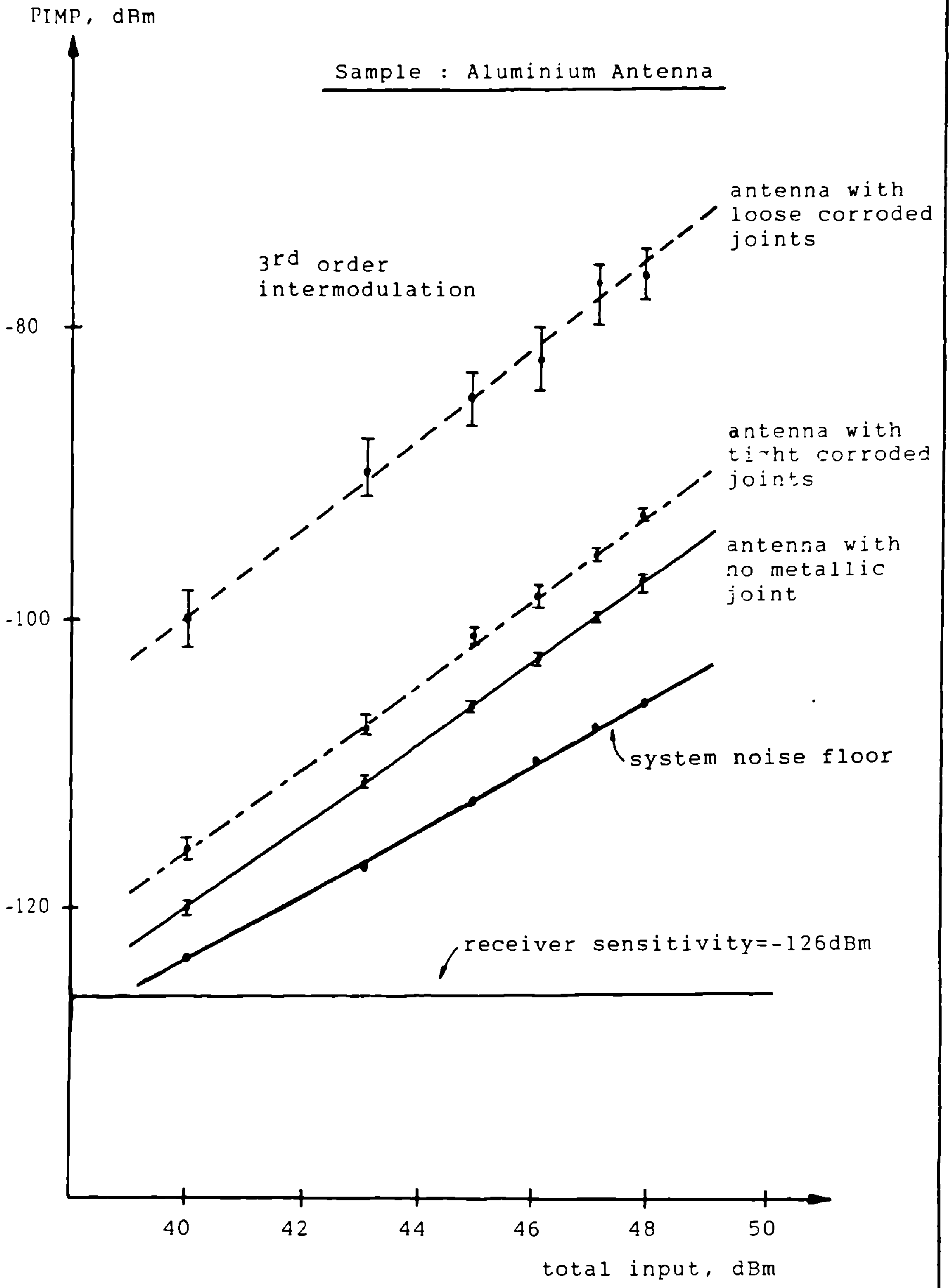

Fig. 4.15 Relationships Between PIMP and Input Levels For 1 m Long Aluminium Antenna

4.5 Relationships Between Vibration and PIMP Levels

Metallic structures and components at radio sites are always subject to various degrees of wind loading. This in turn induces vibration to the structures and may affect the performance of PIMP generation. In this section, the relationships between PIMP levels and vibration are presented. Vibration was induced to the sample by placing a small vibrator on top of the test chamber. Samples used were 1 m long angle irons, steel ropes and steel ropes with shackles and thimbles. First the tightly bolted angle irons with corroded joints were tested. The PIMP levels were measured at constant input power of 10 W over a period of one minute. The result as shown in Fig. 4.16 suggests that the vibration induced in a tight joint has almost no effect on the PIMP levels. However, the PIMP levels fluctuate randomly over a wide range when the loosely bolted angle irons and galvanised steel ropes with shackles and thimbles were used as samples. This can be seen in Fig. 4.17-4.18. The last test was conducted on a pair of steel ropes tied together with insulated wires. Result as shown in Fig. 4.19 suggests that even without vibration, the PIMP levels fluctuate randomly over a wide range. These tests indicate that any lightly touching metals can generate very unstable high level intermodulation signals. This may due to the non-linear properties of high current densities at small mating surfaces. The vibration induced changes the contact areas which in turn cause a highly variable PIMP.

4.6 Relationships Between The Presence of Moisture and PIMP Levels

Radio towers, antennas and related components are constantly exposed to various environmental conditions which may affect PIMP generation. The presence of moisture at joints is one of these conditions and an attempt has been made to study its effect on PIMP generation. Small metallic plates were first measured in a dry

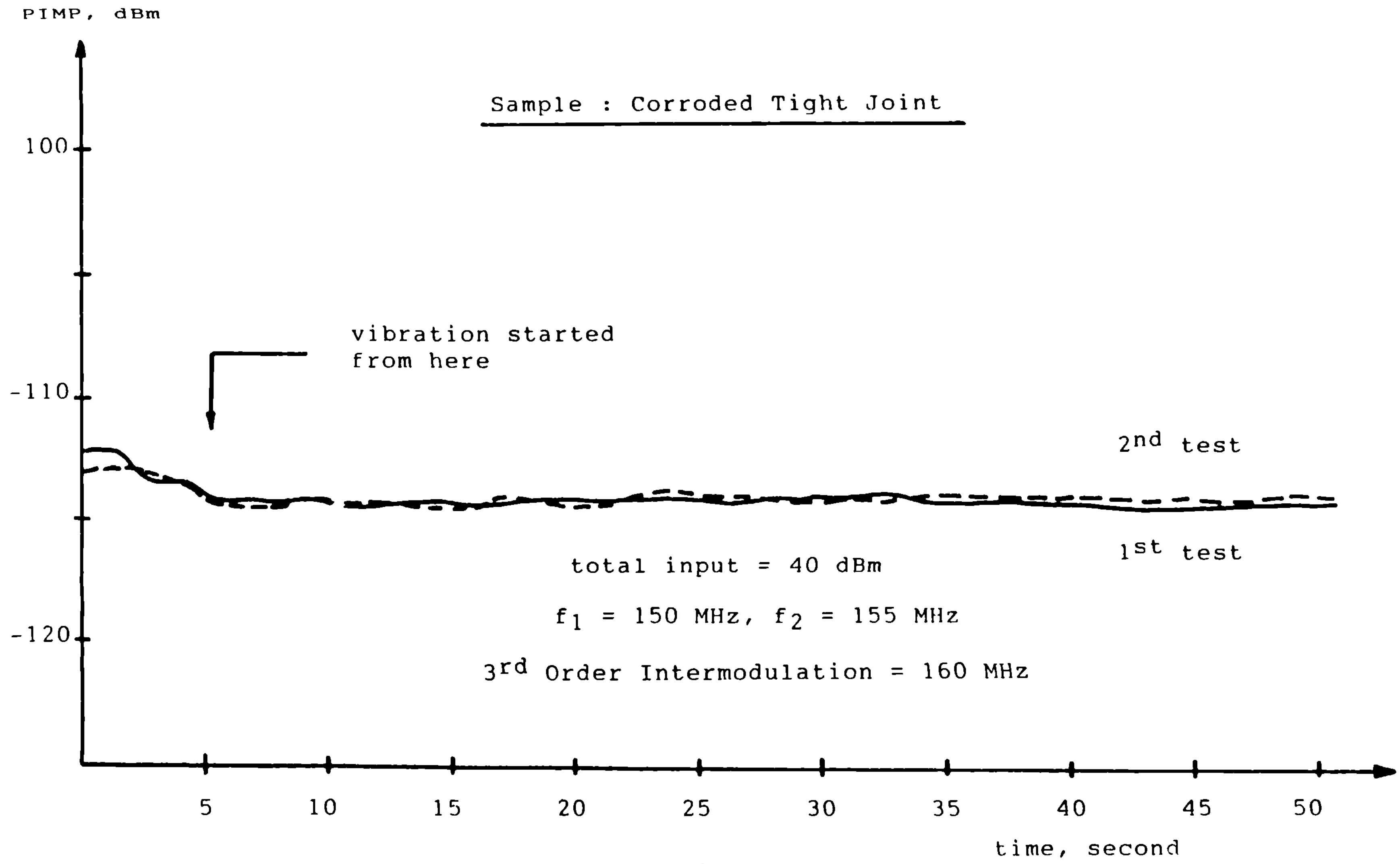

Fig. 4.16 PIMP Levels of an Angle Iron With Corroded Joints

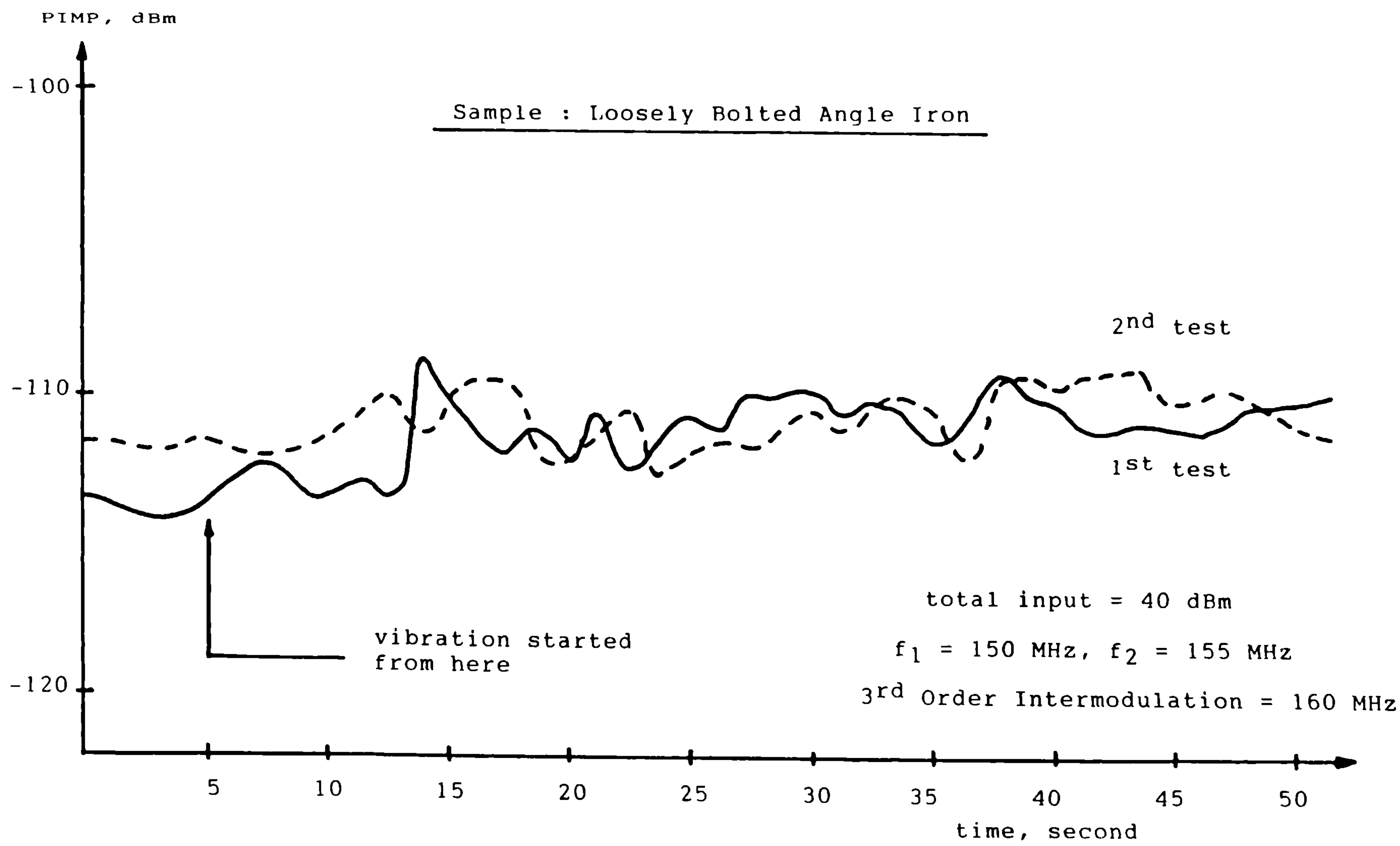

Fig. 4.17 PIMP Levels of a Loosely Bolted Angle Iron

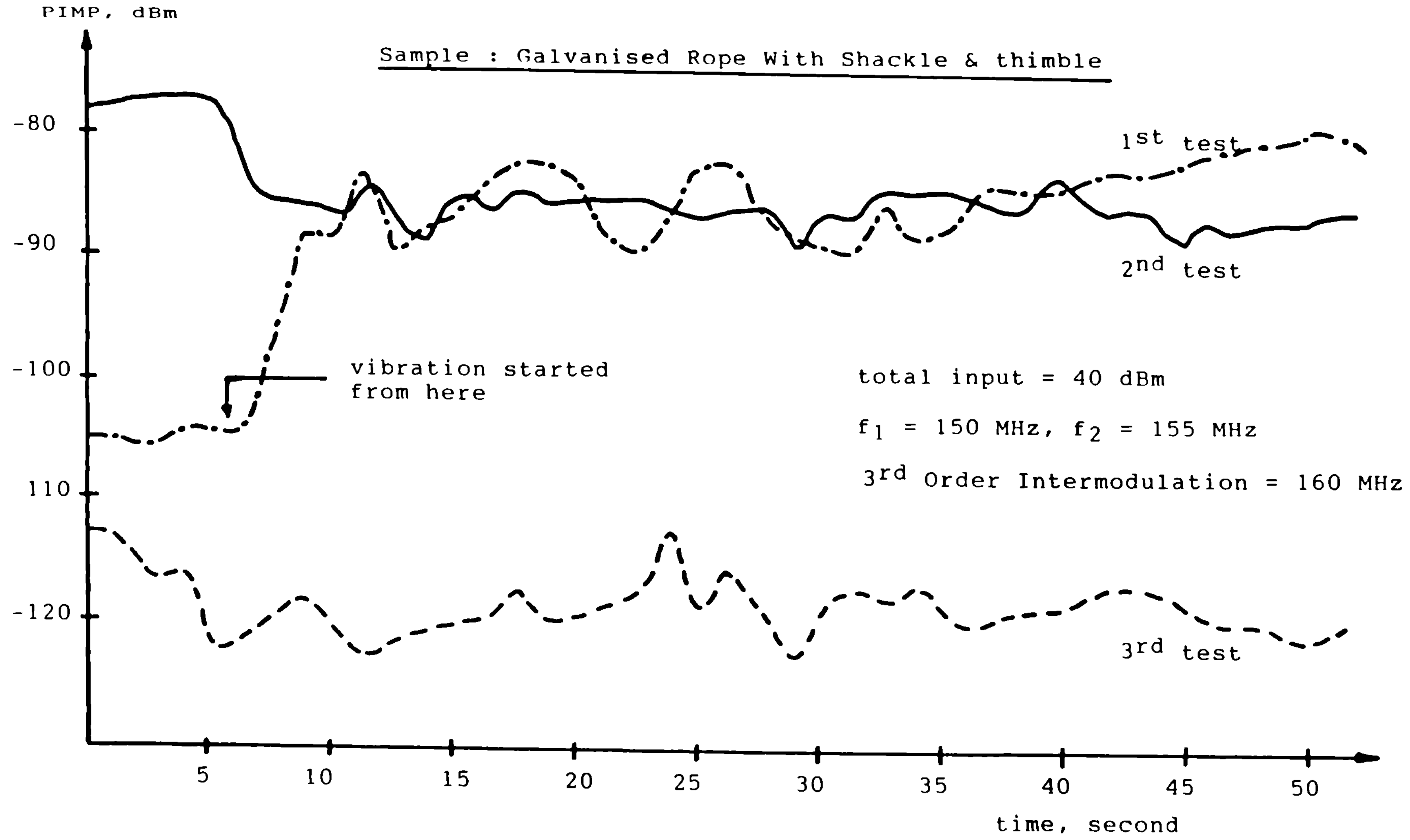

Fig. 4.18 PIMP Levels of a Galvanised Rope With Shackle & Thimble

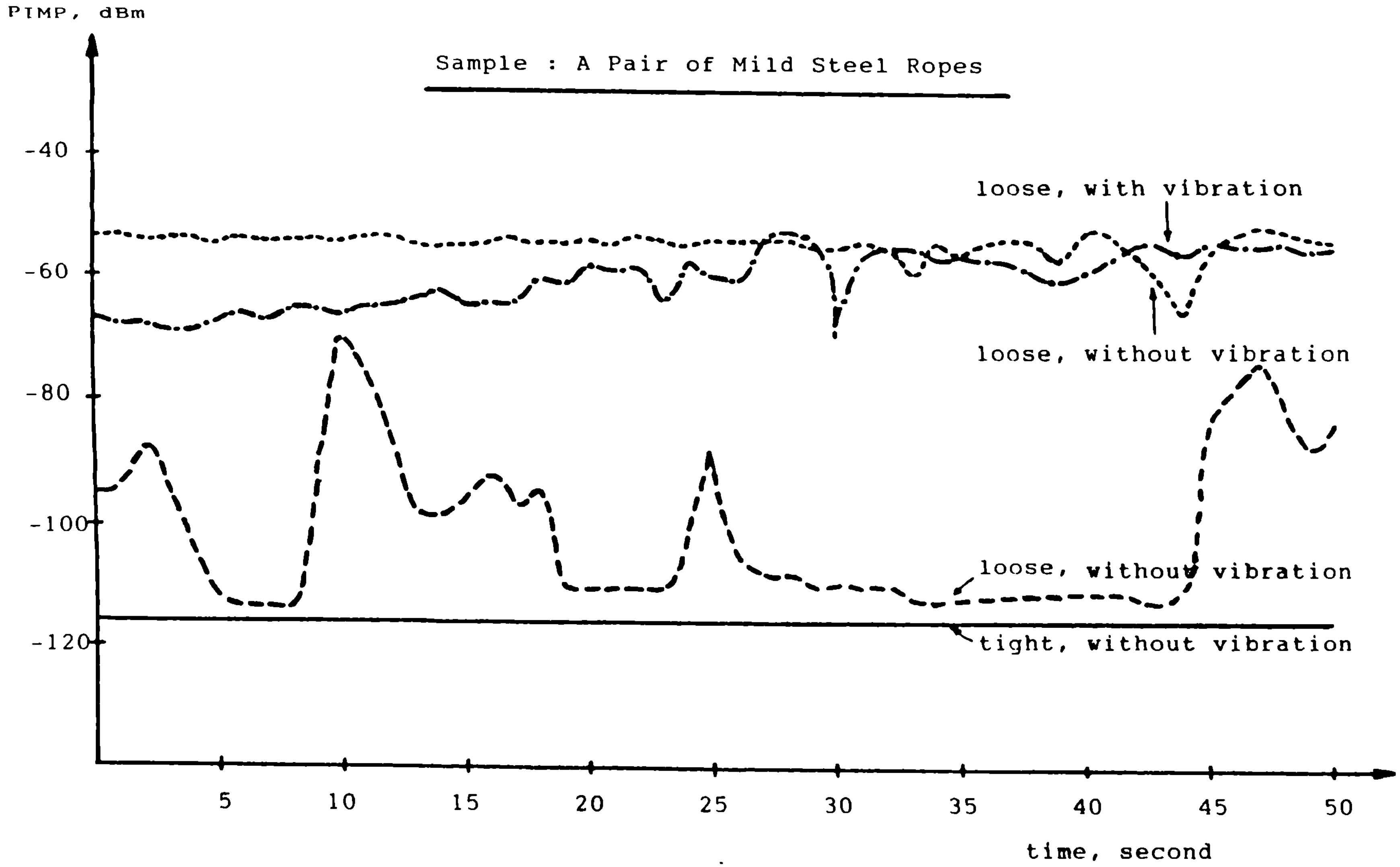

Fig. 4.19 PIMP Levels of a Pair of Mild Steel Ropes Tight Together

condition, then removed and wet by immersion and returned to the test chamber for further measurement. Large structural components were measured in a similar way except that each joint was wetted by spraying tap water on it. The measurement time was one minute for each test and the mean PIMP level was used. A variety of samples have been tested, but the intermodulation signals generated by wet samples were very unstable and no conclusive result can be drawn. To understand the relationships between PIMP levels and wet contacts, perhaps tests need to be carried out in an outdoor environment and long term measurement is necessary to provide convincing results.

4.7 Summary

A total of 89 structural components and small plate samples have been measured and the parameters that affect the generation of PIMP have been studied. The results of the laboratory measurements suggest that the non-linear hysteresis effect in galvanised mild steel structures and components is not a dominant intermodulation interference source at VHF frequencies. This is due to the thick layer of zinc coating which conducts most of the RF currents. However, ferromagnetic materials and structural components with loose and/or small contact areas can generate significant levels of intermodulation signals. A corroded joint is not necessarily the worst offender, if the joint is tight or has low impedance paths, the effects may actually be minimal. However, loose joints are very frequent offenders. This may due to the non-linear properties of high current densities at loose mating surfaces. The 3^{rd} order intermodulation signal and input power relationship varies between 1.5 and 3 dB/dB and may be predicted approximately by a power series. On the other hand, the effects of vibration and moisture on PIMP generation are difficult to model and predict. To understand the behaviour of passive intermodulation signals in relation to environmental changes, long term measurement at radio sites is necessary.

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CHAPTER 4

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CHAPTER 5

Field Measurement System and Passive Intermodulation Product Measurements

5.1 Introduction

This chapter describes the field measurement system, measurement method and preliminary results of an investigation into passive intermodulation products (PIMP) generated by a small radio tower, antennas and related mounting components. The internal and external parameters related to the generation of PIMP were studied. The tests were conducted under conditions similar to a radio site environment and with transmitted powers of up to 25 W at 150 MHz. The field measurement system was developed for the following reasons:

(1) To extend the study of PIMP previously conducted in the laboratory into an outdoor environment.

(2) To observe the behaviour of passive intermodulation signals in relation to environmental changes.

(3) To provide an outdoor test facility for evaluating methods of detecting and locating PIMP sources.

The 'rusty-bolt' effect at land mobile radio sites has been widely reported, however, not many field studies related to this interference problem have been conducted over the last forty years. In this section, a brief review of previous investigations is presented. One of the earliest field study was conducted in the early 50's by a team of engineers from the New Zealand Post Office [1]. They set up a VHF field measurement system and measured the effective radius of the intermodulation interference zone. They concluded that with transmitted power of 25 W, the location of PIMP sources should be confined, initially, to a radius of 100 ft from the transmitting aerials. About twenty years later, a similar test was conducted by a research student in England [2]. In the 80's, there were renewed interest in this subject and several investigations were conducted with different objectives. The measurements carried out by the Southampton University team were aimed at determining the significance of the 'rusty-bolt'effect at land mobile radio sites [3]. They measured three different sites and concluded that at typical transmitted power of 32 W, the PIMP generated by the tower structures, antennas and surrounding metalwork are negligible, however, at higher transmitted power, 500 W, the 11^{th} order PIMP were measurable. The research work at City University was mainly concerned with the suppression of the 'rusty-bolt' effect with chemical agents [4]. A VHF field measurement system with remote data logging facility has been developed for monitoring the intermodulation signals, however, no field test results are available yet. A UK Home Office team also conducted several field measurements [5, 6] in relation to the PIMP levels, polarisation, transmitter configuration and audio impairment. Since the early 80's, all the studies [3-10] conducted in this country were aimed at solving the passive intermodulation interference problems at land mobile radio sites used by the UK Emergency Services.

5.2 Field Measurement System

5.2.1 Introduction

The field measurement of PIMP may be conducted at an operational radio site or at a simulated radio site. The choice depends upon the objectives and both approaches have been used [1-6], however, experience has shown that there are several difficulties in the former.

(1) Tests may interfere with services in use.

(2) User signals may interfere with the measurement process.

(3) The cooperation of the controlling authority must be obtained.

(4) Some travelling is usually necessary.

Such constraints can be eased to some extent in the case where the measurement programme can be achieved by on-site data logging [4]. However, for this investigation, in view of the range of activities anticipated, it was considered that a simulated radio site would be more appropriate. A convenient and relatively low noise location was therefore chosen. This and the field measurement system are described in the following sections.

5.2.2 Measurement Site and Radio Tower

An ideal test site for field experiment needs to be electromagnetically clean, be close to the University and have the essential facilities to support the measurement system. The chosen location is situated on the edge of the campus and is away from the University main buildings. It faces an open field and has a radio amateur station which can be used to house the test equipment.

Initially it was suggested that the measurement system should be set up on an open flat ground where the 'rusty-bolt' sample would be energised by two folded dipoles and the intermodulation signals generated would be detected by a log-periodic antenna. However, after a detailed study of various systems, it was concluded that a small tower with transmit and receive antennas and 'rusty-bolt' samples would be a better configuration. It provides a more realistic test environment and can be used as a permanant facility for studying the 'rusty-bolt' effect. It was therefore decided that a 8 m galvanised angle tower, which forms the top sections of a 89 m radio tower, would be erected. One of the folded dipoles would be used for transmission and the other folded dipole and log-periodic antenna would be used for detection. The specification of the tower and the picture of the test site are shown in Fig. 5.1 and 5.2 respectively.

5.2.3 System Design

The field measurement system design is very similar to the laboratory measurement system design except that both exciting and sampled signals are radiated. The block diagram of the measurement system is shown in Fig. 5.3. In the signal generation and combination section, two unmodulated VHF signals produced by synthesised signal generators are amplified by linear power amplifiers..Two high-Q bandpass cavity filters are used in each transmission arm to filter and isolate the signals. A 3 dB coupler with an isolation of 30 dB is used as a signal combiner and the combiner load is provided by a 300 m length of RG-58C/U coaxial cable. The combined signals are fed to the transmit folded dipole via a through-line power meter which monitors the forward and reflected signals. The isolation between the two transmit signals spaced 2 MHz apart is approximately 85 dB.

In the receive section, signals from the receive folded dipole are filtered by three high-Q bandpass cavity filters tuned to the desired intermodulation signal. Signals received by the log-periodic antenna are attenuated by a 100 m of RG-58C/U coaxial cable, which has an attenuation of approximately 20 dB at 150 MHz. Its function is to reduce the risk of overloading the test receiver. The harmonic and

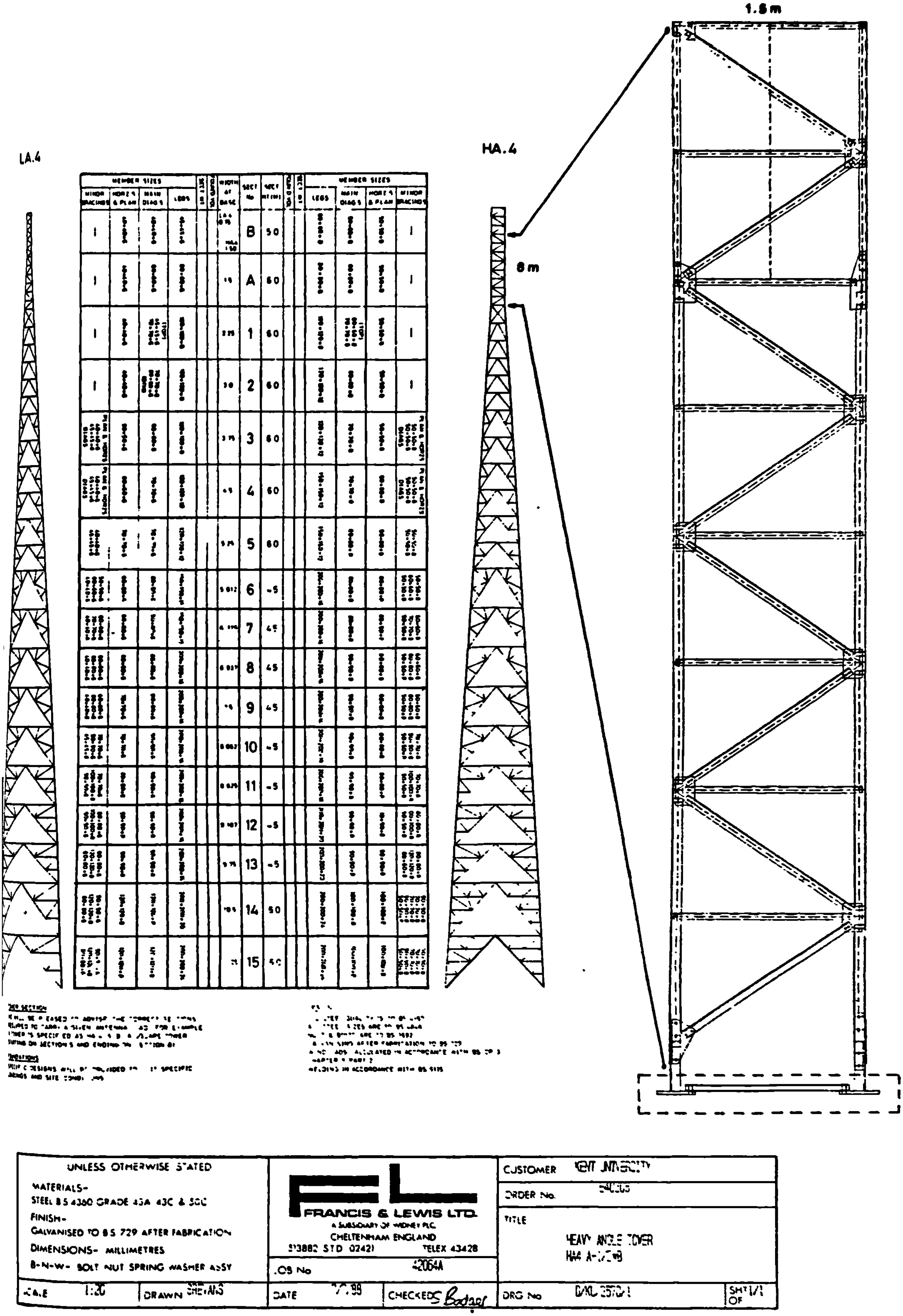
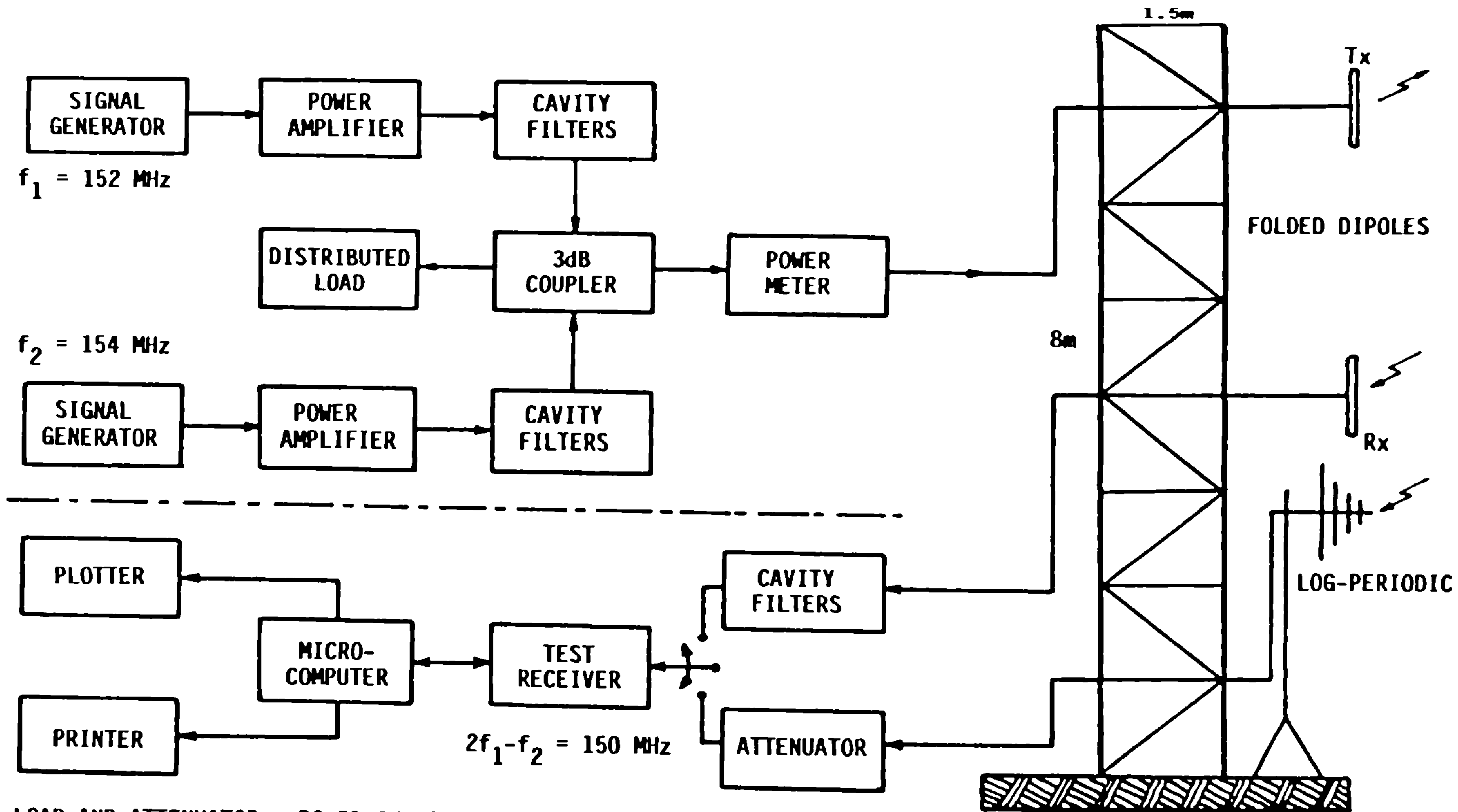


Fig. 5.1 8m Heavy Angle Radio Tower

Fig. 5.2 Field Measurement Site



LOAD AND ATTENUATOR : RG-58 C/U COAXIAL CABLE
CONNECTION CABLE : RG-214U COAXIAL CABLE

FOLDED DIPOLE BW: 143-156 MHz
LOG-PERIODIC BW: 80-1300 MHz

Fig. 5.3 Block Diagram of Field Measurement System intermodulation signals are measured by the receiver and the control and processing of data is done by a microcomputer.

The two folded dipoles are separated by 3 m vertically and 1.5 m horizontally to give sufficient isolation, and the log-periodic antenna is mounted on a tripod below the receive dipole. The folded dipoles, shown in Fig. 5.3, were positioned to give minimum VSWR. The VSWR measured was less than 1.1, but it must be clarified that the actual VSWR should be slightly higher because the reflected signal was attenuated by the coaxial cable. The total loss due to the insertion loss of the cable and mismatch at the antenna is estimated to be 3 dB for each link. The two fundamental and 3^{rd} order intermodulation signals are 152 MHz, 154 MHz and 150 MHz respectively. The two transmit signals are test frequencies allocated by the UK Home Office.

5.2.4 System Hardware and Software

All the system hardware except the three antennas were taken from the laboratory measurement system and the details of these components have been described in Section 3.3. The three sets of cavity filters have been re-tuned to the new test frequencies and their responses are shown in Fig. 5.4. The folded dipoles have a useful bandwidth of 143-156 MHz. For measurement at other frequencies, the log-periodic antenna was used having a bandwidth of 80-1300 MHz. These antennas were used in vertical polarisation and their specifications are shown in Fig. 5.5 and 5.6. The software used for controlling the test receiver and processing the test data was identical to those used for the laboratory measurement and the programme listings are shown in Appendices B to D.

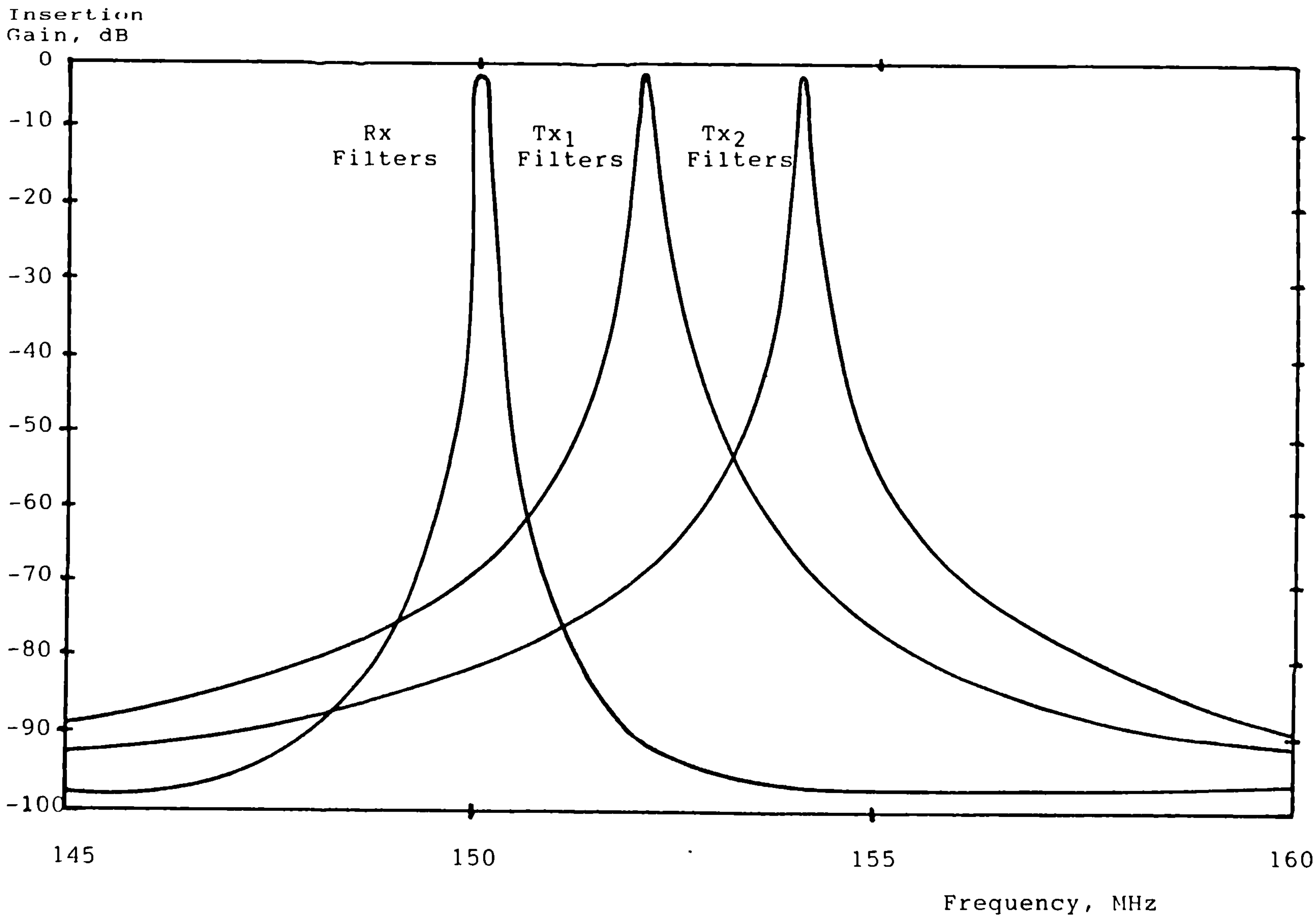
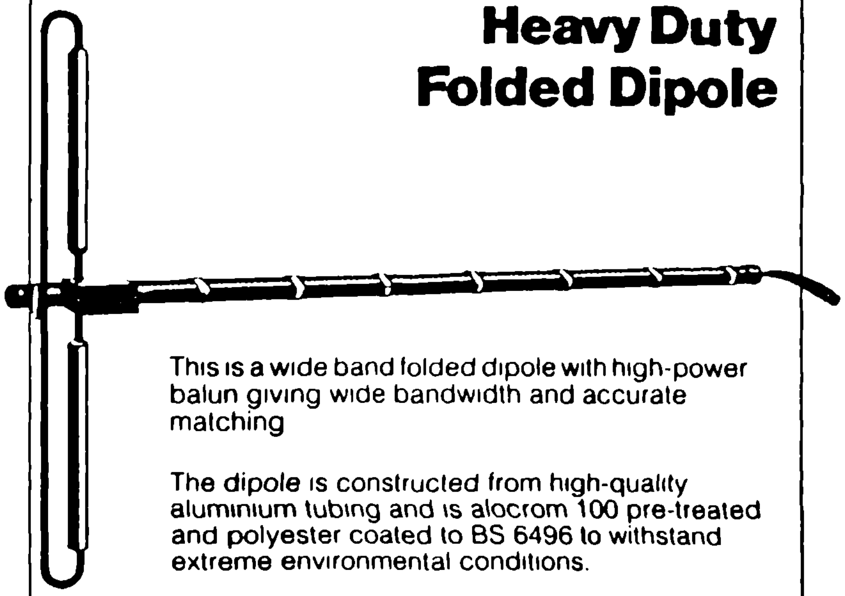


Fig. 5.4 Frequency Response of Cavity Bandpass Filters

HOME OFFICE PART NO. AE 501 P1

VHF Heavy Duty Folded Dipole



This is a wide band folded dipole with high-power balun giving wide bandwidth and accurate matching

The dipole is constructed from high-quality aluminium tubing and is alocrom 100 pre-treated and polyester coated to BS 6496 to withstand extreme environmental conditions.

The antenna may be arranged in a variety of ways on the mast to produce higher gain, directional lobes or interference cancellation and suitable phasing harnesses are available.

HOME OFFICE PART Nº

AE 501 P1

VHF Heavy Duty Folded Dipole

Electrical & Mechanical Specification

Jaybeam Type Number	7388
Frequency Band	143-156 MHz
H O Technical Specification	D 11
Input Impedance	50 ohms
VSWR	143-152 MHz < 1 5 1 152-156 MHz < 1 3 1
Maximum Power (at 50°C)	800 watts 2 Kw p e p
Polarisation	Vertical or Horizontal
Gain over halfwave dipole	Unity
D C Resistance	< 0 01 ohms
Connection	3 5 m of RG214U cable terminating in a N type plug to MIL C 390 2 1A
Construction	All welded assembly
Finish	Alocrom 100 pre treated and Polyester coated to BS 6496
Colour	Duck Egg Blue c BS 4800 Shade 16C33 (standard)
Radiating Element	¾" x 14 swg (19 05 x 2 032 mm HE 30 TB with 1 ¼" x 12 swg (31 75 mm x 2 642 mm) HE 30 TF Sleeve All seamless drawn aluminium tubing
Boom	1 ¾" x 7 swg (46 42 x 4 470 mm) HE 30 TF Seamless drawn aluminium tubing
Element Fittings	Machined HE 30 TF Aluminium alloy
Insulator	Glass reinforced polyester
Balun assembly fixing	Marine quality Stainless Steel
Vibration Damping	10 mm Nylon rope filled internally
Weight	6 kg
Wind Area	0 145 m²
Wind Loading at 190 km/h	25 5 kgf
Dimensions	2000 mm x 910 mm x 112 mm
Packaged Dimensions	2060 mm x 960 mm x 162 mm

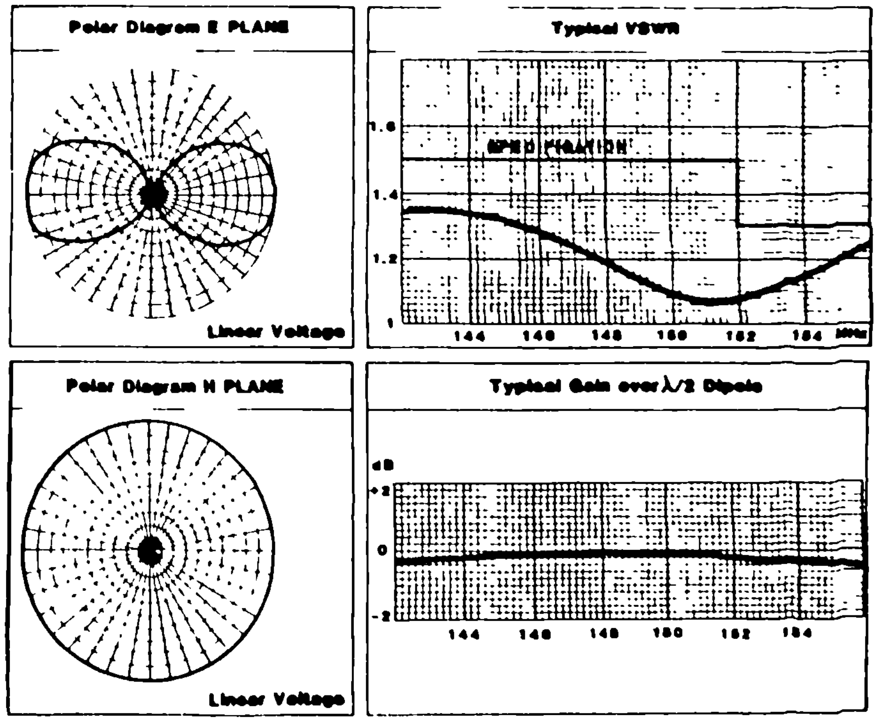
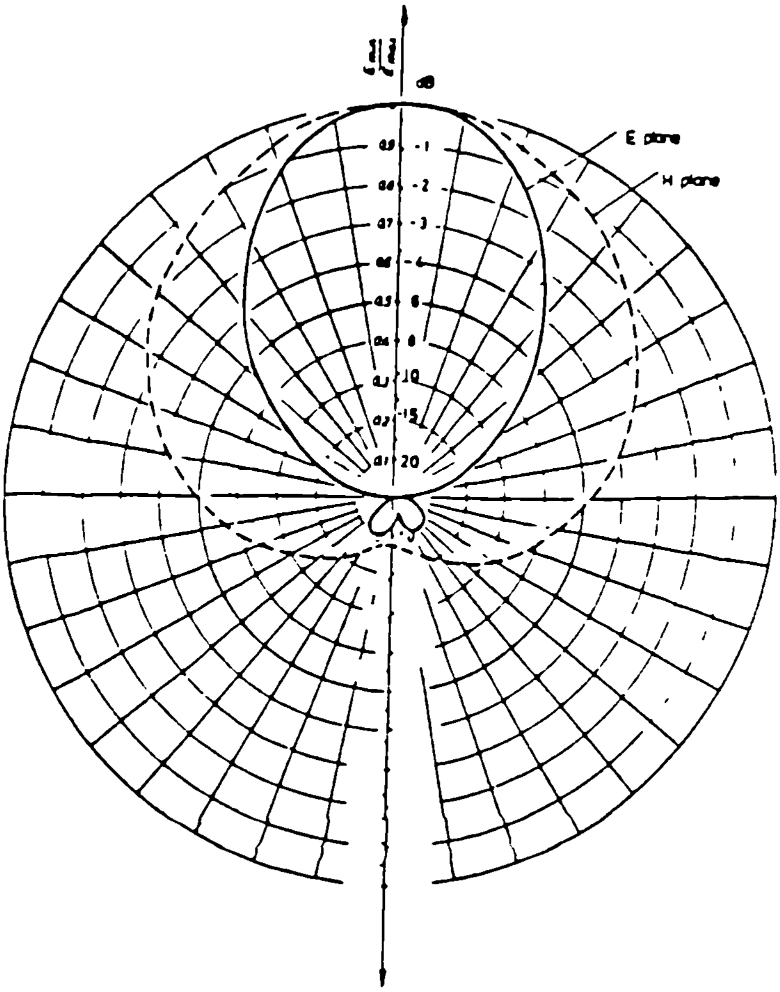


Fig. 5.5 Specification of Folded Dipole

ROHDE&SCHWARZ

LOG-PERIODIC ANTENNA HL 023 A1



Specifications

Frequency range	80 to 1300 MHz
Gain . . . . (referred to isotropic radiator)	approx. 6.5 dBi
Polarization	linear
Input impedance	50 Ω
VSWR	≤ 2 (some peaks may be ≤ 2.5)
Permissible input power	100 W
Dimensions	
Length	1.7 m
Maximum width	1.96 m
Weight	5 kg
Permissible wind velocity	108 km/h
Maximum wind load ($q = 560\ N/m^2$)	
Horizontal installation	140 N
Vertical installation	250 N
RF connector	N female

Fig. 5.6 Specification of Log-Periodic Antenna

5.3 Passive Intermodulation Product Measurements

5.3.1 Test Samples and Test Procedures

The passive intermodulation product sources at radio sites can occur in two main areas, within system components including filters, connectors, feeders and antennas, and in the external environment, such as the radio tower and mast, antenna mounting components and any nearby metallic objects. This project is mainly concerned with the latter. Initially large structural components used in the laboratory measurement were supported on the tower between the two folded dipoles, however, intermodulation signals generated were found to be masked by the intermodulation signals generated by the site non-linearities. It was then decided that the site non-linearities would be used as test samples and these include the 8 m radio tower, antenna mounting components, and adjacent unused radio amateur antennas and masts.

The passive intermodulation product measurement was conducted over a period of three months in mid-1989 and covered the following tests:

(1) To study the relationships between PIMP and transmitters output levels.

(2) To study the variation of PIMP levels over a period of time.

(3) To study the site non-linearities.

(4) To study the influence of weather conditions on PIMP.

Measurement procedures have been standardised to reduce unwanted variables. Tests were conducted with equal output power from both transmitters. Due to the unstable nature of PIMP levels, at each transmit level, the odd order PIMP levels were measured over a period of one minute and at a sampling interval of one second. The average time for each series of tests was approximately an hour. To cover a wider range of weather conditions, the tests were conducted at different time of the day. The mean of each measurement was calculated by the computer, and the weather conditions during the test were monitored by a thermometer and a wind meter.

5.3.2 Test Results

The PIMP spectrum, the relationships between PIMP levels, transmitters output levels, time, wind speed and temperature were studied and the plots, shown in Fig. 5.7 - 5.12, are mean results obtained from measurements. The results of the preliminary field trials have been published recently [12] and they are summarised in the following paragraphs.

Fig. 5.7 shows the typical variation of PIMP level over 4 periods of one minute. The variation is random and is similar to the laboratory test results [10] obtained from two lightly touching metallic objects. Tightly bolted joints, metal with corroded surfaces and mild steel tend to generate stable PIMP levels. These results have been explained by the author in recent publications [7-10]. It is therefore likely that loose metallic contacts are the main cause.

At low power transmission, i.e. not more than 25 W, only the 3^{rd} order PIMP levels are significant. Fig. 5.8 shows the relationships between the 3^{rd} order PIMP levels and combined output power levels. The PIMP levels vary over a wide range but the mean ratio of PIMP to output levels is approximately 2. This generally agrees with laboratory measurements [7-10] on a variety of samples. Although the power series model predicts that the ratio should follow the order of the PIMP, usually the ratio is smaller than the order. This has been observed by other

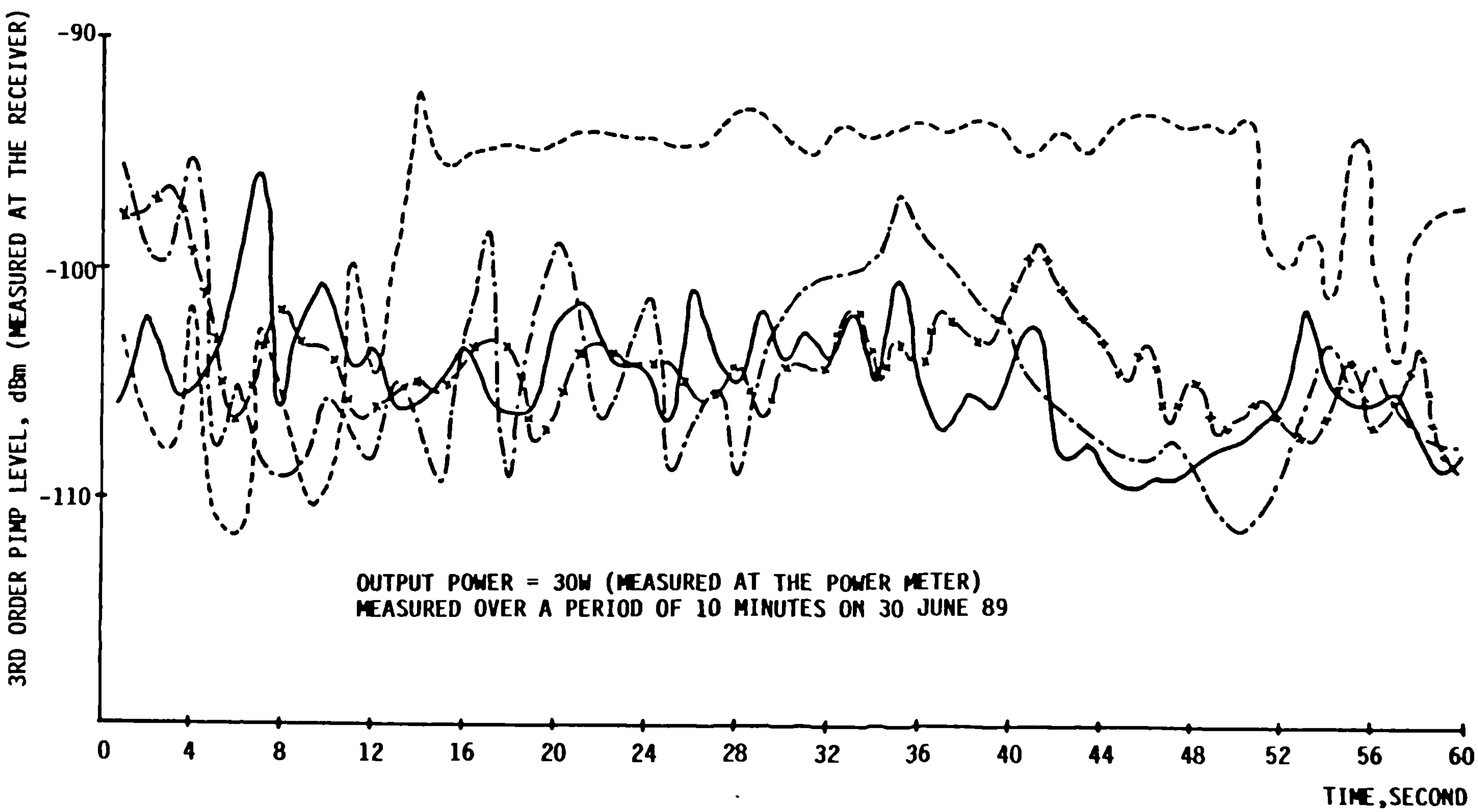


Fig. 5.7 Relationship Between PIMP Levels and Time

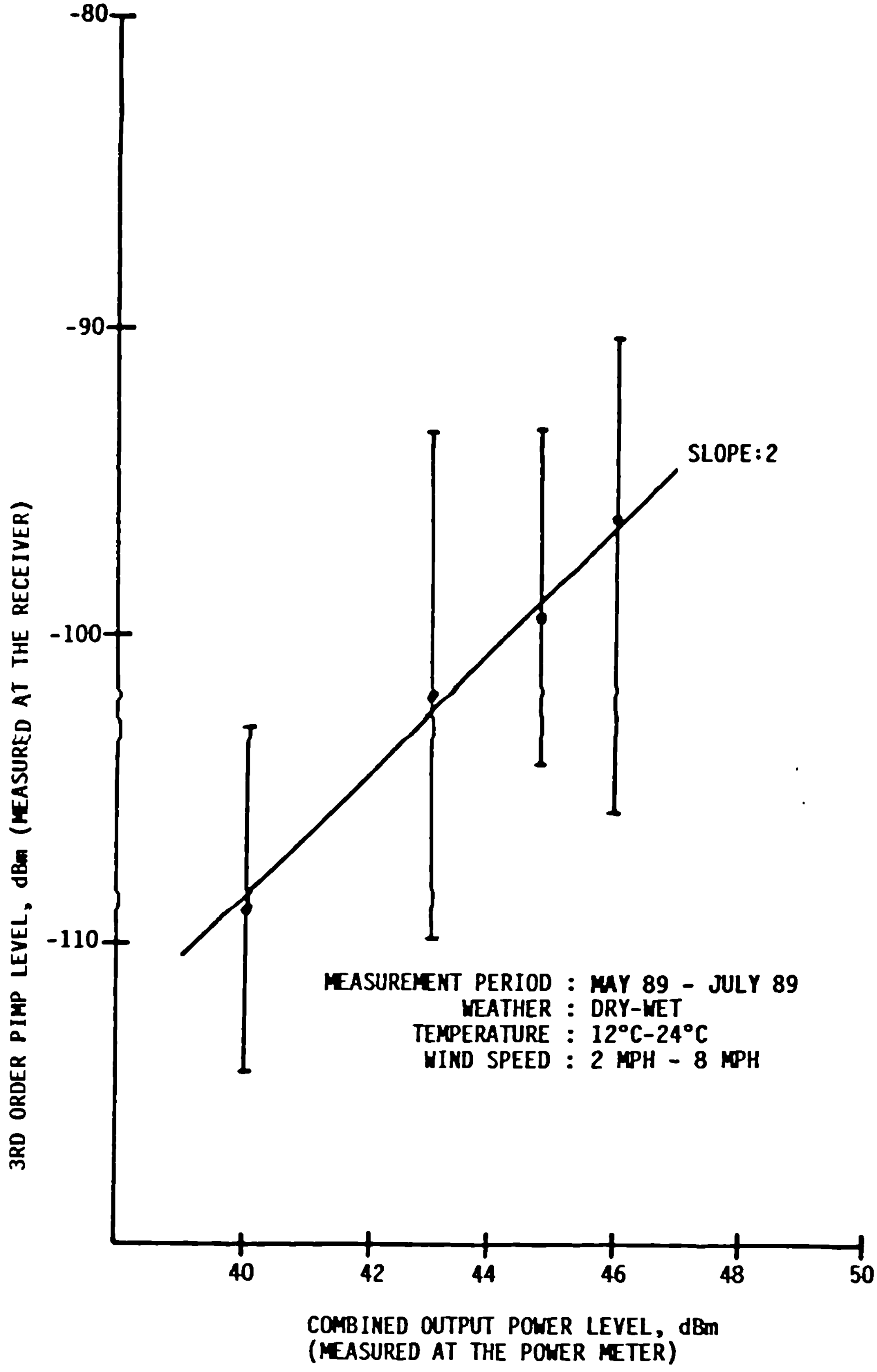


Fig. 5.8 Relationship Between PIMP and Output Levels

researchers and should be taken into account when predicting PIMP levels.

The spectrum of the PIMP, shown in Fig. 5.9, indicates that only the lower order products are significant. Generally, amplitude falls off with increased order and it is only where transmitted powers are high that higher orders must be considered. The amplitude of the products in the second harmonic region is significant and this can be used for locating PIMP sources. The asymmetry of the frequency component amplitudes is thought to be due to the frequency response of the measurement system and the random nature of the 'rusty-bolt' effect.

The result, shown in Fig. 5.10, suggests that structures generate a lower PIMP level in wet weather. This has been observed in other experiments and the explanation given is the high dielectric constant of water [11]. However, due to the small number of rainy days in the measurement period, further work is required to provide more convincing and quantitative results.

The results, shown in Fig. 5.11 and 5.12, suggest that there is no clear relationship between the PIMP level, site temperature and wind speed. Because the PIMP level and wind speed fluctuate over a wide range in a very short time, meaningful measurement was found to be very difficult. Here again, more data collected over a longer period is required.

5.4 Summary

This chapter has described the development of a field measurement system and the preliminary results of a field investigation into the parameters related to the generation of PIMP. Useful field measurement data on PIMP behaviour can be obtained if proper attention is given to the design of the measurement system and

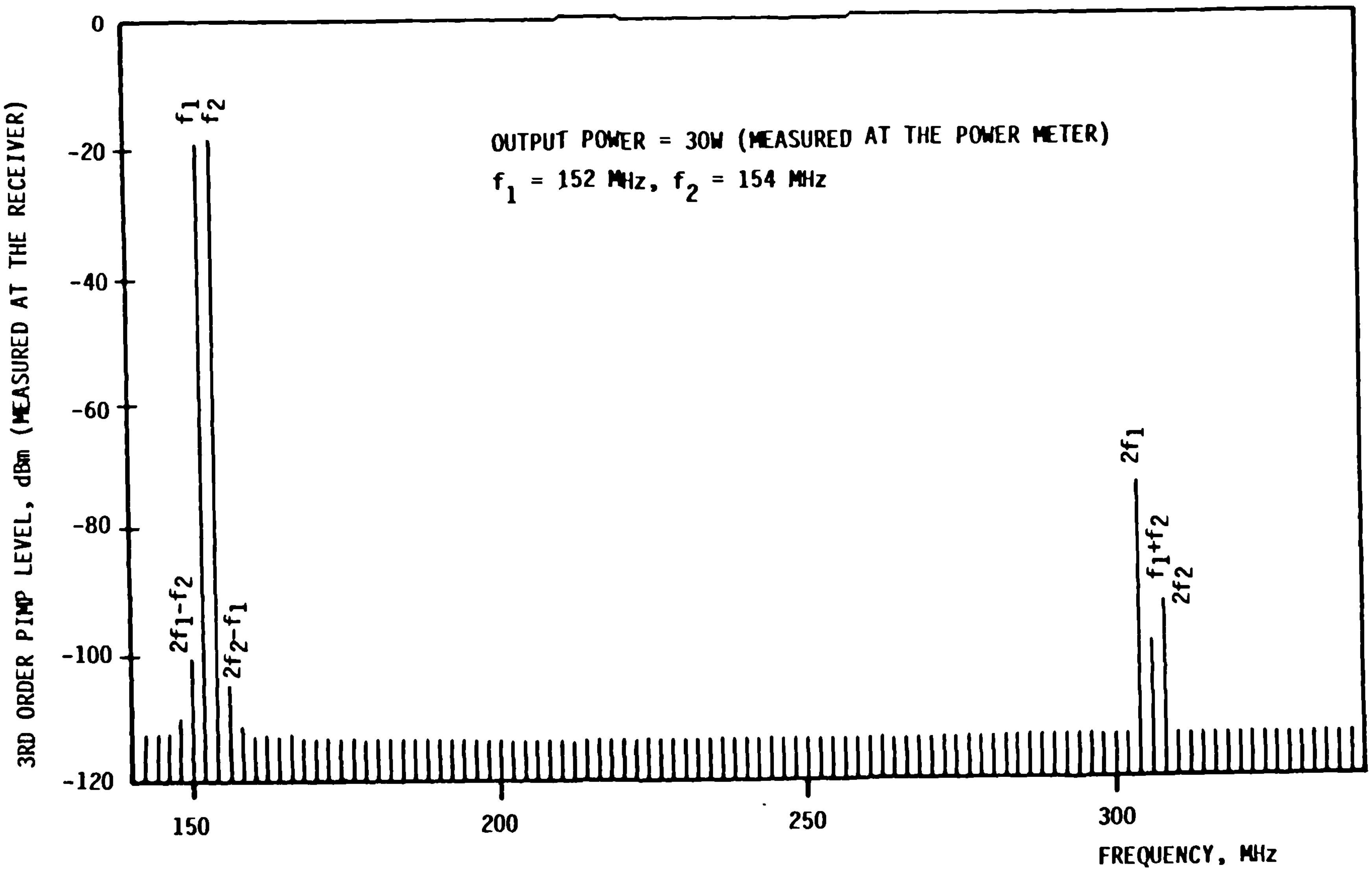


Fig. 5.9 Harmonic and Intermodulation Products Generated By The Measurement Site

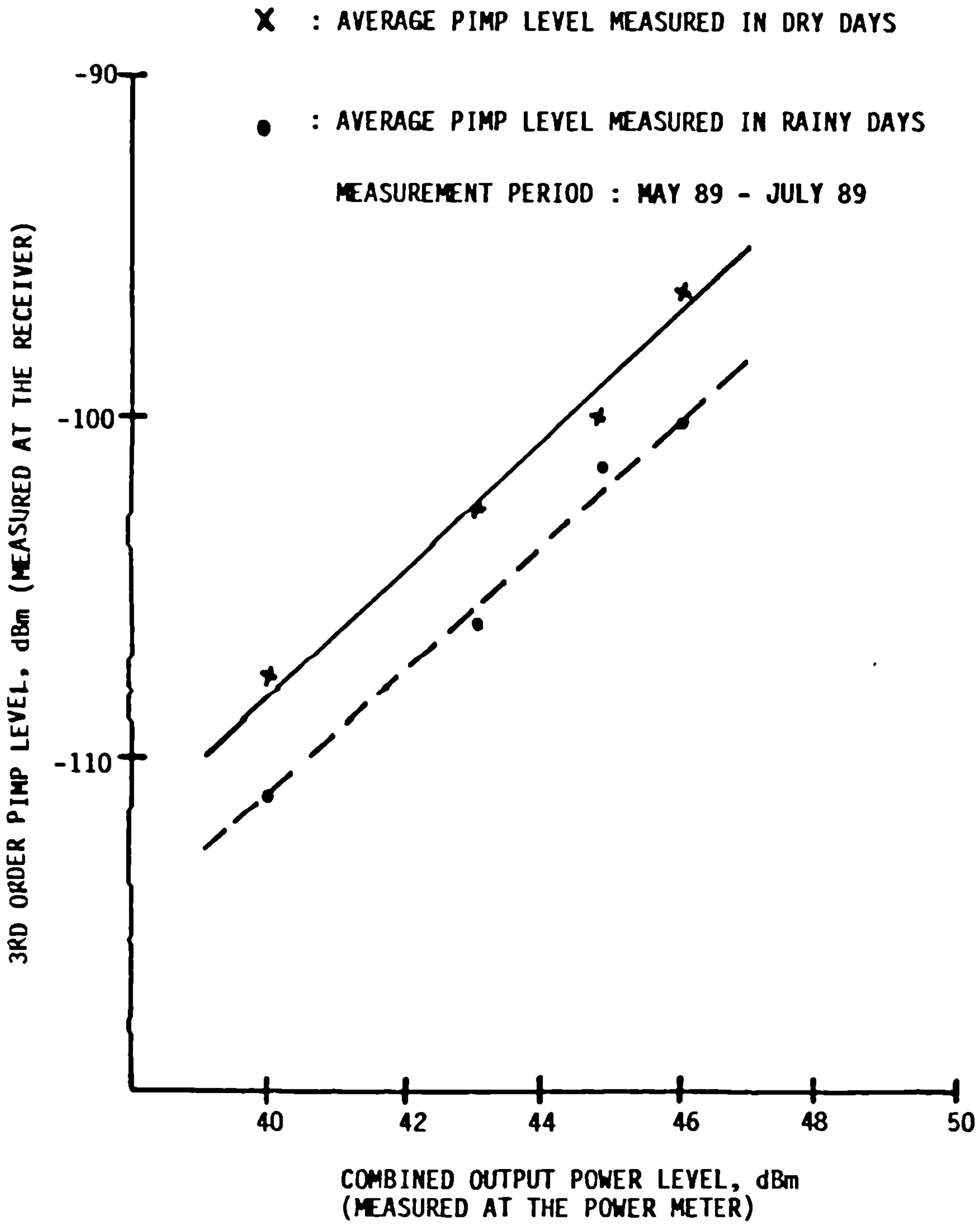


Fig. 5.10 Relationship Between PIMP Levels and Weather Conditions

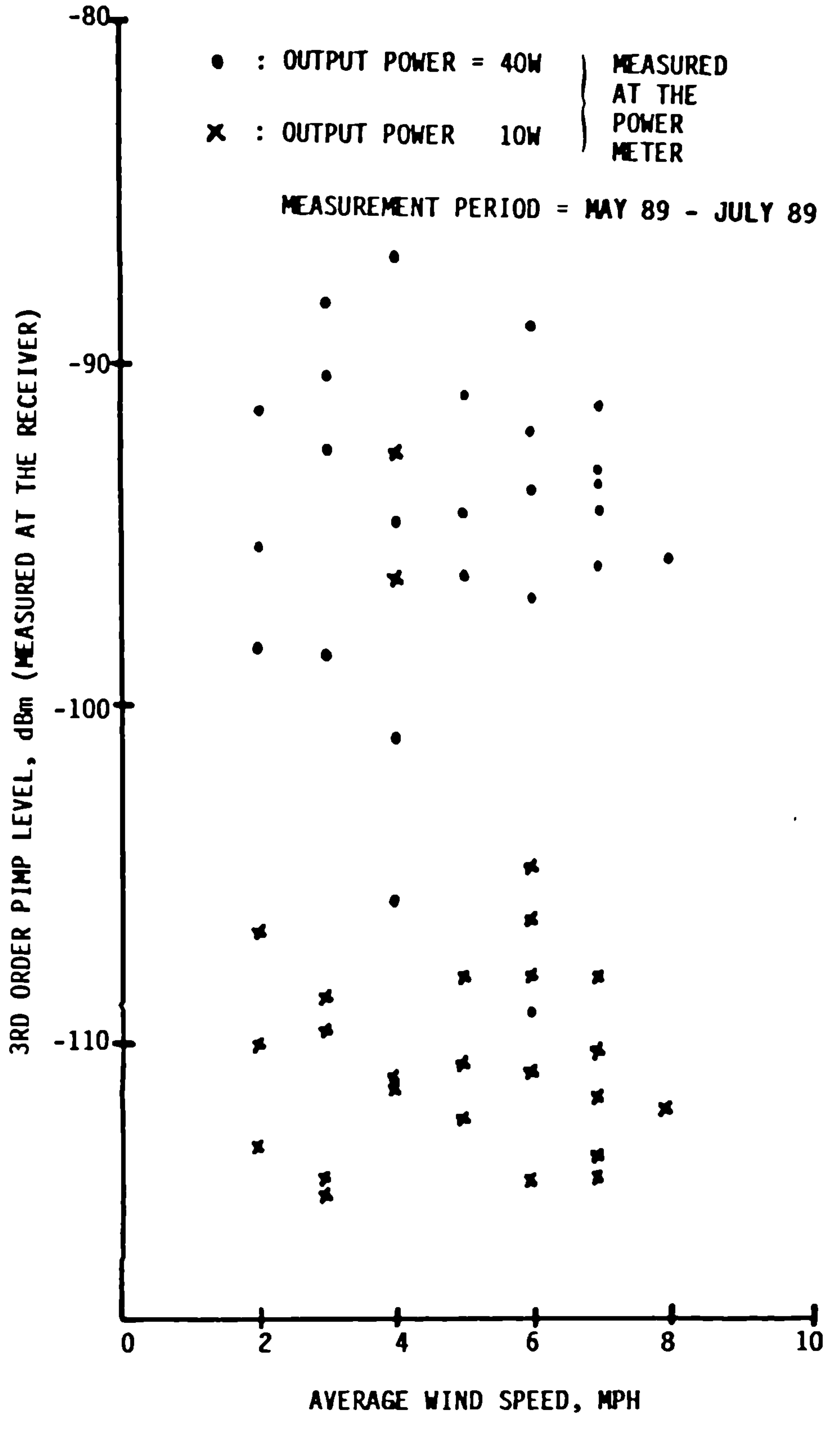


Fig. 5.11 Relationship Between PIMP Levels and Wind Speed

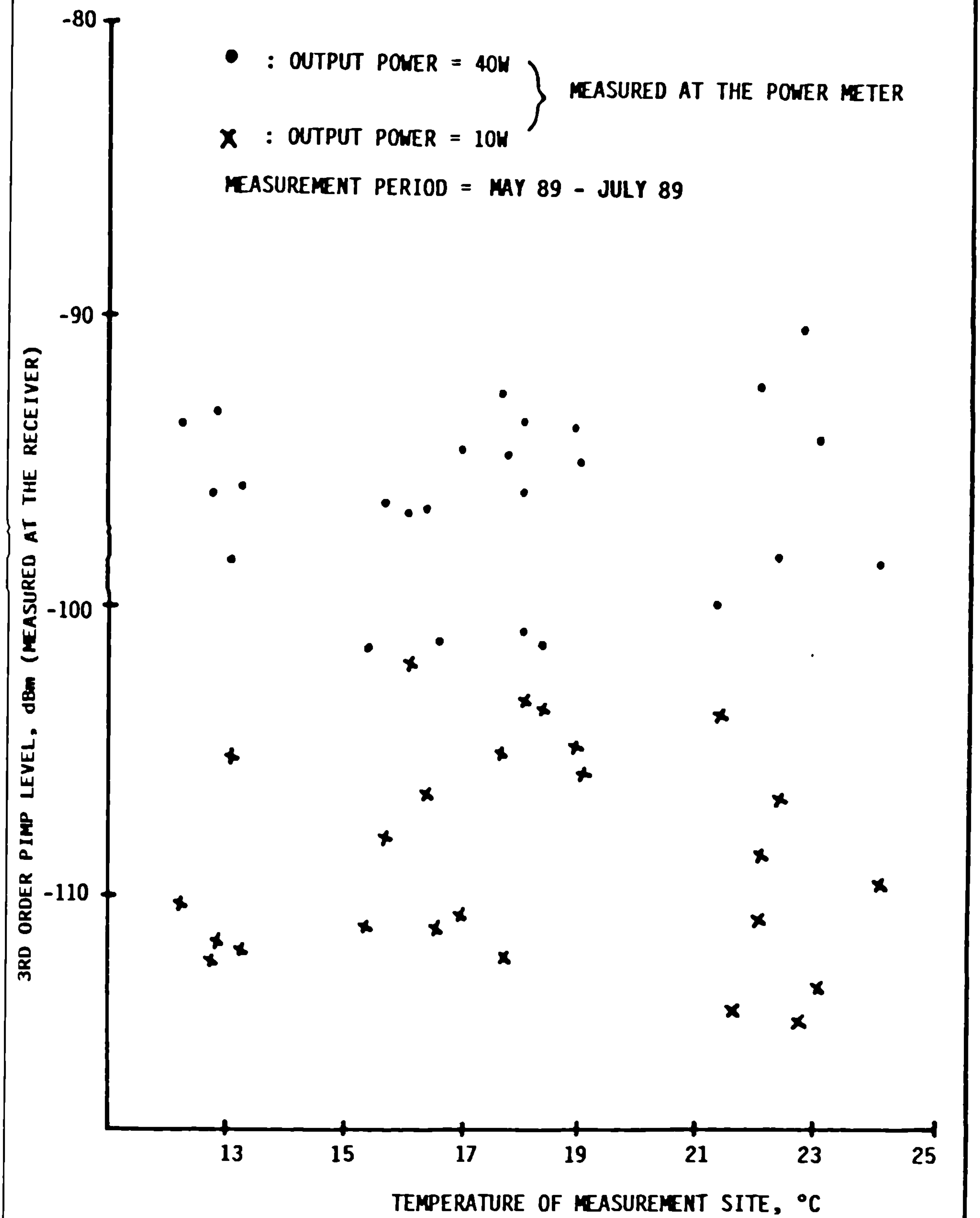


Fig. 5.12 Relationship Between PIMP Levels and Site Temperature

test programme. So far most field measurement results agree with those obtained from the laboratory measurement, however, the unstable nature of the 'rusty-bolt' effect and the highly variable nature of some of the parameters means that quantitative and more conclusive results can only be obtained if measurements are conducted over a longer period.

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CHAPTER 6

Non-linear Mechanisms and Analytical Techniques

6.1 Introduction

In Chapters 1 and 2, the non-linear mechanisms at metallic contacts and the non-linear model used for explaining the generation of harmonic and intermodulation products have been briefly described. The aim of this chapter was to discuss these topics in more details. The first half of the chapter is concerned with the previous studies of non-linear mechanisms. Conclusions are drawn from the study of these mechanisms and the measurement results. The second half gives a brief review of the analytical techniques used for predicting intermodulation signals. A power series is described and the theoretical results are compared with the measurement results.

6.2 Non-linear Mechanisms

6.2.1 Introduction

Several micromechanisms have been assumed or suspected to be responsible for the non-linearity at metallic contacts [1-6]. In the following sections, these mechanisms are more fully discussed and the most dominant one is identified.

6.2.2 Semiconductor Mechanism

Metals commonly in use tend to acquire a thin surface layer of oxide when exposed to the atmosphere. Consequently, where metallic surfaces are in contact, metal-oxide-metal junctions may be formed. In most published literatures concerning passive intermodulation, metallic contacts are always assumed to behave like metal-oxide-metal semiconductor junctions and have non-linear current-voltage characteristics. However, previous study [1] of non-linear mechanisms has pointed out that unless the following conditions are satisfied simultaneously, the semiconductor mechanism alone does not provide an adequate description:

(1) The non-linearity should be independent of atmosphere pressure.

(2) The PIMP level should be somewhat dependent on d.c. bias level for high impedance contact.

(3) The PIMP level should be relatively independent of oxide layer thickness after a certain angstrom layer is established.

Various contact non-linearity tests [1] have shown that conditions (1) and (3) could be satisfied, but not condition (2). Since the three conditions could not be satisfied simultaneously, it was concluded that the classical semiconductor theory does not explain the non-linear effect at metallic contacts [1]. The results obtained from our PIMP measurement [13] suggest that even if the semiconductor mechanism is responsible for the non-linear effect at contacts, it is unlikely to be a dominant mechanism because loose contacts generate stronger intermodulation signals than oxidised contacts.

6.2.3 Electron Tunnelling Mechanism

The basic electron tunnelling theory states that electrons can 'tunnel' through a thin layer of oxide between two conductors and the current across the oxide layer is heavily dependent on the oxide thickness and has a non-linear relationship to the applied voltage. This theory has been used by several researchers to explain the non-linear effect at oxidised aluminium contacts [2,3]. However, disagreement has been expressed among these researchers as to the correct form of the tunnelling equations used [4]. Besides measurements on flange contacts have shown that the PIMP level is independent of oxide thickness [1]. Recently a detailed study of non-linear mechanisms has concluded that the electron tunnelling theory alone is inadequate to explain the non-linear effect at metallic contacts because of the following reasons [5]:

(1) Much research has been done in this area of work but with disagreement as to the correct form of the tunnelling equations.

(2) Current state-of-the-art tunnelling theory can only predict current-voltage curve at d.c. with no frequency dependence.

(3) Measured current-voltage curves on carefully controlled idealised oxidised contacts, even at d.c., are not accurately represented by contemporary electron tunnelling models.

(4) The oxidised contacts occur in the real world are much more complex than those fabricated in the laboratory and are unlikely to behave according to the electron tunnelling models.

The author feels that the electron tunnelling mechanism may be able to explain the PIMP generation at some specially fabricated oxidised contacts, but not at metallic contacts that occur in the natural environment because the latter bear very little resemblance to the former. Like the semiconductor mechanism, it is also unlikely to be a dominant mechanism and much work is needed to understand its contribution to the contact non-linearity.

6.2.4 Microdischarge Mechanism

Microdischarge, a non-linear process, was believed to be caused by the microscopic filaments or whiskers in metals [6]. It has been observed on several occasions that when small burrs and hairs were placed on or near the flange corners, they would greatly enhance the susceptibility of a flange to generate intermodulation signals [1]. It was thought that such a phenomenon was caused by microdischarge which is independent of atmosphere pressure, oxide thickness and d.c. bias, but dependent on contact pressure and surface smoothness. This mechanism has not been reported by other researchers and there is very little information about its characteristics. Perhaps further investigation is needed, especially its behaviour in waveguide components.

6.2.5 Contact Mechanism

A contact model regardless of the suspected non-linear mechanisms, i.e. semiconductor, electron tunnelling and microdischarge, has been used to explain the non-linear effect at metallic contacts [1]. The model requires that the non-linear effect is current dependent and the PIMP level is proportional to the current density at contacts. This model is illustrated in Fig. 6.1 which shows the current flow patterns and the contact points of a progressively tightened metallic joint. When two metal surfaces are lightly touching each other, the contact occurs at a few points and hence there are high current densities. As the joint is tightened, more and more contact points occur and the current is distributed. The PIMP level can therefore be decreased by increasing the contact area or decreasing the input power.

This model was verified by measurements on flanges purposely made coarse with

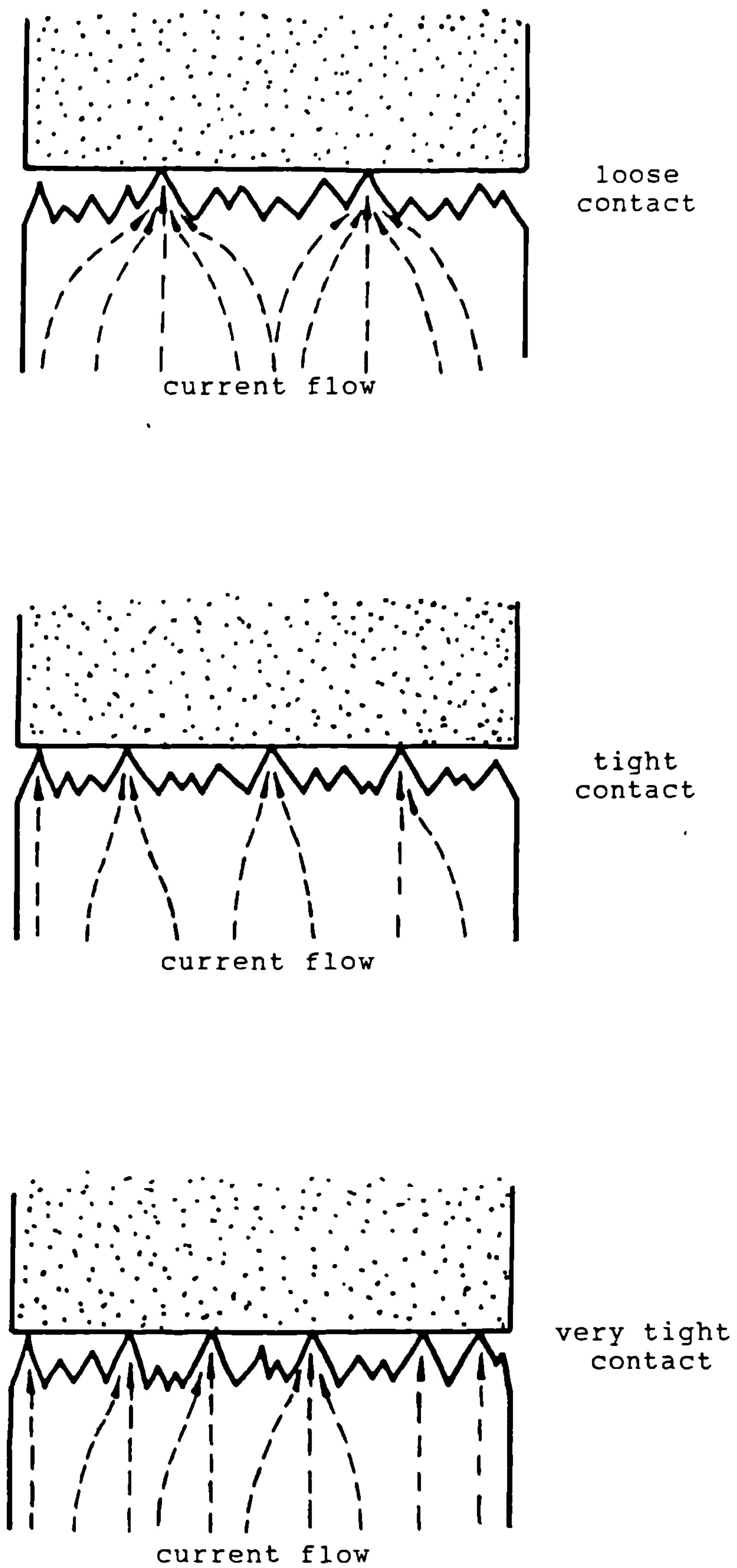

Fig. 6.1 Contact Model

sandpaper grit [1]. These flanges were tested immediately after sanding to ensure the contact surfaces are free of oxide. The measurement results indicate that a rougher surface produces higher PIMP level, and that additional tightening ultimately makes the rougher surface equivalent to a smoother one. This model may also be used to explain the results obtained from another experiment conducted with metallic contacts fabricated in different shapes [7]. Point and spherical contacts, shown in Fig. 6.2, were found to generate stronger intermodulation signals than surface contacts, and larger PIMP levels were obtained from a very low contact load, regardless of the types of contact. Such a model provides a more satisfactory explanation than the non-linear mechanisms mentioned and may be used to explain our measurement results. However, more work is needed to understand the relationship between the current density and contact non-linearity.

6.3 Non-linear Analytical Techniques

6.3.1 Introduction

The prediction of intermodulation frequency and amplitude is very important in radio system planning because it allows the user to assess the system performance before putting it into operation. Several methods have been used for such purpose and generally they can be divided into two types, for memory systems and for memoryless systems. In a memory system such as an amplifier, the history of previous inputs to the system must be taken into account in addition to the instantaneous response, the reactive effects of the components in the amplifier must not be neglected. One of the methods that may be used for such system is the Volterra series, which has been discussed in some recent publications [8,10]. In a memoryless system, only the present inputs are considered. Con-

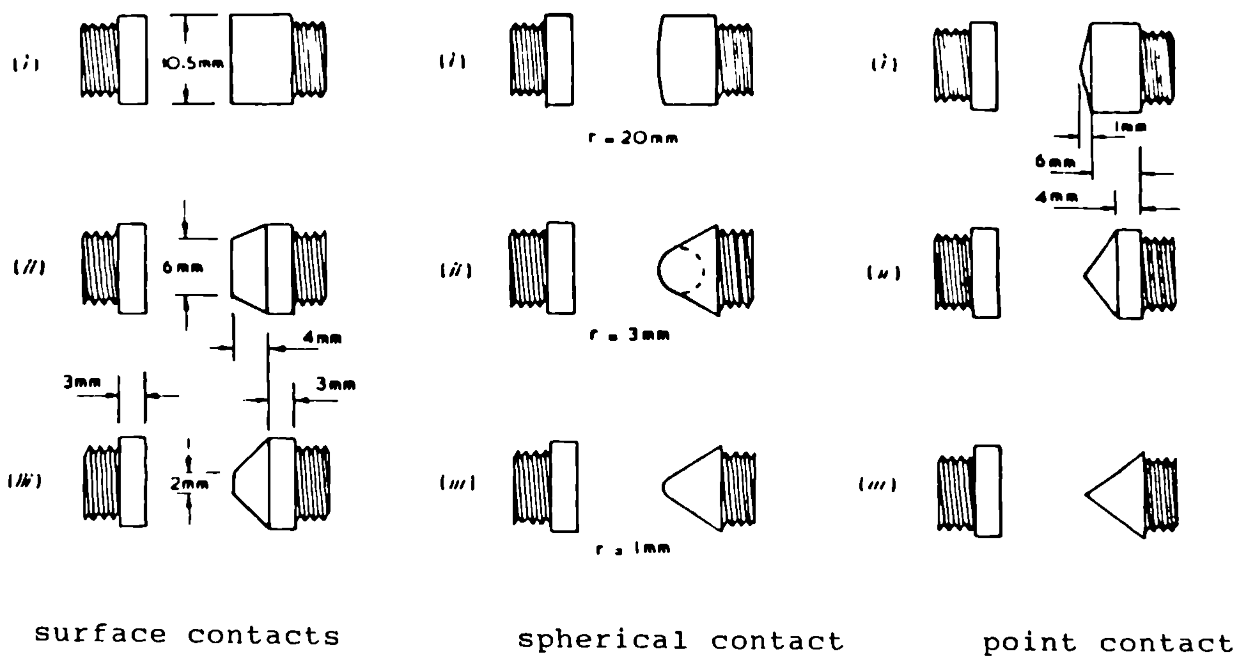

Fig. 6.2 Geometrical Configuration of Test-Sample Pairs

tact non-linearity is generally regarded as a memoryless system and it is often analysed by a power series [8-10].

There are other methods such as the Hyperbolic Approximation Technique [9], Sidorov's Technique [10] and Sine Representation Technique [10], which have been discussed but are not as commonly used as the Volterra series and power series. In the following sections, the discussions are limited to the power series.

6.3.2 Power Series

A simplified power series has been used in Chapter 1 to illustrate the generation of harmonic and intermodulation products. The expansion and manipulation of this series can be done without much difficulty if only two input signals and a low order polynomial are considered. However, if the number of input signals and polynomial order are increased, the expansion process becomes extremely complicated. Very often, one is not interested in a complete expansion of the function, but rather in the amplitude of a particular frequency component. Sea [11,12] has derived formulas which provide this and can be used for any number of carriers and polynomial orders. The formulas derived are shown as follows:

Equation (6.1) shows the power series where x is the input, y is the output and a_0, $a_1, a_2,$ ...... are the coefficients.

$$y = a_0 + a_1 x_1 + a_2 x_2^2 + \text{......} = \sum_{k=0}^{\infty} a_k x^k \tag{6.1}$$

If the input is given by $x = x_1 + \text{......} + x_M$, where $x_i = E_i \cos\theta_i$, and $\theta_i = \omega_i t$, equation (6.1) can then be written as shown in equation (6.2).

$$y=\sum_{k=0}^{\infty}a_k\left[\sum_{m=1}^{M}x_m\right]^k \tag{6.2}$$

Using Euler's identity, binomial expansion theorem and further manipulations, equation (6.2) can be developed and simplified as follows [11]:

$$V=\sum_{L=0}^{\infty}\frac{a_{(N+2L)}(N+2L)!}{2^{(N+2L-1)}}\sum_{q_1,q_2,\cdots q_M}\prod_{p=1}^{M}\frac{E_p^{|\alpha_p|+2_{q_p}}}{(q_p+|\alpha_p|)!q_p!} \tag{6.3}$$

where V = amplitude of a particular intermodulation frequency θ, and $\theta=\alpha_1\theta_1+\alpha_2\theta_2+\cdots+\alpha_M\theta_M$.

L = 0, 1, 2, 3, ...

N = order of product = $|\alpha_1|+|\alpha_2|+\cdots+|\alpha_M|$

M = number of input signal

E_p = amplitude of the input signal

α_p = number specifying the required product

q_p = non-negative integer

Equation (6.3) was later modified by Sea [12] to a different form, shown in equation (6.4), to reduce the computation time.

$$V=\varepsilon_N\left[\prod_{i=1}^{M}E_i^{(|n_i|)}\right]\sum_{L=0}^{\infty}\frac{a_{N+2L}(N+2L)!}{2^{N+2L}}\Phi(M,L) \tag{6.4}$$

where

$$\Phi(M,L)=\sum_{q_1}\cdots\sum_{q_M}\prod_{i=1}^{M}\frac{E_i^{2q_i}}{q_i!(|n_i|+q_i)!}$$

and

$$q_1+q_2+\cdots+q_M=L$$
$$N=|n_1|+\cdots+|n_M|$$
$$\varepsilon_N=\begin{cases}1 & \text{if } N=0\\ 2 & \text{if } N=1,2,\cdots\end{cases}$$

It has been demonstrated in the 60's that with 4 input signals and 20 terms of the power series, the computer took 0.4 second to calculate the value V [12]. This shows the practicality of Sea's equations since 20 terms of the power series expansion should be more than adequate in most applications to predict the intermodulation signals. With today computer technology, it will take less time to compute the value V.

6.3.3 Non-linear Model Verification

This section compares the measurement results with the theoretical results which based on a power series. The equations (1.1) and (1.2) as described in Chapter 1 are used for the following analysis. Substituting equation (1.1) into (1.2) and solving gives the spectrum of V_{out}.

i.e.
$$\begin{aligned}
V_{out} &= \frac{1}{2}K_2\left[V_1^2 + V_2^2\right] \\
&+ \left[K_1V_1 + \frac{3}{4}K_3V_1(V_1^2 + 2V_2^2)\right]\cos 2\pi f_1 t \\
&+ \left[K_1V_2 + \frac{3}{4}K_3V_2(V_2^2 + 2V_1^2)\right]\cos 2\pi f_2 t \\
&+ \frac{1}{2}\left[K_2V_1^2\right]\cos 4\pi f_1 t \\
&+ \frac{1}{2}\left[K_2V_2^2\right]\cos 4\pi f_2 t \\
&+ \frac{1}{4}\left[K_3V_1^3\right]\cos 6\pi f_1 t \\
&+ \frac{1}{4}\left[K_3V_2^3\right]\cos 6\pi f_2 t \\
&+ \left[K_2V_1V_2\right]\cos 2\pi(f_1 \pm f_2)t
\end{aligned}$$

$$+\frac{3}{4}\left[K_3V_1^2V_2\right]\cos 2\pi(2f_1 \pm f_2)t$$
$$+\frac{3}{4}\left[K_3V_1V_2^2\right]\cos 2\pi(2f_2 \pm f_1)t$$

$$+ \ldots\ldots\ \textit{other terms} \tag{6.5}$$

From equation (6.5), the 3^{rd} order intermodulation signal, $f_{IMP} = (2f_2 - f_1)$, has an amplitude as shown in equation (6.6).

$$\textit{i.e.} \qquad V_{IMP} = \frac{3}{4}\left[K_3V_1V_2^2\right]\cos 2\pi(2f_2 - f_1)t \tag{6.6}$$

$$\textit{or} \qquad V_{IMP} \propto V_1V_2^2 \tag{6.7}$$

If P_1, P_2, P_{IMP} are the powers of the signals f_1, f_2, f_{IMP} respectively,

$$\textit{then} \qquad P_{IMP} \propto P_1P_2^2 \tag{6.8}$$

$$\textit{If} \qquad P_1 = P_2, \qquad \textit{then} \qquad P_{IMP} \propto P_1^3 \;\; \textit{or} \;\; P_2^3 \tag{6.9}$$

Let the carrier ratio $R = \dfrac{P_1}{P_2}$ and the total power $P_t = P_1 + P_2 = P_2(1+R)$. When P_t is a constant, the relationship between P_{IMP} and R is shown in equation (6.10).

$$\begin{aligned} P_{IMP} &\propto P_1P_2^2 \\ &\propto RP_2^3 \\ &\propto \frac{R}{(1+R)^3} \end{aligned} \tag{6.10}$$

From these equations, the relationship between P_{IMP}, P_1, P_2 and R can be summarised as follows:

(1) From equation (6.8), P_{IMP} should vary as 2dB/dB with the input P_2 when P_1 is held constant.

(2) From equation (6.9), P_{IMP} should vary as 3dB/dB with the combined input $(P_1 + P_2)$ when $P_1 = P_2$.

(3) From equation (6.10), P_{IMP} should vary as 2dB/dB with R in the linear region of $P_1 > P_2$, and 1dB/dB with R in the linear region of $P_2 > P_1$. The maximum PIMP level should occur in the region of $P_2 > P_1$ when R = 3dB. This relationship is shown in Fig. 6.4 which includes the measurement result.

A comparison between the measurement and theoretical results was made and the results show that when the 3^{rd} order intermodulation signals, generated by plate samples, were measured under the condition where P_1 = 25 W and P_2 varied from 5 W to 40 W, P_{IMP} varies as a linear function of P_2, shown in Fig. 6.3. It can be seen that the slope or P_{IMP}/P_2 ratio is 1.6 for the rusty samples and 1.9 for the clean samples. These measurement results are slightly smaller than the theoretical result which predicts that the P_{IMP}/P_2 ratio should be 2dB/dB.

Most of the laboratory and field measurements were conducted with $P_1 = P_2$. The results as shown in Chapters 4 and 5 indicate that the P_{IMP} and combined input power varies between 1.5 and 3 dB/dB for samples tested in the laboratory and 2dB/dB for samples tested in the field. Generally the measurement results are smaller than the theoretical result which predicts that the variation should be 3dB/dB for a 3^{rd} order intermodulation signal.

The study of the relationship between P_{IMP} and R was conducted with plate samples. The value of R was varied from R = 0dB to R = ±9dB, within the power

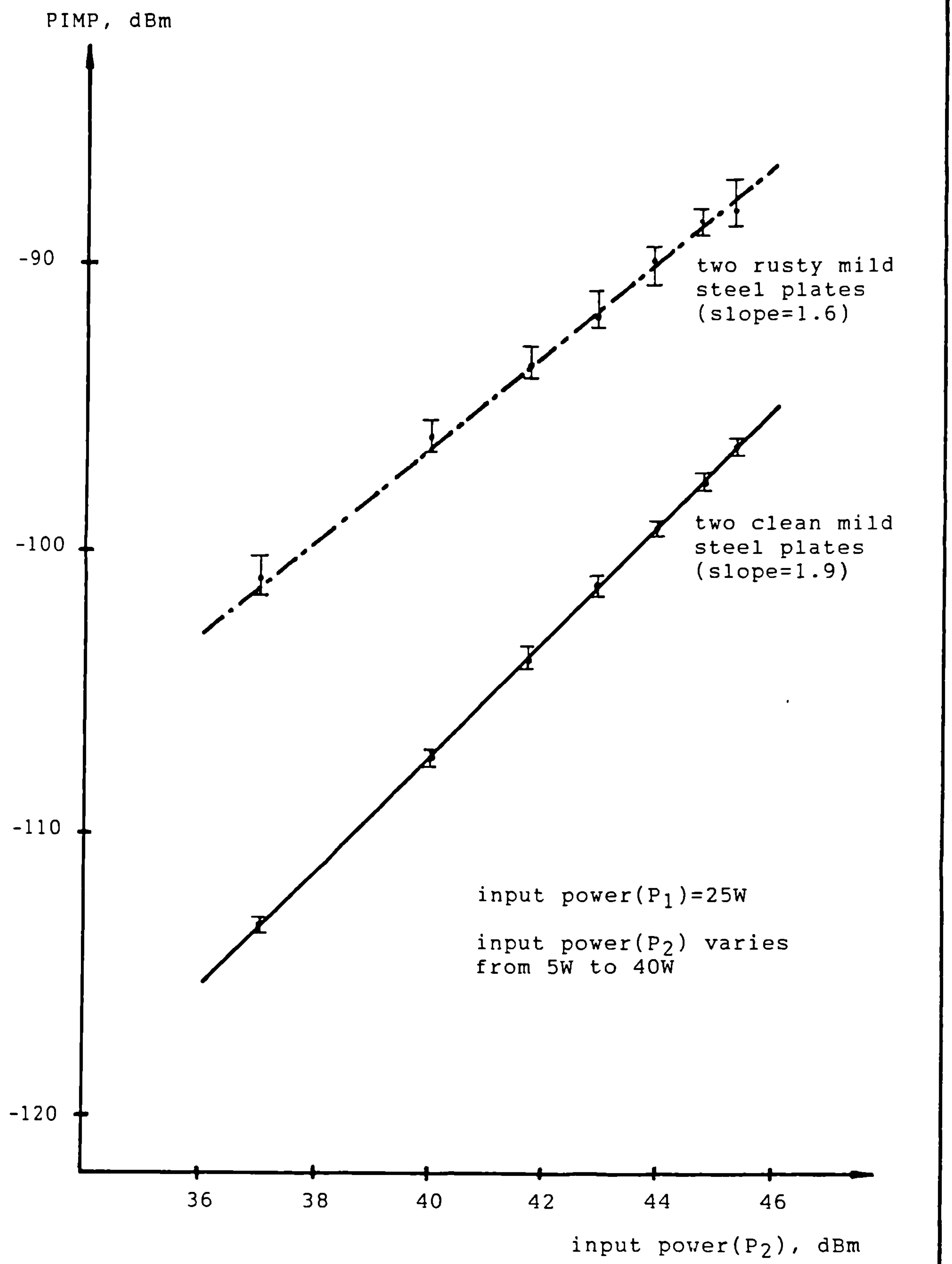

Fig. 6.3 Relationships Between PIMP and Input Levels

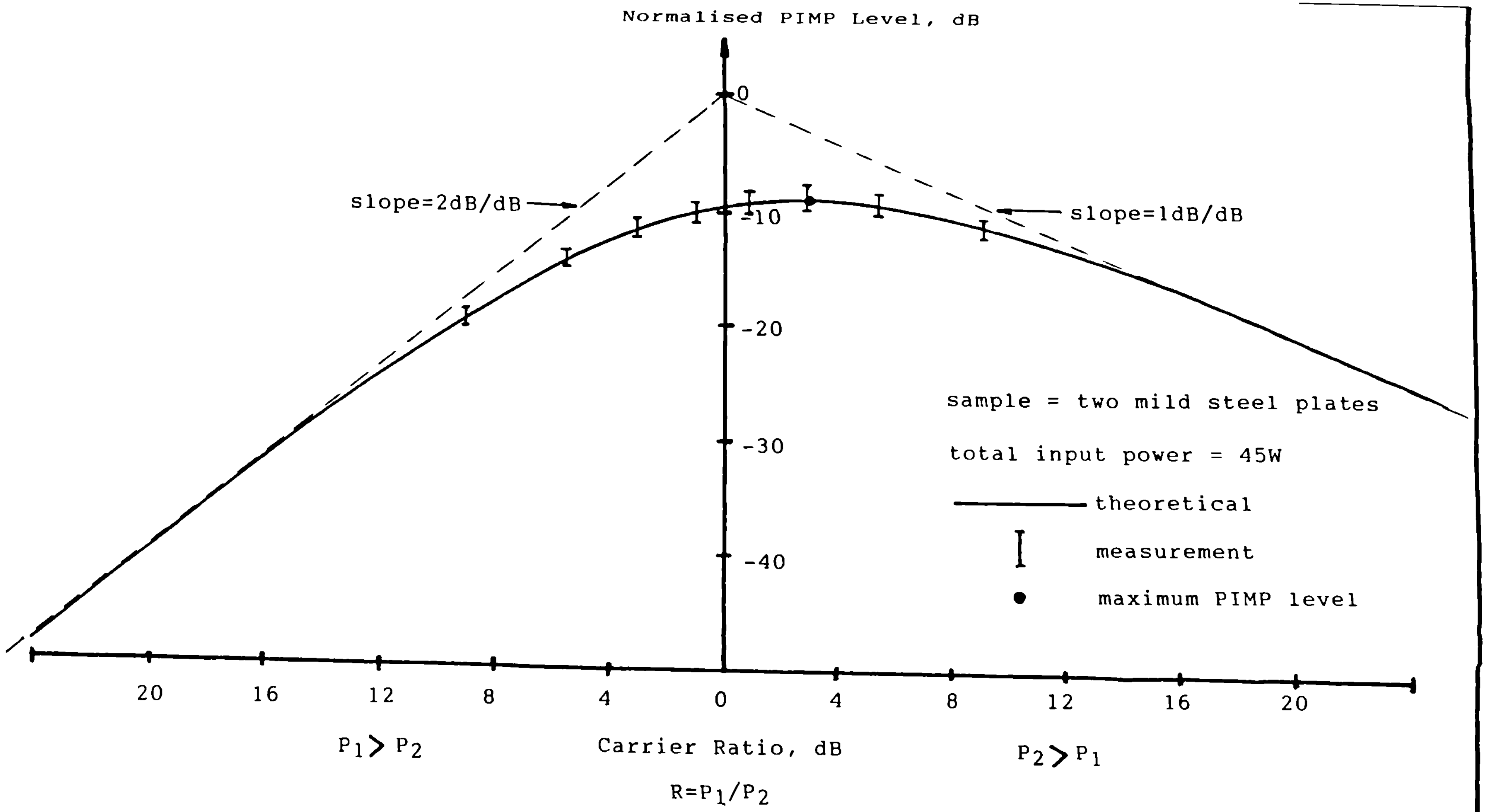

Fig. 6.4 Relationships Between PIMP Levels and Carrier Ratio(R)

rating of the measurement system. The result as shown in Fig. 6.4 suggests that the relationship between P_{IMP} and R agrees with the theoretical prediction which based on equation (6.10). The highest 3^{rd} order PIMP level for a given input power is produced when the transmit carrier closer to the PIMP frequency is 3dB higher than the other carrier, i.e. P_2 is greater than P_1 by 3dB.

6.4 Summary

Four suspected non-linear mechanisms have been described and their significance in the generation of PIMP have been discussed. The contact mechanism is a dominant mechanism and could provide a better explanation of the PIMP phenomenon than the other mechanisms. It may be used to explain the passive IMI problem at radio sites, but further work is needed to provide a quantitative non-linear model. The power series may be used for predicting the intermodulation signals, but the difference between the measurement and theoretical results should be taken into account in order to provide meaningful results. This should apply to other order products as well.

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CHAPTER 7

Detection and Location of Passive IMI Sources

7.1 Introduction

This chapter is concerned with the detection and location of external passive IMI sources at land mobile radio sites. The causes of passive IMI and the basic principles of exciting, detecting and locating passive intermodulation sources are described. A brief review of detection and location techniques is presented, and the experimental studies of audio and radio detection techniques and the development of portable detectors are described. Two detection and location strategies, based on the literature review and experimental studies, are outlined.

7.2 Causes of Passive IMI

There are many non-linear metallic contacts at a radio site, some of which may be excited by the transmitted signals and generate intermodulation signals. The latter may then be radiated and may fall into the passbands of nearby operating receivers. Very often the PIMP generated do not cause passive IMI because they are either not radiated effectively or they fall outside of the receive band. Passive IMI will only occur if the following conditions are satisfied.

(1) The presence of non-linear contacts in metallic structures.

(2) The non-linear contacts are excited by two or more signals.

(3) The non-linear contacts are capable of generating PIMP.

(4) The PIMP generated are radiated by the metallic structures.

(5) The radiated PIMP fall into the passbands of nearby operating receivers.

The number and amplitude of radiated PIMP depend upon the radiation efficiency of the structures. Watson [1,2] has observed in his experiment that the amplitude of the harmonic radiated from a structure decreases rapidly if the structure length is less than a quarter wavelength at the irradiation frequency. This result suggests that at VHF radio sites, the non-linear contacts embedded in structures having the approximate dimensions of VHF antennas are more likely to be the passive IMI sources.

7.3 Principles of Excitation and Detection

7.3.1 Excitation of Non-linear Contacts

Essentially a detection technique requires the structures to be excited so that alternating currents pass through the non-linear contacts and generate harmonic and intermodulation signals. The direction sensing of these signals may then be used for locating the non-linear contacts which may be the passive IMI sources. Generally there are two approaches to excitation. The use of existing operational signals which are by definition frequency related to the interference signals, and the use of a new set of exciting signals which is not frequency related to the interference signals.

The first approach made use of the existing operational signals, but in situations where these signals are not suitable for a detection operation, e.g. when they are not transmitting continuously, the second approach is used. Generally one signal is introduced in harmonic detection [3-5] and two signals are introduced in intermodulation detection [6-8]. These signals are usually chosen to be in the same band of the operational signals and are introduced either from non-operational transmitters or portable sources.

7.3.2 Detection of Harmonic and Intermodulation Signals

Once the non-linear contacts are energised, harmonic and intermodulation signals may be generated and radiated. The detection of these signals can be done by amplitude measurement and phase measurement. The first case refers to measuring the amplitude of the radiated signals. It is a simple and widely used method [1-19] and is usually done by sensing the maximum radiated signals with antennas connected to either radio receivers or spectrum analysers.

The second case refers to measuring the relative phase of the radiated signals. It has been suggested [20-22] that phase measurement is more useful than amplitude measurement because the former is not affected by standing waves [20,21] and no directional antennas [22] are required. The standing waves are generated by the reflected waves and the presence of maximum signals may cause ambiguity in a detection operation. Due to these reasons, two different phase detection systems involving sophisticated hardware and signal processing techniques have been proposed [20-22]. The one proposed by the US Navy [20,21] has been built and tested, but has had limited success in field trials due to the signal phase shift caused by the movement of structural components. The other one, proposed by a UK research team [22], has no implementation result.

It is very obvious that the amplitude measurement method is much simpler than the phase measurement method. The literature review [23] conducted by the author revealed that all the successful detection methods are based on amplitude measurment.

7.3.3 Choice of Harmonic and Intermodulation Products

Passive non-linearities generate many harmonic and intermodulation products and some of which may be used for detection. The lower order products such as the third order intermodulation, second and third order harmonics are usually used for locating the interference sources because of their relatively large amplitude in comparison with higher order products, and their greater potential for causing interference. The higher order products, on the other hand, are often ignored because of their smaller amplitude. However, there were cases where serious interference problems were caused by higher order products. These happened in satellite and marine communications environments where high-power transmitters and low-noise receivers are collocated, and the amplitude of higher order products is relatively large.

In the 70's, a detection method which made use of the higher order products was developed by the US Navy [17,18]. Since each intermodulation signal can have one or more products associated with it, one of these will be the lowest order product. It has been observed that the relative strength of two intermodulation signals is related to their respective lowest orders, i.e. the higher the lowest order the lower will be the relative field strength. Therefore if one intermodulation signal has a lowest order of 5 and a second intermodulation signal has a lowest order of 9, the latter will have a weaker signal strength. The basis of this detection method is, the weakest signal will be chosen for detection because if it is detectable, it must be produced by the strongest source. To minimise the interference problem, the strongest source must first be eliminated. This concept is further explained by the following example [17].

Two operational signals, f_1 = 2279 kHz and f_2 = 4452 kHz, were used to excite the topside of a US Navy vessel. The HF spectrum was monitored and three weaker intermodulation signals, 3127 kHz, 2915 kHz and 954 kHz, were chosen for comparison. Their lowest orders were found to be $25^{th}(17f_1-8f_2)$, $19^{th}(13f_1-6f_2)$ and $27^{th}(18f_1-9f_2)$ respectively. Among these three lowest order signals, the 954 kHz signal has the weakest signal because of its highest order (27^{th}), therefore it was used for locating the passive IMI source.

It is not known whether this higher order method is applicable to other types of radio sites as no one, except the US Navy, has described it. At land mobile radio sites where the transmitted powers are relatively low and only the lower order products are likely to cause interference, the use of lower order products is more appropriate, besides it is the simplest and most widely used method.

7.4 Previous Investigations of Detection and Location Techniques

A review of detection and location techniques has been conducted and the result has been published [23]. Essentially all the detection operations made use of the principles as discussed in Section 7.3. However, due to different site conditions, the detailed implementation plan and equipment used are often different. For example, a portable harmonic detector may be adequate for locating passive IMI sources in a surveillance aircraft, but a few receivers and high-power transmitters are required for the same operation conducted on a naval vessel. The choice of method and equipment used depends upon the problems and site conditions, very often the simpler method tends to be the more successful one.

Because this project is about passive IMI at land mobile radio sites, the author will only discuss the methods used in such an environment. Basically there are two methods. The use of a portable detector which consists of two low power VHF transmitters and a radio receiver tuned to the third order intermodulation product. The two VHF signals are coupled to the suspected non-linear site via two loop antennas and the intermodulation signal generated is detected by the radio receiver. To facilitate detection, one of the VHF signals is modulated by an audio tone. This intermodulation detector was first developed by the Admiralty Signal Establishment in the 40's for locating passive IMI sources on navy vessels [7], in the 50's, the New Zealand Post Office built a similar one for VHF radio sites [8].

The use of a portable radio receiver or spectrum analyser with a small loop antenna tuned to the interference signal or related harmonic and intermodulation signals [9-12]. This second method is usually used in conjunction with the operating transmitters and the location of passive IMI sources is done by searching for the maximum interference signal in the suspected areas. This method has been widely used at land-based radio sites as well as on naval vessels. It is a simple detection method and requires no sophisticated equipment.

7.5 Experimental Studies of AF and RF Detection Techniques

7.5.1 Introduction

The following sections are concerned with the experimental studies of detecting and locating non-linear contacts. The laboratory investigation of an audio frequency (AF) detection technique, the evaluation of portable radio receivers and radio frequency (RF) detection techniques, and the development of RF detectors are described. The aim of these studies was to study a new detection technique as well as some well developed ones.

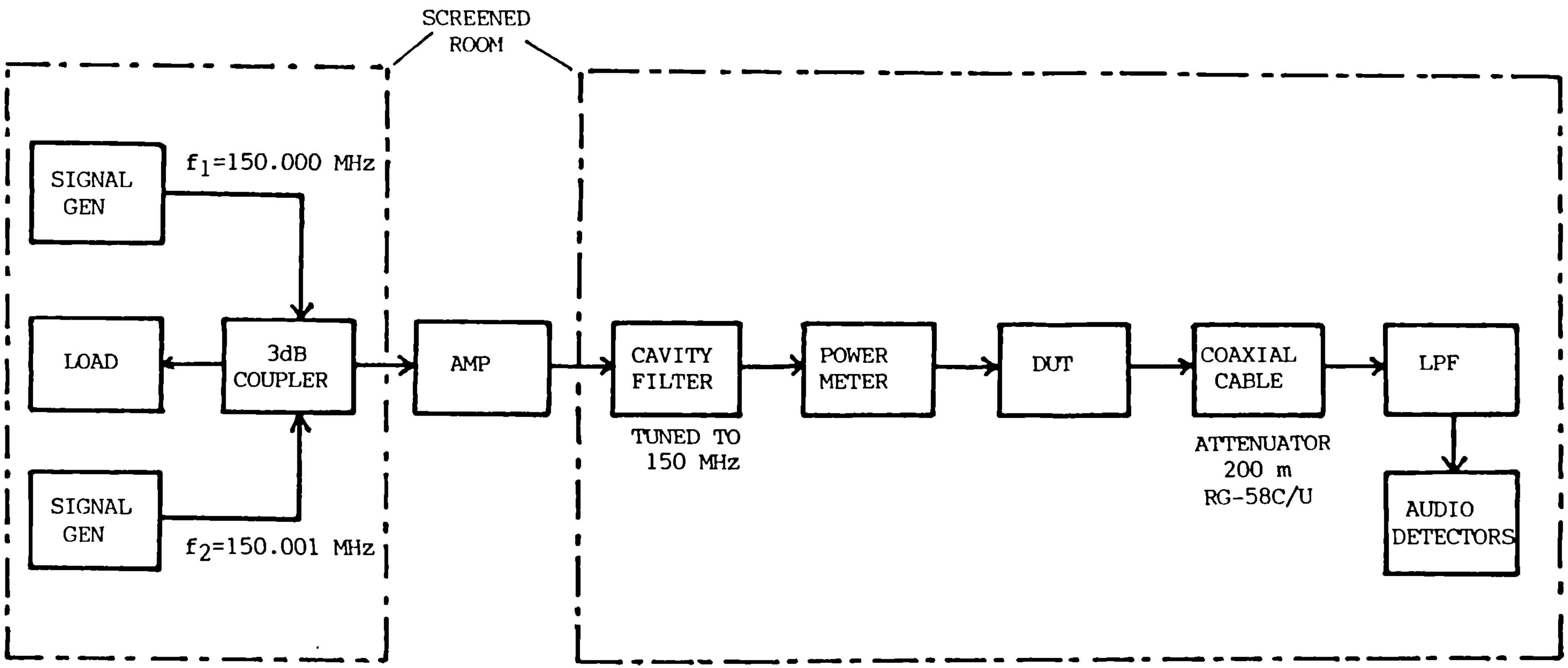
7.5.2 Audio Frequency Detection Technique

An AF detection technique involving the mixing of two closely spaced RF signals has been suggested. It was thought that an audio signal, due to the second order product (f_2-f_1), may be generated when two VHF signals separated by a few kHz are mixed at the non-linear metallic contacts. To investigate the feasibility of this idea, the following tests were conducted. The test equipment used were identical to those described in Chapter 3 and the laboratory measurement system used is shown in Fig. 7.1.

Two equal VHF signals, f_1 = 150.000 MHz and f_2 = 150.001 MHz, produced by synthesised signal generators were combined by a 3 dB coupler. The combined signal was then amplified by a high-power linear amplifier, filtered by two high-Q bandpass cavity filters and measured by a through-line power metre. A metallic chain, a highly non-linear component, was used as a test sample. The output signals from the test chamber were attenuated by a 200 m length of RG-58C/U coaxial cable and filtered by an audio R-C low pass filter. The 150 MHz signals were attenuated 80 dB by the coaxial cable and R-C filter. The signal detection was done by two audio amplifiers with designs as shown in Fig. 7.2 and 7.3.

The tests were conducted with combined input power varied between 0.5 W and 20 W. Over this test range, the 1 kHz audio tone was audible with different loudness, however, there are two places, the non-linear sample and the audio detector, where this signal might be generated. To identify the signal source, the following tests were conducted:

Test-1: The above experiment was repeated without the non-linear sample and test chamber.



LOAD = 300 m RG-58C/U COAXIAL CABLE
CONNECTION = RG-214U COAXIAL CABLE
DUT = DEVICE UNDER TEST
LPF = LOW PASS FILTER

Fig. 7.1 Measurement System For Investigating Audio Frequency Detection Technique

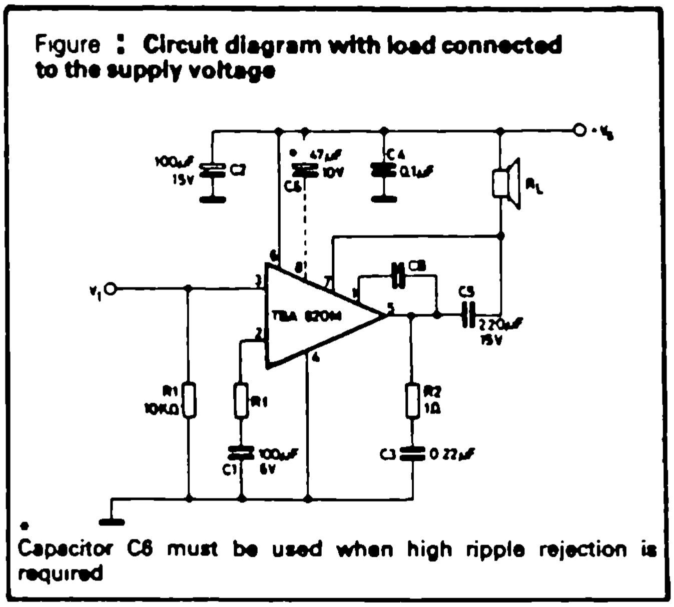


Fig. 7.2 Audio Amplifier For Audio Detection

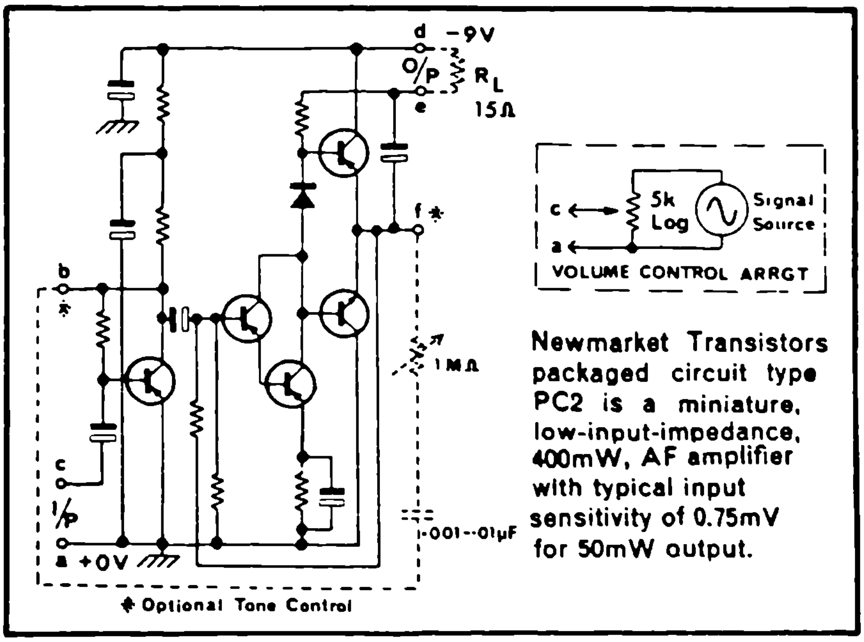


Fig. 7.3 Audio Amplifier For Audio Detection

Test-2: Two low level VHF signals, f_1 = 150.000 MHz and f_2 = 150.001 MHz, were sent from the signal generators directly to the audio detectors.

The 1 kHz tone was again audible in both tests. These tests suggested that the audio signal was generated in the audio detectors. Although an attenuator and a low pass filter were used to attenuate the VHF signals, low level VHF siganls may enter the audio detectors. These signals may generate intermodulation signals since many commonly used electronic components are non-linear devices [24]. The experimental study of AF detection technique was adjourned because it is not a very promising detection technique as there was no clear evidence of the generation of audio signal at the non-linear metallic contacts. Besides it has no major advantage over the conventional RF detection techniques. The audio signal may be generated, but this will require large exciting signals which in turn will create more radio interference problems, including the IMI problems in detectors. Also the audio signal generated will not radiate as most structures at radio sites are relatively too small to radiate audio signals, thus detecting audio signals becomes a very difficult task.

7.5.3 Radio Frequency Detection Techniques

A variety of RF detection techniques for different communications environments have been described in a review paper [23]. Basically they made use of one or more RF signals to excite the suspected non-linear sites and detect the radiated harmonic and intermodulation signals. The direction finding of these signals provides the location information of the non-linear contacts or passive IMI sources. Two RF detection experiments have been conducted. The first one as described in the following paragraph was conducted in a screened room with the aim of experimenting with simple RF direction finding.

A signal generator, tuned to 150 MHz, was used to simulate a passive IMI source and a small wire, placed at the output of the signal generator, was used to radiate the 150 MHz signal. The direction finding was carried out with a small loop antenna connected to a test receiver via a long length of coaxial cable. The VHF signal was first transmitted in continuous wave (CW) and then in modulated wave (internally modulated by a 1 kHz tone). It was discovered that the direction finding was much easier when the signal was modulated. The type of modulation, FM and AM, is not important. The 1 kHz tone was audible and became much clearer when the loop antenna was placed within a foot from the signal generator. In this experiment, very good pin-pointing accuracy has been achieved.

The second experiment was conducted at the field measurement test site, shown in Fig. 5.2. The aim of this experiment was to evaluate the conventional RF detection technique and two portable radio receivers, borrowed from Anritsu and Chase. The test set-up is shown in Fig. 5.3. Two amplified and filtered VHF signals, 152 MHz and 154 MHz, were transmitted by a folded dipole to excite the tower and surrounding metalwork. The 152 MHz signal was sent in CW mode and the 154 MHz signal was sent in FM mode, modulated by a 1 kHz tone. The third order intermodulation signal, 150 MHz, was monitored by a test receiver and a portable radio receiver. The former was connected to another folded dipole via three high-Q bandpass filters tuned to 150 MHz. The latter, with a small loop antenna, was used as a portable detector to locate the passive intermodulation sources at the site.

The intermodulation signal was detectable and the 1 kHz tone was audible in all receivers. However, the location of the sources with a portable radio receiver was found to be difficult because of the poor directivity of the small loop antenna. If a directional antenna was used instead of a small loop antenna, the general direction of the intermodulation signal could be identified. The close range detection could then be done with a small loop antenna. This field experiment did indicate that the conventional RF detection technique and the two portable radio receivers could be used for locating passive IMI sources. But directional antennas are required for far field detection and additional filtering and screening at the portable radio receiver is required for working in a high field strength environment.

7.5.4 Development of RF Detectors

Although a portable radio receiver may be used as a RF detector to locate passive intermodulation sources, it requires two transmitters to provide the exciting signals. In situations where these transmitters are not available or suitable for detection, alternative detector such as the harmonic detector [3-5], shown in Fig. 7.4, may be used. It consists of a signal source to provide an exciting signal and a radio receiver to detect the harmonic signals generated by the non-linear contacts. Based on this concept, a prototype second harmonic detector was built.

It consists of a ready-made single channel, 80 MHz, 1.5 W FM transmitter, a ready-made single channel, 160 MHz, FM receiver and a 1 kHz tone generator. These units were battery operated and the transmitter and receiver were housed in separate diecast boxes to increase signal isolation. Two small wire loops were used as transmitting and receiving antennas and the 80 MHz signal was coupled to a variety of 1 m long non-linear samples. The 1 kHz tone was detected by the 160 MHz receiver, but further test showed that the second harmonic signal was produced by the transmitter instead of the non-linear samples. This detector did not

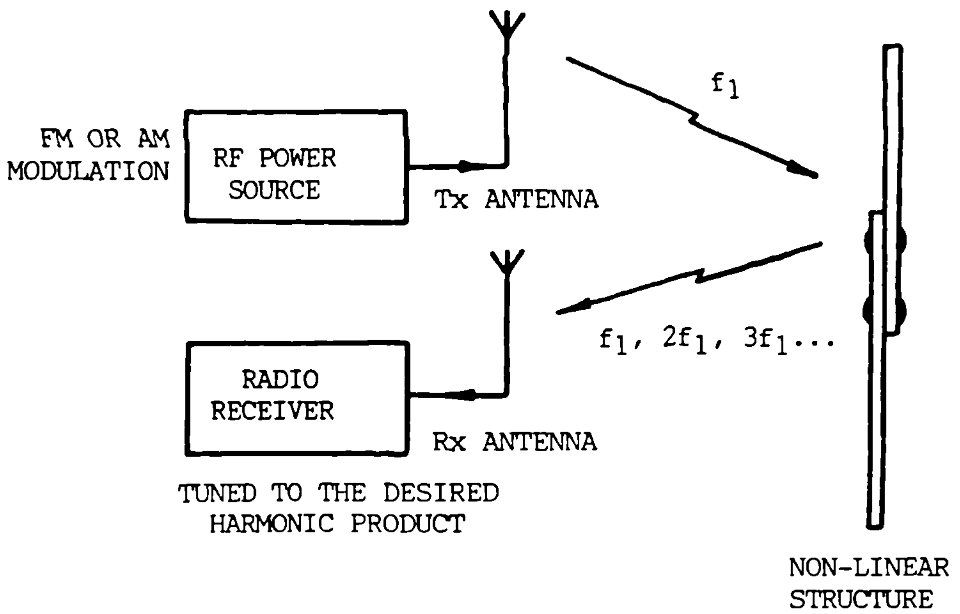


Fig. 7.4 Harmonic Detection System

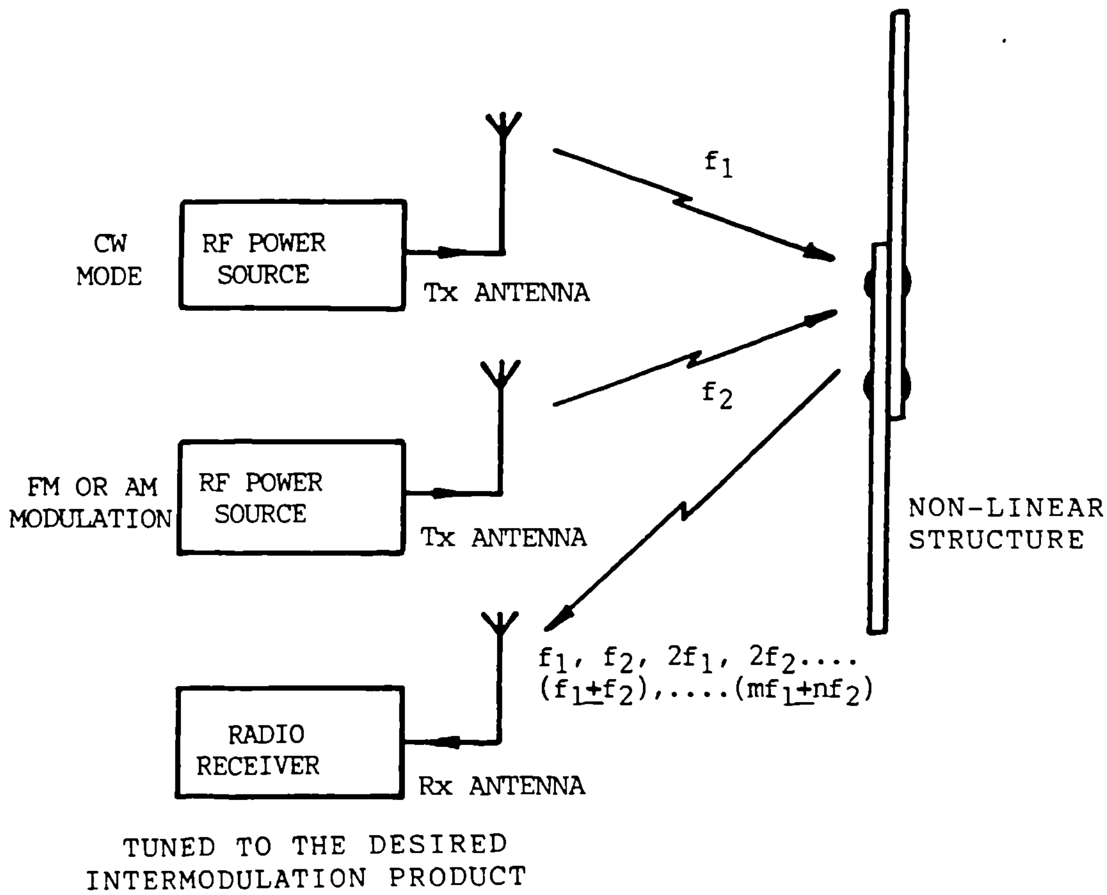


Fig. 7.5 Intermodulation Detection System

produce satisfactory test results, but the experiment did provide some useful design information. The detector requires additional filtering to provide a cleaner signal, and a stronger signal source and a tuned antenna to couple enough energy to a suspected non-linear site.

An alternative to the harmonic detector is the intermodulation detector, shown in Fig. 7.5 and described in Section 7.4. A prototype unit is being built, however, due to some technical problems, no test result is available yet.

7.6 Detection and Location Strategies

When IMI problems exist at a radio site, it is required to locate the IMI sources and take remedial action. The test procedure for such work has been described briefly in a paper as shown in Appendix A. The following discussions concentrate on the detection and location of external passive IMI sources. The strategies outlined are based on the following studies.

(1) A detailed literature review [23] of various detection and location techniques for different communications environments.

(2) The experimental studies related to passive intermodulation as described in this thesis.

(3) A 5-day field study trip with the Home Office engineers at a land mobile radio site encountered passive IMI problem.

(4) The technical discussions with Mr P Shelswell of the BBC Research Department [25], field engineers of the UK Home Office and radio inspectors of the Department of Trade and Industry.

Strategy-1: When the interference signal is transmitting continuously.

The location of the sources can be done by RF direction finding. First by finding the general direction of the interference signal with radio receivers and directional antennas, and then followed by a close range detection with a small loop antenna and a portable detector. The portable detector, either a radio receiver or a spectrum analyser, is usually tuned to the interference signal although related harmonic and intermodulation signals may be used. If the operation is carried out in a high field strength environment, additional filtering and screening to the detector is required. The interference signal is also monitored continuously with another receiver to check whether the metallic contacts located are actually responsible for the interference.

Strategy-2: When the interference signal is not transmitting continuously.

This problem actually happened at a radio site near Plymouth where the interference signal was caused by a paging signal and a mobile radio signal. The interference signal only occured when both paging and mobile radio signals were transmitting. The direction finding of such a short duration signal is difficult and under such a condition, new exciting signals are required. They are used to excite the suspected non-linear sites and generate new harmonic and intermodulation signals for detection. The exciting signals may come from some unused transmitters or portable sources and one of the exciting signals may be modulated by an audio tone. The choice of exciting frequencies is arbitrary, but usually they are chosen to be in the same band of the operational signals.

The strategies for detecting and locating passive IMI sources are relatively simple, but as each interference problem is different, the detection plan, the types of test equipment used and the time taken to locate the sources can vary considerably. The study conducted by the author concluded that there is no shortage of test equipment and detectors for such work although some detectors have been developed. Over the years, many passive IMI sources have been located with simple direction finding techniques. This has been confirmed by a recent discussion with an engineer from the BBC Research Department [25]. The use of quality equipment, the ability to recognise likely passive IMI sources and the understanding of IMI problems are all very important factors in a successful detection operation.

7.7 Summary

The causes of passive IMI and the basic principles of exciting, detecting and locating passive IMI sources at radio sites have been discussed. Experimental studies of AF and RF detection techniques have been conducted and strategies for a detection operation have been outlined.

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CHAPTER 8

Conclusions and Recommendations

8.1 Conclusions

This section concludes the study of passive intermodulation interference due to non-linearities in metallic structures. The works conducted are briefly described and the main results of the project are discussed.

The objective of this project was to investigate the characteristics of passive intermodulation products generated by radio towers and nearby metallic objects, and devise methods and detectors to locate the passive intermodulation interference sources. First, a detailed literature review of topics related to passive intermodulation was conducted. It covers the measurement, characterisation, detection, analysis and modelling of passive intermodulation products in communications systems. The review findings were analysed and then applied to various aspects of the project, such as the design of measurement systems and experiments, analysis of passive non-linearities, and location of passive intermodulation sources.

There are two approaches in the investigation of passive intermodulation interference problems. The investigation could be approached either from a theoretical point of view or from a practical angle based on measurements. The theoretical approach has produced models to describe the passive non-linearities and predict the interference levels, but provided no practical solutions to the problems. On the other hand, the widely used measurement approach has provided information which could be used to identify the potential interference sources and minimise the problems. It was therefore decided that the measurement approach should be used.

Based on the measurement approach, computer-controlled measurement systems were developed. The laboratory measurement system was developed for measuring the third order intermodulation signals generated by plate samples and structural components under controlled conditions. The field measurement system was used to study the behaviour of passive intermodulation signals in relation to environmental changes, and as a test facility to evaluate methods of locating passive intermodulation sources.

Using the laboratory measurement system, the relationships between the passive intermodulation product levels and combined input power levels, types of metals and joints, tightness and looseness at joints, effect of vibration and presence of moisture were studied. A total of 89 test samples were fabricated and measured. These samples consist of small metallic plates with dimensions of 6.5 x 0.2 x 15.8 cm and 1 meter long structural components incorporating a variety of fixtures. The tests were conducted with input power levels varied from 10 W to 63 W at high band VHF.

The field measurements were conducted under conditions similar to a radio site environment and with transmitted powers of up to 25 W at high band VHF. The aim of the measurement was to study the relationships between the passive intermodulation product levels, transmitter output levels and weather conditions. The non-linearities of the test site and the variation of intermodulation signals with time were also measured.

In addition to the measurement work, the previous studies of non-linear mechanisms and non-linear analytical techniques were investigated. The results were used to explain the non-linear effects at contacts, and model the input and output power relationships. Finally experimental work which involved the design, development and evaluation of detection techniques and detectors was conducted. Two detection and location strategies based on the laboratory and field studies were outlined.

The detailed results of above works have been discussed in previous chapters and presented in three conferences, two colloquia and one journal. In the following paragraphs, only the main results are discussed.

The laboratory measurement system developed by the author has met the stated requirements and overcome most of the limitations suffered by other measurement systems. The main practical feature of it, besides the computer-controlled facilities, is its capability to accommodate different types of test samples (i.e. metallic plates and structural components). This is due to the design of a 50 ohm and a half-wavelength long test chambers. Since proper attentions were given to the system design and the choice of components, the system has a dynamic range wider than comparable systems. With little or no modifications to the setup, the system can be used to measure the non-linearities of coaxial cables, connectors and other RF components.

From the laboratory measurement results, it was found that mild steel generates strong intermodulation signals, but if it is galvanised, then the layer of zinc coating will conduct most of the RF currents and the hysteresis effect will become insignificant. According to British Standard BS 729 (a standard used for galvanising tower components), the minimum thickness of zinc coating for metals with thickness greater than 5 mm is 85 microns. This thickness is nine times the skin-depth of zinc at 150 MHz and makes the galvanised mild steel behaves as a linear metal at VHF frequencies.

Very often the rusty metallic contacts are assumed to be responsible for the passive intermodulation interference problems, but the laboratory measurement results show that they generally do not generate strong intermodulation signals unless they are loose or have small contact areas. If the rusty contacts or joints have low impedance paths, the effect may actually be minimal. However, loose metallic contacts, regardless of the surface conditions and metals, generate strong and erratic intermodulation signals. These signals are very unstable and sensitive to physical motion. This is most probably due to the non-linear effect of high current densities at small and unstable mating surfaces.

Therefore at land mobile radio sites, the tower components are unlikely to generate strong intermodulation signals because they are all galvanised metals and are tightly bolted together. However, any loose metallic contacts embedded in structures having the approximate dimensions of VHF antennas can cause serious interference problems. Typical examples are perimeter fences, twisted guy wires, antenna support clamps, gutterings, drain pipes, vehicles and joints between wires, shackles and thimbles. To eliminate the interference problems, the sources must either be removed, insulated, cleaned and tightened or bypassed with copper straps.

The laboratory and field measurement results show that the third order intermodulation product level is a linear function (in dB) of the combined input power level, but the n^{th} order product level does not always vary as n dB/dB with the input power level. It varies between 1.5 and 3 dB/dB and has a mean of 2 dB/dB for a third order intermodulation signal. This suggests that the theoretical model which based on a simple power series does not represent the characteristics of passive non-linearities accurately. This is because when a power series is used to model the passive non-linearities, only the first few terms of the series are used. The higher order terms are ignored because the coefficients of these terms are small, as a result errors are introduced. Also the passive non-linearities in metals and contacts are due to a number of non-linear mechanisms which are not well understood and cannot be modelled accurately. Therefore there are differences between the theoretical and measurement results. Since measurement results show the actual responses of the non-linearities, they should be used for signal prediction. The intermodulation product amplitude generally falls off with increasing order, at radio sites where the transmitted powers are relatively low, only the lower order products are significant.

The field measurement system has provided a permanent outdoor facility for measuring intermodulation signals and evaluating detection techniques. The field measurement results show that there is no clear relationship between the passive intermodulation product levels, wind speed and site temperature. Although the product levels measured in wet weather were lower than those in dry weather, further test is required to provide more convincing and quantitative results. To understand the influence of weather conditions on passive intermodulation product generation at radio sites, long term observation is essential.

Although the semiconductor, electron tunnelling, microdischarge and contact mechanisms have been assumed or suspected to be responsible for the non-linear effect at metallic contacts, so far only the contact mechanism provides a more satisfactory explanation. It suggests that the non-linear effect is current dependent and the product level is proportional to the current densities at contacts. This may be used for explaining the non-linear effect at contacts, but further work is needed to provide a more rigorous model.

The studies show that there is no shortage of test equipment and detectors for locating passive intermodulation sources although some portable detectors have been developed. In a detection operation, the use of quality equipment and the ability to recognise likely intermodulation sources are very important, but the most important factor is to have a team of qualified technical staff who can analyse the problems and produce practical detection plans. Over the years, many sources have been located with direction finding techniques using radio receivers and directional antennas. The most commonly used method at land mobile radio sites is to search the suspected areas with a small loop antenna and a portable radio receiver or spectrum analyser tuned to the intermodulation frequency of interest.

8.2 Recommendations

This section recommends some of the work which may be extended or improved in the future. The recommendations for minimising passive intermodulation product generation in communications systems are also included.

Although the performance of the laboratory measurement system is better than comparable systems, there is room for improvement. For example the RG-58C/U coaxial cable (load) could be replaced by the RG-214U coaxial cable which has better power handling and screening specifications. The two signal generators and the power meter could be replaced by programmable units thus providing a fully automatic measurement system. The system dynamic range could be extended by adding a notch filter or a passive intermodulation product cancellation section as described in Section 3.5.2 to reduce the system noise floor. Also the two test chamber designs could be modified for larger test samples.

The laboratory measurement of passive intermodulation products has provided many useful information about the characteristics of non-linear metals and metallic joints, but this work could be extended. This is to create a database which could be used for the design and construction of linear components, such as cables, connectors, filters and loads. Since there is very little understanding of the actual mechanisms at non-linear contacts, future work in this area is essential.

The field measurement of passive intermodulation products has provided some preliminary results, but due to the unstable nature of the 'rusty-bolt' effect and the highly variable nature of some of the test parameters, more conclusive and useful results can only be obtained if measurements are conducted over a longer period. Therefore the continuation of field measurement is highly recommendated. Finally the development of harmonic and intermodulation detectors may be continued as they can be used as alternative detectors.

Over the last forty years, passive intermodulation interference has caused many problems to various types of communications systems. From the recent published literatures [1-4], it is clear that these problems have not been solved and many engineers and researchers are still looking into ways to minimise them. In Appendix E, there are some general guidelines which could be used for such purpose. Although these guidelines may not be applicable in every situation, they form a framework for approaching the problems. In addition to these guidelines, careful planning, good workmanship, stringent quality control and high standards of maintenance are equally important. However, it should be borne in mind that no system is completely free from passive intermodulation products, although proper attention to detail during the design and construction stages can make a substantial reduction in level. The generation of passive intermodulation products should always be considered in the design and operation of multi-frequency communications systems.

REFERENCES

CHAPTER 8

[1] IEE Colloquium on 'Passive Intermodulation Products in Antennas and Related Structures', Digest No. 1989/94, June 1989

[2] Mieth, W. B. : 'A Cost Effective Solution to Measurement of Hull Generated Intermodulation Interference on US Navy Ships', National Symposium on Electromagnetic Compatibility, USA, May 1989, pp. 186-189

[3] Chamberlin, K. : 'Quantitative Analysis of Intermodulation Product Interference', IEEE Trans. on EMC, Vol. 31, No. 3, 1989, pp. 316-319

[4] Aspden, P. L. and et al. : 'Microwave Imaging of Intermodulation Product Sources Applied to Reflector Antennas', Proc. 6th ICAP. 1989. pp. 463-467

Appendix A

Typical Diagnosis of Interference Sources at Base Station Sites

In this example, interference is being experienced by a receiver, the interfering transmitter(s) is/are unidentified and may be co sited or at another communal site in the near vicinity. Before any fault finding can be carried out it will be necessary to obtain permission from the users of the equipment at the other sites to key or switch their equipment on and off for short periods in order to identify the sources. It is essential that notes are made of the results, both positive and negative. If there is more than one site involved, additional personnel will be required. In this case it is also fundamental to have two way communication between sites.

Starting at the site where the troubled receiver is located the interfering transmitter is located by keying each transmitter in turn and listening to the receiver for interference. It may be necessary to extend this to the other sites in order to locate the offending transmitter. For simplicity the diagnostic chart which follows assumes that there is only one interfering source, when more than one transmitter is involved the pattern is similar, the complexity being greater.

Having located the transmitter causing the interference the first step is to replace the transmitter antenna by an r f watt meter. This action will have one of three results, shown in the diagnostic chart as follows –

(a) There is no change in the interference level. The cause is therefore direct radiation from the transmitter itself. This can be from the chassis or the associated wiring direct but not via the antenna. In order to clear the trouble additional screening may be necessary and possibly the addition of power supply filters. It may also be necessary to filter the audio input control leads. Having cured the direct radiation, proceed as in (c)

(b) The level of interference is reduced. This means that there is some direct radiation, which must be cured first by following the instructions as in (a)

(c) There is no direct radiation from the chassis etc. *In this case the transmitter antenna is replaced via an* additional high or low pass filter in order to reduce any spurious emissions from the transmitter.

It is worth noting here that the interfering source may not necessarily be a transmitter; it could be another receiver. The procedure is similar; one should read 'receiver' in place of 'transmitter' on the chart.

(d) and (e) are self explanatory, the filters being fitted permanently in order to eliminate or reduce the spurious emissions. In the final sub section (f), the problem lies with one or more of the following:

(i) Two or more discrete transmitter frequencies

(ii) The transmitter being keyed is involved in the formation of intermodulation products in the vicinity of the transmitter site, i.e. antennas etc.

(iii) Interference is produced in the vicinity of the receiver site

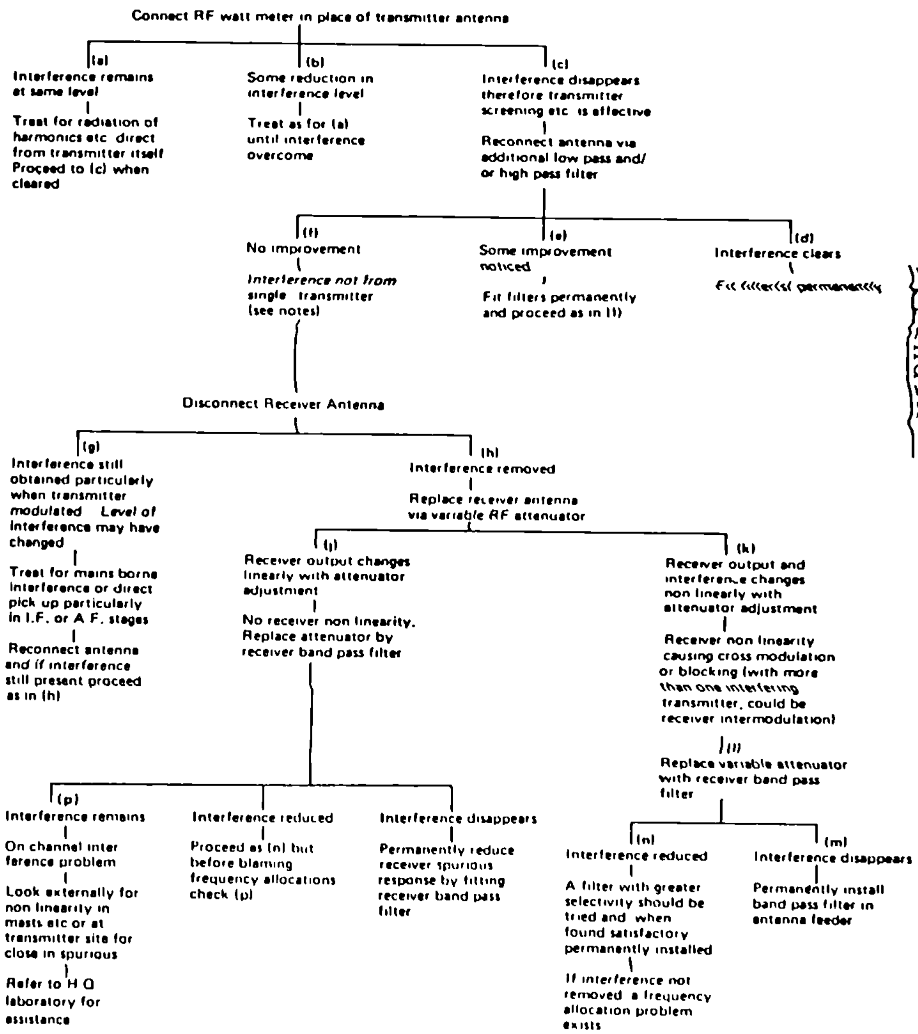
Having eliminated faults caused by other transmitters the next step is to check the receiver, starting by disconnecting the receiving antenna. (g) needs no further explanation, (h) infers that the offending signal(s) is/are coming down the antenna lead. The interference can be either on or off channel.

The receiver must now be checked to determine if it behaves linearly or non linearly with changes in signal level. This can be achieved by replacing the receiver antenna via a variable r.f. attenuator, preferably continuously variable. In (g), both the wanted and unwanted signal vary linearly with attenuator setting. This is indicative of a possible received spurious response or an externally-produced receiver co-channel product. (k) shows that the higher level unwanted signal varies non linearly with the attenuator setting. (The crash point is reached – compare measurements for intermodulation etc., where this occurs quickly with generator attenuator setting). Thus the interference problem is not one of receiver co channel interference, although the frequency planning problem could be present due to a transmitter being very close in frequency to the receiver frequency. The non linear effect in this case would be due to the very high level of transmitter signal input.

Following the non linearity path through the diagnostic chart, (n) and (m) indicates that the offending off-channel signals must be removed by means of filtering, this normally being achieved with band pass filters. In certain cases it may be necessary to increase the selectivity. In order to achieve this, additional filters may have to be added.

Continuing on from (g) the choice is between the following: external non linearity causing an on frequency product, a receiver spurious response; or the transmitter is on the receive channel frequency. Having replaced the variable attenuator by a receiver band pass filter, if the interference disappears the problem is one of receiver spurious responses. In the case where the interference is only reduced, additional filters must be added to obtain greater selectivity. If this does not help, it may mean that the transmitter *is on the receiver frequency*. In (p), where the interference is unaffected by the band pass filter, an on channel interference problem exists. In this case checks should be carried out external to the receiver for the possibility of non linearity in masts etc. both at the receiver and transmitter sites. The transmitter spectrum should also be examined and any close in spurious emissions eliminated. If the interference still remains, specialist assistance may be advisable.

DIAGNOSTIC CHART



This diagnostic chart was taken from the following references

(1) 'Interference Problems at VHF & UHF Base Station Sites' by Gourlay I G, SFRT Journal, Vol. 5, May 1971, pp.63 64

(2) 'Interference Problems at VHF & UHF Base Station Sites' Pye Telecom Engineering Notes, pp. 17-18

Appendix B

```
10      !*****************************************************************
20      !* TITLE    : 2P                                                 *
30      !* FUNCTION : GENERAL PROGRAM TO TEST TWO-PORT NETWORK           *
40      !* OWNER    : NOISE MEASUREMENT GROUP, UKC                       *
50      !* DATE     : FEBRUARY 1988                                      *
60      !*****************************************************************
70          C$=CHR$(255)&"K"
80          OUTPUT 2 USING "#,K";C$
90          PLOTTER IS CRT,"INTERNAL"
100         BEEP 50,.1
110         INPUT "ENTER TITLE",X$
120         ON KBD GOTO 130
130 Kbd:    !
140         SELECT UPC$(KBD$)
150         CASE "A"
160         BEEP 50,.1
170                 PRINT TABXY(20,18);"                  "
180                 PRINT TABXY(1,19);"INPUT REC FREQ     "
190                 PRINT TABXY(1,20);"REC FREQ IN MHz = ";A
200                 INPUT A
210                 OUTPUT 718;"FR";A
220                 PRINT TABXY(1,20);"REC FREQ IN MHz = ";A
230          IF A<20 OR A>1300 THEN PRINT TABXY(1,23);"OUT OF RANGE ERROR"
240         CASE "B"
250         BEEP 50,.1
260                 PRINT TABXY(20,18);"                  "
270                 PRINT TABXY(1,19);"INPUT START FREQ   "
280                 PRINT TABXY(1,20);"START FREQ IN MHz = ";B
290                 INPUT B
300                 OUTPUT 718;"SA";B
310                 PRINT TABXY(1,20);"START FREQ IN MHz = ";B
320          IF B<20 OR B>1300 THEN PRINT TABXY(1,23);"OUT OF RANGE ERROR"
330         CASE "C"
340         BEEP 50,.1
350                 PRINT TABXY(20,18);"                  "
360                 PRINT TABXY(1,19);"INPUT STOP FREQ    "
370                 PRINT TABXY(1,20);"STOP FREQ IN MHz = ";C
380                 INPUT C
390                 OUTPUT 718;"SO";C
400                 PRINT TABXY(1,20);"STOP FREQ IN MHz = ";C
410          IF C<20 OR C>1300 THEN PRINT TABXY(1,23);"OUT OF RANGE ERROR"
420         CASE "D"
430         BEEP 50,.1
440                 PRINT TABXY(20,18);"                  "
450                 PRINT TABXY(1,19);"INPUT STEP SIZE    "
460                 PRINT TABXY(1,20);"STEP SIZE IN MHz = ";D
470                 INPUT D
480                 OUTPUT 718;"SE";D
490                 PRINT TABXY(1,20);"STEP SIZE IN MHz = ";D
500          IF D<.0001 OR D>1300 THEN PRINT TABXY(1,23);"OUT OF RANGE ERROR"
510         CASE "E"
520         BEEP 50,.1
530                 PRINT TABXY(20,18);"                  "
540                 PRINT TABXY(1,19);"INPUT MAX LEVEL IN dB"
550                 PRINT TABXY(1,20);"MAX LEVEL IN dB = ";E
560                 INPUT E
570                 OUTPUT 718;"SU";E
580                 PRINT TABXY(1,20);"MAX LEVEL IN dB = ";E
590          IF E<-140 OR E>200 THEN PRINT TABXY(1,23);"OUT OF RANGE ERROR"
600         CASE "F"
610         BEEP 50,.1
620                 PRINT TABXY(20,18);"                  "
630                 PRINT TABXY(1,19);"INPUT MIN LEVEL IN dB "
640                 PRINT TABXY(1,20);"MIN LEVEL IN dB = ";F
650                 INPUT F
660                 OUTPUT 718;"SL";F
670                 PRINT TABXY(1,20);"MIN LEVEL IN dB = ";F
680          IF E<-140 OR E>200 THEN PRINT TABXY(1,23);"OUT OF RANGE ERROR"
690         CASE "G"
700         BEEP 50,.1
710                 PRINT TABXY(20,18);"                  "
720                 PRINT TABXY(1,19);"INPUT MEASURING TIME IN SEC    "
730                 PRINT TABXY(1,20);"MEASURING TIME IN SEC = ";G
740                 INPUT G
750                 OUTPUT 718;"TS";G
760                 PRINT TABXY(1,20);"MEASURING TIME IN SEC = ";G
770          IF G<.0050 OR G>1000 THEN PRINT TABXY(1,23);"OUT OF RANGE ERROR"
780         CASE "H"
790         BEEP 50,.1
800                 PRINT TABXY(20,18);"                  "
810                 PRINT TABXY(1,19);"INPUT RF ATTENUATION (dB) "
820                 PRINT TABXY(1,20);"RF ATTENUATION (dB) = ";H
830                 INPUT H
840                 Ha=H/10
850                 OUTPUT 718;"RA";H
860                 PRINT TABXY(1,20);"RF ATTENUATION (dB) = ";H
```

```
870        CASE "I"
880        BEEP 50,.1
890                PRINT TABXY(20,18);"                    "
900                PRINT TABXY(1,19);"INPUT IF ATTENUATION (dB) "
910                PRINT TABXY(1,20);"IF ATTENUATION (dB) = ";I
920                INPUT I
930                OUTPUT 718;"1A";I
940                PRINT TABXY(1,20);"IF ATTENUATION (dB) = ";I
950         IF I'0 OR I 40 THEN PRINT TABXY(1,23);"OUT OF RANGE ERROR"
960        CASE "J"
970        BEEP 50,.1
980                J$="LOW NOISE SELECTED"
990                PRINT TABXY(20,18);"                    "
1000               PRINT TABXY(1,19);"LOW NOISE                          "
1010               OUTPUT 718;"A1"
1020               PRINT TABXY(1,20);"LOW NOISE SELECTED                 "
1030       CASE "K"
1040       BEEP 50,.1
1050               K$="LOW DIST  SELECTED"
1060               PRINT TABXY(20,18);"                    "
1070               PRINT TABXY(1,19);"LOW DISTORTION                     "
1080               OUTPUT 718;"A2"
1090               PRINT TABXY(1,20);"LOW DISTORTION SELECTED "
1100       CASE "L"
1110       BEEP 50,.1
1120               L$="IF   1MHz SELECTED"
1130               PRINT TABXY(20,18);"                    "
1140               PRINT TABXY(1,19);"IF  BW 1MHz SELECTED      "
1150               OUTPUT 718;"B1"
1160       CASE "M"
1170       BEEP 50,.1
1180               M$="IF 120KHz SELECTED"
1190               PRINT TABXY(20,18);"                    "
1200               PRINT TABXY(1,19);"IF  BW 120KHz SELECTED  "
1210               OUTPUT 718;"B2"
1220       CASE "N"
1230       BEEP 50,.1
1240               N$="IF 12KHz  SELECTED"
1250               PRINT TABXY(20,18);"                    "
1260               PRINT TABXY(1,19);"IF  BW 12KHz SELECTED    "
1270               OUTPUT 718;"B3"
1280       CASE "O"
1290       BEEP 50,.1
1300               O$="IF 7.5KHz SELECTED"
1310               PRINT TABXY(20,18);"                    "
1320               PRINT TABXY(1,19);"IF  BW 7.5KHz SELECTED  "
1330               OUTPUT 718;"B4"
1340       CASE "P"
1350       BEEP 50,.1
1360               P$="CHECK SELECTED    "
1370               PRINT TABXY(20,18);"                    "
1380               PRINT TABXY(1,19);"CHECK SELECTED                     "
1390               OUTPUT 718;"C1"
1400       CASE "Q"
1410       BEEP 50,.1
1420               Q$="TOTAL SELECTED    "
1430               PRINT TABXY(20,18);"                    "
1440               PRINT TABXY(1,19);"TOTAL SELECTED                     "
1450               OUTPUT 718;"C2"
1460       CASE "R"
1470       BEEP 50,.1
1480               R$="RGE 20dB SELECTED "
1490               PRINT TABXY(20,18);"                    "
1500               PRINT TABXY(1,19);"OP RANGE 20dB SELECTED  "
1510               OUTPUT 718;"L1"
1520       CASE "S"
1530       BEEP 50,.1
1540               S$="RGE 40dB SELECTED "
1550               PRINT TABXY(20,18);"                    "
1560               PRINT TABXY(1,19);"OP RANGE 40dB SELECTED  "
1570               OUTPUT 718;"L2"
1580       CASE "T"
1590       BEEP 50,.1
1600               T$="RGE 60dB SELECTED "
1610               PRINT TABXY(20,18);"                    "
1620               PRINT TABXY(1,19);"OP RANGE 60dB SELECTED  "
1630               OUTPUT 718;"L3"
1640       !**************************************************************
1650       !OUTPUT  TO THE INK JET PRINTER
1660       !**************************************************************
1670       CASE "U"
1680       BEEP 50,.1
1690               PRINT TABXY(21,18);"                    "
1700               PRINT TABXY(1,19);"PRINTING VALUES                    "
1710               C$=CHR$(255)&"K"
1720               OUTPUT 2 USING "#,K";C$
1730               PRINTER IS 701
```

```
1740      PRINT "************************************************************"
1750      PRINT "*                                                          *"
1760      PRINT "*NOISE MEASUREMENT GROUP LABORATORY REPORT                 *"
1770      PRINT "*                                                          *"
1780      PRINT "*PROGRAM FOR TWO PORT TEST ON ESVP                         *"
1790      PRINT "*GROUP REF NO:";X$
1800      PRINT "* RX FREQUENCY (MHz)  =";A
1810      PRINT "* START FREQ   (MHz)  =";B
1820      PRINT "* STOP  FREQ   (MHz)  =";C
1830      PRINT "* STEP SIZE    (MHz)  =";D
1840      PRINT "* MAXIMUM       (dB)  =";E
1850      PRINT "* MINIMUM       (dB)  =";F
1860      PRINT "* MEASURING TIME(SEC) =";G
1870      PRINT "* RF ATTENUATION (dB) =";H
1880      PRINT "* IF ATTENUATION (dB) =";I
1890      PRINT "* LOW NOISE SELECTED  =";J$
1900      PRINT "* LOW DISTORTION      =";K$
1910      PRINT "* BW 1MHz   SELECTED  =";L$
1920      PRINT "* BW 120KHz SELECTED  =";M$
1930      PRINT "* BW 12KHz  SELECTED  =";N$
1940      PRINT "* BW 7.5KHz SELECTED  =";O$
1950      PRINT "* CHECK SELECTED      =";P$
1960      PRINT "* FULL CAL SELECTED   =";Q$
1970      PRINT "* OP RANGE 20dB       =";R$
1980      PRINT "* OP RANGE 40dB       =";S$
1990      PRINT "* OP RANGE 60dB       =";T$
2000      PRINT "LISTING COMPLETED"
2010      CASE "V"
2020      !*************************************************************
2030      !OUTPUT TO THE PLOTTER
2040      !*************************************************************
2050 S1:          !
2060              C$=CHR$(255)&"K"
2070              OUTPUT 2 USING "$,K";C$
2080              GINIT
2090              PLOTTER IS 705,"HPGL"
2100              GRAPHICS ON
2110              X=100*MAX(1,RATIO)
2120              Y=100*MAX(1,1/RATIO)
2130              DEG
2140              LORG 6
2150              LDIR 0
2160              CSIZE 3.5
2170              MOVE 30,100
2180              LABEL "GRAPH -";X$
2190              PENUP
2200              DEG
2210              LORG 6
2220              LDIR 0
2230              CSIZE 3.5
2240              MOVE 30,5
2250              LABEL "FREQUENCY (MHz)"
2260              PENUP
2270              DEG
2280              LORG 6
2290              LDIR 90
2300              CSIZE 3.5
2310              MOVE 0,50
2320              LABEL "INSERTION  GAIN (dB)"
2330              PENUP
2340              Yaxis=15
2350              DEG
2360              LORG 6
2370              LDIR 0
2380              CSIZE 2.5
2390              MOVE 13,Yaxis
2400              LABEL B
2410              PENUP
2420              DEG
2430              LORG 6
2440              LDIR 0
2450              CSIZE 2.5
2460              MOVE 41,Yaxis
2470              LABEL "    "
2480              PENUP
2490              DEG
2500              LORG 6
2510              LDIR 0
2520              CSIZE 2.5
2530              MOVE 67,Yaxis
2540              LABEL "    "
2550              PENUP
2560              DEG
2570              LORG 6
2580              LDIR 0
2590              CSIZE 2.5
2600              MOVE 94,Yaxis
2610              LABEL "    "
```

```
2620            PENUP
2630            DEG
2640            LORG 6
2650            LDIR 0
2660            CSIZE 2.5
2670            MOVE 120,Yaxis
2680            LABEL C
2690            PENUP
2700            DEG
2710            LORG 6
2720            LDIR 0
2730            CSIZE 2.5
2740            MOVE 8,22
2750            LABEL F
2760            PENUP
2770            DEG
2780            LORG 6
2790            LDIR 0
2800            CSIZE 2.5
2810            MOVE 8,35
2820            LABEL " "
2830            PENUP
2840            DEG
2850            LORG 6
2860            LDIR 0
2870            CSIZE 2.5
2880            MOVE 8,49
2890            LABEL " "
2900            PENUP
2910            DEG
2920            LORG 6
2930            LDIR 0
2940            CSIZE 2.5
2950            MOVE 8,62
2960            LABEL " "
2970            PENUP
2980            DEG
2990            LORG 6
3000            LDIR 0
3010            CSIZE 2.5
3020            MOVE 8,76
3030            LABEL " "
3040            PENUP
3050            DEG
3060            LORG 6
3070            LDIR 0
3080            CSIZE 2.5
3090            MOVE 8,90
3100            LABEL E
3110            PENUP
3120 P1:        VIEWPORT .1*X,.9*X,.2*Y,.89*Y
3130            FRAME
3140            WINDOW B,C,F,E
3150            AXES 10,10,B,F,5,10,3
3160            AXES 10,10,C,E,5,10,3
3170            FOR L=B TO C STEP 10
3180            LINE TYPE 1
3190            PLOT L,0
3200            PENUP
3210            NEXT L
3220            OUTPUT 718;"SF91"
3230            OUTPUT 718;"SF00"!THIS IS ESSENTIAL FOR GRAPH WHY?
3240            OUTPUT 718;"SA";B
3250            OUTPUT 718;"SO";C
3260            OUTPUT 718;"SE";D
3270            OUTPUT 718;"SU";E
3280            OUTPUT 718;"SL";F
3290            OUTPUT 718;"TS";G
3300            OUTPUT 718;"L3"
3310            OUTPUT 718;"N1"
3320            OUTPUT 718;"B4"
3330            OUTPUT 718;"A1"
3340            OUTPUT 718;"M2"
3350            OUTPUT 718;"SR"
3360            FOR D=B TO C STEP D
3370            ENTER 718;A
3380            ENTER 718;B
3390            LINE TYPE 1
3400            PLOT A,B
3410            NEXT D
3420            PENUP
3430            PEN 1
3440            STOP
```

```
3450      !*****************************************************************
3460      !OUTPUT TO THE CRT  - PARAMETER SETTINGS
3470      !*****************************************************************
3480       CASE "W"
3490               PRINT TABXY(21,18);"
3500               PRINT TABXY(1,19);"PRINTING VALUES
3510               C$=CHR$(255)&"K"
3520               OUTPUT 2 USING "#,K";C$
3530               PRINTER IS CRT
3540       PRINT "PROGRAM FOR TWO PORT TEST ON ESVP"
3550       PRINT X$
3560       PRINT "* RECEIVER FREQUENCY (MHz)=";A
3570       PAUSE
3580       PRINT "* START FREQUENCY (MHz)   =";B
3590       PAUSE
3600       PRINT "* STOP  FREQUENCY (MHz)   =";C
3610       PAUSE
3620       PRINT "* STEP SIZE       (MHz)   =";D
3630       PAUSE
3640       PRINT "* MAXIMUM LEVEL   (dB)    =";E
3650       PAUSE
3660       PRINT "* MINIMUM LEVEL   (dB)    =";F
3670       PAUSE
3680       PRINT "* MEASURING TIME  (SEC)   =";G
3690       PAUSE
3700       PRINT "* RF ATTENUATION  (dB)    =";H
3710       PAUSE
3720       PRINT "* IF ATTENUATION  (dB)    =";I
3730       PAUSE
3740       PRINT "* LOW NOISE SELECTED      =";J$
3750       PAUSE
3760       PRINT "* LOW DIST SELECTED       =";K$
3770       PAUSE
3780       PRINT "* BW 1MHz   SELECTED      =";L$
3790       PAUSE
3800       PRINT "* BW 120KHz SELECTED      =";M$
3810       PAUSE
3820       PRINT "* BW 12KHz  SELECTED      =";N$
3830       PAUSE
3840       PRINT "* BW 7.5KHz SELECTED      =";O$
3850 -     PAUSE
3860       PRINT "* CHECK SELECTED          =";P$
3870       PAUSE
3880       PRINT "* FULL CAL SELECTED       =";Q$
3890       PAUSE
3900       PRINT "* OP RANGE 20dB.          =";R$
3910       PAUSE
3920       PRINT "* OP RANGE 40dB           =";S$
3930       PAUSE
3940       PRINT "* OP RANGE 60dB           =";T$
3950       PAUSE
3960       PRINT "NEXT KEY PRESS WILL CLEAR DISPLAY"
3970       PAUSE
3980               C$=CHR$(255)&"K"
3990               OUTPUT 2 USING "#,K";C$
4000      !*************************************************************
4010      !OUTPUT TO THE CRT - GRAPHED DATA
4020      !*************************************************************
4030       CASE "X"
4040 S2:           !
4050               C$=CHR$(255)&"K"
4060               OUTPUT 2 USING "#,K";C$
4070               GINIT
4080               PLOTTER IS CRT,"INTERNAL"
4090               GRAPHICS ON
4100               X=100*MAX(1,RATIO)
4110               Y=100*MAX(1,1/RATIO)
4120               DEG
4130               LORG 6
4140               LDIR 0
4150               CSIZE 3.5
4160               MOVE 30,100
4170               LABEL "GRAPH -",X$
4180               PENUP
4190               DEG
4200               LORG 6
4210               LDIR 0
4220               CSIZE 3.5
4230               MOVE 35,5
4240               LABEL "FREQUENCY (MHz)"
4250               PENUP
4260               DEG
4270               LORG 6
4280               LDIR 90
4290               CSIZE 3.5
4300               MOVE 0,50
4310               LABEL "INSERTION GAIN (dB)"
```

```
4320        PENUP
4330        Yaxis=15
4340        DEG
4350        LORG 6
4360        LDIR 0
4370        CSIZE 2.5
4380        MOVE 13,Yaxis
4390        LABEL B
4400        PENUP
4410        DEG
4420        LORG 6
4430        LDIR 0
4440        CSIZE 2.5
4450        MOVE 41,Yaxis
4460        LABEL "     "
4470        PENUP
4480        DEG
4490        LORG 6
4500        LDIR 0
4510        CSIZE 2.5
4520        MOVE 67,Yaxis
4530        LABEL "     "
4540        PENUP
4550        DEG
4560        LORG 6
4570        LDIR 0
4580        CSIZE 2.5
4590        MOVE 94,Yaxis
4600        LABEL "     "
4610        PENUP
4620        DEG
4630        LORG 6
4640        LDIR 0
4650        CSIZE 2.5
4660        MOVE 120,Yaxis
4670        LABEL C
4680        PENUP
4690        DEG
4700        LORG 6
4710        LDIR 0
4720        CSIZE 2.5
4730        MOVE 8,22
4740        LABEL F
4750        PENUP
4760        DEG
4770        LORG 6
4780        LDIR 0
4790        CSIZE 2.5
4800        MOVE 8,35
4810        LABEL " "
4820        PENUP
4830        DEG
4840        LORG 6
4850        LDIR 0
4860        CSIZE 2.5
4870        MOVE 8,49
4880        LABEL " "
4890        PENUP
4900        DEG
4910        LORG 6
4920        LDIR 0
4930        CSIZE 2.5
4940        MOVE 8,62
4950        LABEL " "
4960        PENUP
4970        DEG
4980        LORG 6
4990        LDIR 0
5000        CSIZE 2.5
5010        MOVE 8,76
5020        LABEL " "
5030        PENUP
5040        DEG
5050        LORG 6
5060        LDIR 0
5070        CSIZE 2.5
5080        MOVE 8,90
5090        LABEL E
5100        PENUP
```

```
5110 Cr:           VIEWPORT .1*X,.9*X,.2*Y,.89*Y
5120               FRAME
5130               WINDOW B,C,F,E
5140               AXES 10,10,B,F,5,10,3
5150               AXES 10,10,C,E,5,10,3
5160               FOR L=B TO C STEP 10
5170               LINE TYPE 1
5180               PLOT L,0
5190               PENUP
5200               NEXT L
5210               OUTPUT 718;"SF91"
5220               OUTPUT 718;"SF00"!THIS IS ESSENTIAL FOR GRAPH WHY?
5230               OUTPUT 718;"SA";B
5240               OUTPUT 718;"SO";C
5250               OUTPUT 718;"SE";D
5260               OUTPUT 718;"SU";E
5270               OUTPUT 718;"SL";F
5280               OUTPUT 718;"TS";G
5290               OUTPUT 718;"L3"
5300               OUTPUT 718;"N1"
5310               OUTPUT 718;"B4"
5320               OUTPUT 718;"A1"
5330               OUTPUT 718;"M2"
5340               OUTPUT 718;"SR"
5350               FOR D=B TO C STEP D
5360               ENTER 718;A
5370               ENTER 718;B
5380               LINE TYPE 1
5390               PLOT A,B
5400               NEXT D
5410               PEN 2
5420               STOP
5430               GOTO 5450
5440        CASE ELSE
5450        PRINTER IS CRT
5460        PRINT TABXY(1,4);"PROGRAM FOR TWO PORT TEST ON ESVP"
5470        PRINT TABXY(1,6);"[ A=REC FREQ  ]"
5480        PRINT TABXY(17,6);"[ B=STRT FREQ ]"
5490        PRINT TABXY(33,6);"[ C=STOP FREQ  ]"
5500        PRINT TABXY(51,6);"[ D=STEP SIZE ]"
5510        PRINT TABXY(1,7);"[ E=MAX LEVEL ]"
5520        PRINT TABXY(17,7);"[ F=MIN LEVEL ]"
5530        PRINT TABXY(1,8);"[ G=MEAS TIME ]"
5540        PRINT TABXY(1,9);"[ H=RF ATTEN  ]"
5550        PRINT TABXY(17,9);"[ I=IF ATTEN  ]"
5560        PRINT TABXY(1,10);"[ J=LOW NOISE ]"
5570        PRINT TABXY(17,10);"[ K=LOW DIST  ]"
5580        PRINT TABXY(1,11);"[ L=IF   1MHz ]"
5590        PRINT TABXY(17,11);"[ M=IF 120KHz ]"
5600        PRINT TABXY(33,11);"[ N=IF 12KHz   ]"
5610        PRINT TABXY(51,11);"[ O=IF 7.5KHz ]"
5620        PRINT TABXY(1,12);"[ P=CHECK     ]"
5630        PRINT TABXY(17,12);"[ Q=TOTAL     ]"
5640        PRINT TABXY(1,13);"[ R=OPR 20dB  ]"
5650        PRINT TABXY(17,13);"[ S=OPR 40db  ]"
5660        PRINT TABXY(33,13);"[ T=OPR 60dB   ]"
5670        PRINT TABXY(1,14);"[ U=PRNT-JET  ]"
5680        PRINT TABXY(17,14);"[ V=PLOT-PLOT ]"
5690        PRINT TABXY(1,15);"[ W=PRNT-CRT  ]"
5700        PRINT TABXY(17,15);"[ X=PLOT-CRT  ]"
5710        PRINT TABXY(1,17);"IF INPUT ERROR THEN RESELECT ALPHA CHARACTER"
5720        END SELECT
5730        GOTO 120
5740 Finished:     !
5750               END
```

Appendix C

```
10  ! ******************************************************************
20  ! * TITLE    : SAMPLER10K                                          *
30  ! * FUNCTION : THIS PROGRAM IS USED TO MEASURE AN INPUT LEVEL IN dBm     *
40  ! *            OVER A PERIOD OF TIME SPECIFIED BY THE USER           *
50  ! *            THE PROGRAM HAS A CAPACITY OF ACCEPTING UP TO 10K SAMPLES *
60  ! * OWNER    : NOISE MEASUREMENT GROUP, UKC                          *
70  ! * DATE     : FEBRUARY 1988                                         *
80  ! ******************************************************************
90    INPUT "ENTER '1' FOR CRT AND '2' FOR PRINTER",E
100   IF E=1 THEN
110   PLOTTER IS CRT,"INTERNAL"
120   END IF
130   IF E=2 THEN
140   PRINTER IS 701
150   END IF
160   !
170   DIM Samples(10000)
180   INPUT "ENTER MEASURING PERIOD IN MINUTES OR FRACTION OF",T1
190   INPUT "ENTER MEASURING TIME IN SECONDS OR FRACTION OF  ",T2
200   B=((T1*60)/T2)
210   PRINT "NO. OF SAMPLES TO BE TAKEN",B
220   PRINT "MEASURING PERIOD (MINUTES) ",T1
230   PRINT "MEASURING TIME   (SECONDS) ",T2
240   PRINT
250   OUTPUT 718;"RC0"
260   OUTPUT 718;"P0"
270   OUTPUT 718;"WZ2"
280   OUTPUT 718;"X5"
290   ENTER 718;E$
300   PRINT E$
310   OUTPUT 718;"X4"
320   ENTER 718;G$
330   PRINT G$
340   INPUT "ENTER FREQUENCY (MHz)",K$
350   PRINT "FREQUENCY SELECTED (MHz) ",K$
360   OUTPUT 718;"TS";T2
370   OUTPUT 718;"SF03"
380   OUTPUT 718;"FR"&K$
390   FOR P=1 TO B
400   OUTPUT 718;"SF03"
410   OUTPUT 718;"O2"
420   OUTPUT 718;"A2"
430   OUTPUT 718;"L1"
440   OUTPUT 718;"D1"
450   OUTPUT 718;"SF12"
460   OUTPUT 718;"SF02"
470   ENTER 718;A
480   Samples(P)=A
490   Total=Total+(Samples(P))
500   M=A/2
510   E=M+55
520   PRINT
530   PRINT TAB(55),"*";TAB(E),".";TAB(56),A;TAB(66),P
540   NEXT P
550  !PRINT Total ! REMOVE REM IF VALUE DESIRED
560   FOR X=1 TO B
570  !PRINT X;Samples(X);((Samples(X))*(Samples(X))) ! REMOVE REM IF NECESSARY
580   Totalsamples=Totalsamples+((Samples(X))*(Samples(X)))
590  !PRINT Totalsamples ! REMOVE REM IF NECESSARY
600   NEXT X
610   PRINT
620   PRINT "MEAN (MHz) =",(Total/B)
630   W1=((Total)*(Total))/B
640   W2=(Totalsamples)-W1
650   PRINT
660   PRINT "STANDARD DEVIATION (MHz) =",SQR(ABS((1/B)*(W2)))
670   END
```

Appendix D

```
10   !**********************************************************************
20   !* TITLE    : FLAG6                                                   *
30   !* FUNCTION : THIS PROGRAM IS USED TO SCAN THE SPECTRUM AND INDICATE  *
40   !*            THE SIGNAL LEVEL IN dBm OF UP TO SIX DIFFERENT FREQUENCIES *
50   !* OWNER    : NOISE MEASUREMENT GROUP, UKC                            *
60   !* DATE     : FEBRUARY 1988                                           *
70   !**********************************************************************
80       !
90       C$=CHR$(255)&"K"
100      OUTPUT 2 USING "#,K";C$
110      PLOTTER IS CRT,"INTERNAL"
120      INPUT "START FREQUENCY (MHz)",A
130      INPUT "STOP  FREQUENCY (MHz)",B
140      INPUT "STEP  FREQUENCY (MHz)",C
150      INPUT "MAX SIG LEVEL   (dBm)",D
160      INPUT "MIN SIG LEVEL   (dBm)",E
170      !
180      PRINT "START FREQUENCY (MHz)",A
190      PRINT "STOP  FREQUENCY (MHz)",B
200      PRINT "STEP  FREQUENCY (MHz)",C
210      PRINT "MAX SIG LEVEL   (dBm)",D
220      PRINT "MIN SIG LEVEL   (dBm)",E
230      !
240      INPUT "ENTER 1ST FREQUENCY REQUIRED FLAGGED (MHz)",L1
250      INPUT "ENTER 2ND FREQUENCY REQUIRED FLAGGED (MHz)",L2
260      INPUT "ENTER 3RD FREQUENCY REQUIRED FLAGGED (MHz)",L3
270      INPUT "ENTER 4TH FREQUENCY REQUIRED FLAGGED (MHz)",L4
280      INPUT "ENTER 5TH FREQUENCY REQUIRED FLAGGED (MHz)",L5
290      INPUT "ENTER 6TH FREQUENCY REQUIRED FLAGGED (MHz)",L6
300      !
310      !
320      PRINT
330      PRINT "1ST FREQUENCY (MHz) LOCATED IS ",L1
340      PRINT "2ND FREQUENCY (MHz) LOCATED IS ",L2
350      PRINT "3RD FREQUENCY (MHz) LOCATED IS ",L3
360      PRINT "4TH FREQUENCY (MHz) LOCATED IS ",L4
370      PRINT "5TH FREQUENCY (MHz) LOCATED IS ",L5
380      PRINT "6TH FREQUENCY (MHz) LOCATED IS ",L6
390      !
400      INPUT "ENTER '1' IF ABOVE VALUES CORRECT AND '2' IF NOT",R
410      IF R=1 THEN
420      GOTO 480
430      END IF
440      IF R=2 THEN
450      GOTO 120
460      END IF
470      !
480      INPUT "ENTER '1' FOR CRT AND '2' FOR PLOTTER",G
490      INPUT "ENTER TITLE OF GRAPH OR REFERENCE",W$
500      INPUT "ENTER X-AXES LABEL",Q$
510      INPUT "ENTER Y-AXES LABEL",Z$
520  !**********************************************************************
530  !*OUTPUT TO THE PLOTTER
540  !**********************************************************************
550 S1:  !
560      C$=CHR$(255)&"K"
570      OUTPUT 2 USING "#,K";C$
580      GINIT
590      IF G=1 THEN
600      PLOTTER IS CRT,"INTERNAL"
610      END IF
620      IF G=2 THEN
630      PLOTTER IS 705,"HPGL"
640      END IF
650      GRAPHICS ON
660      X=100*MAX(1,RATIO)
670      Y=100*MAX(1,1/RATIO)
680      DEG
690      LORG 6
700      LDIR 0
710      CSIZE 3.5
720      MOVE 60,100
730      LABEL W$
740      PENUP
750      DEG
760      LORG 6
770      LDIR 0
780      CSIZE 3.5
790      MOVE 60,5
800      LABEL Q$
810      PENUP
820      DEG
830      LORG 6
840      LDIR 90
850      CSIZE 3.5
860      MOVE 0,50
870      LABEL Z$
880      PENUP
```

```
890     VIEWPORT .1*X,.9*X,.2*Y,.89*Y
900     FRAME
910     WINDOW A,B,E,D
920     AXES 5,10,A,E,10,10,3
930     LORG 6
940     LDIR 0
950     CLIP OFF
960     CSIZE 2.5,.5
970     IF ((B-A)/C) 21 THEN
980     B2=((B-A)/2)+A
990     B1=((B2-A)/2)+A
1000    B3=((B-B2)/2)+B2
1010    !
1020    DEG
1030    LORG 6
1040    LDIR 0
1050    CSIZE 2.5,.5
1060    MOVE B,E-5
1070    LABEL B
1080    MOVE B1,E-5
1090    LABEL B1
1100    MOVE B2,E-5
1110    LABEL B2
1120    MOVE B3,E-5
1130    LABEL B3
1140    MOVE A,E-5
1150 .  LABEL A
1160    GOTO 1290
1170    END IF
1180    CSIZE 2.5,.5
1190    FOR I=A TO B STEP C
1200    IF E<0 THEN
1210    T=-5
1220    END IF
1230    IF E>0 THEN
1240    T=5
1250    END IF
1260    MOVE I,E+T
1270    LABEL USING "$,K";I
1280    NEXT I
1290    LORG 8
1300    FOR I=E TO D-STEP 10
1310    MOVE A,I
1320    LABEL USING "$,DDDD,3X";I
1330    NEXT I
1340    LINE TYPE 1
1350    MOVE A,0
1360    DRAW B,0
1370    PENUP
1380    OUTPUT 718;"SF90"
1390    OUTPUT 718;"SF00"
1400    OUTPUT 718;"SA";A
1410    OUTPUT 718;"SO";B
1420    OUTPUT 718;"SE";C
1430    OUTPUT 718;"SU";D
1440    OUTPUT 718;"SL";E
1450    OUTPUT 718;"TS";.5
1460    OUTPUT 718;"L3"
1470    OUTPUT 718;"A2"
1480    OUTPUT 718;"N1"
1490    OUTPUT 718;"B4"
1500    OUTPUT 718;"02"
1510    OUTPUT 718;"D1"
1520    OUTPUT 718;"SR"
1530    FOR X1=A TO B STEP C
1540    ENTER 718;A
1550    ENTER 718;B
1560    !*******************1ST FREQUENCY LOCATION
1570    IF A=L1 THEN
1580    PEN 2
1590    MOVE A,E
1600    DRAW A,B
1610    LORG 2
1620    LDIR 0
1630    PEN 1
1640    MOVE A,B+10
1650    LABEL "V"
1660    MOVE A,B+12
1670    !LABEL "I"
1680    !MOVE A,B+20
1690    LORG 2
1700    LDIR 90
1710    LABEL A,"MHz";B,"dBm"
1720    END IF
1730    !*******************2ND FREQUENCY LOCATION
1740    IF A=L2 THEN
1750    PEN 2
1760    MOVE A,E
1770    DRAW A,B
```

```
1780      LORG 2
1790      LDIR 0
1800      PEN 1
1810      MOVE A,B+10
1820      LABEL "V"
1830      MOVE A,B+12
1840     !LABEL "I"
1850     !MOVE A,B+20
1860      LORG 2
1870      LDIR 90
1880      LABEL A,"MHz";B,"dBm"
1890      END IF
1900      !******************3RD FREQUENCY LOCATION
1910      IF A=L3 THEN
1920      PEN 2
1930      MOVE A,E
1940      DRAW A,B
1950      LORG 2
1960      LDIR 0
1970      PEN 1
1980      MOVE A,B+10
1990      LABEL "V"
2000      MOVE A,B+12
2010     !LABEL "I"
2020     !MOVE A,B+20
2030      LORG 2
2040      LDIR 90
2050      LABEL A,"MHz";B,"dBm"
2060      END IF
2070      !******************4TH FREQUENCY LOCATION
2080      IF A=L4 THEN
2090      PEN 2
2100      MOVE A,E
2110      DRAW A,B
2120      LORG 2
2130      LDIR 0
2140      PEN 1
2150      MOVE A,B+10
2160      LABEL "V"
2170      MOVE A,B+12
2180     !LABEL "I"
2190     !MOVE A,B+20
2200      LORG 2
2210      LDIR 90
2220      LABEL A,"MHz";B,"dBm"
2230      END IF
2240      !******************5TH FREQUENCY LOCATION
2250      IF A=L5 THEN
2260      PEN 1
2270      MOVE A,E
2280      DRAW A,B
2290      LORG 2
2300      LDIR 0
2310      PEN 1
2320      MOVE A,B+10
2330      LABEL "V"
2340      MOVE A,B+12
2350     !LABEL "I"
2360     !MOVE A,B+20
2370      LORG 2
2380      LDIR 90
2390      LABEL A,"MHz";B,"dBm"
2400      END IF
2410      !******************6TH FREQUENCY LOCATION
2420      IF A=L6 THEN
2430      PEN 1
2440      MOVE A,E
2450      DRAW A,B
2460      LORG 2
2470      LDIR 0
2480      PEN 1
2490      MOVE A,B+10
2500      LABEL "V"
2510      MOVE A,B+12
2520     !LABEL "I"
2530     !MOVE A,B+20
2540      LORG 2
2550      LDIR 90
2560      LABEL A,"MHz";B,"dBm"
2570      END IF
2580      !******************END OF FREQUENCY LOCATION ROUTINES
2590      LINE TYPE 1
2600      PEN 2
2610      MOVE A,E
2620      DRAW A,B
2630      NEXT X1
2640      PENUP
2650      PEN 0
2660      STOP
2670      END
```

Appendix E

General guidelines for minimising passive intermodulation products generation:

(1) Non-linear materials such as nickel, mild steel and carbon fibre should not be used in or near the current paths. If for some reason they have to be there, they should be coated with linear materials.

(2) Keep the current densities low in the conduction paths by using larger conductors or having bigger contact areas between metals.

(3) Minimise metallic contacts, especially loose contacts and rotating joints. If these cannot be avoided, then provide insulators or alternative current paths at the contacts or joints. Also minimise the exposure of loose contacts, rough surfaces and sharp edges to radiated signals.

(4) Keep thermal variations to the minimum as the expansion and contraction of metals and materials can create non-linear contacts.

(5) Use bonded joints if possible, but make sure that these joints are good and have no non-linear materials, cracks, contamination and corrosion.

(6) Avoid having tuning screws or moving parts in the current paths. Keep all joints and contacts clean and tight, and if possible keep them free from vibration.

(7) Cable length, in general, should be minimised and the use of low passive intermodulation product cables and connectors is essential.

(8) Minimise the use of non-linear components, e.g. lumped dummy loads, circulators, isolators and some semiconductor devices.

(9) Achieve good isolation between the high power transmit signals and the low level receive signals by physical separation and filtering.

(10) Frequency planning should take account of the higher order products as they can be potential interference signals in some systems.