Some Investigations into the Interference Problems in the Satellite Communications with Special Reference to Geo-synchronous Orbit

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By

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CERTIFICATE

This is to certify that the thesis entitled "Some Investigations into the Interference Problems in the Satellite Communications with Special Reference to Geo-synchronous Orbit" and submitted by Mr. Malapaka Yagneswara Satyanarayana Prasad, ID No. 2000 PHXF419 for award of Ph. D. Degree of the Institute, embodies original work done by him under my supervision.

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***

Abstract

Background to the Research Work

The growth of Satellite Communications in the last four decades had been phenomenal, with increase of the satellites orbited into Geo-stationary orbit (GSO). The area of Communication Satellites in GSO has become one of the dominant sectors of Space field, with 340 satellites, currently in GSO, being used operationally. The inter-satellite orbital separation has become less than even 2 deg longitude in many of the orbital slots. The other technical developments like frequency re-use, high power communication transponders, use of higher frequency bands for communications, and wide range of Services have further added to complexity of Satellite Communications. The applications today cover TV broadcasting, Telecommunications, Radio networking, Mobile Communications and Closed-User-Group networks employing VSATs. Digital modulation, data compression, and coding technologies, being used in recent times, have increased the efficiency of transmission of number of bits per Hz of the bandwidth – at the same time increasing complexity of satellite communications.

The subject of interference is as old as communications, and has also grown in complexity along with the developments in the Satellite Communications field. International Telecommunication Union (ITU), with its scope of Regulation of spectrum use and orbital slots in the unique GSO circle, contributed significantly in the technical areas of frequency sharing and avoidance of interference. These technical studies of ITU have a direct relevance to the Investigations taken up in the Research work.

Indian National Satellite System (INSAT) is one of the strongest domestic satellite communication systems. Presently, six operational communication satellites are positioned in five orbital slots in the GSO circle – at 48 deg E, 55 deg E, 74 deg E, 83 deg E and 93.5 deg E. Total onboard transponder capacity of all these satellites put together is 132, and they are being used for applications like Telecommunications to the far-flung and inaccessible areas, TV broadcasting carrying 83 TV and Feeder

transponders, and VSAT Networks employing 30,000 VSAT terminals. It is not surprising that such a wide communication network and applications experience a number of interference issues.

The interferences in Satellite Communications result in loss of usable bandwidth, loss of revenue, customer dissatisfaction, and disruption of traffic during critical phases. Efficient operation of the System requires quick resolution of such interference problems.

Objective of the Research

Objective of the Research is to carry out the Investigations into typical and complex interference problems in the INSAT system, with the aim of deriving a generalized approach to characterise the interferences, analyze the problems and resolve the interference situations in a systematic manner. The goals of the research were:

- Identification of the interference signals in the downlinks.
- Analysis of the data to differentiate between satellite-generated interferences, and ground-generated interferences (reaching the satellites as uplink signal).
- Analysis of the modulations on the interferences signals and their effect on the wanted signals.
- Measurement and analysis techniques to localize the ground sources of interference.
- Possible methodologies to eliminate the interferences, or reduction of interferences.

Investigations are carried out into eight Interference Cases as below:

- Case 1 : Uplink interference from adjacent satellite network into INSAT-2E transponders.
- Case 2 : Radar interference into INSAT-2E lower Ext. C band transponders.

- Case 3 : Wide band noise interference in Ext. C band channels of INSAT-3C.
- Case 4 : Wide band noise floor interference in the transponders of INSAT-3C.
- Case 5 : FM Radio pick up by VSATs and retransmission as uplink interference to the satellites.
- Case 6 : Interference during the relocation and drift-orbit phase of the satellites.
- Case 7 : Radar interference into the MSS payloads, and
- Case 8 : On board generated intermodulation interference in INSAT-3A.

The ITU Recommendations on avoidance of interference in shared frequency bands, on off-axis radiation patterns of ground antennae, off-axis EIRP limits from terrestrial microwave communication Earth Stations, and power flux density limits on the radiation from the satellites, are studied for their relevance to the Investigations, and also to help the Coordination process to resolve the problems. Similarly, the interference tolerance criteria of analog and digital TV, and the specific characteristics of VSAT terminals are also studied in the course of Investigations.

The Investigations in each of the Cases involved extensive study and characterization of interference, estimation of the characteristics of suspected source of interference, simulations to confirm the estimates, Coordinated network tests, and approximate geo-location of the source of the interference (in some cases) using Time Difference Of Arrival (TDOA) and Frequency Difference Of Arrival (FDOA) principles. The analytical aspects connected with TDOA and FDOA, signal detection, cross correlation of weak signals were studied and used in the Investigations. A large number of antennae, in different frequency bands, downlink and uplink equipments, spectrum analyzers, etc. are utilized for tests and measurements connected with the Investigations. A specialized equipment called Telecom Carrier Analyzer (TCA) was procured with specifications specially suited for interference measurements, and the experiments were designed using TCA.

The Investigations into interference cases required extensive work as described above, and resulted in resolving most of the problems during the last four years at MCF.

Most Important conclusions of the Research Work

The Research work resulted in the following important results:

1. Very complicated interference cases were resolved and the bandwidth, which was not usable due to interference, was retrieved successfully. Each of the cases investigated was a real challenge, requiring extensive experimental and analytical work to resolve the interferences.

2. Detailed understanding of interference-coupling mechanisms resulted in additional input to the knowledge base, and to establish procedures for systematic experimental Investigations.

3. Some of the complicated signatures of the interference were due to non-adherence to certain ITU Regulations, or poor maintenance of outdoor equipments – and the Investigations led to preparation of technical guidelines for use by Network Operators.

4. The importance of TDOA / FDOA measurements and geo-location of the source of interference were brought out by the Investigations. The TDOA measurements and geo-location using the measurement results helped to identify the source of interference in one of the cases investigated. The other cases of investigations also brought out the limitations of the methodology and their non-applicability in certain cases of interference.

5. Coordinated tests involving Users resulted in attendant awareness on interference problems and the seriousness of the problems.

6. A generalized engineering approach to systematically investigate interference cases had been synthesized based on the experience of the interferences faced.

The present Research is also useful for further development of automated softwares, development of a light-weight measuring equipment, and further development of specialized software with many capabilities.

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Abbreviations

AIAA	American Institute of Aeronautics and Astronautics
API	Advanced Publication Information
ARSR	Air Route Surveillance Radar
ASR	Airport Surveillance Radar
BOA	Back-Off Attenuation
BSS	Broadcast Satellite Service
CCD	Charge Coupled Device (Camera of INSAT-2E)
CCIR	Consultative Committee of International Radio (now ITU-R)
CCTV	China Central TV
CW	Continuous Wave
DoT	Department of Telecommunications
DTH	Direct to Home
EIRP	Effective Isotropic Radiated Power
EMI	Electro Magnetic Interference
EMC	Electro-Magnetic Compatibility
ESA	European Space Agency
ESOC	European Space Operation Center
EUTELSAT	European Telecommunication Satellite (Organisation)
Ext.-C	Extended C-band
FBW	Forward Band Working (for non-GSO links)
FCC	Federal Communications Commission (of USA)
FDOA	Frequency Difference Of Arrival
FM Radio	Frequency Modulation Radio
FSS	Fixed Satellite Service

GSO	Geo-stationary Orbit
INSAT	Indian National Satellite (System)
INTELSAT	International Telecommunication Satellite (Organisation)
IRD	Integrated Receiver Demodulator
ISRO	Indian Space Research Organisation
IOT	In-Orbit Tests
ITU	International Telecommunication Union
LEO	Low Earth Orbit
LNBC	Low Noise Block Converter
MPEG	Motion Picture Experts Group
MSS	Mobile Satellite Service
NOCC	Network Operations Control Center
NTIA	National Telecommunications & Information Administration (of USA)
PFD	Power Flux Density
QPSK	Quadrature Phase Shifting Keying
RBW	Reverse Band Working (for non-GSO links)
RFI	Radio Frequency Interference
RFZ	RFI-Free Zone
SCPC	Single Carrier Per Channel
SSPA	Solid State Power Amplifiers
SUIRG	Satellite Users Interference Reduction Group
TCA	Telecom Carrier Analyzer
TDOA	Time Difference Of Arrival
UN	United Nations
VSAT	Very Small Aperture Terminal

Chapter - 1

Chapter-1

Introduction

Introduction to the Chapter

This Chapter introduces the growth of communication satellites, and presents the status of the Geo-stationary orbit in terms of the number of satellites and categorization of them. The other features of the growth of satellite communications in terms of frequency re-use, collocation of satellites, use of VSAT Terminals etc. are briefly covered to give the background of the present day scenario of interference in satellite communications. The earliest cases of interference are covered, along with the highlights on the contributions of International Telecommunication Union (ITU) to the reduction of interference in satellite communications.

The research work is briefly described, and the organisation of the Thesis Report is presented.

1.1 The growth of Communication Satellites in Geo-Stationary Orbit (GSO)

The field of communications had experienced an unprecedented expansion and development both on the theoretical and applied fronts in the 20th century. The communications over a pair of cables had grown into communications using terrestrial radio links, communications utilizing satellites and communications using optical fibres as the media.

The concept of Geo-Stationary Orbit (GSO) was first proposed in 1945 by Arthur. C. Clarke in an article titled "Extra-Terrestrial Relays" published in the journal "Wireless World" [1]. He proposed in the Article that 'it will be observed that one orbit, with the radius of 42,000 km, has a period of exactly 24 hours. A body in such an orbit, if its plane coincided with that of the earth's equator, would revolve with the earth and would thus be stationary above the same spot on the planet'. One of his conclusions in the paper said 'it is the only way in which true world coverage can be achieved for all possible types of services'. This concept became practical in 1960s with the launch of Syncom-II satellite into GSO in 1963.

The designation "Geo-Stationary Orbit (GSO)" is used all through this work in preference to the term "Geo-Synchronous Orbit". Though both of them refer to the orbit, which is synchronized to the Earth's rotation, 'Geo-Stationary' is more specific as the circular orbit in the equatorial plane with the orbital period equal to Earth's sidereal period.

In the last four decades, the subject of Satellite Communications had grown by leaps and bounds, and reached into a highly profitable commercial area. Today, the Satellite Communications, using the satellites in GSO, is one of the most profitable areas of the Space field itself. The initial launches of spacecraft into GSO was followed by a large number of satellites being launched for communications. Table 1.1.1, which is compiled from the statistics of the annual launches of satellites, gives the number of commercial communication satellites launched and placed in GSO, decade- wise :

Table-1.1.1 : Commercial Geo-stationary Communication Satellite - Launches by Decade

Decade	No. of Satellites	No. of Satellites per year
1960's	13	1.3
1970's	35	3.5
1980's	69	6.9
1990's	200	20

The number of satellites being launched into GSO continue to be 20 to 25 per year so far.

1.2 Occupancy of GSO – the present status

Geo-Stationary Orbit is recognized as a unique natural resource available to the humankind. The data base with respect to objects in the region of Geo-stationary orbit is regularly compiled by European Space Agency (ESA), and the Reports on the status of these space objects are released every year [2]. Even through this database is generated mainly for the space debris purposes, the data-base is an important source of information for investigations of interference cases.

As of end 2003, the total number of objects in the geo-stationary region is 1036. They can be classified as follows:

- 340 are controlled (217 under longitude and inclination control, and the remaining controlled in longitude only),
- 395 are in drift orbits,
- 140 are in libration orbits around stable points,
- 87 are uncontrolled with no orbital elements available,
- 10 could not be classified (i.e. there are too few orbital elements available).
- 64 are un-catalogued objects.

Thus, it shows only about one-third of the objects near GSO are controlled satellites used operationally. Fig. 1.2.1 represents the above break-up as pie chart.

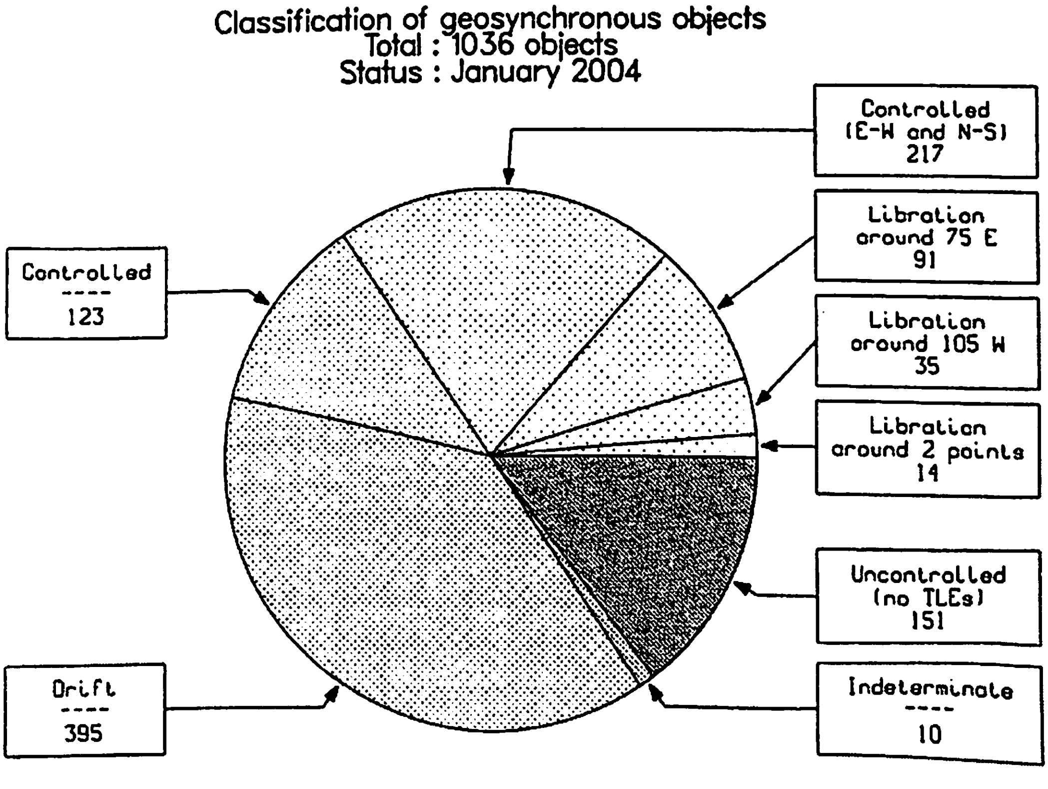


Fig. 1.2.1: The classification of objects in geo-stationary region

The satellites which are functional and are in control, and thus important for interference studies, are examined for their occupancy in GSO. Most of the controlled satellites are being used for Satellite Communications and a few for Meteorological observations. The tremendous growth of the communication satellites in the GSO has reduced the inter-satellite orbital separation. Two degrees, or sometimes even one-degree separation between two satellites in the GSO has become a common practice today. Number of satellites are, nowadays, being positioned and maintained at the same orbital slot, which is called 'Collocation', in many orbital slots having advantageous footprint and visibilities to the commercially active regions. Fig. 1.2.2 gives number of objects in 2 deg. longitude bins [2].

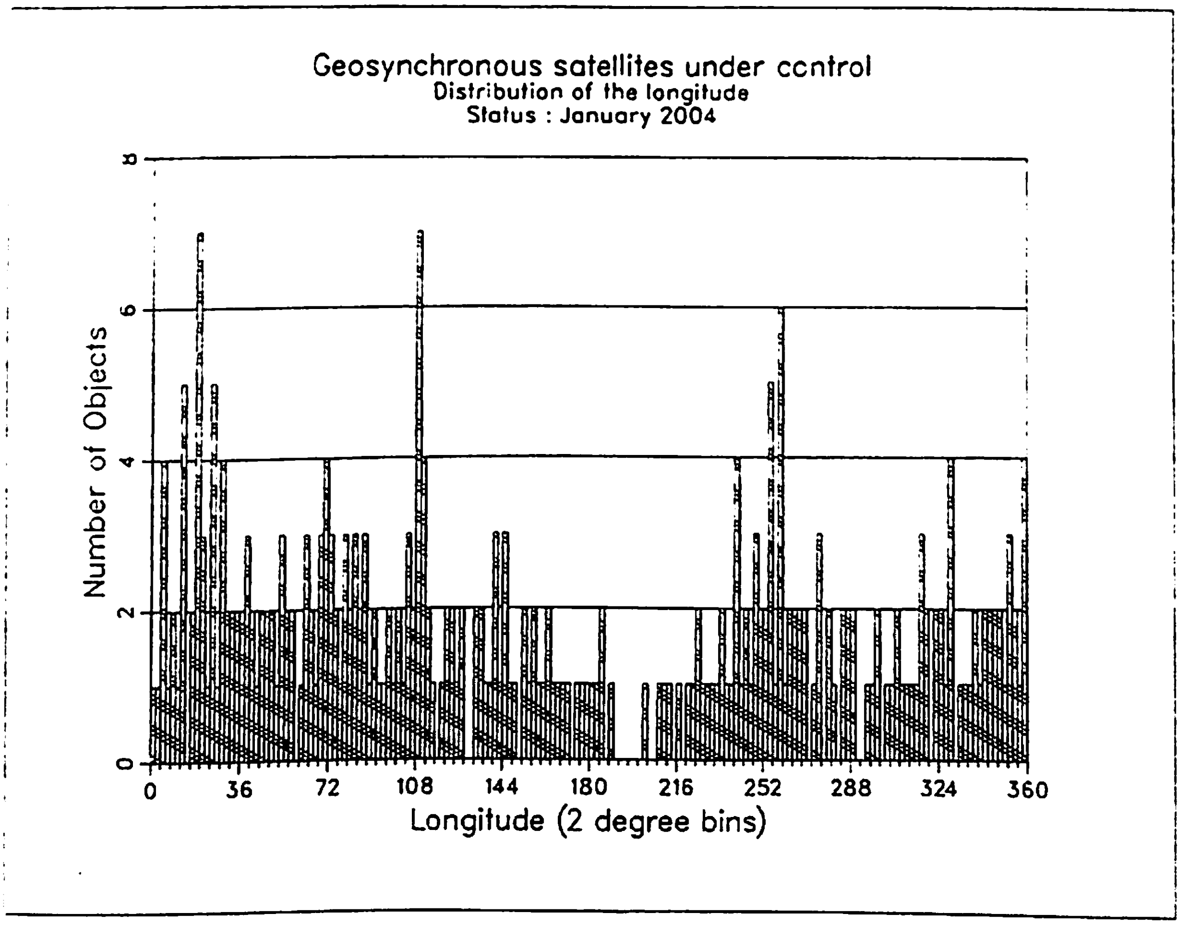


Fig. 1.2.2: GSO satellites – distribution of the longitude of the satellites under control.

As can be seen from the Fig. 1.2.2, there are some orbital slots around which even two degrees of orbital separation between satellites does not exist.

1.3 The other developments in the Satellite Communications

C band frequencies were allotted originally by ITU for GSO satellite communications, with uplinks being in 5925 to 6425 MHz and downlinks in 3700 to 4200 MHz. Later Ext. C band, with uplinks in 6725 to 7025 MHz and downlinks in 4500 to 4800 MHz, was also allowed to be used for the GSO satellite communications. However, the uplinks were in a shared band with the terrestrial radio links. A total of 500 to 750 MHz only was thus available for satellite communications in these frequency bands.

Along with the increase of the launch of communications satellites into GSO, another important technological innovation led to the expansion of satellite-based communications. It was "frequency reuse" i.e., utilizing same frequency bands for satellite communications from within the same footprint region utilizing orthogonal polarizations. This concept was conceived and developed by the organisation INTELSAT to double, and later to multiply many times, the bandwidth available for communications [3].

The continuous pressure for the increase in the bandwidth for satellite communications has lead to use of higher frequency bands for satellite communications like Ku and Ka bands with consequent availability of the larger bandwidth. The use of higher frequency bands have also led to a very revolutionary communication network concept using Very Small Aperture Terminals (VSATs). The VSATs made possible reception of Direct-To-Home (DTH) TV, as well as Corporate Networks for data transfers, more popularly in Ku-band.

Another important change in the communications field had been the growth of digital communications from late 80s onwards. The digital communications and associated developments in the data compression and computer technologies made it possible to transmit a large amount of data on available bandwidths by increasing the bits transmitted per Hertz of the bandwidth. The coding and compression technologies developed for the digital communications have also led to the digital video standards like MPEG. Today a large amount of satellite communications is carried out in the digital domain at the baseband level. These technologies brought forward a big change in interference tolerance criteria, and susceptibility to the interferences.

1.4 The International Telecommunication Union

ITU is a specialized Agency of United Nations (UN) to maintain international cooperation for the improvement and rational use of telecommunications of all kinds. It also promotes development of telecommunication facilities and their efficient operation to improve telecommunication services. The structure of ITU is divided into three sectors called Radio Communications Sector, Telecommunication Standardization Sector, and Telecommunication Development Sector. The aim of the Radio Communication Sector is to ensure rational, equitable, efficient and economical use of the Radio Frequency Spectrum and Satellites Orbits. The Radio Regulations of ITU are intended to establish procedures and limits to prevent harmful interference from effecting the proper operation of services sharing the same frequency bands or networks of a certain service operating in the same frequency bands.

The world has been divided into three Regions for the allocation of the frequencies [4], as shown in Figure 1.4.1.

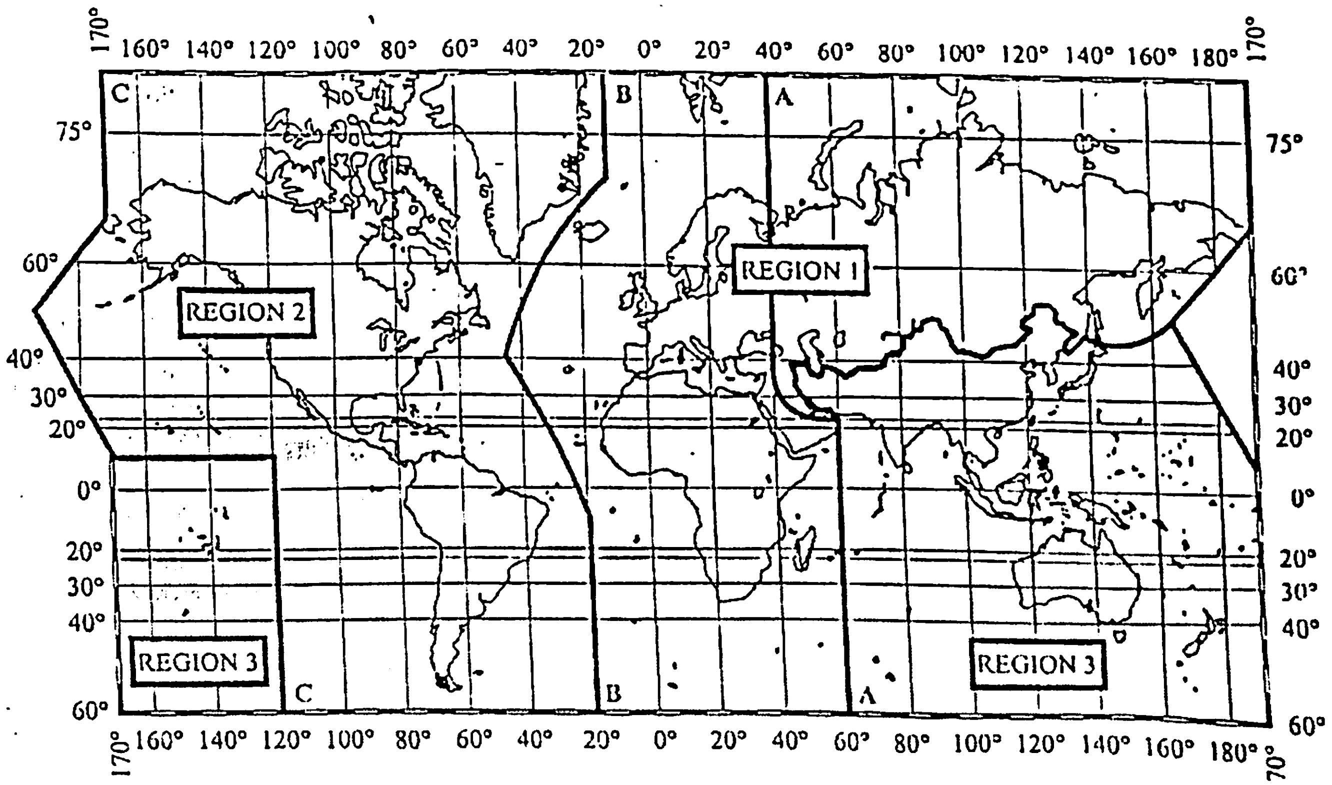


Figure 1.4.1: The Regions and Areas for allocation of frequencies.

India falls in the Region-3 for the purposes of allocation of frequencies by ITU.

Right from its establishment in 1963, International Telecommunication Union (ITU) had done a yeoman service to the field of reliable communications and avoidance of interference. A number of technical studies were carried out by ITU on various aspects of radio wave propagation, interferences, protection criteria, coordination procedures etc., and a number of Recommendations were issued on this subject. Most of these Recommendations have become the basis of regulating the use of frequencies and transmission in many Countries [5].

1.5 The subject of Interference

The subject of Interference is as old as the subject of Communication itself. The interference mechanisms have also grown in the same order as the growth of the satellites, in terms of complexity. The details of interference between the Earth Stations of terrestrial microwave systems and domestic communication satellite systems were examined in a paper published by AIAA in 1968 [6]. Interference became a subject of concern because the domestic communication satellite systems were proposed based on sharing the frequency band of 5925-6425 MHz for Earth-to-Space use along with the terrestrial microwave systems. Simultaneous with this proposal, the interference avoidance by adhering to certain sharing criteria was studied and proposed by the CCIR.

Similarly, the XI Plenary of CCIR adopted recommendation 406-1 which advised to avoid pointing the antennae of terrestrial radio relay systems towards the Geo-Stationary Satellite Orbit. The recommendation also provided a computation method to be used by the terrestrial radio relay system planners. The emphasis of the recommendation was on the refraction of the microwave signals in the atmosphere during the signal propagation and for different climatic conditions. The CCIR recommendation also provided a limit on the amount of power flux density that could be radiated by the satellites in the shared bands, not to affect the terrestrial microwave communications. This recommendation, its impact and the implementation of the recommendation to avoid interference between satellites in GSO and terrestrial stations was examined in a technical paper published by AIAA 1968 [7]. At that time there were only eight satellites in the GSO.

As the satellite communications and TV broadcasting through satellites grew, the reception of TV signals with a dish antenna became quite widespread in USA. One of the pioneering satellite TV broadcast Operators, Home Box Office, decided on 15th January 1986 to scramble its signals and charge the programme fees. This has led to the often quoted incident of 'Captain Midnight'. When HBO was airing a movie through satellite on 27th April at 12:32 a.m., the satellite bandwidth was captured by a stronger signal and for 4½ minutes and the following message flashed on all the TVs [8] :

"Good evening HBO
From Captain Midnight
$ 12.95 / month
No Way!
(Showtime/Movie channel beware)

This became the first infamous incident of deliberate interference into the satellite communication channel. Similarly in a recent incident, China Central TV channel (CCTV) of Peoples Republic of China was captured for ten minutes with a strong uplink in August 2002, allegedly by a group called Falun Gong. They displayed big posters, which were against Chinese Government. The same was repeated on two days during August 2003 capturing the TV channel being carried by SinoSat satellite. These deliberate capture of the communication satellites brought forward in a dramatic way the vulnerability of satellite communications to deliberate jamming / interference.

1.6 The Interference in Satellite Communications

Interference in communications is inevitable as long as we use the radio spectrum. The Interference, which is dealt with in this Thesis work, concentrates on the subject of Interference in the Satellite Communications with special emphasis on the satellites in the GSO. The investigations covered in this Thesis deal with inter-system interference, or interference caused by different networks and different systems into each other. Hence, only the detectable unwanted signal, which degrades the quality of the wanted signal is considered to constitute the Interference. In that sense, for the present Thesis, Interference is defined as the effect of an unwanted signal on the reception of a wanted signal. The detectability of interference depends on the characteristics of wanted signal, the unwanted signal, and the communication system / channel characteristics [9].

The subject of Interference in Satellite Communications has become a complicated field due to:

- Sharing of the frequency bands among the satellite communications and the terrestrial microwave radio relay communication systems.
- Increase in the number of satellites in the GSO and the reduction of orbital separation between the satellites.
- Use of higher frequency bands for communications, and hence use of satellites with higher EIRP onboard (due to exclusive use of these frequency bands and lack of necessity to avoid higher EIRP from frequency sharing criteria).
- Use of VSAT terminals with wider beam-width.
- Tremendous growth of number of VSATs and their Hub Stations which are employed in the satellite communication networks.
- Use of orthogonal polarization within the same satellite system.
- Deliberate jamming / causing interference into the operational channels of the satellites.

Lack of expertise and operational discipline in dealing with a highly sophisticated field like satellite communication by the Operators have further complicated the basic technical reasons listed above in increasing the interference cases.

The impact of interference can be mitigated by making the receiving systems (and the modulation techniques employed) more tolerable to the interference. Another solution, where this approach cannot work, is to identify the exact location of source of interference, and then to coordinate to avoid harmful radiation.

1.7 EMI / RFI

Another type of interference also became popular by the name "Electro-Magnetic Interference (EMI)", or "Radio Frequency Interference (RFI)". The subject of EMI and RFI is more relevant and concentrates on the electronics subsystems, within which the interference phenomena takes place. The use of a large number of electronic devices, miniaturization of the circuits, and use of Integrated Circuits and large-scale integration had all led to interference between various sections of electronic subsystems. The branch of reducing or mitigating the effects of EMI had become popular with subsystem and system designers. The subject of mitigating the effect of EMI is more commonly known as Electro-Magnetic Compatibility (EMC) [10]. However, this type of interference is not the subject of study of this research work.

1.8 Interference between GSO and non-GSO satellites

Non-Geostationary satellites (non-GSO) systems, in particular using low orbiting satellites, are being considered for establishing mobile and fixed communication networks. A few systems are already in operation but many other systems, which were earlier planned were dropped recently due to financial viability problems. Systems using non-GSO are proposed in the FSS and the frequency bands 18.9 to 19.3 GHz and 28.7 to 29.1 GHz were allocated by ITU to the non-GSO on a primary basis at World Radio Conference (WRC) – 95.

WRC – 95, and WRC – 97 allotted the following frequency bands for the feeder links of non-Geostationary satellites in the mobile-satellite service:

- Uplink : 5091 to 5150 MHz and Downlink : 6700 to 7075 MHz
- Uplink : 15430 MHz to 14630 MHz

- Downlink : 6700 to 7075 GHz
- Uplink : 5150 to 5250 MHz and Downlink : 5150 to 5256 MHz
- Uplink : 19310 to 19700 GHz and Downlink : 15430 MHz to 15630 MHz
- Uplink : 29100 to 21500 GHz and Downlink : 19310 to 19700 GHz

All the above mentioned pairing is not compulsory and, except for those frequency bands being used for GSO communications in the same direction.

Sharing between non-GSO and GSO networks are analyzed by ITU in terms of interference and performance criteria for Forward Band Working (FBW), and Reverse Band Working (RBW) in which the uplink frequency and downlink frequency of one system with respect to another system are reversed.

Non-GSO satellites being in low earth orbit, interference occurs for any satellite communication link only for a brief period when the non-GSO satellites come in-line of Earth Station and GSO satellites. GSO Earth Stations suffer severe interference from non-GSO satellite downlink when an in-line situation occurs (non-GSO satellite within the main beam of the GSO Earth Station).

In WRC 97 ITU's Regulation states "Non-GSO satellite system shall not cause unacceptable interference to GSO satellite system in the FSS and BSS operating in accordance with ITU Regulation".

An excellent survey on interference suppression techniques in mobile communications interference / fading problems is given by Stavroulakis in a recent paper [11]. Even though this type of interference is one of the important areas, the present research work does not deal with this aspect because such interferences in the INSAT system are not a serious concern today.

1.9 The Research Work

The present research work is taken up in the context and the background described above. The Indian National Satellite System (INSAT) is an important geo-stationary satellite segment of Indian Space Research Organisatiion. Presently, there are six operational communication satellites of ISRO in the GSO at five orbital slots between 48 deg E to 111.5 deg E longitudes. The number of transponders available in the Space segment are about 130 covering frequency bands of C, Ext. C, MSS (SxC & CxS), and Ku bands. The satellites are being used for Telecommunications, TV broadcasting, networking of AIR signals, and various types of VSAT networks. 203 Earth Station / Hub Station antennae and a total of 30,000 VSATs are involved in the Networks which work with various transponders of INSAT system. A total of 83 TV channels, private and Prasar Bharati channels put together, operate through the various transponders of INSAT satellites.

There are a number of foreign satellites, servicing different countries and areas of Asia-Pacific region, which are also located in the longitude range of 50 deg to 130 deg East longitude. The geographic coverage of these satellites and the frequencies being used were as approved by ITU. However, a number of practical deviations occur in the final usage, and certain restrictions, accepted during Coordination, might be violated unintentionally.

Due to the vast size of the INSAT network, and the other reasons described, a lot of interference cases in satellite communication had cropped up in the use of INSAT system during the last five years. Some of the interference cases led to loss of revenue due to inability to use the leased bandwidth by the customers. Active investigations were carried out into each of these cases. Many of the major interference problems were resolved, some of them in a record time.

In the context of interference in INSAT satellite communications described above, the present Research is taken up with objectives of systematic study and analysis of different types of interferences experienced in the INSAT system using the extensive facilities available at the MCF. The goals of the research were:

- Identification of the interference signals in the downlinks.

- Analysis of the data to differentiate between satellite-generated interferences, and ground-generated interferences (reaching the satellites as uplink signal).
- Analysis of the modulations on the interferences signals and their effect on the wanted signals.
- Measurement and analysis techniques to localize the ground sources of interference.
- Possible methodologies to eliminate the interferences, or reduction of interferences.

The Investigations into the interference problems in INSAT communications are undertaken as a Research work under the Ph.D. course of BITS, Pilani. The cases for detailed systematic analysis and investigations are selected from the severe interference problems experienced in INSAT system, which were causing heavy disruption to the traffic and to the effective utilization of the bandwidth.

The present Thesis Report records all the work carried out and the results achieved in the course of this Research.

1.10 Organisation of the Thesis Report

The subsequent Chapters of this Thesis Report describe in detail the work carried out:

Chapter-2: Review of Literature – This chapter covers the Literature survey carried out, and reviews important contributions to the field of interference in satellite communications, as reported in the Literature.

Chapter-3: The Interferences in Satellite Communication – This chapter covers different causes of interference in the satellite communication with special emphasis on satellites in Geo-Synchronous Orbit.

Chapter-4: ITU Regulations and their relevance to the interference studies – This chapter deals with the various Regulations and recommendations of ITU on the

subject of interference. ITU recommends the ΔT/T method and C/I method to calculate the expected interference, and also recommends the tolerance levels. One of the important recommendations of the ITU is on Off-axis radiation pattern of the ground antennae involved in satellite communications. Summary and important aspects of these recommendations are given, as a background material used in the Investigations into the interference cases.

Chapter-5: **Analytical & Experimental tools for Interference studies** – This chapter covers the analytical and experimental tools used in the Investigation of interference cases. The localization of the source of interference involves the principles of Time Difference of Arrival (TDOA), and Frequency Difference of Arrival (FDOA), and the measurement of the same. The theory and analysis of cross-correlation of signals, the measurements of TDOA, FDOA, and the limitations of TDOA-FDOA test methodology in handling all types of interferences are covered in this Chapter.

Highly sophisticated equipment and a number of antennae are used to configure and carry out the measurements required during the investigations. An equipment called "Telecom Carrier Analyzer (TCA)" with customized features was procured specially for interference measurements. Experiments with TCA and its use in developing cross correlation software are also covered in this Chapter.

Chapter-6: INSAT System & Investigations of Interference Cases - This is the main chapter, and the first section briefly outlines the INSAT system, its current transponder capacity, and various applications of INSAT system – which forms the background to understand the interference cases experienced. Remaining sections cover Investigations of eight major interference cases, experienced in the INSAT system. The cases included interference from adjacent satellite networks, interference from ground-based radars, wideband noise-floor-rise problems, pick-up and retransmission of FM radio signals, interference during flyby operations, interference into the MSS transponder, and the interference generated on-board the satellite payload. The description of the interference problem, characterization of interference, special measurements carried out to understand the interference coupling mechanism, analysis carried out to define the features of source of interference, and finally localization of the source / resolution of the interference are covered for each of the cases investigated. The interference cases are covered in eight sections of this Chapter.

Chapter-7: Most important conclusions of the thesis and further work – The chapter summarises the Investigations carried out on the interference cases and identifies different approaches used to characterize and resolve the interference cases. The approaches used in investigating all major interference cases are used to develop a step-by-step generalised approach in a Flow Chart form, which can be used in future by anybody to resolve interference problems quickly.

The further scope of the work is also outlined as a section of this Chapter.

References: All the References used during the Investigation of interference cases are given at the end.

Next Chapter covers the review of literature on interference problems in Satellite Communications.

Chapter - 2

Chapter-2

Review of Literature

Introduction to the Chapter

Reference material is drawn from published literature in the course of the Investigations into the interference problems in INSAT system. Review of the Literature on interference problems in Satellite Communications is covered in this Chapter. Many Books on Satellite Communications covered 'Interference' as one of their chapters. Articles were published in journals on specific works carried out on different aspects of interference. Recently, an informal Group of Experts was formed by the Satellite Operators to exchange their experiences on interferences in Satellite Communications. This Group, called 'Satellite Users Interference Reduction Group', meets every year, and technical presentations on interference problems are made in these meetings.

The references used from all these sources are reviewed in this Chapter.

2.1 Review

Arthur C. Clarke proposed the concept of Geo-stationary orbit in an Article published in the Journal "Wireless World" in October 1945. This Article [1] is a visionary document for the subsequent work carried out to orbit the Communication Satellites into Geo-stationary earth orbit (GSO). The number of Communication Satellites launched every year increased in the past four decades. The number of satellites in the GSO, and the Space Objects in the Region of GSO has become a subject of current concern even from the Space Debris point of view. European Space Operation Center (ESOC) of European Space Agency (ESA) maintains a database on geosynchronous objects and classifies them and releases a document every year giving the status of GSO and the objects in the GSO Region. The latest database document released in transmission of Home Box Office (HBO) in 1986 [8] brought home the importance of the subject of 'Interference and jamming' among all the concerned.

The subject of interference, for the purposes of systematic analytical study, is clearly defined by Wilbur Pritchard [9]. He defined interference as the effect of a detectable unwanted signal on the reception of a wanted signal. He also covered excellently the analysis of optimizing the inter-satellite orbital separation from interference point of view using C/I method.

Electromagnetic interference is also very popular subject for subsystem designers. Henry W Ott covered the subject of EMI in terms of cabling, grounding, shielding etc. in a book [10]. This book mainly deals with the conducted and radiated electromagnetic interference between electronic circuits / subsystems ; and the methods to achieve Electro-Magnetic Compatibility (EMC). Similarly, the interference between GSO and non-GSO satellites in terms of frequency use and satellite visibilities is well covered in the ITU Hand Book on Satellite Communications. The developments in the subject of interference for the mobile satellite communications was reviewed by Stavroulakis [11], specially covering interference suppression techniques by using different modulation schemes, using 'more stringent cross-correlation properties, and transversal combining' etc. However, EMI of subsystems and Interference in mobile communications are not dealt with in the present Research work, because such interferences in the INSAT system are not a serious concern today.

Unintentional interference originating from ground radars, and the geometric and power spectral aspects of the same were analyzed by Charles C. Wang et. al. [12]. This paper illustrated an approach to assess the impact of such interference on a geo-stationary satellites. Several factors, which influence the level of interference, such as geography, frequency, power and time were considered in the analysis. The paper suggested RFI Free Zone (RFZ) from which a scanning radar signals cannot reach the satellites in the GSO. But the RFZ suggested in the paper can be computed only if the elevation angle, at which the interfering radar operates is known, which is generally not the case in many practical applications. R J Matheson et al. carried out an excellent work of monitoring the spectrum of various types of radars, and the same was reported in NTIA Report [13]. This work clearly brought out the amount of spurious generated by the Transmitter Tubes used in many radars. The report documented systematic spectral measurements carried out on different types of radars – Airport surveillance radars in S-band, long-range air route surveillance radars in L-band, air-transportable height-finder radars in S-band, and weather radars in C-band and S-band.

The SSPAs used in the ground terminals, sometimes, oscillate and create sweeping CW interference. One such case was Investigated very carefully, and Siegfried Fiedler of EUTELSAT reported their work in the SUIRG meetings of the years 2000 and 2001 [14], [15]. A detailed analytical model was generated for the SSPA, and it was found out that the amplifier was marginally stable in cold weather conditions. Ken Kashin of PANAMSAT reported generation of spurious intermodulation signal in Ku band in one of the ground terminals, and its re-transmission to the satellites [16], which was Investigated by them in 2001 / 2002. The details on such reported problems are all used in the present Research work to list all causes of interference, and link them to the experience of INSAT system.

Adherence to the ITU Regulations is important in disciplined operation of ground and satellite systems, and to avoid interferences. Richharia excellently summarizes the role of ITU in equitable use of radio spectrum, and its role in carrying out technical studies to avoid interference. The ITU Recommendations dealing with maximum permissible off-axis EIRP levels, off-axis radiation pattern of ground antennae, and the procedures for determining whether Coordination is required or not [18], [19] [20] are very important for the Investigations taken up in the present Research work. Similarly, the procedures of ΔT/T and C/I calculations for establishing interference tolerance criteria [21], [22], are useful to consider the intensity of interference cases. All these ITU Recommendations are studied, and recommendatory/ regulatory technical details are given in Chapter 4 of this thesis, as ready reference to the interference investigations carried out.

The interference tolerance criteria for analog FM TV and digital TV were covered by Benoit [23], [24], by Gomez [25], and Ken Ryan [26]. The technical details of direct broadcast satellite communications system were detailed by Donald C. Mead [27], which is essential to deal with interference in digital TV. The details given in these books on digital TV and its interference related aspects clearly bring how high C/I values are required for proper operation of digital TV compared to analog TV.

Even though the use of VSAT terminals in the satellite communications is very widespread today, no common standard or Regulation exists. The technical aspects of VSAT system design and interferences are covered in the INTELSAT Handbook [28] and in the ITU Recommendations [29]. The INTELSAT handbook covers Network design details, in addition to clear technical description of VSAT configurations.

The analytical and experimental tools used during the course of present Investigations into interference cases are derived from many references. The concept of geometry involving an un-known interference source and two adjacent satellites was covered by Wilbur Pritchard and Joseph Sciulli [30]. The principle of TDOA and FDOA were covered by Chestnut [31]. William Smith Jr. and colleagues can be credited with the first work on interference location system using TDOA and FDOA principles. Their work was reported in an Article in 1989 [32]. These papers elaborated the principles, measurement techniques, and use in geo-location of the TDOA and FDOA. The articles also provided detailed examination of the accuracies achievable in the measurement and in geo-location of the source of interference.

Interference signal detection is an important aspect of TDOA / FDOA measurement and Spectrum Analyzers can be very effectively used for the same [33]. The case of detecting the weak interference signals was covered by Charles Knapp and Clifford Carter [34]. The maximum likelihood estimator was developed for determining the time delay between signals received through separate antennae by them. The correlation of signals by Angle Of Arrival methods was also covered by Richard Wiley [35]. The optimum angle of separation of the inter-sector satellites for geo-location of frequency hopping transmitters was covered by Alexendar Sonnen Schein et al. in an article [36] in 1993. The fundamentals of cross-correlation and computation of the same in frequency domain using digital signals were well covered in the book on Interferometery in Radio Astronomy by Richard Thompson et al. [37]. The procedure for cross correlation for digital signals was also studied in standard mathematics books [38], [39], [40], [41]. All these articles provided the fundamental basis for cross-correlation of two signals, especially if one of the signals is near-noise level. The principles covered both the time-domain and frequency-domain analysis.

The work on interference localization system was reported by Haworth, Smith et al. in 1997 [42]. This paper covered practical demonstration of localizing the source of interference using EUTELSAT satellites, along with discussion on accuracies.

The Telecom Carrier Analyzer (TCA) has been configured at MCF for detailed interference studies like cross correlation of signals, and detection of interference embedded in the occupied spectrum. The features of Telecom Carrier Analyzer and its use are covered in its Operational Manuals [43].

The cases of interference reported by other Satellite Operators like Indonesian Palapa system [44], SES Astra [45], by SATMAX [46], and by Singapore Telecom [47] in the SUIRG meetings are studied during the course of Investigations. The interference into INSAT system was also presented in the SUIRG meeting of 2002 [48], to derive the benefit of discussions with other Experts.

The analysis of pick-up of FM radio signals and their retransmission to the satellites is covered by Molnar et al. [49]. Precautions to be taken in the ground stations to avoid such pick-up is explicitly given in the Users Manual of Intersputnik [50].

In a personal communication, Mr. Bruce Nelson, Interference Expert at INTELSAT, suggested that development of a light-weight, portable measurement equipment will greatly help VSAT operators, and future interference studies. This idea is further progressed at MCF and is covered in the last Chapter briefly.

The above Review of Literature covers only the references cited in the present Thesis Report, depending on their direct applicability

Chapter - 3

Chapter-3

The Interferences in Satellite Communications

Introduction to the Chapter

The various causes of interferences in the satellite communications are examined in this Chapter. The sources of interference and the interference coupling mechanisms into uplink / down link satellite signals are explained.

The spurious signals generated by the radars, much beyond their operational frequency band, were often found to be the reasons for interference from radars to satellites. Ground-based radars can also cause interference if their peak power is high, or their operational elevation angle happens to coincide with the satellite elevation angle from that site.

The pick up of FM radio signals by the VSAT terminals and re-transmission of the same to satellites, after frequency conversion, is a very dominant interference problem in the Asian Region. Poor shielding of the cables or un-terminated ports (at IF level) in the VSATs usually pick up the radio signals and cause this type of interference.

The interference in the satellite communications can happen due to radiations from adjacent satellites or due to the ground networks operating on the adjacent satellites. In some cases SSPAs of VSATs were found to oscillate and cause sweeping CW interferences.

Undisciplined increase of uplink power, poor maintenance of outdoor equipment by the Network Operators, SNG terminals uplinking to wrong satellites fall under the category of the causes which are due to lack of professional standards and guidelines, or non-adherence to the guidelines in the operations. However, these causes can create very complex interference problems as experienced in the INSAT system.

Antennae with bad off-axis radiation or with poor cross-polarisation isolation cause interference either to the same satellite or to the satellite operating in adjacent orbital slots.

A study of the causes of interference is taken up based on experience in INSAT satellites, and also based on the reported interference cases of other Operators. These causes are explained briefly in the following paragraphs. Some of the cases of interference experienced in the INSAT satellites are given as examples wherever relevant.

3.2 The Causes of Interference

Following are some of the types of interferences, which are being experienced. The causes are also identified in each case:

3.2.1 Ground-based radar transmitters

Radar systems may be operating in the frequency bands adjacent to the ones allotted for Earth-to-Space or Space-to-Earth communications. Also, the radar transmitters may have harmonic emissions, which fall within the frequency bands used by the Satellite / Earth Station receivers. Usually, the Earth Stations are located away from the vicinity of major airports to avoid downlink interference from airport radars.

The occurrence and level of unintentional uplink interference from the ground based radars depend on the geographic position of the radars, the footprint of the satellite, frequency, power, and spatial relationship between the radar and the effected satellite. Two most important parameters out of the above are: geographic location of the radar and the interference power caused by the spectral components of the radar. As the nature of the radar is generally to detect any low-flying objects, the elevation angle of this scanning region has an upper limit. Similarly, the interference power up-linked to the satellite depends on the total spectral power of the radar and the frequency separation between the radar and the satellite. However, some of the weather monitoring radars scan up to an elevation angle as high as 70 deg. In such cases radar signals can easily reach the GSO satellites as interference through the side-lobes of the radar antenna.

The Fig. 3.2.1 and 3.2.2 given below illustrate the relationship between the source of interference and affected satellite [12].

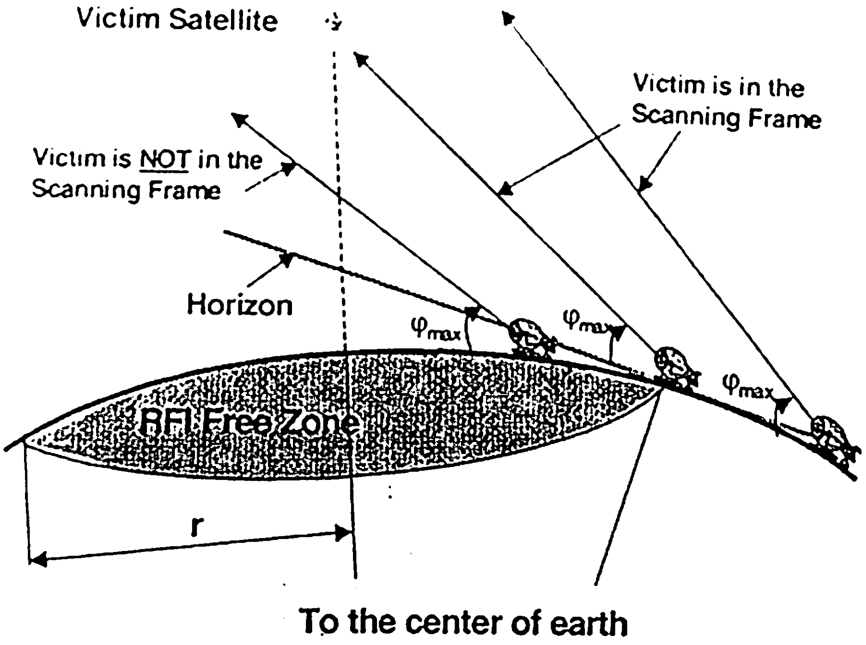


Fig. 3.2.1: RFI-Fee Zone (RFZ)

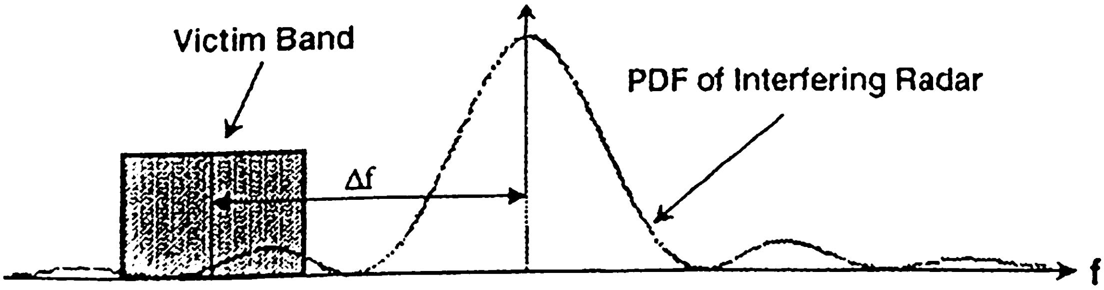


Fig. 3.2.2: In-band Interference Power

Because the scanning radars are limited by the maximum elevation angle, the radars located in a particular circle centered on the sub-satellite point of the effected satellites will not cause interference. Therefore, a "RFI-Free Zone" (RFZ) exists. The radius of RFZ is given by:

$$r = R_e \cos\left[\varphi_{\max} + \sin^{-1}\left(\frac{R_e}{R_{GEO}}\cos\phi_{\max}\right)\right] \tag{1}$$

R_e = radius of Earth

R_{GEO} = radius of Geostationary orbit

ϕ_{max} = Maximum elevation angle of the radar.

Based on the RFZ, certain geographical area can be eliminated in the geo location process.

The interference power of the radar spectrum (which is given in the Fig. 3.2) is given by the equation:

$$P_0 = \int_{y'-B}^{y'+B} T_d . \sin c^2 (T_d f) \qquad (2)$$

B = one sided receive frequency band of the satellite

Δf = Centre frequency off set between the interfered satellite and the radar

Sinc (x) = sin(x)/x ...... PDF of the rectangular pulses

Based on the above equation, the interfering power from a radar into the reception band of the satellite can be computed. The interference exists if the computed power is above the detection threshold of the affected satellite.

It was also reported that the magnetrons used in some of the radars, over a time, can generate a lot of spurious outputs beyond their frequency band [13].

INSAT system experienced uplink interference from ground-based radars in one of its transponders. Through the Time Difference Of Arrival (TDOA) measurements, the approximate location of the ground-based radars causing the interference was identified. The Coordination resulted in solving the problem. Fig. 3.2.3 gives two spectrum plots of the transponder affected by uplink interference from ground-based radars.

3.2.2 Terrestrial FM radio signals

FM radio signals sometimes appear as unauthorized carriers in the satellite transponders.

ITU has allocated 87-100 MHz, and 100-108 MHz for terrestrial broadcasting. FM radio transmissions work in these bands. The satellite VSAT networks usually employ 70 MHz as the IF frequency with a range of ±20 MHz, before up converting to the satellite transmit band. But the bandwidth of the up-converts are generally wider than ±20 MHz needed. Hence, IF equipments or cables can pick up FM radio signals and cause interference, if they are in the vicinity of these radio stations.

Usually, FM radio signals are picked-up by long and unprotected cables of VSATs, and these signals are up-converted to the satellite uplink band. Poor screening at IF four to five transponders. (i.e. range of 200 MHz). The rate of sweep and staying time at any one frequency differ from case to case.

3.2.5 Undisciplined Uplink Power Increase

Usually the customers increase their uplink EIRP whenever they find some small degradation in the E_b / N_o. If this degradation happens to be due to noise floor rise, the increase of the EIRP further aggravates the problem and there will be further rise in the noise floor. Some times the aggravated noise floor can cause problem to the adjacent traffic. Strict discipline in the uplink power control by the customers is very essential for normal functioning of all the traffic.

A similar case occurred in the case of INSAT system. Fig. 3.2.6 gives the spectrum plots of the rise in noise floor, which happened due to one of the customers raising the uplink power. The same was corrected after the customer was alerted.

3.2.6 Operator Errors or Omissions

High levels of skills and standards are required to operate ground systems in the satellite communications. Very serious interferences to the satellites can occur due to the operational mistakes in the ground terminals.

A severe interference problem was experienced by two transponders in the INSAT system for more than a month, with degradation of E_b/N_o to the VSAT traffic. The VSAT traffic in the affected channels was very heavy, and consequently the diagnostic testing became very difficult. It was found that the noise floor of the transponders was disturbed, and a peak-to-peak variation of 10 to 15 dB was measured, through coordinated testing.

After detailed analysis and coordinated testing, the interference was estimated to be caused by a loop-back between downlink and uplink in one of the ground terminals. An alert to all the VSAT Operators made the offending ground personnel to realize their mistake. The problem disappeared after the alert.

3.2.7 SNG terminals uplinking to wrong channel/wrong satellites

Satellite News Gathering terminals usually move to the site of action, from where they uplink video to the hub station of the customers. They set up the ground antenna and adjust the azimuth and elevation angles to look at the satellite to be used. In this process of trial and error, some times these SNG terminals, cause interference to the satellites which are adjacent to their intended satellite.

The tuning of the uplink frequency allotted to them is also done many times without proper equipments, thus causing interference to the adjacent transponders of their intended satellite.

3.2.8 Antennae with wrong adjustment of polarization

The ground antennae employed by the customers have to be adjusted for proper uplink polarization. If the polarizer is not adjusted correctly, interference into the orthogonal polarization of the same satellite, or interference into the adjacent satellites (employing orthogonal polarization) can occur. Many such cases can be analyzed only with the complete knowledge of the traffic plans of the concerned transponders. It is always better to take care of such possibilities while approving the traffic plans. Many cases of interference into INSAT system occurred due to wrong polarization adjustment of the ground terminals, and the same were tackled with real time Coordination.

3.2.9 Antennae with bad off-axis radiation

The antennae employed in the uplinking station have to meet off-axis radiation limits of ITU recommendation S.580-5. In the case of India, NOCC of DOT is the Agency to test and certify that the antennae meet the ITU recommendations. The criteria to approve the Ground Transmitting antennae should be strictly adhered to, for avoiding interference into satellite systems.

But in many cases the validation procedure of ground antennae in the other countries in the Region is not clear. Specially, VSAT networks employ 3.8 m to 1.2 m antennae, which have wide beam widths. Interference can occur from the ground antennae employed by VSAT networks to the nearby satellites.

3.2.10 Insufficient testing of new equipment

The new equipments have to be tested completely before they are put into service. The upconverters and SSPAs / HPAs create spurious in some cases. These spurious will

Such cases of onboard generated spurious can be confirmed by eliminating the other causes and conducting subsystem on/off operations. One serious intermodulation interference case occurred in INSAT-3A, and it was confirmed as due to unintended coupling between the downlink and uplink signals in the on-board payload. Fig. 3.2.7 gives spectrum plot of interference generated on-board INSAT-3A.

3.2.14 Interference due to drifting satellites

The communication satellites drift to their final orbital slot at the end of orbit raising operations. The drift rate usually is around 2 deg of longitude per day. Some times, a satellite may have to be relocated to a new orbital slot, which is done by raising / lowering the orbital altitude, thus allowing it to drift westward / eastward respectively. Interferences to others satellites can occur during such drifting phase of the satellites.

Fig. 3.2.8 shows interference experienced in one of the transponders of INSAT-2E due to an unknown satellite, which was in drifting phase.

3.3 Conclusion

Various types of interference, along with the causes are explained. Relevant examples from the interference cases experienced in the INSAT system are given. All the major causes of interference were investigated, and reported in detail in Chapter 6. But before proceeding to investigations, the ITU Regulations / Recommendations on mitigating interferences are examined in the next Chapter.

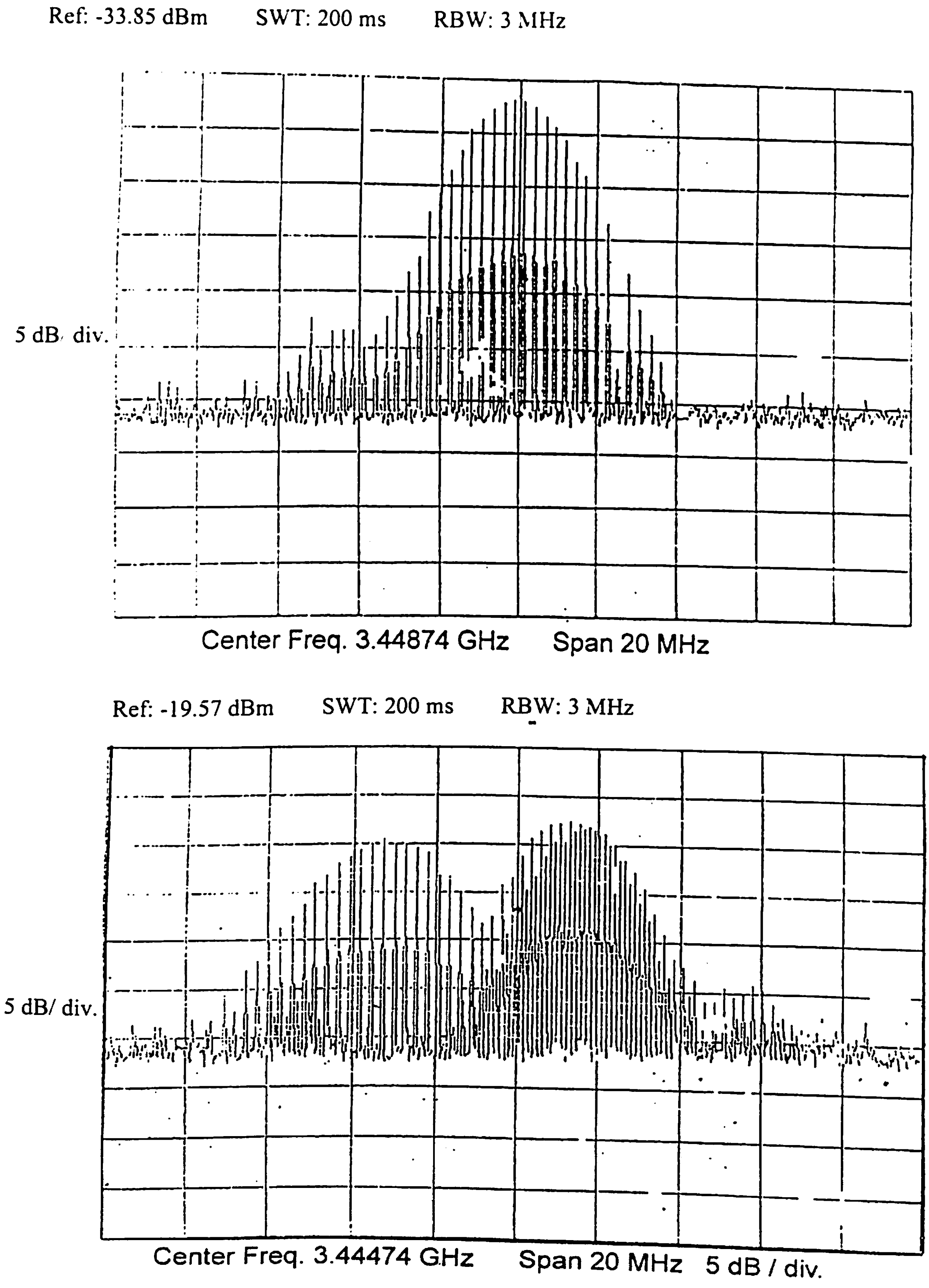


Fig. 3.2.3 Spectrum Plots of Radar Interference into INSAT satellites

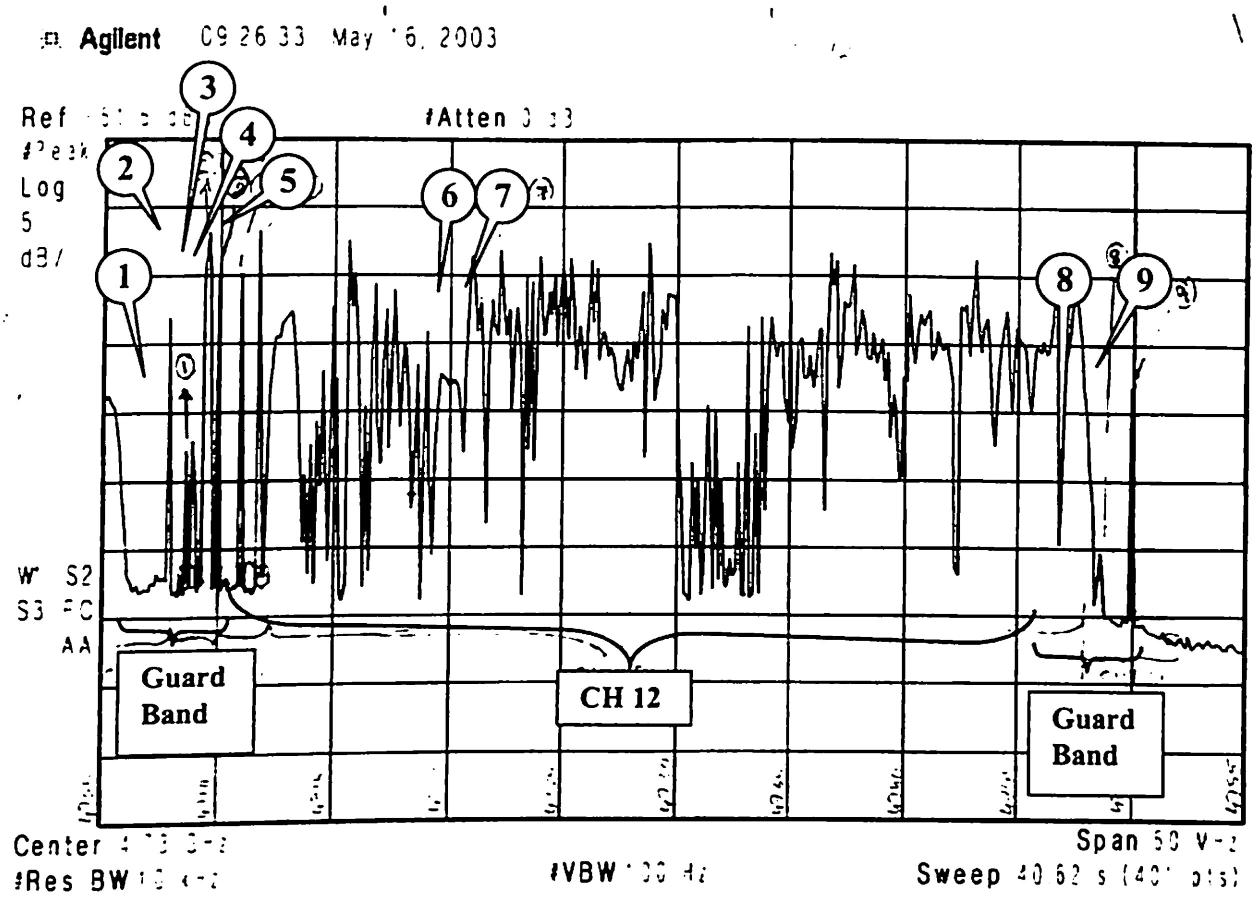


Fig. 3.2.4 : Spectrum plot of one of the INSAT transponders showing FM radio interference (Signals shown with numbers are the individual FM Radio Signals)

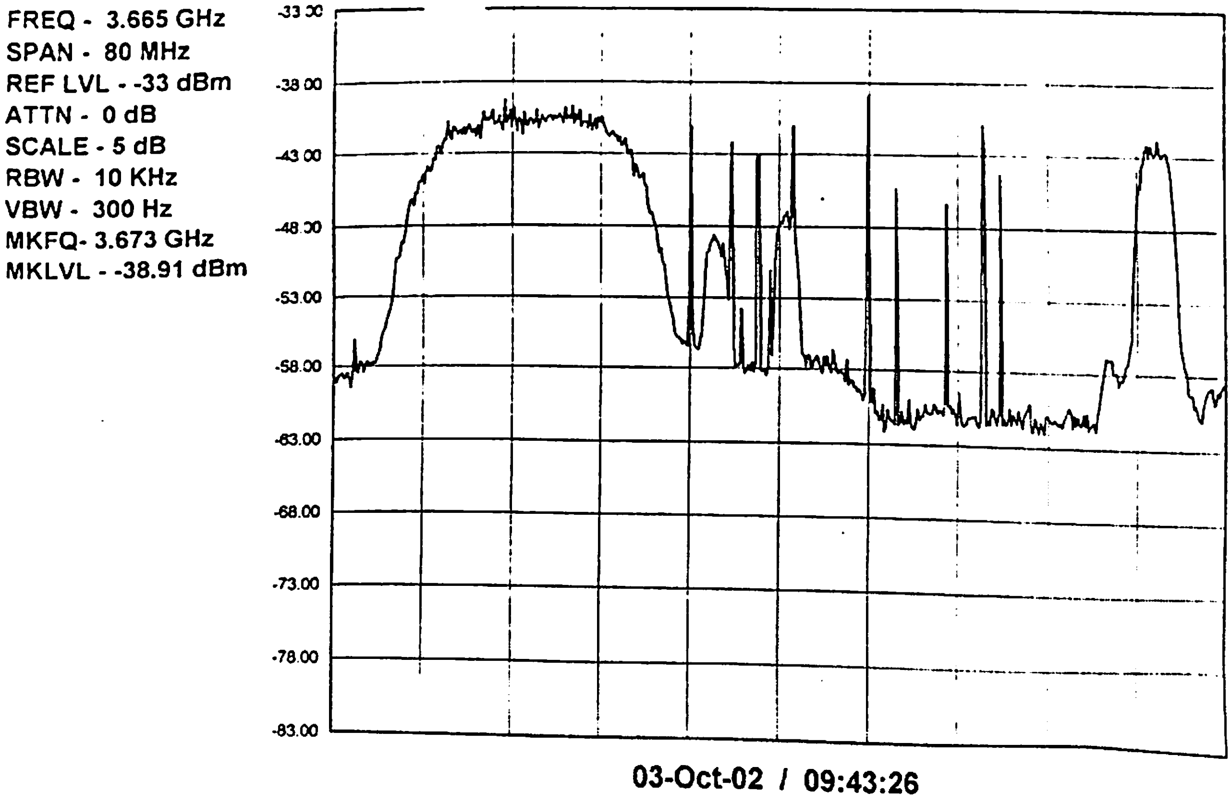


Fig.3.2.5: Interference into INSAT-3E Transponder #6 from adjacent satellite network

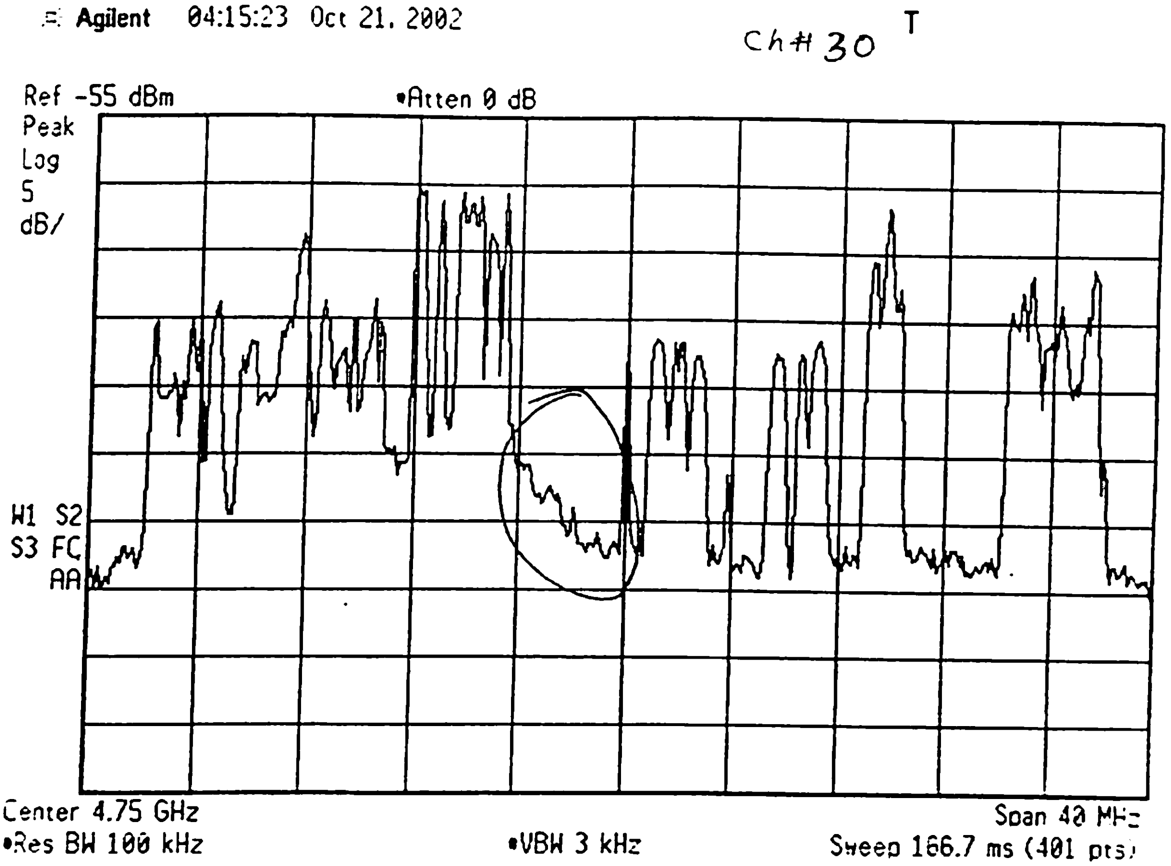
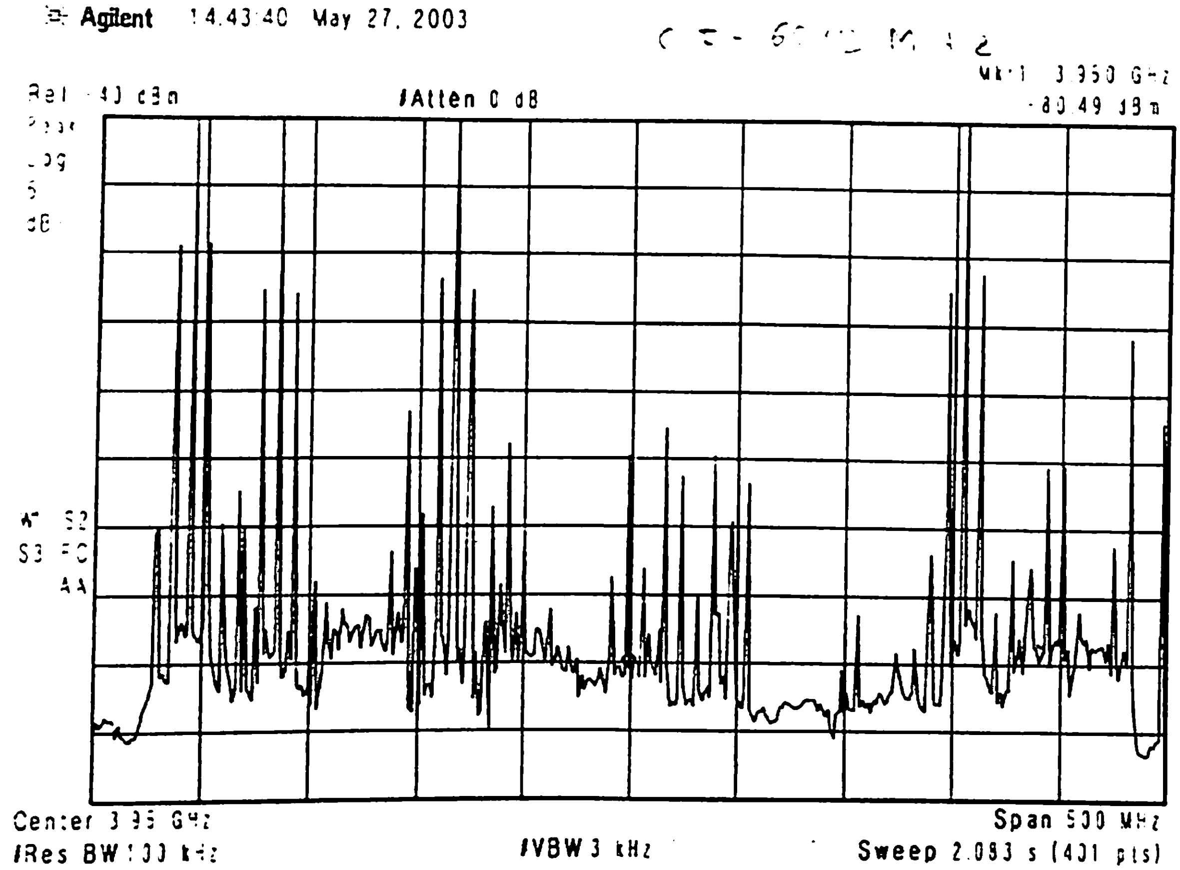


Fig. 3.2.6: Rise in the Noise Floor due to undisciplined increase in the uplink power by one of the customers



Agilent 14:43:40 May 27, 2003

C.F - 6[illegible] MHz

Ref -43 dBm #Atten 0 dB

Mkr1 3.950 GHz

-80.49 dBm

Peak

Log

5

dB/

W1 S2

S3 FC

AA

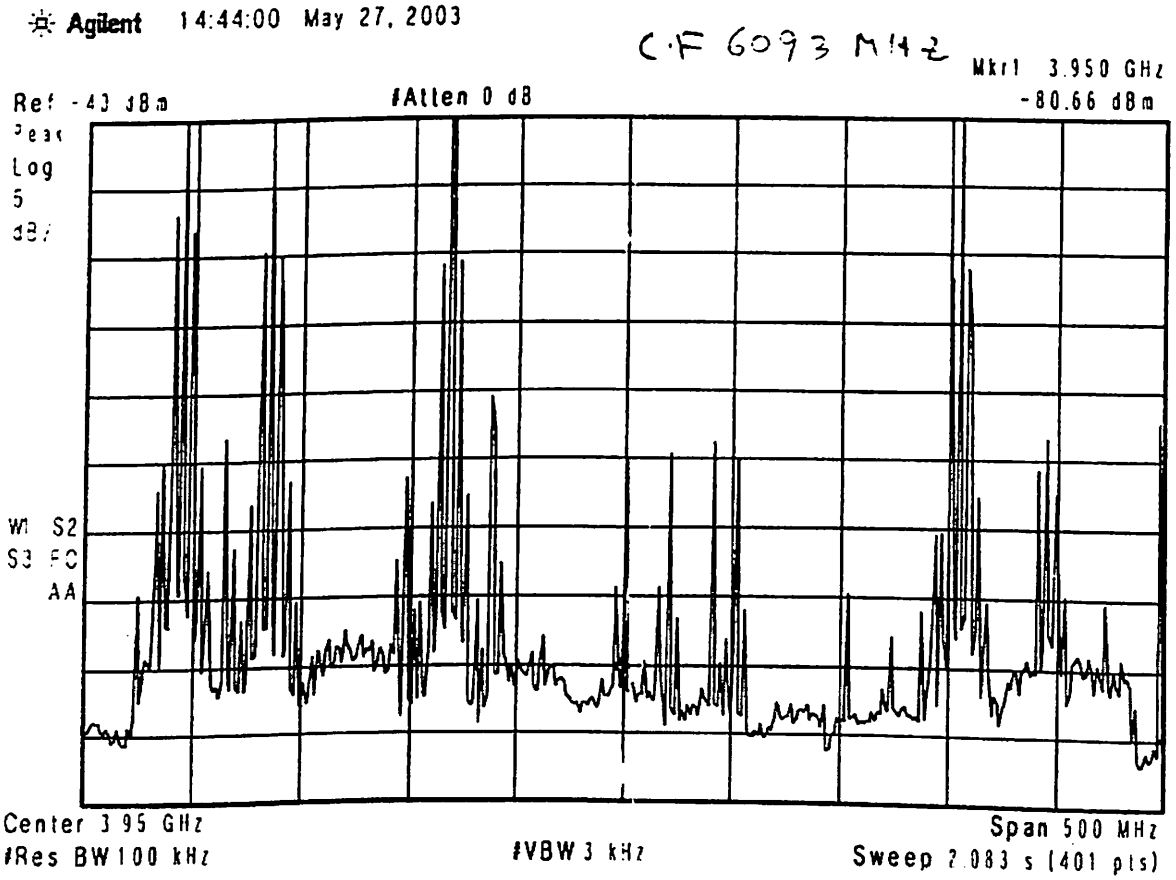
Center 3.95 GHz

#Res BW 100 kHz

#VBW 3 kHz

Span 500 MHz

Sweep 2.083 s (401 pts)



Agilent 14:44:00 May 27, 2003

C.F 6093 MHz

Mkr1 3.950 GHz

Ref -43 dBm #Atten 0 dB

-80.66 dBm

Peak

Log

5

dB/

W1 S2

S3 FC

AA

Center 3.95 GHz

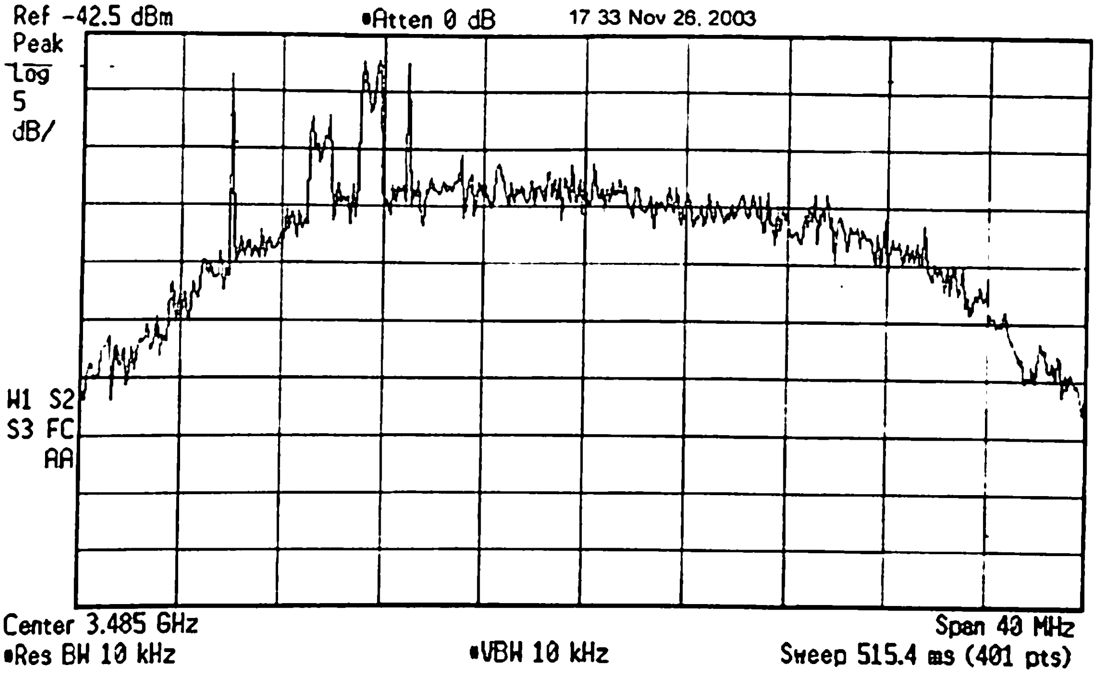
#Res BW 100 kHz

#VBW 3 kHz

Span 500 MHz

Sweep 2.083 s (401 pts)

Fig. 3.2.7: Spectrum plots showing onboard generated Intermodulation products in INSAT 3A with uplink only two carriers



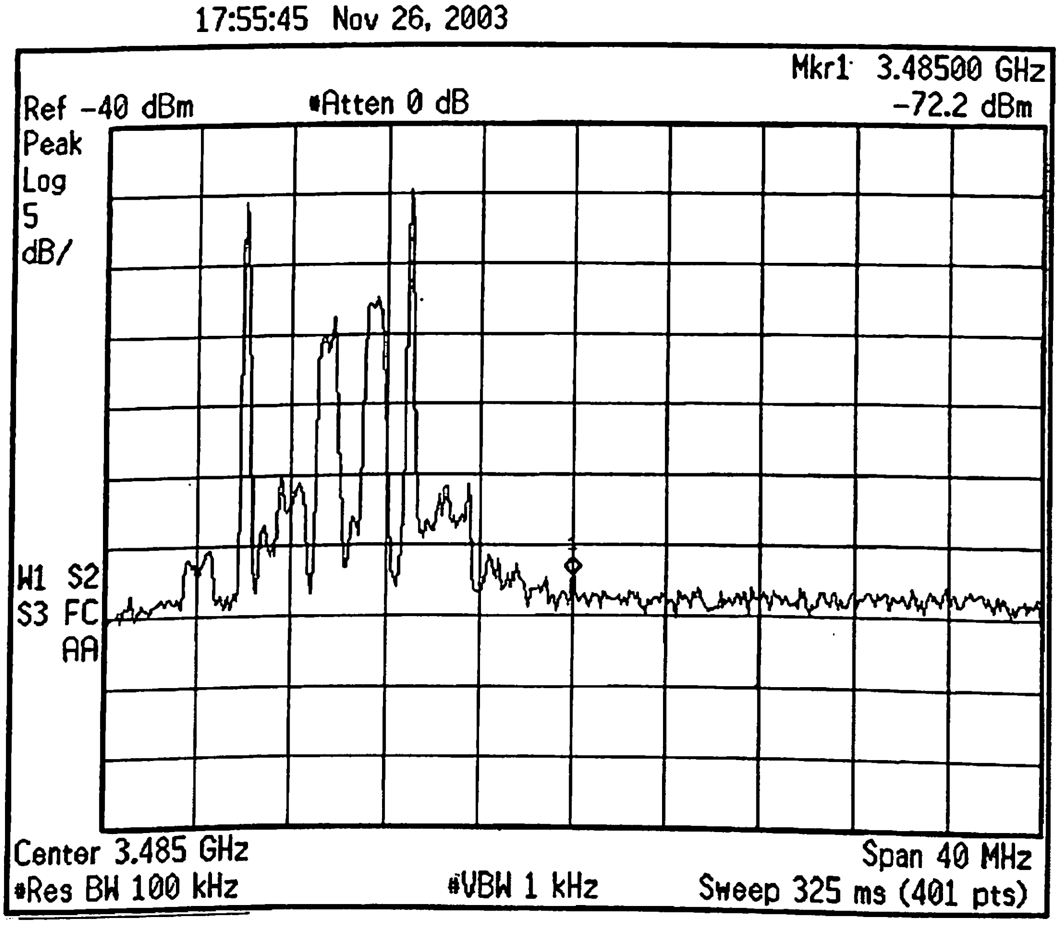


Fig. 3.2.8: Interference signal from the drifting satellite into INSAT-2E – (with and without traffic)

Chapter - 4

Chapter-4

ITU Regulations and their relevance to Interference studies

Introduction to the Chapter

The investigations into interference cases require the knowledge on the allocation of frequency bands for various services, and their actual use. Similarly, tolerable interference levels have to be considered before attempting to resolve the interference cases. In the case of interference from adjacent satellite networks, there should be a common technical basis to carry out Coordination.

International Telecommunication Union (ITU) is the agency, which regulates use of frequency spectrum, and allocates orbital slots. ITU has also developed excellent knowledge base on interferences, and recommended standard procedures to quantitatively define the interference. Hence, all relevant aspects of ITU Recommendations with respect to interference are summarized in this Chapter.

Section 4.1 introduces the concept of detectable interference and tolerance criteria. Section 4.2 identifies the main types of satellite communication services, as defined by ITU. Section 4.3 elaborates different modes of interference and the ITU recommended solutions in terms of off-axis power flux density / limitations on the radiations. This Section also covers interference tolerance aspects of analog and digital TV. Section 4.4 covers VSAT communications and the limits for off-axis emissions for VSAT being considered by ITU.

The contents included in this Chapter were studied and considered in the interferences cases investigated and reported in Chapter 6.

4.1 Interference, Detectable Interference, and Tolerance Criteria

Interference can be defined as the effect of an unwanted signal on the reception of a wanted signal. Only when this effect is of such a level as can be detected by the system, then the detected interference becomes an issue of concern. The detectability of interference depends on the characteristics of the wanted signal, the characteristics of unwanted signal and the communication system. [9]

Interference affects a number of Services and Applications which are based on Communication satellites. Traditionally, the voice communications across the Continents was a leading Application utilizing satellites. The Applications and Services are of varied nature today. The dominant Applications of the Communication Satellites are:

- Analog TV broadcasting
- Digital TV broadcasting
- Radio Networking
- Voice communications
- Mobile communications
- Data, voice and video communications using VSATs

All other Applications will be a combination of the above. Each of these Applications require certain minimum level of signal power, or more precisely Signal-to-Noise-Ratio S/N, for its proper functioning. The quality of each of these Applications is a function of S/N, which is in turn a function of Carrier-to-Noise-Ratio C/N. The interference can also be visualized, ultimately, as an element in the total system noise, and thus will contribute to the composite carrier-to-signal-ratio C/N.

Each of these Applications will have certain tolerance to the unwanted signal, i.e., interference. Hence, the interference problem has two main parts: the relative strength of interference compared to the wanted signal, and the tolerance of the system to the interference.

Minimum acceptable performance standards of each service define maximum noise level which can be tolerated under specified conditions. Specific fractions of this maximum level of noise are allotted to signal degradation occurring within the system, to the interference from other subsystems of the same Service (intra-system interference) and the interference from networks of other Services (inter-system interference). The last two components can be combined and can be called "Permissible Interference".

4.2 Classification of services by ITU

The radio spectrum is a limited natural resource, which should be shared by all types of radio services. ITU allots the frequencies for each service on a global and regional basis to avoid interference between the various services.

ITU has categorized the radio services according to their broad functions. Frequency allocations are made for each service, either globally or in a particular Region. At present, ITU has defined 35 radio services. The present work deals with only Fixed Satellite Service (FSS), Broadcast Satellite Service (BSS), and the Mobile Satellite Service (MSS). The FSS applies to systems, which interconnect fixed points through satellites. BSS refers to Broadcast Satellite Service of television or radio programming directly to the public. MSS service refers to communication to mobile terminals and individuals using satellites.

Many networks might be working in the sub-bands of a single Service to which a frequency band is allotted. The various networks, if do not operate within their allotted limits, cause interference to other networks in the same Service.

When a frequency band is shared between two Services, there are bound to be interferences between the Services – for example between terrestrial radio relay Service and Fixed Satellite Service (FSS). When the frequency spectrum is allotted by ITU, the allocations are of three categories – Primary, Permitted and Secondary. Primary and Permitted Services have equal rights, with Primary Service also having priority in choice of frequencies. Secondary Services have no rights against Primary or Permitted Services concerning the potential for harmful interference transmitted or received. The interference between the Services with allocation of equal status is mostly resolved by adhering to the stipulated limits and coordination.

The terrestrial microwave communication, which is traditionally a part of the domestic communication network in many countries, works in C-band as well as in Extended C-band. The satellite Services and terrestrial communication services are having equal status in sharing the Extended C-band frequency spectrum. This is a classic case of the type of possible interference described above.

The uplink and downlink signals of a particular satellite system can reach the adjacent satellite system as interference, due to improper antenna radiations or improper system parameters. This is more frequent where the orbital separation between adjacent satellites is reduced from 3 deg to 2 deg, (and further to 1 deg in certain Regions). The interference problems between the Networks / Services of two adjacent satellites are resolved usually by prior planning and Coordination.

One of the satellite applications of recent origin is the mobile telephony using Low-Earth Orbit (LEO) satellite constellations. These constellations (like Globalstar, Orbcom etc.) and their mobile telephony applications have potential to cause interference to the communication satellites in GSO, due to usage of common frequency bands, and / or generation of spurious signals in the frequency bands used by GSO.

Military satellites are also used for a large amount of voice and data communications. Even though the frequency bands allotted for these applications are different, there were cases of interferences generated by such systems.

In this context, ITU worked on interference in satellite communications, since its inception, mainly to harmonize various services and achieve optimum usage of frequency spectrum.

The subsequent sections cover inter-system interference, and the various methods as recommended by ITU to compute and specify interference tolerance criteria, and also to quantify the impact of the interference on various Satellite Communications Applications.

4.3 Modes of Interference in the FSS, & ITU Recommendations

The different modes of interference between terrestrial stations, satellite earth stations, the satellites, and between the networks using satellites is shown in Fig. 4.3.1. [5]

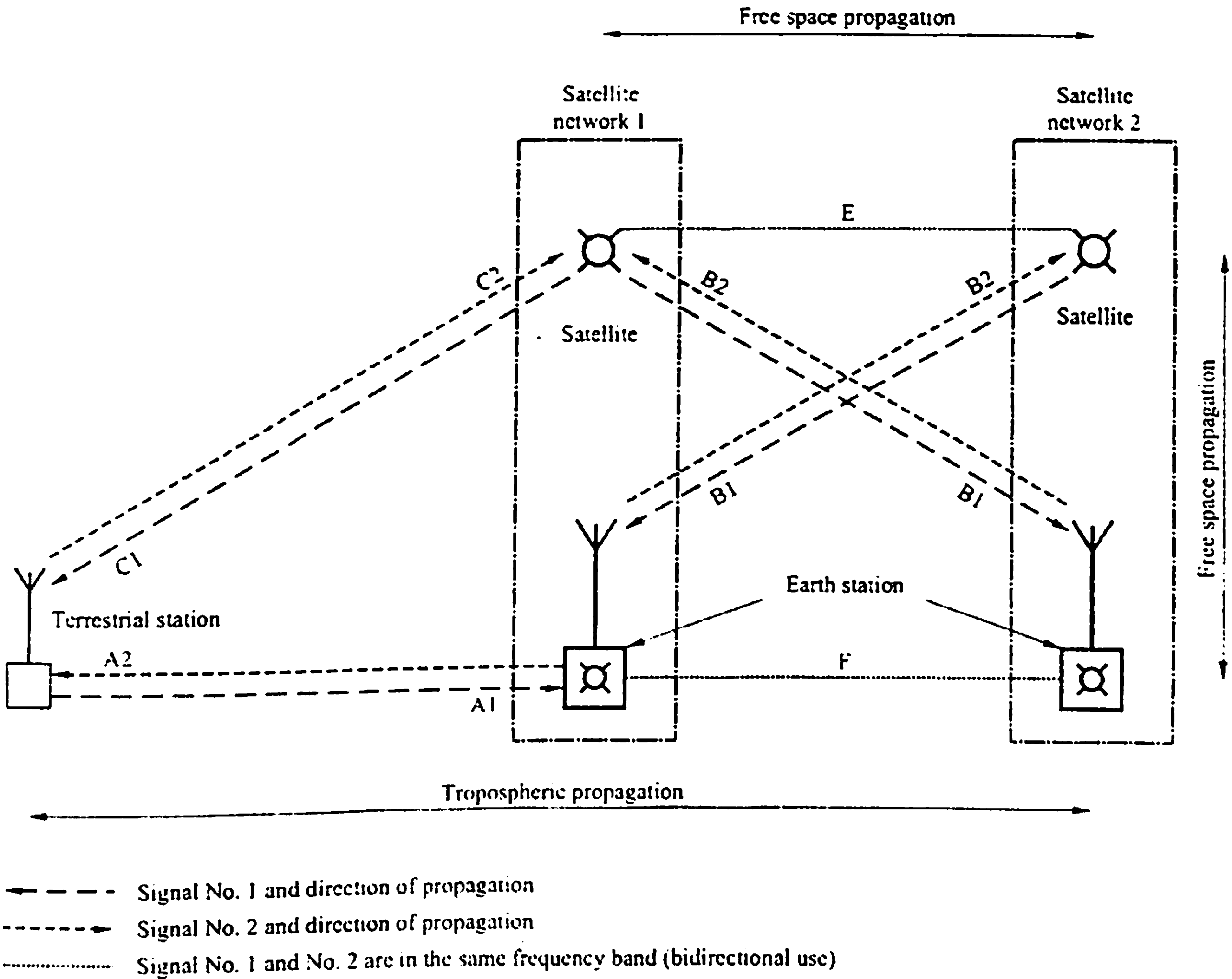


Fig.4.3.1 Modes of interference concerning the FSS in the frequency bands allocated with equal rights for terrestrial radio communications.

This figure and the nomenclature used are taken from the ITU recommendations. Difference modes of interference are as below:

A1 Terrestrial-station transmissions possibly causing interference to reception by an satellite earth station.

A2 Satellite Earth-station transmissions possibly causing interference to reception by a terrestrial station.

B1 Space-station transmission of one satellite possibly causing interference to reception by an earth station of another satellite network.

B2 Earth-station transmissions of one satellite network possibly causing interference to reception by another satellite.

C1 Satellite transmissions possibly causing interference to reception by a terrestrial station.

C2 Terrestrial-station transmission possibly causing interference to reception by a satellite.

ITU provides a number of recommendations and regulations to deal with the planning, coordination and resolution of the type of interference problems described above. These regulations / recommendations can be summarized under the following categories: [17]

- Frequency allocation for various satellite communication services.
- Constraints on the maximum permissible RF power spectral density from earth stations.
- Restrictions on the antenna pattern of earth stations.
- Constraints on the maximum permissible transmission levels from satellites.
- Permissible interference from other networks.

The general practice recommended is to coordinate and change characteristics of two networks if the interference originates from a limited number of identifiable stations. If the number of interfering stations is potentially large, then constraints on the characteristics on all such stations are imposed so that the aggregate level of interference will be acceptable.

Fig. 4.3.2 schematically identifies the type of solutions recommended by ITU for different modes of interference.

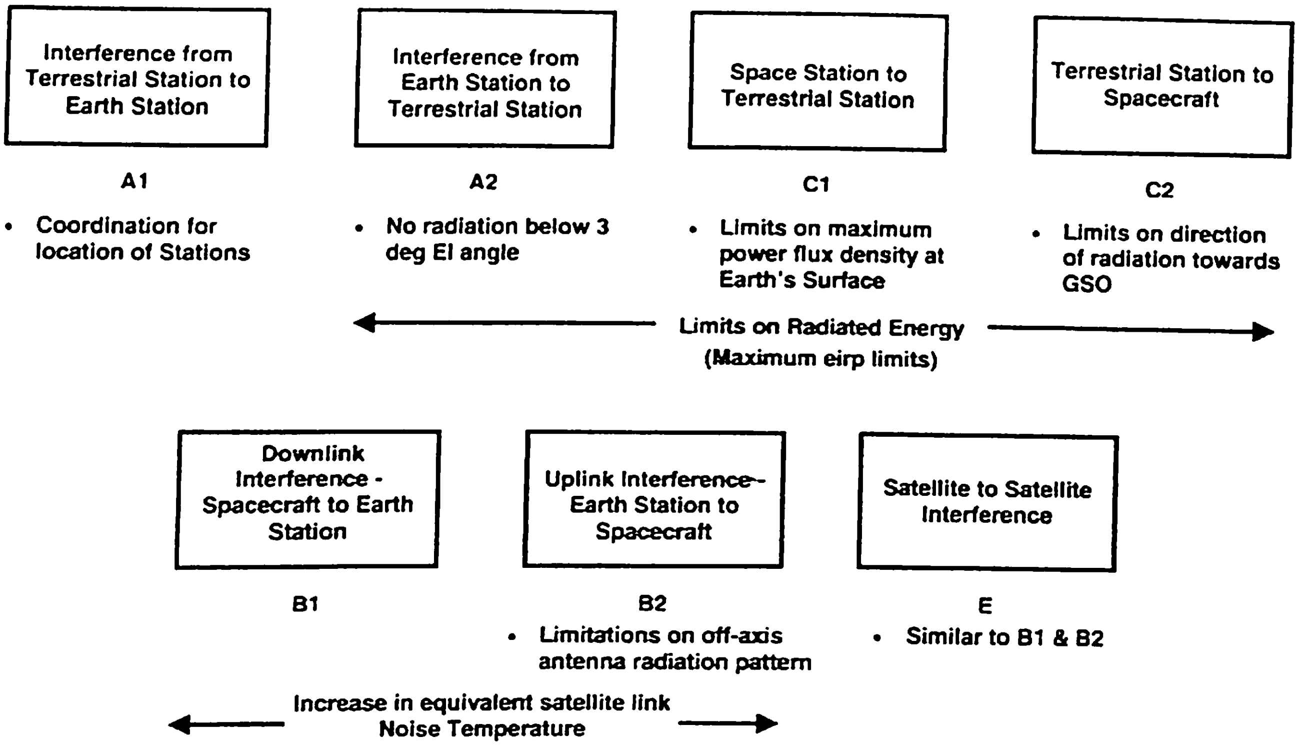


Fig. 4.3.2 : Modes of interference between Satellite Networks. and Satellite Systems to Terrestrial Stations in Sharing FSS Band; and ITU recommended solutions

4.3.1 Limits on Radiated Energy

(A) To avoid interference in the A2 mode – i.e., interference from satellite earth station to the terrestrial station, ITU restricts earth station antennae from transmission at elevation angles less than 3 deg above the horizontal plane. Also, the maximum permissible EIRP in any direction towards the horizon when the elevation angle of the antenna is less than or equal to 5 deg is given below in Table-4.3.1.

Table-4.3.1 : Maximum permissible EIRP for A2 mode of interference

Frequency bands (F, GHz)	E/s e.i.r.p. (dBW)	Bandwidth (kHz)	$3^\circ < \delta \leq 5^\circ$ e.i.r.p. (δ) (dBW)
$1 < F < 15$	40	4	$40 + 3.\delta$
$F > 15$	64	1000	$64 + 3.\delta$
No restrictions for elevation angle δ above 5 deg.			

(B) To avoid interference to the satellites in GSO from the Fixed Service (FS), or Mobile Service (MS) stations, i.e., mode C2 type of interference, the Stations are restricted in the transmission of EIRP beyond the limits given in Table-4.3.2.

Table-4.3.2 : Maximum allowed EIRP for C2 mode of interference			
Frequency range (GHz)	**Maximum allowed EIRP as a function of avoiding angle δ from the GSO (dBW)**		**Maximum power delivered to the antenna (dBW)**
1-10	+35	$\delta > 2^\circ$	+13
10-15	+45	$> 1.5^\circ$	+10
The maximum EIRP of a Station in the FS or MS shall not exceed +55 dBW.			

(C) To avoid interference of mode B2 type i.e., radiation from an earth station to the unintended satellite in the GSO, maximum permissible levels of off-axis EIRP density from earth stations were recommended by ITU and given in the Table-4.3.3 below [18]:

Table-4.3.3 : Maximum off-axis EIRP density for B2 mode of interference			
Frequency bands (F, GHz)	**E/s EIRP (dBW)**	**Bandwidth (kHz)**	**φ° (angle off the main lobe axis)**
6	32-25 log (φ)	4	$2.5^\circ < \delta \leq 7^\circ$
14	39-25 log (φ)	40	$2.5^\circ < \delta \leq 7^\circ$
	32-25 log (φ)*		$2.0^\circ < \delta \leq 7^\circ$
The off-axis EIRP for FM-TV emissions at 14 GHz with energy dispersal (or properly modulated) should not exceed the following value: 53-25 log (φ) dBW.			
*For VSAT earth stations operating with GSO satellites in 14 GHz band.			

The off-axis EIRP when an FM-TV is being transmitted from an earth station, could be incompatible and may not conform to the ITU recommendations in certain cases – specially if low level carriers like Single Channel Per Carrier (SCPC) transmissions are involved in the adjacent satellite network in the same frequencies. Recognizing this type of severe incompatibility, the conclusion reached was that adequate protection could not be attained, either by satellite separation or by EIRP restrictions. The type of solutions recommended in such cases are:

- Frequency planning to ensure the TV transmissions in one network do not use the same frequencies as SCPC telephony transmission in a network using adjacent satellite.

- Usage of different methods of carrier energy dispersal for the TV transmissions to reduce their power spectral density.

Often the above procedures are used in the Coordination / Negotiations in the satellite systems planning.

(D) The side-lobe characteristics of earth station antennae is one of the main factors in determining minimum orbital spacing between the satellites, and to efficient use of the radio frequency spectrum in the management of Geo-Stationary satellite Orbit (GSO). Hence, ITU recommended the maximum allowable envelop for the side-lobe peaks of the antennae as given below in Table-4.3.4, with reference to Fig. 4.3.3. [19]

Table-4.3.4 : Off-axis radiation pattern recommended by ITU

D / λ	**Allowable gain of at least 90% of the side-lobe peaks**	**Remarks**
> 150	$G = 29 - 25 \log \varphi$	$1^\circ \leq \varphi \leq 20^\circ$ for new antennae to be installed
Between 50 and 150	$G = 32 - 25 \log \varphi$	φ between 1° or 100 λ / D to 20°
Between 50 and 150	$G = 29 - 25 \log \varphi$	φ between 1° or 100 λ / D to 20°; and for antennae installed after 1995
The recommendation on side-lobe envelope for D / λ < 50 to be finalized		

This recommendation of the ITU is the most widely used in the earth station designs. This is practically adopted as the regulation in many Countries. The full text of the ITU Recommendation S.580-5, dealing with this subject, is included as Annexure at the end of this chapter, for ready reference.

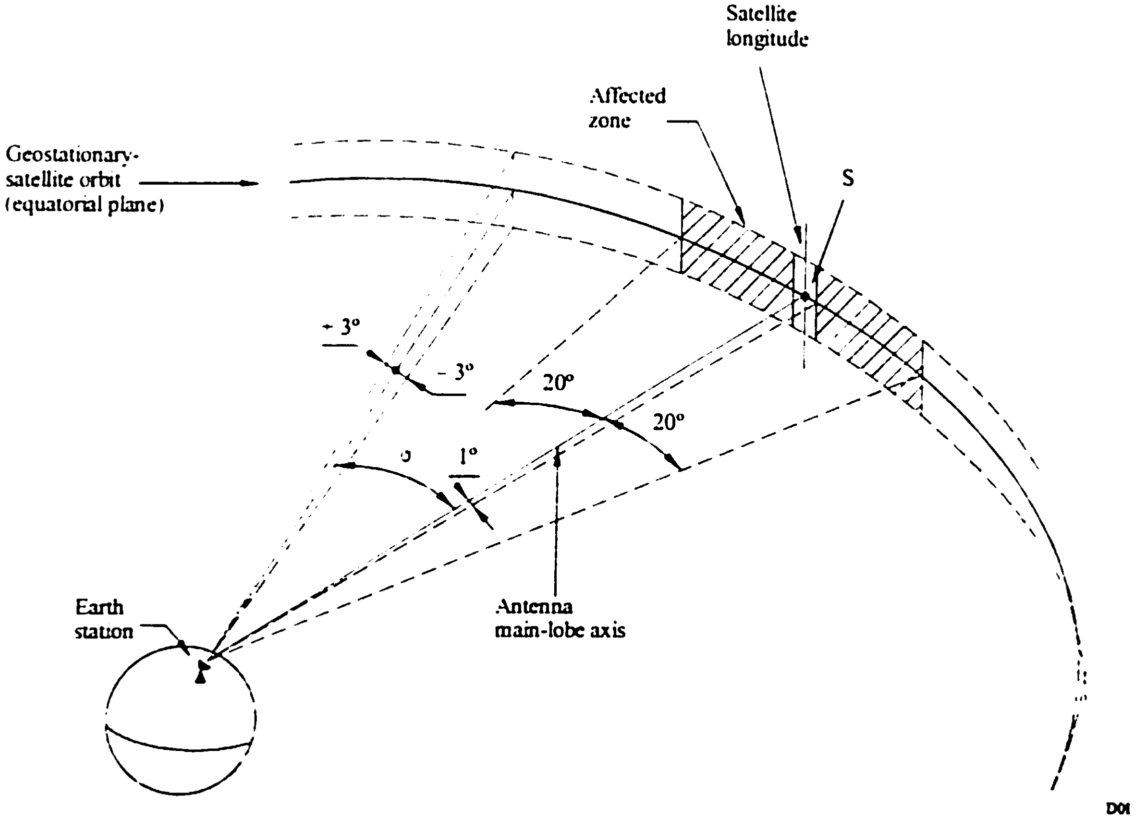


Fig. 4.3.3: Example of a zone around the GSO to which the design objective for earth-station antennae applies

(E) The maximum allowable power flux density produced by satellite on earth's surface was recommended by ITU to avoid interference to the earth stations in the networks of adjacent satellites (B1 mode of interference), or to the earth stations in the terrestrial services (C1 mode of interference). These limits, which are of relevance in the C and Ku-bands services for India (Region 3 of ITU), are given in the Table-4.3.5.

Table-4.3.5 : Maximum power flux density from the satellites (B1 and C1 modes of interference)

Frequency range (GHz)	**Maximum power flux-density as function of a arrival angles δ (dB (W/m^2))**				**Service**
	$0° < \delta \leq 5^0$	$5° < \delta \leq 25^0$	$25° < \delta \leq 90^0$	Reference bandwidth	
2.500-2.690	-152	-152+0.75 (δ-5)	-137	In any 4 kHz band	GSO FSS (and MSS)
3.400-4.200 4.500-4.800 7.250-7.750	-152	-152+0.5 (δ-5)	-142	In any 4 kHz band	GSO FSS
10.7-11.7	-150	-150+0.5 (δ-5)	-140	In any 4 kHz band	GSO and non-GSO FSS
11.7-12.2	-148	-148+0.5 (δ-5)	-138	In any 4 kHz band	BSS Plan or GSO and non-GSO FSS
12.2-12.5	-148	-148+0.5 (δ-5)	-138	In any 4 kHz band	GSO and non-GSO FSS

4.3.2 Maximum Permissible Interference : ΔT / T method

ΔT / T method was recommended by ITU as one of the methods to calculate interference between GSO networks sharing the same frequency band. This method is based on the concept that the noise temperature of the system, subject to interference, undergoes an apparent increase due to the effect of the interference. Since the number of parameters characterizing interference are so large, this simple method is devised to determine whether there is any risk of interference between two given satellite networks. The power of interference signal is assumed to be spread evenly over the frequency bandwidth, with a power density equal to its maximum power density. Although, this would result, in most cases, in a pessimistic result, the method is simple and can be used irrespective of the modulation characteristics and the exact carrier frequencies employed by the interference source and the affected system.

The ratio ΔT / T is expressed as a percentage.

The geometry of wanted and interfering networks sharing the same frequency band for both uplinks and downlinks is given in Fig. 4.3.4. [20]

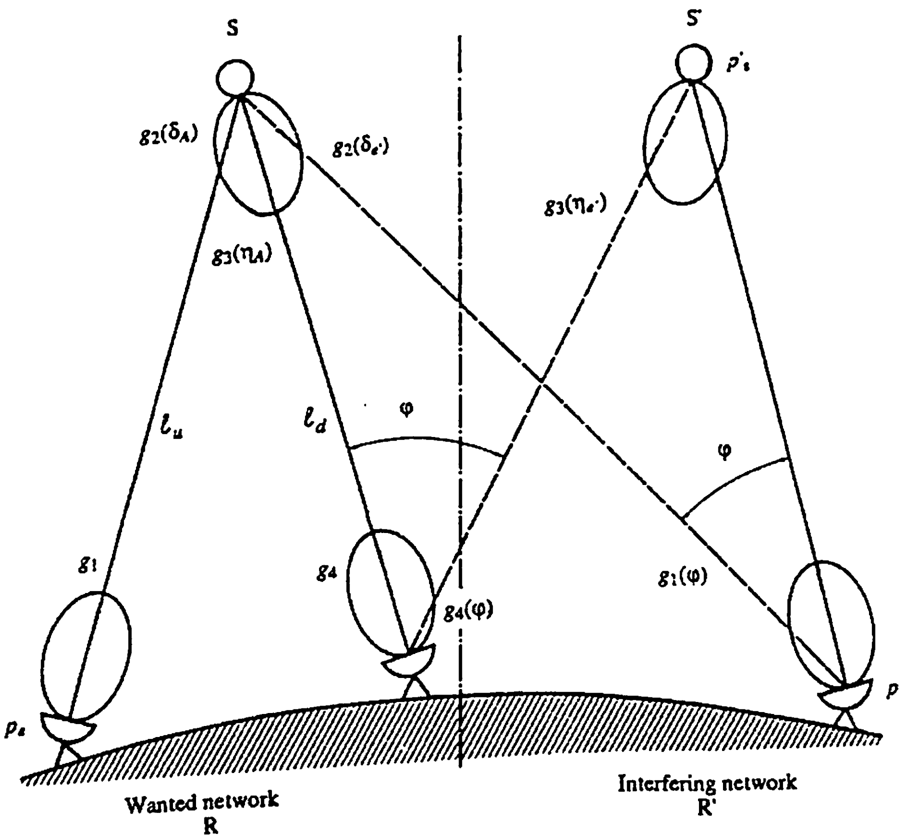


Fig. 4.3.4 Schematic of Interference for ΔT / T calculations.

The parameters are defined as follows (for the wanted satellite link):

T: the equivalent satellite link noise temperature, referred to the output of the receiving antenna of the earth station (K)

T_s: the receiving system noise temperature of the satellite, referred to the output of the receiving antenna of the satellite (K)

T_e: the receiving system noise temperature of the earth station, referred to the output of the receiving antenna of the earth station (K)

ΔT: apparent increase in the equivalent noise temperature for the entire satellite link referred to the output of the receiving earth station antenna, caused by interference emissions from other satellite networks

l_d: Free space loss on the downlink

l_u: Free space loss on the uplink

γ: Transmission gain of a specific satellite link subjected to interference, evaluated from the output of the receiving antenna of the satellite to the output of the receiving antenna of earth station (numerical power ratio, usually, less than 1)

p_e: Maximum power density per hertz delivered to the antenna of the transmitting earth station.

G_1: Transmitting antenna gain of earth station

g_2: Receiving antenna gain of the satellite

g_4: Receiving antenna gain of the earth station

φ: Topo-centric angular separation between the two satellites

Calculation of the equivalent satellite link noise temperature ΔT/T

In bent-pipe transponders, ΔT/T can be calculated using the transmission gain γ, and the fundamental Transmission Equation. The procedure is given below: [20]

The transmission gain is expressed as follows:

$$\gamma = \frac{p_s g_3(\eta_4) g_4 \, l_u}{p_e g_1 g_2(\delta_4) \, l_d} \tag{1}$$

where g_1 and g_4 are the maximum (on-axis) transmitting and receiving gains of the earth station antenna respectively.

$$\gamma = \frac{e.i.r.p._s \, g_4 \, BO_i \, 4\,\pi}{W_s g_2(\delta_4) \, l_d \; BO_o \, \lambda^2} = \frac{(C/N_0)_d}{(C/N_0)_u} \, \frac{T_e}{T_s} \tag{2}$$

The equivalent link noise temperature is expressed as follows:

$$T = \frac{(C/N_0)_d}{(C/N_0)_t} \, T_e \tag{3}$$

where:

$(C/N_0)_u$: up-link carrier-to-noise density ratio including only thermal and other background noises (numerical ratio)

$(C/N_0)_d$: down-link carrier-to-noise density ratio including only thermal and other background noises (numerical ratio)

$(C/N_0)_t$: total link equivalent carrier-to-noise density ratio including intra-satellite impairment (intra-satellite interference, intermodulation), thermal and other background noises (numerical ratio)

$e.i.r.p._s$: satellite saturation e.i.r.p. (W)

λ : the wavelength (m) of the up-link frequency

BO_i : transponder input back-off with respect to single carrier saturation (numerical value)

BO_o : transponder output back-off with respect to single carrier saturation (numerical value)

W_s : saturation power flux density at the satellite (W/m^2).

ΔT between the wanted and interfering networks sharing the same frequency band (in the same direction of transmission) can be calculated as below:

The parameters ΔT_s and ΔT_e are given by the following equations:

$$\Delta T_s = \frac{p_e' \, g_1'(\varphi) \, g_2(\delta_{e'})}{k l_u} \tag{4}$$

$$\Delta T_e = \frac{p_s' \, g_3'(\eta_e) \, g_4(\varphi)}{k l_d} \tag{5}$$

The increase in the equivalent satellite link noise temperature is the result of interference entering at both the satellite and earth station receiver of the wanted link.

This can therefore be expressed as follows:

$$\Delta T = \gamma \Delta T_s + \Delta T_e \tag{6}$$

$$\Delta T = \gamma \frac{p_e' \, g_1'(\varphi) \, g_2(\delta_{e'})}{k l_u} + \frac{p_s' \, g_3'(\eta_e) \, g_4(\varphi)}{k l_d} \tag{7}$$

Hence the above equation combines the up-link and the downlink interference.

Having calculated ΔT and T, the ratio of ΔT/T can be computed. If the ΔT/T (expressed in percentage) is more than or equal to 6%, the interference between the two networks requires coordination / negotiations. 6% threshold value is a general criteria recommended by ITU. [20]

However, this is a conservative number and admissible ΔT/T can be computed by a method of power density-averaging bandwidth, if details of the network and modulation parameters are available. In such cases, the ΔT/T threshold values higher than 6% can be allowed. ITU also recommends admissible equivalent link noise temperature (ΔT/T) for Single-Carrier-to-Single-Carrier with different types of modulations employed by the required carrier and the interfering carrier. The recommended values are given in the Table-4.3.6.

Detailed computations for representative services (like FM-TV, digital SCPC etc.) are given in the ITU Recommendation [21].

Table-4.3.6: Single carrier to single carrier $\Delta T/T$ threshold values

	Interfering carrier	FDM-FM				Wideband digital				SCPC	FM-TV	
Wanted carrier	B_{OC} (MHz)	< 3	3-7	7-15	> 15	< 3	3-7	7-15	> 15	PSK	$\Delta f \leq 7$	$\Delta f > 7$
	< 3	13	12	12	11	8	10	10	8	9	11	11
	3-7	23	14	12	12	11	10	10	8	29	11	13
FDM-FM	7-15	40	20	14	12	17	10	10	8	56	12	19
	> 15	102	46	24	14	40	19	11	8	148	23	45
	< 3	15	10	9	9	9	9	9	9	21	9	9
Wideband	3-7	49	21	12	9	19	9	9	9	71	11	21
digital (2)	7-15	100	44	21	11	39	17	9	9	146	22	44
	> 15	176	77	38	15	69	31	15	9	257	39	77
SCPC	PSK (4) CFM (3)	9 11	9 11	9 11	9 11	9 11	9 11	9 11	9 11	9 11	2 21	2 36
FM-TV	$\Delta f \leq 7$ $\Delta f > 7$	73 23	32 10	16 5	6 2	29 9	13 4	6 2	2 1	107 34	16 5	32 10

Note

(1) Criterion used: 800 pW0p single entry and 7 000 pW0p total. For PM-TV interference a 20% allocation to external satellite interference is assumed.

(2) Criterion used: 6% single entry and 70% total. For FM-TV interference a 20% allocation to external satellite interferences is assumed and a value of 12.3 dB is assumed for energy per bit to noise power density ratio (BER = 10^{-6}).

The above Recommendations of ITU refers to Single-Entry Interference and criteria for Coordination. But, noise is introduced into the satellite communication network by other satellites and terrestrial systems in both the uplinks and downlinks. A total interference noise budget of 20% is a reasonable compromise for most purposes (i.e., Interference Noise = 20% of total allowed noise).

4.3.4 Maximum Permissible Interference – C/I Method [9], [22]

The system tolerance criteria are usually defined in terms of C/I, the ratio of the wanted signal power C to the unwanted interference power I. The Carrier-to-Interference-ratios can be used for all modulation methods and signal types.

Using the transmission equation, the power received can be calculated as:

$$C = P_t + G_t - L + G_r \qquad (8)$$

Where

P_t = transmitted power in dBW

G_t = transmit antenna gain, dB

L = free space loss in dB

G_r = receive antenna gain in dB

Using the same Fig. 4.3.4, we can compute the interference power also using the same equation (as used for computing carrier power above).

The ratio C/I can be computed by combining the equations for the received Carrier Power, and Interference Power.

$$C/I = \Delta E - \Delta L_d + \Delta G_4 + Y_d$$

Where

ΔE = the difference in EIRP of wanted and interfering transmissions

ΔL_d = the difference between downlink free space path loss for wanted and interfering signals.

ΔG_4 = is the difference of the earth station receive antenna gain between main axis pointed towards the wanted satellite, and the gain in the direction of interference.

Table-4.3.8: Subjective quality grades for analog TV			
Grade *Q*	**Perceived Quality**	**Weighted S/N**	**C/N**
5	Excellent	> 45 dB	> 16 dB
4	Good	> 41 dB	> 12 dB
3	Correct picture	38 dB	9 dB
2	Poor	36 dB	7 dB
1	Bad / Unusable	< 35 dB	

For many practical television applications, the Quality Grade between 4 and 5 is often recommended, for which the required C/I is 25 dB. Weighted Signal-to-Noise-ratio of the order of 45 dB can be achieved with a satellite signal received with C/N of the order of 15 dB.

Energy Dispersal for Reduction of Interference

The FM modulation of the analog TV results in an RF signal of almost constant frequency containing all the transmitted energy which could result in interference with the neighbouring services like SCPC, voice signals of adjacent satellite network. To avoid this type of problem an energy dispersal system consisting of a saw tooth of 25 Hz, of which the slope is inverted at every field of synchronization is superimposed onto the modulating video signal. Such a video signal with energy dispersal signal is shown in Fig. 4.3.5.

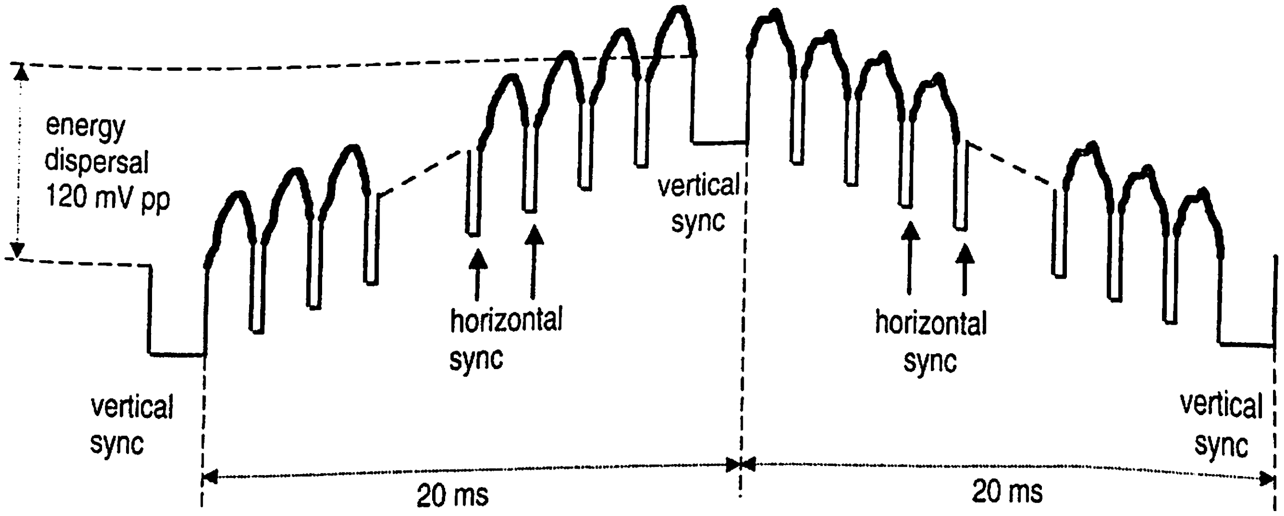


Fig. 4.3.5: Video signal with (exaggerated) energy dispersal signal

Fig. 4.3.6 below shows spectral density distribution of the analog FM-TV carrier modulated by a live video signal plus energy dispersal causing 1 MHz peak-to-peak deviation not exceeded for various percentages of time.

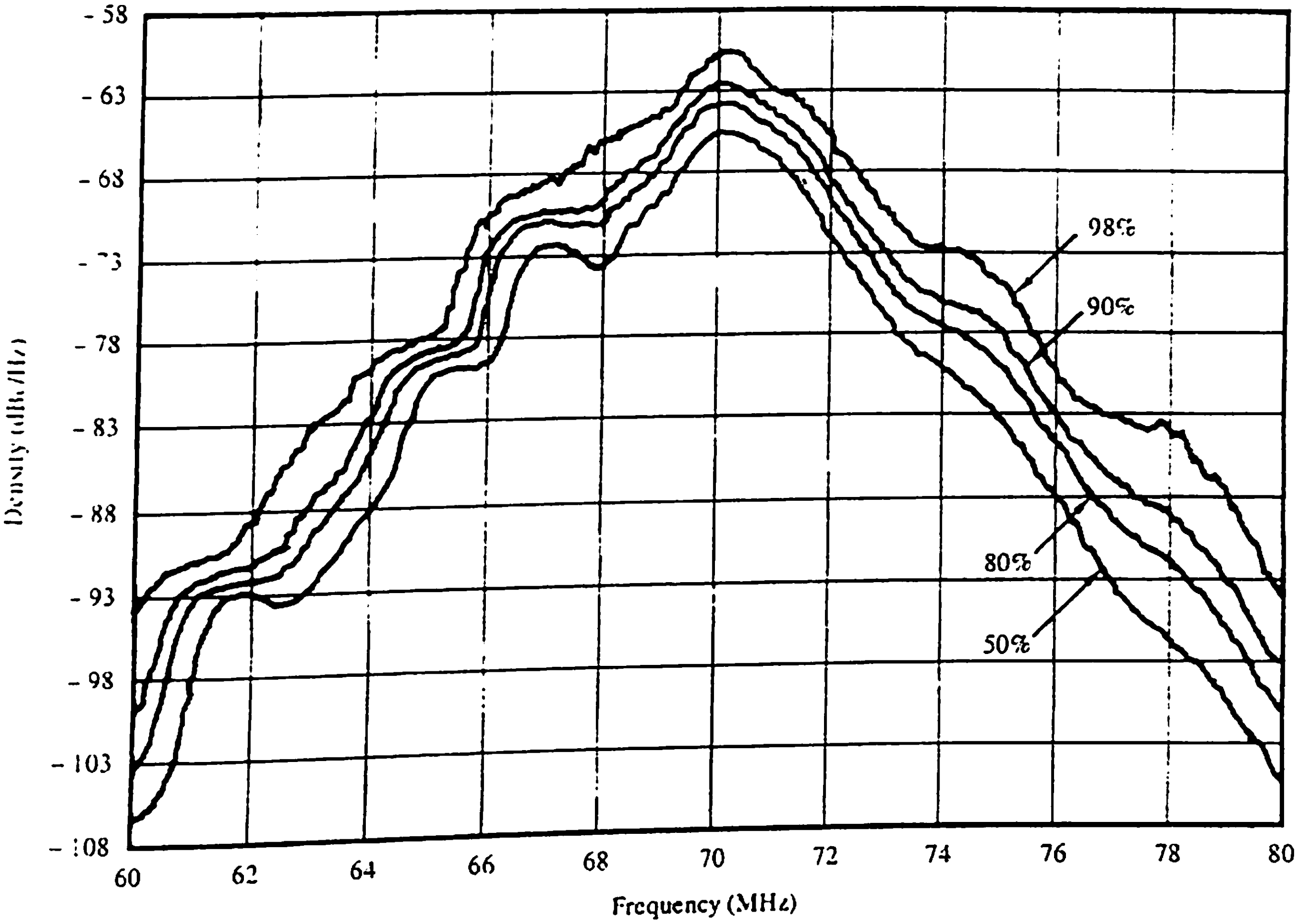


Fig.4.3.6: Spectral distribution of a 20 MHz FM-TV carrier modulated by NTSC live video plus 1 MHz energy dispersal

FM-TV usually creates interference to the narrow band SCPC signals in the same frequency band. If the interference from FM-TV is found to exceed the permissible C/I level, it is not usually necessary to eliminate completely the overlapping between carriers and it may be sufficient to arrange for quite small frequency separation between the carriers, resulting in an increased interference reduction factor.

In the analog FM-TV, the protection ratio i.e. C/I can be reduced by increasing the deviation. Thus a higher deviation can tolerate higher co-channel interference.

4.3.6 Tolerance Criteria for Digital-TV [23], [24], [25] and [26]

Digital-TV is the most popular mode of satellite TV broadcasting, both for Direct-To-Home reception (DTH) in Ku-band, as well as for reception by Cable TV service providers in C-band and Ext. C-band. As the digitization of the signal results in large bit rates, compression techniques are used for reducing the occupied bandwidth.

MPEG-2 is widely used, and gives an integrated transport mechanism for multiplexing the video, audio and other data through packet generation. Using MPEG-2, VHS quality movie can be transmitted at an information bit rate of 1.5 Mbps, a news or general entertainment TV programme at 3.4 to 4 Mbps, and live sports programmes at 4 to 6 Mbps.

However, de-multiplexing and decompression process of MPEG-2 are highly sensitive to bit error rates (BER). As a result, an extremely low BER is required to provide acceptable service. The maximum BER that can be tolerated is of the order of 10^{-10} to 10^{-11}.

Digital-TV usually employs QPSK modulation, for reduction in the occupied bandwidth. But, the BER at the output of the QPSK demodulator is usually low. Hence, the systems employ error correction inner codes and outer codes (Viterbi coding, and Reed-Solomon coding) to improve BER performance. Thus, the BER of the order of 10^{-2} at the output of QPSK demodulator is improved to a BER of 10^{-11} after RS decoding. Fig. 4.3.7 depicts this improvement schematically [25].

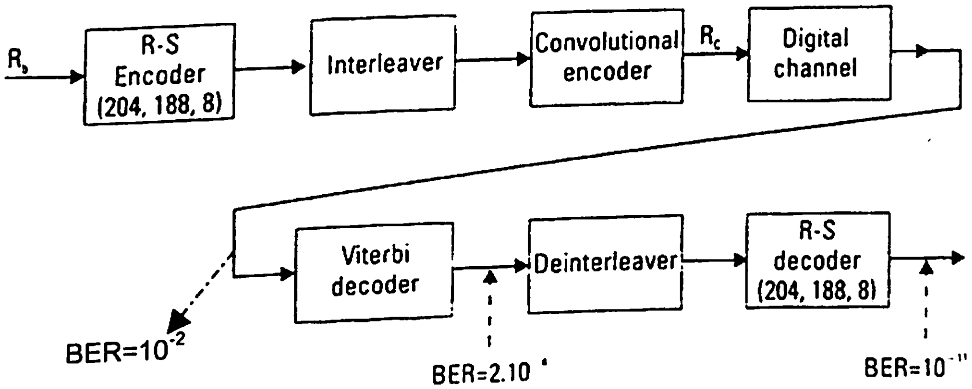


Fig. 4.3.7: BER improvement at different stages in the Digital-TV process

A C/N ratio (or E_b/N_o) ratio of 13.5 dB is required for QPSK to achieve BER of 10^{-11} without any coding. With the use of Viterbi and RS codes, a C/N ratio of 4.5 dB is sufficient to achieve the same level of BER ratios.

One of the major consequences of Digital-TV is with respect to interference. The reception of digital signals from satellites requires a cleaner interference environment than analog signals, with little tolerance from undesired in-band noise. The low C/N ratios, at which the high compression of bit rates are achieved, puts a high demand on the management of interference. A C/I ratio of 25 dB gives very small degradation of C/N in analog TV, but a low level of interference has to be achieved (a C/I ratio of the order of 35 to 40 dB), not to degrade the composite C/N beyond 10 dB, for good quality Digital-TV reception.

4.3.7 Effect of the rain on System Noise Temperature [27]

The rain causes heavy attenuation in the Ku-band used for Direct-TV broadcasting. The rain causes three effects – attenuation, depolarization of the signal, and increase in the System Noise Temperature. The increase in the System Noise Temperature is given by:

$$\Delta T = T_r * \left[1 - \frac{1}{A_p}\right] \qquad (10)$$

Where T_r = ambient temperature to be taken as 273°K

A_p = total rain attenuation computed using rain attenuation models

A 3 dB increase in the rain attenuation will usually result in increase in the System Noise Temperature, and reduction of G/T of ground station by 3 to 3.5 dB.

This aspect also has to be considered while computing C/N ratios, and allowable C/I which will not degrade the composite C/N ratio.

4.4 VSAT Communications

A relatively recent application of satellites communications is the Corporate networks using Very Small Aperture Terminals (VSATs). A typical VSAT consists of communication equipment and small antenna with diameter less than 3.5 m. The transmitting RF amplifier is usually incorporated in the outdoor unit of the VSATs.

VSATs are configured either in Mesh configuration or in Star configuration. In the Mesh configuration any terminal can be connected to any other terminal through the satellite. But in the Star configuration the traffic from one remote VSAT has to reach the destination VSAT only through the Hub station – i.e., with two hops through the satellite. The Hub stations are usually located where the bulk of the network traffic originates and/or terminates. Most of the traffic in VSAT systems use QPSK modulation. Because the links are bandwidth limited, BPSK modulation, which is not bandwidth-efficient, is avoided. BPSK is used only if the on-axis emission constraints are exceeded with other types of modulations.

A comprehensive treatment of VSAT configurations and the practical System design aspects are covered in the VSAT Handbook of INTELSAT [28].

The interference aspects connected with VSATs are relatively bad due to:

- Antennae being of small size, the beam-widths are large.
- The outdoor equipment develop problems due to environmental effects.
- The cables, which interconnect indoor equipment and outdoor equipment, cause often problems.
- Even though a few recommendations of ITU are available with respect to VSAT characteristics, no Standard has evolved. Practically, every major manufacturer of VSAT systems has his own specifications.

Fig. 4.3.8 below summarizes the ITU recommendations [29] on the maximum permissible level of spurious emissions from VSATs.

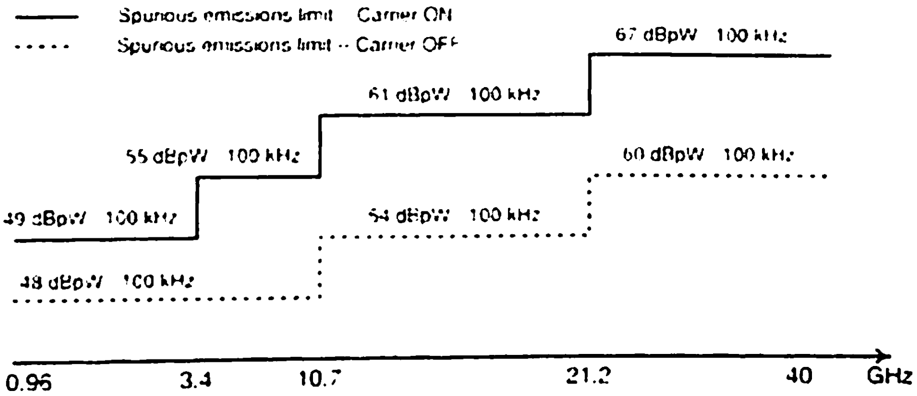


Fig. 4.3.8: Limits for Off-Axis Spurious Emissions

The on-axis spurious limit in any 4 kHz band is 4 dBW.

However, it is reasonable to state that a large number of interference problems in the satellite communications today are due to VSAT systems. This is partly due to the large number of VSAT networks employed presently in any satellite system.

4.5 Conclusions

1. The classification of services as per ITU are explained and the ITU Recommendations with respect to different types of interferences are compiled.
2. The off axis radiation pattern recommended by ITU is elaborated, which is essential to analyze and investigate interference cases.
3. The computations for maximum permissible interferences for various services, along with tolerance criteria are detailed. The specific features of VSAT communications are also given.

This background information was used during investigations of interference cases, and included here for complete understanding of the investigations reported in Chapter 6.

Reference [19]

RECOMMENDATION ITU-R S.580-5

RADIATION DIAGRAMS FOR USE AS DESIGN OBJECTIVES FOR ANTENNAS OF EARTH STATIONS OPERATING WITH GEOSTATIONARY SATELLITES

The ITU Radiocommunication Assembly,

considering

a) that efficient utilization of the radio spectrum is a primary factor in the management of the geostationary-satellite orbit (GSO);

b) that the side-lobe characteristic of earth-station antennas is one of the main factors in determining the minimum spacing between satellites and therefore the extent to which the radio spectrum can be efficiently employed;

c) that the radiation diagram of antennas directly affects both the e.i.r.p. outside the main radiation axis and the power received by the side lobes;

d) that the construction of antennas with improved side-lobe characteristics may be envisaged using current design techniques but that their practical applications may involve increase in cost;

e) that the Radiocommunication Study Groups are studying the potential advantages of using antennas with improved side-lobe characteristics for a better utilization of the GSO,

recommends

1. with regard to antennas having a D/λ exceeding 150:

   - that new antennas of an earth station operating with a geostationary satellite should have a design objective such that the gain (G) of at least 90% of the side-lobe peaks does not exceed:

$$G = 29 - 25 \log \varphi \qquad \text{dBi}$$

(G being the gain relative to an isotropic antenna and being the off-axis angle in the direction of the geostationary-satellite orbit referred to the main-lobe axis).

This requirement should be met for any off-axis direction which is within 3° of the GSO and for which $1° \leq \varphi \leq 20°$ as illustrated in Fig. 1;

2. with regard to antennas having a D/λ between 50 and 150:

   - that antennas should have a design objective such that the gain (G) of at least 90% of the side-lobe peaks does not exceed:

$$G = 32 - 25 \log \varphi \qquad \text{dBi}$$

   - that antennas installed after 1995 (this date takes into account the needs of developing countries and every effort should be made to achieve the design objective at an earlier date) should have a design objective such that the gain (G) of at least 90% of the side-lobe peaks does not exceed:

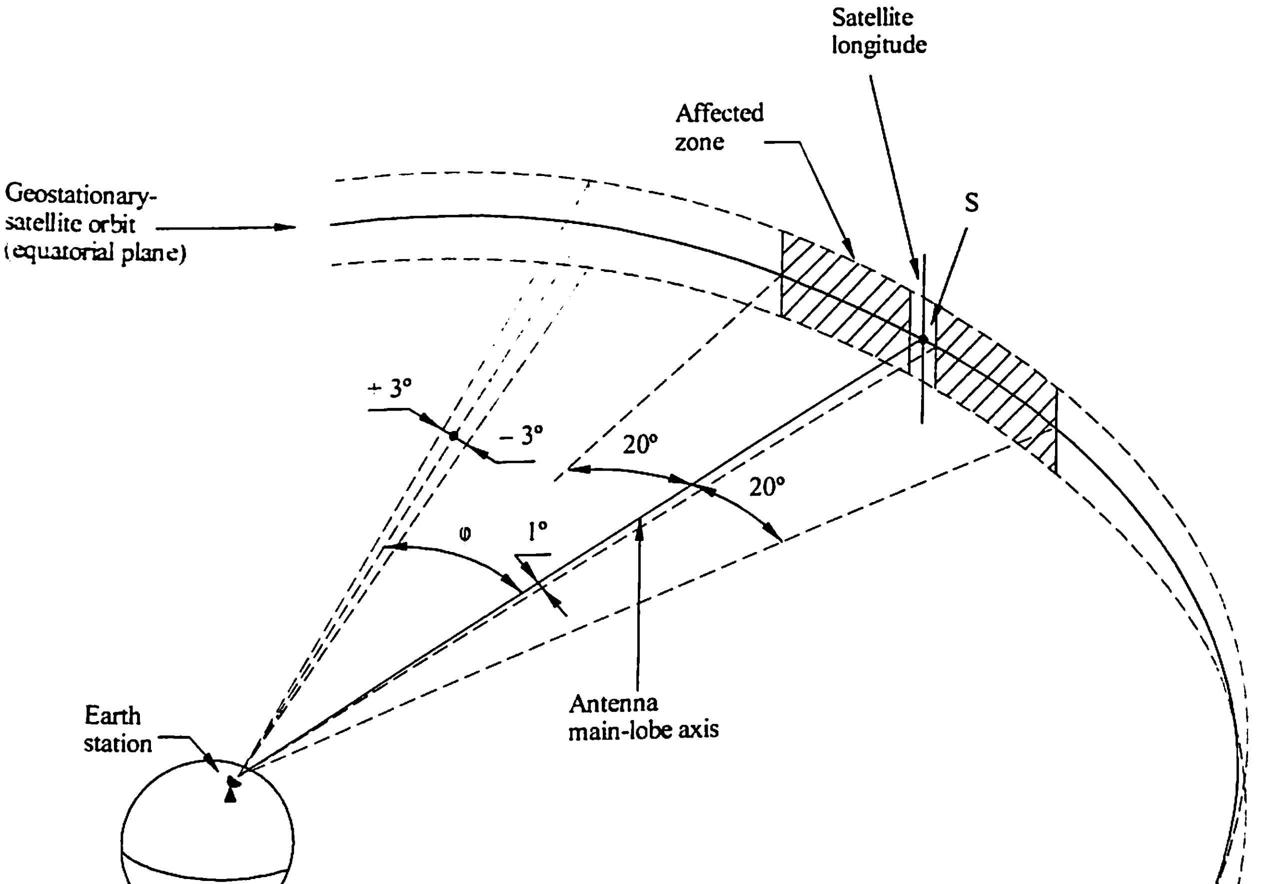
$$G = 29 - 25 \log \varphi \qquad \text{dBi}$$

   These requirements should be met for φ between 1° or $(100\ \lambda / D)$ whichever is the greater and 20° for any off-axis direction which is within 3° of the GSO;

3. for an off-axis angle, φ, greater than the limits specified above, Recommendation ITU-R S.465 should be used as a reference (see Note 7);

FIGURE 1

Example of a zone around the GSO to which the design objective for earth-station antennas applies



4. that the following Notes should be considered part of this Recommendation.

Note 1 – This Recommendation does not apply to existing antennas.

Note 2 – This Recommendation primarily addresses the GSO sharing criteria. However, it must be emphasized that the application of this Recommendation should not prejudice the antenna characteristics concerned with frequency coordination between the fixed-satellite service and terrestrial services (see Recommendation ITU-R S.465).

Note 3 – When elliptical beam antennas are used the side-lobe radiation in the direction of the GSO can be reduced if the minor axis of the beam (major axis of the antenna) is oriented so that it is parallel to the GSO. Further study is required on the application of this Recommendation in the case of the minor axis of the antenna which would correspond with a $D/\lambda < 50$.

Note 4 – Further study is required to determine a design objective for antennas having a D/λ less than 50.

Note 5 – The method of statistical processing of side-lobe peaks is dealt with in Recommendation ITU-R S.732.

Note 6 – This Recommendation may need modification in the light of further decisions made by future World Radiocommunication Conferences, especially in the orbital arcs and frequency bands where recognition is given to the special needs of developing countries.

Note 7 – In those cases where there is discontinuity between this design objective Recommendation and the reference radiation patterns of Recommendation ITU-R S.465, the gain (G) of at least 90% of the side-lobe peak is defined as follows:

$$G = -3.5 \quad \text{dBi} \qquad \text{for } 20° < \varphi \leq 26.3°$$

Note 8 – Small earth-station antennas with improved main beam and side-lobe characteristics are being developed. It is indicated that the efficient use of the GSO may necessitate reflecting these improved characteristics in the ITU Radiocommunication Assembly texts and Recommendations.

Note 9 – The performance objectives in § 2 have been met by off-set-fed type antennas operating in the 10-14 GHz with $D/\lambda \geq 35$ and by off-set-fed type receive only antennas operating in the 10.7-11.7 GHz band with $D/\lambda \geq 22$.

Note 10 – Theoretical calculations supported by preliminary test results of the side-lobe radiation pattern, in the diagonal plane, for square microstrip array antennas with $D/\lambda \cong 26$ meet the current design objective of § 2. These tests were performed on an active array in the 14 GHz band. Further studies are required to confirm that this design objective can be applied to square microstrip phased array antennas.

Chapter - 5

Chapter-5

Analytical & Experimental tools for Interference studies

Introduction to the Chapter

This chapter covers the analytical and experimental tools used during the Investigations of interference cases. Use of these tools had become essential during the investigations to correctly characterise the interference signals, and to approximately identify the geo-location of the interference sources.

Section 5.1 describes the principles, the measurement methodologies, and the fundamentals of geo-location, concerned with localization of the source of interference. If an uplink signal reaches two adjacent satellites as interference and gets translated to the downlinks of both the satellites, these signals can be measured at a single measurement site to derive Time Difference of Arrival (TDOA) and Frequency Difference of Arrival (FDOA) of the signals (through the two satellite paths). These values can be used in the geo-location equations to generate loci on which the source of interference lies.

The received signals can be detected either by spectrum analysers or through the cross-correlation of signals. The zero span provision of the spectrum analysers can be gainfully used to detect the interference signal and get the video output. The cross-correlation methods will have advantage of detecting the weak interference signals. The principles of TDOA, FDOA, geo-location, and cross-correlation using digital signals are detailed. Also, the conditions for successful interference source location using these methods, and the limitations of the methodology are highlighted.

Section 5.2 describes the experimental tools used in the Investigations. The generalized measurement setup and important specifications / parameters of different equipment, which are relevant for interference measurements, are highlighted.

An equipment called Telecom Carrier Analyser (TCA) with custom-built features was procured for detailed interference measurements. This Section covers the details of the TCA, and experiments designed and carried out to demonstrate the features of TCA.

A software was designed to implement the cross-correlation of two digital signals, which were the outputs of TCA, and same was demonstrated with simulated inputs. This software will be very useful for future investigations of interference cases, if one of the signals is very weak compared to the other.

Section 5.3 gives the photographs of the antennae, earth station equipment, TCA, digital video signal detection equipment used in the measurements carried out during the Investigations.

5.1 Localisation of source of Interference

The interference scenario being considered here is the interference to the communication satellites from an unknown uplink station. Usually, the Earth Stations uplink the signals to the satellites in the Geo-Stationary Orbit. The signal being uplinked to a satellite can reach another satellite in the GSO through the side-lobe of the uplinking antenna. This signal reaching from an unintended uplink Station can cause interference to the normal signal traffic in another satellite.

This problem is aggravated due to close spacing of the satellites in the GSO, and deployment of Earth Stations with smaller diameter antennae (with a resulting broad beam, and higher levels of side-lobes). This situation in a general form is shown in the Fig. 5.1.1 [30].

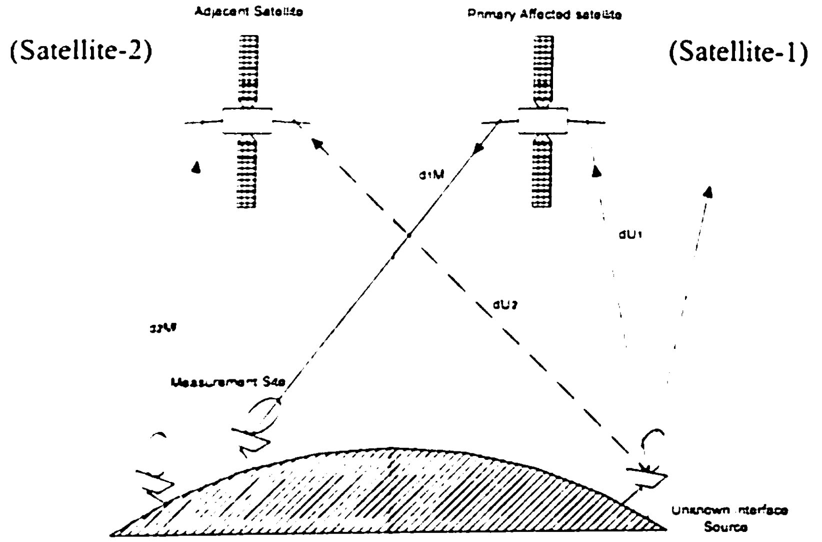


Fig 5.1.1: General Schematic of Satellite Interference from an un-known source

A method to estimate the location of transmitter using the measurement of Time Difference of Arrival (TDOA) and Frequency Difference of Arrival (FDOA) of the interference through two satellites was developed and reported in the literature. The principles of TDOA and FDOA are described in the following sections:

5.1.1 Geometry considerations of the TDOA

The signal from unknown uplinking station will travel through satellite-1 and satellite-2 to the measuring Earth Station. ~~The~~ if the r_1 and r_2 are the total distances travelled from the unknown uplinking station to the measurement station through satellites S1 and S2 respectively, the time difference between the signals received is [31]:

$$T = (r_1 - r_2) / c \tag{1}$$

Where T = The Time Difference of Arrival, and c = the velocity of propagation of signals, which is nearly same as the velocity of light.

Further, referring to Fig. 5.1.1,

$$r_1 = d_{U1} + d_{1M} \tag{2}$$

$$r_2 = d_{U2} + d_{2M} \tag{3}$$

Where d_{U1} = distance between unknown terminal to Satellite-1

d_{1M} = distance between Satellite-1, and the measurement terminal

d_{U2} = distance between unknown terminal to the Satellite-2

d_{2M}= distance between the Satellite-2 and the measurement terminal.

Hence

$$T= (d_{U1} + d_{1M}) - (d_{U2} + d_{2M}) / c \qquad (4)$$

The location of the satellite1 and satellite2 with respect to the measurement terminal are assumed known. Hence, d1M and d2M are known.

Then, the equation can be rearranged as below:

$$(d_{U1}- d_{u2}) + (d_{1M} - d_{2M}) = T . c \qquad (5)$$

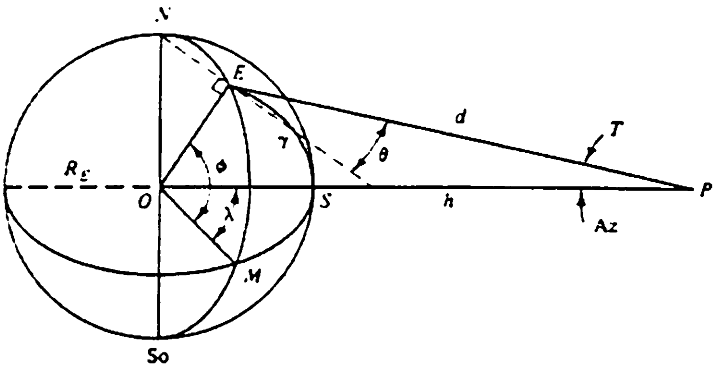
This can be further rearranged as:

$$(d_{U1}- d_{u2}) = T . c - (d_{1M} - d_{2M}) = K \qquad (6)$$

Where is K is a constant

For a given TDOA value of T, and hence for a given constant value K, the above equation represents the surfaces of constant delay between the satellites. These surfaces, in the two dimensional case, form a hyperboloid of two sheets centered along the axis of the line segment connecting both satellites and opening away from the centre point of the segment. The two intersections of these hyperbolic branch surfaces with the sphere of the Earth provide terrestrial curves of constant delay, which include the location of uplink station. [32].

Fig. 5.1.2 gives the basic geometry of satellite in GSO [30].



ϕ = goecentric latitude of earth station at E
λ = difference in longitude between E and subsatellite point S (taken positive if earth station is to the west of satellite)
γ = great circle arc ES = ∡ EOS
T = angle of inclination at satellite
R_E = equatorial radius of the earth
h = satellite altitude
θ = angle of elevation at earth station
Az = azimuth angle at earth station = ∡ NES (measured through east from north)
d = slant range from satellite to earth station
P = satellite

Fig. 5.1.2: Basic Geometry of Earth-Satellite in GSO

The slant range between receiving Earth Stations and the satellite, d, is given by:

$$d = \sqrt{R_E^2 + (R_E + h)^2 - 2R_E(R_E + h)\cos\gamma} \tag{7}$$

$$d = \sqrt{h^2 + 2R_E(h + R_E)(1 - \cos\theta\,\cos\lambda)} \tag{8}$$

Knowing R_E = Radius of Earth = 6378 km,

h = height of the GSO above Earth's surface = 35786 km

θ = latitude of the Earth Station and

λ = the relative longitude of the Earth Station with respect to the sub-satellite point

The above equation reduces to [17].

$$d = 35786[1 + 0.4199(1 - \cos\theta\,\cos\lambda)]^{1/2}\ km \tag{9}$$

By substituting (9) into (6) the measured TDOA value is related to the latitude of the unknown uplink station, and the difference of longitude between the unknown Earth Station with the sub-satellite points of each of the satellites.

Since, the variables to be found are two – i.e. the longitude and latitude of the unknown Earth Station, the measurement of TDOA alone cannot solve the location problem unambiguously.

5.1.2 Geometrical consideration of FDOA

The measurement of the frequency of the received signal traveling through the two spatially separated moving satellites can be measured to estimate the location of the uplink transmitter. This measurement is called Frequency Difference of Arrival (FDOA). The basic concepts of this measurement are the same as the one developed by radio astronomers, and this is also called Differential Doppler or the Time Derivative of TDOA.

If the signal is monitored for a time ΔT, then the average frequency over this interval is given by [31].

$$f_{av} = f_c - (r_{12} - r_{11}) / \lambda \, \Delta T \qquad (10)$$

Where f_c = the transmitted frequency

λ = wavelength

r_{12}, r_{11} = the distances from the unknown transmitter to the measurement site at the beginning and end of the time interval ΔT.

When the frequency of the signal traveling through the two adjacent satellites is measured over time interval of ΔT, two average frequency values f_1 and f_2 will be obtained. The FDOA is defined by:

$$\begin{aligned} \text{FDOA} &= f_1 - f_2 \\ &= (1 / \lambda\Delta T)\,[r_{22} - r_{21} - r_{12} + r_{11}] \qquad (11) \end{aligned}$$

This equation defines a surface in three-dimensional space on which the unknown transmitter must lie [31]. The intersection of this surface with the spherical Earth defines a curve on the Earth on which the unknown emitter lies. It is essentially same as measuring the relative range rate of the two satellites with respect to the unknown transmitter and the measurement site.

The intersection of the curves obtained with the FDOA and TDOA measurements provides the estimate of the location of the unknown transmitter.

5.1.3 TDOA Measurement Set-up

The interference signals have to be received from two adjacent satellites in a coherent manner for TDOA measurement. The measurement setup typically consists of two antennae, each looking at each of the adjacent satellites, and the attendant downlink electronics like LNAs, Down Converters etc., and a system to coherently synthesize/demodulate the signals. A typical measurement set-up is shown in Fig. 5.1.3.

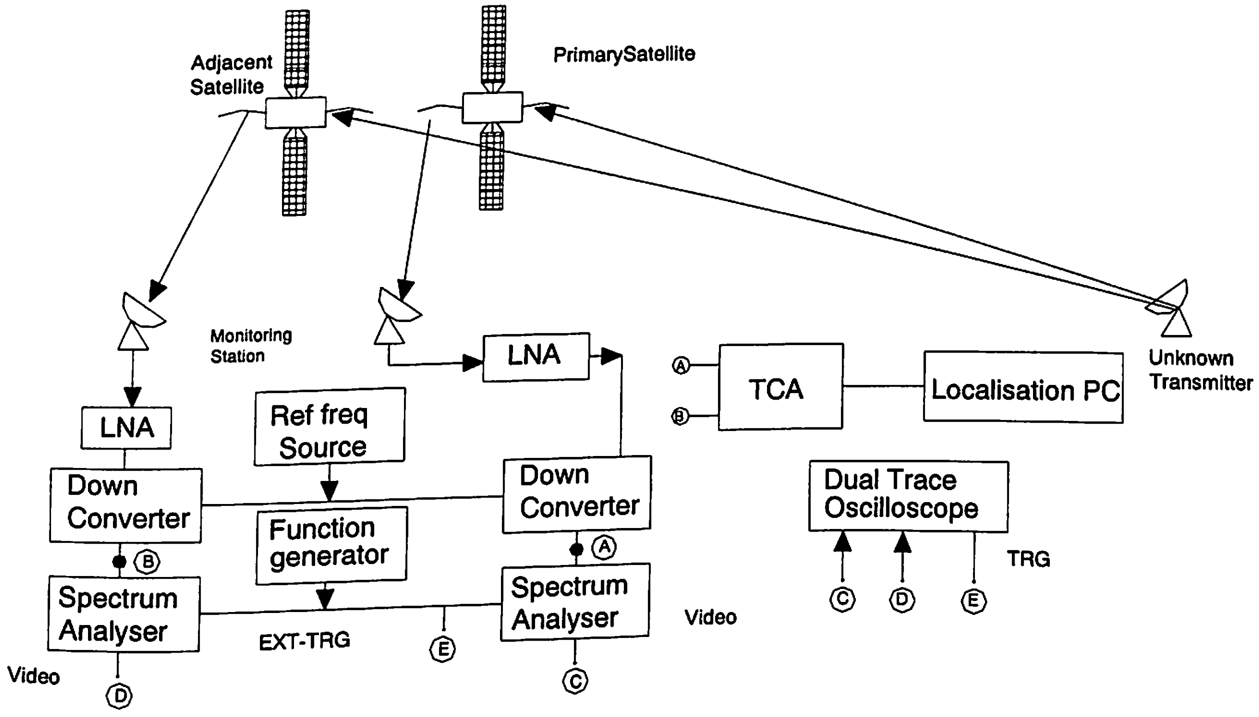


Fig. 5.1.3: A Typical TDOA measurement set up

If the incoming interference signals are well above the noise floor of the spectrum analyzer, they can be detected using zero span method. The time domain signals can be compared using a dual trace oscilloscope which is triggered using a coherent trigger source. The TDOA value will not exactly indicate which of the two signals is leading. This uncertainty can be resolved by calculating the latitude and longitude of the unknown source assuming one of the signals as leading or lagging compared to the second signal. This method will give two curves on the surface of the Earth each falling on the east and west side of the centre line between the two adjacent satellites. General knowledge of the likely location of the interference source can be used to eliminate the ambiguity. Alternatively, the FDOA curve can be determined which will intersect only one of the TDOA curves. Another way is "TDOA-only" measurements with two pairs of satellites, the primary affected satellite being common in both the pairs.

5.1.4 Signal Detection

TDOA and FDOA methods require coherent detection of signals received from two adjacent satellites. The signals in the frequency domain can be synthesized into signals of time domain for measurement using spectrum Analyzers.

Spectrum Analyzers operate according to the principles of heterodyne receivers. The block diagram of such a receiver is shown in Fig. 5.1.4. [33]

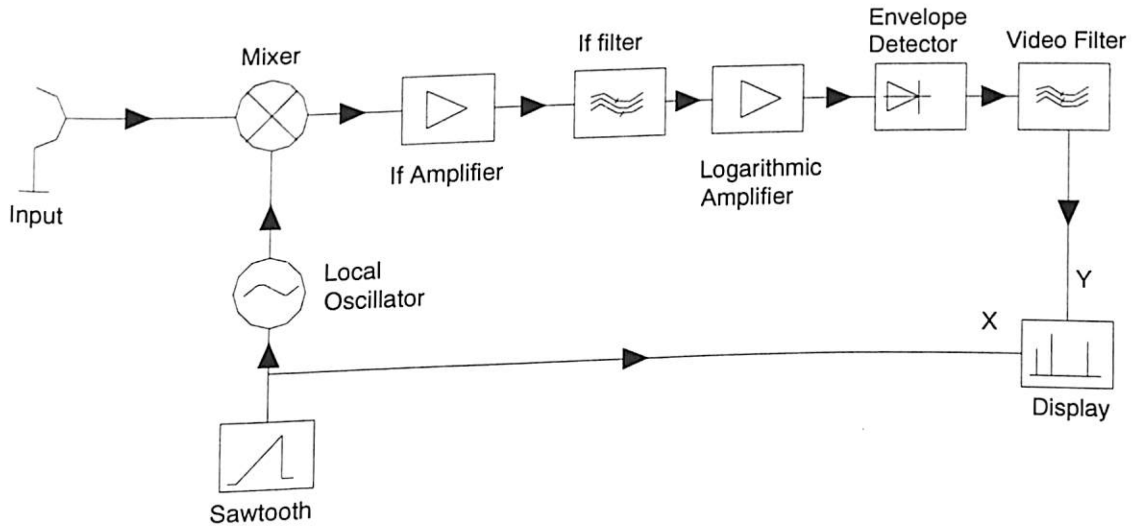


Fig. 5.1.4: Block Diagram of Spectrum Analyzer Operating on Heterodyne principle

The heterodyne receiver converts the input signal with the aid of a mixer and a Local Oscillator (LO) to an Intermediate Frequency (IF). The tunable Local Oscillator converts the Input Frequency range to a constant intermediate frequency by varying the LO frequency. The resolution of the analyzer is then given by a filter at the IF with fixed centre frequency.

The converted signal is amplified before it is applied to the IF filter which determines the resolution bandwidth. This IF filter has a constant centre frequency so that the problems associated with tunable filters are avoided.

Most of the spectrum analyzers include features of minimum peak, maximum peak and auto peak detection. By setting the span of the spectrum analyzer to ‘0’ the ramp tuning signal to the LO is cut off, and LO becomes fixed value. In that configuration, the spectrum contained in the resolution bandwidth is detected by envelope detector and is available at the output of video filter. This Y output signal of the spectrum analyzer can be used as the demodulated time domain signal.

The configuration of the detectors is shown in Fig. 5.1.5.

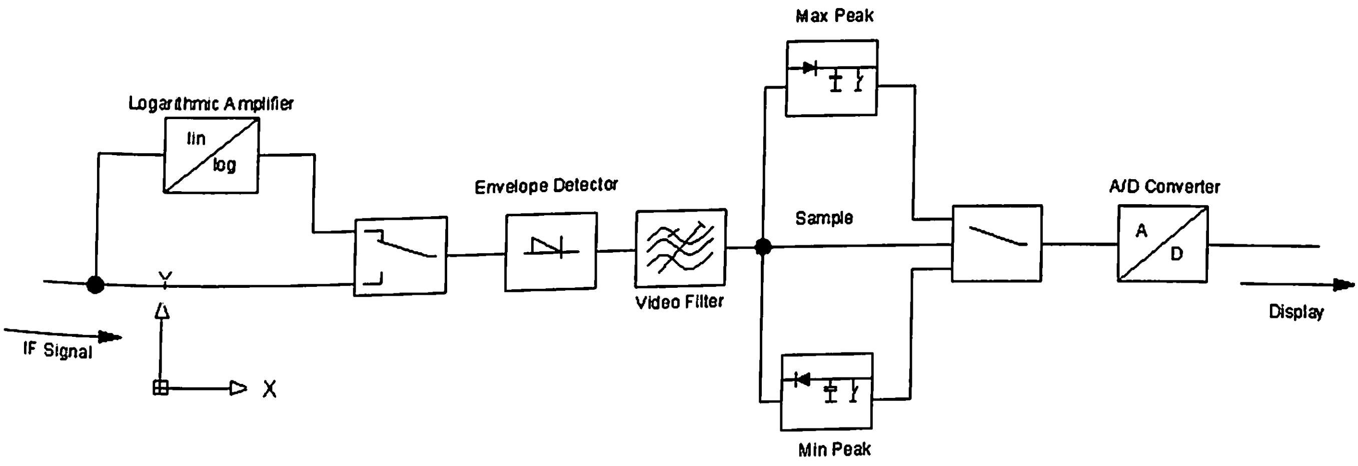


Fig. 5.1.5: Analog Realization of Detectors

The max peak detector displays the maximum value. From the samples allocated to a pixel the one with the highest level is selected and displayed. Even if wide spans are displayed with very poor resolution bandwidth (span/RBW >> number of pixels on frequency axis), no input signals are lost. Therefore this type of detector is particularly useful for interference measurements. The min peak detector selects from the samples allocated to a pixel the one with the minimum value for display. The auto peak detector provides for simultaneous display of maximum and minimum value. The two values are measured and their levels displayed, connected by a vertical line.

Quasi peak detector is a peak detector for interference measurement applications with defined charge and discharge times.

With a constant sampling rate of the A/D converter, the number of samples allocated to a certain pixel increases at longer sweep times. The effect on the displayed trace depends on the type of the input signal and the selected detector.

The above features of signal detection by spectrum analyzer were utilized during Investigations of interference caused by radars into one of the communication satellite transponders. However, this type of signal detection has some inherent limitations.

Limitations

The spectrum analyzer detectors cannot perform detection on the following:

- Phase modulated signals
- Non-periodic waveforms
- The signals, which are below the noise floor of the spectrum.

When the signals are very close to noise levels, correlation by Cross Ambiguity Function (CAF) methods have to be used.

5.1.5 Correlation Method for Detection of Signals

A signal emanating from unknown interference source, traveled through two adjacent satellites separately, and monitored at the measurement sites with two receivers can be mathematically modeled as [34]:

$$x_1 (t) = s_1 (t) + n_1 (t) \tag{12}$$

$$x_2 (t) = \alpha s_1 (t+\tau) + n_2 (t) \tag{13}$$

Where $s_1(t)$ is assumed to be uncorrelated with the noises $n_1(t)$, and $n_2(t)$.

τ is the time difference between the signals received.

Various parameter estimation methods were proposed for estimating the value of τ, which are the general forms of cross-correlation function.

The block diagram of a correlation process is given in Fig. 5.1.6. [35]

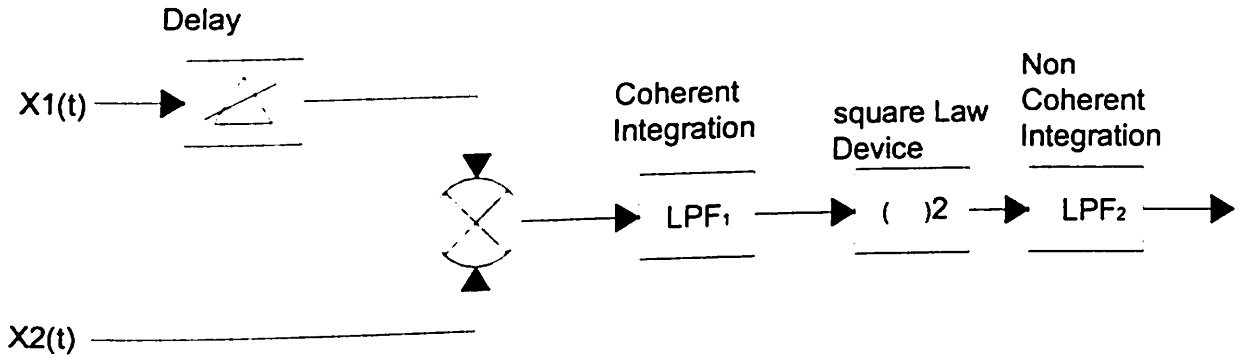


Fig. 5.1.6: Block Diagram of a Correlation Process

The Time Difference of Arrival (TDOA) of signals can be directly estimated by correlating the two incoming signals, coming through each of the adjacent satellites. The correlation results in a peak of the correlation function for the correct TDOA of value τ. The correlation technique is specially advantageous with the signals having unknown structures.

The generalization of the correlation function known as the Cross Ambiguity Function (CAF) is given by [36]:

$$A(\tau, f) = \int_0^T s_1(t) s_2^*(t-\tau) e^{-j2\pi ft} dt \qquad (14)$$

Where s_1 & s_2 = complex envelopes of two waveforms that have common component

τ = Time lag, or TDOA

f = Frequency offset, or FDOA

s_2^* Represents the complex conjugate of s_2

The absolute value of CAF $|A(\tau, f)|$ achieves its peak for values of τ and f for the actual values of TDOA and FDOA respectively. The integral is the Fourier transform of the product $s_1(t)s_2^*(t-\tau)$ over the time window t = 0 to T.

The CAF processing technique provides a means of accurately computing FDOA and TDOA in the presence of noise and interference signals. Implicit in this cross-correlation approach is that the time delay obtained is always an integer multiple of sampling interval. Hence, the accuracy of TDOA measurement through this technique will be high with higher sampling rate.

The output Signal to Noise Ratio (SNR) for the CAF computation is given by [36]:

$$\left(\frac{S}{N}\right)_o = \frac{2BT\left(\frac{S}{N}\right)_I^2}{K\left[1+\left(\frac{S}{N}\right)_I\left(1+\frac{1}{K}\right)\right]} \tag{15}$$

Where $\left(\frac{S}{N}\right)_o$ = Output SNR

$\left(\frac{S}{N}\right)_I$ = Input SNR

B = Channel noise bandwidth

T = Integration time

K = Input SNR of main channel÷Input SNR of adjacent channel

The term 2BT is called the Processing Gain, which is equal to number of sample points per channel while digitizing the signal. Hence, the sampling rate of the input signal determines the Processing Gains. An output SNR of 20 dB is required for a clear correlation, free of spurious correlations.

5.1.6 Digital Signal Processing for cross-correlation

If the signal processing for Cross-Correlation is carried out with digital data, the accuracy of compensating time delays to measure correlation improves greatly. Correlators with time delays whose accuracy depends only on the sampling time pulses, and with wide dynamic range can be implemented easily.

A simplified schematic diagram to perform correlation with two input signals is given in Fig. 5.1.7 [37]. The convolution signal in time domain is nothing but the product in the frequency domain [38], [39], [40], [41]. Hence, correlators can be implemented easily with digital spectral measurements. Correlators can be realized by measuring correlation of the spectrum samples of two signals as a function of time offset.

Spectral correlator design involves Fourier transformation of the signals before Cross-Correlation. For each antenna, both in-phase and quadrature components of each signal are sampled, as in sampling for a complex correlator. The samples then go to a special processor that performs a Fast Fourier transform (FFT) in which sequences of N samples emerge as N values of complex signal amplitudes. The phase in these output values is measured relative to the sampler clock. The complex amplitudes are then cross-correlated by pairs, and the time delay (or equivalent shifting of number of spectral samples) where the correlation peaks gives the value of the delay time between the two signals. This approach is chosen for implementing Cross-Correlation for investigation of interference cases, and a software is developed, which is described in section 5.2.4.

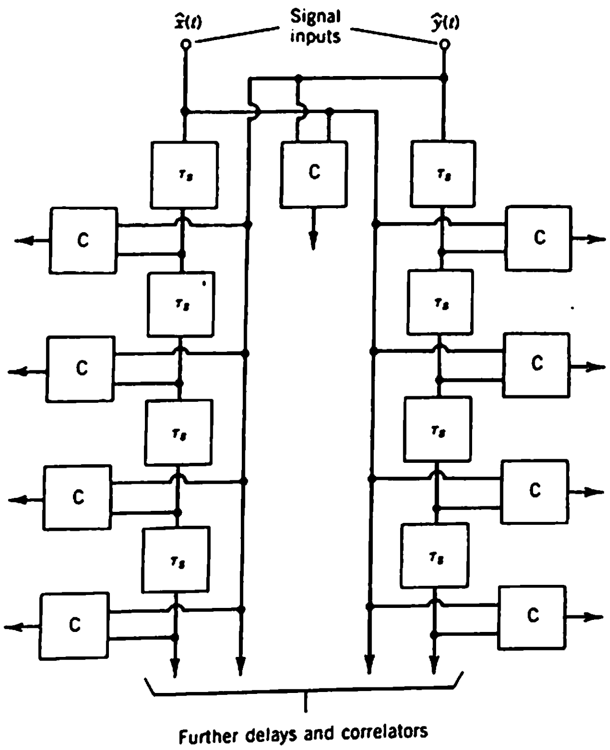


Fig. 5.1.7: Correlation process with two digital signals as inputs

5.1.7 Conditions for Successful Location of Interference Source

The TDOA and FDOA measurements as described above should be carried out with certain conditions met, for the location of the unknown transmitter with least uncertainty/ambiguity. They are:

- There should be two adjacent satellites operating in the same frequency band in which the unknown uplink transmitter is radiating the signals.
- The position of the two spacecrafts relative to the measurement station should be known precisely.
- The differential time delay through the two paths should be less than 1/f (where f is the frequency of the signal) to identify the location of the unknown transmitter unambiguously.
- The TDOA can be measured successfully on the modulated signals by measuring the differential time delay of some unique portion of the waveform. But, the measurement of TDOA on CW signals is very difficult.

- The measurement of FDOA is essentially range rate measurement over a time. If there is no motion then the measurement is not possible; the greater the motion, the more accurate results will be obtained. Hence, the estimate of emitter location is extremely sensitive to the relative motion of the two adjacent satellites in the GSO. If the two adjacent satellites are well controlled with respect to East-West and North-South Station Keeping, the FDOA measurement will be difficult.

- The FDOA measurement requires precise satellite ephemeris data at the time of measurement. If the adjacent satellite used for the TDOA and FDOA measurements is an inclined orbit satellite, the knowledge of ephemeris is very important. Otherwise the RMS location error (from the measured values of TDOA and FDOA) may tend to infinity twice per day.

  If the two adjacent satellites do not belong to the same Operator, it is difficult to get the accurate satellite ephemeris data.

- The signals from the two paths have to be correlated together with different time and frequency offsets until a peak response in the correlation power is obtained. If correlation is not possible, alternatively, the signal may have to be synthesized from the frequency domain to time domain, which is a much more difficult problem.

- The combined TDOA and FDOA measurements may have to be made at times usually separated by several hours to yield good result for the location of source of interference.

- The small drifts in the Local Oscillators of the satellites will set the ultimate limit on the accuracy of measured FDOA.

- It is difficult to assess whether the signal traveling through the adjacent satellite will be detectable or not – i.e. whether the SNR will be sufficient for a proper correlation / detection. Many times, through the knowledge of the environment and the measurement terminals employed, it will be possible to infer the limit to the EIRP of unknown interference radiation.

The total measurement gain through the adjacent satellite, to which the signal from unknown transmitter reaches through the side lobe of the transmitting antenna, should be sufficient enough for detection of the signal. Hence, high sensitivity equipment is required for the adjacent satellite downlink.

For accurate TDOA the signals should be processed in the maximum available bandwidth, and for accurate FDOA the signals have to be processed in the maximum available time. These parameters set the value of Processing Gain (PG) to be decided for the measurement.

Annexure-1 gives a sample calculation of the relative gains of the antenna of the interference source. This calculation is included only to indicate the difference in the uplink level of the interference signal reaching the two satellites. The following assumptions are used in the sample calculation:

- A station located at 143 deg E longitude, 13 deg N latitude is assumed to be radiating. (One station around this location interfered with one of the satellites earlier).
- The station radiates in C-band with an antenna which meets ITU 580-5 recommendations for the off-axis antenna gain. In the actual case of interference, the station radiated radar signals in C-band.
- The signals from this station reach two adjacent satellites. In the actual case the interference was detected using two adjacent satellites located at 83 deg E and 78.5 deg E.

In the above case the off-axis antenna pattern difference towards the adjacent satellite is 5 dB. This is relatively a better situation for interference detection. In many cases the off-axis antenna gain difference may require high Processing Gain to be employed at the measurement site.

generated in the measurement setup. This may not be possible sometimes, if the adjacent satellite is occupied at the frequency of interest.

- The frequency hopping interference sources (like the military radars which keep changing the RF frequency randomly) pose a special problem for the measurements described above. The FDOA measurements fail unless the correlation time is much faster than the interval of frequency hopping.

5.1.8 The Accuracies of Location of Interference Source

The accuracies achievable in the TDOA and FDOA methods are also analyzed in some published papers [32], [35], [42].

(A) Table-5.1.1 identifies the error sources to be considered in the TDOA and FDOA measurements, to arrive at RMS errors.

Table-5.1.1: Errors sources in TDOA & FDOA measurements

Error sources for TDOA measurement	Error sources for FDOA measurement
Delay residual Thermal noise Ionospheric noise Orbit position error	LO residual Reference residual Thermal noise Ionospheric noise Orbit velocity error Orbit position error

RMS errors, as computed with the above listed sources, have to be converted into RMS Geo-location error. Usually, the result of the combined TDOA-FDOA measurement will be an ellipse on the surface of the Earth with the location of the unknown source lying within the ellipse.

Usually, the TDOA errors are anticipated to be small of the order of 10 to 20 ns. These errors are negligible compared with the geo-location errors due to frequency measurements. The geo-location errors due the errors in the FDOA measurement are much larger compared to TDOA errors.

(B) The factors contributing to the errors in FDOA are:

- Propagation
- Satellite translation oscillators
- Satellite relative velocity with respect to the other satellite
- Oscillators used for earth station down-converters

The large errors in the FDOA are primarily caused by the limitation in the accuracy of satellite ephemeris information available, and also due primarily to very low inclination of the well-maintained satellite. If one of the satellites in a pair (receiving the interference) is in an inclined orbit, an order of improvement in the location accuracy is possible.

Minimum achievable error is dominated by the errors of the satellite ephemeris, which is due to the errors in the ranging and prediction of satellite velocities. Two techniques can be used to refine ephemeris information:

- To perform geo-location on sources at known locations to derive corrections to the ephemeris.

- To use the initial geo-location of sources to find a closer source to the unknown source as a reference, and make FDOA measurement on that reference signal.

The main disadvantage of the second method is the need for a source of known location in the vicinity of unknown source.

(C) The typical errors quoted for the case of experiment involving Eutelsat satellites are as below [42]:

- The mean error of location due to errors in the FDOA is 69.3 km, which is primarily caused by the accuracy of ephemeris information.

- The mean error of location due to errors in the TDOA is 4.85 km, when measured in a sample bandwidth of 300 KHz.

Even after using a reference signal for canceling common errors, the residual errors estimated for EUTELSAT experiments are:

▪ For TDOA	Of the order of 0.1 µs
▪ For FDOA	Of the order of 14 mHz

The gradients of the TDOA and FDOA in this experiment were 5 km / µs, and 1 km / mHz. Thus the FDOA error dominates the final geo-location ellipses. The FDOA accuracy of 14 mHz translates to frequency stability of 2 x 10^{-12} at 6 GHz.

(D) In the case of INSAT system the accuracies are as below:

▪ Short-term stability of the onboard transponders over a day (IOT results).	5 x 10^{-8}
▪ The accuracy of satellite position estimate	5 km (3 σ)
▪ Accuracy of satellite velocity estimate	100 mm /s

The satellite position accuracy is expected to improve to around 200m (3 σ) by implementing two-station ranging in near future.

One of the biggest problems in carrying out geo-location using FDOA is the knowledge of satellite ephemeris of the adjacent satellite, which does not belong to the same satellite Operator. The only source is the NASA's Orbital Two Line Elements (TLEs), which are not very accurate.

5.2 Experimental Tools

The Communication Satellites of ISRO are located at six orbital slots in the Geo-Stationary Orbit (GSO). The communication transponders operate in different frequency bands like C, Ext. C, Ku, and MSS (CxS and SxC).

The different orbital locations and the frequency bands used for communications require different antennae to receive signals from each of the satellites. The satellites being in GSO at an altitude of 35,786 km, received signal strength at the ground station is very low, of the order of −130 dBm. Hence, a high gain ground antenna is required to receive and analyse the signals (i.e. antennae with high G/T). The antennae should also be capable of being driven in azimuth and elevation to point towards satellite of interest. After pointing towards the satellite, the antenna should be capable of auto-tracking the carrier.

MCF has various antennae to cater to different frequency bands. Two types of antennae are deployed – one type capable of 360 deg azimuth movement which are called Full Motion Antennae (FMA). These antennae are used during the orbit raising operations, and satellite relocation operations. The antennae used to receive signal from well-controlled GSO satellites need to have only limited capability of movement in the azimuth angle – usually 120 deg. These antennae are called Limited Motion Antennae (LMA).

The signals received by antennae in microwave frequency bands are usually down-converted to an intermediate frequency (IF) using down-converters. Similarly, the signals to be up-linked or signals to be injected at the LNA point of antennae, are generated at 70 MHz IF frequencies, and they need to be up-converted to the appropriate frequency band and amplified to the levels required. The up-converters and the High Power Amplifiers achieve these functions.

Most of the interference measurements are carried out using either the Spectrum Analyzers or specialized equipment at the IF level. Wherever required, these signals are demodulated to Base-band level for further investigation. Spectrum Analyzers and a specialized equipment called Telecom Carrier Analyzer (TCA) are used at the IF level for the above purpose.

MCF is specially equipped, for its regular satellite maintenance operations, with Antennae in different frequency bands, Up-converters, Down-converters, Spectrum Analyzers, Modulator, and Demodulators. The TCA was specially configured for

Table-5.2.1: Important specifications of the different equipments used in the experiments/measurements during Investigation of Interference cases

Equipments used for Investigation	Important Parameters relevant to Interference	Value
11m Ext-C Band Antenna	Band of operation	TX : 6.7- 7.0 GHz RX : 4.5-4.8 GHz
	Maximum EIRP	85 dBW
	G/T	31.8 dB/deg K
	XPD(LP)	33 dB
	Tracking	Step track system
7.2m C Band Antenna	Band of operation	TX : 5.8- 6.4 GHz RX : 3.7-4.2 GHz
	Maximum EIRP	82 dBW
	G/T	28 dB/deg K
	XPD(LP)	33 dB
	Tracking	Step track system
Low Noise Amplifier	Noise temperature	45 deg K
	Gain	60 dB
	Gain Flatness	<0.01 dB/MHz
LNBC	Input Frequency	3.7 to 4.2 GHz 4.5 to 4.8 GHz
	Output Frequency	950 to 1450 MHz
	Gain	50 dB
	Noise Temperature	25 deg K
Up converter	Frequency range	70 MHz to 5.8-6.4 GHz
	Step Size	1KHz
	Gain	35 dB
	Instantaneous bandwidth	40 MHz
Down Converter	Frequency range	3.7-4.2 GHz to 70 MHz
	Step Size	1KHz
	Gain	45 dB
	Instantaneous bandwidth	40 MHz
High Power Amplifier	Frequency range	5.8-6.4 GHz
	Number of channels	24
	Instantaneous bandwidth	40 MHz
	Gain	60 dB
	Rated output Power	2.5 KW
Integrated Receiver Decoder	Input Frequency	950 to 2150 MHz
	Signal level	-65 dBm to –25 dBm
	Symbol rate	1 to 45 M symbols/s
	Demodulation	QPSK
	Decoder Input	DVB-ASI input
	FEC decoder	Convolution code rates 1/2, 2/3, 3/4,5/6 and 7/8
	Decoding	MPEG 2 4 : 2 : 0
	Video	Composite video
	Audio	Analog and Digital

Spectrum Analyzer	Frequency	9 KHz to 22 GHz
	Resolution Bandwidth	10 Hz to 10 MHz
	Frequency Span	0, 10 Hz to 20 GHz
	Video bandwidth	1 Hz to 10 MHz
	Sweep time	2.5 ms to 16000 s
	Frequency Counter resolution	1Hz to 10 KHz
Signal Generator	Frequency	10 MHz to 20 GHz
	Frequency Stability	1×10^{-9}/ day
	Calibrated output	-110 to +15 dBm
	Internal Modulation	AM, FM, PM and Pulse modulation
	Frequency Resolution	1 Hz
	Level Resolution	0.01 dB

5.2.2 The Telecom Carrier Analyzer (TCA)

A standard equipment to store the database and monitor the satellite communication traffic is called Telecom Carrier Analyzer (TCA). Usually, this standard equipment has only one input at the microwave frequency. An equipment with two inputs to carry out TDOA / FDOA measurements was required for investigations of interference cases.

One of the interference localization methods is the Time Difference of Arrival (TDOA) and Frequency Difference of Arrival (FDOA) measurements between two signals translated through two adjacent satellites. Hence, the equipment to facilitate TDOA / FDOA measurements should have two inputs. The accuracy of the TDOA / FDOA measurements depend on sampling rate and the bandwidth. The higher the sampling rate, better will be accuracy. Some of the interference can occupy a large bandwidth in a transponder. Hence, the equipment used for the measurement should handle bandwidth of one transponder completely i.e., 36 MHz.

The standard TCA does not have interference localization capability. However, it was considered that use of TCA and development of interference localization software outside of this equipment as a cost-effective solution. The localization software was planned to be developed in the form of a special PC-based software, which has to run in a separate PC. Hence, the digitized data of the two input channels should be available from TCA on a serial port for acquisition into an outside PC.

Based on the above specific requirements, the TCA was procured for the following specific features:

- Should handle two RF inputs.
- Both inputs should be at the down-converter output frequency – i.e., 70 MHz.
- Both signals should be digitized at high sampling rate within the TCA.
- All the standard features of TCA, like carrier measurement (power, C/N etc.), spectrum displays, unauthorized carrier detection should be available.
- The detection of carriers embedded within an occupied spectrum, which is also a standard feature of TCA should be available.
- The digitized data of both channels should be made available to an outside PC through TCP/IP protocol.

The configuration of TCA is given in Fig. 5.2.2.

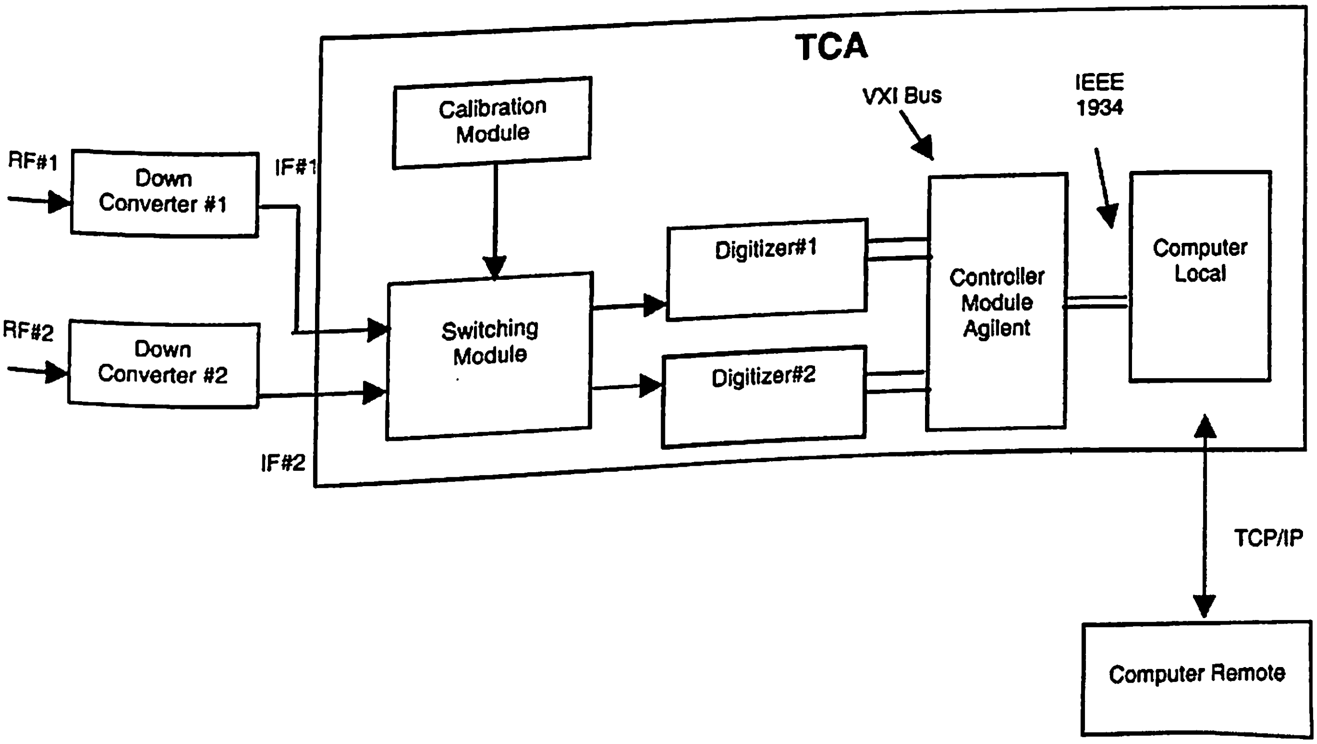


Fig. 5.2.2: Configuration of TCA

The other specific features of the configuration are as below:

- Single Calibration Module is used for performing frequency and power calibration of digitizer#1 and digitizer#2
- Switching unit is used to switch calibration module and IF inputs between two digitizers.
- Controller Module connects digitizer#1, digitizer#2, calibration module, and switching unit over VXI bus and provide IEEE interface to PC.
- Down Converters can be controlled by Local/Remote PC over RS232 interface.
- Remote PC can acquire data over TCP/IP.

Specifications of TCA [43]

Digitizer-

- Two digitizers
- Resolution: 12bit
- 90dB sfdr (Spurious free dynamic range)
- 95 M samples/sec
- I/P level 30dBm to −111dBm
- Input Freq 70 MHz (IF)
- Input BW 36 MHz

Measurement Accuracy-

- Power: +/- 0.2 dB
- C/N0: +/- 0.3 dB
- Freq: +/- 1% of defined BW

  - Bandwidth: +/- 1% of defined BW

Signal Acquisition and Processing-

  - Up to 200 million of acquired data points
  - FFT processing

Measurement Performances-

  - Power: up to 50 carriers/sec
  - Full monitoring: up to 25 carriers/sec

Principal Capabilities of TCA-

- RF Measurements of single or set of carriers
  - Carrier power
  - Carrier to noise ratios ($C/N, C/N_0, E_b/N_0$ for digital ones)
  - Carrier occupied BW
  - Carrier center frequency
- Spectrum Trace Acquisition.
- N_0 (Noise density) Measurement
- I&Q (Raw) Data acquisition.
- Analog Demodulation(AM/FM/PM) and Digital demodulation
- Carrier Detection over a defined BW or inside a defined carrier
- Auto calibration of digitizers.
- External TCP/IP Interface for Remote use.

5.2.3 Experiments using TCA

Studies were carried out to experimentally demonstrate the specific feature of TCA to detect interference embedded within an occupied bandwidth:

A signal at 70 MHz, after combining with an interference signal at a frequency which was within the occupied bandwidth, was given to the Ch #1 of TCA. The TCA was configured to detect the embedded interference, and to take spectrum plot showing the interference (Fig. 5.2.3).

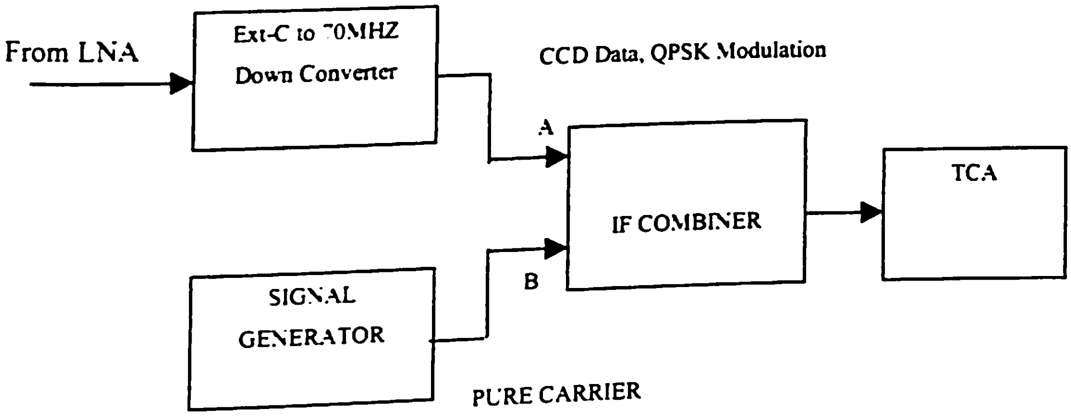


Fig. 5.2.3: Test configuration for detection of embedded carrier

The CCD data from one of the satellites was received in the Extended C-band frequency of 4508.5 MHz. The bit rate of the data is 1228.75 kbps, and is QPSK modulated. This signal was down-converted to 70 MHz and given to Ch #1 of TCA. The normal spectrum of this signal occupied about 5 MHz. The main lobe of the spectrum occupied ±0.5 MHz.

Another pure carrier is selected to be within the main lobe of the occupied spectrum at 70.3 MHz. This signal at a level of –70 dBm was combined with the CCD data at IF level before inputting to TCA.

The objective of the test was to detect the interference signal, from the total spectrum, and to take separate spectrum plots of the interference and the signal.

Principle:

This involves a carrier demodulation. Carriers defined in the currently loaded carrier set can be demodulated (if clearly defined) to extract the "error vector spectrum", which is the difference between the received spectrum and a reference spectrum, which is re-modulated using recovered bits and the defined modulation characteristics. Error vector spectrum is then analyzed by detecting signal level which is above specified threshold parameters for detection inside a carrier.

Parameters to be configured:

- Known carrier parameters: Frequency, Bandwidth, Type of modulation and for Digital ones Bit rate, FEC, Reed Solomon, Overhead etc.
- Threshold: This value is the absolute power that is used for carrier detection. If Error vector spectrum bin goes through this value, the carrier is analyzed to determine all its RF parameters. User can enter this value. In this case same value is used for the whole frequency range. If auto is selected the threshold is automatically calculated from the N0 (Noise Density) values previously measured or entered. So noise calibration is required before this measurement.
- Resolution: this value is the resolution bandwidth of the acquired spectrum over which the detection is performed. This threshold can be entered by user or set to Auto. In the Auto case, the resolution is automatically calculated to be around 0.1% of the channel bandwidth.

Output Plots:

The figures given below, clearly identified the embedded interference:

Fig. 5.2.4: The spectrum plot of Combined Signal & Embedded Interference

Fig. 5.2.5: The spectrum plot of Detected known Carrier & Detected Interference Signal.

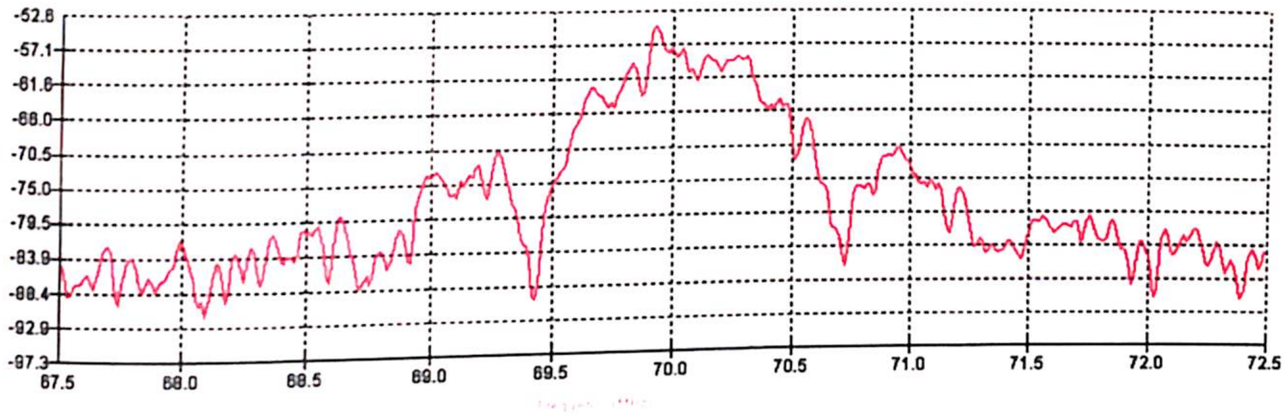


Fig. 5.2.4: The spectrum plot of Combined Signal & Embedded Interference

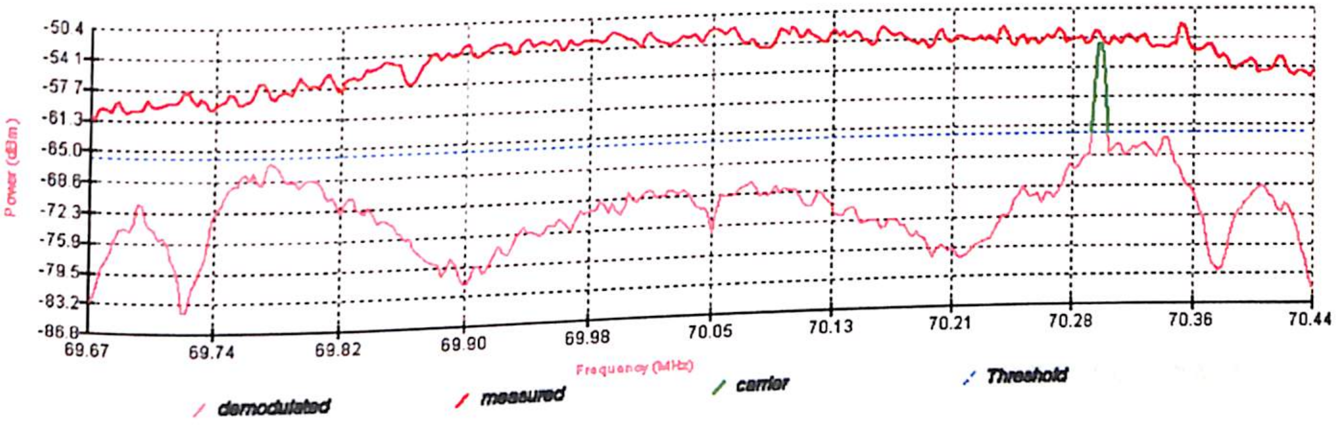


Fig. 5.2.5: The spectrum plot of Detected known Carrier & Detected Interference Signal.

5.2.4 Implementation of Cross-correlation using TCA

The Cross-Correlation of signals in digital domain, described in section 5.1.6, was implemented using TCA. The procedure is as below:

(A). TCA digitizes the signal at 70 MHz with a sampling rate appropriate for the signal bandwidth. The spectral bandwidth and the sampling frequency can be selected depending upon the type of signal being received. FFT is carried out on the samples.

(B). TCA provides each sample as I and Q components.

(C). The amplitude of each spectral sample is computed as $A=\sqrt{I^2+Q^2}$.

(D). An array is formed with the amplitudes A1 and A2 from the spectral samples of the two signals.

(E). The correlation output is computed using the formula:

$$H = \sum_{j=1}^{j=M\ 2} (A1_j.A2_j) + (A1_j.A2_{j+1}) + (A1_j.A2_{j+2}) \ldots\ldots \qquad \text{and}$$

$$H = \sum_{j=-1}^{j=-M\ 2} (A1_j.A2_j) + (A1_{j+1}.A2_j) + (A1_{j+2}.A2_j) \ldots\ldots$$

Where M = maximum number of samples.

The above equations compute the sum of the product of spectral samples with one sample shift for every value of j, with second signal being shifted one sample at a time with respect to the first signal, and then repeating the same for the first signal.

(F). The plot of j Vs correlation output H will peak for a particular value of j, which when multiplied with the sampling period / number of samples offset gives the time delay τ between the signals.

The value of τ thus found out will give the difference of time delay between the two signals given to the two input ports of TCA.

Fig. 5.2.6 gives flowchart of the software developed for acquisition of data from TCA into PC. Fig. 5.2.7 gives flowchart for cross-correlation of two sets of data acquired from TCA.

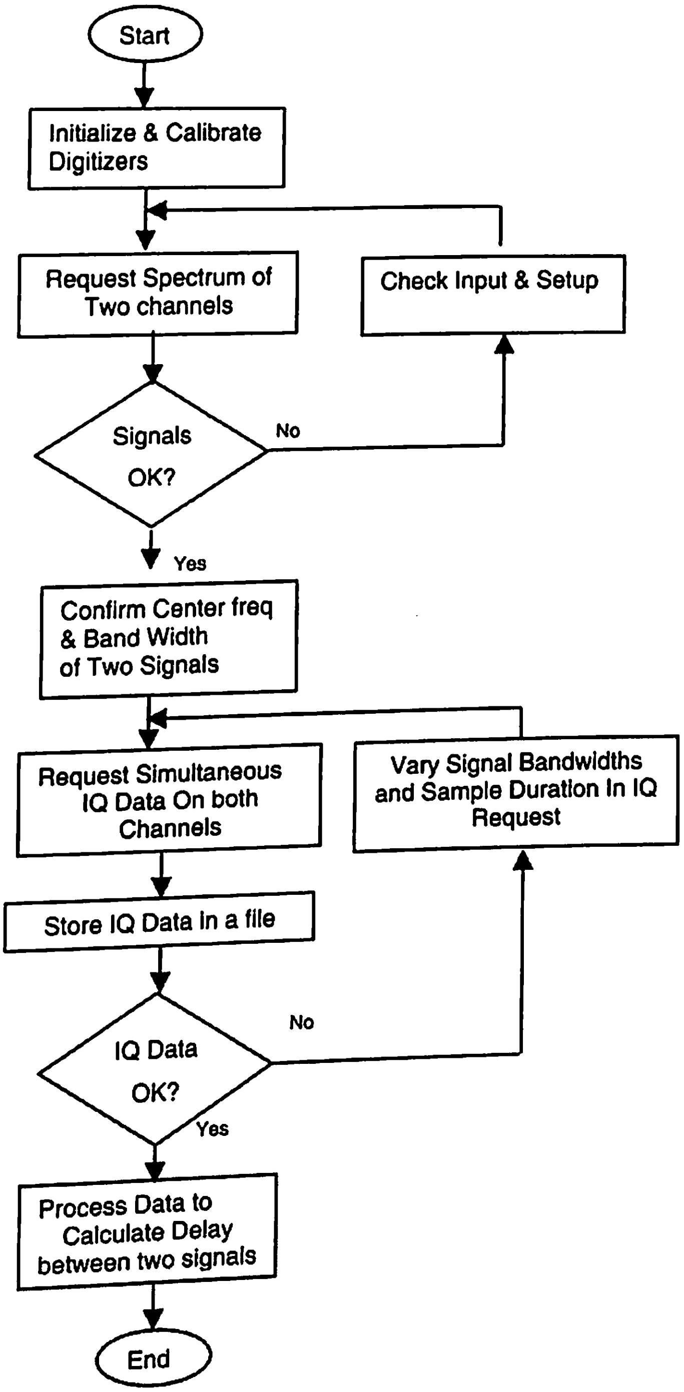


Fig. 5.2.6: Flowchart for data acquisition from TCA

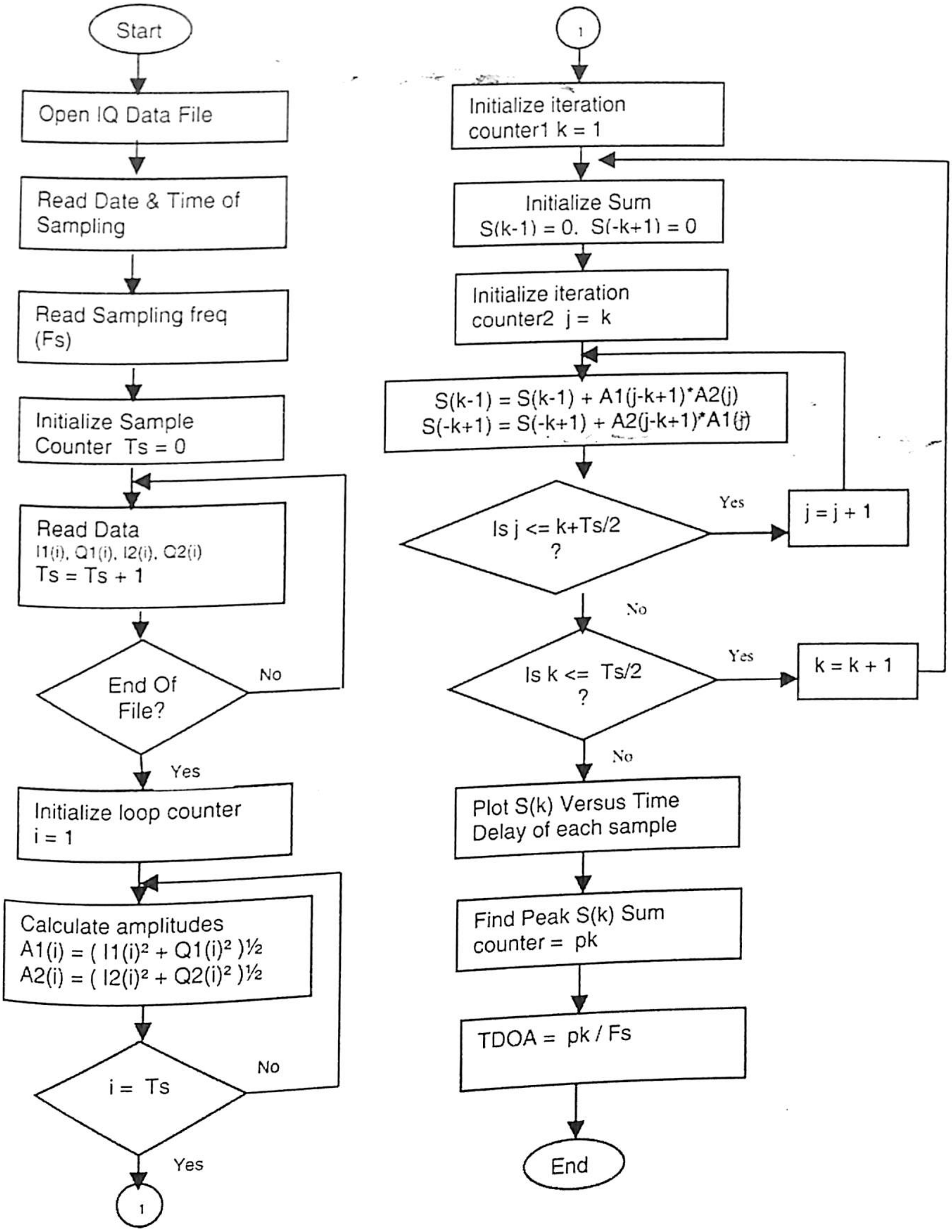


Fig. 5.2.7: Flowchart for cross-correlation

Experimental demonstration of cross-correlation

A measurement was carried out to verify the Cross-Correlation in the spectral domain between two signals, as designed in the TCA. The test setup is given in Fig. 5.2.8 and Fig. 5.2.9.

A pulse modulated signal at 70 MHz was used, first with zero delay and then with a delay of 1.156 micro seconds. The delay was introduced by passing the signal through a filter.

The characteristics of the signal and sampling parameters used were:

Modulation : Pulse modulation

Pulse width = 2 micro seconds

Pulse repetition rate = 2.5 KHz (PRT of 400 msec)

Bandwidth = 3 MHz

Sampling frequency = 5.94 MHz

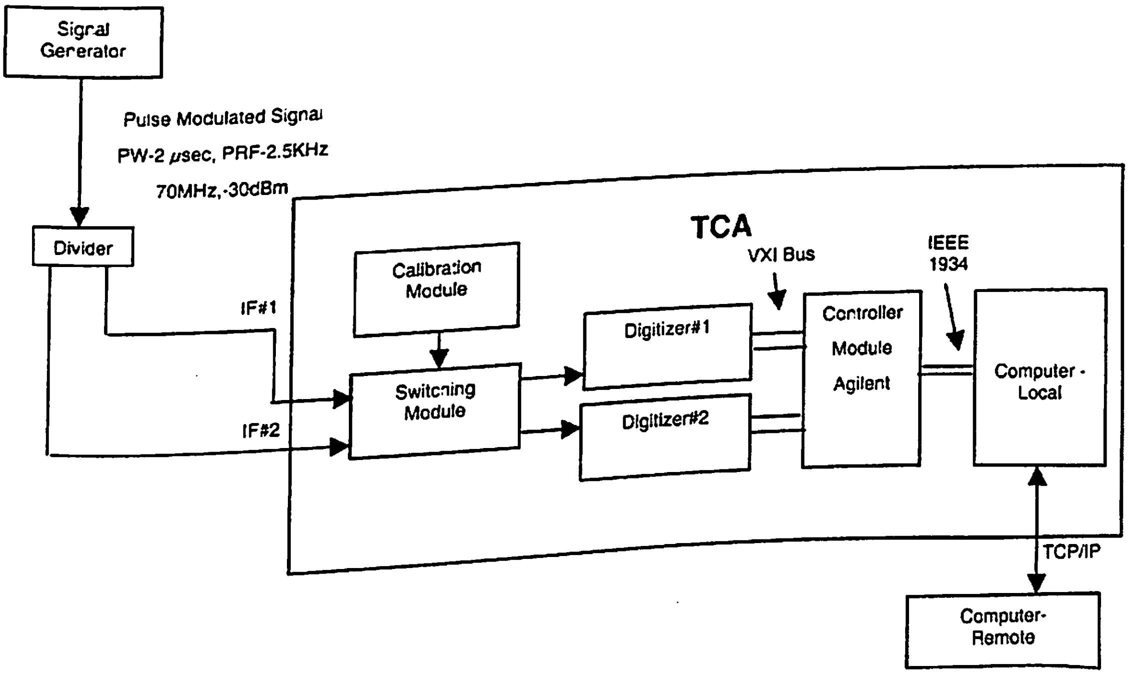


Fig. 5.2.8: Test Set-up-1

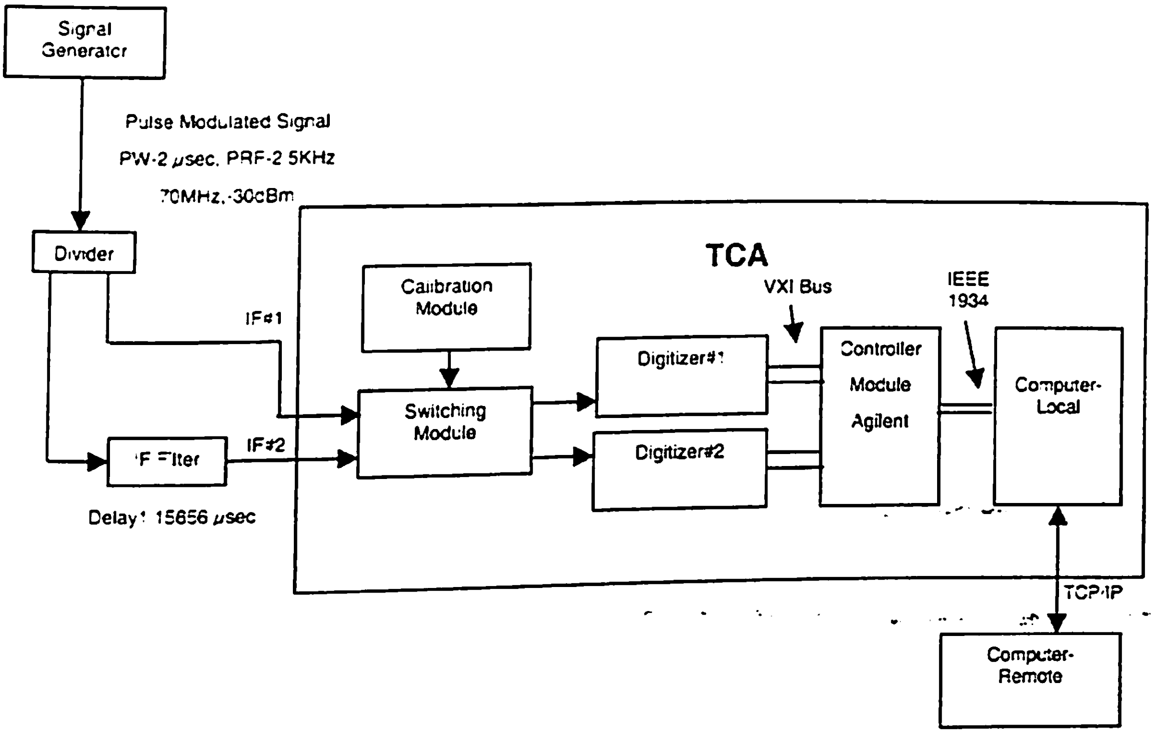


Fig. 5.2.9: Test Set-up-2

Results

The figures, which follow in this section, give the results. The details are:

Fig. 5.2.10: Correlation plot for pulse modulated signals (time delay = 0 nsec)

Fig. 5.2.11: Correlation plot for pulse modulated signals (time delay = 1.179 µ sec)

Fig. 5.2.12: Filter delay measured in network analyzer

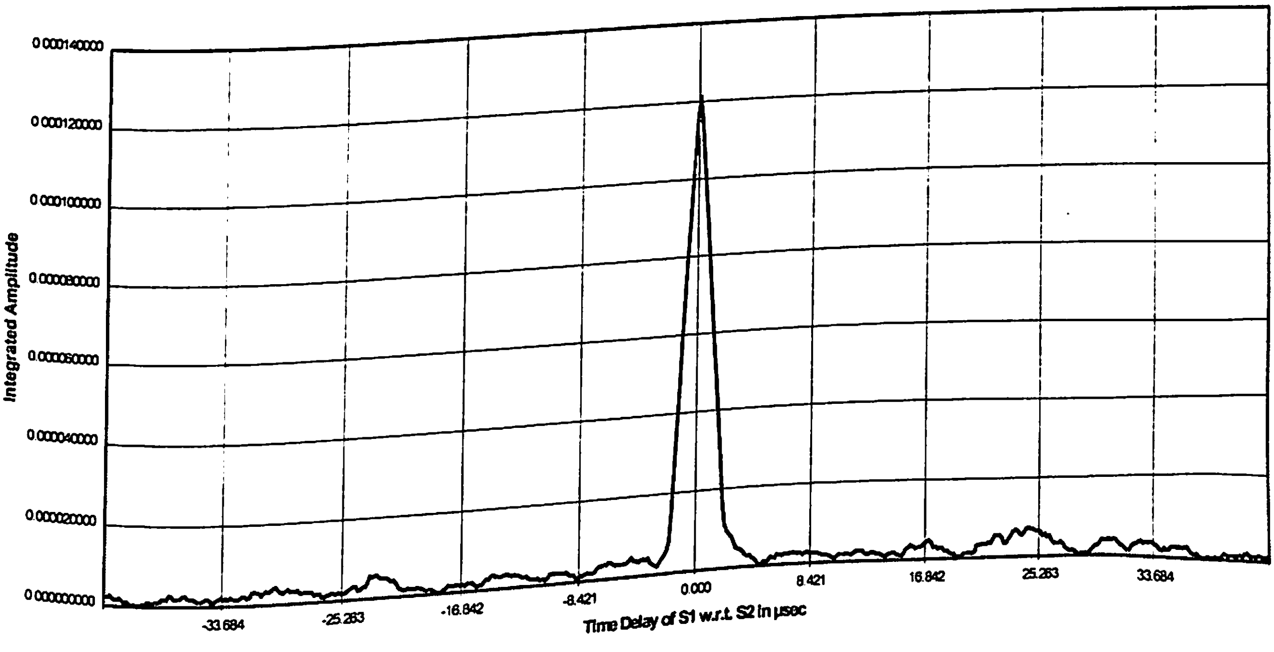


Fig. 5.2.10: Correlation Plot (TDOA=0 nsec) Date: 11/9 Time: 05:35:09.47

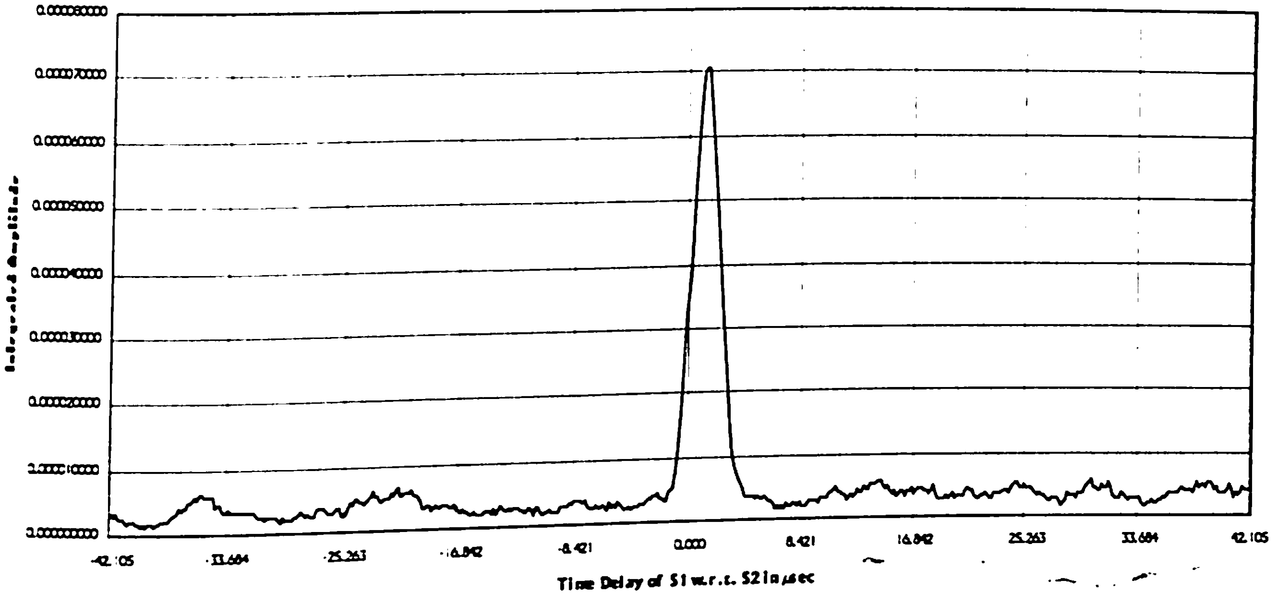


Fig. 5.2.11: Correlation Plot (TDOA=1.178947 μ sec) Date: 11/18 Time: 05:35:09.47

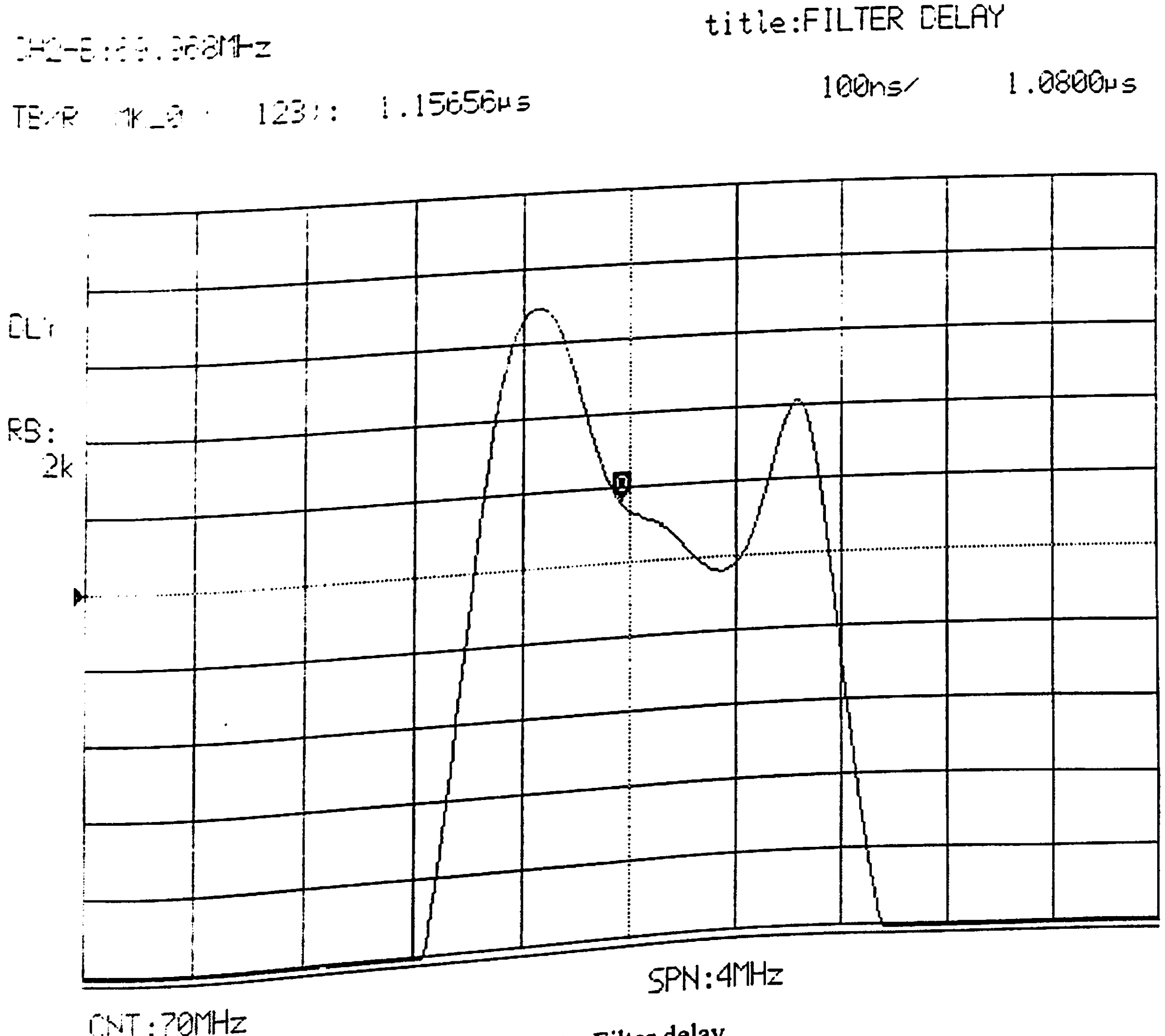


Fig. 5.2.12: Filter delay

Summary of initial experiments with TCA

1. Tests were designed and the capability of TCA to detect an interference embedded in the occupied bandwidth was verified.
2. A software was developed to acquire TCA signals into an external PC for processing.
3. A software was designed to implement Cross-Correlation algorithms.
4. Tests were designed with Telecom Carrier Analyzer (TCA) equipment and an external PC to demonstrate Cross-Correlation between two input signals.
5. The time delays measured through Cross-Correlation matched very well with the independently measured delay of the delay line (filter). The difference in time delay was found to be 0.022 microseconds for the pulse modulated signal, which is 1.9% of the value of the time delay measured.

5.3 The equipments used in the experiments

The photographs of antennae and other equipments used as experimental tools are given as Fig. 5.3.1 to 5.3.9 in this section. The IRD and video monitor shown in Fig. 5.3.7 were specially used to demodulate and see the video interference / signals experienced.

Fig. 5.3.1: Ext. C-band antenna (11 m dia)

Fig. 5.3.2: Limited Motion 7.2m antenna

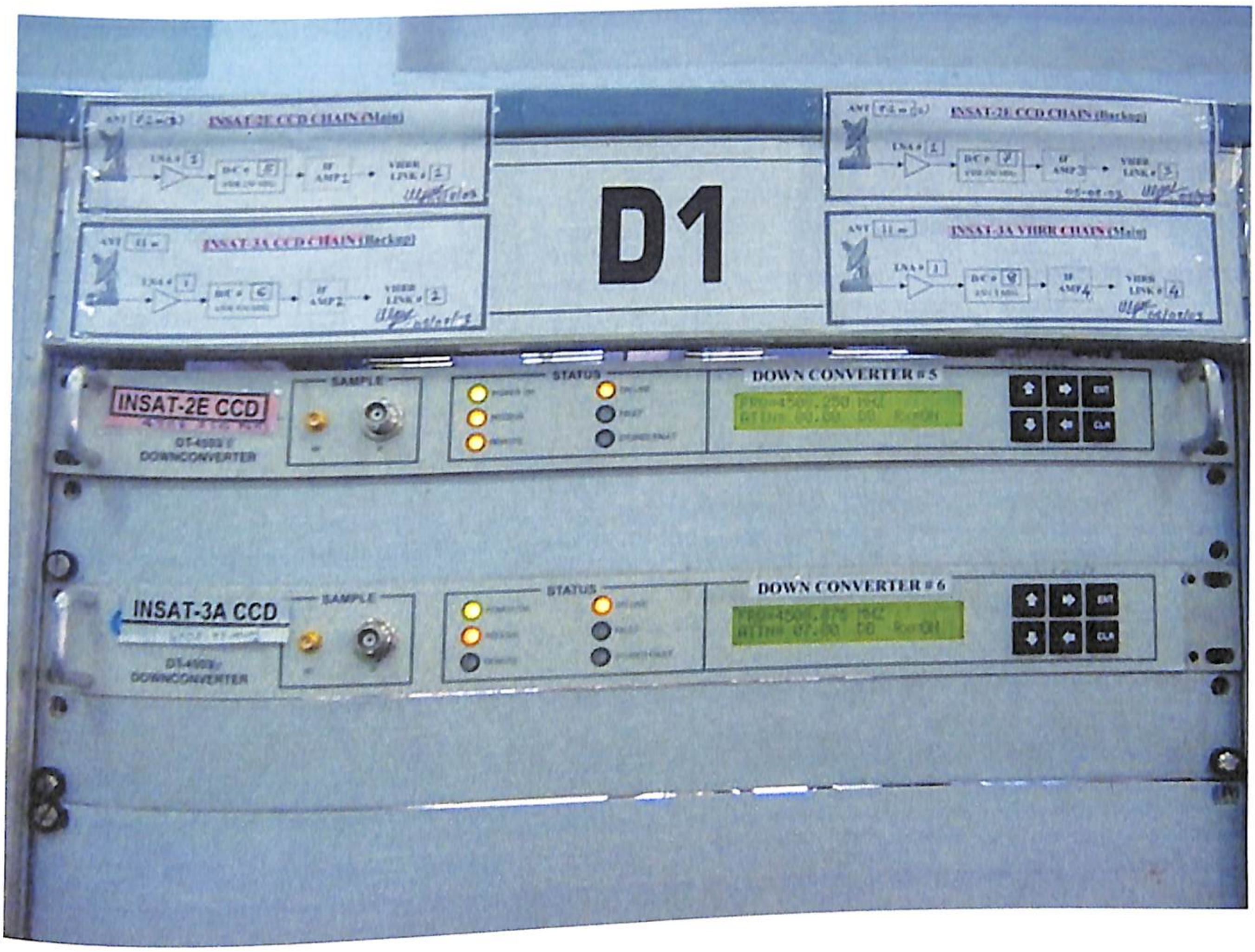


Fig. 5.3.3: Down Converter

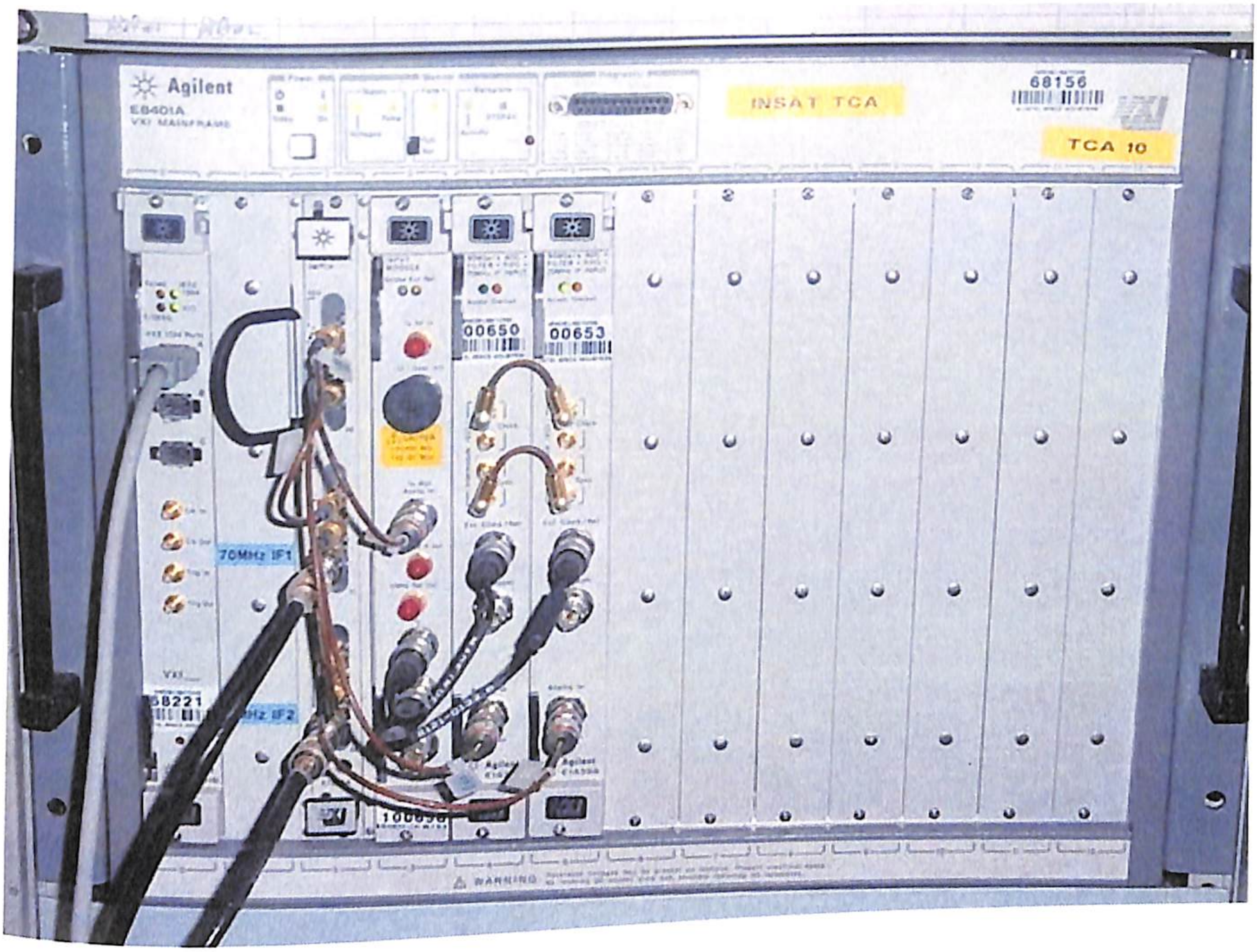


Fig. 5.3.4: Telecom Carrier Analyzer (TCA)

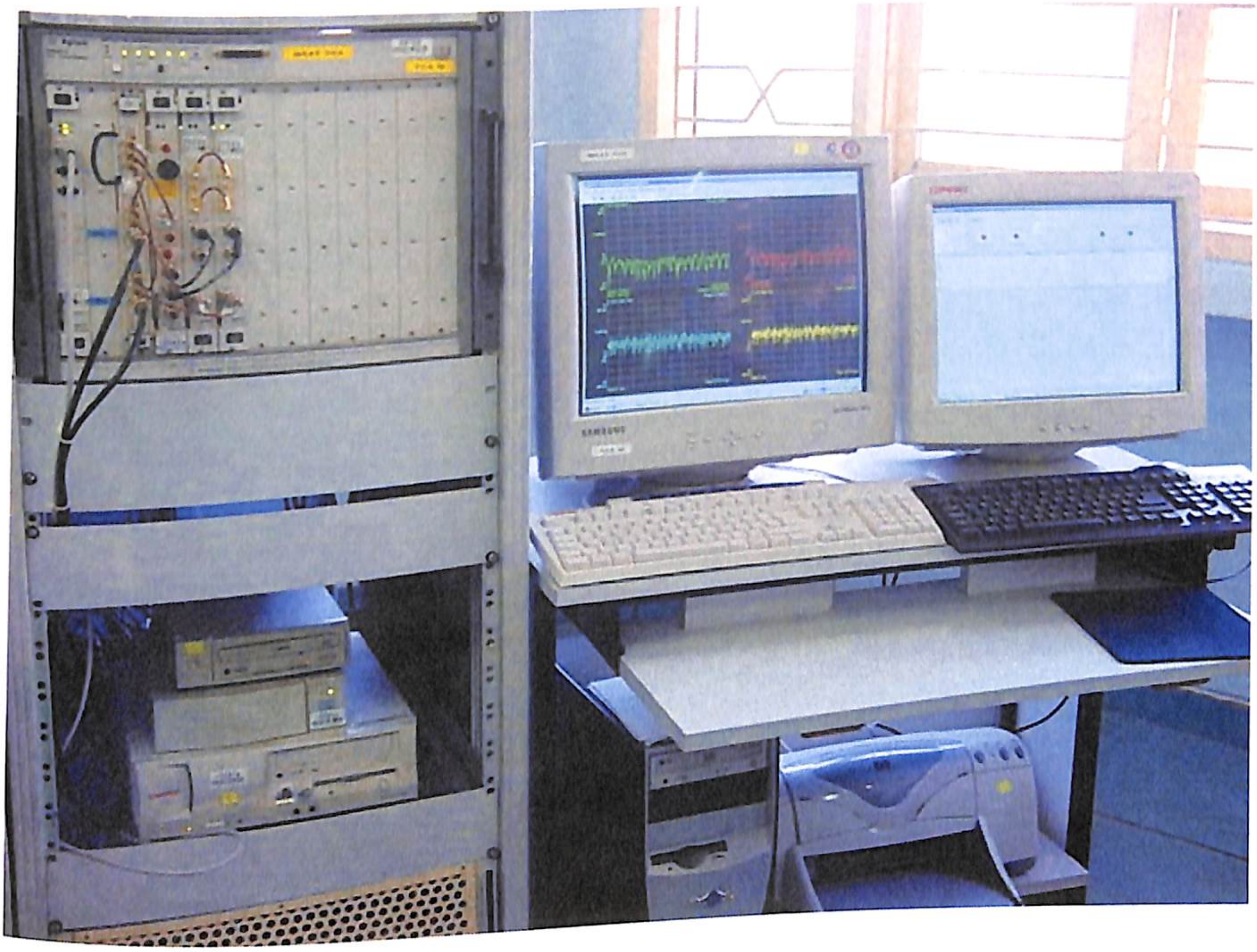


Fig. 5.3.5: TCA with remote PC

Fig. 5.3.6: Spectrum Analyzer

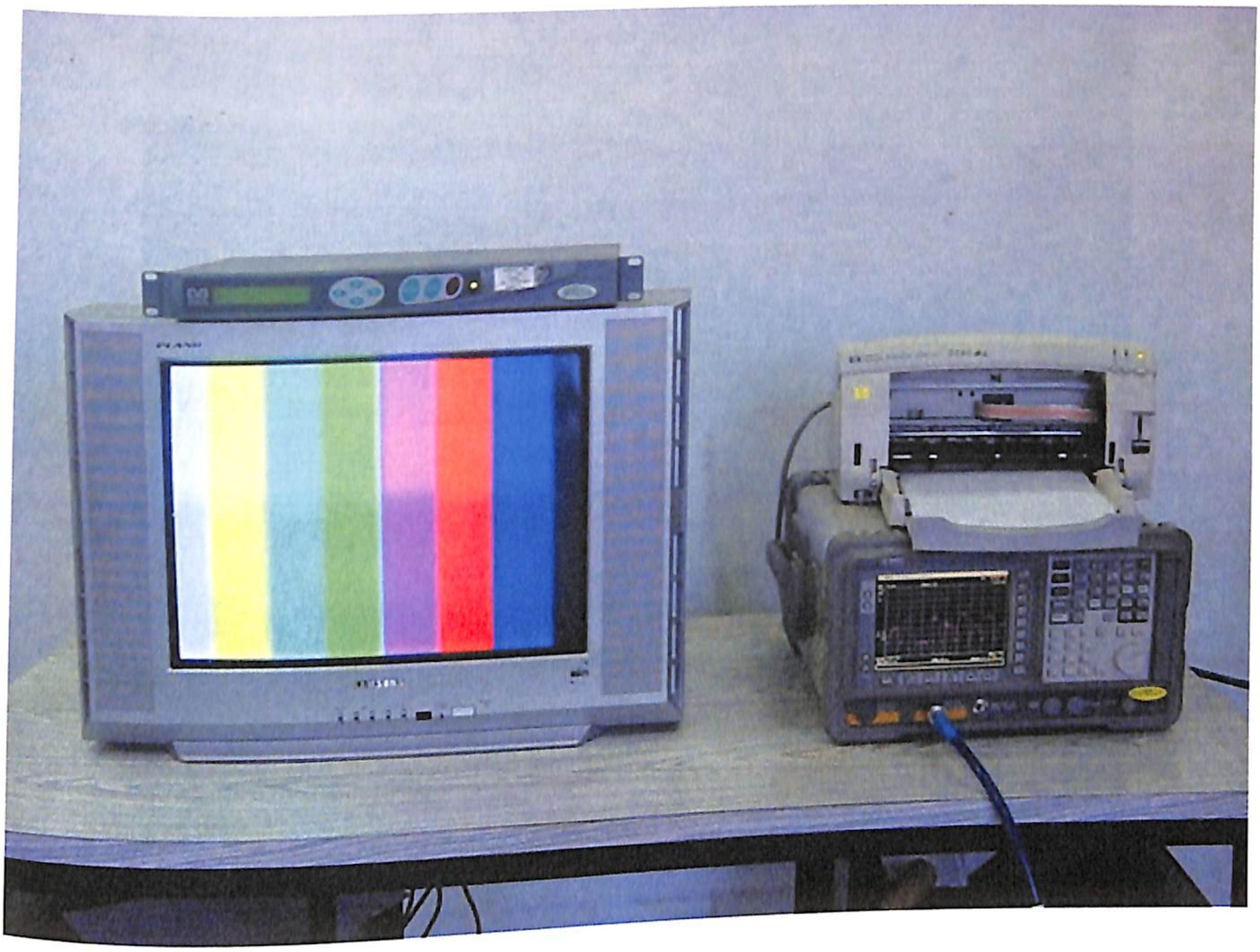


Fig. 5.3.7: Spectrum Analyzer, IRD and Video Monitor for detection video interference signals

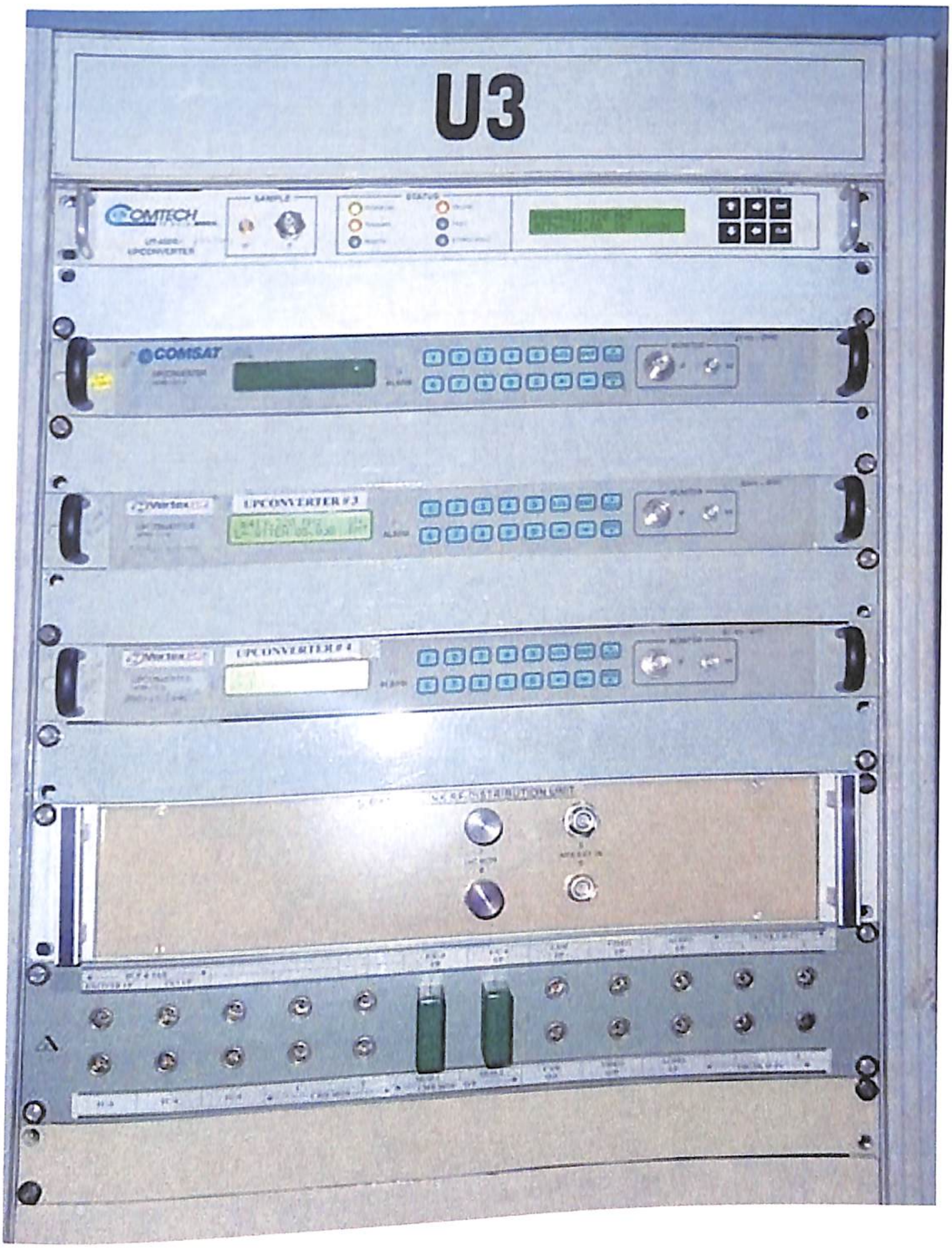


Fig. 5.3.8: Up-converters

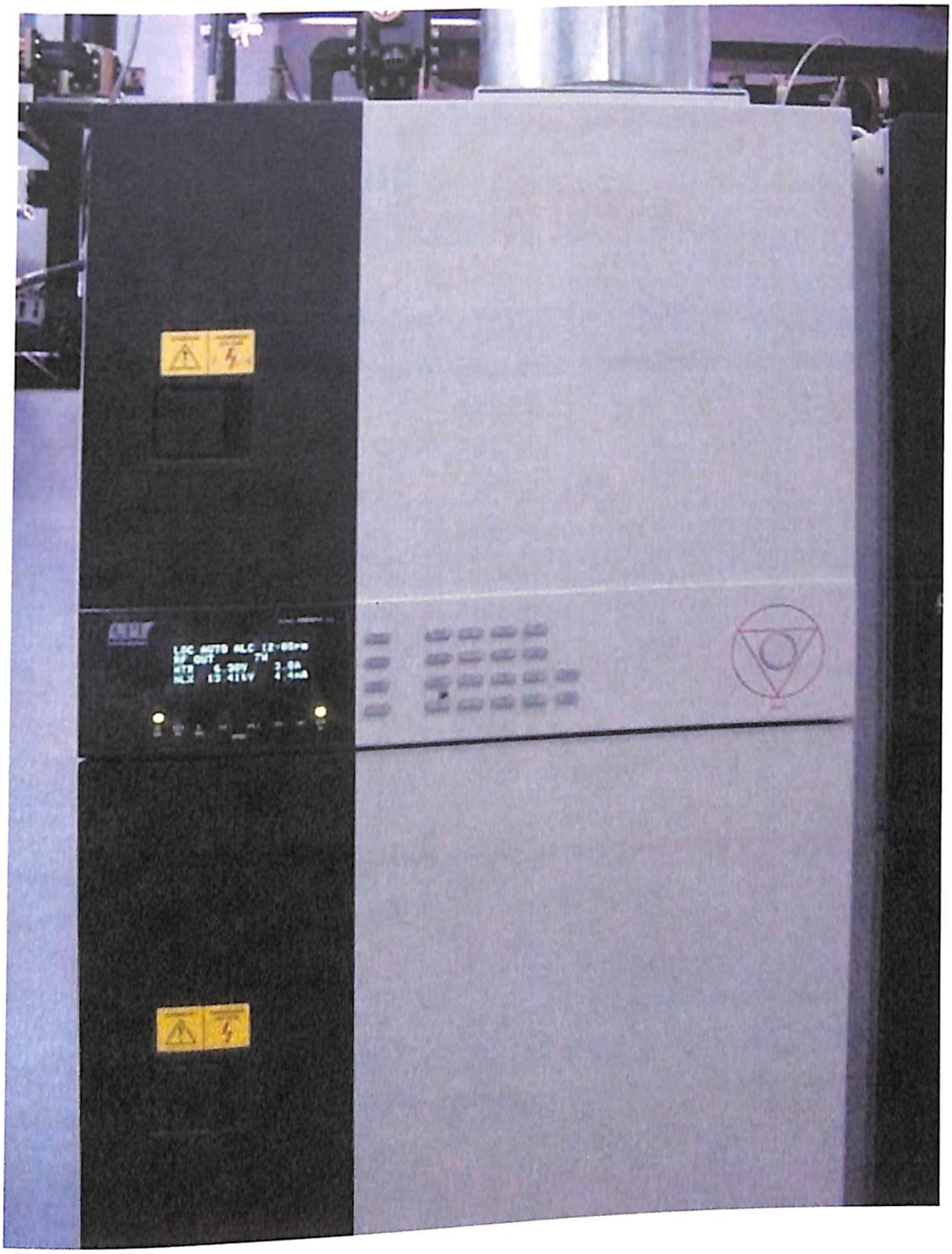


Fig. 5.3.9: High Power Amplifier

Annexure

Transmit Antenna Gains to the Spacecrafts at different Offset Longitudes

Assumptions Made:	
Earth Station	Guam (Longitude of E/S: 143° E; Latitude of E/S: 13° N)
Antenna Dia	7.5 m
Frequency	C Band (6 GHz)
Longitude of ref. S/C	94° E

Long	**Δ Long**	**El**	**Az**	ΔAz	**Gain (dB)**
74	-20	11.87	265	6.13	9.548362
76	-18	13.88	264.48	5.61	10.59794
78	-16	15.9	263.94	5.07	11.79869
80	-14	17.93	263.39	4.52	13.16252
82	-12	19.96	262.83	3.96	14.73077
84	-10	22	262.24	3.37	16.63078
86	-8	24.06	261.62	2.75	19.00432
88	-6	26.12	260.98	2.11	22.06353
90	-4	28.19	260.31	1.44	26.41294
92	-2	30.26	259.61	0.74	33.86088
94	0	32.34	258.87	0	51.6
96	2	34.43	258.07	0.8	33.5156
98	4	36.52	257.26	1.61	26.20475
100	6	38.61	256.37	2.5	21.73186
102	8	40.7	255.43	3.44	18.59506
104	10	42.79	254.41	4.46	16.12949
106	12	44.89	253.31	5.56	14.11861
108	14	46.98	252.12	6.75	12.4226
110	16	49.06	250.83	8.04	10.96243
112	18	51.13	249.41	9.46	9.666258
114	20	53.2	247.85	11.02	8.514788

Note:

1. It is assumed that the Earth Station antenna is directly looking at the satellite located at 94°E longitude.

2. The off-axis radiation pattern is computed as per ITU R:580-5 i.e.,

$G = 29 - 25 * \log\{\Delta Az * \cos(El)\}$

Chapter - 6

Chapter 6

INSAT System & Investigations of Interference Cases

Introduction to the Chapter

Indian National Satellite System (INSAT System) is described in the section 6.1. INSAT System consists of Communications and Meteorological satellites in Geo-Stationary Orbit, and their Service segment covering Telecommunications, TV broadcasts, Radio networking, and VSAT networks. The meteorological segment involves ground reception systems and data processing. INSAT space segment started with INSAT-1 series of multipurpose satellites, and later grew into INSAT-2 and INSAT-3 series of satellites. Some of the satellites in the INSAT-2 and INSAT-3 series were multipurpose type (with Communications and Meteorological payloads), and the remaining are exclusive satellites for Communications and Meteorology. This section covers the communication payload details of currently operational satellites and their associated Service segments. As the cases investigated related to interference into satellite communications, emphasis is given only on the communication payloads and their ground networks.

Section 6.2 covers the details of the investigation into an interference case experienced in the transponders of INSAT-2E. The interference was analysed and found to be an uplink interference originating from one of the ground terminals of an adjacent satellite – Raduga 1-6 of Russia. The interference was eliminated after the results of investigation were presented and Coordination was carried out with Russian Administration.

Section 6.3 covers radar type interference experienced in the lower Ext. C-band transponders of INSAT-2E. The mechanism of radar signals coupling into the INSAT transponders was investigated and the interfering radar signals were characterized. The approximate location of the source of interference was found out using Time

Difference of Arrival (TDOA) measurements, and the results were presented to FCC of USA (as the transponders involved were leased out to INTELSAT) and the approximate location was found to be Guam. The interference disappeared after discussions with FCC.

Section 6.4 covers a wideband noise experienced in Ext. C-band channels of INSAT-3C, which were carrying VSAT traffic. The interference coupling mechanism was analysed and found to be a loop-back at IF level in one of the ground terminals. The characteristics of the ground terminal generating the noise were estimated, and all the VSAT network Operators were alerted. The cause of the interference was eliminated by the Operators, and the interference ceased.

Section 6.5 covers the investigations into wideband noise floor rise experienced across 5 transponders of INSAT-3C. The network and the ground terminal originating the noise were found out through the coordinated switch-off test. The exact terminal, which was pumping the noise, was identified and detailed tests were carried out to understand the mechanism of noise generation. The configuration of culprit terminal was corrected and the interference problem was solved.

Section 6.6 covers the investigations into pick-up of FM radio and VHF signals by the VSAT terminals, and uplinking them to the satellite after conversion from IF level to satellite uplink frequency band. The mechanism of interference coupling was clearly understood and the interfering FM radio stations were identified. The interference was solved after the concerned VSAT terminals were corrected with proper shielding of the interface cables.

Section 6.7 covers the interference into satellites during the drift orbit phase, and relocation phase of the satellites. The interferences experienced by INSAT system, and by other Operators because of the drifting INSAT satellites, were investigated and the coupling mechanisms were understood. The interferences were resolved in real time.

Section 6.8 covers the interference experienced in the MSS payload of INSAT system from the ground-based radars. The investigations carried out so far are detailed in this section. As the exact source of interference is still not identified, the problem is unresolved.

Section 6.9 covers the case of intermodulation interference generated onboard the communication payload of INSAT-3A. Detailed investigations resulted in understanding the interference generation mechanism and identifying the uplink / downlink signals whose intermodulation products were falling in the bandwidths of the other transponders. Two transponders were switched-off, thus eliminating the interference into the other transponders.

6.1 INSAT System

Indian National Satellite (INASAT) System was conceived to provide domestic national services for Telecommunications, TV broadcasting, Radio networking, and the Closed-User Group VSAT networks. The INSAT-1 series of satellites were succeeded by INSAT-2 series of satellites. Among them INSAT-2B, and 2C were in service in 1999, when the investigations into interference cases were started as part of this thesis work. Subsequently, both the satellites were re-orbited at the end of their operational life in 2003.

6.1.1 Presently operational satellites

Presently, seven satellites are operational in the Geo-Stationary Orbit, and one satellite was positioned at the orbital slot only to protect the slot. All these satellites are positioned in the GSO slots allotted by ITU to India. Current operational satellites and their orbital slots are as below:

GSAT-2	at 48 deg E longitude
INSAT-3E	at 55 deg E longitude
INSAT-3C	at 74 deg E longitude

Kalpana-1	at 74 deg E longitude
INSAT-2DT	at 82 deg E longitude
INSAT-3B	at 83 deg E longitude
INSAT-2E	at 83 deg E longitude
INSAT-3A	at 93.5 deg E longitude

Among the above satellites, INSAT-2DT is being used only to protect the particular orbital slot. Kalpana-1 is an exclusive meteorological satellite. INSAT-2E and INSAT-3A have meteorological payloads along with communication payloads. All other satellites carry only communication payloads. The total value of on-orbit assets of INSAT system is roughly Rs. 4,000 Cr.

Fig. 6.1.1 gives the location of INSAT satellites in the GSO.

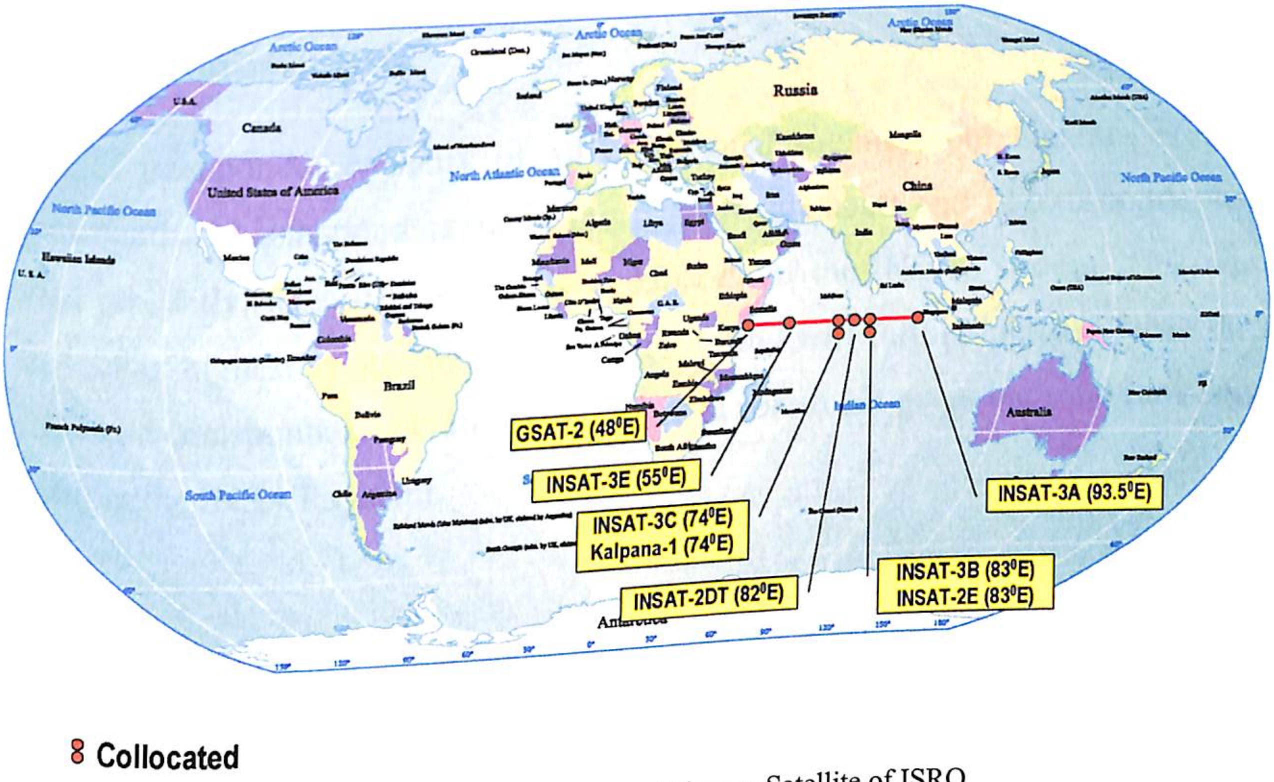


Fig. 6.1.1: Location of Geo-stationary Satellite of ISRO

6.1.2 Communication payloads in INSAT System

The communication payloads in different satellites operate in the frequency bands as given in Table-6.1.1.

Table-6.1.1: Frequency bands used in INSAT system		
Normal C-band	Uplink frequencies	5925 to 6425 MHz
	Downlink frequencies	3700 to 4200 MHz
Ext. C-band	Uplink frequencies	6735 to 6975 MHz
	Downlink frequencies	4510 to 4750 MHz
Lower Ext. C-band (only in INSAT-2E)	Uplink frequencies	6450 to 6670 MHz
	Downlink frequencies	3425 to 3645 MHz
MSS band	Forward link frequencies (CxS)	6450-6470 MHz/2500-2520 MHz
	Return link frequencies (SxC)	2670-2690 MHz/3680-3690 MHz
Ku-band	Uplink frequencies	14250 to 14500 MHz
	Downlink frequencies	11450 to 11700 MHz

Downlink telemetry carriers are located at the upper edge of the C-band between 4190 to 4200 MHz, and the uplink commanding and ranging frequencies are located between 6413 to 6420 MHz.

The total transponder capacity of all operational satellites put together is 132 in various bands. 13 transponders out of this capacity are spare and 12 transponders to be allotted presently, thus giving 82% of occupancy of the INSAT system. This rate of occupancy is highest in the Asia Pacific region, and will further increase when the 12 Ext. C-band transponders are allotted to users. Table-6.1.2 gives the total transponder capacity in the INSAT system.

<table>
<tr><th colspan="7">Table-6.1.2: Transponder Capacity in the INSAT System</th></tr>
<tr><th rowspan="3">Spacecraft & Location</th><th colspan="6">Transponder Type</th></tr>
<tr><th rowspan="2">Normal C</th><th colspan="2">Ext. C</th><th rowspan="2">Ku</th><th rowspan="2">MSS</th><th rowspan="2">BSS</th></tr>
<tr><th>Lower</th><th>Higher</th></tr>
<tr><td>INSAT-3A (93.5° E)</td><td>12</td><td>-</td><td>6</td><td>6</td><td>-</td><td>-</td></tr>
<tr><td>INSAT-3B (83° E)</td><td>-</td><td>-</td><td>12</td><td>3</td><td>-</td><td>-</td></tr>
<tr><td>INSAT-3C (74° E)</td><td>24</td><td>-</td><td>6</td><td>-</td><td>1</td><td>2</td></tr>
<tr><td>INSAT-2E (83° E)</td><td>12</td><td>5</td><td>-</td><td>-</td><td>-</td><td>-</td></tr>
<tr><td>GSAT-2 (48° E)</td><td>4</td><td>-</td><td>-</td><td>2</td><td>1</td><td>-</td></tr>
<tr><td>INSAT-3E (55° E)</td><td>24</td><td>-</td><td>12</td><td>-</td><td>-</td><td>-</td></tr>
<tr><td rowspan="2">Total</td><td rowspan="2">76</td><td>5</td><td>36</td><td rowspan="2">11</td><td rowspan="2">2</td><td rowspan="2">2</td></tr>
<tr><td colspan="2">41</td></tr>
<tr><td colspan="7">Total Transponders Available: 132</td></tr>
</table>

The footprint of the satellites cover Indian land mass and islands for both uplink and the downlink, except for INSAT-2E. INSAT-2E has a wide coverage for both uplink and downlinks extending from Gulf area in the west to Australia in the east, and upto Russia in the north. 11 transponders (of equivalent 36 MHz bandwidth) out of the total 17 transponders of INSAT-2E were leased to INTELSAT due to the extended coverage and the specific extended C-band frequencies required by them.

6.1.3 Utilisation of INSAT transponder capacity

Department of Telecommunications, Prasar Bharati, VSAT Operators, and Private TV Operators are the four major users of INSAT capacity, as of now, in the decreasing order of the occupied transponders. The Telecommunications to the North-East India, J&K, Andaman-Nicobar islands and Lakshadweep islands are configured using exclusively INSAT capacity by DOT, keeping in view the difficult land terrain and the nature of islands. The utilization of INSAT capacity for the above mentioned telecommunication services is in addition to the telecommunication traffic between metros, part of which is also carried on the satellites.

168 TV channels are being beamed over India presently, which includes 55 TV channels of Doordarshan. INSAT system carries 83 of these total channels, including Doordarshan channels and those private channels operating on the transponders leased by INTELSAT.

Closed user group VSAT networks are being operated by DOT before 1994, when the Government of India permitted operation of private VSAT networks over INSAT system. Today, the VSAT networks, utilizing INSAT, is one of the largest segments with about 30,000 operational VSAT terminals. National Stock Exchange, Banks, Financial Institutions and Credit Card Companies are connected through the VSAT networks. Roughly 20% of daily economic transactions in the country are carried over these VSAT networks.

Presently, data rates upto 2 Mbps are allowed on the VSAT communications. The networks utilize both mesh type and star type connectivity. The VSAT terminals utilize antennae upto 1.8 m diameter, and the Hubs use antennae of the size of 3.8 m and above.

Table-6.1.3 gives the allocation of INSAT transponders to various Users.

Table-6.1.3: INSAT Transponder Utilisation

Space Craft & Location	Transponder Type & Availability		Utilisation									
			DOT	DD	Private TV	Private VSAT	AIR	MSS	INTELSAT	DOS	Govt Use	Spare
INSAT-3A (93.5^{0} E)	Normal C	12	3	5	1	-	-	-	-	1 (RRI)	-	2
	Ext. C	6	-	-	1	-	-	-	-	1	3	1
	Ku	6	-	-	4	2	-	-	-	-	-	-
INSAT-3B (83^{0} E)	Ext. C	12	-	-	-	9	-	-	-	2	-	1
	Ku	3	-	-	1	1	-	-	-	1(AP)	-	-
INSAT-3C (74^{0} E)	Normal C	24	12	7	1	-	-	-	-	-	2	2
	Ext. C	6	-	-	-	5	-	-	-	-	-	1
	BSS	2	-	-	-	-	2	-	-	-	-	-
	MSS	1	-	-	-	-	-	1	-	-	-	-
INSAT-2E (83^{0} E)	Normal C	12	3	5	-	-	-	-	4	-	-	-
	Lower Ext. C	5	-	-	-	-	-	-	5	-	-	-
GSAT-2 (48^{0} E)	Normal C	4	-	-	-	-	-	-	-	-	4	-
	Ku	2	-	-	-	-	-	-	-	-	2	-
	MSS	1	-	-	-	-	-	-	-	-	1	-
INSAT-3E (55^{0} E)	Normal C	24	11	7	-	-	-	-	-	-	-	6
	Ext. C	12	-	-	-	-	-	-	-	-	-	12
	Total	132	29	24	8	17	2	1	9	5	12	25

6.1.4 Interferences in the INSAT System

The utilization of the INSAT transponders is very extensive with different types of Services being operational through the satellites. The type of ground terminals deployed, the size of the networks, the type of services and the modulations used are highly varied over different transponders in the INSAT system. The Operators were highly experienced in some cases, and in some cases a mix of trained and untrained staff are involved. Sometimes the violations of the rules and regulations on the leased transponders occur in such wide networks, in many cases being unintentional. However, violation of either the operational power levels or bandwidth by even one Operator can cause a lot of difficulties for the remaining network Operators.

In this context a number of interferences were experienced in the communications involving INSAT system. However, INSAT is not the only system experiencing interferences, other international Satellite Operators have also reported different types of interferences.

A number of severe interference cases were investigated in the last four years in the INSAT system, and many problems were solved. A few of the problems continue to be under investigation. Eight typical interference cases were investigated systematically and thoroughly as a part of this thesis work.

Some of the interference problems presented by other Satellite Operators in the SUIRG meetings, having a relevance to the present investigations, are also studied during the analysis [44], [45], [46], [47] of some case studies. A few cases of interferences into INSAT system were also presented in the SUIRG meeting 2002 in Singapore [48] to gain the benefit of discussions with other Experts.

Subsequent sections deal with each case, giving in detail the Investigations carried out through measurements and analysis to resolve the problems.

6.2 Case Study-1: Uplink interference from adjacent satellite network

6.2.1 Introduction

Nine Transponders in INSAT-2E, two of them with 72 MHz bandwidth, were leased to INTELSAT. One of the Transponders (Transponder #6) has an uplink center frequency of 5890 MHz, and the downlink center frequency of 3665 MHz, and bandwidth of 72 MHz. The lower half of the transponder was occupied by 2 TV carriers, and the upper half was identified by the Customer for VSAT traffic.

INSAT-2E is located at 83 deg E longitude, and has a wide footprint for both uplink and downlink. The satellite has a G/T of –5 dB/K in its primary coverage. The EIRP of the transponder is 39 dBw.

6.2.2 Statement of the Problem

An interference in the upper half of the Transponder #6 was observed. The initial observations showed that the interfering spectral components change in frequency and vary in level (Fig. 6.2.1, 6.2.2, 6.2.3). The following details of the interference were also noted:

- The spurious at 3669.99 MHz had 8 PSK modulation with side bands of 8 KHz.
- The spurious at 3657.2 MHz also had 8 PSK modulation but with a higher data rate.
- A few of the interfering carriers were present almost all the time, and a few of the interfering carriers pop up occasionally and stay for a few hours.

As the interference components were narrow in bandwidth an analog TV carrier, occupying complete upper half of the transponder, would not have been affected by this type of interference. But, the particular bandwidth was not coordinated for use with analog TV carriers during the orbit / frequency allocation coordination process.

Hence, such a use was not possible, and the upper half of the transponder became unusable due to this interference, resulting in loss of bandwidth and revenue.

6.2.3 The measurements at MCF

The interference was confirmed by monitoring the satellite downlink in the frequency band of the affected transponder. Detailed plots were taken on each interfering component to identify the possible modulation on the spurious signals. (Fig. 6.2.4 to 6.2.9). Summary of the modulations are given in Table-6.2.1.

Table-6.2.1: Summary of Modulations on Interference Signals

Centre Frequency (MHz)	Bandwidth	Modulation
3657	200 KHz	8 PSK
3669	20 KHz	8 PSK
3671	40 KHz	PSK
3688	20 KHz	QAM
3691	30 KHz	PSK

The above details indicated that digital data traffic was appearing as interference.

6.2.4 Identification of the interference coupling mechanism

The interference with narrow-band modulated signals was possible by the following three coupling mechanisms:

- Uplink interference from the ground terminals of INSAT Network.
- Uplink interference from the ground terminals of neighbouring satellite network, owing to wide coverage area for satellite receive antenna.
- Downlink interference from a neighbouring satellite having undesired coverage.

(A) The experiments were carried out on the transponder of INSAT-2E by changing onboard BOA settings. The interference components were measured by changing the onboard attenuator. The level variation of the interfering components corresponded to the change of onboard attenuation, which confirmed that the interference was being created by unknown uplinks.

(B) The close analysis of INSAT carriers, operating on this satellite, and the monitoring of corresponding uplink levels at ground amplifier output ruled out the possibility of interference from INSAT network.

It was concluded that the interference was being caused due to uplink from a neighbouring satellite network.

(C) The downlink C/KT were measured for each of the interference components using a 7.2 m dia antenna with a G/T value of 28.5 dB / deg K. The C/KT values were converted to EIRP by comparing with the injected carrier. The values are given in Table-6.2.2.

Table-6.2.2: EIRP Estimation for the Interference Components

Downlink frequency (MHz)	**Corresponding uplink frequency using an LO value of 2225 MHz (MHZ)**	**C/KT (dBHz)**	**EIRP (dBW)**
3657.2030	5882.2030	54.44	10.18
3660.8860	5885.8860	52.19	9.55
3663.2305	5888.2305	60.05	2.82
3666.3729	5891.3729	51.28	6.18
3673.0010	5898.0010	62.87	6.21
3680.1028	5905.1028	59.07	2.57
3683.2530	5908.2530	62.56	3.77
3684.9216	5909.9216	59.37	1.81

The levels of interference as estimated from the above measurements / computations were much hither than the limits applicable as per ITU Recommendations, if being caused by the adjacent satellite network (as was suspected to be).

6.2.5 Identification of probable Network causing interference

(A) By going through the GSO satellite database, it was identified that a Russian satellite Raduga 1-6 is at 85 deg E location, and is one of the adjacent satellites to the INSAT-2E. The following details of Raduga series of satellites were collected from different literature:

- Raduga 1 series of satellites were second-generation military communication satellites of Russia, carrying data traffic.

- Each satellite in the Raduga 1 series was launched, and reached to GSO and left with an inclination of -1.4 deg without correction. This inclination would gradually come down and cross the equatorial plane and would increase upto +1.4 deg in roughly four years' time. The satellites were used generally in the inclined orbit for a period of four years from launch.

- Raduga 1-6 was launched in October 2001, and the inclination of the satellite was - 0.77 deg when the interference was identified in INSAT-2E in August 2002.

Raduga 1-6 has 6 transponders in C-band. The transponder plan is given in Table-6.2.3 below.

Table-6.2.3: Frequency Plan of the Transponders in the Raduga Satellite

Transponder No.	Bandwidth (MHz)	Uplink Center Frequency (MHz)
1	36	5750
2	36	5800
3	36	5850
4	36	5900
5	36	5950
6	36	6000

The polarization is LHCP for satellite receive, and RHCP for satellite transmit signals. The transponders have 32 dBw EIRP and with a footprint covering Africa to Australia.

The frequency plan clearly indicated that there are uplinks to the Raduga satellite corresponding to the transponder of INSAT-2E which is experiencing the interference – i.e., in the uplink frequency band of 5890 MHz to 5930 MHz. Transponder #4 of Raduga 1-6 has uplink frequencies in this affected band.

(B) The Raduga 1-6 satellite was in the inclined orbit with an inclination of 0.77 deg. If an adjacent satellite is in inclined orbit, and if the culprit ground antenna is tracking it, the level of interference reaching 2E will have variations. The inclination of the satellite induces a variation in the instantaneous latitude of the satellite, and the longitude drift rate. The change in satellite longitude over-a-day for this small value of inclination will be only of the order of 0.01 deg. Similarly, the inter-satellite distance varies over a day depending on the values of eccentricities of both the satellites. If the variations of this distance is large, then again the interference levels vary.

Hence, to verify the cause of variations in the interference levels, the inter-satellite distance between the Raduga 1-6 and INSAT-2E were computed. (Fig. 6.2.10). The downlink signal levels of the interference in the INSAT transponder were monitored for 24 hours for a few days and it was found that the level variation of interference signal was about 1.5 dB peak-to-peak (Fig. 6.2.11). Though the level variations were small, the systematic change in the level of interference components (which were always present) over-a-day for several days indicated that the interference could be from the networks operating on the adjacent satellite, which could be in inclined orbit.

(C) The LO frequency of the adjacent satellite is 2325 MHz as given in the published literature. Using this information, the downlink spectrum of the adjacent satellite was monitored to identify any correspondence between its signals and interfering signals of INSAT transponder. No exact correspondence could be established.

As there was no correspondence between downlink signals of Raduga and the interference observed in INSAT-2E when the declared LO was used, the exact onboard LO frequency was found out using a small signal uplinked to the satellite. The LO frequency in this particular satellite was found to be 2279 MHz. When the above LO value was used, the correspondence between the downlink signals of the Raduga satellite and the interference signals in the INSAT-2E transponder could be established. (Fig. 6.2.12).

From all the above measurements / data / analysis, it was concluded that some uplink signals to the Raduga 1-6 satellite were reaching unintentionally to the INSAT-2E, causing the interference.

6.2.6 Resolution of the Problem

The findings of the MCF were conveyed to the Russian Administration as per the Coordination procedure. More details, including the ground station characteristics and 24 hours monitoring of the interference, were requested by the Russian Administration and the details were provided. After a year of continuous coordination, the Administration was convinced that the interference was originating from one of the ground terminals of their satellite network. The Administration removed the interference source from 17th November 2003.

Fig. 6.2.13 gives the spectrum of the complete transponder, with interference, taken during October 2002. Similar spectrum plot of the same transponder, with interference, taken on 3rd November 2003 is given in Fig. 6.2.14. The spectrum plot of the transponder after solving the interference problem is given in Fig. 6.2.15.

Conclusions

1. The complaint of the Customer on interference was confirmed.
2. The interfering components were characterized as digital data traffic.
3. Through the measurements and analysis of data, it was concluded that the interference was being caused by an uplink signal to Raduga 1-6, unintentionally reaching INSAT-2E.
4. Detailed Coordination meetings were held with the Russian Administration, and the interference was eliminated.

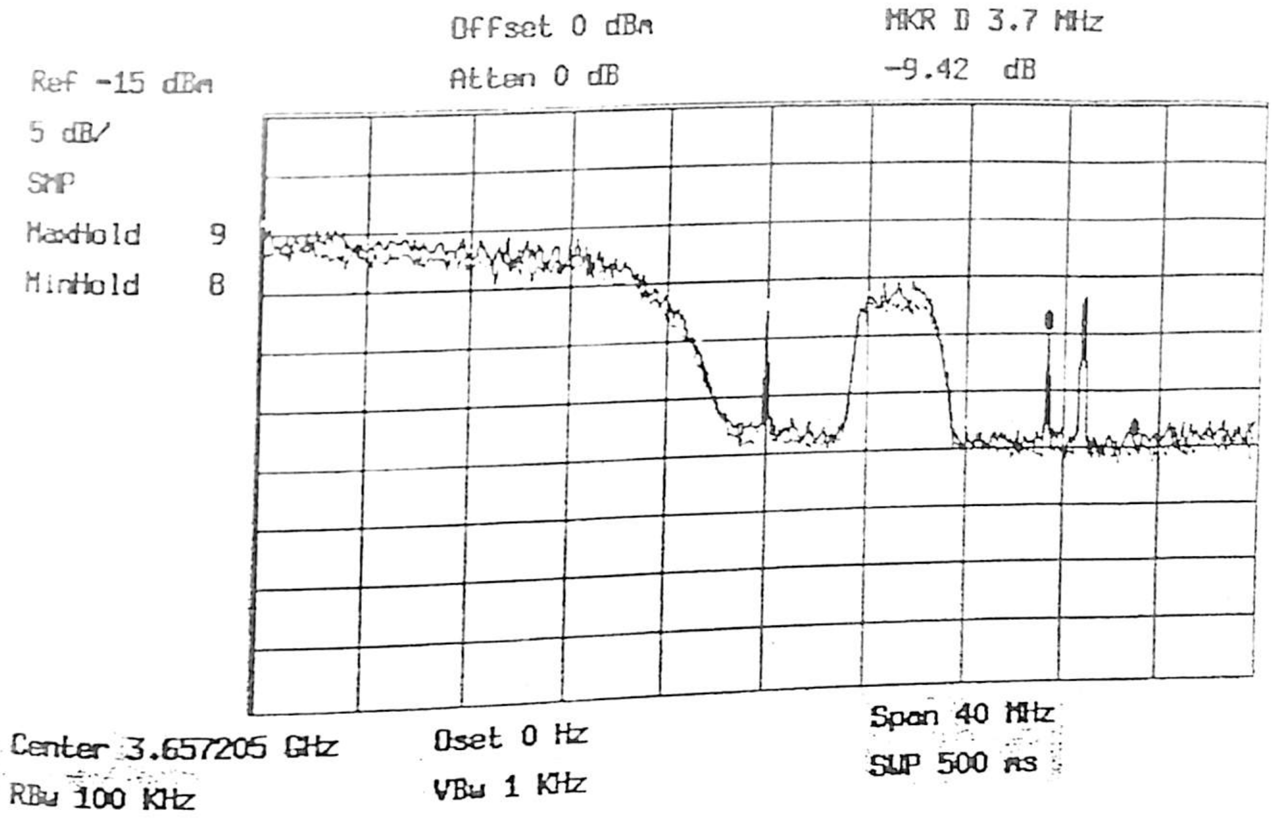


Fig. 6.2.1: The interference spectral components

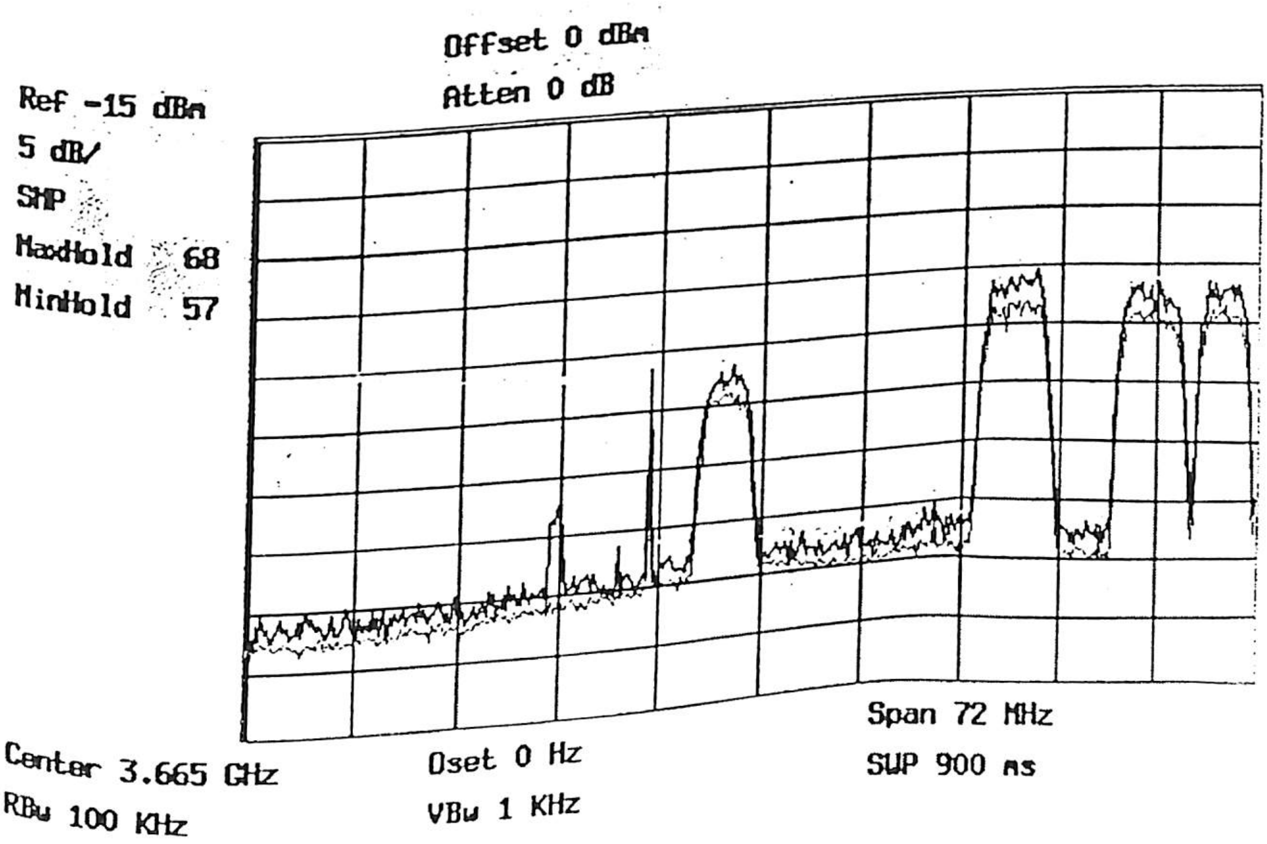


Fig. 6.2.2: The variations in the level of interference spectral components

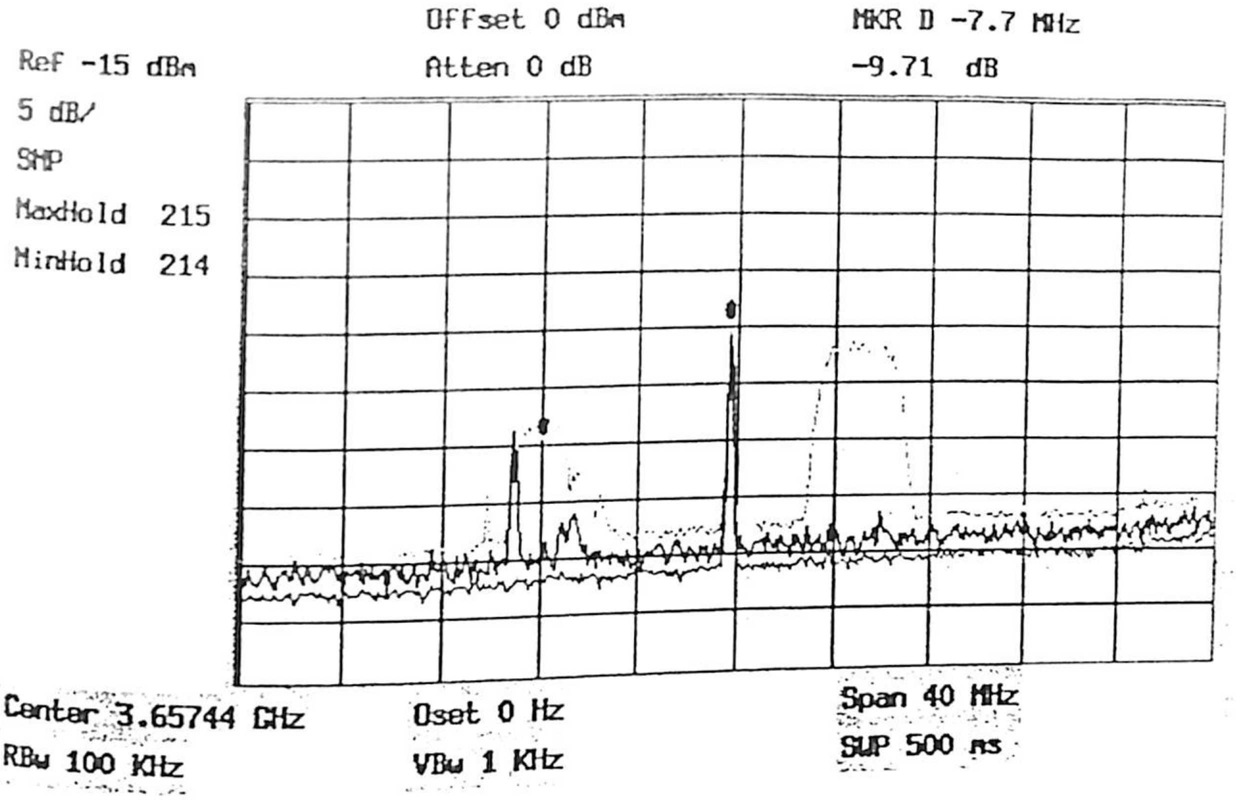


Fig. 6.2.3: The random appearance of interference spectral components

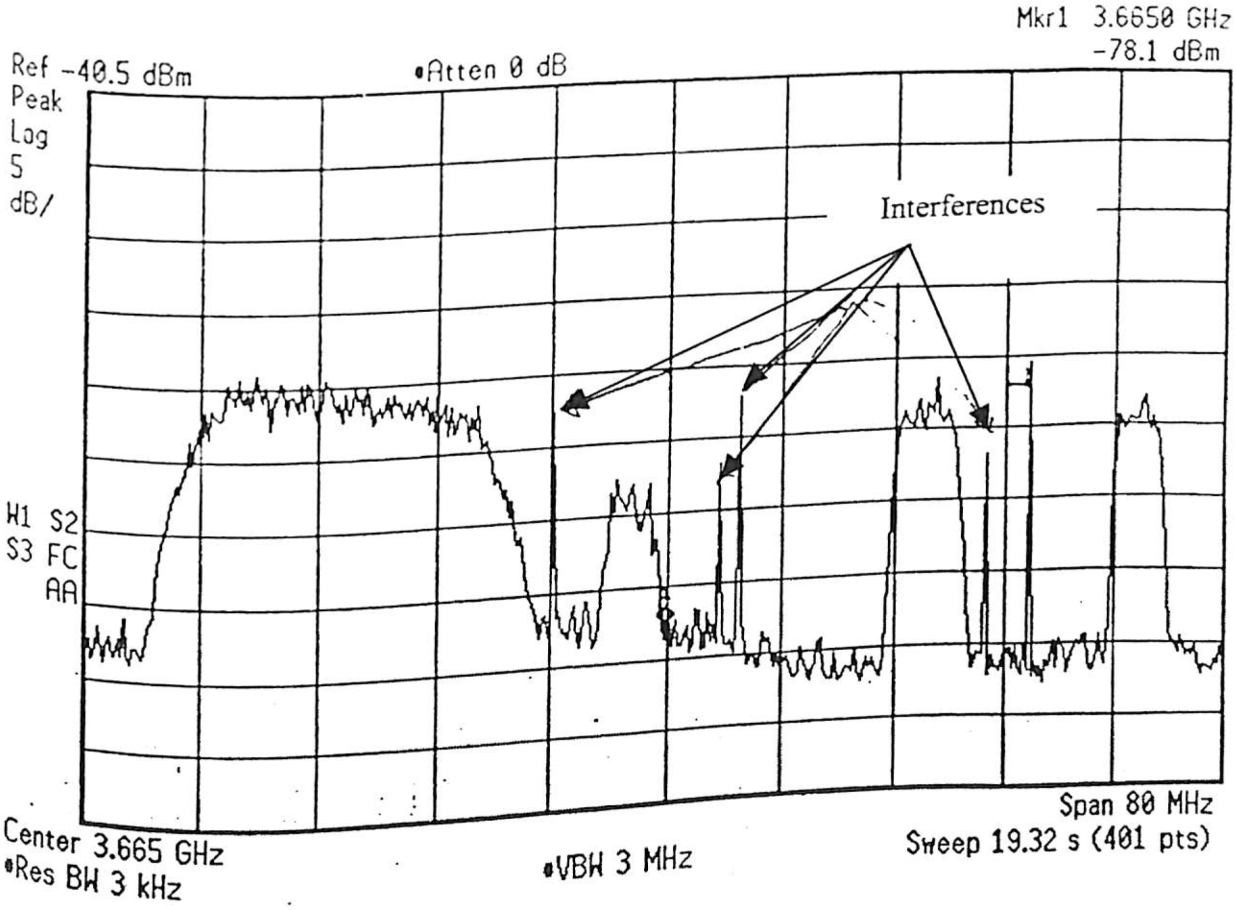


Fig. 6.2.4: The interference components taken up for modulation study

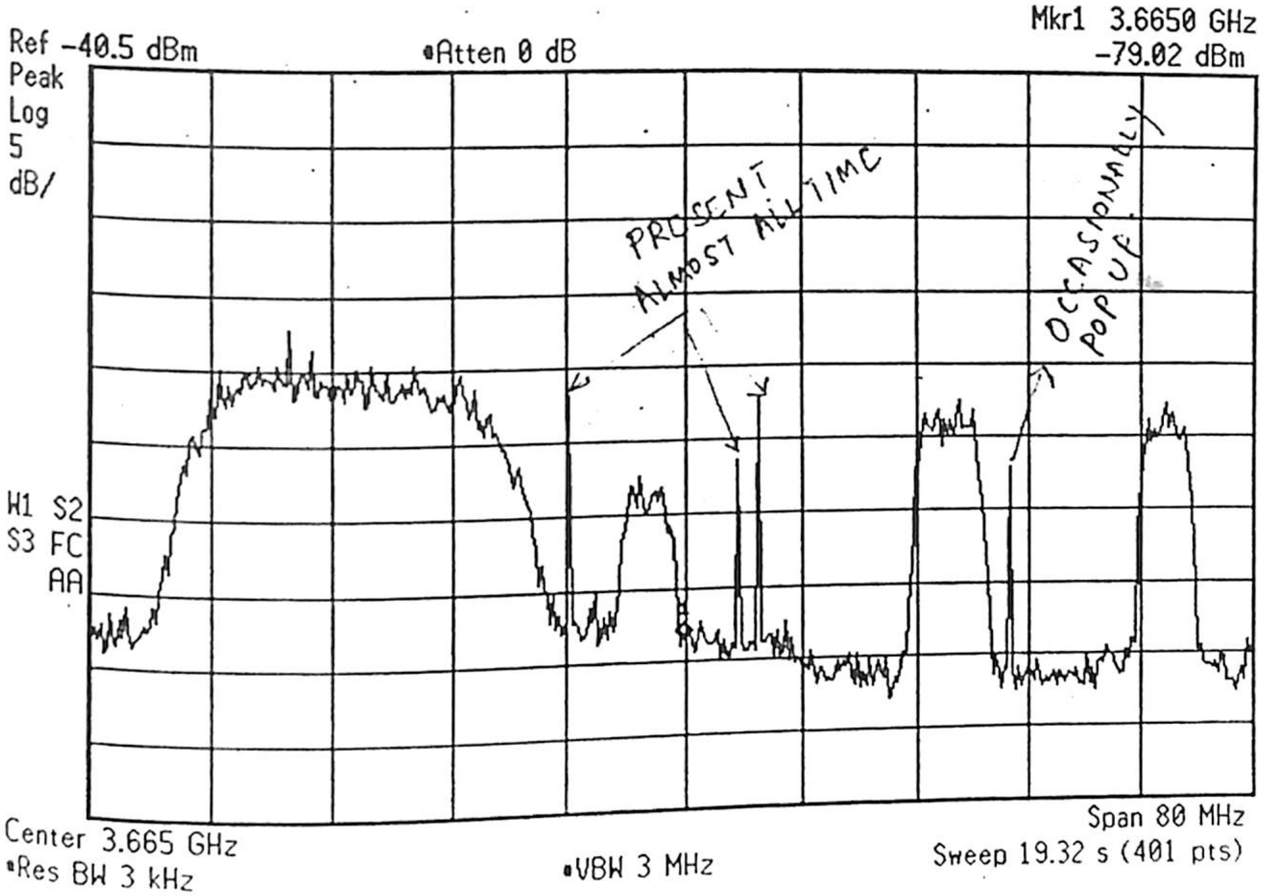


Fig. 6.2.5: Interference components and their presence

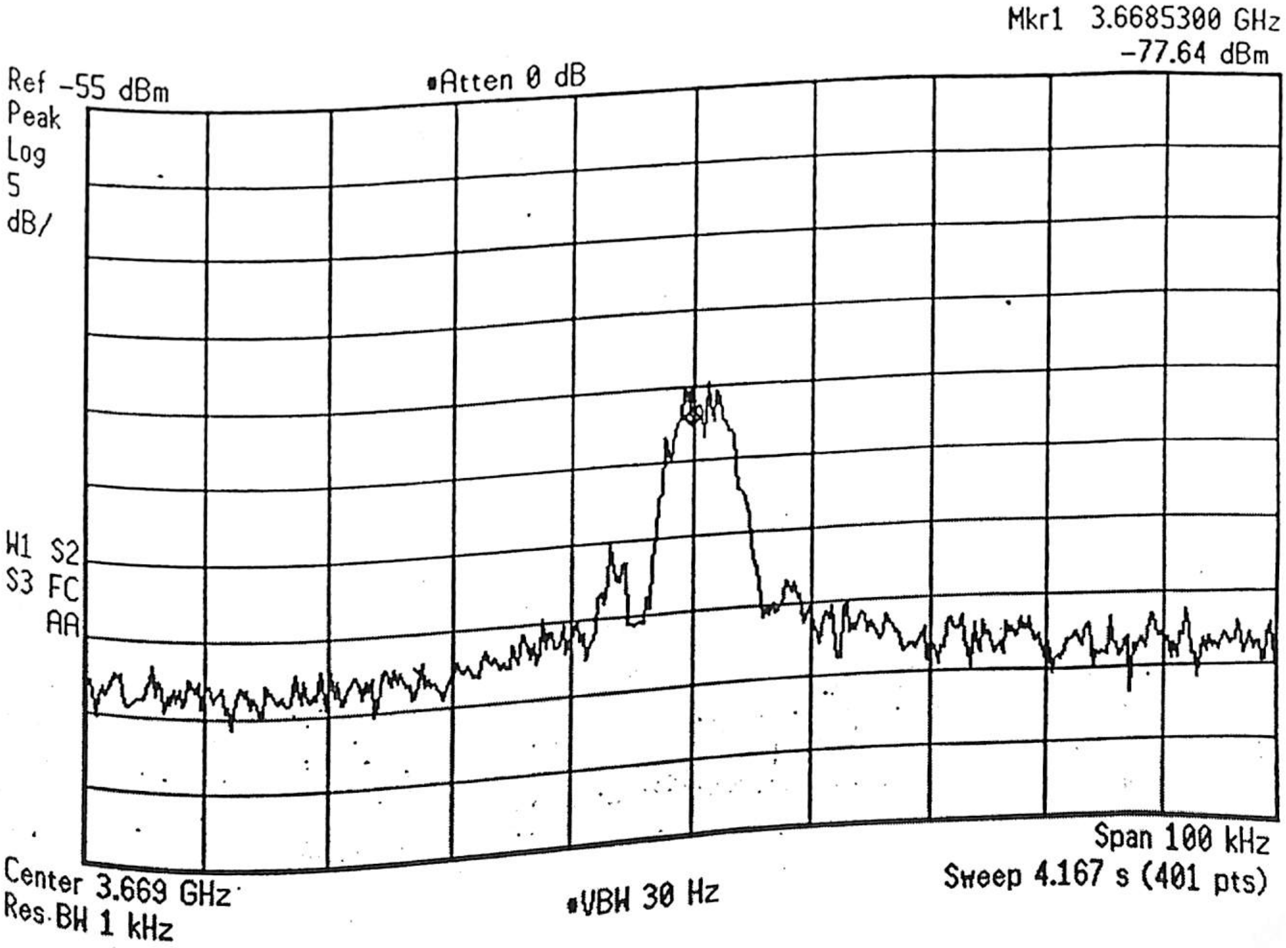


Fig. 6.2.6: Modulation on one of the components

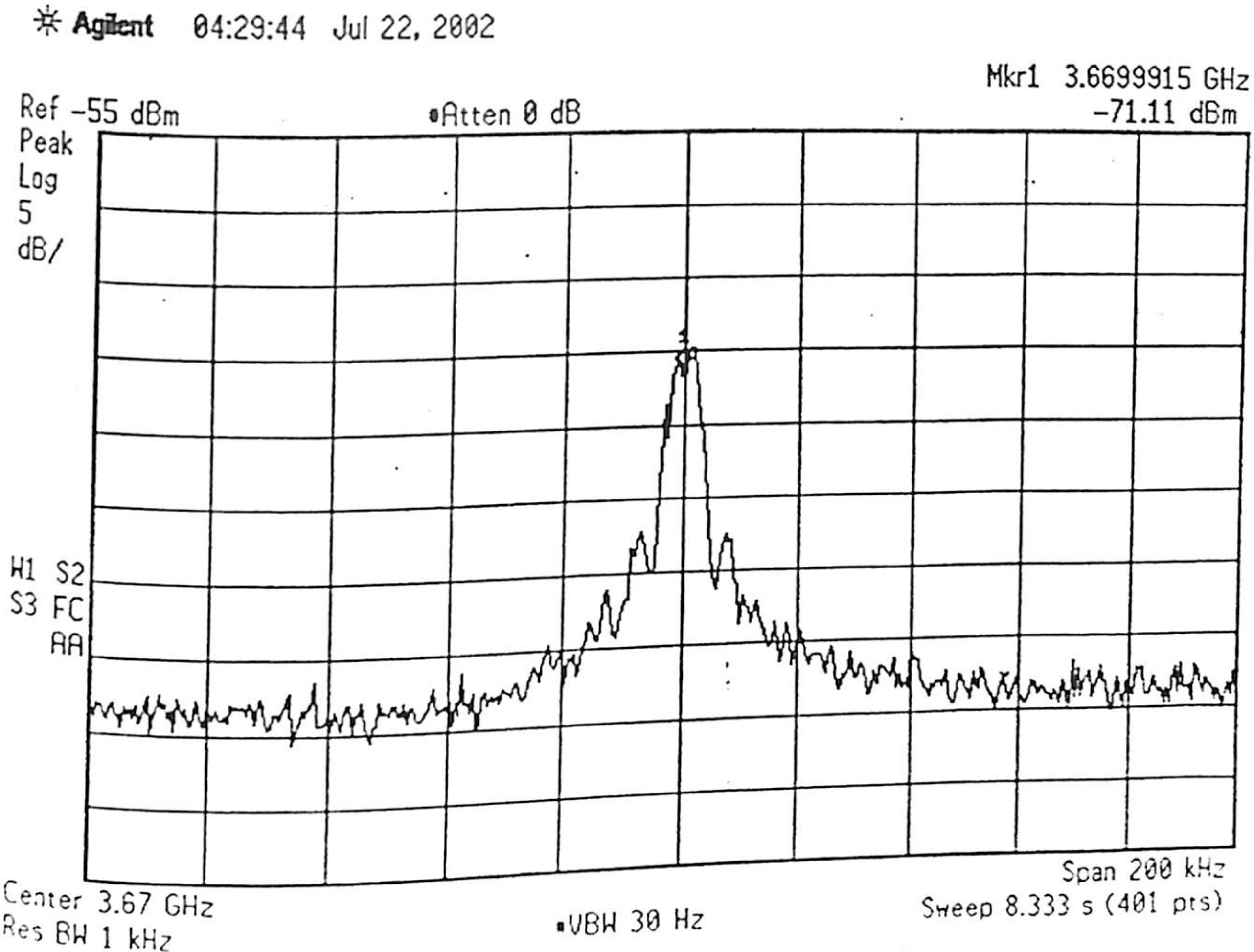


Fig. 6.2.7: Modulation on one of the components

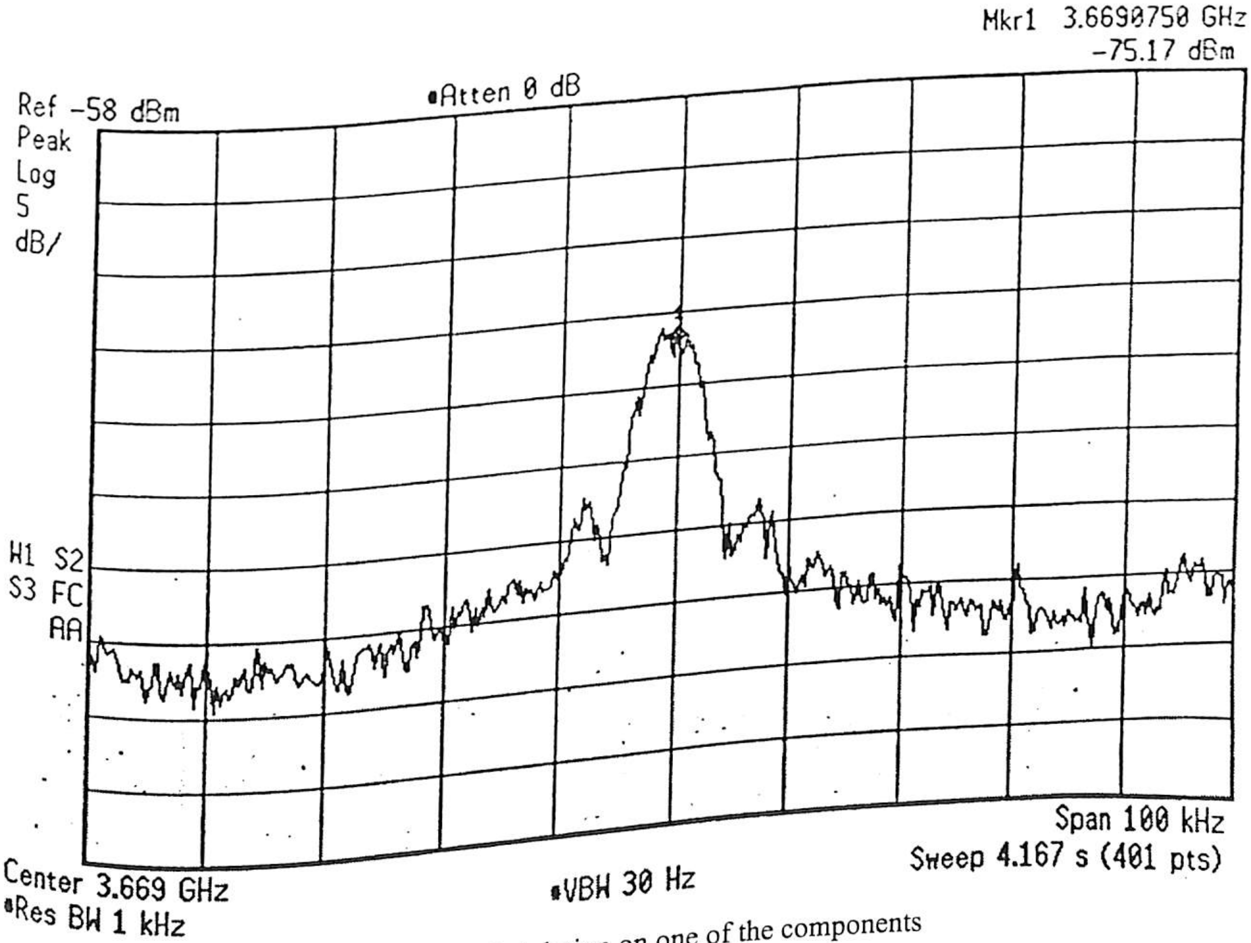


Fig. 6.2.8: Modulation on one of the components

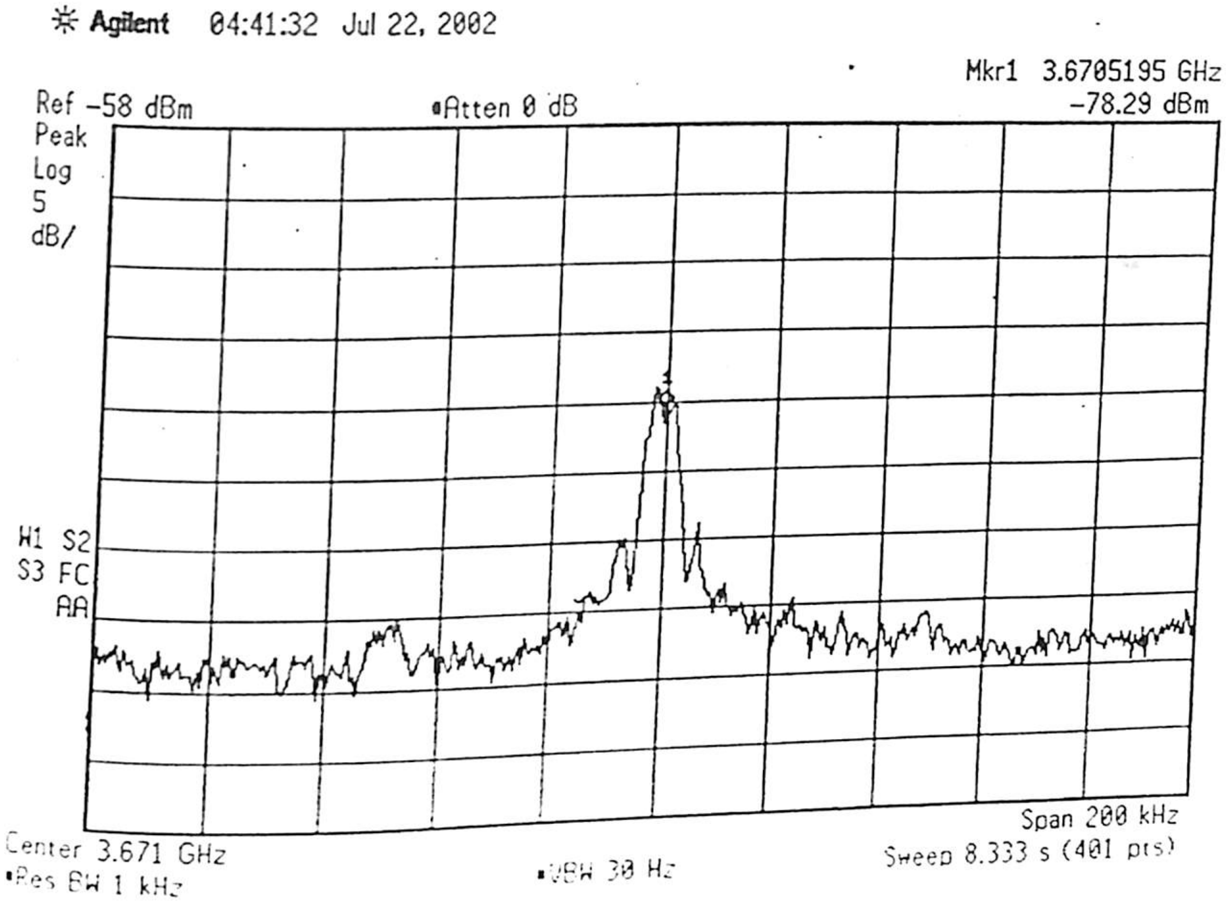


Fig. 6.2.9: Modulation on one of the components

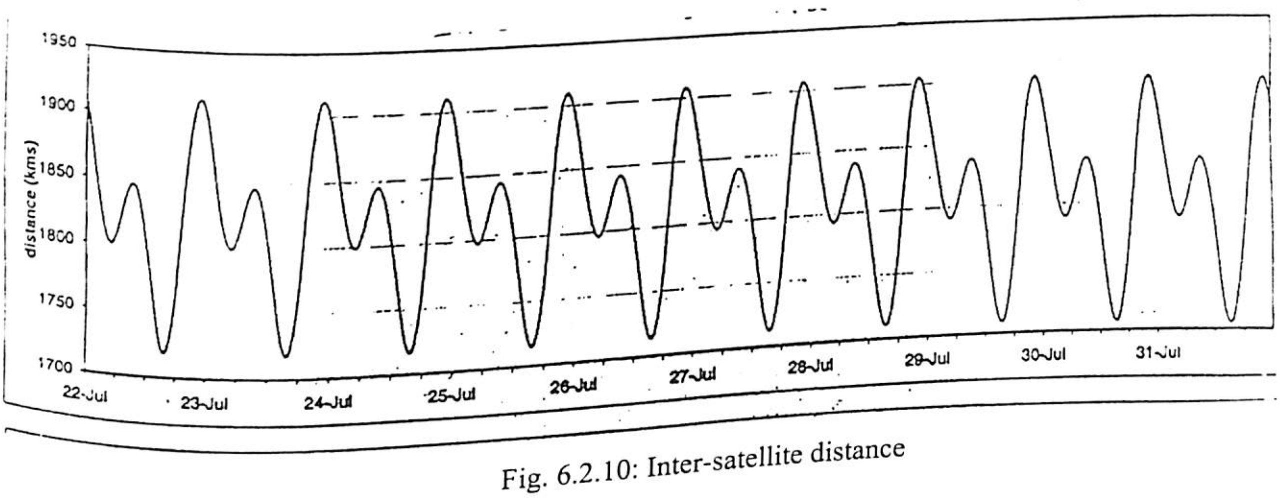


Fig. 6.2.10: Inter-satellite distance

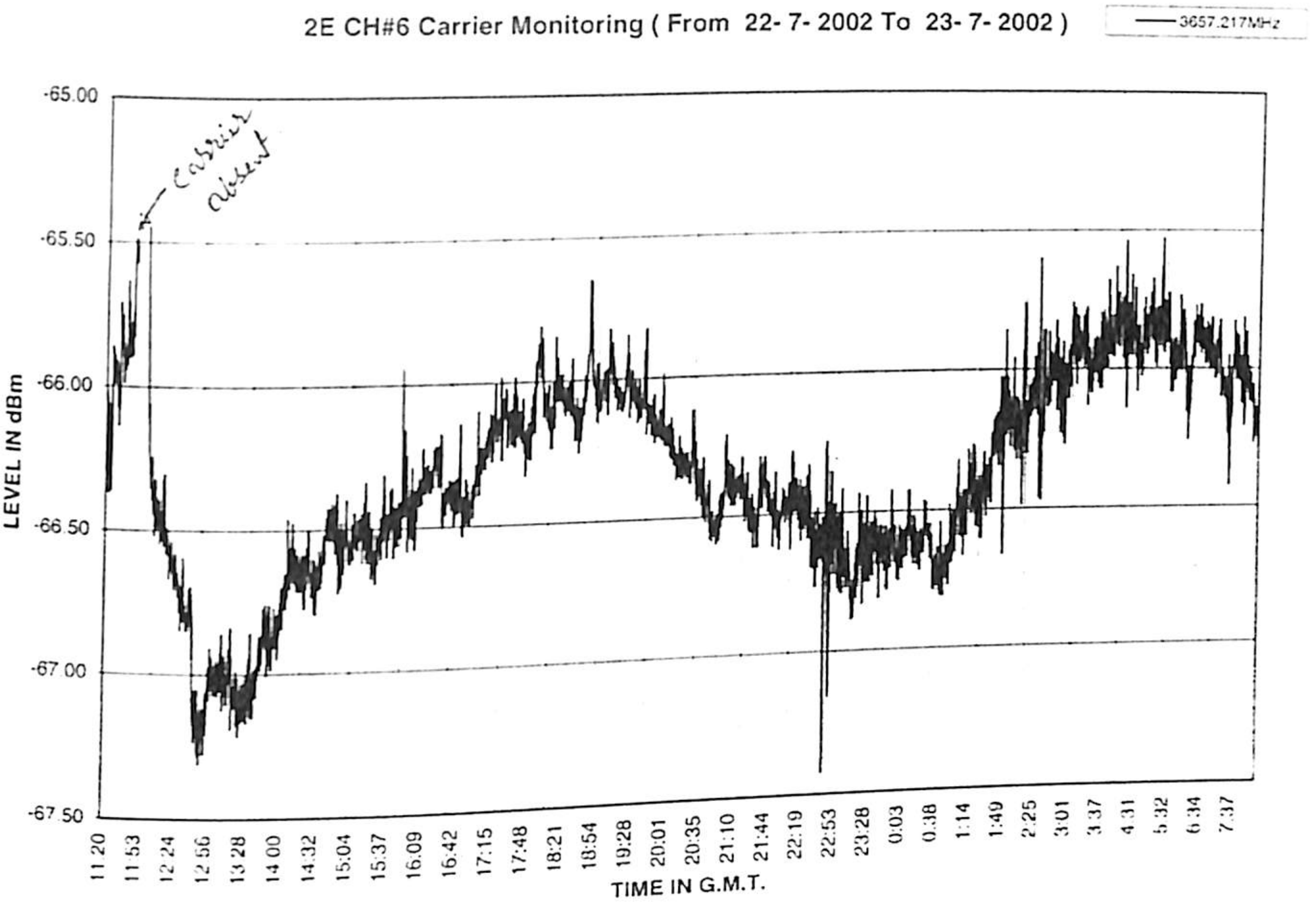
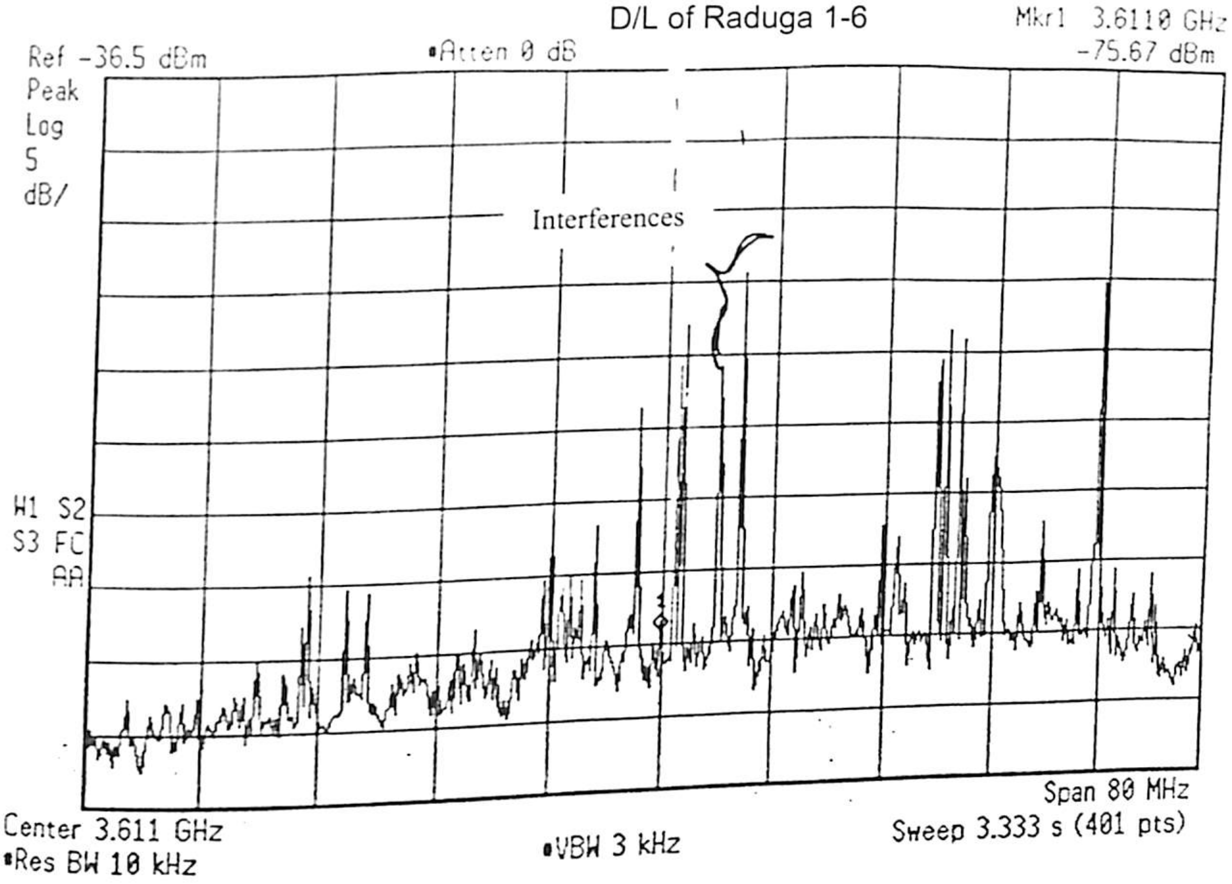


Fig. 6.2.11: The variations of the interference levels during 24-hour monitoring



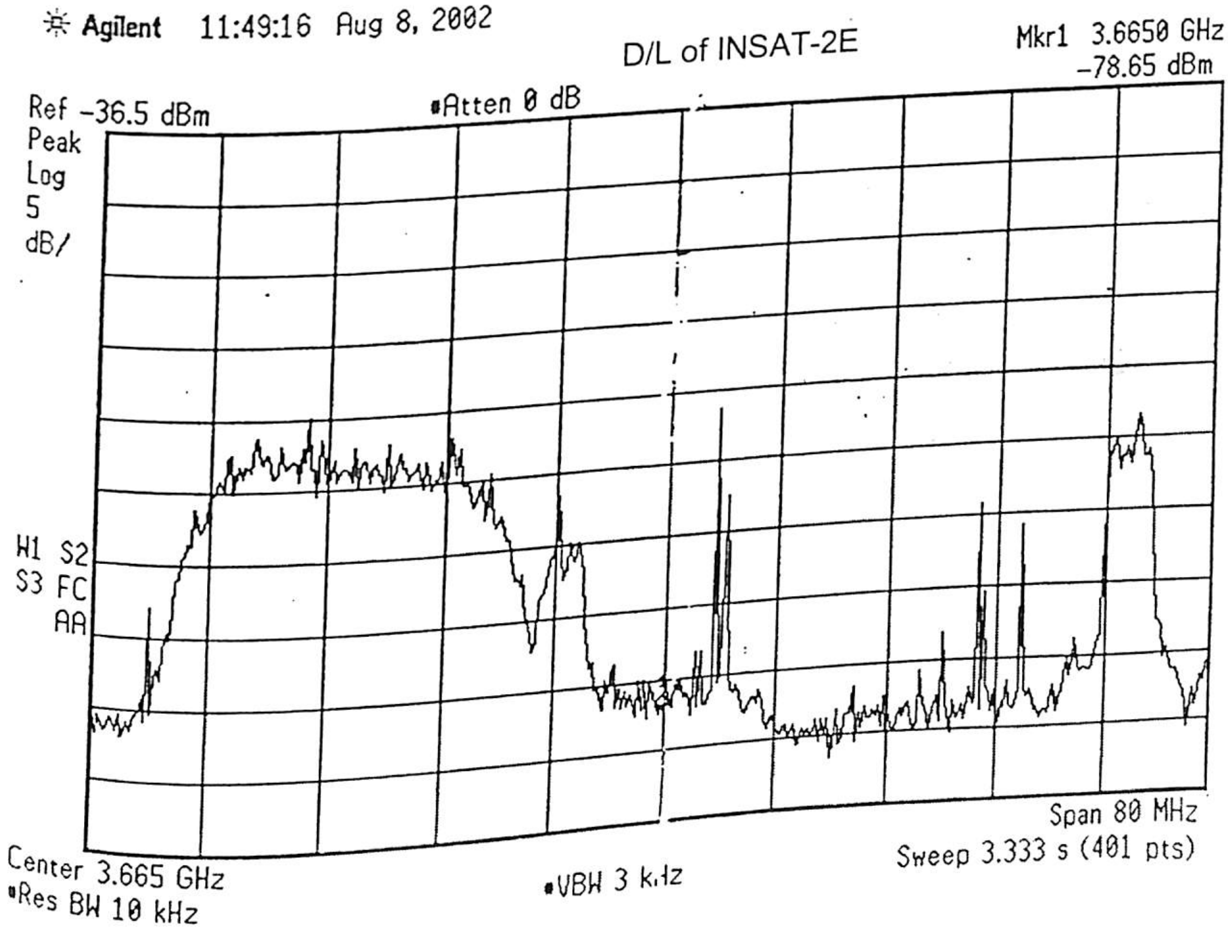


Fig. 6.2.12: Correspondence between the downlink signals when new LO frequency was used for monitoring

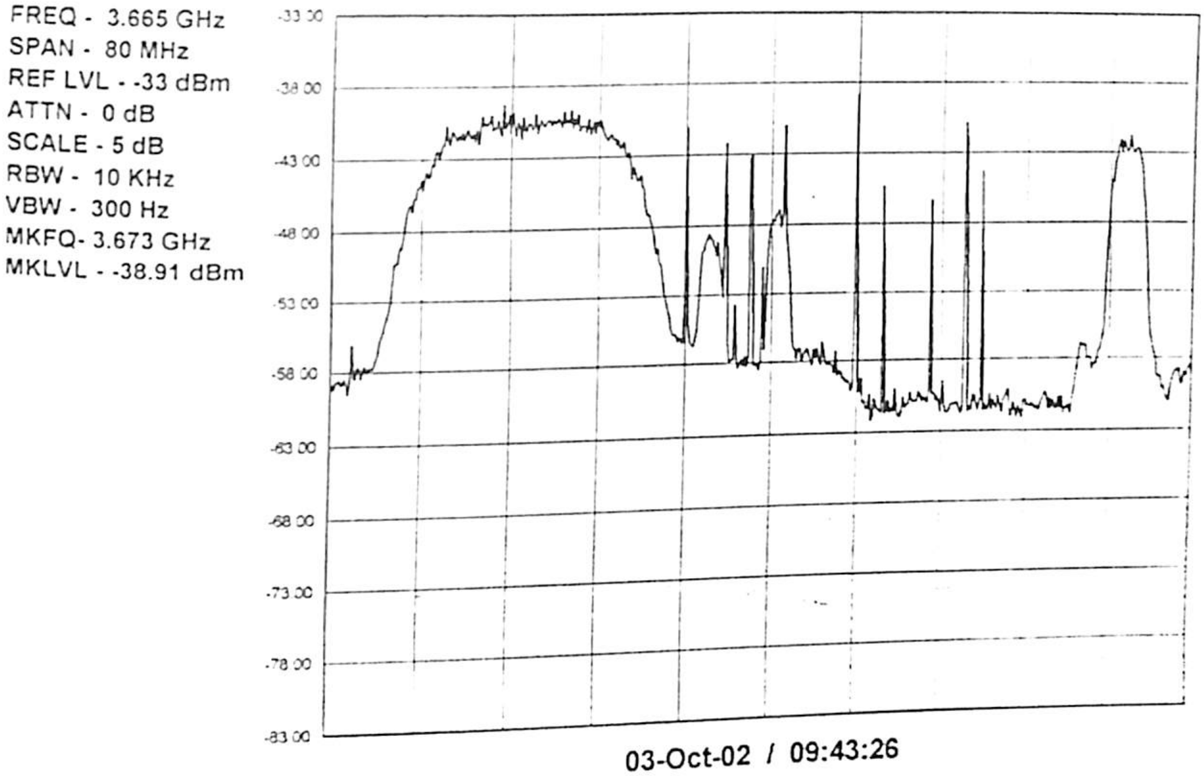


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Fig. 6.2.13: The spectrum plot of transponder with interference during October 2002

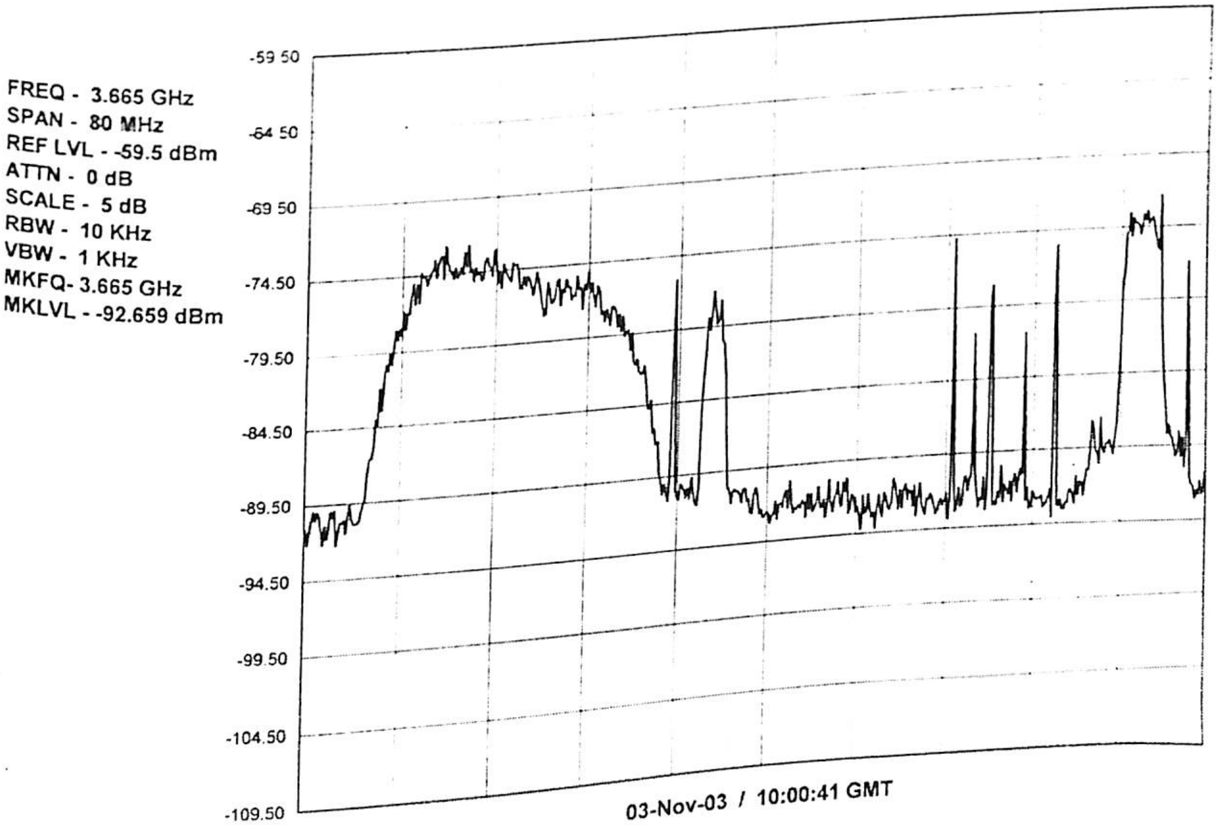

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Fig. 6.2.14: The spectrum plot of transponder with interference during November 2003

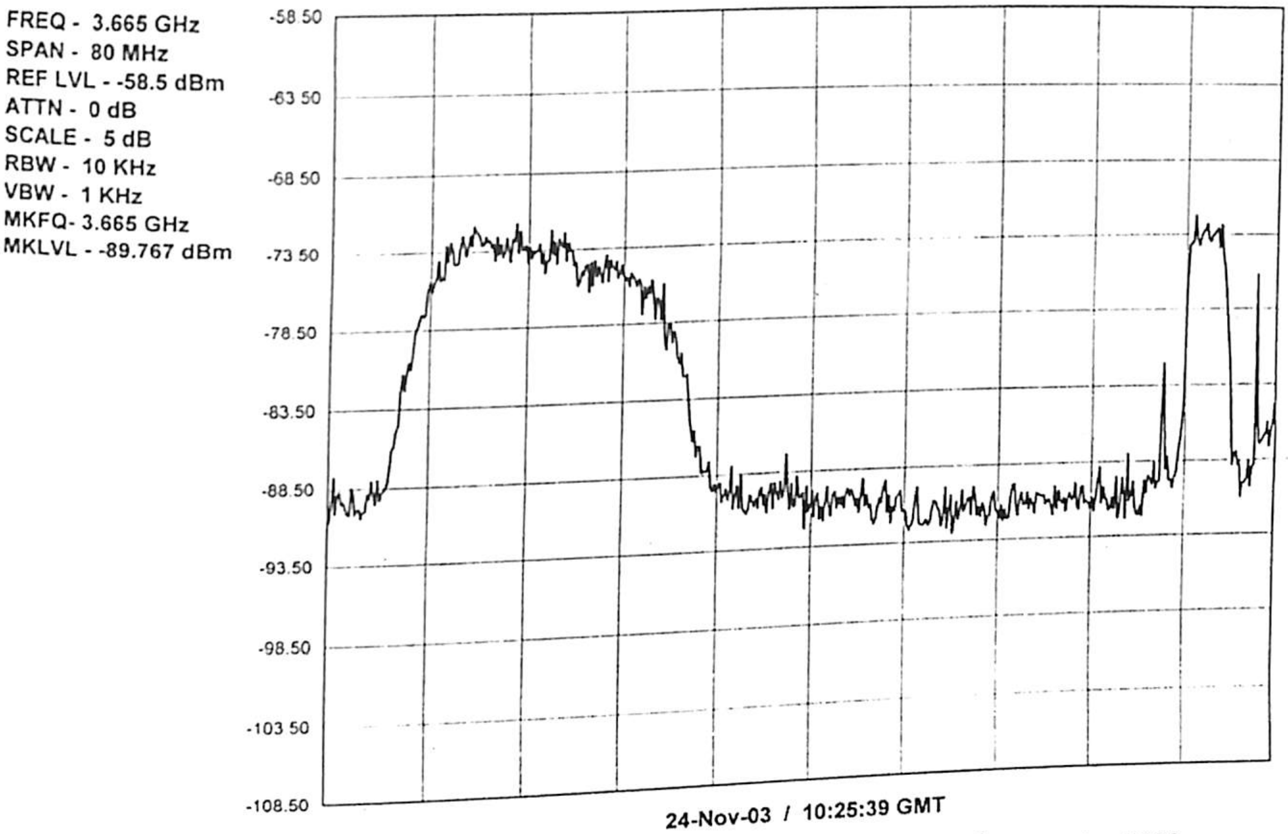


Fig. 6.2.15: The spectrum plot of transponder without interference after 17th November 2003

6.3 Case Study-2: Radar type interference in INSAT-2E

6.3.1 Introduction

In Satellite communication, Radio frequency interference from ground radars had never been a concern in the early days while using analog modulation schemes. This was due to the fact that interference levels received at the geo-stationary height from ground radars were far below the power level of the desired signal, so as to cause noticeable performance degradation. But in the recent years, with the introduction of numerous advanced communication technologies such as digital modulation and signal coding in Satellite communication, reliable data communications can be achieved with very low E_b/N_o. This creates a possibility of even a small interference power making systems susceptible to interference.

One such Interference from ground radar was observed in INSAT system. Nine Transponders of INSAT-2E were leased to INTELSAT. Transponder #1 to #5 use uplink frequency in the range of 6450 to 6650 MHz, and downlink frequencies in the range of 3425 to 3625 MHz (i.e., the downlink in the lower extended C-band). Interference in the form of suspected Radar bursts were first observed in the downlink signals of Transponder #3, and later in the Transponders 4 and 5.

Through tests and analysis, the interference was characterized and the source was localized.

6.3.2 Statement of the Problem

In May 1999, INTELSAT reported high levels of spurious on the leased capacity of INSAT. Initial observations indicated Radar like burst interference in the lower extended c-band transponders (3400-3700 MHz). The interference affected low power/low data rate links. Whenever radar burst occurred, burst errors were observed in the data links and the links were loosing lock. Wide band digital video links (high power/high data rate) survived without any BER degradation in the presence of these interference signals. The radar burst interference was found to be random in nature and hopping in frequency over 5 transponders.

Fig. 6.3.1 shows the Radar burst interference monitored in the downlink spectrum of the transponders.

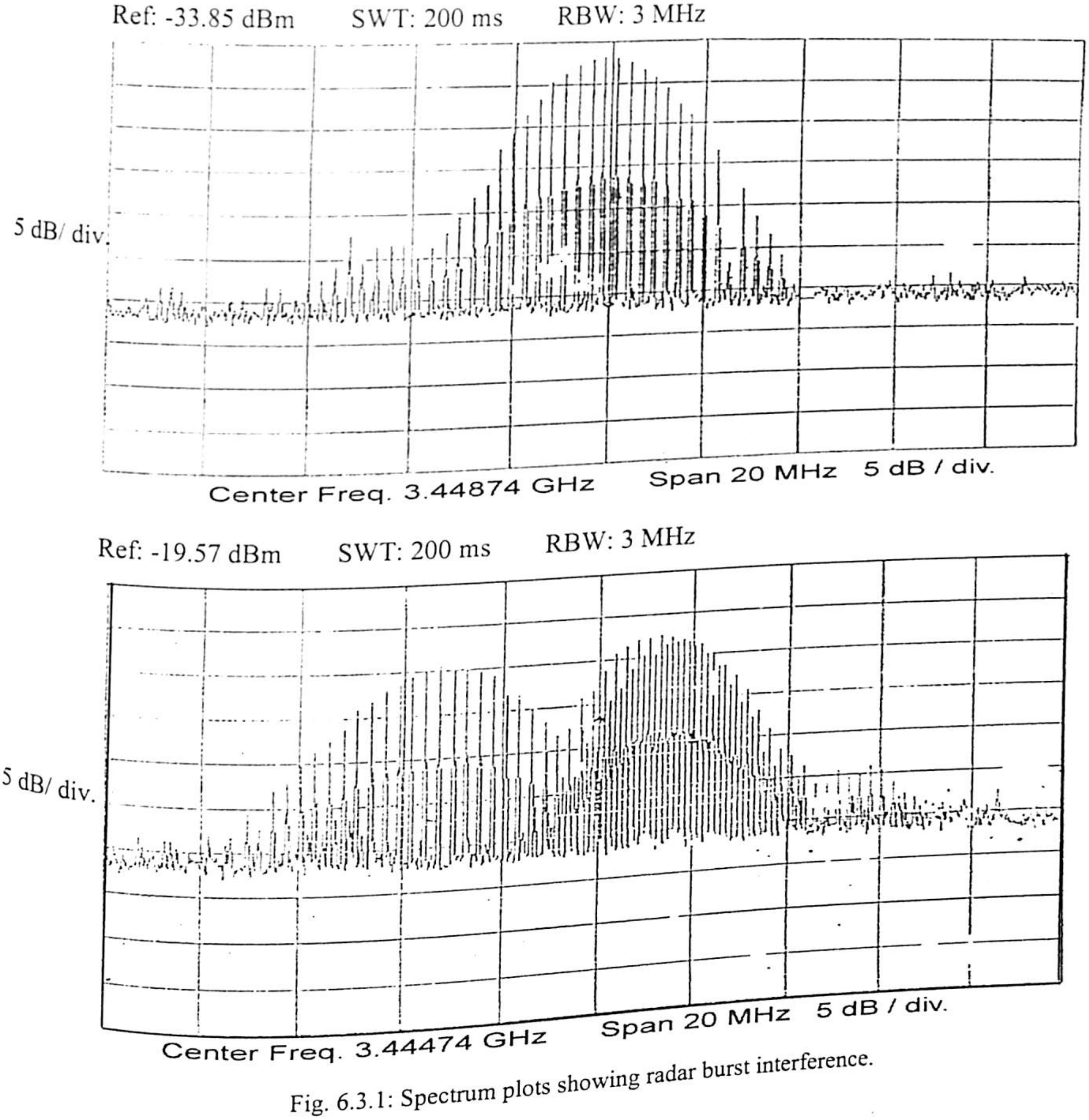


Fig. 6.3.1: Spectrum plots showing radar burst interference.

6.3.3 Initial analysis

The following tests were carried out to confirm whether the interference was due to an uplink or due to the downlinks of other satellites:

1. Observations involving multiple Stations, which are geographically separated (Beijing, MCF and VSNL Chennai) – If the interference reaches the satellite through the uplink and gets translated to the downlink frequencies, then the

Stations, which are widely separated geographically, receive the same interference. If the interference is downlink interference, all stations will not be affected equally.

2. Checking for receiver front end overload
3. Varying on board attenuator and monitoring the variation in the level of interference signals.
4. Monitoring the downlink spectrum with transponder OFF. If the interference originated through the uplinks, then the interference disappears when the transponder is made off. The interference will be present in the downlink signals if its origin is in the downlink of other satellites.

The results of the above tests confirmed that the interference was uplink interference, reaching INSAT-2E from some unknown ground terminal / radar.

6.3.4 Characterization of Interfering Radar

6.3.4.1 Characteristics of interfering radar

The downlink signals were monitored to characterize the radar bursts. Higher resolution bandwidth was used on spectrum analyser to capture the line spectrum of typical (Sin x / x) shape. Similarly zero span option of the spectrum analyser was used to capture the reconstructed radar pulses in time domain. Fig. 6.3.2 gives the spectrum plot showing the line-spectral components; and Fig. 6.3.3 gives the detected interference signal pulse shape. Fig. 6.3.4 gives the scan rate of the radar.

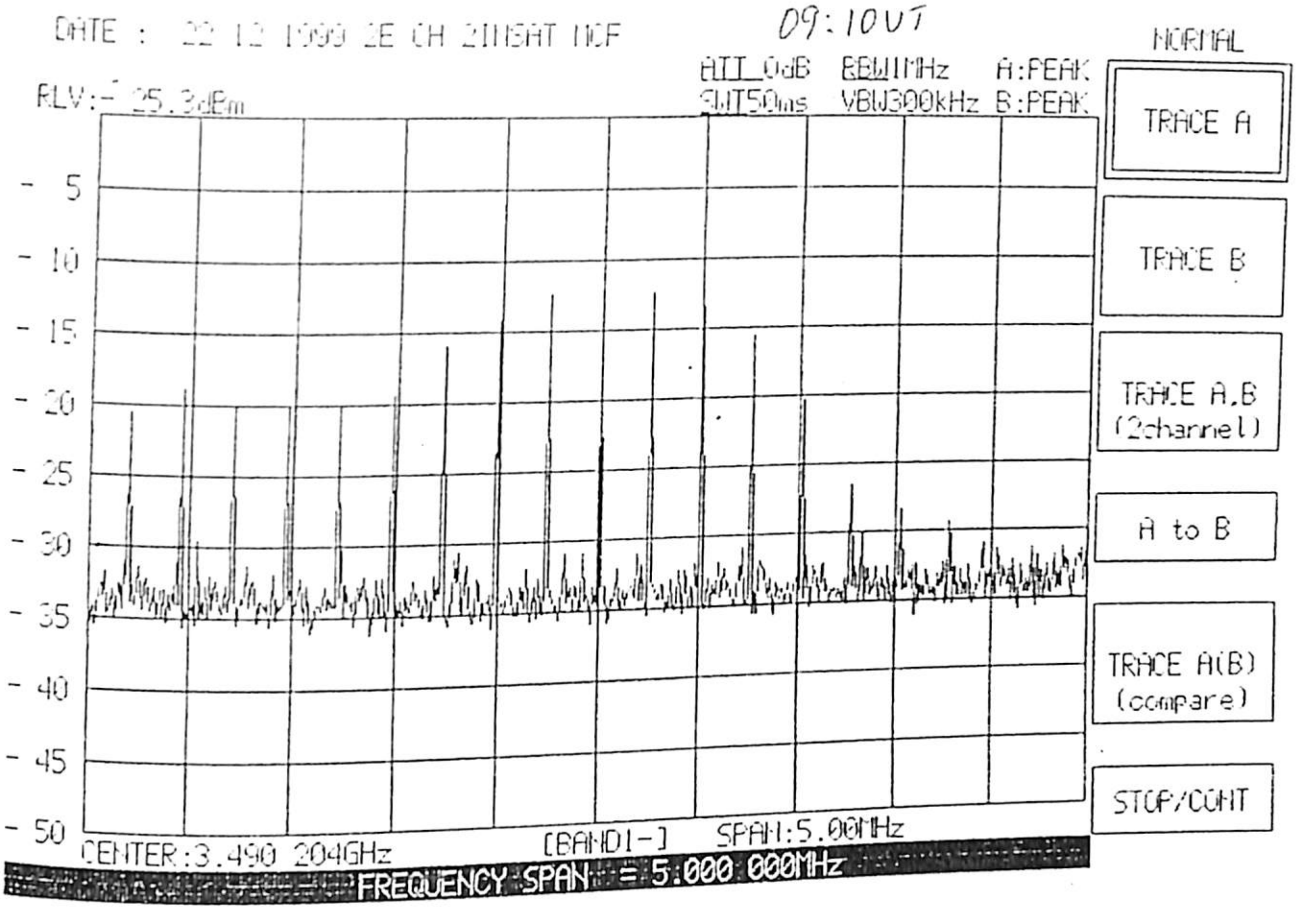


Fig. 6.3.2: Spectrum plot of line-spectral components

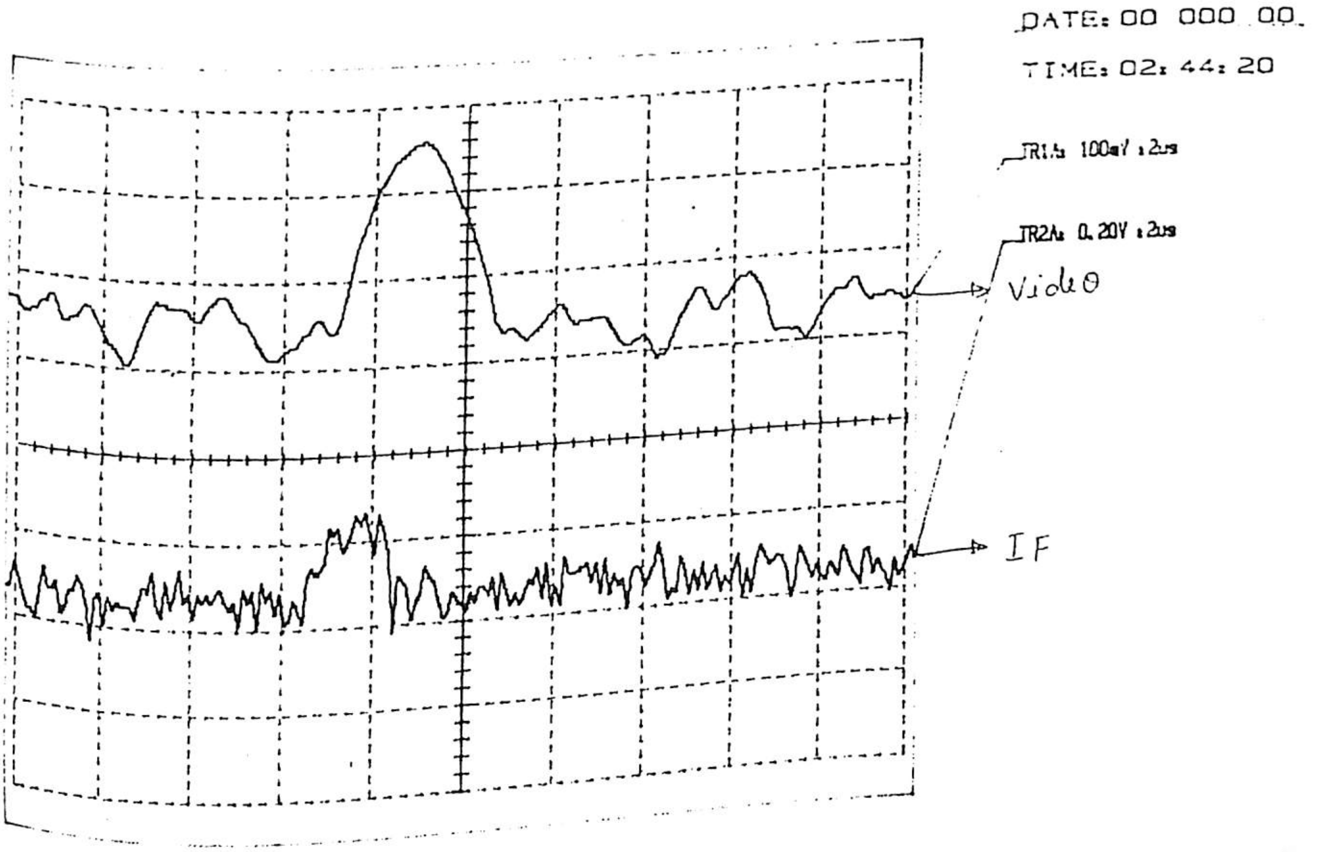


Fig. 6.3.3: Spectrum plot of detected interference signal pulse shape

Based on these measurements the characteristics of the radar, generating the interference, were estimated. Table-6.3.1 gives the characteristics of the radar, captured using spectrum analyser.

Table-6.3.1: Characteristics of interfering radar

Pulse width	2 to 5μ sec
PRF	350 to 400 Hz
Scan rate	15 to 18 RPM
EIRP towards Satellites	48 dBW

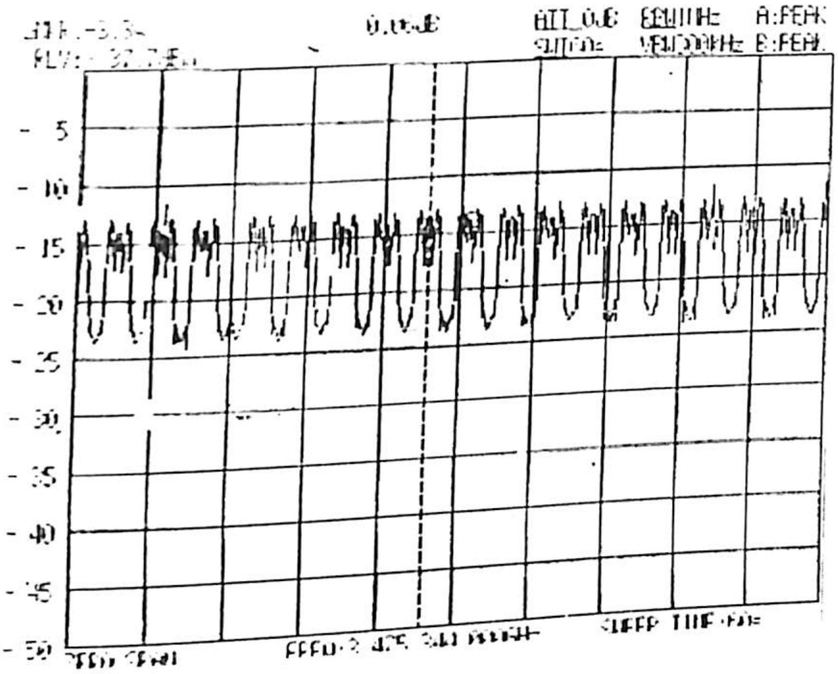


Fig. 6.3.4: Radar Scan rate measurement

6.3.4.2 Estimation of Radar EIRP

A pulse modulated signal was injected at the LNA of the receiving station, and the level was adjusted to match the line spectrum observed in the interference. Thus the downlink signal level was estimated. This value was translated to the satellite EIRP, and the power level of the interfering radar was estimated. Table-6.3.2 gives the calculations and the estimate of the power of the interfering radar.

Table-6.3.2 : Calculation of power of interfering radar

Injected level of the modulated signal at LNA input	-47.74 dBm
Offset factor (from LNA inject point to the satellite including path loss)	83.9
Spacecraft EIRP	4.24 dBW
Earth Station EIRP to achieve 4.24 dBW at spacecraft	48 dBW (approx)
1m antenna gain at 6 GHz	35 dB
Power required	13 dBW (20 W)
Pulse width	4 micro seconds
Pulse repetition	2.5 ms (400 Hz)
Peak power	12.5 kW

6.3.4.3 RFI-free zone for radar interference

The scanning radars operating within an upper limit of elevation angle cannot view the satellites in GSO, if the radar is too close to the nadir point of the satellite. [12] Hence, a RFI-free zone (RFZ) exists as a circle of radius r with the sub-satellite point of the affected satellite as the centre. Based on the RFZ, certain geographical area can be eliminated in the geo location process. This is explained earlier in Chapter 3, section '3.2.1 Ground-based radar transmitters'.

The radius of RFZ is given by:

$$r = R_e \cos\left[\varphi_{\max} + \sin^{-1}\left(\frac{R_e}{R_{GEO}}\cos\phi_{\max}\right)\right] \qquad (1)$$

R_e = radius of Earth

R_{GEO} = radius of Geostationary orbit

$\phi_{\max}$ = Maximum elevation angle of the radar.

The value of RFZ is computed for approximate operational elevations as below:

Elevation angle 10 deg $r = 6045$ km

Elevation angle 20 deg $r = 5620$ km

The above computation indicated that the radar causing interference should be at least 5600 km away from the sub-satellite point of the satellite being affected.

6.3.5 Radar interference coupling mechanism

Many types of Radars are used at airports, ships and at meteorological observatories. These radars operate in different frequency bands. The radar signals can reach the GSO satellites, if the operating elevation angle and distance (from the sub-satellite point) to the radar match the required conditions. The Radar signals can also reach the satellites through the antenna side lobes, if the transmitter power is sufficiently high.

Fig. 6.3.5 gives schematic view of Radar interference coupling mechanism to the GSO satellites.

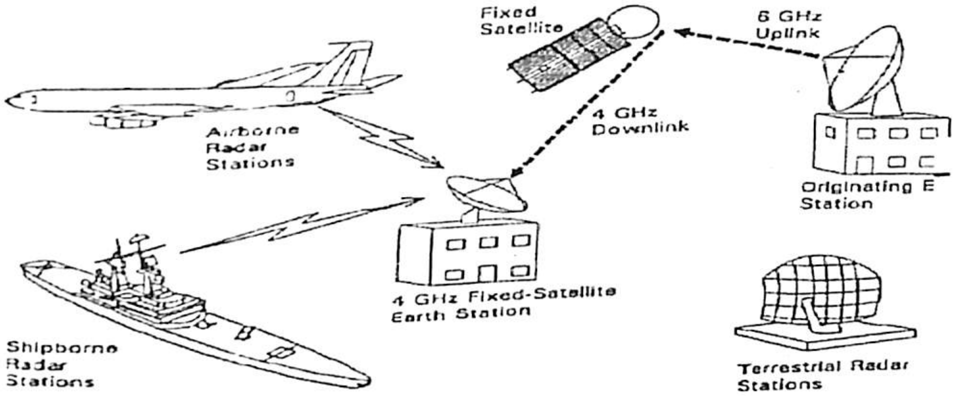


Fig. 6.3.5 Radar interference coupling mechanism

The general characteristic of the Radars in use were verified to check which type could be the potential source of the interference. Table-6.3.3 below gives the details of the Radars, collected from the literature.

Table-6.3.3: Types of Radars in use and their characteristics		
Radar Type	**Radar Use**	**Typical characteristics**
ASRs	Airport surveillance	Freq. : 2700-2900 MHz Pulse width : Usually 1 μ Sec PRF : 1000 to 1100 Peak power : 400 kW
ARSRs	Long-range detection; Air-route surveillance	Freq. : L-band, 1215 to 1400 MHz Pulse width : 2 μ Sec PRF : 350 Peak power : 4 MW
FPS type	Height finding Radars	Freq. : 2730 to 2800 MHz Pulse width : 2 to 4 μ Sec PRF : 300 to 400 Peak power : 4 to 5 MW
WSR type	Weather Radars	Freq. : C-band, 5540 to 5640 MHz S-band, 2840 to 2890 MHz Pulse width : 2 to 4 μ Sec PRF : 160 to 320 Peak power : 500 kW

None of the known type of radars as listed above operate in the frequency band to create interference to INSAT-2E i.e., in 6450 to 6650 MHz range. However, three possibilities existed as below:

- The radar transmitters can generate spurious signals much beyond their operating range. The coaxial magnetrons used in some of the Radars can be the source of spurious signals. Some of the C-band weather Radars were found to generate spurious beyond 5700 MHz range. [13]
- The frequency band of 5925 to 6700 MHz is allotted to 'Mobile Services' in addition to 'Fixed Satellite (Earth-to-Space)' by ITU. The Mobile services, in principle, include mobile earth stations, maritime mobile service, and aeronautical mobile services. Hence, interference can be from a radar being used for mobile services.
- Military Radars were suspected to be working in this band with advanced features like frequency hopping, which was observed during the interference monitoring.

The estimated peak power of the radar interference was a high value of 12.5 kW, which eliminated the possibility of spurious signal as the cause of interference. The estimated peak power of interference was 16 to 25 dB below the operational peak power of the radars given in Table 6.3.3, which indicated the interference could be reaching INSAT-2E through one of the side lobes of the radar antenna.

Hence, it was decided to carry out TDOA measurements to geo-locate, at least approximately, the operational area of interfering radar.

6.3.6 Localization of source of interference through measurements

6.3.6.1 TDOA Measurements

Measurement of Time Difference of Arrival (TDOA) and Frequency Difference of Arrival (FDOA), and analysis of the data is being used to localize the source of interference. During the investigation of the present problem, 'TDOA-only' measurements were carried out with two pairs of satellites, and the locus on which the source of interference could lie was plotted. The TDOA measurements were carried out using INSAT-2E (83 deg E orbital slot) and ST-1 (88 deg E orbital slot) as one pair, and with INSAT-2E and Thaicom-3 (at 78.5 deg E orbital slot) as another pair of satellites.

Since the interference from unknown radar was affecting the three satellites, which are separated by 10 deg of orbital arc, the TDOA value with each pair of satellites could be used to generate two loci on the surface of the earth. The intersection / convergence of the loci could indicate the approximate location of the source of interference.

The results of the TDOA measurements are given in Table-6.3.4 and 6.3.5.

Table-6.3.4: TDOA measurement for radar interference on INSAT-2E and ST-1

RF FREQ (MHz)	TDOA with 2E leading (m.sec)	TDOA with ST-1 leading (m.sec)	TDOA Distance With 2E leading (km)	TDOA Distance With ST-1 leading (km)	path Distance With 2E leading (km)	path Distance With ST-1 leading (km)
6559	1.215	1.305	364.5	391.5	260	495

Table-6.3.5: TDOA measurement for radar interference on INSAT-2E & THAICOM-3

RF FREQ (MHz)	TDOA with 2E leading (m.sec)	TDOA with THAICOM leading (m.sec)	TDOA Distance With 2E leading (km)	TDOA Distance With THAICOM leading (km)	path Distance With 2E leading (km)	path Distance With THAICOM leading (km)
6552	1.46	1.125	438	337.5	462	314

6.3.6.2 Geo-location of the source of interference

The TDOA values were used in geo-location software. The approach used in the software is as below:

- The value of Time Difference of Arrival (of interference signals through two satellites) is due to the difference between the range from the unknown interference source to each satellite (i.e., uplink range) and from satellites to the measurement site (i.e., downlink range).
- The downlink range is calculated for each satellite to the measurement site, with the knowledge of the orbital location of the concerned satellite. Through this step, the TDOA value is converted to the difference in the uplink ranges from unknown source to both the satellites in the pair. (As described in section 5.1.1)
- One location with a longitude value, latitude value and height (above the mean sea level) for the interference source is assumed, and the uplink ranges to the two satellites are computed. If the difference of the uplink ranges matches with the uplink range difference computed from the TDOA value, the assumed location is logged as one point of the locus on the surface of the earth.

The process is repeated for different values of longitude and latitude, within the ranges defined, to obtain number of points of the locus. The height of the interference source (above the mean sea level) was used consistent with the measurement error possible in the TDOA values.

6.3.6.3 Results of the geo-location

The result of the geo-location software, with the TDOA values measured with each pair of satellites, is given in Fig. 6.3.7. The loci indicated the approximate location of the radar, which was causing interference. The distance as indicated by the intersection / convergence of the loci from the sub-satellite point was also consistent with the computation given in section 6.3.4.3, and was approximately 7000 km from the sub-satellite point of INSAT-2E.

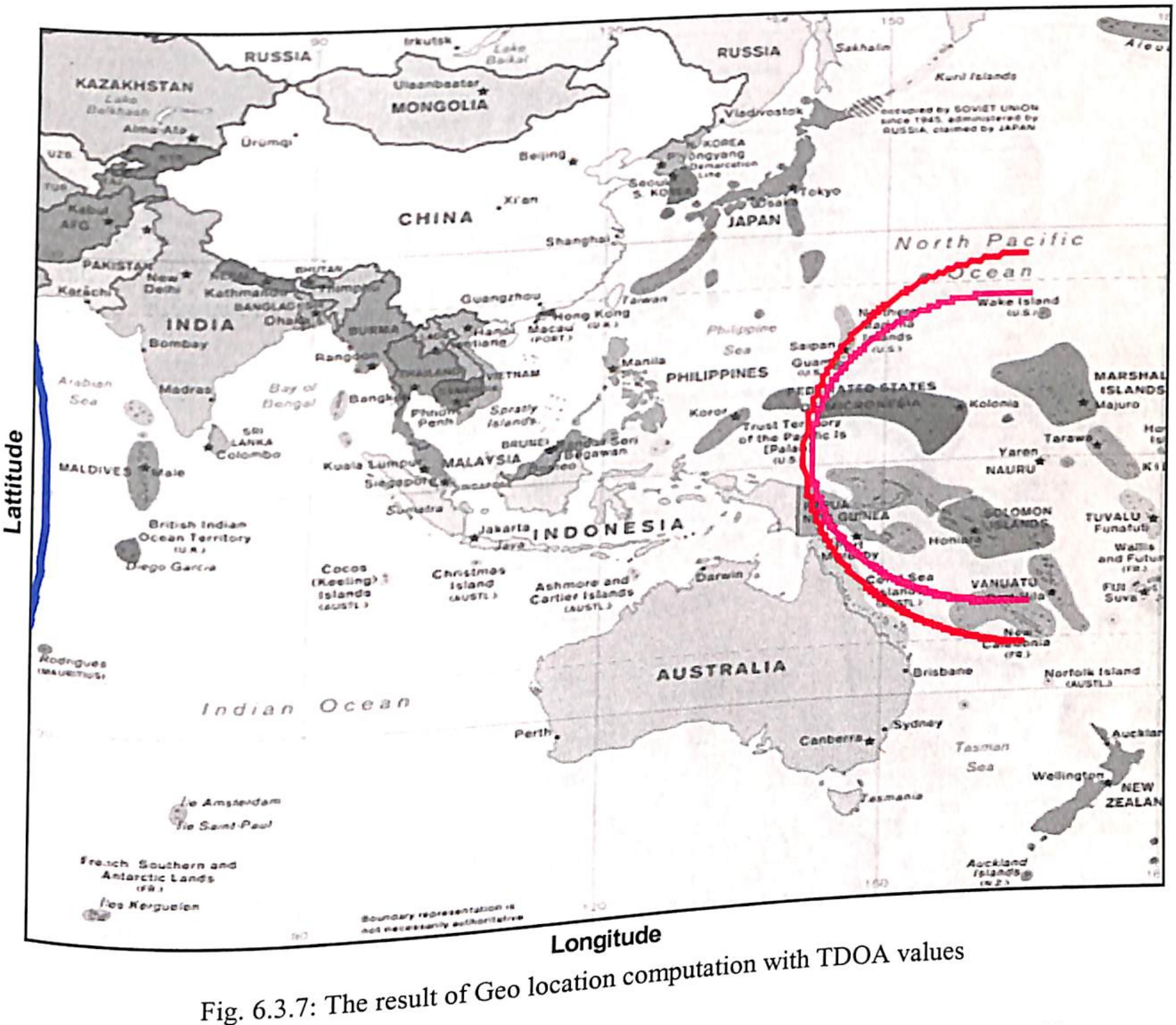


Fig. 6.3.7: The result of Geo location computation with TDOA values

The approximate location of the interfering Radar was identified as Guam and forwarded to Regulatory authorities. The Interference ceased with in a month of reporting the approximate location of the source to the FCC of USA.

6.3.6.3 Results of the geo-location

The result of the geo-location software, with the TDOA values measured with each pair of satellites, is given in Fig. 6.3.7. The loci indicated the approximate location of the radar, which was causing interference. The distance as indicated by the intersection / convergence of the loci from the sub-satellite point was also consistent with the computation given in section 6.3.4.3, and was approximately 7000 km from the sub-satellite point of INSAT-2E.

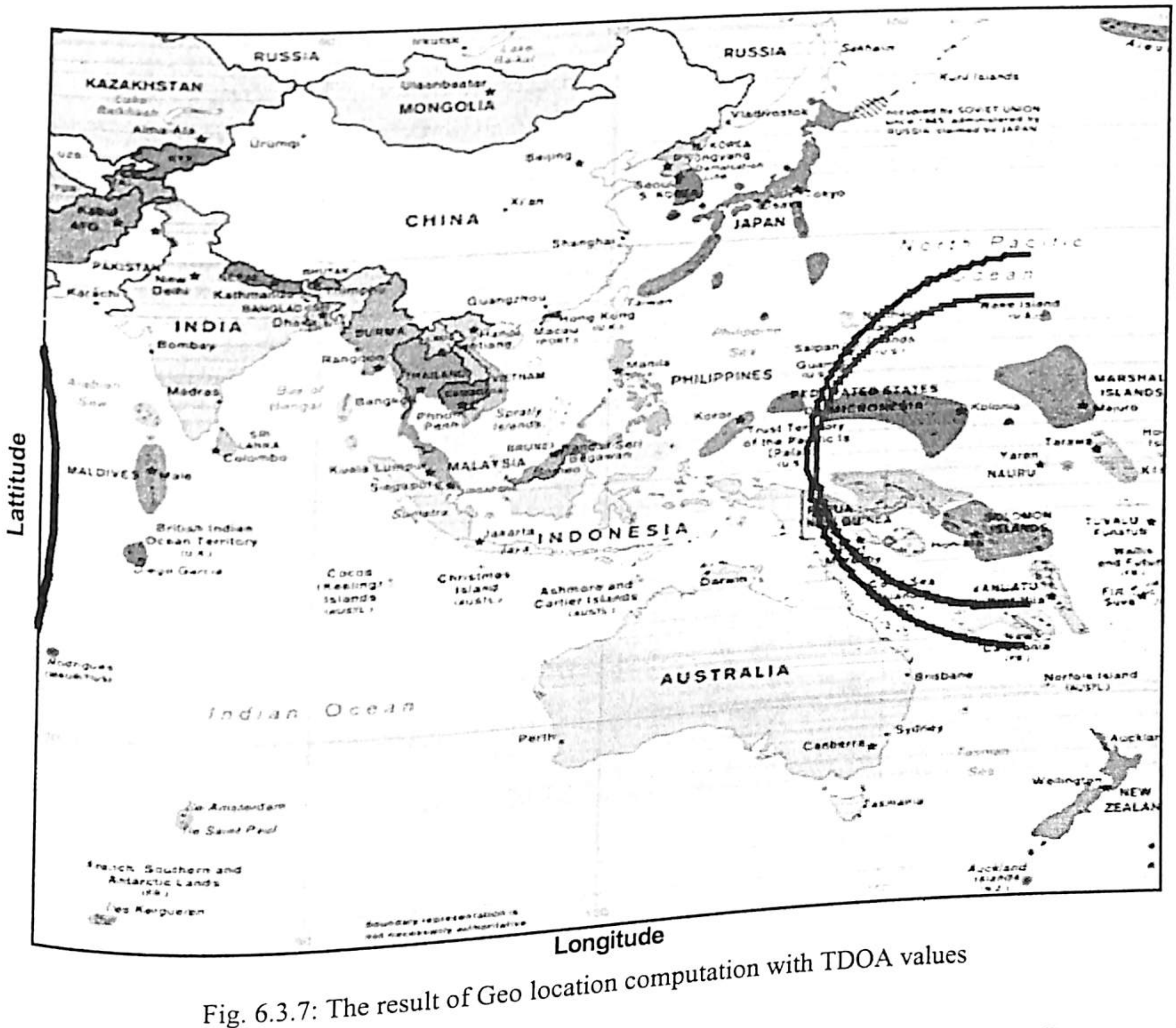


Fig. 6.3.7: The result of Geo location computation with TDOA values

The approximate location of the interfering Radar was identified as Guam and forwarded to Regulatory authorities. The Interference ceased with in a month of reporting the approximate location of the source to the FCC of USA.

6.4 Case Study-3: Wideband Noise Interference In Satellite Channels

6.4.1 Introduction

One of the transponders of INSAT-3C carrying VSAT networks, experienced 5 to 6 dB degradation in the E_b/N_o value. This variation caused disruption to the traffic (carrying low data rate signals). The E_b/N_o degradation for the carriers in a transponder can happen due to:

- Degradation of the EIRP of the transponder.
- Rise in the noise floor due to over drive in the allotted adjacent bandwidth.
- Interference from ground terminals.

It was decided to investigate the problem and identify the cause.

6.4.2 Preliminary investigation

It was verified that E_b/N_o degradation was not caused by overdrive by checking the uplink transmit levels of different Operators who were allotted bandwidth in the transponder.

It was planned to verify the EIRP of the transponder to rule out the possibility of degradation of transponder performance. A test with shutdown of networks in the transponder was planned for this purpose. During this test, when all networks were shutdown, a wide band disturbed noise floor with a peak amplitude of 10 dB was observed. Spectrum plots for the transponder, when carriers of all the Operators were brought down is given in Fig. 6.4.1. The spectrum plot showed the following details:

- An uneven rise in noise floor with peak-to-peak variation of around 10 dB.
- Two unknown carriers with roughly 18 dB and 6 dB C/N value.

EIRP measurement was not possible in the presence of this type of disturbed noise floor. However, it was decided to verify whether the rise in the noise floor level was due to any degradation of the transponder or due to the presence of extra noise in the input signals to the satellite.

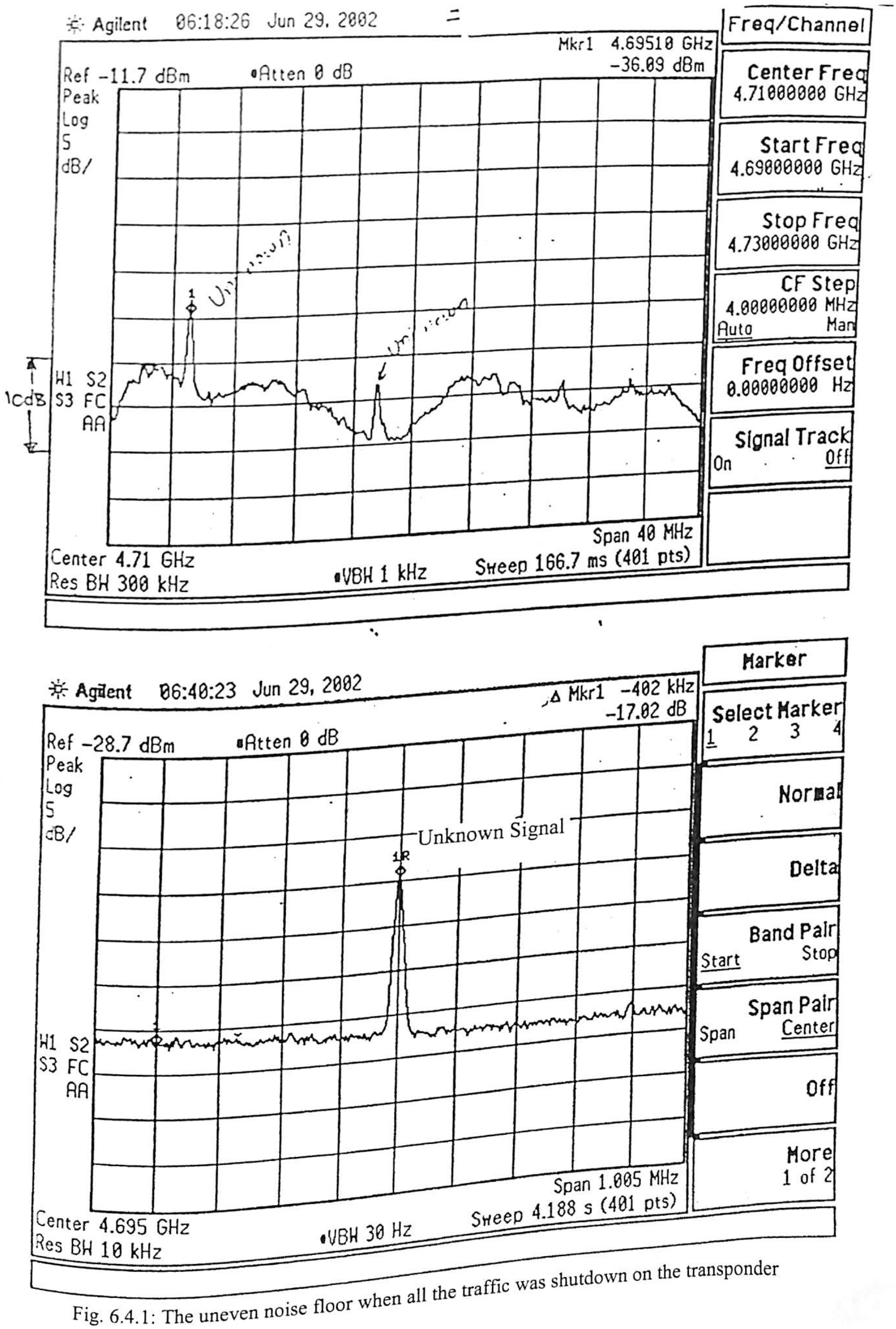
Onboard attenuation for the affected transponder and the adjacent transponder were varied and spectrum plots showed corresponding change in downlink noise floor. (Fig. 6.4.2). The spectrum plots also showed a rise in the noise floor in the upper end of the adjacent transponder. (Fig. 6.4.3).

This test indicated that the additional noise was present at the input of the transponder, and could most probably due to the noise being generated and being uplinked from one of the ground terminals. The presence of the noise in a part of the adjacent transponder also indicated that the source was generating wideband noise.

The degradation of E_b/N_o was basically from the rise of the noise floor, which in turn could be due to noise being uplinked over 60 MHz bandwidth. Simulations were carried out to identify the wideband noise generation and coupling mechanism.

6.4.3 Simulation, Analysis & Identification of Wideband Noise Coupling Mechanism from ground terminals

(A) A low level carrier was uplinked to the affected transponder, and the downlink was monitored. Multiple downlink returns were observed for the single uplink carrier (Fig. 6.4.4). The multiple returns observed in the downlink had to be explained. Hence, the downlinks spectral components (i.e., multiple returns) were analyzed carefully for the frequency offset, and time delay.


Agilent 06:18:26 Jun 29, 2002

Mkr1 4.69510 GHz
-36.09 dBm

Ref -11.7 dBm
Atten 0 dB
Peak
Log
5
dB/

H1 S2
S3 FC
AA

Center 4.71 GHz
Res BW 300 kHz
VBW 1 kHz
Span 40 MHz
Sweep 166.7 ms (401 pts)

Freq/Channel
Center Freq 4.71000000 GHz
Start Freq 4.69000000 GHz
Stop Freq 4.73000000 GHz
CF Step 4.00000000 MHz Auto Man
Freq Offset 0.00000000 Hz
Signal Track On Off

Agilent 06:40:23 Jun 29, 2002

Δ Mkr1 -402 kHz
-17.02 dB

Ref -28.7 dBm
Atten 0 dB
Peak
Log
5
dB/

H1 S2
S3 FC
AA

Center 4.695 GHz
Res BW 10 kHz
VBW 30 Hz
Span 1.005 MHz
Sweep 4.188 s (401 pts)

Marker
Select Marker 1 2 3 4
Normal
Delta
Band Pair Start Stop
Span Pair Span Center
Off
More 1 of 2

Fig. 6.4.1: The uneven noise floor when all the traffic was shutdown on the transponder

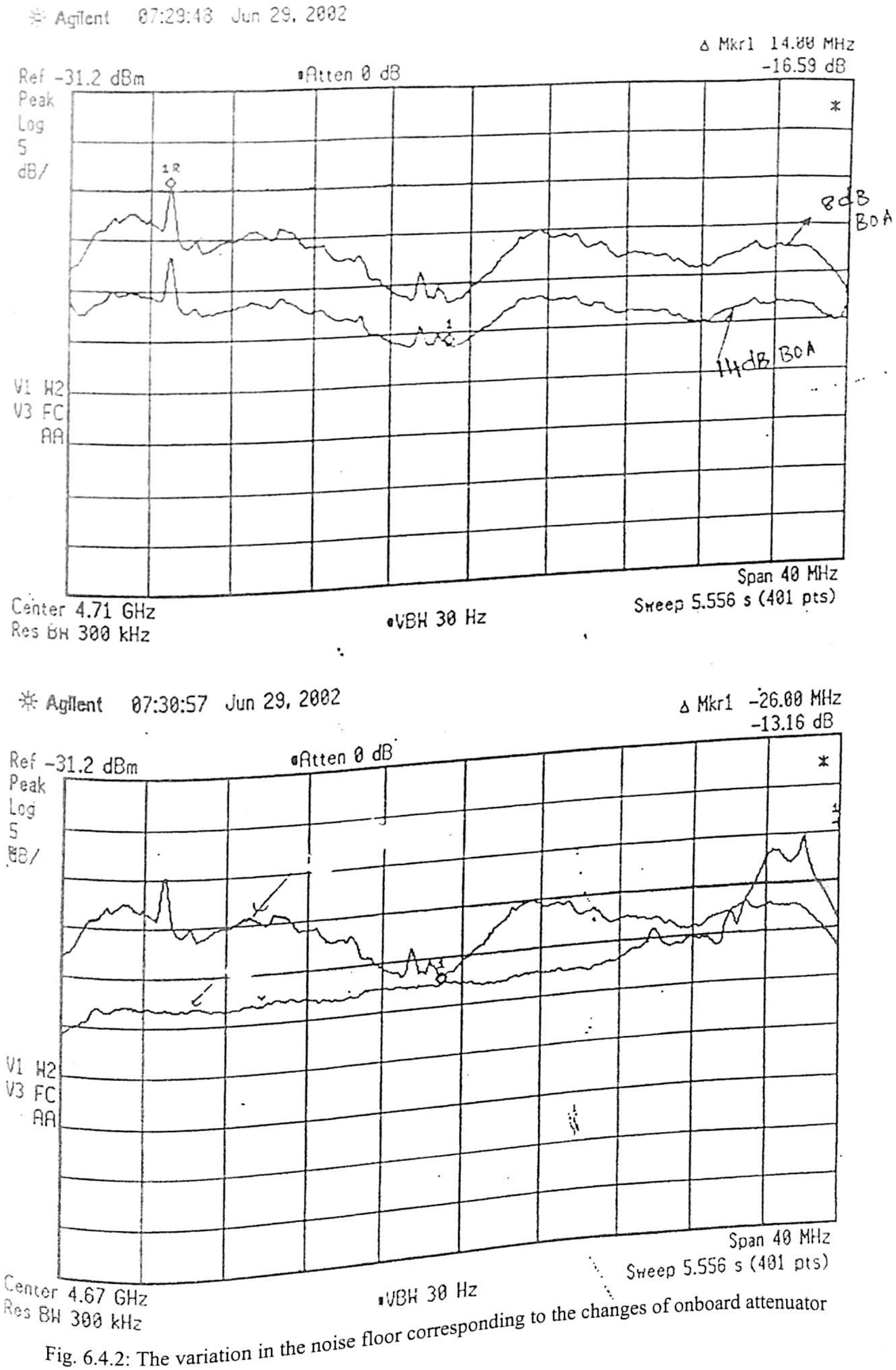


Fig. 6.4.2: The variation in the noise floor corresponding to the changes of onboard attenuator

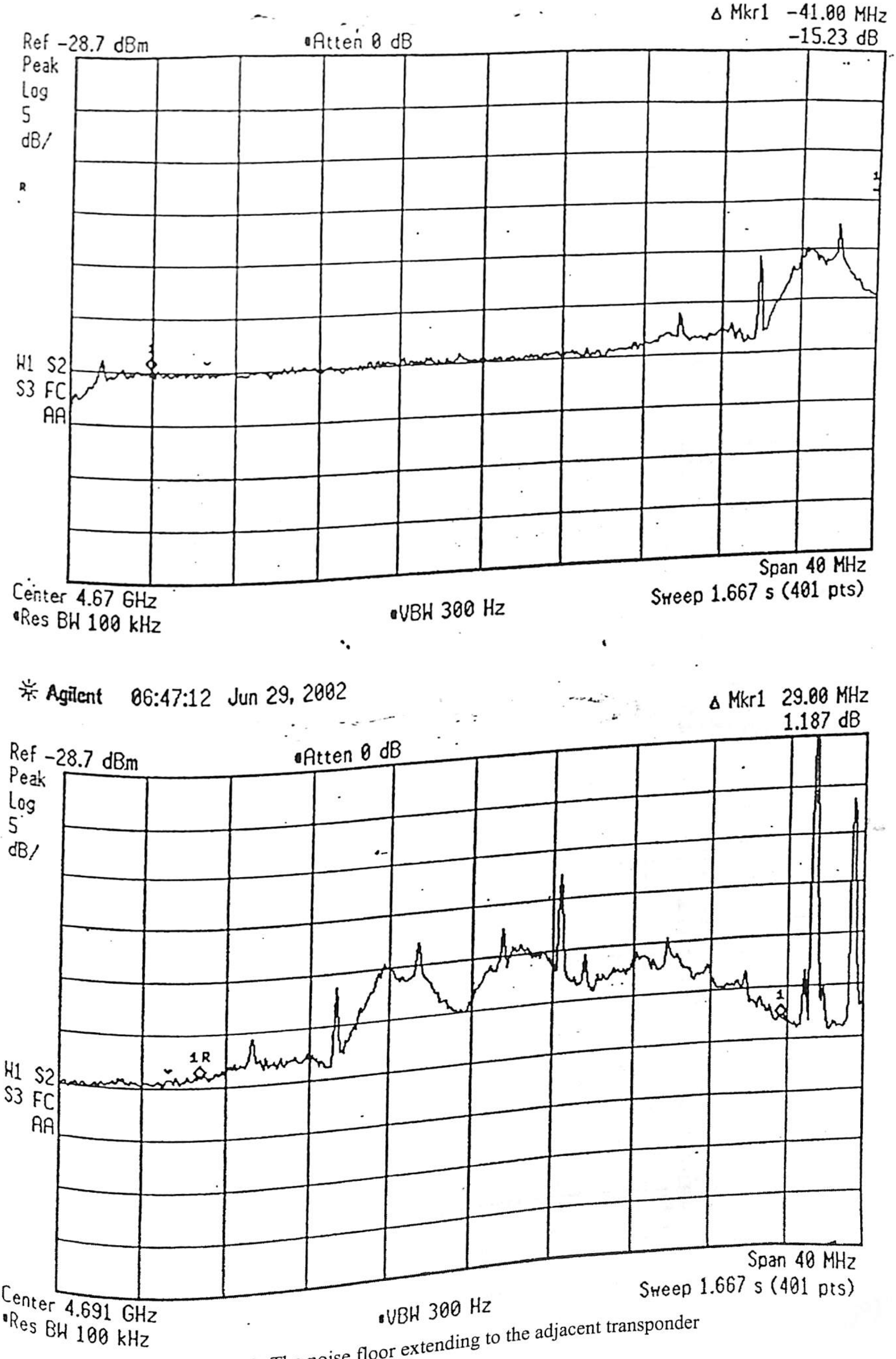
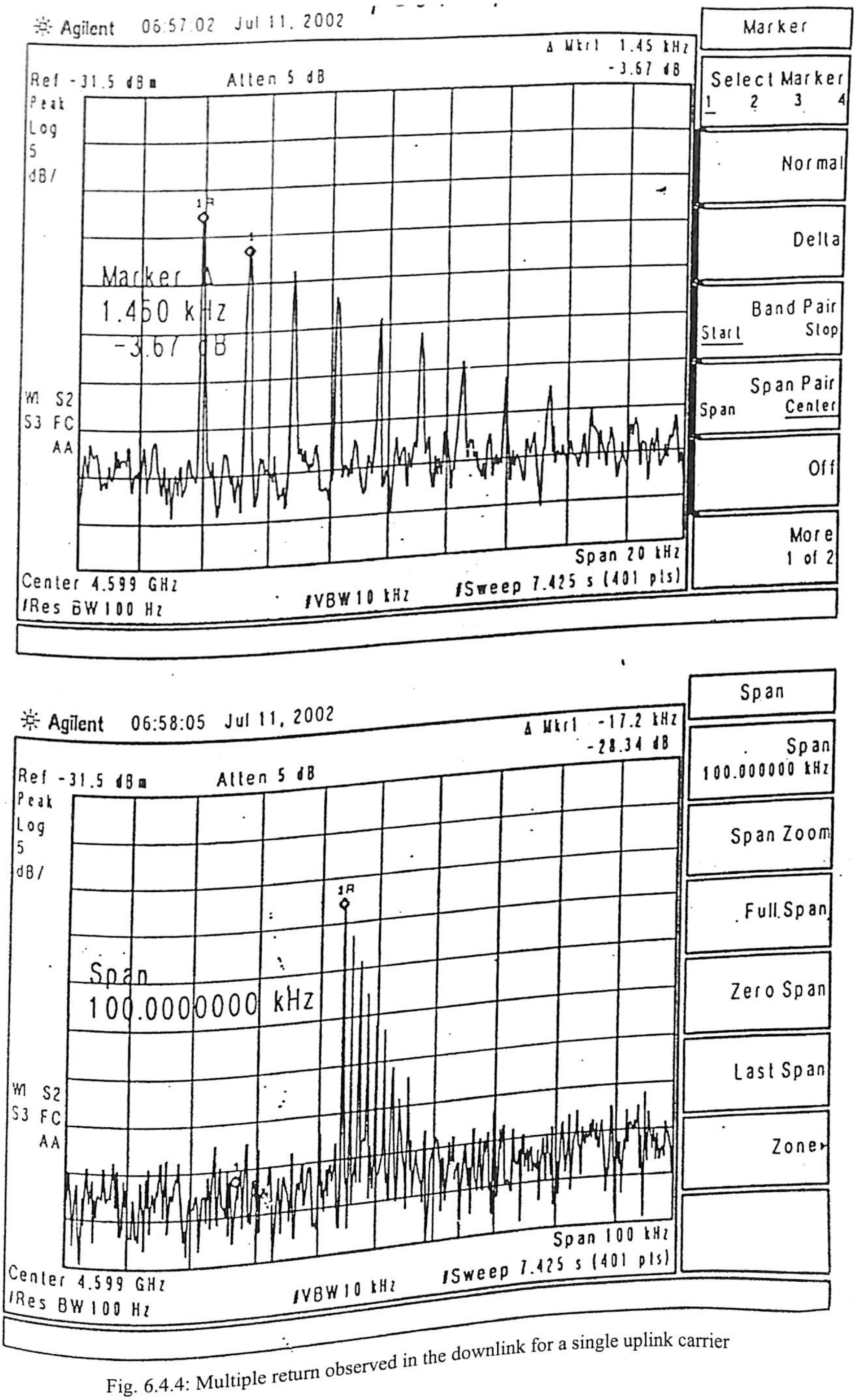


Fig. 6.4.3: The noise floor extending to the adjacent transponder



Agilent 06:57:02 Jul 11, 2002

Δ Mkr1 1.45 kHz -3.67 dB

Ref -31.5 dBm Atten 5 dB

Peak Log 5 dB/

Marker Δ 1.450 kHz -3.67 dB

W1 S2 S3 FC AA

Center 4.599 GHz

#Res BW 100 Hz #VBW 10 kHz

Span 20 kHz

#Sweep 7.425 s (401 pts)

Agilent 06:58:05 Jul 11, 2002

Δ Mkr1 -17.2 kHz -28.34 dB

Ref -31.5 dBm Atten 5 dB

Peak Log 5 dB/

Span 100.0000000 kHz

W1 S2 S3 FC AA

Center 4.599 GHz

#Res BW 100 Hz #VBW 10 kHz

Span 100 kHz

#Sweep 7.425 s (401 pts)

Fig. 6.4.4: Multiple return observed in the downlink for a single uplink carrier

Fig. 6.4.5 shows the typical block diagram of IF loop-back in a satellite communication terminal.

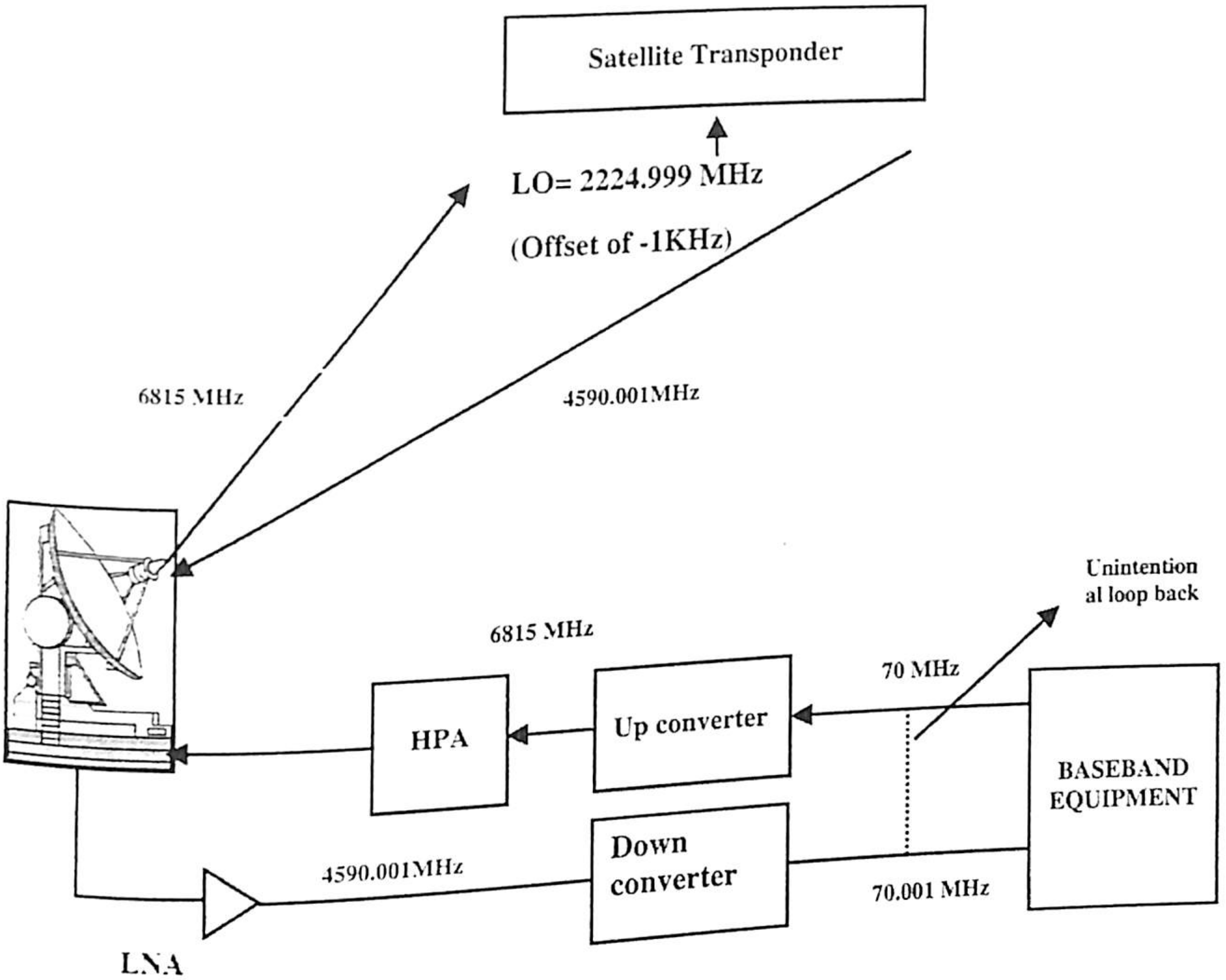


Fig. 6.4.5: Block diagram of IF loop-back in satellite communication terminal

Ideally, when a carrier frequency (say 6815 MHz) is uplinked to transponder, a downlink carrier at (4590.001 MHz) frequency only should appear. The downlink signal frequency should be lower than uplink frequency by an amount equal to onboard LO (2224.999MHz) i.e. Downlink Frequency = (Uplink frequency-onboard LO). If the terminal is tuned for 6815 MHz uplink frequency and 4590 MHz downlink frequency, it will have 70 MHz at its uplink IF and 70.001MHz at its downlink IF.

If an unintentional loop back at an IF frequency is assumed in this terminal, multiple uplinks with offset in frequency by 1KHz (corresponding to onboard LO offset) will occur. The Table-6.4.1 shows the multiple uplink frequencies which will get generated in the event of IF loop back at this terminal and the corresponding downlink and IF frequencies.

Table-6.4.1: The Uplink and Downlink Frequencies if a loop back at IF is present at the ground terminal

S/L No.	Uplink IF (MHz)	Uplink Frequency (MHz)	On-board LO (MHz)	Downlink Frequency (MHz)	Downlink IF (MHz)
1	70.000	6815.000	2224.999	4590.001	70.001
2	70.001	6815.001		4590.002	70.002
3	70.002	6815.002		4590.003	70.003
4	70.003	6815.003		4590.004	70.004

And so on.....

This analysis explained the presence of multiple returns should be due to a loop back at one of the ground terminals. The resulting rise in the noise could have caused degradation of E_b/N_o when the traffic is present.

(B) A simulation was carried out with an intentional loop-back at IF level of the MCF ground terminal by directly patching the down converter output to up converter, and uplinking the signal to another spare transponder.

The wide band noise (similar to that observed in transponders 5 and 6) was observed on this test transponder (Fig. 6.4.6 and 6.4.7). The amplitude of this noise was found to have direct relation to the EIRP capability of the ground terminal. The response of this noise floor also varied with mismatch level at the ground terminal IF.

(C) Once the mechanism of noise generation was understood, the power level being transmitted by the culprit ground terminal was estimated to match with the observed noise floor rise in the downlink spectrum. The HPA power required to generate wideband noise of 10 dB peak-to-peak amplitude in the downlink noise was measured at the antenna coupler. The EIRP of the ground terminal to generate wideband noise interference was estimated using the test results and Transmission equation as to be 60 dBW. By looking at this EIRP value, the VSAT and HUB terminals operating on this transponder were analyzed. Table-6.4.2 and 6.4.3 give the maximum EIRP capability of the VSATs and Network Hubs operating on this transponder.

Table-6.4.2: Estimation of EIRP of VSAT terminal

Antenna diameter (m)	1.2	1.8	3.8
Gain (dBi) @ 6815 MHz (66% efficiency)	36.8	40.4	46.9
Power output (dBW) 1) 5W	7.0	7.0	7.0
2) 20 W	-------	------	13.0
VSAT EIRP (dBW) max.	43.8	47.4	53.9 (5w) 59.9 (20w)

Table-6.4.3: The estimation of EIRP of Network Hubs

Antenna diameter (m)	7.2	9.0	11.0
Gain (dBi) @ 6815 MHz (66% efficiency)	52.4	54.6	56.0
Power output (dBW) 400 w	26.0	26.0	26.0
Wave guide loss (dB)	2.0	2.0	2.0
HUB EIRP (dBW) max.	76.4	78.6	80.0

The EIRP causing wideband noise interference was estimated earlier to be around 60 dBW. Hence, a 3.8 m terminal with 20W amplifier in the user network was suspected.

(D) An alert message was sent, to all the Operators, based on the above findings to verify and remove IF loops in the VSAT network sites. The problem disappeared within a few hours of alert message to the users. Thus it was concluded that an unintentional loop back at one of the user terminals caused the wide band noise problem.

The spectrum plots of disturbed noise floor and traffic, and normal noise floor plus traffic in the affected channels are given in Fig. 6.4.8a & 6.4.8b.

Conclusions

1. A big interference problem involving two transponders and nearly 3000 VSAT operators occurred for almost one month (June to July 2002) affecting the service severely. Coordinated tests and simulations gave clue to identify the possible source of interference.
2. A small VSAT terminal can create a wide band noise causing interference to whole of the transponder, if a loop back exists between uplink and downlink at any ground terminal.
3. The Interference coupling mechanism was identified through monitoring, testing and simulation.
4. Localization of terminal causing wideband noise interference, with large number of VSAT network spread across the country, requires understanding of network and co-operation from the Operators.

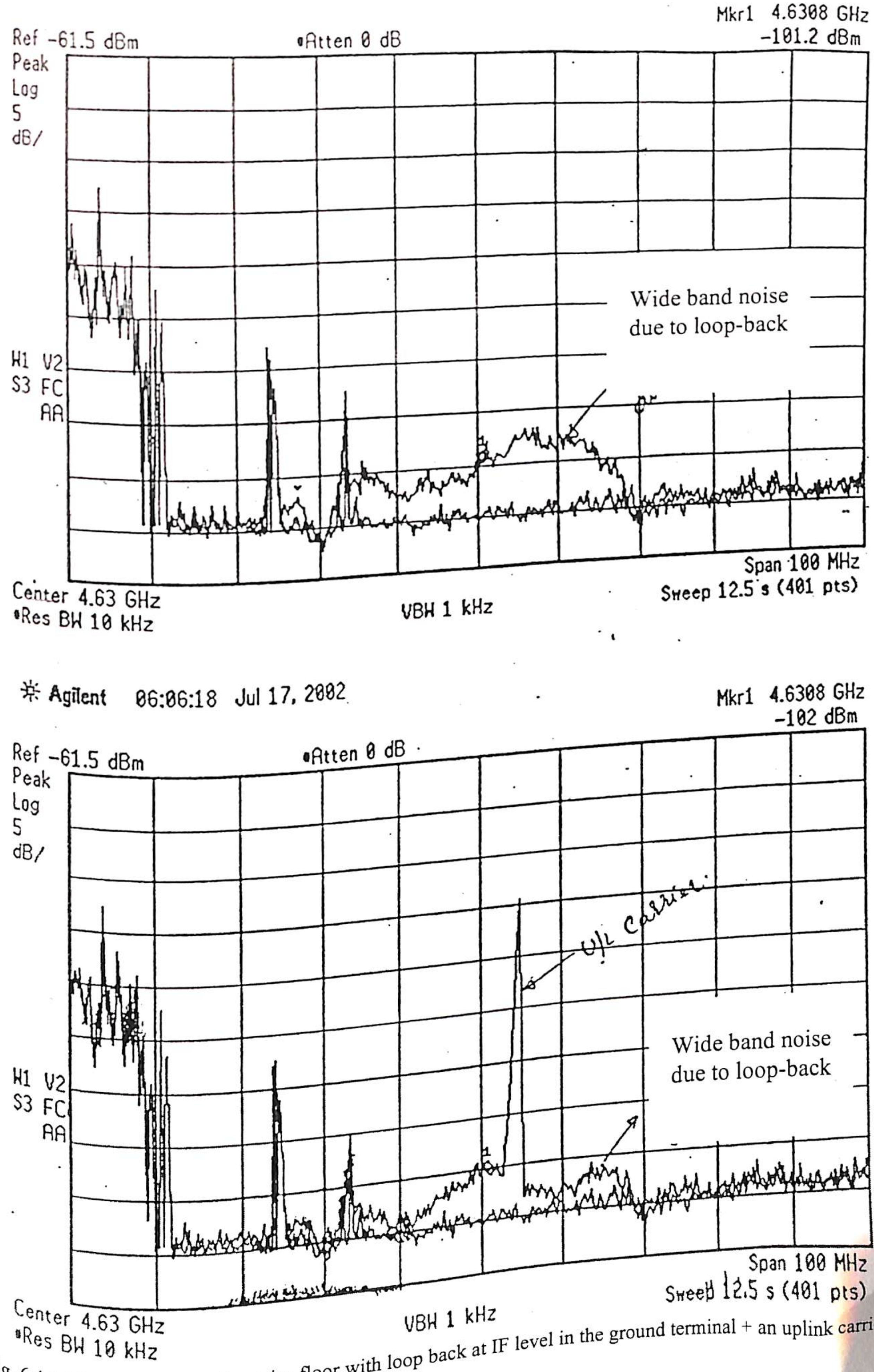
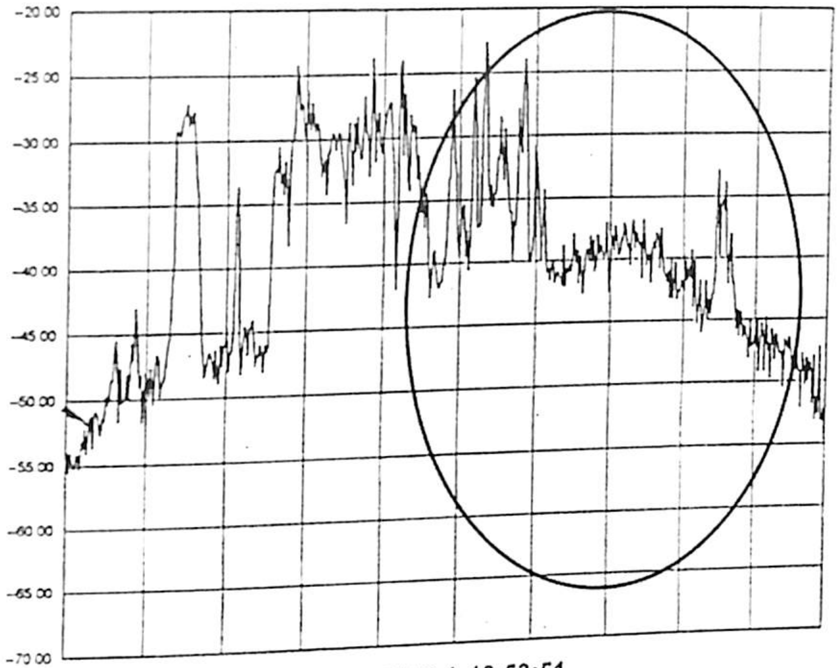


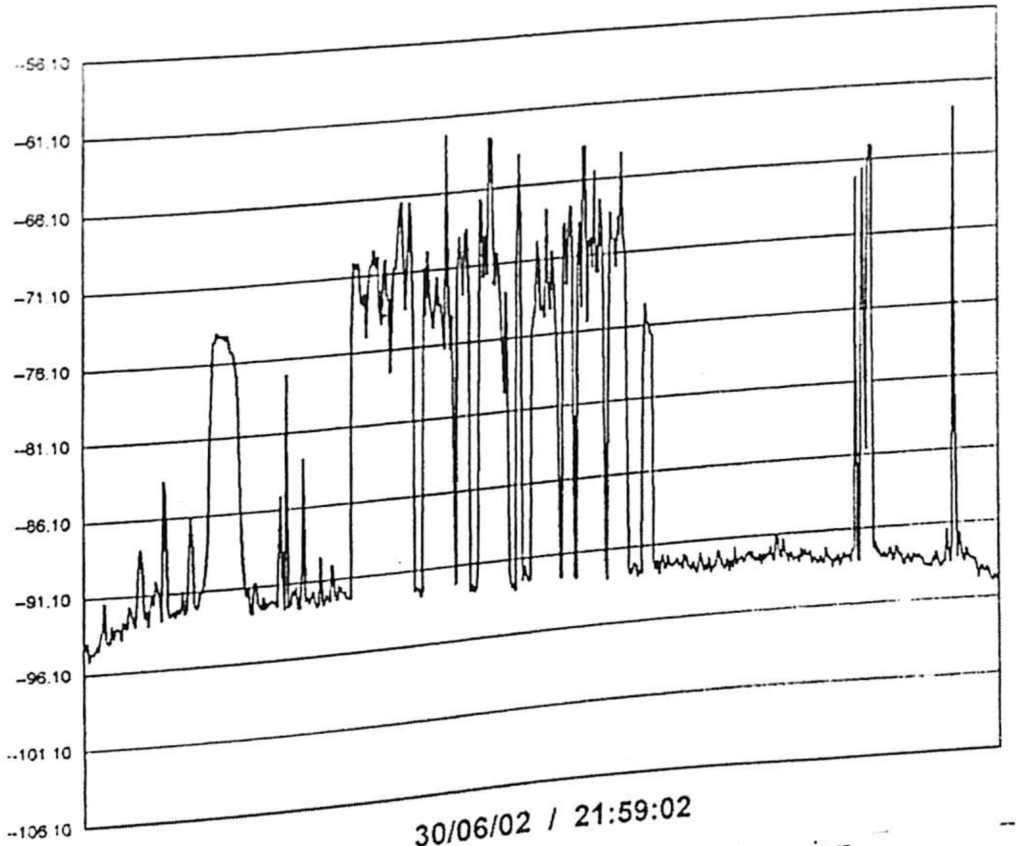
Fig. 6.4.7: The variations in the noise floor with loop back at IF level in the ground terminal + an uplink carrier



FREQ - 4.59 GHz
SPAN - 40 MHz
REF LVL - -20 dBm
ATTN - 0 dB
SCALE - 5 dB
RBW - 100 KHz
VBW - 100 KHz
MRKFRQ- 4.60424 GHz
MRKLVL - -35.33 dBm

06/07/02 / 10:53:51

Fig. 6.4.8a: Downlink spectrum plot – with disturbed noise floor, and traffic carriers



FREQ - 4.59 GHz
SPAN - 40 MHz
REF LVL - -56.1 dBm
ATTN - 0 dB
SCALE - 5 dB
RBW - 30 KHz
VBW - 300 Hz
MRKFRQ- 4.60408 GHz
MRKLVL - -65.12 dBm

30/06/02 / 21:59:02

Fig. 6.4.8b: Downlink spectrum plot – with normal noise floor, and traffic carriers

6.5 Case Study-4: Investigations into the wideband noise floor interference problem

6.5.1 Introduction

The INSAT System as on April 2003 had around 27000 VSATs operating in it, with bulk of the services operational in the Extended C-band transponders of INSAT-3B at 83 deg E, and INSAT-3C at 74 deg E. During the last week of June 2003, many VSAT service providers, working in the Extended C-band transponders of INSAT-3C, experienced degradation of the quality of service / disruption in their networks.

Some of the VSAT service providers (Customer #1 operating on transponders #25 & 26 and Customer #2 operating on transponder #29) of INSAT-3C complained of degradation / disruption of their network operations owing to abnormal rise in the noise floor in their operational bands. The noise floor rise reported was of the order of 5 to 6 dB, with an associated degradation in the E_b/N_o of the service carriers. No degradation in the absolute power levels was however reported.

6.5.2 Identification of Problem

The occupancy of Ext. C-band transponders by various VSAT service providers in the INSAT-3C satellite is given in Table-6.5.1:

Table-6.5.1 : Occupancy of transponders of INSAT-3C

Channel No.	VSAT Operator	Bandwidth Occupied (MHz)
25	Customer #1	36
26	Customer #1	22.5
	Customer #3	4.5
27	Spare	
28	Customer #4	18
	Customer #1	13.5
29	Customer #5	4.5
	Customer #6	4.5
	Customer #7	9.0
	Customer #7	8.5
	Customer #8	0.45
	Customer #2	9.0
30	Customer #9	9.0
	Customer #10	9.0
	Customer #11	9.0
	Customer #12	9.0

6.5.3 (A) Initial Analysis

- Preliminary observations at Master Control Facility (MCF) indicated a uniform rise in the noise floor spanning the whole of the Extended C-band. Comparison of spectrum plots with the reference plots taken during June 2002, with same measurement setup showed the rise in noise floor by 3 to 6 dB (Fig. 6.5.1 to 6.5.6). No degradation in the absolute power levels was however observed, indicating nominal onboard transponder gains.

- Network Operations Control Centre (NOCC) near Delhi, had, in the meanwhile, received complaints from Customer #2 about the noise floor rise in their operational band in transponder #29. Coordinated switch-off tests were conducted on the 28th June to ascertain the possibility of the noise being generated within their Network. There was, however, no change in the noise floor situation with the switch-off test.

- A spare transponder (Transponder #27) was available with 30 dB On-Board Attenuation (OBA). The OBA was changed to 8 dB and noise floor measurements were taken in this channel, which indicated a rise in the noise floor in this transponder also. The amount of noise floor rise with respect to nominal values, for individual transponders are given in Table-6.5.2.

Table-6.5.2 : Noise floor rise across transponders

Channel No.	OBA Setting (dB)	Rise in Noise Floor (dB)
25	6	5
26	6	6
27	8	4
28	8	5
29	8	3
30	8	4

- This type of uniform noise floor rise spread across the whole 240 MHz of the Extended C-band spectrum was seen for the first time. Also, 3 to 6 dB rise in noise floor with the traffic ON represents rise in noise floor of 12 to 15 dB without the traffic (presence of the traffic carriers usually suppress the noise floor level).

Rise in noise floor in the Extended C-band transponders occurred earlier during June-July 2002. However, the noise floor rise affected only two channels at a time during that period.

- The wide band noise coupling covering entire Ext. C-band was possible due to following two reasons:
  - Wide band noise interference from a ground VSAT terminal.
  - On-board receiver malfunction.

(B) Verification of Normalcy of Onboard Transponder

- To confirm the normalcy of the Spacecraft, the following tests were conducted on the vacant Transponder #27 using a 11m ground station terminal.
  - Saturated EIRP to validate nominal gains of the transponder.
  - Spacecraft G/T to validate the nominal Noise Figure at the front end.
- The tests indicated:
  - Nominal Gain of the transponder
  - Degradation in the Spacecraft G/T of the order of 12 dB. (-12 dB/deg K in place of original 0.34 dB/deg K during the earlier in-orbit tests)
- Degraded spacecraft G/T confirmed that the wideband noise is present at the input of the spacecraft. But still the source (Spacecraft or Ground terminal) could not be localized.
- It was decided to switch-on the redundant Receiver into operation and observe the impact on the noise floor to rule out the possibility of any degradation in the

onboard Receiver. There was no change in the noise floor with the change of the Receiver.

It was confirmed, through this test, that the source of the noise was not the onboard Receiver. All further tests were carried out with the original on-board Primary Receiver in the operational chain.

(C) Simulations at MCF

- Simulated tests were conducted at MCF to check whether any VSAT uplink with wideband front-end equipment could be causing the problem (owing to overdrive of the up converter/Wide band amplifier stage). Tests were conducted by transmitting onto the vacant transponder #27, with the up converter and final power ampler (TWTA) set for maximum gains. A noise floor rise of the order of 3 to 4 dB spread over about 80 MHz was observed under this condition.

  This condition of noise floor did not match with the reported problem with respect to affected bandwidth, mainly due to the 80 MHz filter existing in the up-converter used for the simulation test.

- RF link was estimated to characterize a ground terminal configuration that could generate, and pump noise across 240 MHz of the spectrum into the spacecraft, which is given in Table-6.5.3. This estimation pointed to a terminal, which could be generating the noise, with the following configuration:

  - 3.8m antenna
  - Transmitter delivering more than 20 watts of RF power
  - Wide band up converter (Possibly operating in the L-band with bandwidth of 500 MHz)
  - A degraded preamplifier (SSPA/TWTA) being overdriven.

Table-6.5.3 : Link Calculations for Estimating the EIRP of the Terminal Causing Interference

Noise floor raise : 5.0 dB (Average)

Bandwidth : 240 MHz

C/KT : 5.0+10log 240 E +6 = 88.8 dBHz

EIRP : C/KT+PL-G/T+K = 60.2 dBW

Noise power calculations

Nominal Noise level measured in transponder #27 = - 55.0 dBm (in 2002)

Interfering Noise level measured in transponder #27 = - 50.0 dBm (in 2003)

Rise in the noise power = -51.65 dBm

Bandwidth (Over 6 transponders) = 240 MHz

Absolute noise power increased over 240 MHz = 32.15 dBm

This indicates nearly 3.0 dB rise in noise power at a terminal with 3.8m and 20 watts of SSPA. The terminal should also use L-band Transceivers/Up converters, in an overdriven condition to generate a wideband (240MHz) noise.

Assumption: A terminal is uplinking a C/N of 5.0 dB over 240 MHz bandwidth and it is uplink limited.

6.4.4 (A) Localization of Source of Interference

Having confirmed that the noise generating mechanism was ground based, NOCC and MCF proceeded with the coordinated switch-off test, during the night of 5th July, which yielded the following results:

- The noise floor rise abruptly vanished around 2210 Hrs on 5th July, with many of the operators yet to shut down their transmitters.
- The noise floor continued to be nominal through out the turn-off exercise, which was completed around 0300 Hours of 6th July 2003 after which time, operators were permitted to resume their transmissions (Fig. 6.5.7).

- The noise floor rise abruptly reappeared in the transponders around 0315 Hours of 6th July, during the process of the restoration of the services by operators indicating that one of the terminals, which reported back on the network, had created the problem (Fig. 6.5.8).

The Network, which restored their services around this time, was of Customer #12, working in the transponder #30. They were immediately asked to shutdown their services one by one. During this exercise, the terminal causing the problem was identified as the VSAT located in Kolkata, working in the Network of Customer #12 in the Demand Assigned Multiple Access (DAMA) mode.

The terminal was turned-on and off for a couple of times, and at every instance of turn-on, the increase in noise floor across the transponders was observed.

Customer #12 was instructed to stop services with this terminal and the noise floor became normal since then (Fig. 6.5.9).

(B) Tests & Analysis at Customer's site

A joint team of engineers from NOCC and MCF visited the VSAT site at Kolkata, to study the site-specific conditions and equipment configurations that could have caused the abnormal noise floor rise. Detailed investigations and tests were conducted, the highlights of which are:

- The terminal size and front-end configuration matched with the analysis carried out at MCF. The VSAT terminal was configured around an offset fed 3.8m antenna, employing 40-Watt final Solid State Power Amplifier providing maximum EIRP of around 62 dBW. The front-end electronics employed are:
    - Outdoor Radio Unit (ORU) – It consisted of L to Extended C-band converter and a 5 W power amplifier of Scientific Atlanta make. The interface with the Indoor Units (IDU) was at 750 ±18 MHz in the U/L, and 950-1450 MHz in D/L. The IDU output had ±18 MHz filter, but the converter-cum-amplifier in the ODU had no filter.

  - Booster Amplifier, 40 Watt – Microwave Corporation, Canada model C 9771-40B-OD serial no. 4997.

The VSAT configuration is given in Fig. 6.5.10.

- A heliax cable was used between the data channel unit (Indoor Equipment) and the front end Outdoor Radio Unit (ORU) carrying IF signals at 750 ± 18 MHz to the uplink, and 950-1450 MHz in the downlink. Connector of this cable was found loosely mated with the input of the ORU, causing intermittent contact and improper grounding at the connector. The connector, on detailed inspection, was found to have broken connectivity between the body and the shielding.

- Based on the preliminary observations, ground tests were carried out at the site with the original equipment configuration. The tests included
  - Measurements at the data channel-end (Indoor) to isolate any possible cause at the source (L Band): No anomalous behavior was observed even with the RF output being saturated.
  - Measurements at 5 Watt ORU: Since the cable connection at the ORU input was observed to be loose, efforts were made to simulate the possibility of noise generation at this end. It was observed, during this test, that the noise floor jumps abruptly whenever the cable / input connector was disturbed. Similar exercise with a freshly laid IFL cable (RG213) did not show any abnormal increase in noise levels (Fig. 6.5.11).
  - Measurements at 40 Watt SSPA: Measurements with the 40 Watt final amplifier with the disturbed cable/connector (at 5W transmitter input) showed:
    - Abnormal noise response over the whole band (Fig. 6.5.12)
    - 7.8 dB response over 240 MHz
    - High Noise Floor at the beginning of the Ext. C band, slowly tapering towards the end of the band.

  - These results correlated with those made at MCF and NOCC, with operators on Transponders #25 & 26 being affected more, where as Customer #12 operating in Transponder #30 had no degradation in services.

  - Test with alternate set up: Tests were also carried out with the alternate setup arranged at the site to verify nominal performance and compare with those obtained with the original configuration. This set up however had a ≈18 MHz filter built in, thus band limiting the operations to the assigned transponder. The configuration is given in Fig. 6.5.13.

- Tests with the Satellite (Single Carrier Operation): After verifying the nominal performance of the ground systems, tests were carried out, with the satellite using the alternate setup. Tests were initially carried out on Transponder #27 and thereafter on Transponder #30. Only one CW carrier was brought up during the tests, with the carrier level gradually being increased from minimum to maximum, to saturate the SSPA (Outdoor Unit). No rise in the Noise Floor was observed during these tests.

(C) Results of Investigation

From the tests and observations at the VSAT site, it was concluded that:

- The reported wideband noise rise across the Ext. C-band Transponders was attributable to the bad connection between the Indoor Unit and the Outdoor Unit. The severed connection between the connector body and the outer shield of the heliax cable at the ORU-end caused the wideband noise.

- There being no band limiting filter in the Scientific Atlanta ORU, wideband noise generated owing to the bad connection was amplified by the RF equipment and radiated on to the Spacecraft, causing the anomalous rise in the noise floor. The 40 W booster amplifier also contributed to amplify the noise rise.

- The noise generating mechanism was related to the local weather conditions also. The site weather condition was in general humid. The situation could occur at other sites also, which incorporate similar configurations.

- The alternate setup involved interface at IF (70 MHz) between the Indoor and the outdoor Unit with inherent filtering of center frequency ±18 MHz. This type of configuration would not generate wideband noise.

6.5.5 Simulation Tests at MCF

The wide band noise generating mechanism observed during the reported anomaly was found to be an improper connection of the ground at the ORU-end, causing intermittent ground and resultant noise by the SSPA. It was therefore important to simulate this situation and validate the possibility of the noise generation. This test was carried out at MCF to simulate and validate the noise generating mechanism owing to the bad grounding. The setup was as illustrated in Fig. 6.5.14.

The noise plots were taken with improper grounding at the SSPA input end. (Fig. 6.5.15 and 6.5.16). The observations during these tests are:

- The SSPA performance was nominal with input drive levels up to 6 dB back-off (3 dB Output Back Off), with or without proper grounding at the connector.

- As the drive levels were increased and the SSPA driven to near saturation with an improper grounding at the connector, wideband noise floor was observed along with the signal at the output.

- The bandwidth of the noise floor gets wider, as the drive levels were increased.

- The level of the noise floor depends on how bad is the connection.

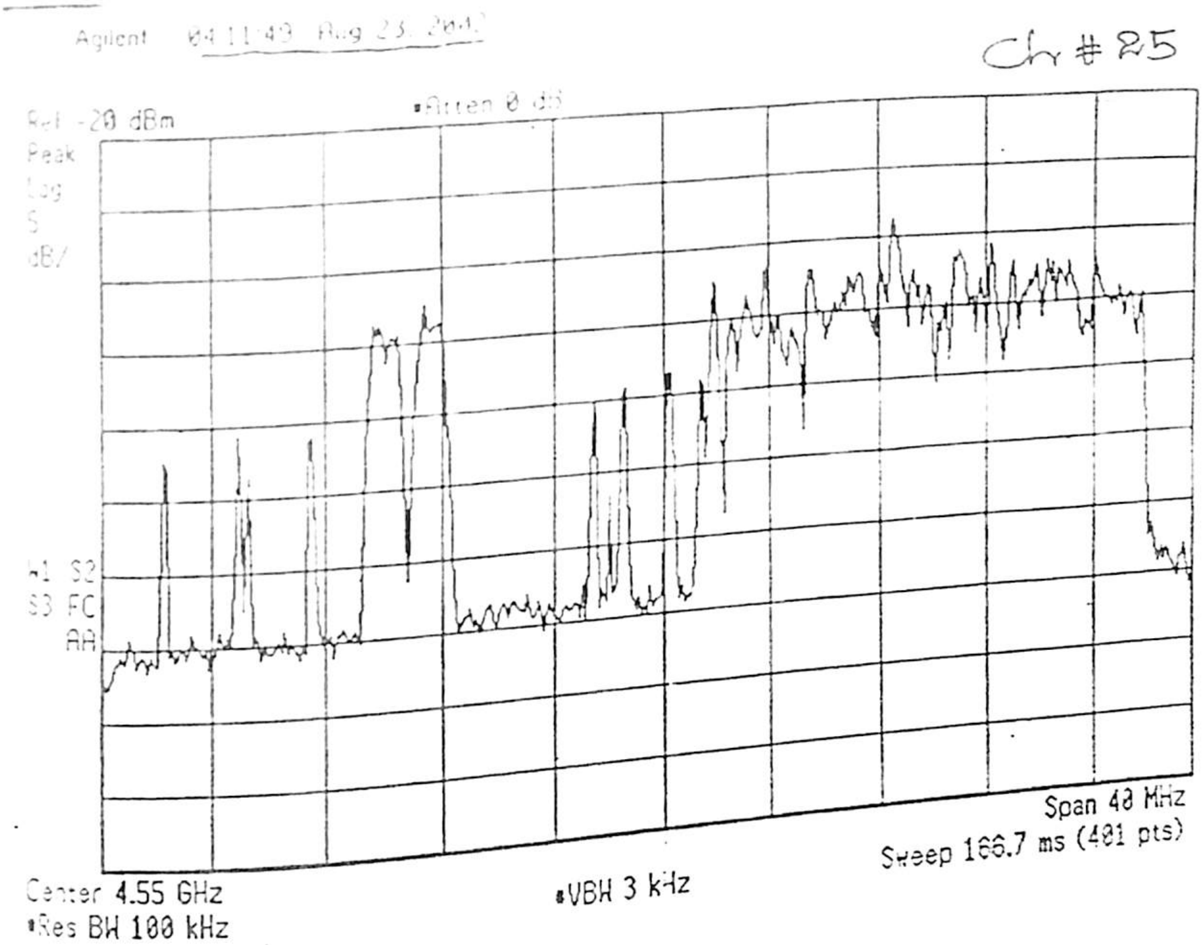
From the above observations, it was concluded that a wide band amplifier with improper/broken ground at the input connector, while operating near saturation, generated wideband noise at its output.

6.5.6 Conclusions

1. A wideband noise floor rise, spanning the whole of the Extended C-band, causing degradation/disruption in services in the Extended C-band transponders of the satellite was observed during the last week of June 2003. The problem was resolved through coordinated tests and simulations.

2. The cause of the wideband noise floor rise was a VSAT operating on Transponder #30, and pumping wide band noise onto the satellite owing to the broken / intermittent ground at the input of the transmitter.

3. A single VSAT terminal could generate and pump wideband noise spanning multiple transponders in the spacecraft degrading/disrupting services in the whole of the band. The noise generating mechanism is intimately related to the site-specific conditions like equipment configuration, integrity of the Inter-facility link, equipment rating, and local weather.



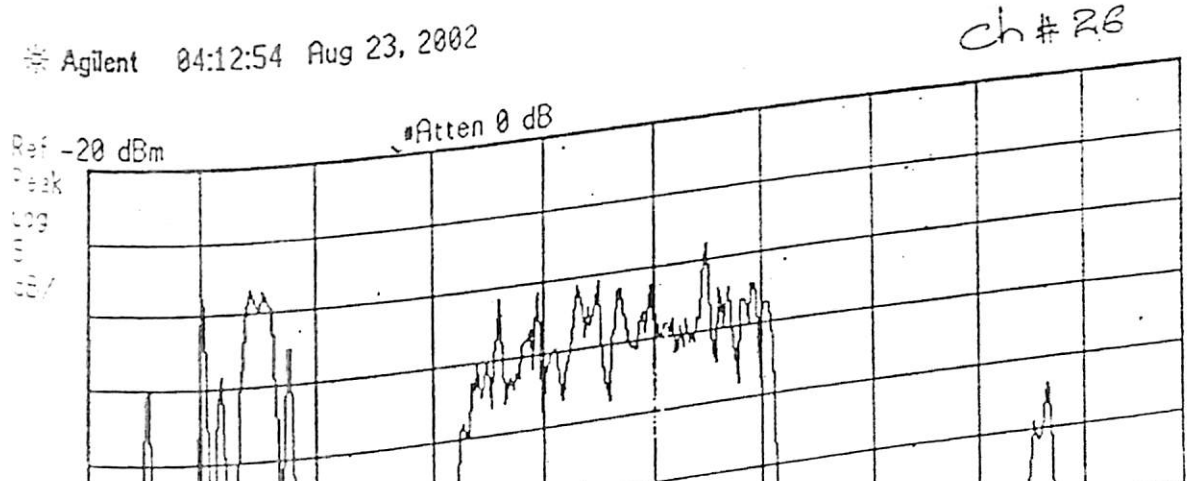
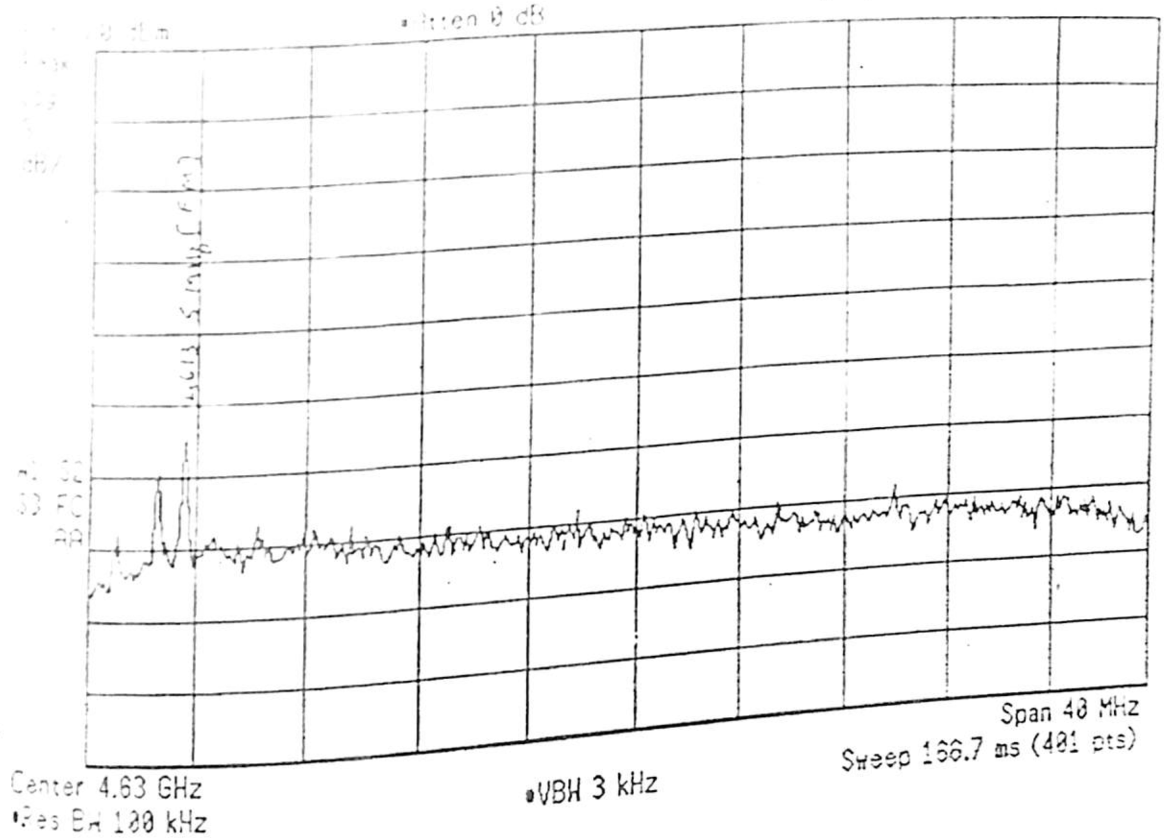


Fig. 6.5.1: Spectrum Plots of Transponders 25 & 26 in 2002

Ch #27



Ch#28

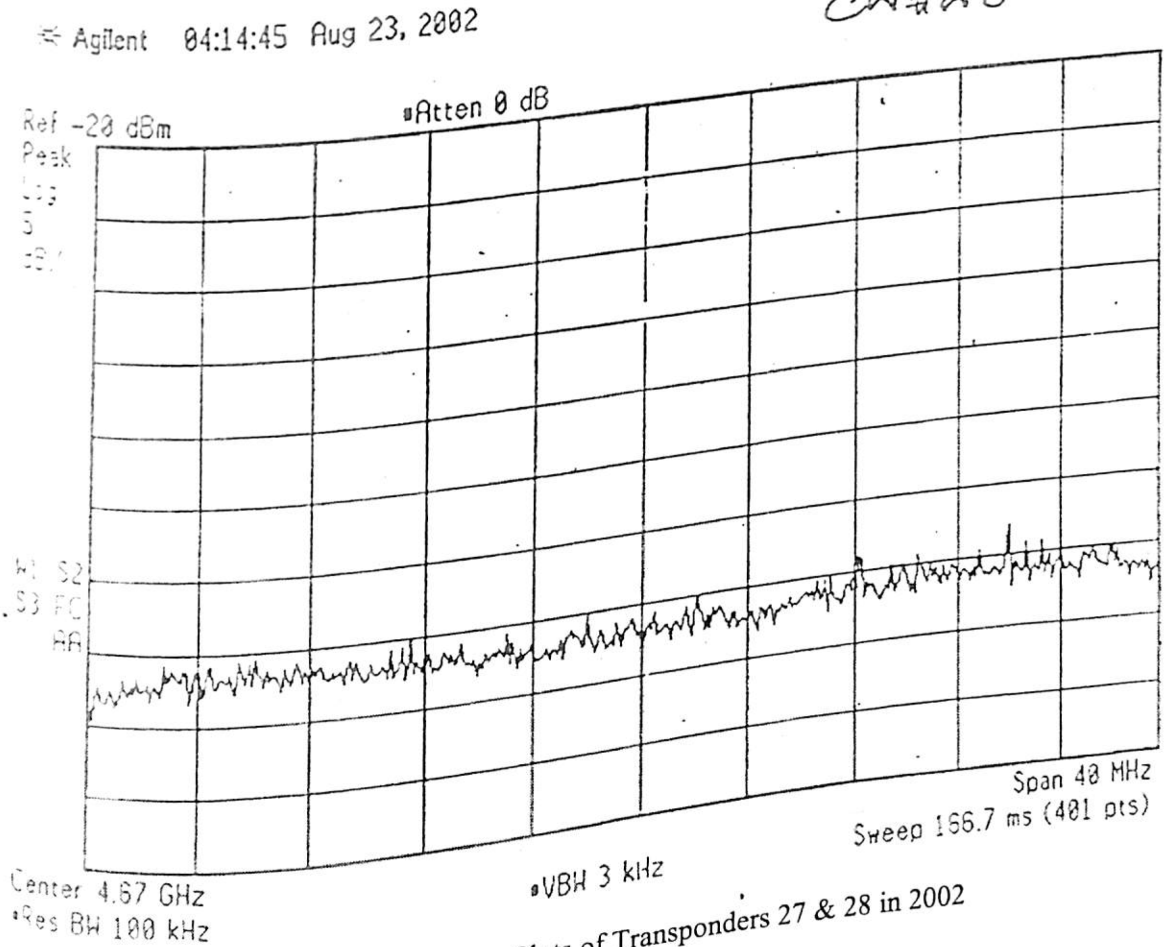
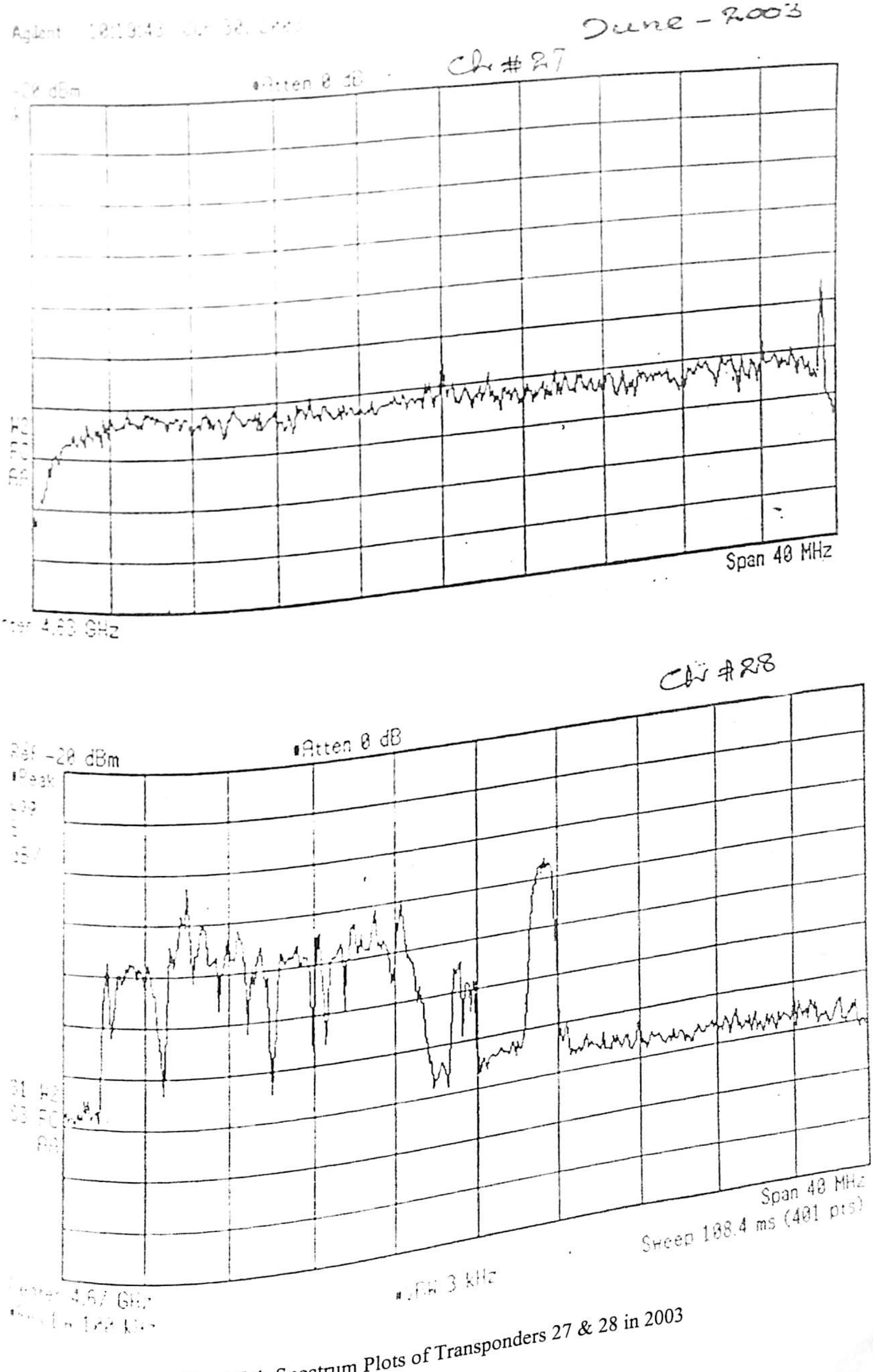


Fig. 6.5.3: Spectrum Plots of Transponders 27 & 28 in 2002

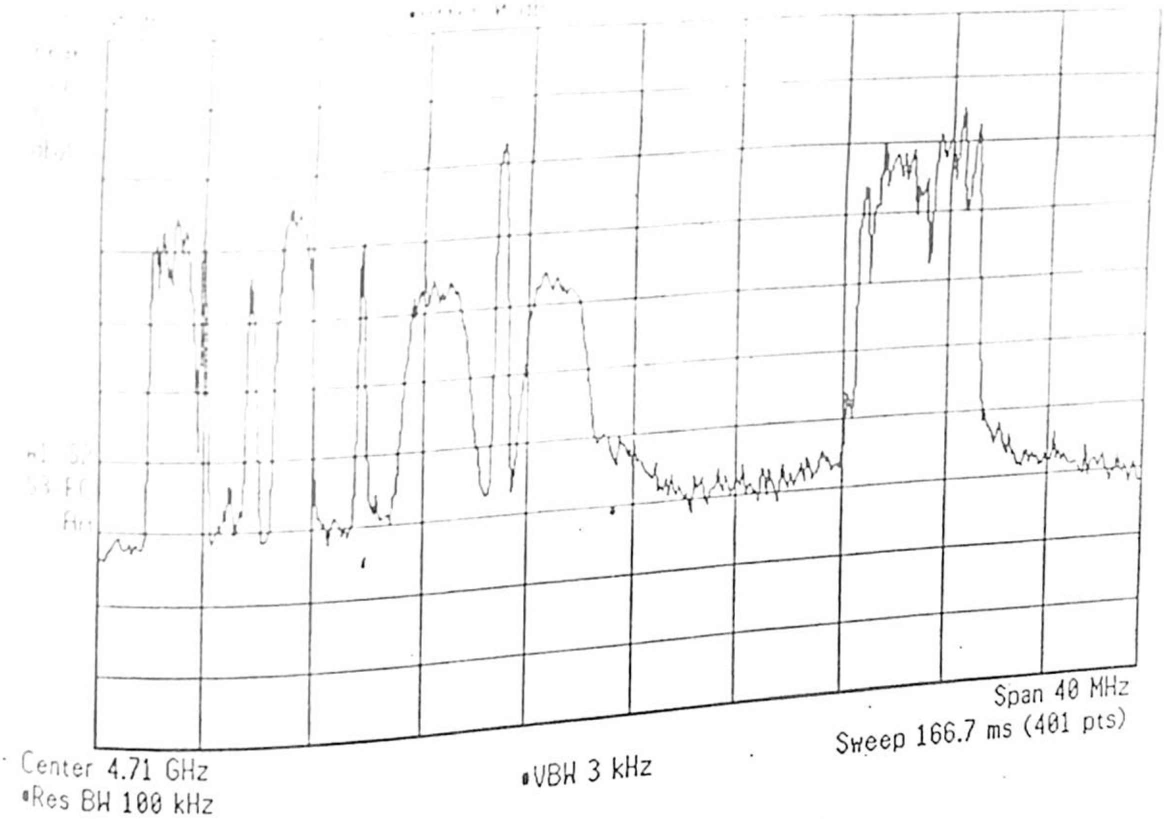

June - 2003

Ch #27

Ch #28

Fig. 6.5.4: Spectrum Plots of Transponders 27 & 28 in 2003

U
Ch #29



Ch #30
~~Ch #30~~

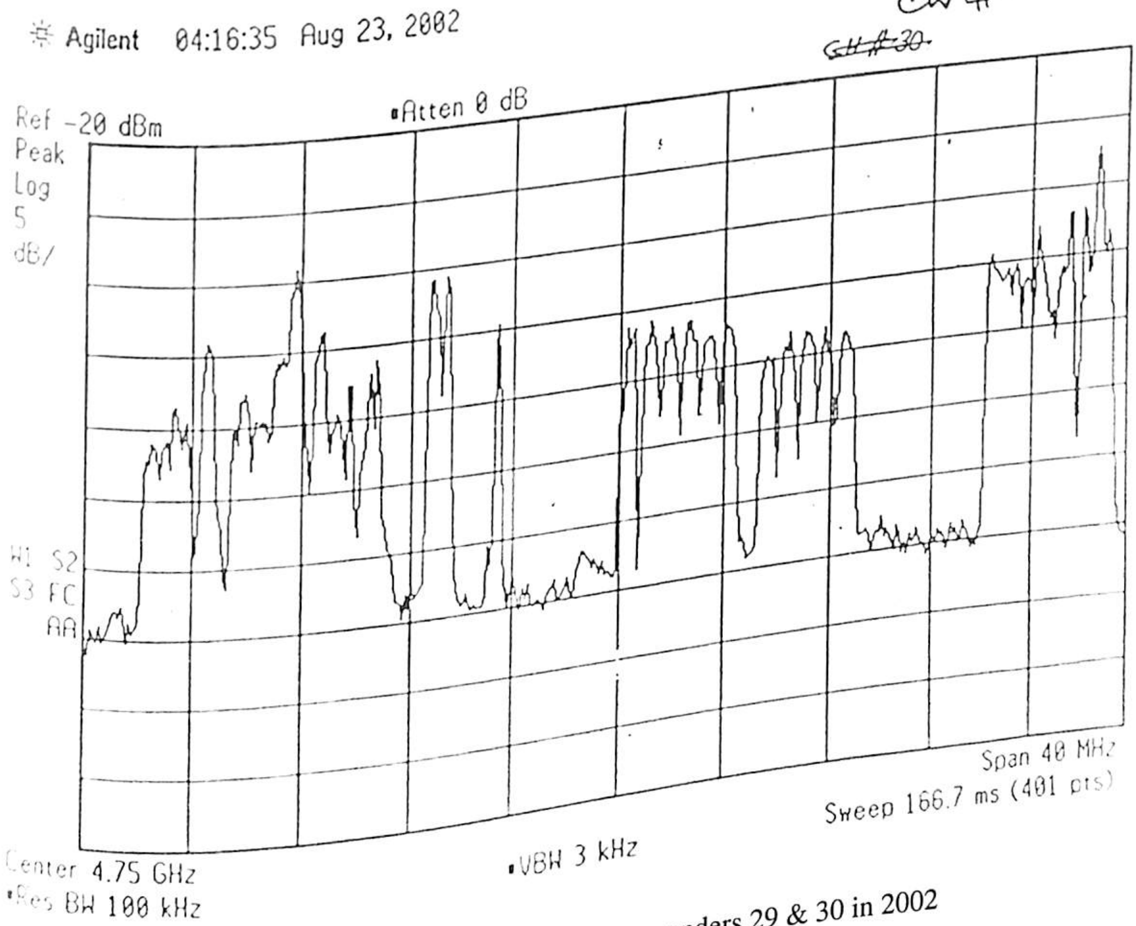
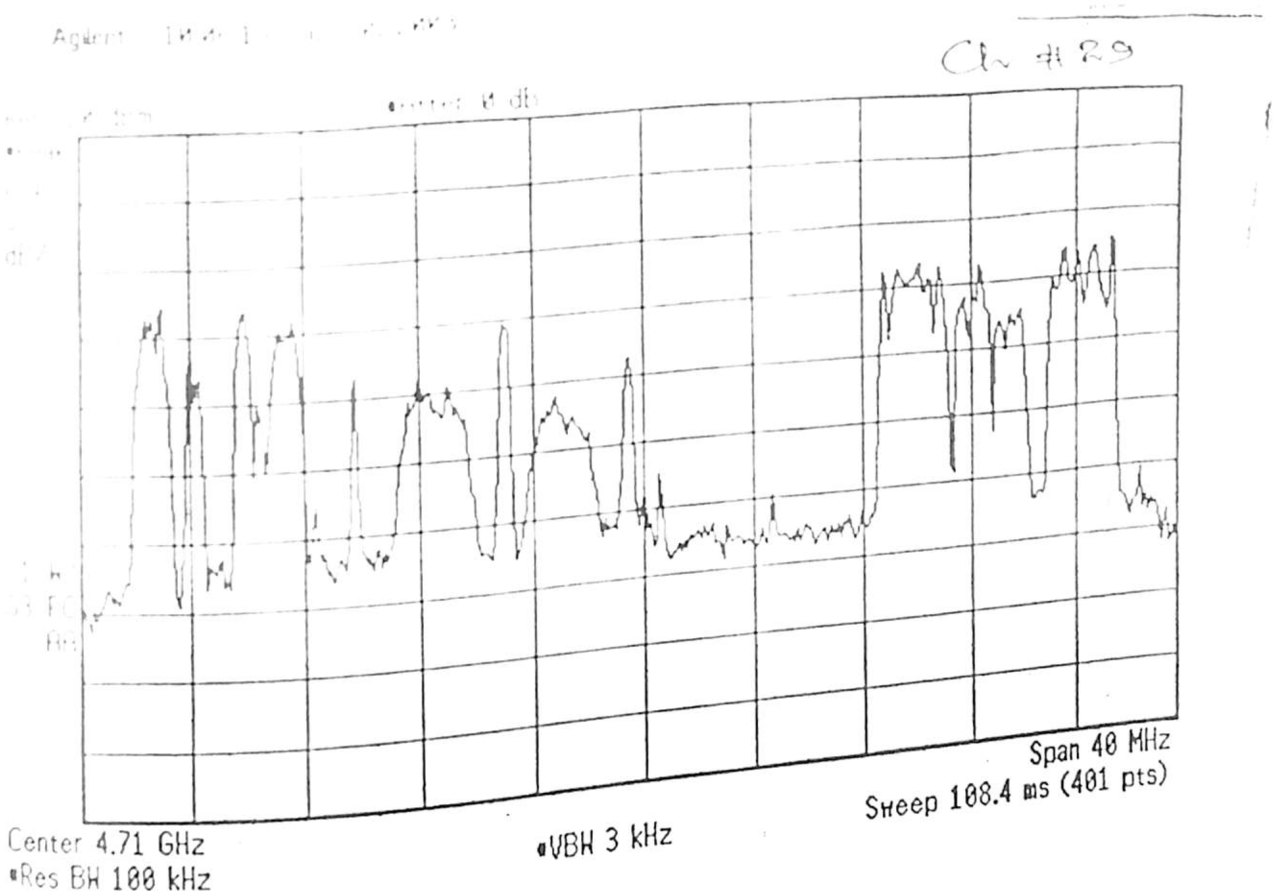


Fig. 6.5.5: Spectrum Plots of Transponders 29 & 30 in 2002



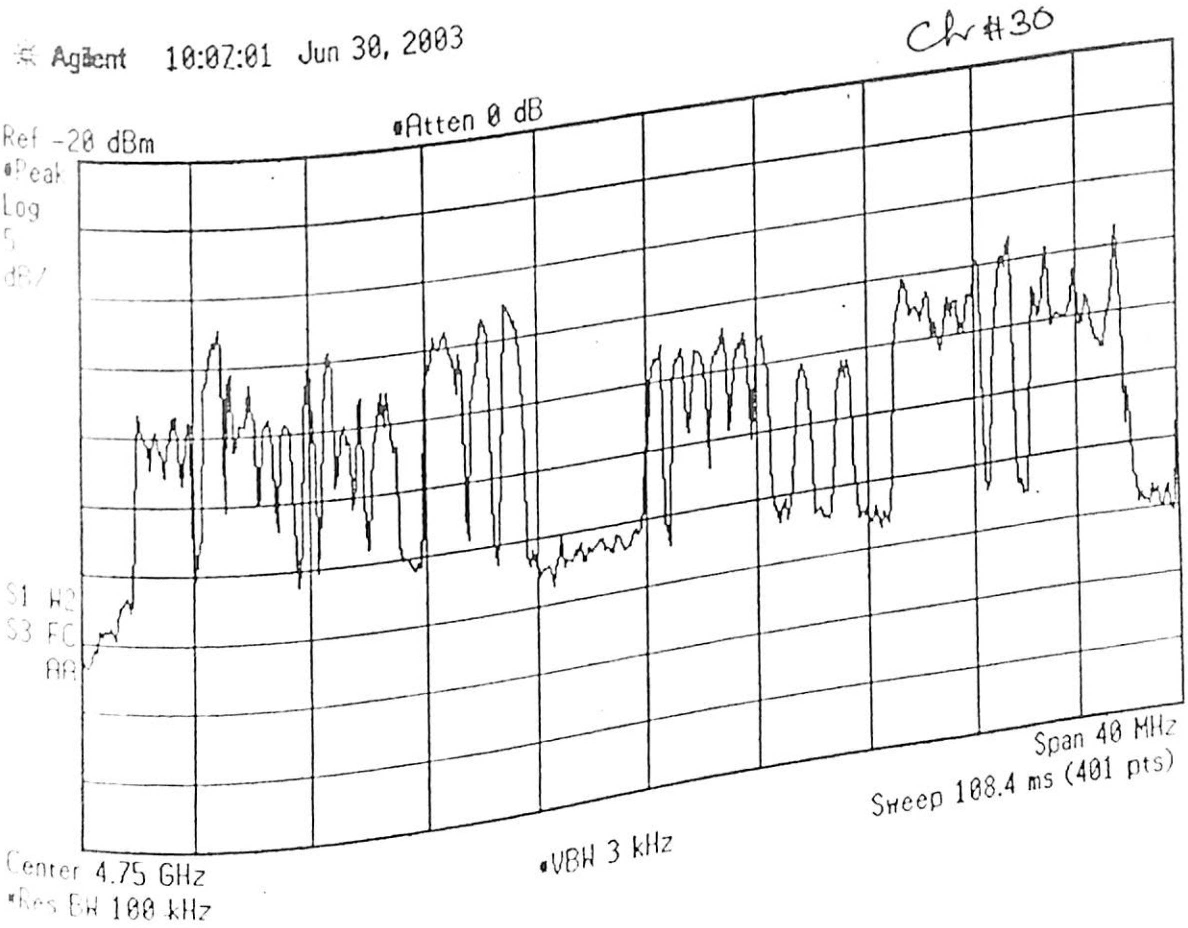


Fig. 6.5.6: Spectrum Plots of Transponders 29 & 30 in 2003

Plot #8

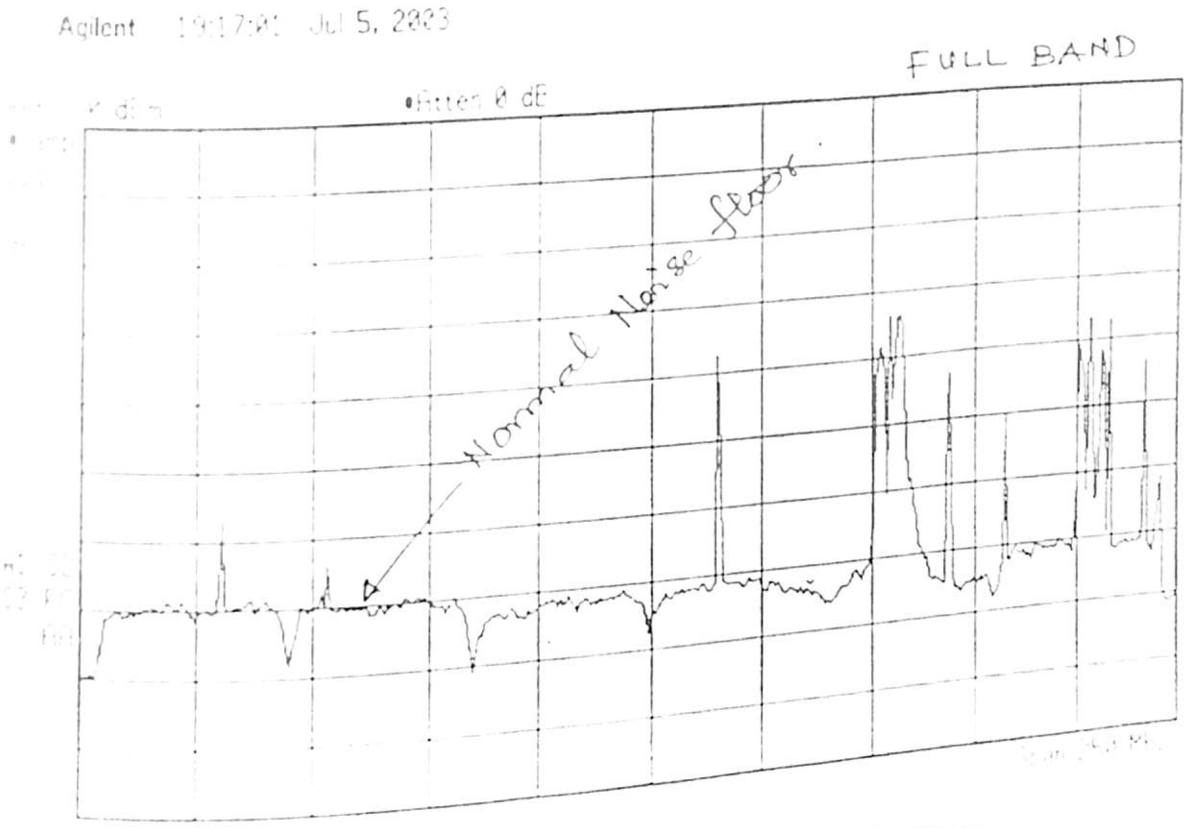
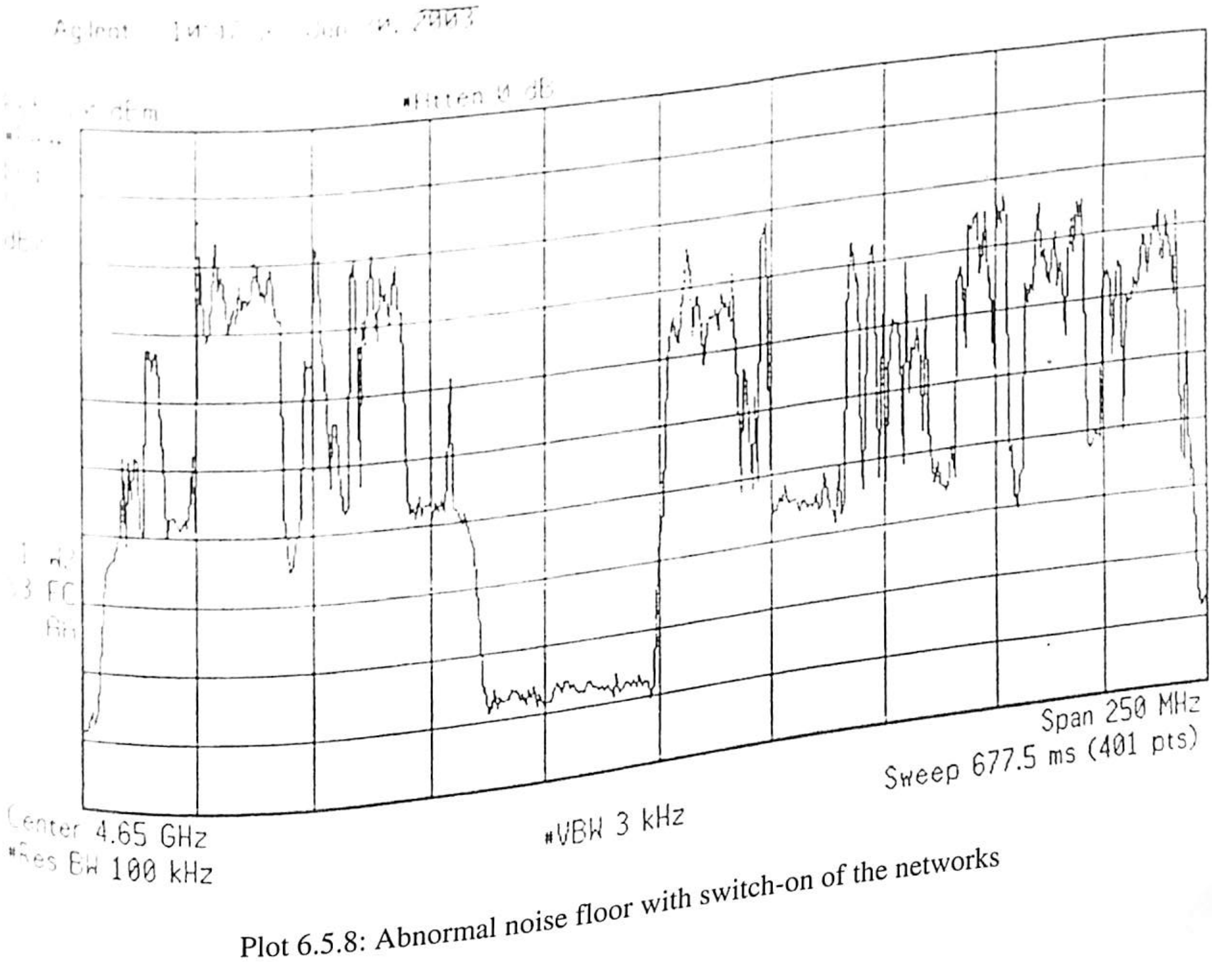
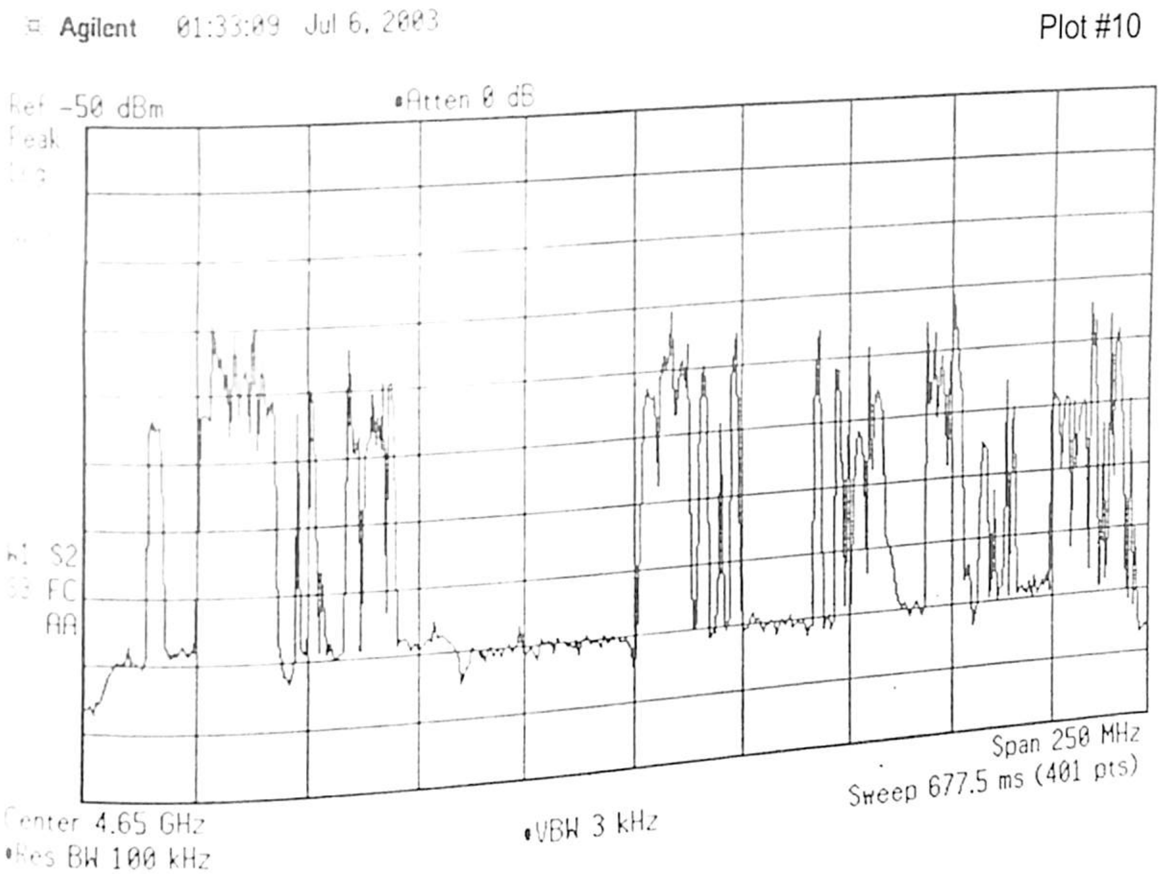


Fig. 6.5.7: Noise floor which became normal during switch-off tests



Plot 6.5.8: Abnormal noise floor with switch-on of the networks



Plot 6.5.9: Nominal noise floor in full band

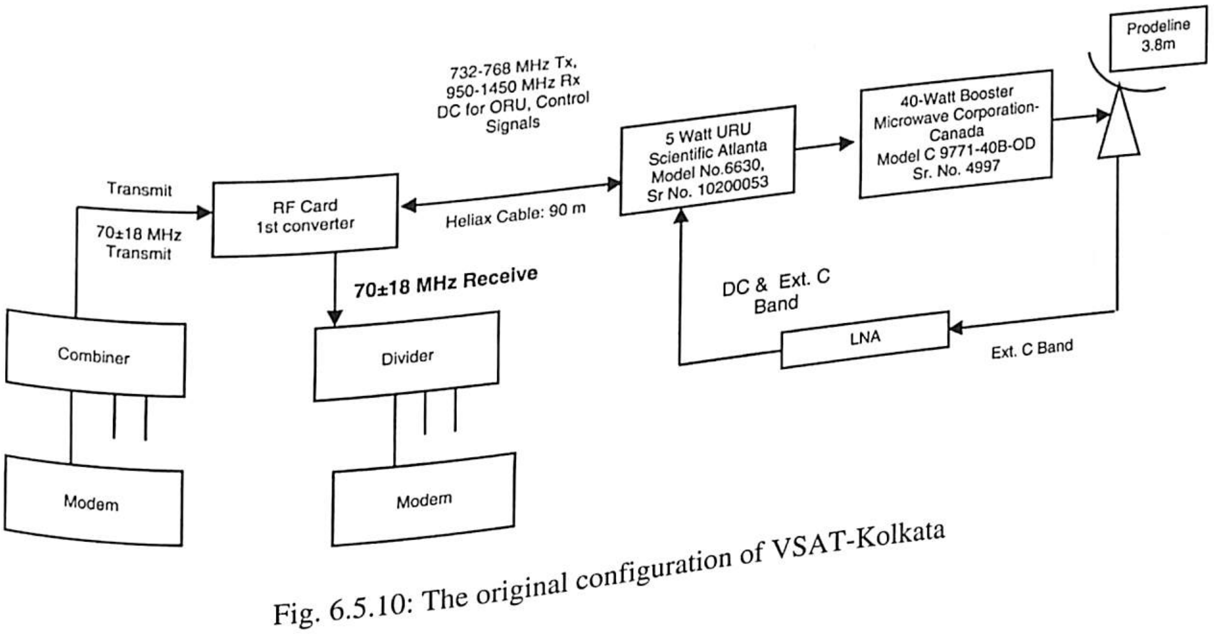


Fig. 6.5.10: The original configuration of VSAT-Kolkata

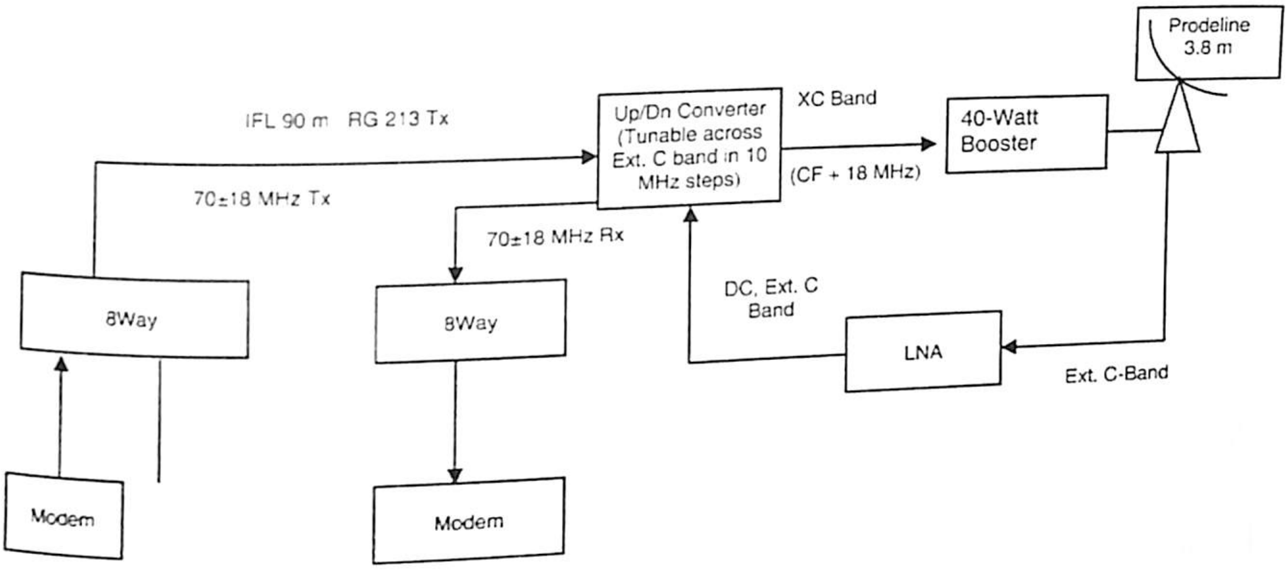


Fig. 6.5.13: New configuration for VSAT-Kolkata

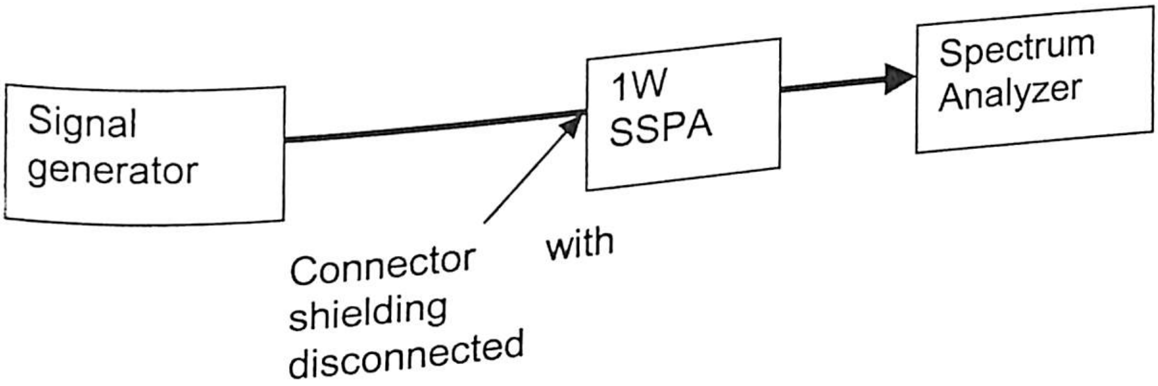
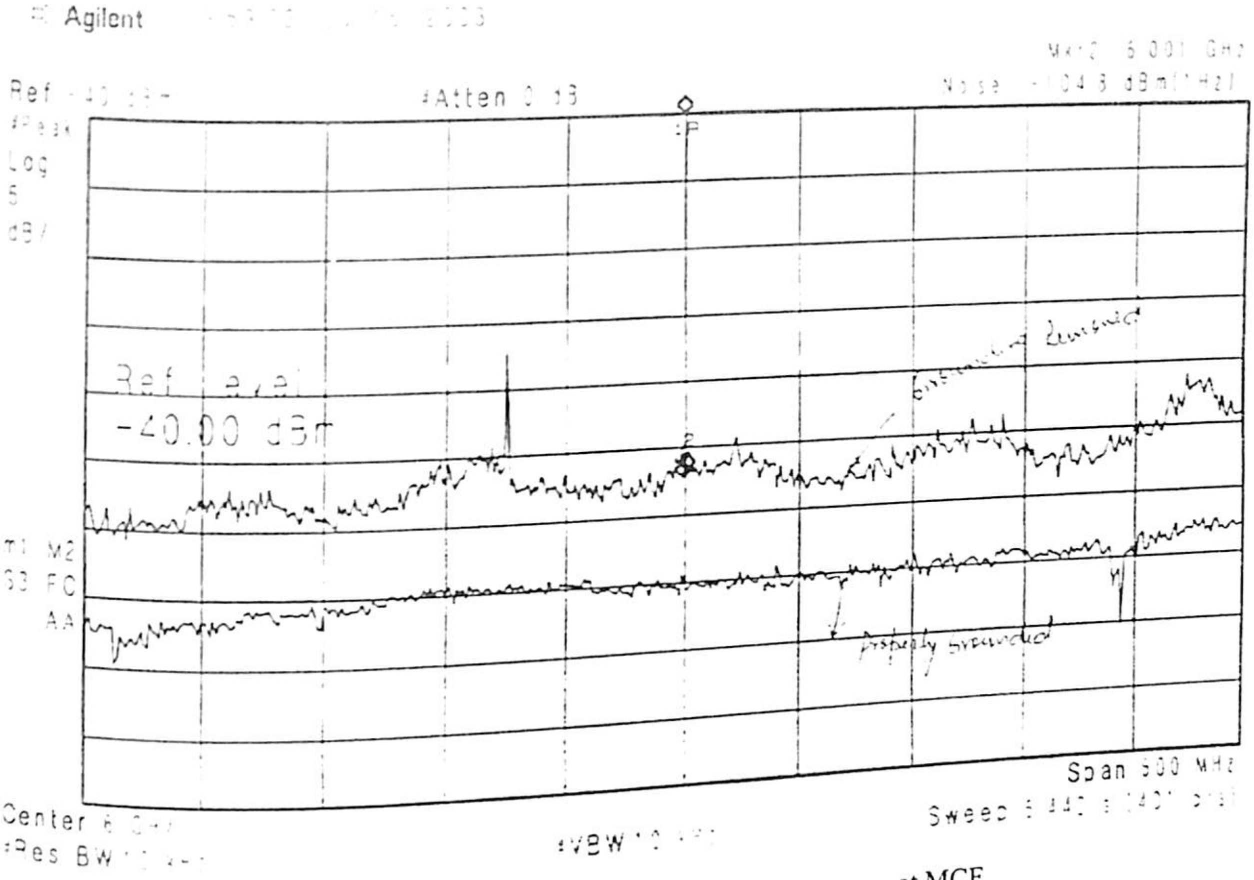
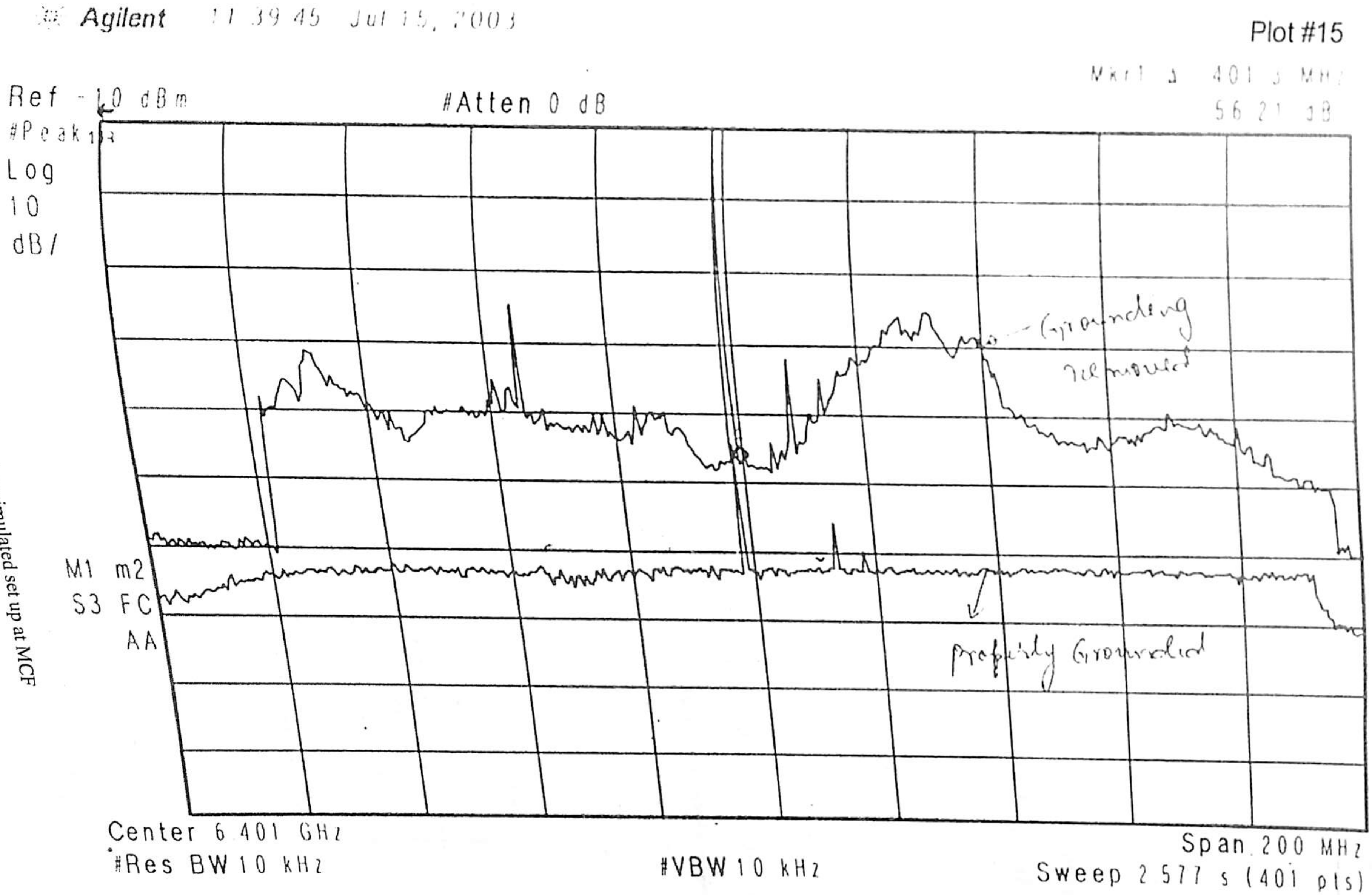


Fig. 6.5.14: Configuration of simulation at MCF



Plot 6.5.15: Noise floor measured on simulated set up at MCF



Plot 6.5.16: Noise floor measured at simulated set up at MCF

6.6 Case Study-5: Investigation of interference of FM radio and VHF signals through VSAT terminals into INSAT satellites

6.6.1 Introduction

In this case investigation of FM radio and VHF transmitter interference into INSAT-3B and INSAT-3C Spacecrafts was carried out.

VSAT operators in INSAT 3C (extended-C Band) experienced the interference in their communication traffic during July 2002. Detailed testing/analysis of the interference was carried out in co-ordination NOCC.

6.6.2 FM Radio interference in INSAT satellites

6.6.2.1 INSAT-3C Case

(A) FM Radio interference was observed in Transponder 27 of INSAT-3C. The measured spectrum is given in Fig. 6.6.1, and the details of the interference signals were analysed for their content.

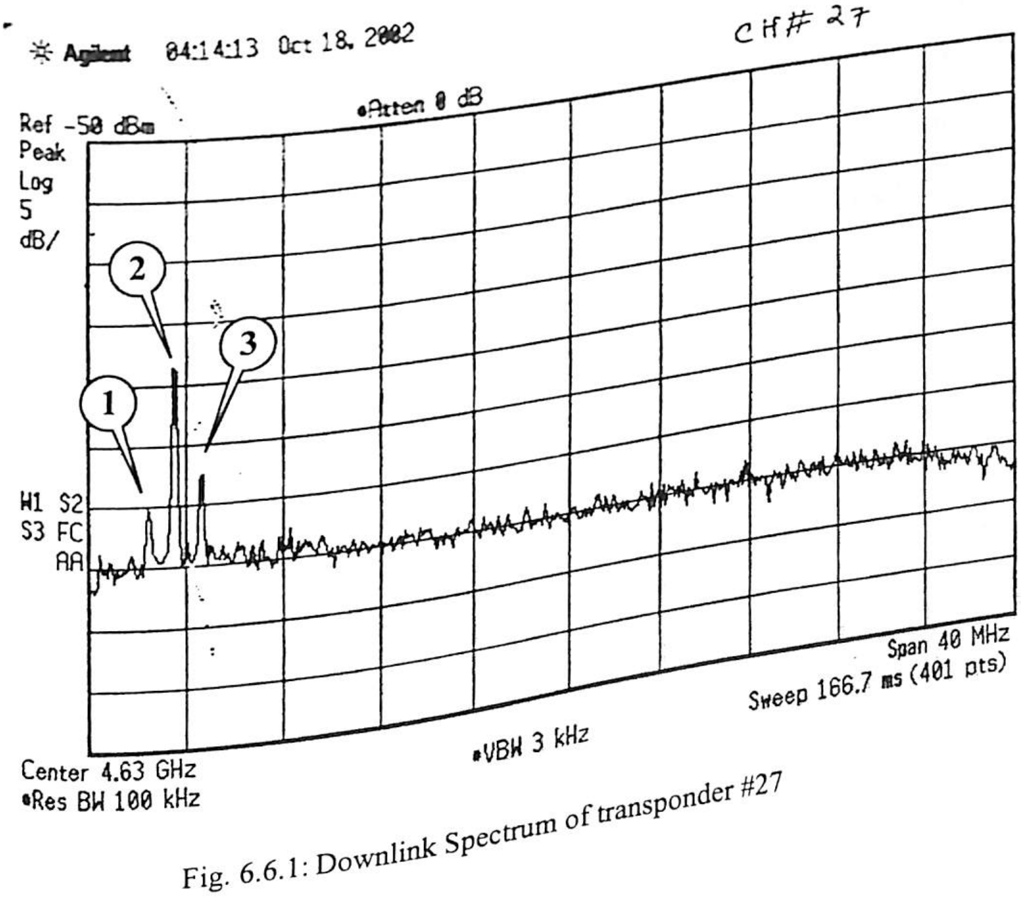


Fig. 6.6.1: Downlink Spectrum of transponder #27

By demodulation and hearing the audio, it was observed that the interference was originating from the three FM radio broadcasts from Mumbai. Table-6.6.1 gives test results for the observed interference components, as well as the translated frequency of the culprit Radio Stations.

Table-6.6.1: INSAT 3C Transponder interference from FM Radio signals

Sl No	FM Station	FM radio Transmitter Frequency	Center Frequency at D/L interference	Occupied Bandwidth	C/N$_o$ (dBHz)	Space Craft EIRP (dBW)
1	Radio Midday	92.5 MHz	4612.5 MHz	200 KHz	54 dBHz	- 2.8 dBW
2	Radio Today	93.5 MHz	4613.5 MHz	200 KHz	66 dBHz	+ 9.2 dBW
3	Radio Millennium	94.6 MHz	4614.6 MHz	200 KHz	57 dBHz	+ 0.2 dBW

(B) Fig. 6.6.2 shows the frequency response of an up-converter. The up-converter's input frequency specification is 70 ± 20 MHz. But in practice it accepts frequency range from 20 MHz to 125 MHz (total 105 MHz bandwidth). This bandwidth is more than 2.5 times the bandwidth of a given transponder. Wide band TWTAs are commonly used as an output stage of a VSAT terminals, which can pick-up FM Radio signals, amplify the interference, and retransmits to the satellite. This plot also depicts the IF band of frequencies, transponder uplink & downlink frequencies and the channels affected due to the possible interfering signals in the range of 10 MHz to 130 MHz. Hence, the FM Radio pick-up could be by a VSAT operating in Transponder #26.

(C) The level variations of the interference components were studied over a long time. Fig. 6.6.3 shows the signal strength variation of the interfering signals over a period of time, due to various reasons like weather condition, obstruction between FM radio transmitters and VSAT terminal, degree of degradation in shielding etc. The signatures analysed in the variation of signal strengths give the details about whether the interference is taking place in a common VSAT terminal or in separate VSAT terminals for individual signals. If the variation is identical for all the signals over a period of time, then the re-transmission is taking place by a common VSAT terminal and if the variation in each signal is not identical then the re-transmission is taking place by separate VSAT terminals for individual signals.

Detailed analysis of the problem was carried out. The coordinated tests conducted by the teams of Engineers at MCF, NOCC, AIR and the FM radio stations resulted in identifying the VSAT which was picking up the interference.

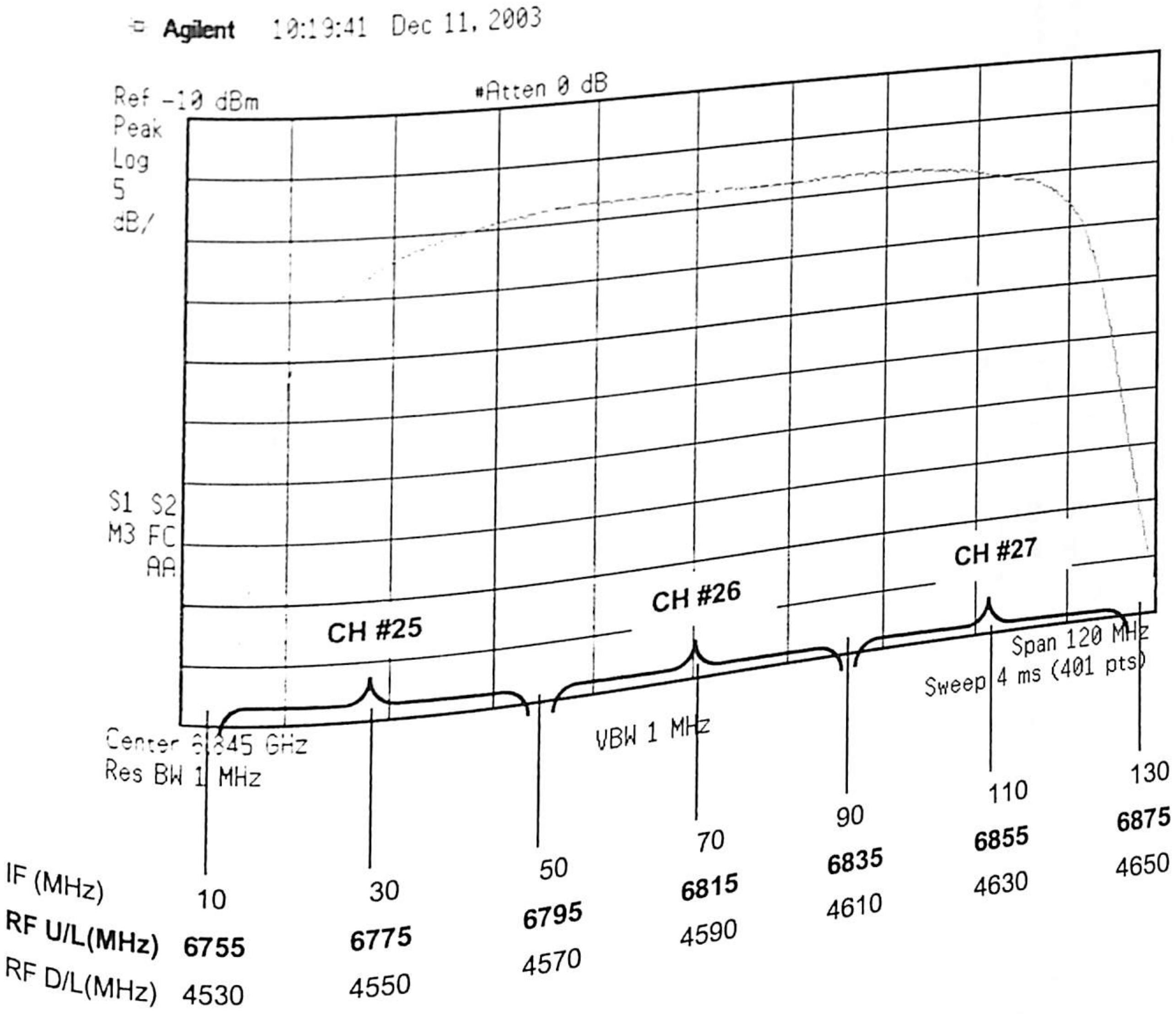


Fig. 6.6.2: Frequency response of an up-converter

FM RADIO INTERFERENCE IN INSAT 3C CH # 27

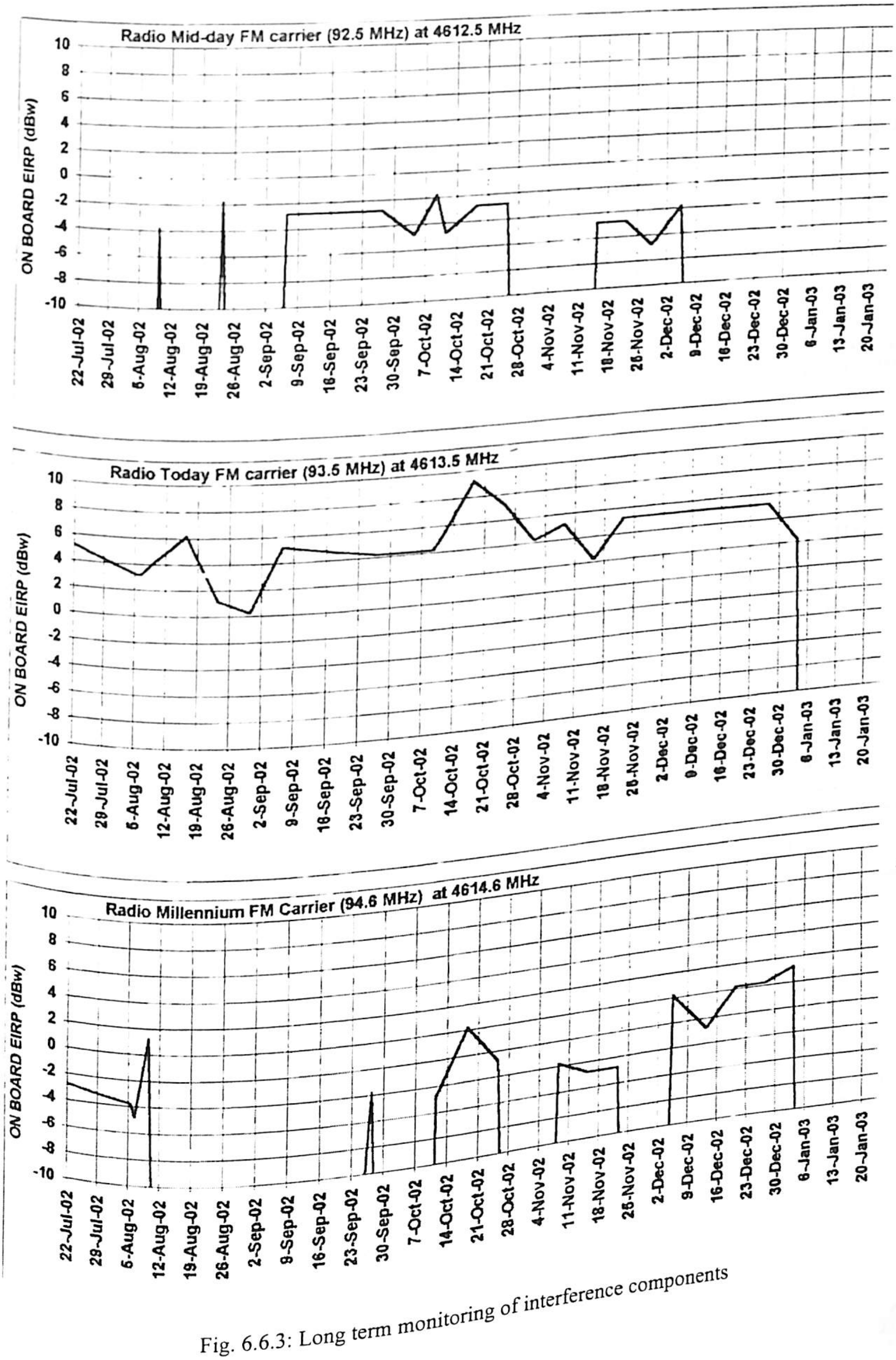


Fig. 6.6.3: Long term monitoring of interference components

6.6.2.2 INSAT- 3B Case

(A) Interference from FM radio signals was observed in Transponder #12 of INSAT-3B. The spectrum plot of the downlink of Transponder #12 is given in Fig. 6.6.4. All the interfering components were analysed with small value of span in spectrum analyser, and their content identified by envelope detection. Fig. 6.6.5 and 6.6.6 give the detailed spectrum plot for two of these components, and all components are listed in Table-6.6.2.

Table-6.6.2: FM / VHF Transmitters interfered in INSAT 3B Transponder

Sl. No.	Carrier D/L Frequency	Frequency of interfering signal	Type of carrier	Occupied Bandwidth
1	4708.8 MHz	88.8 MHz	Mobile radio telephony	700 KHz
2	4709.5 MHz	89.5 MHz	2 IDR Carriers	200 KHz
3	4710 MHz	90 MHz	Pure carrier	-
4	4711 MHz	91 MHz	Radio city FM91 Bangalore	150 KHz
5	4711.73 MHz 4711.799 MHz	91.73 MHz 91.799 MHz	IDR IDR	15 KHz 15 KHz
6	4721.3 MHz	101.3 MHz	FM Bangalore 101.3 MHz	Affecting the usable BW Frequency.
7	4722.9 MHz	102.9 MHz	FM like carriers (Mobile radio telephony)	Affecting the usable BW Frequency.
8	4748.2 MHz	88.2 MHz	FM like analog modulated carrier	200 KHz
9	4750 MHz	90 MHz	Analog FM modulated carrier	40 KHz

(B) Observations and Analysis of Interference

Multiple FM carriers and VHF carriers (probably from mobile radio telephone) were retransmitted to INSAT – 3B by one of the VSAT terminals operating in the Transponder #11 with a frequency 6915 MHz / 4690 MHz located in Bangalore.

Tests were coordinated by NOCC and the interference issue was carefully analysed. The problem was solved in co-ordination with the concerned VSAT Operator.

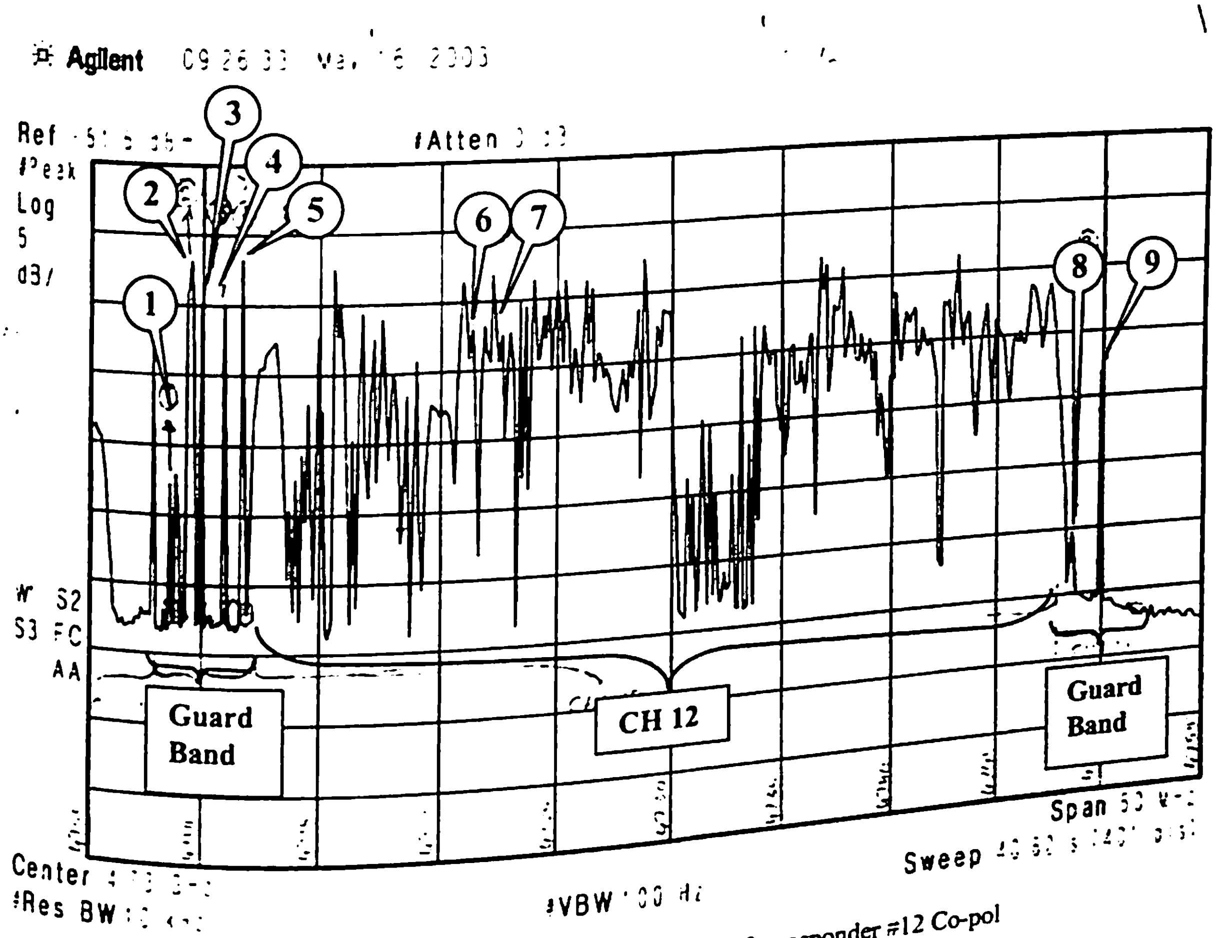


Fig. 6.6.4: Downlink Spectrum of transponder #12 Co-pol

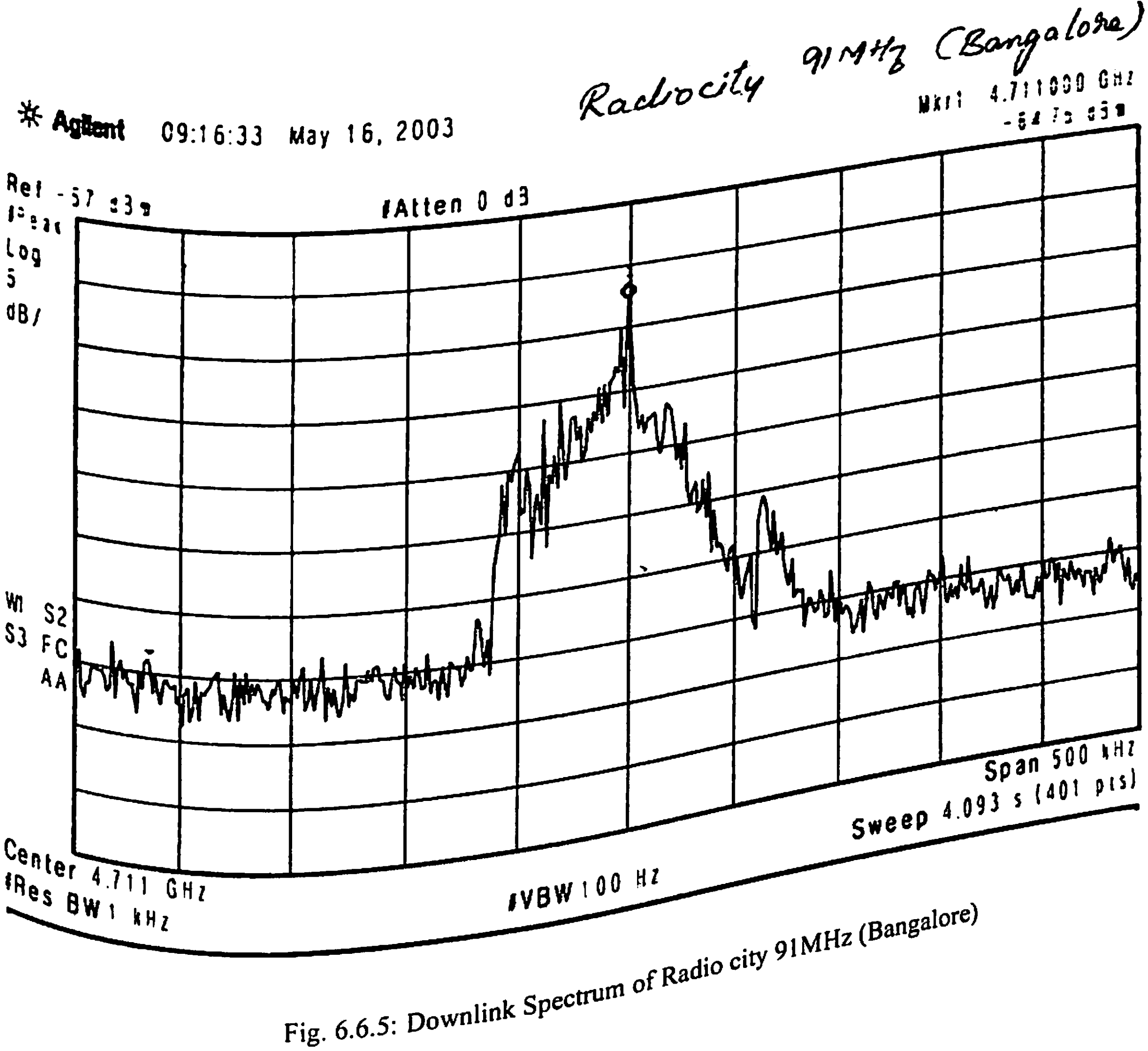

Radiocity 91MHz (Bangalore)

Fig. 6.6.5: Downlink Spectrum of Radio city 91MHz (Bangalore)

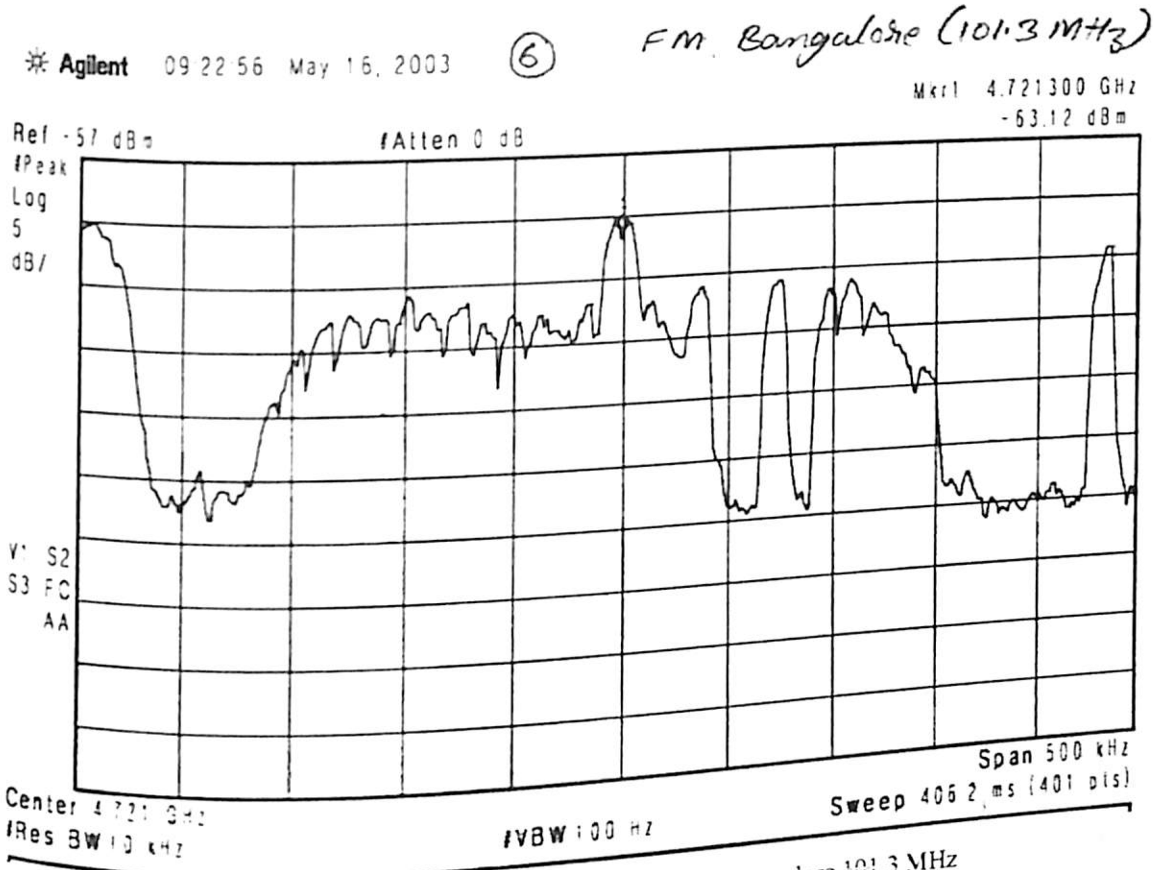


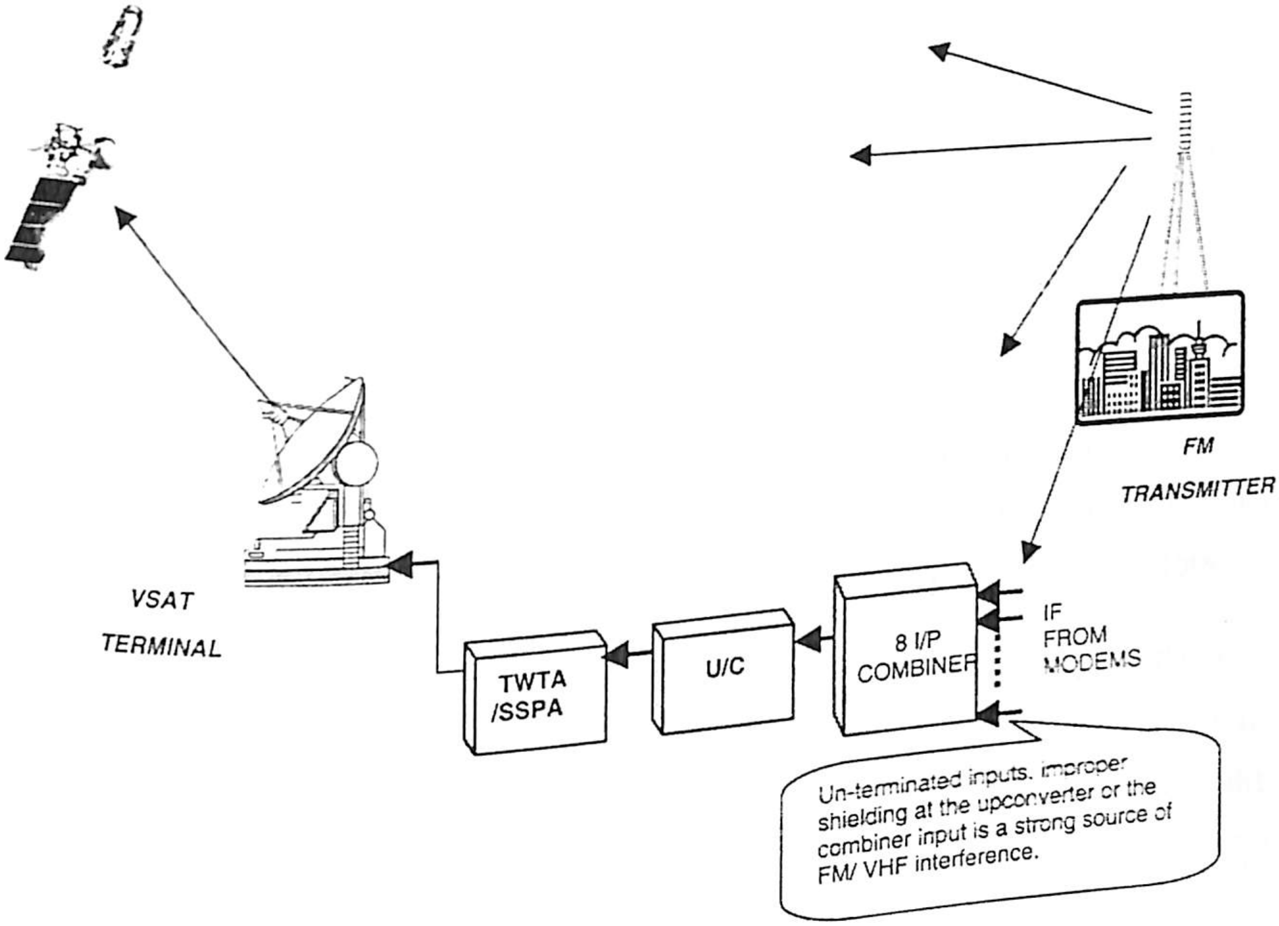
Fig. 6.6.6: Downlink Spectrum of FM Bangalore 101.3 MHz

6.6.3 Identification of Interference-coupling mechanism from FM & VHF Transmitters to Satellite Transponder

Since the broadcast frequency bands of FM radio and VHF transmitter are having very close proximity to the IF band of satellite earth stations, there are possibilities of interference for satellite communication. The interfering signal is converted to the satellite uplink and downlink frequency bands and can give rise to this kind of interference [49].

(A) In general the interfering signals are injected unintentionally, in to pre-modulation stages or the post-modulation stages. By looking at the transmitter output spectrum, the interfering path can be identified. If an interfering signal is getting injected in to the pre-modulator stages, then the interfering signal will undergo the modulation and hence the modulation characteristics can also be seen on the interfering signal similar to that of the authorized signal. (For example: symmetrical output spectrum, showing the interfering signal on both the sides of the carrier in case of AM and FM.) On the other hand, if an interfering signal is getting injected in to the post-modulator stages, then, it results in an asymmetrical output spectrum showing the interfering signal at only one side of the carrier. This kind of interference signal may get injected in to the IF or RF stage.

Fig. 6.6.7 shows an example of interference signal injection in to the post modulation (IF) stage.



Un-terminated inputs. improper shielding at the upconverter or the combiner input is a strong source of FM/ VHF interference.

Fig. 6.6.7: FM radio Signal Interference/Re-transmission by VSAT terminal to the satellite.

Here the main cause of the interference is due to:

- Improper shielding in the up-converter input.
- Improper shielding in the modem IF output connector.
- Un-terminated and unused inputs of an up-converter.
- Un-terminated input port in the combiner prior to up-converter.

70 MHz is generally used as the IF frequency in satellite C-band earth stations. Many Ku-band receivers, available in the market, are designed with 140 MHz as the IF frequency. Many VSATs are also configured with L-band as the intermediate frequency. The frequency allocation in India are given in Annexure-1 to identify all possible operators/ transmitters in these frequency bands of interest.

(B) The severity of interference is mainly dependent on the following factors

- Coverage area of broadcast,
- Number of broadcasting transmitters in the vicinity of VSAT terminal locality,
- Distance between the broadcasting transmitters and the VSAT terminal,
- The transmitted power.

The transmitted power of FM radio/VHF transmitters is higher than that of L band transmitters. The high transmit power encountered in this band causes serious interference in satellite IF stages. Following are the main interference contributors.

- TV transmitters in the 49 to 56 MHz band and in the band above 174 MHz i.e., VHF Band 174 MHz to 230 MHz and UHF 240 MHz to 315 MHz. The VHF frequency transmission in High Power Transmitters (HPTs) may affect the satellite IF 140 ± 40 MHz version.
- FM Radio broadcast transmitters in the 87.5 to 108 MHz (CCIR band): FM broadcast transmitters are also located in many cities / towns of India. There are a total of 215 FM radio stations in India, and they are densely located in major cities.
- Analogue mobile radio telephones in the 73 to 87 MHz and 108 to 175 MHz bands. Since the transmitter is mobile, the interference of this kind is of intermittent type.

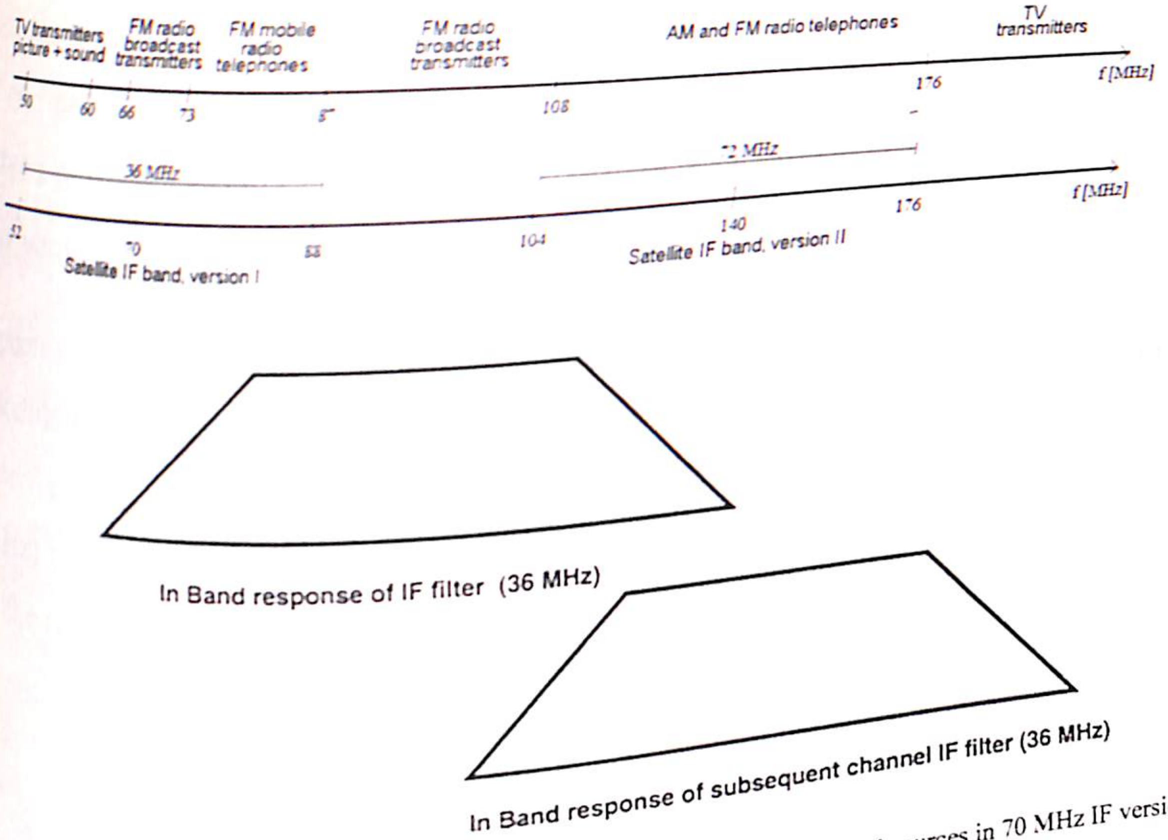


Fig. 6.6.8:Frequency spectrum showing the possible FM Radio interfering signal sources in 70 MHz IF version.

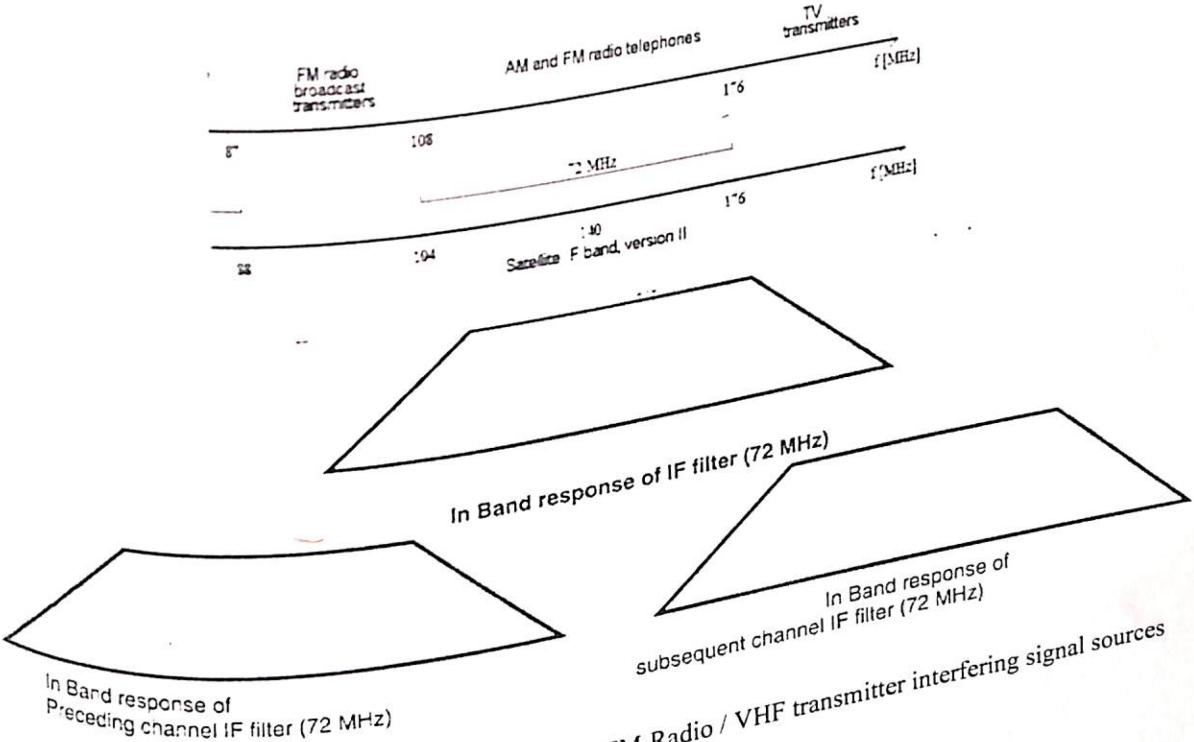


Fig. 6.6.9: Frequency spectrum showing the possible FM Radio / VHF transmitter interfering signal sources

6.6.4 Measurements of FM Radio pick-up

FM Radio / VHF signal interference into satellites can best be analysed by measuring the downlink spectrum of the transponders.

Fig. 6.6.10 shows the spectrum analysis in different stages of the VSAT transmit section. The total RF bandwidth in 240 MHz (6 transponders with bandwidth of 40 MHz each) is extended C-band, and 70 MHz ± 20 MHz IF band for each transponder are shown in the figure.

Spectrum analysis carried out at RF stage will give better results especially for post-modulation interference. It is, in some cases, especially for pre-modulation interference, advisable to carryout spectrum analysis in the IF stage (70 MHz or 140 MHz) or in the LNBC (Low Noise Block converter) output for whose IF frequency is in the range of 950 to 2050 MHz.

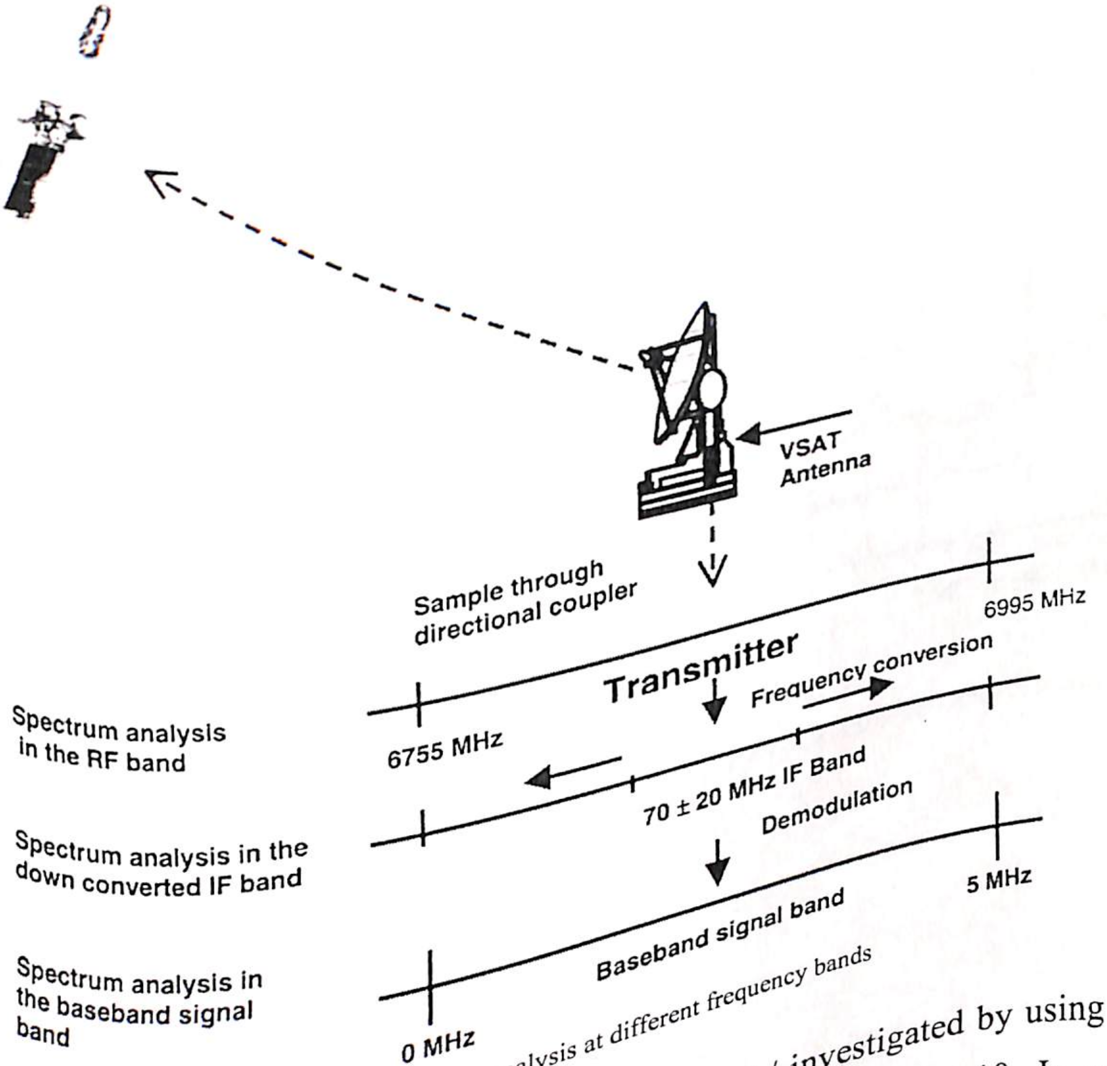


Fig. 6.6.10: Spectrum analysis at different frequency bands

analysed / investigated by using a test in Fig. 6.6.10. In case of to have the spectrum analyser in that frequencies. In such cases IF spectrum may be investigated which gives comparable results by taking into due consideration of correction factors, spectrum inversions, if any applicable.

Pick-up of FM Radio signals of Hassan Radio Station were measured at MCF in 100 MHz band and the satellite Transmit band, and are given in Fig. 6.6.11 and Fig. 6.6.12.

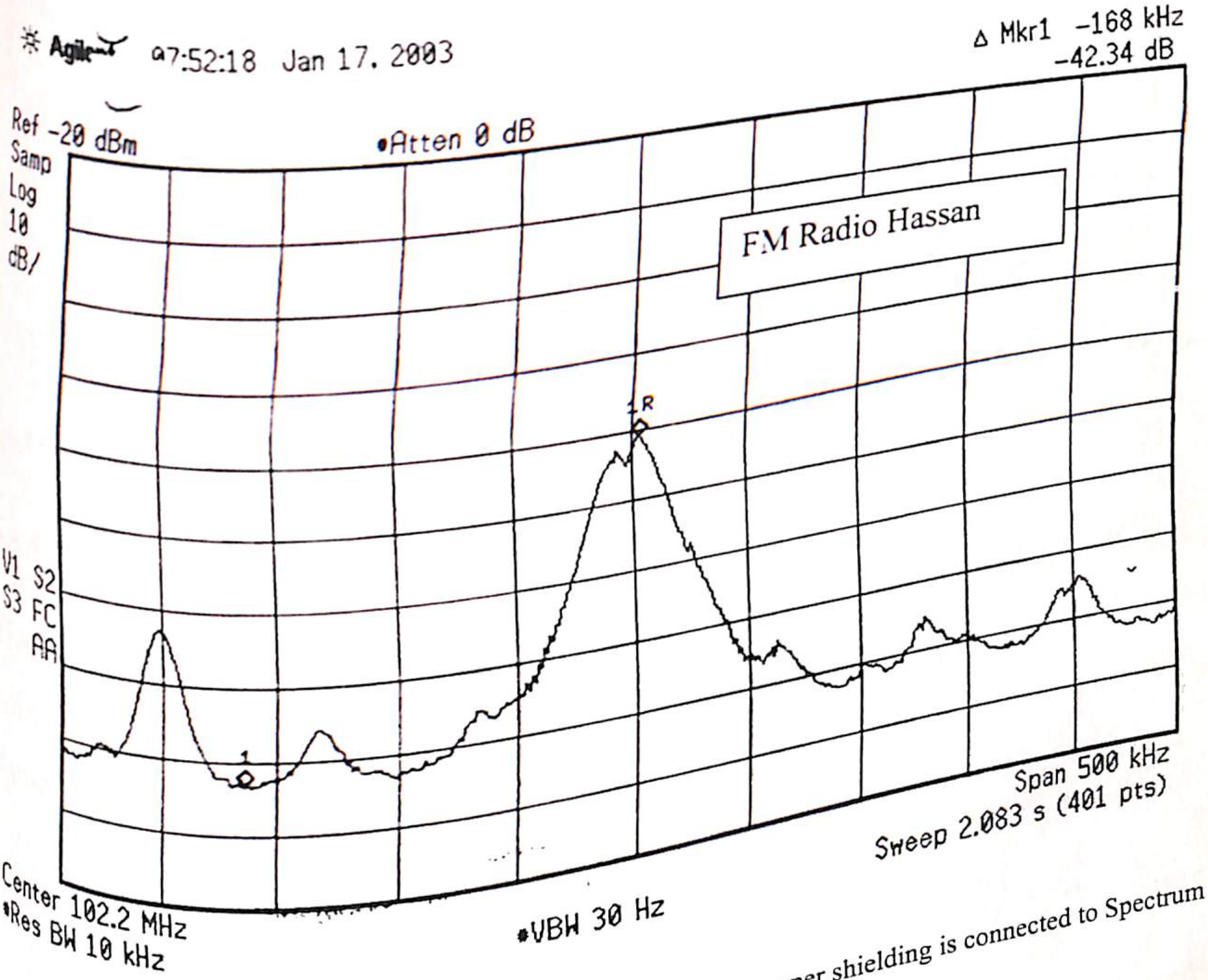


Fig. 6.6.11: Spectrum Plot at IF stage, BNC to open cable with improper shielding is connected to Spectrum Analyser.

④

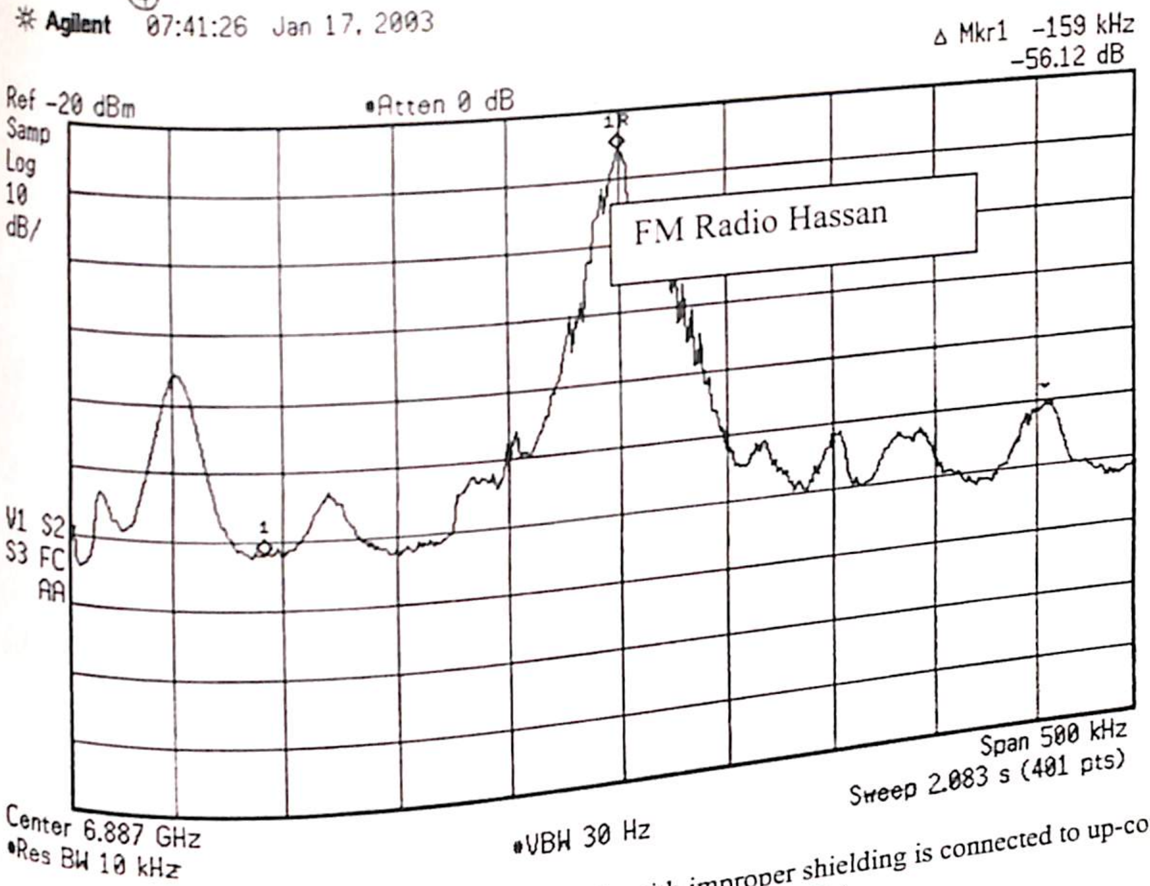


Fig. 6.6.12: Spectrum Plot at RF stage, BNC to open cable with improper shielding is connected to up-converter input (Up-converter CF is set to 6855 MHz)

6.6.5 FM Radio Stations In India

There are a total of 215 FM Radio stations operational in India, mostly crowded in cities. The number of FM stations, and the number located in major cities are given in Table-6.6.3 and 6.6.4.

Table-6.6.3: FM radio stations in India.	
FM Radio Stations operated by AIR	138
FM Radio Stations licensed for Private Broadcasting	77
Total FM Radio Stations	215

It is apparent from Table-6.6.5 that the 3 V/m limiting field strength value applies for the interested band of IF (both 70 ± 18 and 140 ± 36 MHz versions) and L bands. Hence it is good to consider this specification of the limit of field strength during the site survey, preceding the earth station installation.

From the above Tables it is evident that no satellite ground terminals should be installed within a distance of 500 m from an 80 kW FM or VHF transmitter. Similarly Table-6.6.5 gives distance limit for different ERP signals, assuming an ideal VSAT terminal with standard shielding and terminations. Whenever there is a need to install the VSAT terminal in the vicinity of this distance limit, it is required to take the strict screening precautions for the VSAT terminal, especially in the IF stage, in order to overcome the danger of exceeding the electromagnetic immunity limit.

(C) Intersputnik users handbook has set this immunity limit to a distance of 2 Km. For FM radio and TV centres located less than 2 Km away from the VSAT terminal, the handbook recommends to screen the VSAT equipment room [50].

6.6.7 Conclusions

Expansion of FM broadcast services and VSAT networks is resulting in the installation of more and more FM Radio Transmitters as well as VSAT terminals at a rapid rate. In view of the interference aspects of FM Radio Transmitters to VSAT networks, it is very essential to take in to the consideration the nearby FM Radio and VHF transmitters while choosing the site for VSAT terminal. These transmitters or the interfering sources operate in the satellite IF frequency bands. And this causes interference in satellite communication. The kind of interference observed in INSAT-3B and INSAT-3C could be avoided by proper shielding and installation of an appropriate band pass filter in the IF stage (in the input to the Up-converter).

ANNEXURE-1

Frequency Allocation in India (Covering 70 MHz and 140 MHz IF Band and L Band)

Application	Frequency Band
Fixed/Mobile services	54 - 68 MHz; 91.5 - 95 MHz; 100 -108 MHz
Broadcast services	87 - 91.5 MHz and 95 -100 MHz
Radio astronomy service	79.75-80.25 MHz, 150.05 -153 MHz
Car rallies/Sports activities.	143.950 MHz, 150.175 MHz & 150.9 MHz
Amateur Service	144 -146 MHz; 1260 -1300 MHz
Wide area radio paging systems and talk-back facility	146.45 -147.95 MHz, 151.5 -153 MHz, 164.5 -166.5 MHz and 171 -173 MHz. 146.5625MHz, 146.6125MHz, 146.6375 MHz, 151.6125 MHz (except Pune), 151.6625 MHz, 165.3625 MHz (Delhi only), 165.4625 MHz, 165.6625 MHz, 166.1125 MHz, 166.1625 MHz (except Delhi), 166.2375 MHz & 166.2875 MHz (Bombay only), 166.3125 MHz, 166.3625 MHz, 166.3875 MHz, 166.4375 MHz, 172.8635 MHz. 172.8875 MHz and 172.9375 MHz
Cordless telephone remote units	150.350 MHz, 150.750 MHz, 150.850 MHz and 150.950 MHz
All India Radio (between O.B. Vans & Field Staff)	150.525 MHz
Film shooting	151.250 MHz
Maritime mobile services	156-156.7625MHz.
Port operations (from shore to ship)	156.375 MHz, 156.475 MHz, 156.575 MHz, 156.850 MHz. 156.675 MHz, 156.475 MHz & 156.750 MHz 8268.0 (A)/8266.6 (C) kHz, 12361.4 (A)/12360 (C) kHz
Remote control of E.O.T cranes	166.875 MHz & 167.725 MHz
Doordarshan (for use by O.B. Vans)	166.950 MHz
Cellular mobile telephone	890-902.5 MHz & 935-947.5 MHz
Supervisory control and data acquisition system (SCADA).	849.0125/933.0125, 849.0250/933.0250, 849.0375/933.0375, 849.0500/933.0500, 849.0625/933.0625, 849.0750/933.0750, 849.0875/933.0875, 849.1000/933.1000, 849.1125/933.1125, 849.1250/933.1250 MHz
Cellular and WLL	1700 -2000 MHz ;1710 -1785 MHz &1805 -1880 MHz, 1710 -1785 MHz &1805 -1885 MHz &1700-2000 MHz
Radio navigation service	1215 -1300 MHz
Radio determination-satellite service (Earth-to-space)	1610 -1626.5 MHz
Meteorological aids service	1660.5 -1668.4 MHz
Space research service	1700 -1710 MHz
Space operation (Earth-to-space)	1750 -1850 MHz

ANNEXURE – 2

FM radio broadcasting transmitter technical parameters

1. GENERAL :

a) Frequency Range	87.5 to 108 MHz. (Menu driven in 10 kHz increments)
b) Class of Emission	F3E
c) Stereo transmissions	According to CCIR Recommendation 450 – section 2 (Pilot tone method).
d) Rated Frequency deviation	+/-75 KHz.
e) Nominal Frequency deviation	Capable upto +/- 100 KHz.
f) Pre-emphasis	0, 50 or 75 micro seconds locally selectable

2. RF OUTPUT :

a) Rated output power	1 kW nominal output.
b) Rated output(Load)impedance	50 ohm .
c) Permissible VSWR	i. 1.5: 1 on full power; ii. Automatic power reduction beyond 1.5:1 iii. Tr. should be protected for short and open circuit conditions.
d) Harmonics Suppression and Spurious radiation	Within limits as stipulated in Radio Regulations FCC/IC/DOC/ CCIR. Actual values to be indicated.
e) Modulation Type	Direct Carrier Frequency Modulation.
f) Overall efficiency	Better than 40 %.
g) Output signals	i. AF sound broadcasting signals, ii. RDS Signals iii. SCA signals in DARC (Data Radio channel) in Stereo , mono & composite mode.

3. INPUTS :

a) Modulating input	The Transmitter should be able to accept Analog audio Mono & composite signals, AES/EBU digital signals, RDS Signals, SCA signals inputs. Cost of External Coder / additional module required if any is to included.
b) Input impedance and Analog input level for 75 KHz deviation	Nominal 600 ohms (Balanced) to ground . Additional Impedance level may also be provided, and Impedance level and input level to be consonant to work with Audio Processor and Stereo Encoder described elsewhere.

4. POWER SUPPLY :

a) Line voltage	230 volts, single phase.
b) Permissible voltage fluctuations	± 15%
c) Frequency	50 Hz ± 6 %
d) Power factor	better than 0.9.
e) Power Line Harmonics	As indicated in IEEE 519-1992.

5. **AMBIENT CONDITIONS** :

a) Temperature range for operation : -10 Deg C to + 50 Deg C.

b) Relative humidity : 90 percent, non condensing.

c) Working altitude : upto 3000 meters AMSL

6. **TRANSMISSION CHARACTERISTICS** : (for full base band)

a) Frequency Stability : ± 300 Hz. (0 to 50 degree C)

b) Synchronous AM S/N Ratio with no de-emphasis (at 75 kHz Deviation at 400 Hz) : Better than 60 dB below equivalent 100 % Amplitude modulation.

c) Asynchronous AM S/N Ratio unweighted with no de-emphasis (without FM modulation) : Better than 60 dB below equivalent 100 % Amplitude modulation at 400 Hz.

d) **WIDEBAND COMPOSITE OPERATION:**

i) FM S/N ratio at 75 KHz deviation rms ,unweighted Reference 400 Hz at +/- 75 KHz frequency Deviation with 50 us de-emphasis and DIN 'A' weighting 20 Hz to 80 kHz Bandwidth. : Better than 70 dB

ii) Total Harmonic Distortion + Noise : Better than 0.1 %.

iii) Amplitude response 30 Hz to 100 KHz : Better than +/-0.3 dB

e) **MONO OPERATION** :

i) FM S/N ratio at 75 KHz deviation in 50 Hz to 15 kHz Band Width rms, unweighted with 50 us de-emphasis. : Better than 70 dB

ii) Total Harmonic Distortion (50 Hz to 15 kHz) with 50 us de-emphasis at 100% mod. : Less than 0.1 % including all harmonics upto 30 kHz

iii) Amplitude response 30 Hz to 15 KHz : Better than +/-0.3 dB

f) **STEREO OPERATION** :

i) Stereo separation(sine wave) (30 Hz to 15 KHz) : Better than 50 dB

iii) Linear Cross Talk referred to 100% modulation (30 Hz to 15 KHz) : Better than 45 dB

iv) Non-linear Cross Talk referred to 100 % modulation : Better than 65 dB

v) FM S/N ratio at 75 kHz deviation in 50 Hz to 15 kHz Band Width rms, unweighted with 50 us de-emphasis : Better than 60 dB

vi) Total Harmonic Distortion (30 Hz to 15 kHz) with 50 us de-emphasis at 90% mod. : Less than 0.3 % including all Harmonics upto 30 kHz

vii) Pilot Carrier : 19kHz ± 0.1 Hz (Locally Selectable ON or OFF)

viii) Audio Amplitude Response (20 Hz to 15 kHz) : ± 0.5 dB or better.

6.7 Case Study-6: Interference during relocation of satellites and drift orbit phase of the satellite

6.7.1 Introduction

A number of communication satellites had been re-orbited or relocated in the geo synchronous orbit in the recent past. Relocation in orbit is primarily on account of the evolving operational / payload utilization / due diligence requirements. During drift phase of the relocation, the satellites fly-by other operational satellites in the geo synchronous orbit. A satellite is likely to interfere with another system when it passes-by, and in the GSO vicinity of ± 1.5 deg of longitude of other satellite. So, the interference potential exists over a 3 deg longitudinal span of the GSO for each satellite.

Interference potential to operational spacecraft results basically on two counts.

1. Interference onto the transponders owing to the Tele-Command & Ranging operations of the Satellite which is in drift orbit.
2. Interference in the downlink signal from the Telemetry beacons of the satellite, which is in drift orbit.

Apart from the above, TTC operations of the drifting satellite also get affected due to the operations of the satellites, it is passing by.

A detailed investigation of the interference caused to other operational satellites during the relocation operations of INSAT-2B INSAT- 2C is detailed in this case.

6.7.2 Identification of Interference potential during satellite relocation

(A) Command & Ranging Operations

al satellites is primarily on account of the
The command carriers for
This band

During normal operations, the EIRP for command and ranging operations is limited to around 70 dBW, the minimum EIRP that would ensure reliable command execution and ranging data integrity. For this EIRP, the flux density at the GSO is around –92 dBW/m^2. The C/No at the satellite receiver input for a nominal Satellite G/T of -5dB/deg. K is around 95 dBHz. Signals at this level will cause interference to the communication transponders or the other satellites operating in this band. In case of satellites with better G/T (0 dB/deg. K or better), the impact would be much higher.

(B) Interference in down link from Telemetry beacons

The telemetry beacons of the INSAT satellites in GSO operate in the 4185 to 4200 MHz band and overlaps the operational transponder bandwidth in the C band for some communication satellites. During drift operations, telemetry beacons are configured for high power (Omni) mode. The telemetry beacons become interference in the receive band of the other satellites that it passes-by. The interfering signal caused by these beacons, considering nominal telemetry EIRP of 0 dBW, is of the order of 62 dBHz C/No at the input of a 7.2m terminal with G/T of 29dB/deg. K and can cause interference to low power/data rate links of VSAT and IDR networks.

6.7.3 Relocation cases

(A) INSAT-2C relocation operations

INSAT-2C was relocated to the 48 deg. E from the 93.5 deg. E longitudinal slot. All communication transponders were switched off and a westward drift rate of 1.59 deg/day was induced. With this drift rate, interference potential existed to each satellite INSAT-2C passed by, for a maximum duration two days. The satellites which were passed-by INSAT-2C during the relocation is given in Fig. 6.7.1.

Telemetry transmitter #2 was configured for high power mode (Omni). Command carrier, with an EIRP of 70 dBW, was brought down and was brought up as and when required for operation to avoid interference to others. Ranging operation was cancelled whenever any Operator informed about interference.

(B) INSAT-2B relocation operations

INSAT-2B was relocated to the 111.5 deg E longitudinal slot from the 93.5 deg E. The satellites crossed by INSAT-2B during the relocation is given in Fig. 6.7.2.

The relocation operations were completed between the 19th February and 7th April 2002. Prior to drifting, the communication payloads were switched off. An eastward drift rate of 0.60 deg/day was induced and with this drift rate, interference potential to each satellite INSAT-2B passed by, existed for five days duration maximum.

Telemetry transmitter 2 was ON and configured for high power mode (Omni). Command carrier EIRP was kept nominally at 70 dBW. There was extensive commanding during the initial phase, owing to pulsing operations. Command carrier was brought up during the commanding sessions and during the other times, RF silence was observed.

6.7.4 Interference problems due to drifting/transfer orbit satellites

(A) Interference to transponder in 2E

On the 26th November 2003 15:00 GMT, interference was observed to an operating Digital TV service in one of the transponders of INSAT-2E (positioned at 83 deg E longitude).

- Spectrum plot of the transponder showing interference is given in Fig. 6.7.3.
- The traffic carriers in this transponder were removed for verification of interfering signal. (Fig. 6.7.4).
- The spectrum plots with lower frequency span width (Fig. 6.7.5 and 6.7.6) clearly showed two un-modulated carriers at 3471 and 3478 MHz, and two modulated carriers at 3474 and 3477 MHz, indicating frequency deviation ± 400 KHz
- The signature of the two carriers at 3474 & 3477 MHz indicated presence of Command / Ranging modulation.

- Two telemetry signals were found in the downlink (Linier H Polarization), with centre frequencies of 3448.76 MHz and 3450.16 MHz. Both of them carried a sub-carrier modulation at 48 kHz (Fig. 6.7.7).

- Some other satellite was suspected to be very close to INSAT-2E satellite, and within the beam width of the ground antenna.

- The interfering carrier was present till 3:00 GMT of 27th Nov. 2003.

- The interfering carrier was monitored for two days and the longitude of the interfering satellite was estimated from Az and El angles of the ground antenna. The longitude history showed that the satellite drifted westwards for some time then started moving eastwards, finally reaching 85.7 deg E longitude. The drift rate of the satellite worked out to be 10.5 deg/day and the satellite was in 23 hours 20 mn orbit. The movement of the satellite westward and then eastward indicated that it was near Apogee.

- The interfering carrier again appeared at 14:00 GMT on the 27th Nov. 2003. The services were severely affected during the interfering period. Immediately the on-board attenuator setting was changed from 4 dB to 9 dB in order to reduce the effect of uplink interference getting translated through INSAT-2E transponder. The services were restored with marginal improvements.

- The interfering signal disappeared completely on the morning of 28th Nov. 2003.

(B) Interference to ChinaStar during drift orbit phase of INSAT-3A

- During post AMF# 3 fly by, ChinaStar operating at 87.5 deg East longitude experienced interference and disruption in Ranging operations at 6423 MHz due to Ranging carrier of INSAT-3A operating at 6423.496 MHz. Downlink spectrum plots for the ChinaStar taken at MCF indicated presence of Ranging Frequency carriers of both the Satellites (refer Fig. 6.7.8 and 6.7.9). The issue was resolved through planning of Ranging sessions alternately for INSAT-3A and ChinaStar.

6.7.5 Conclusions

1. The TTC operational band of frequency for satellites in GSO falls in the upper edge of the normal C band, with the likelihood of interference onto the upper edge of the communication transponder. The uplink EIRP though limited to 70 dBW, can even cause transponder saturation, requiring coordination with the Operators likely to be affected.
2. Telemetry beacons, can cause interference in the downlink, to low power/data rate links of VSAT and IDR networks.
3. Though the number of satellites passed by, carrying C-Band payload is 17 & 4 for INSAT-2C & INSAT-2B respectively, the number of satellites interfered with were less due to coordinated operations.
4. There is a large potential of interference during drift orbit / flyby phase of the GSO missions. Coordination and control of ground EIRP for ranging and command uplinks can reduce interference.

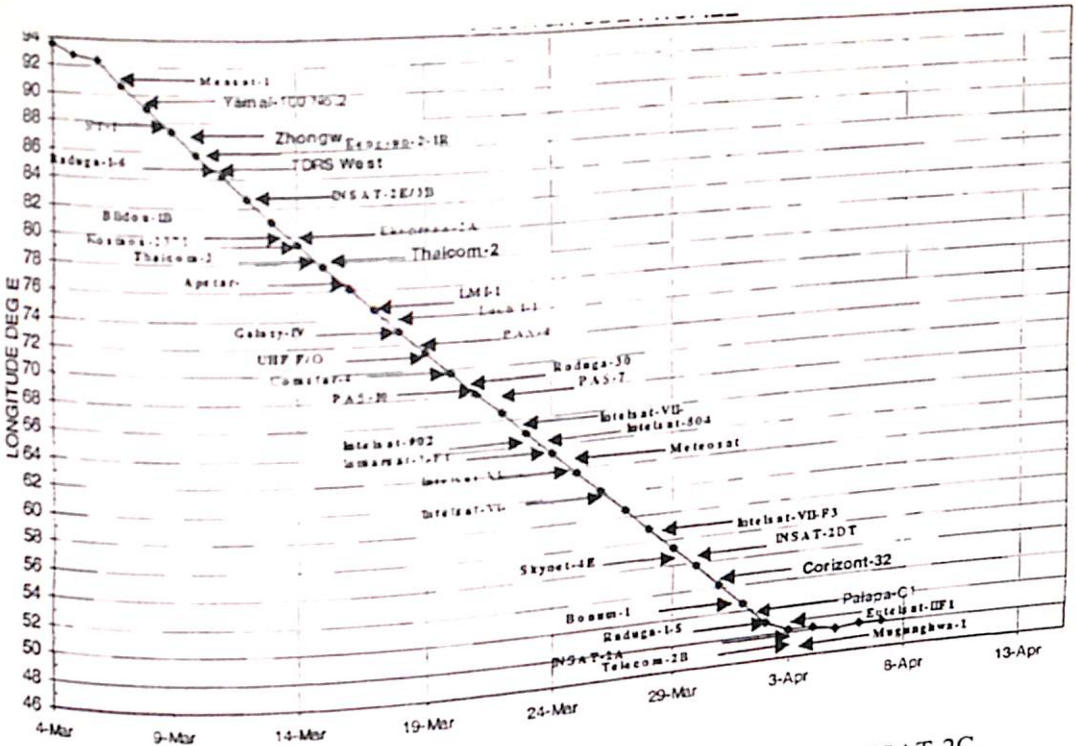


Fig. 6.7.1: Operational satellites crossed during relocation of INSAT-2C

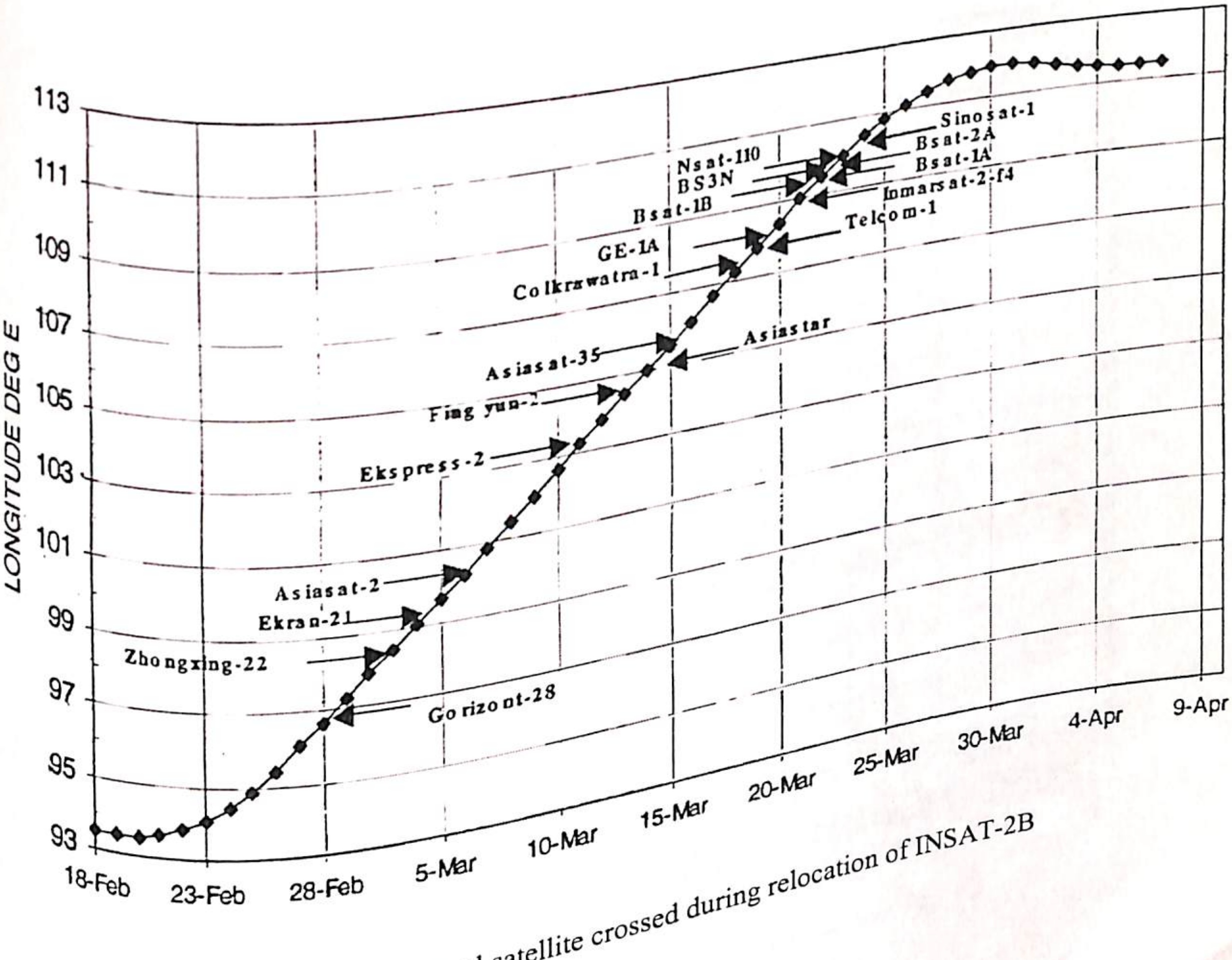


Fig. 6.7.2: Operational satellite crossed during relocation of INSAT-2B

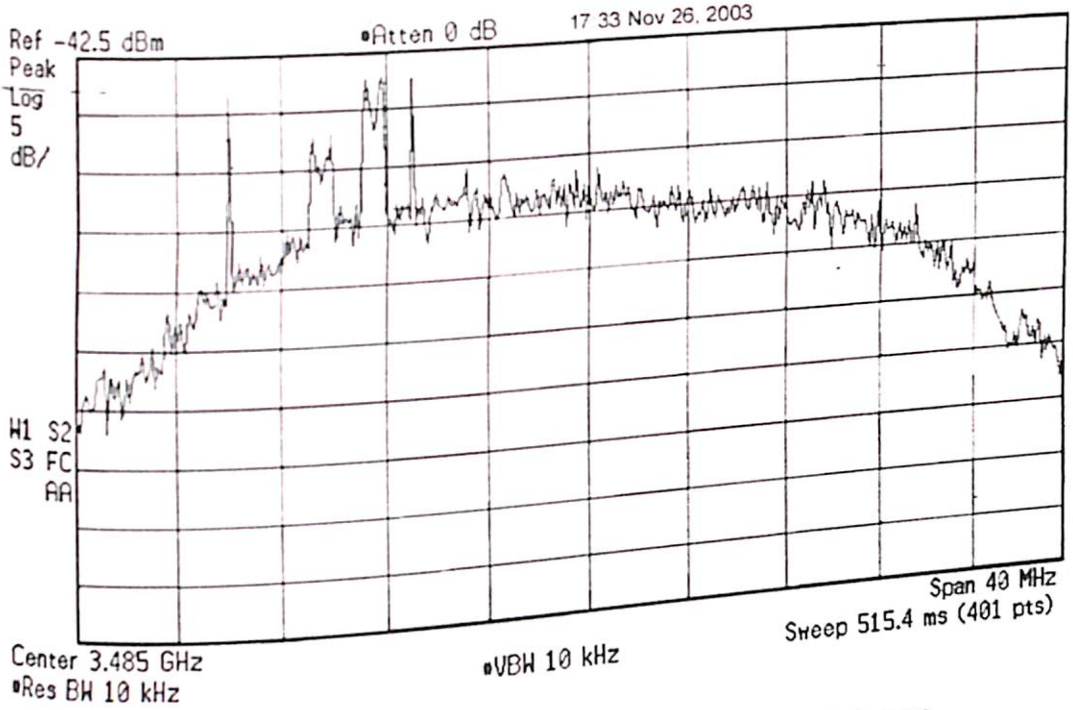


Fig. 6.7.3: Spectrum of digital TV along with reported interference

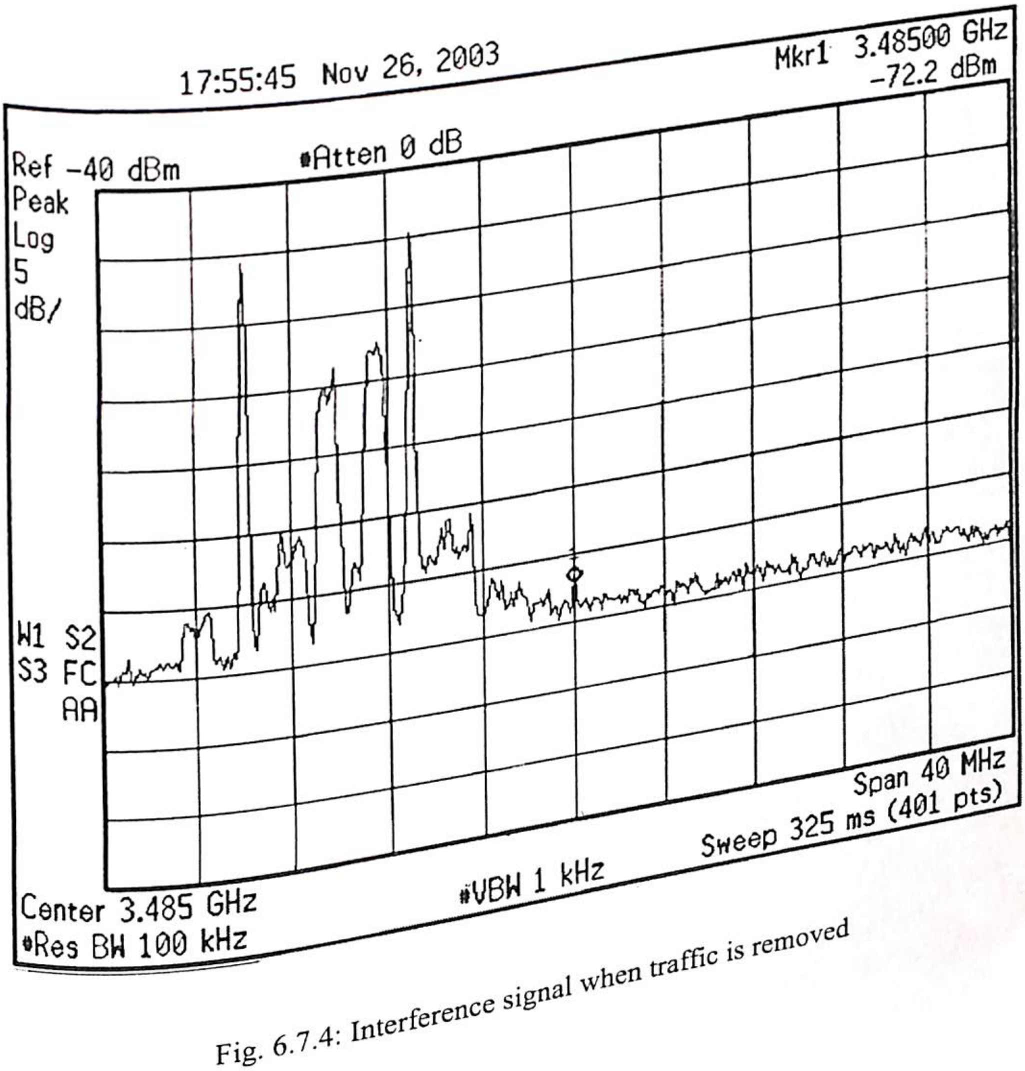
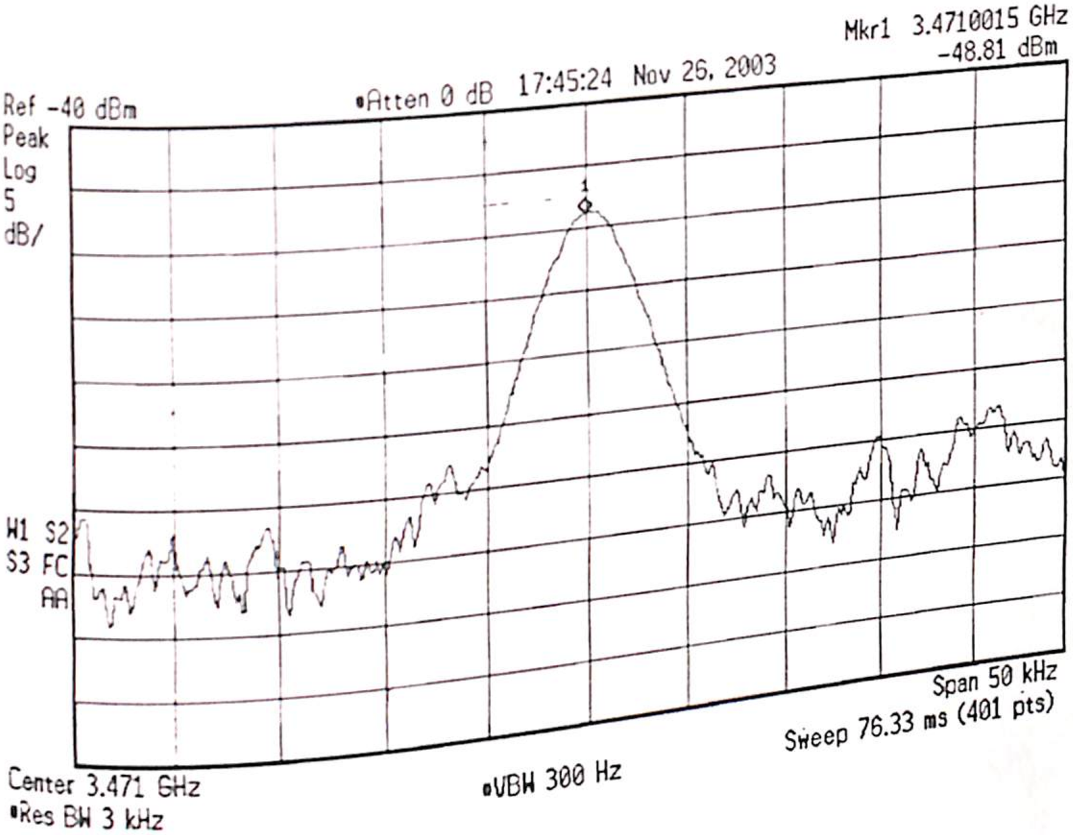
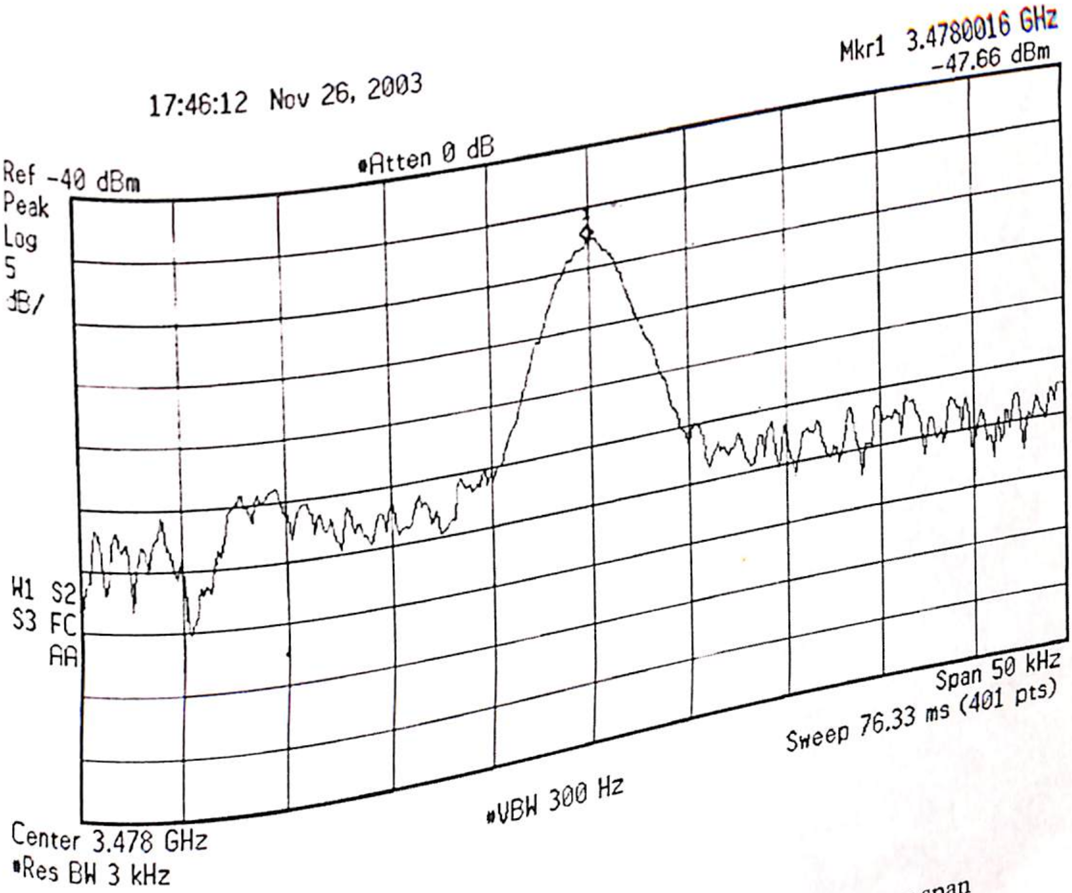
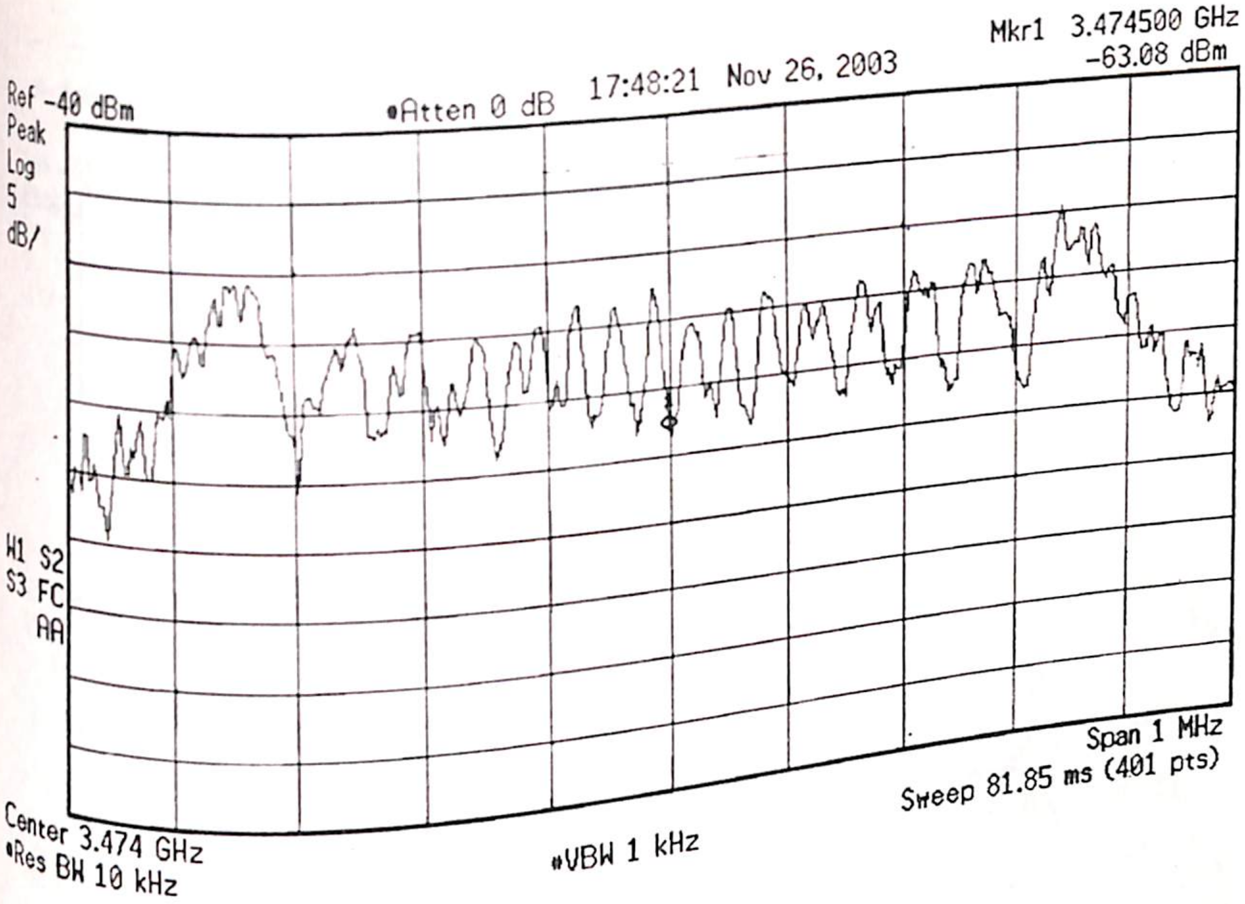


Fig. 6.7.4: Interference signal when traffic is removed





nals with lower span



Mkr1 3.474500 GHz
-63.08 dBm

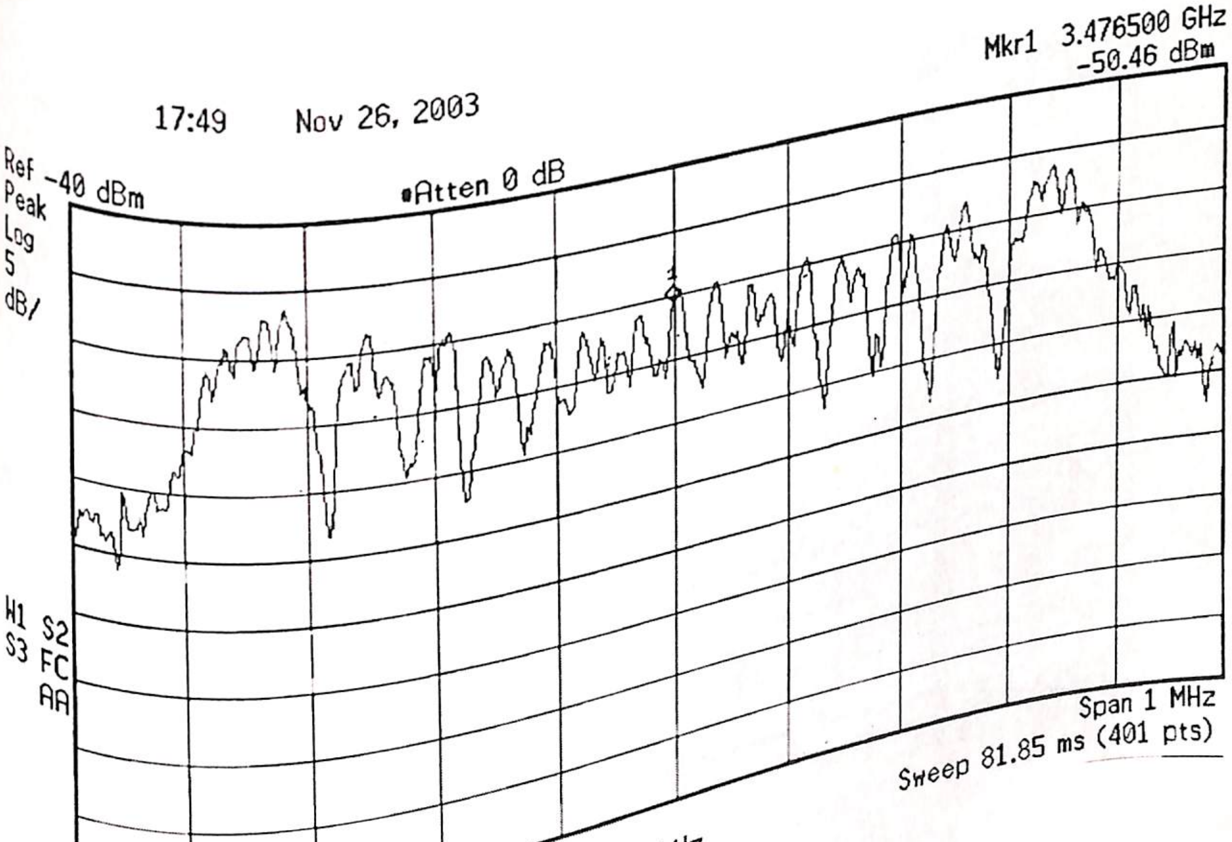
Ref -40 dBm
#Atten 0 dB
17:48:21 Nov 26, 2003

Peak
Log
5
dB/

W1 S2
S3 FC
AA

Center 3.474 GHz
#Res BW 10 kHz
#VBW 1 kHz

Span 1 MHz
Sweep 81.85 ms (401 pts)



Mkr1 3.476500 GHz
-50.46 dBm

17:49 Nov 26, 2003

Ref -40 dBm
#Atten 0 dB

Peak
Log
5
dB/

W1 S2
S3 FC
AA

Span 1 MHz
Sweep 81.85 ms (401 pts)

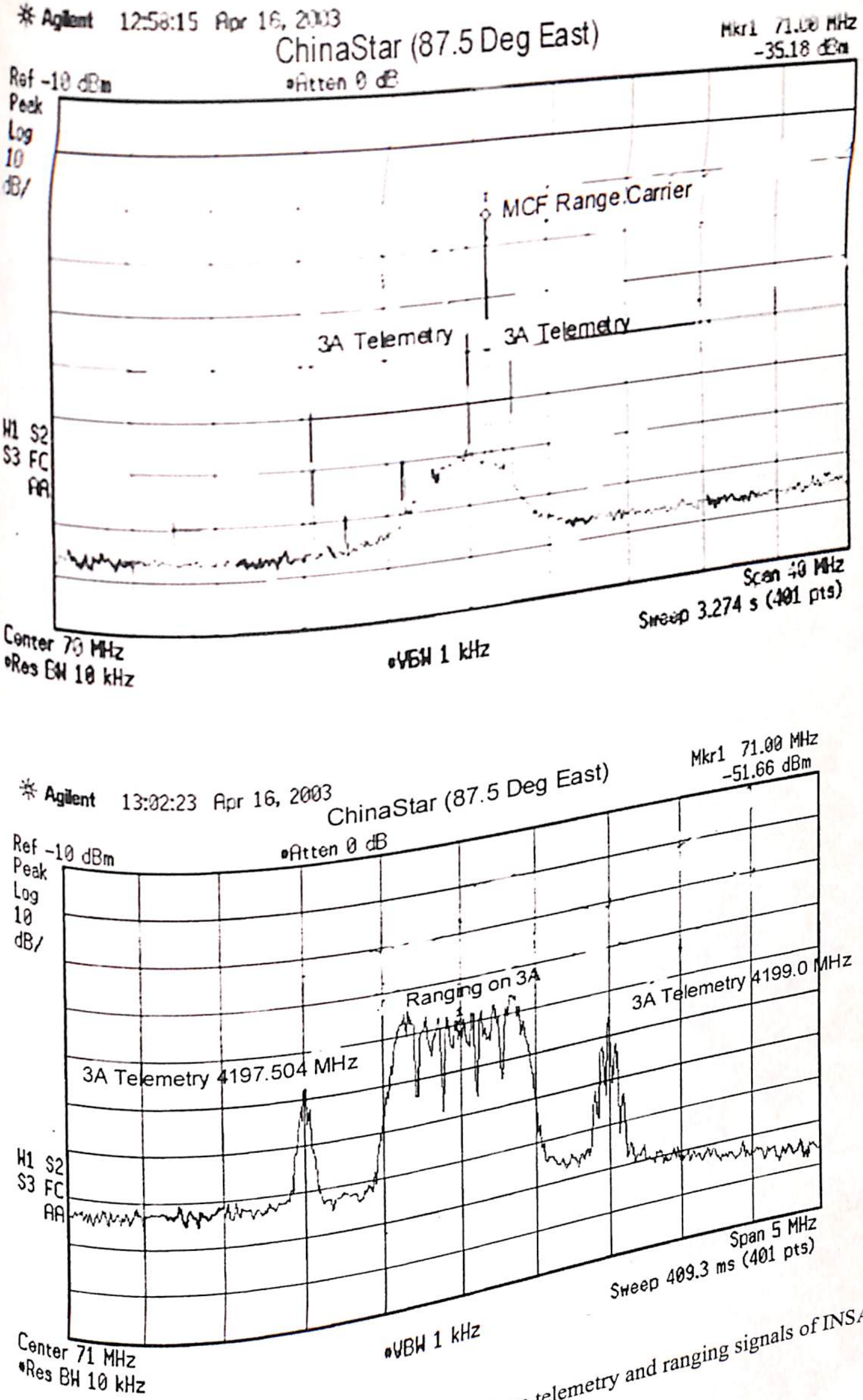


Fig. 6.7.8: Spectrum plots of ChinaStar with interference from telemetry and ranging signals of INSAT-3A

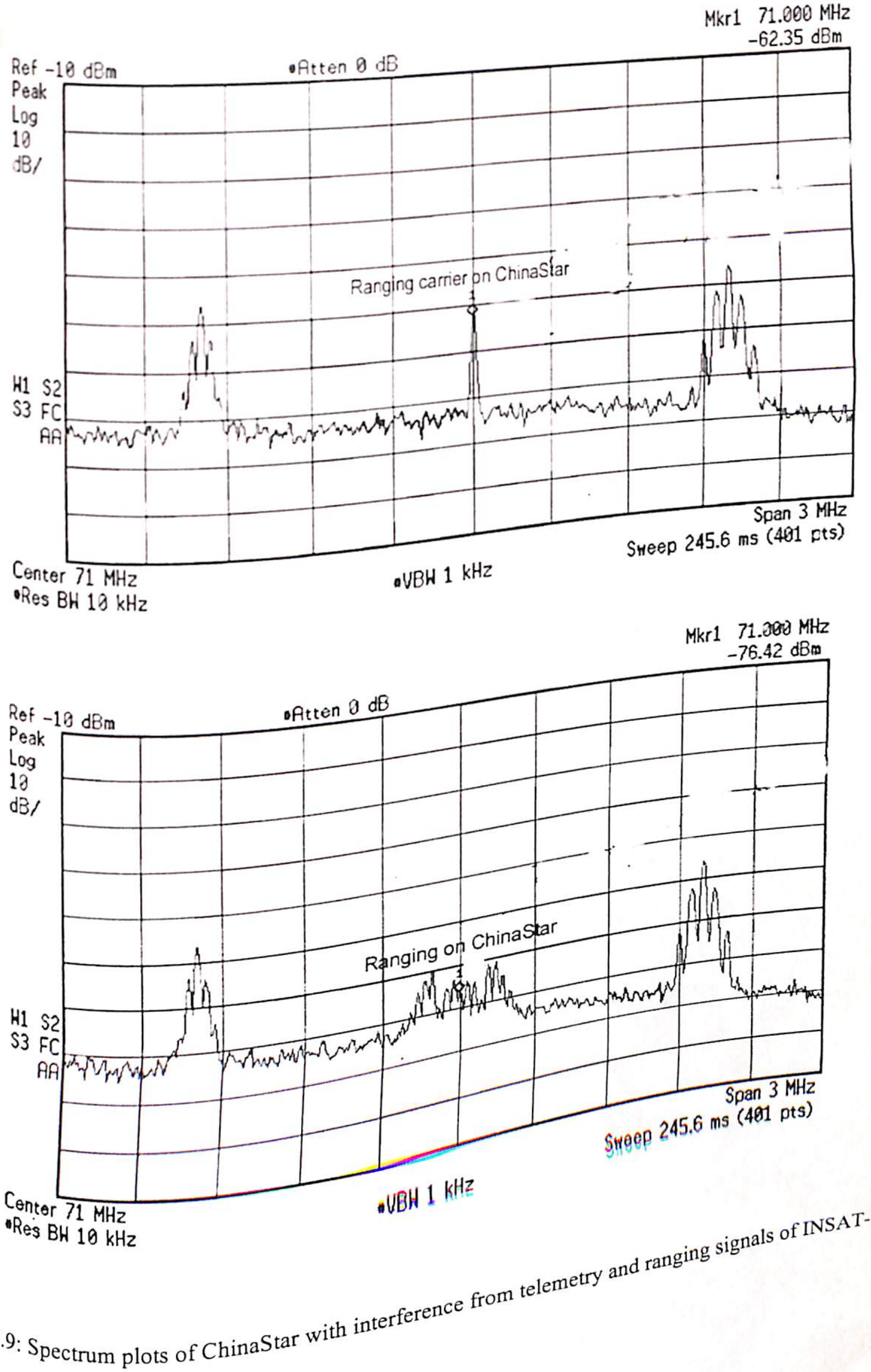


Fig. 6.7.9: Spectrum plots of ChinaStar with interference from telemetry and ranging signals of INSAT-3A

6.8 Case Study-7: Interference in INSAT MSS Payload

6.8.1 Introduction

INSAT-2C, 3B, 3C and GSAT-2 have the Mobile Satellite Service (MSS) Payload. Currently INSAT-3C and GSAT-2 are operational. The major payload characteristics along with footprints are highlighted in Table-6.8.1 and Fig. 6.8.1a and 6.8.1b. The overall block diagram of MSS network is given in Fig. 6.8.2a and 6.8.2b. The system supports voice communication between mobile terminals either in land or in maritime environment and PSTN subscribers, with the Hub as the gateway. Data and Fax services are supported between mobile and PSTN subscribers. Single Channel Per Carrier (SCPC) Mode of communication is implemented on demand using signaling channels. Further, the system provides a separate store and forward messaging services using common communication channels and a separate reporting service for mobile users.

Table-6.8.1: INSAT MSS Transponder Major Specification

S/N	**Parameters**	**Forward link (CXS)**	**Reverse link (SXC)**
1	Receive frequency (MHz)	6450-6470 (BW 20 MHz)	2670-2690MHz
2	Transmit Frequency (MHz)	2500-2520 (BW 20 MHz)	3680-3689 MHz (BW 9 MHz: F_1) 3691-3700 MHz (BW 9 MHz: F2)
3	Receive polarization	LP-V	LHCP
4	Transmit Polarization	LHCP	LP-H
5	Saturation flux density (dBW/m^2)	-92± 2	-109± 2
6	SFD range (dBW/m^2)	-92.0 to – 80.0	-109 to –87.0
7	Back off attenuation (dB)	12	22
8	Transponder saturated EIRP (dBW)	37	30
9	Transponder receive G/T (dB/K)	-5.0	-7.5
10	HPA out put (Watt)	50 watt TWTA	4 watt SSPA
13	XPD/Axial ratio (dB)	3.0(A.R)	26.0 dB(XPD)

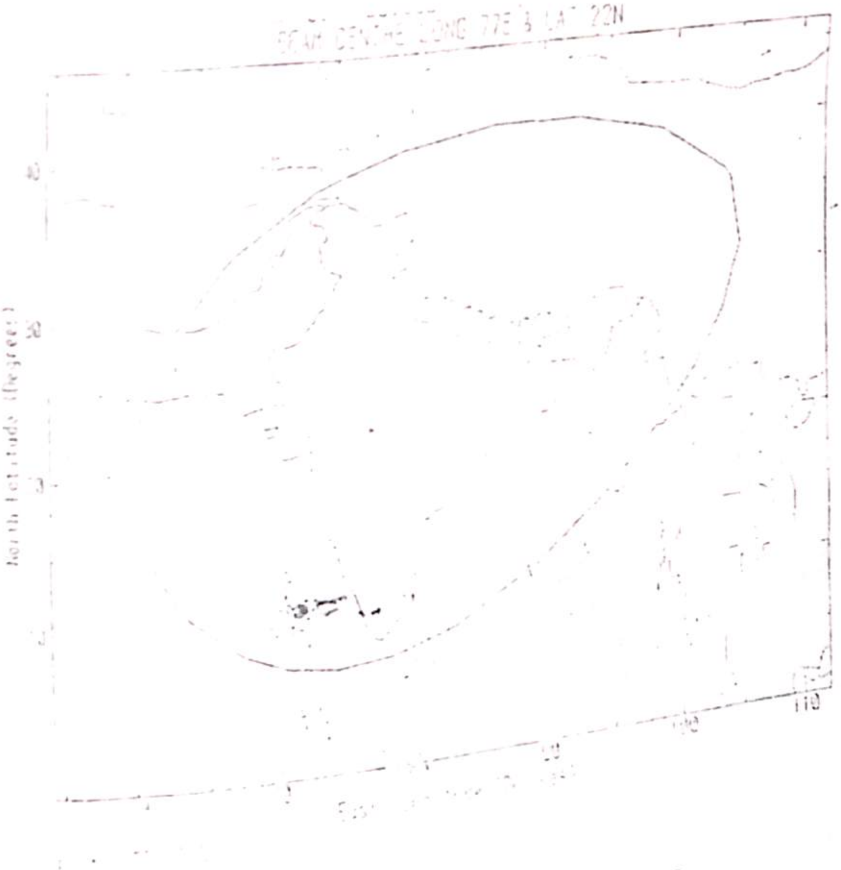


Fig. 6.8.1a: GSAT-2 C-band service area

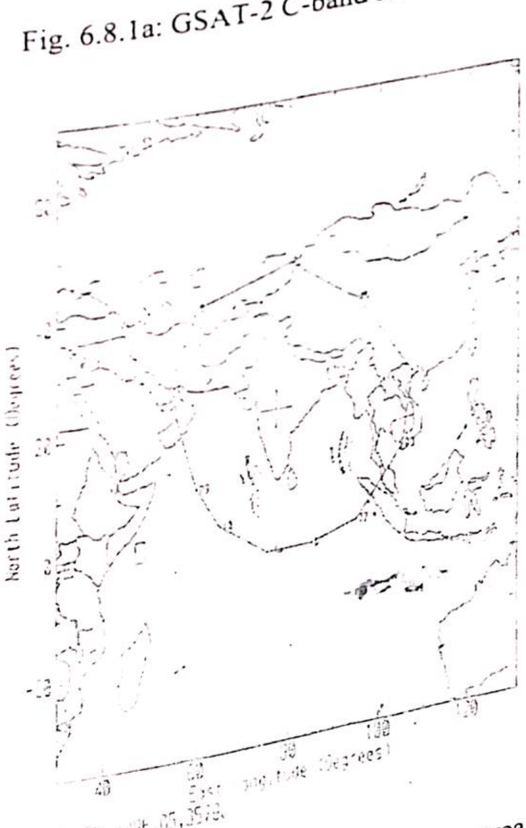


Fig. 6.8.1b: GSAT-2 S-MSS service area

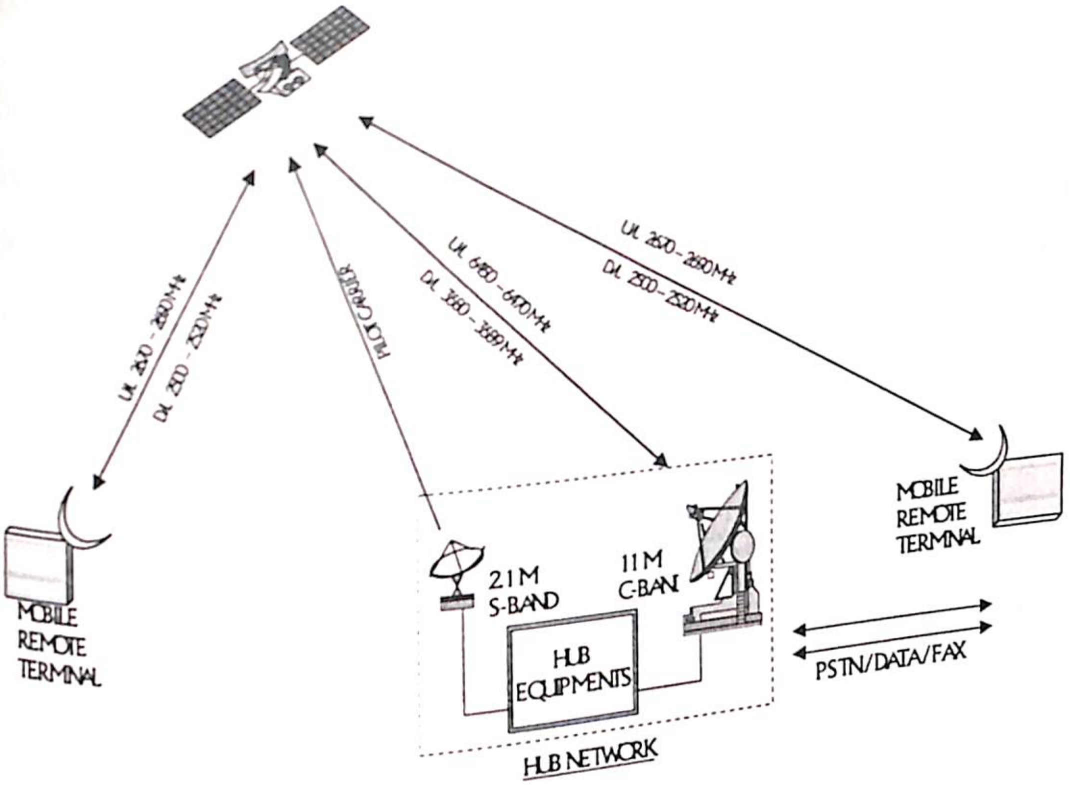
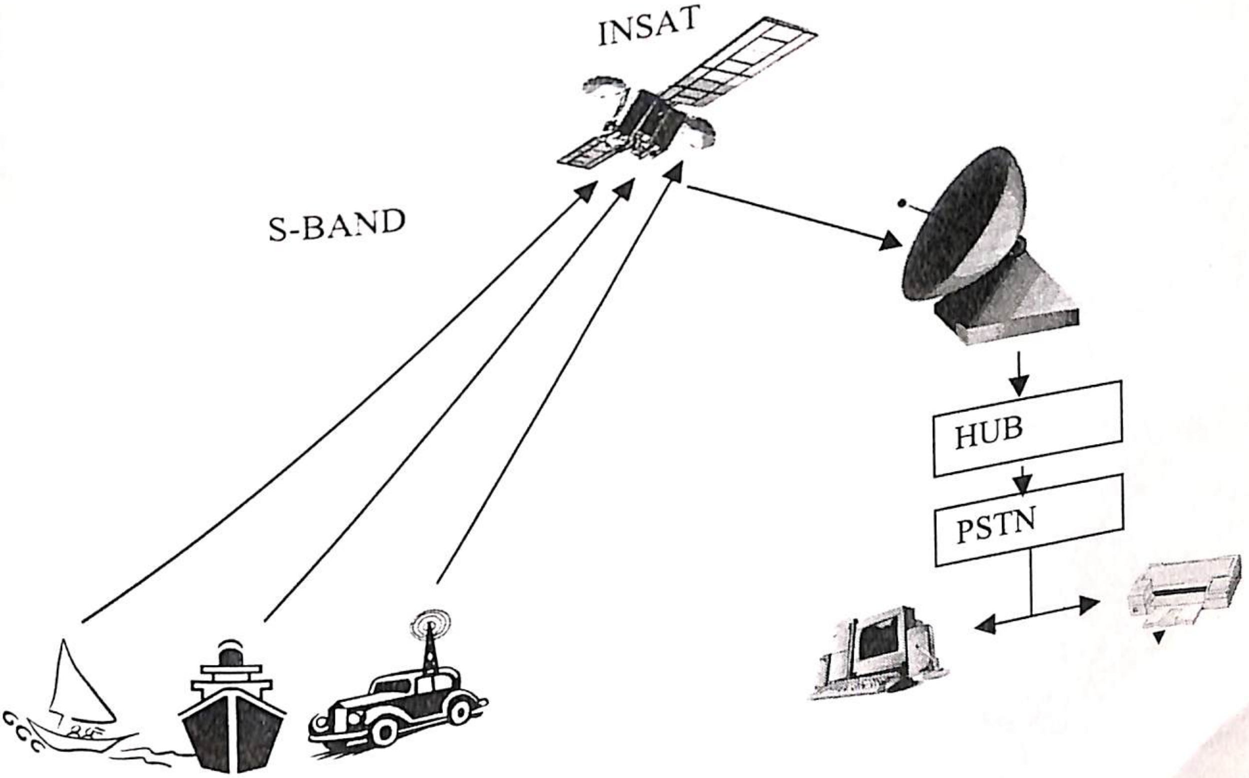


Fig. 6.8.2a: INSAT MSS configuration



6.8.2 Definition of the Problem

Occasional burst type interference was observed within 9 MHz bandwidth of INSAT MSS payload C-Band downlink spectrum. Selecting high-resolution bandwidth of the spectrum analyzer, the sin x/x type of spectrum could be observed. The traffic losses in digital and analog circuits were also experienced. Attempts were made to measure the characteristics of the interference and its location.

6.8.3 Characterisation of Radar burst signal

(A) Characterisation of Interference

To characterize the interference signal, following measurements were conducted with the test configuration given in Fig. 6.8.3a:

- Signatures of Radar burst signal.
- 24 hours Recording.
- EIRP Calculation.
- TDOA measurement

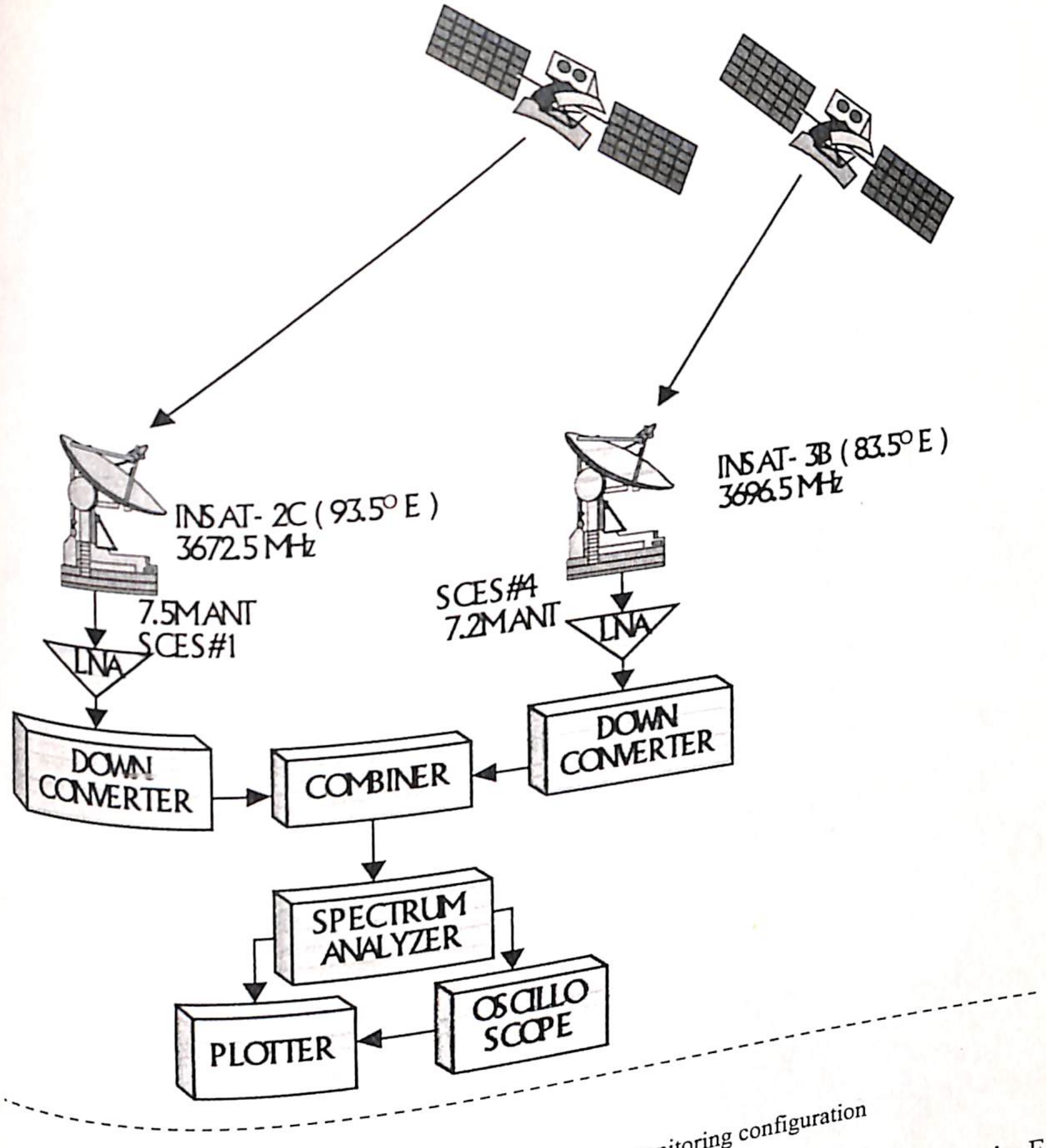
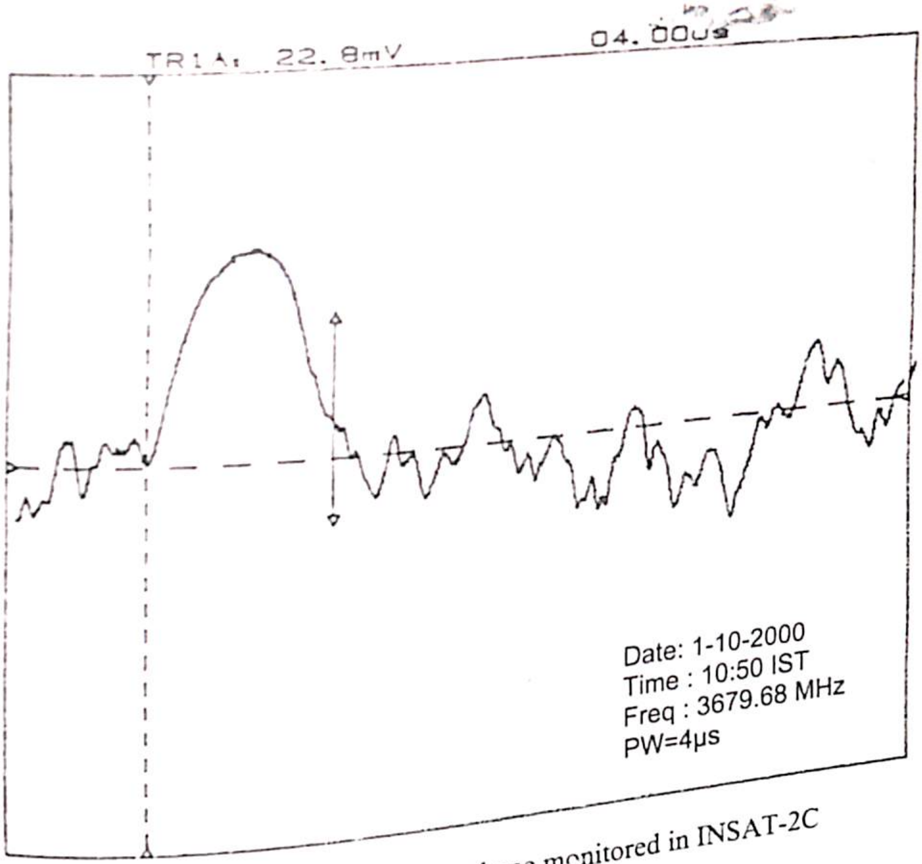


Fig. 6.8.3a: INSAT-2C & 3B interference monitoring configuration

The plots for Pulse width, Pulse repetition time and Scan rate were shown in Fig. 6.8.3b to 6.8.3e. The characteristics of radar bursts were found to be:

- Pulse width : 2 to 5 µ sec
- PRF : 350 to 450 Hz
- Scan rate : 15 to 18 rpm



Date: 1-10-2000
Time : 10:50 IST
Freq : 3679.68 MHz
PW=4μs

Fig. 6.8.3b: Radar pulse shape monitored in INSAT-2C

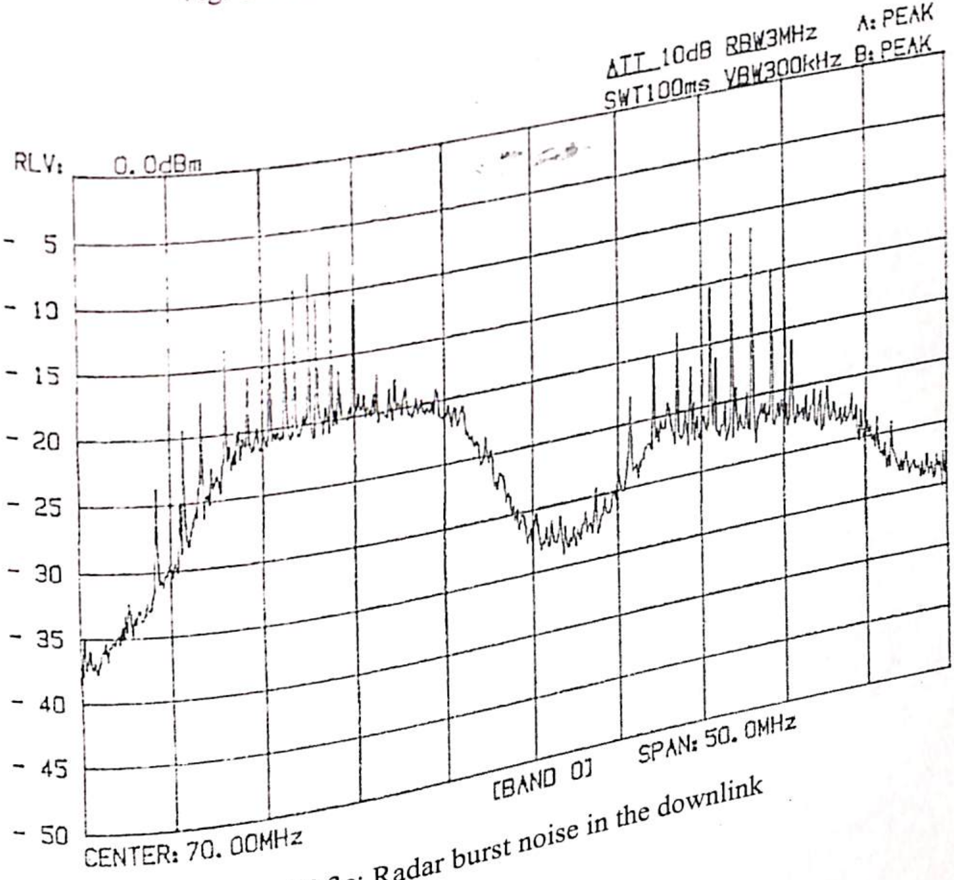


Fig. 6.8.3c: Radar burst noise in the downlink

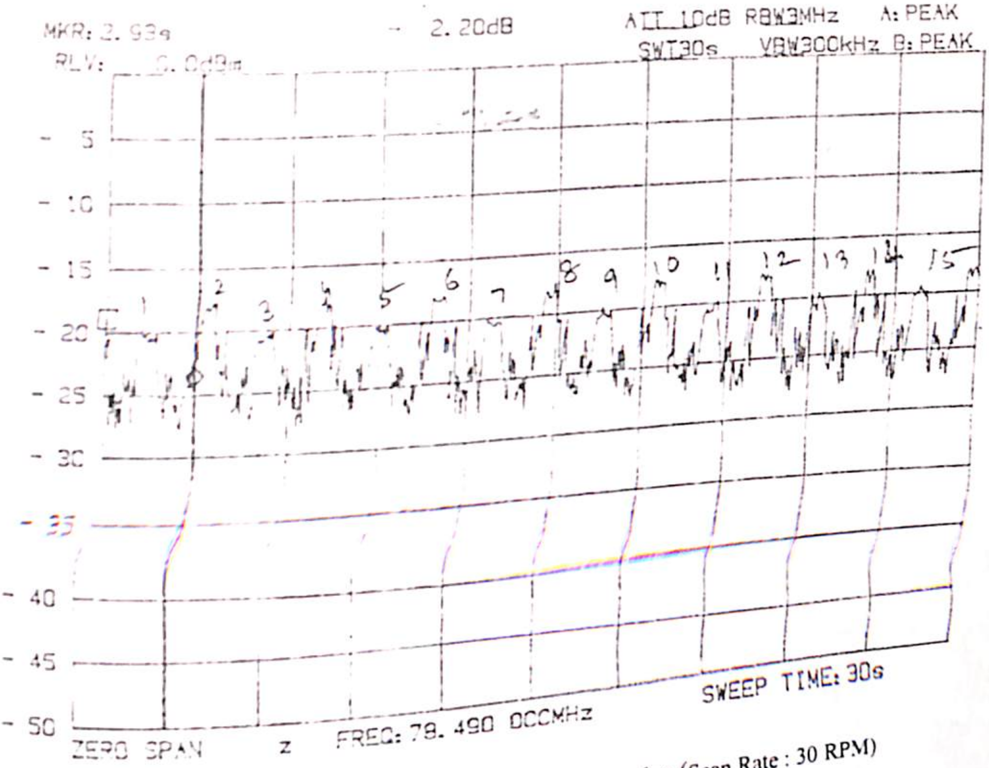


Fig. 6.8.3d: Radar scan rate in the spectrum plot (Scan Rate : 30 RPM)

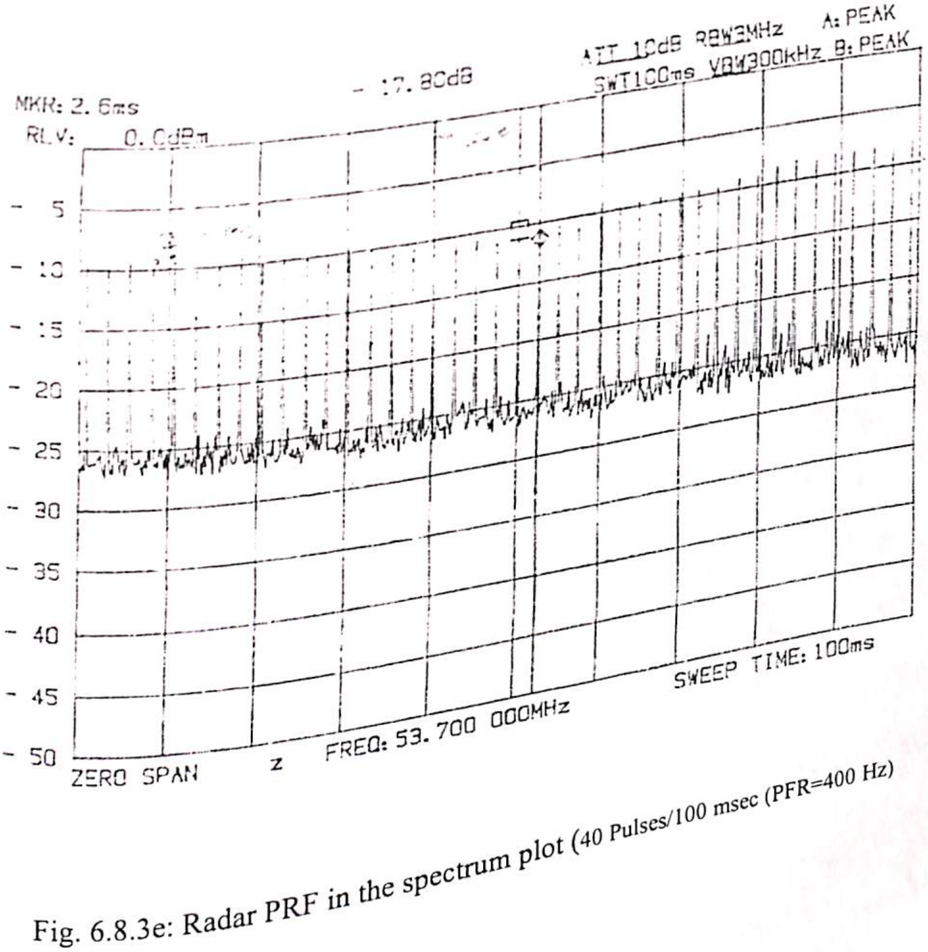


Fig. 6.8.3e: Radar PRF in the spectrum plot (40 Pulses/100 msec (PFR=400 Hz)

(B) 24 Hours Recording

To study the time of occurrence of interference, the IF spectrum of both INSAT-2C and INSAT-3B were recorded on 24 hours basis. The Level Vs Time of the multiple interference signals were recorded during Sept. 2000 and given in Fig. 6.8.4a. Further, the same test was conducted for INSAT-3C and GSAT-2 during October 2003 and the C/N Vs Time is given in Fig. 6.8.4b. From the observations, it is seen that the interference was present for most of the time of the day.

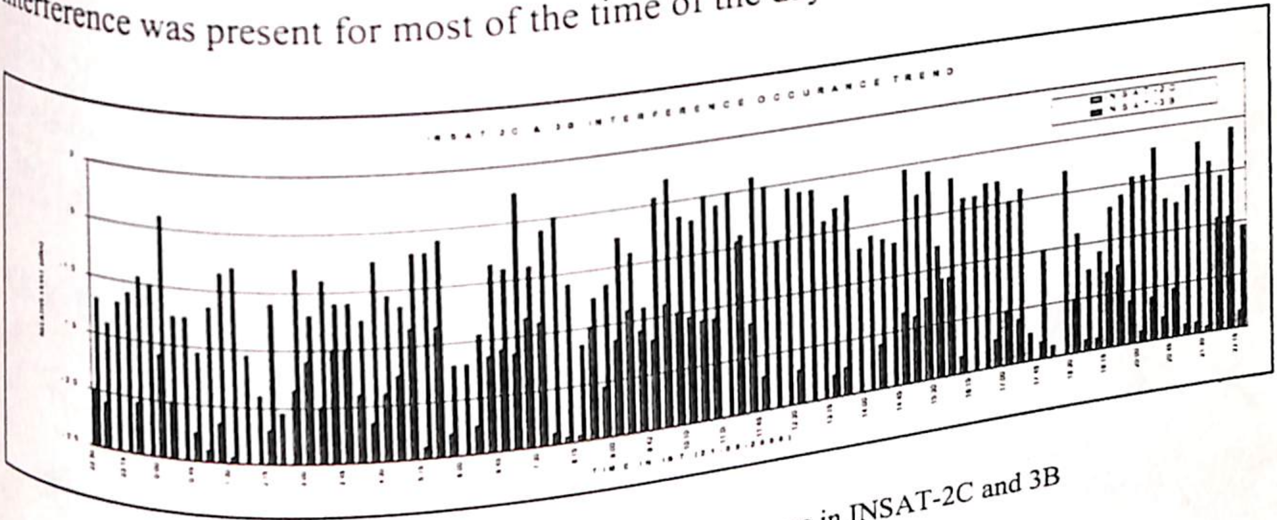


Fig. 6.8.4a: Long term observation of interference in INSAT-2C and 3B

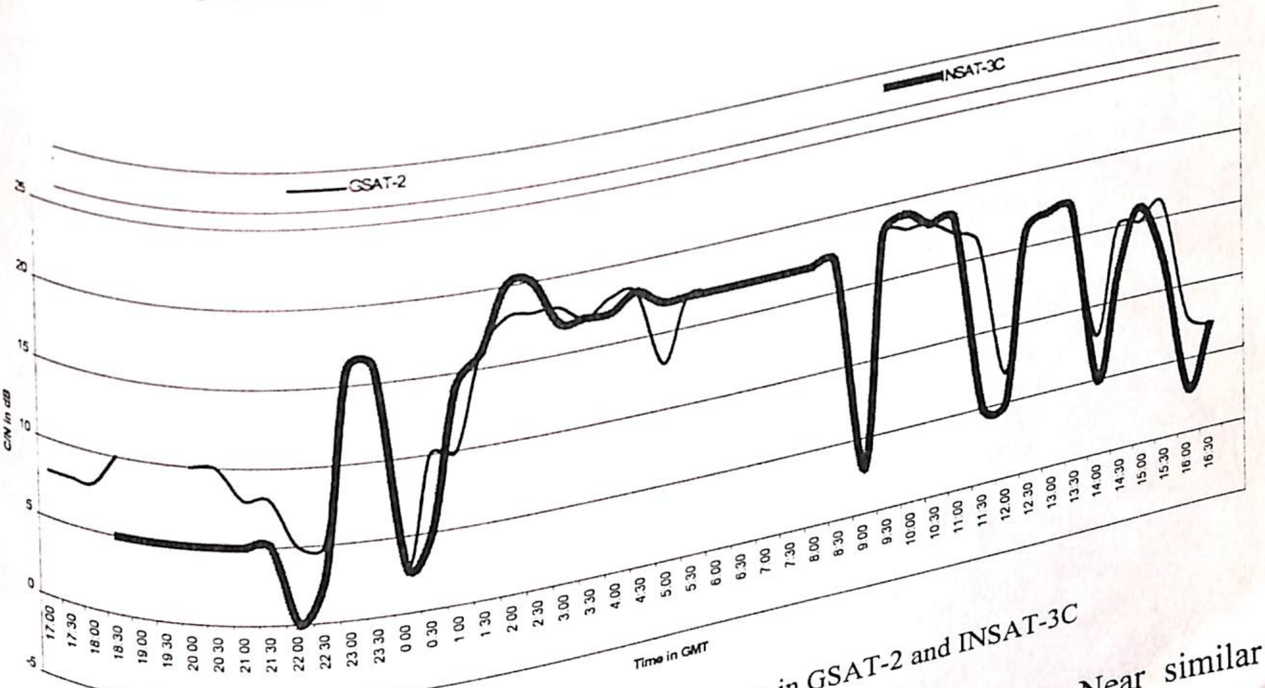


Fig. 6.8.4b: Long term observation of interference in GSAT-2 and INSAT-3C

GSAT-2 was located at 48 deg E, and INSAT-3C at 74 deg E. Near similar interference in such widely separated satellites show that the culprit radar could be scanning in the whole range of azimuths involved.

The measured down link radar bust signals and their characteristics are *tabulated in* Table-6.8.2.

Table-6.8.2: Characteristics of Radar Burst Measured

INSAT#2C				INSAT#3B			
D/L Freq. (MHz)	Corresponding U/L Freq. (MHz)	PRT (ms)	PW (µ Sec)	D/L Freq (MHz)	Corresponding U/L Freq. (MHz)	PRT (ms)	PW (Micro Sec)
3679.50	2669.5	2.67	4.0	3679.77	2669.77	2.675	4.00
3684.62	2674.62	2.33	4.0	3682.90	2672.90	2.330	3.66
3690.5	2680.5	2.33	4.0	3687.51	2677.51	2.34	4.00

6.8.4 Possible Sources

- The possible sources of interference could be from Radar, Tropo-scatter link or any other emitters operating in S-band frequencies.
- The interfering frequency could be either the carrier frequency or the harmonics or sub-harmonic of the carrier.
- The power radiated from the interfering source might be through the main lobe or side lobe of the antenna.

Possible operating Radars with frequencies and main characteristics of the signal are listed in Table-6.8.3.

Table-6.8.3: Possible Radars Operating in S & L Band		
Frequency Band(MHz)	**Peak power /Pulse Width/PRF**	**Service**
2700- 2900	600 kW/2μ sec/250 Hz	Meteorological Radar IMD India
2700- 2900	2.5 MW/4.7μ sec/250-270 Hz	Height Find Radar
2880 MHz	450 KW/1.05 μ sec/478 Hz	Polarization diversity Radar
1220-1350 MHz	2.0MW/2 μ sec/400 Hz	Mobile Surveillance Radar
851-942 MHz	280 KW/125 μ sec/ 280,800,1000 Hz	Tracking Radar
1275MHz	1 KW/33.4 μ sec/1463 -1640 Hz	Sea sat mission
2700-2900	1 MW/1 μ sec/1200 Hz	2-D Surveillance radar, Bendix Ground, static
2700-2900	0.45 MW/1 μ sec/1050 Hz	Raytheon, Ground, transportable
2700-2900	0.425 MW/0.833 μ sec/713, 950, 1050, 1120, 1173, 1200Hz	Texas instruments Ground, static
2700-2900	0.5 MW/1.1 μ sec/960Hz	Raytheon, Ground, static
2700-2900	1 MW/6 μ sec/300Hz	ATC 2D Airport Surveillance radar, Ground, static
2700-3900	2.5 MW/6 μ sec/300Hz	3D Stacked beam surveillance radar Westinghouse Ground, Transportable
2695-3125	1 MW/1.8 – 3.1 μ sec/375 Hz	Russian, Ground, Transportable

6.8.5 EIRP estimation

Interference Carrier EIRP could be determined by injecting a known carrier at Receive Earth Station LNA input by equalizing the inject and the interfering signal through spectrum analyzer. The schematic diagram is presented in Fig. 6.8.5.

Path loss U/L = Path Loss between Radar station to Satellite at 2680 MHz

S/C gain = Gain from the satellite In orbit Test result

Path loss D/L= Path loss between the satellite and the receive station at 3690 MHz

Antenna gain= 7.2 m receive antenna gain at 3690 MHz

6.8.6 TDOA Measurement

The unknown interference source/transmitter could be located by measuring TDOA of the interfering signals arriving at the measurement site through two adjacent GSO satellites operating in the same frequency band. Fig. 6.8.6 gives TDOA measurement set-up.

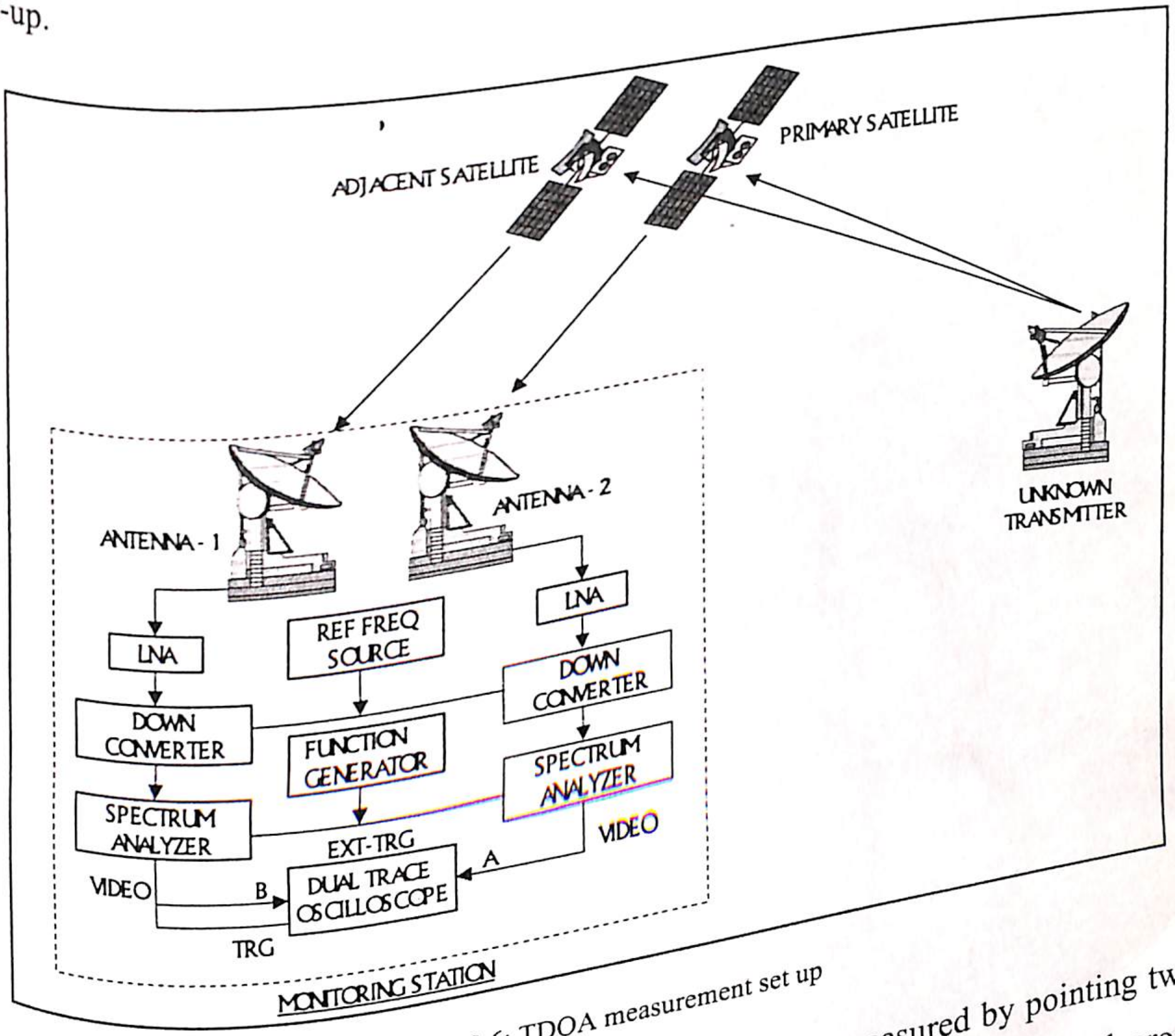


Fig. 6.8.6: TDOA measurement set up

The difference in Time of arrival of the signals could be measured by pointing two-ground station antennae terminals towards the two adjacent satellites, and cross-correlating the signals received in a coherent manner.

TDOA measurement was carried out using INSAT-2C and INSAT-3B satellites. The output of the TDOA measurement was used to geo-locate the source. The loci on which the interference source could lie are given as two curves in the Fig. 6.8.7.

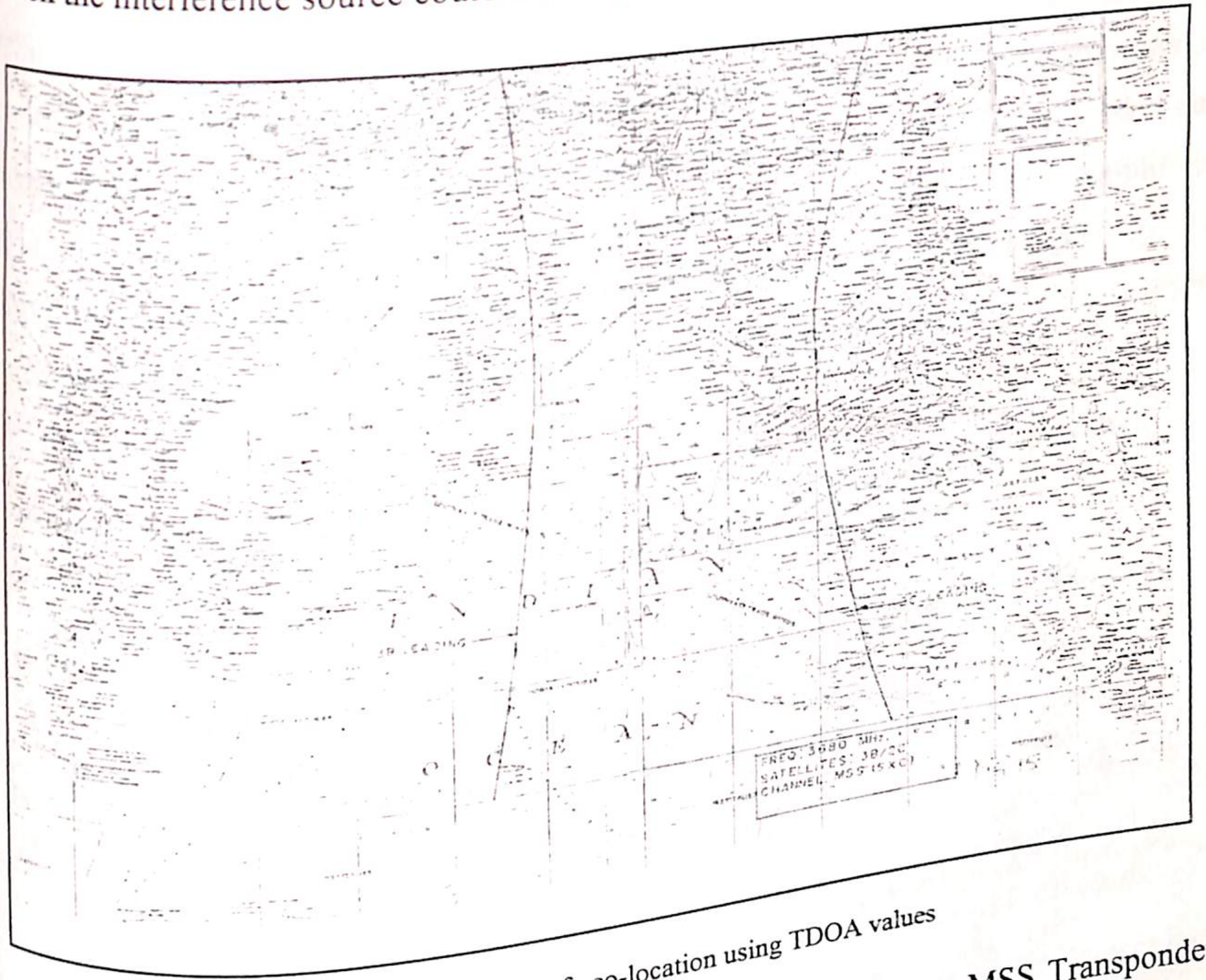


Fig. 6.8.7: The result of geo-location using TDOA values

The geo-location work for the source of Radar interference into MSS Transponder was incomplete by the time INSAT-2C was re-orbited in 2003. Same is being continued with MSS payload being available in GSAT-2 and INSAT-3C.

6.8.7 Conclusions

Radars emit high power levels and can cause interference within the Line-Of-Sight of satellite terminals. It is observed that many of the VSAT terminals, and onboard MSS payload got affected due to radar bursts.

At present the radar interference case into MSS payloads of INSAT system is still a pen

6.9 Case Study-8: Onboard generated intermodulation interference in INSAT-3A

6.9.1 Introduction

INSAT-3A is a multi-purpose satellite with communication payload and meteorological payload. The communication payload consisted of 12 transponders in normal C-band, 6 transponders in Ext. C-band, and 6 transponders in Ku-band. 9 out of 12 normal C-band transponders employed Travelling Wave Tube Amplifiers (TWTA), and 3 transponders employed Solid State Power Amplifiers (SSPA). The important characteristics of the main communication payload of INSAT-3A is given in Table-6.9.1.

Table-6.9.1: Main communication payload of INSAT-3A

Transponder number	U/L Frequency Band (MHz)	D/L Frequency Band (MHz)	Device used	Eirp (dBW)	Remarks
1-6	5950-6190	3725-3965	TWTA of 63 W power	41 to 42	Normal C-band
7-9	6190-6310	3965-4085	SSPA of 19 W power	38	Normal C-band
10-12	6310-6415	4085-4190	TWTA of 63 W power	41 to 42	Normal C-band
13-18	6755-6995	4530-4770	SSPA of 15 W power	37 to 38	Ext. C-band
19-24	14250-14490	11450-11690	TWTA of 70 W power	47	Ku-band

The reception and transmission of 9 normal C-band TWTA channels are combined in a dual polarization feed of the onboard antenna, whose deployable 1m reflector was mounted on the east facing side of the satellite. Reception of Ext. C-band signals and transmission of 6 Ext. C-band and 3 normal C-band channels, all employing SSPAs, are combined in a dual polarization feed of the onboard antenna whose 2m deployable reflector was mounted on the west facing side of the satellite.

Normally, the onboard LNAs, receivers and the amplifiers used before and after frequency translation employ high gain. Typically, an input signal of the order of –94 dBW has to be amplified to a downlink EIRP of 42 dBW – which means a total onboard translation gain of 135 dB. The processing electronics onboard should have a gain of 105 to 110 dB after accounting for the gains of antenna. Hence, very high sensitive receivers and low noise output wave-guides have to be employed in the total system. Usually, an onboard attenuator variable from 0 to 15 dB is also employed to adjust the input sensitivity according to the uplinking capabilities of the various customers of the transponders.

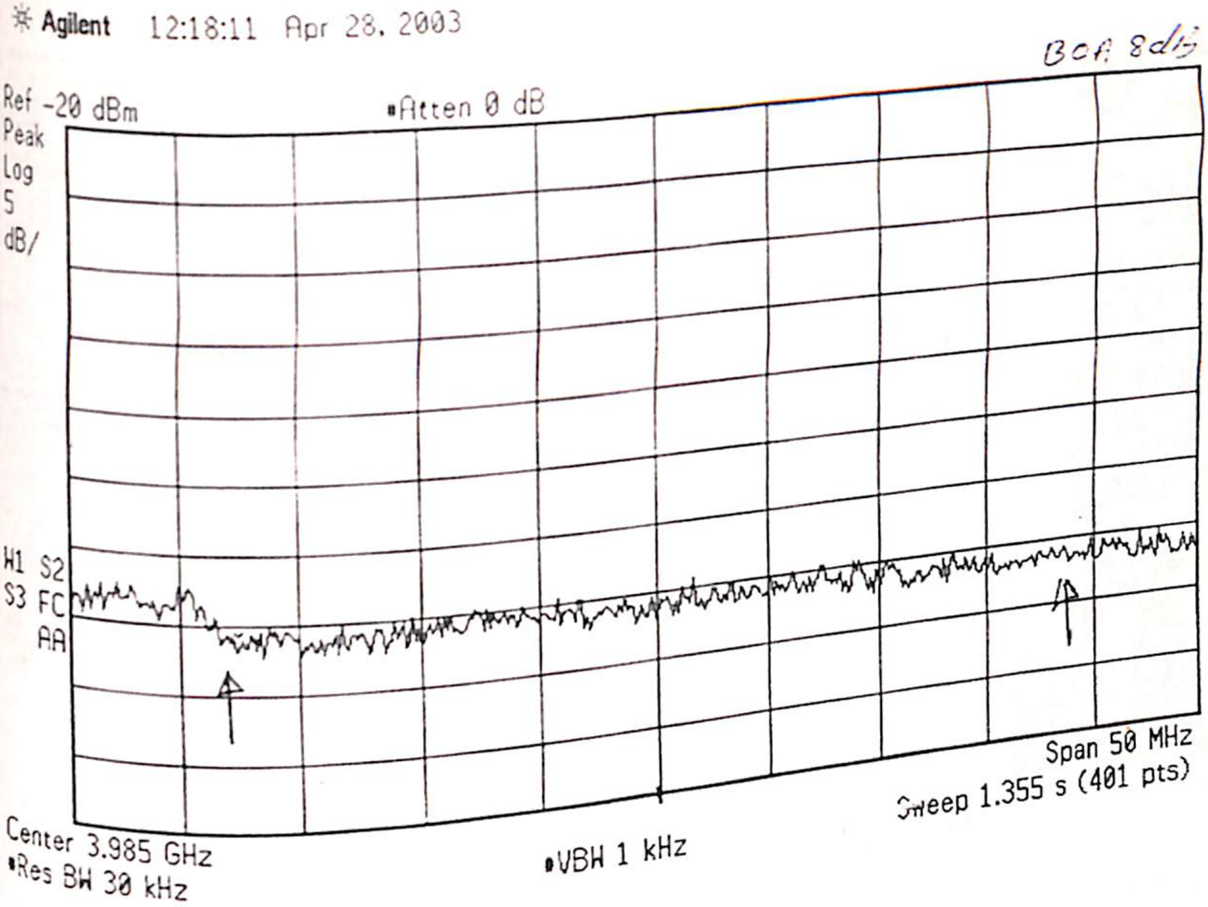
After launch and orbit raising operations, INSAT-3A was positioned at its allotted orbital slot of 93.5 deg E longitude. The In-Orbit Testing (IOT) of the payload was carried out with satellite at this orbital location.

6.9.2 Identification of the problem

The transponder frequency response test is one of the standard tests carried out during IOT, along with other tests like downlink EIRP, saturation flux density (SFD) etc. The onboard frequency response is usually measured at a nominal onboard attenuation of (BOA) of 8 dB. The specification for the frequency response is 1 dB peak-to-peak in the transponder bandwidth.

It was observed that the results of the frequency response of normal C-band channels using SSPAs met the specification (Fig. 6.9.1 for channel 7 and 8). The frequency response of the transponders using TWTAs showed large ripples in the bandwidths (Fig. 6.9.2). The ripples were of the order of 5 dB peak-to-peak at the nominal onboard attenuation of 8 dB. The ripples remained at this high values, and in fact increased to much higher levels for some of the channels, with the redundant onboard Receiver-2 (Fig. 6.9.3).

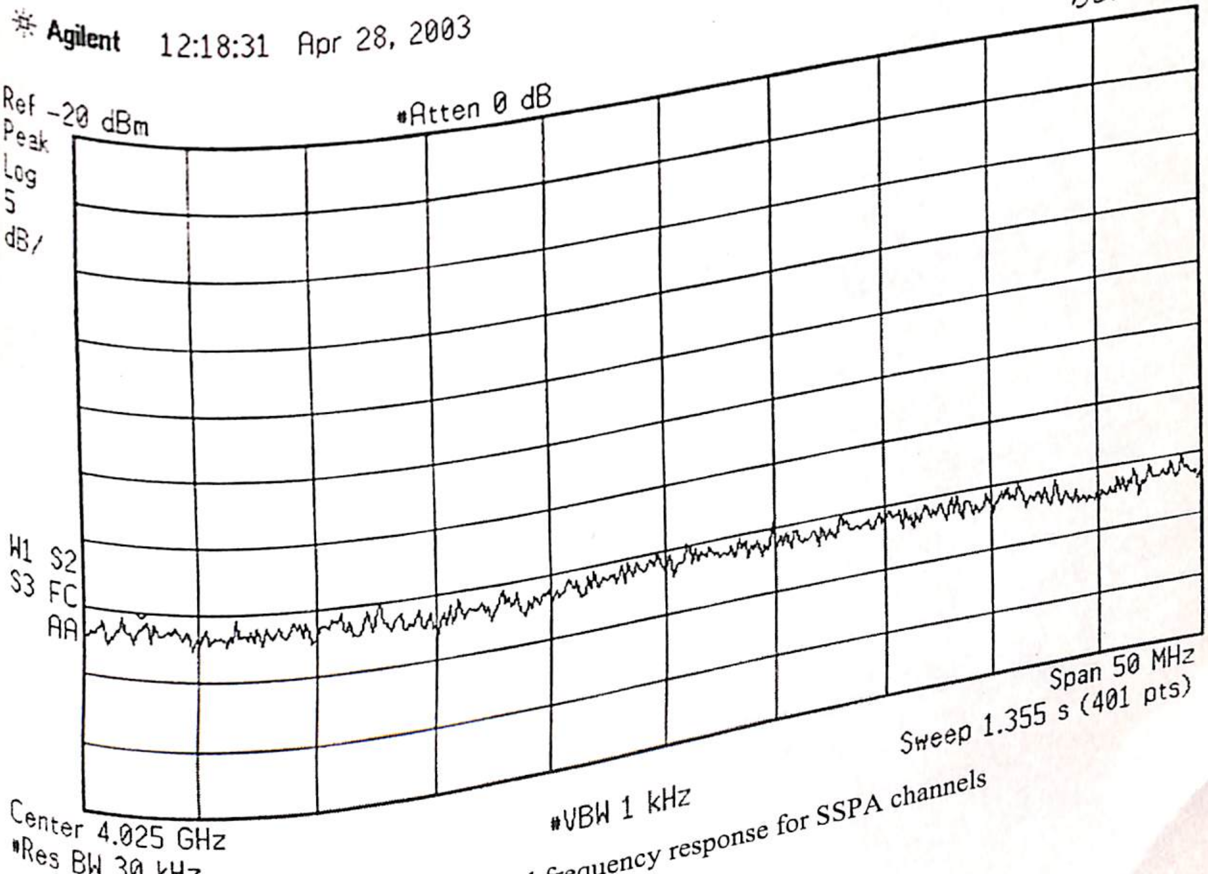
Since this high level of ripples was not acceptable it was decided to investigate this probl



BOA 8dB

Ch# 8

BOA 8dB



Normal frequency response for SSPA channels

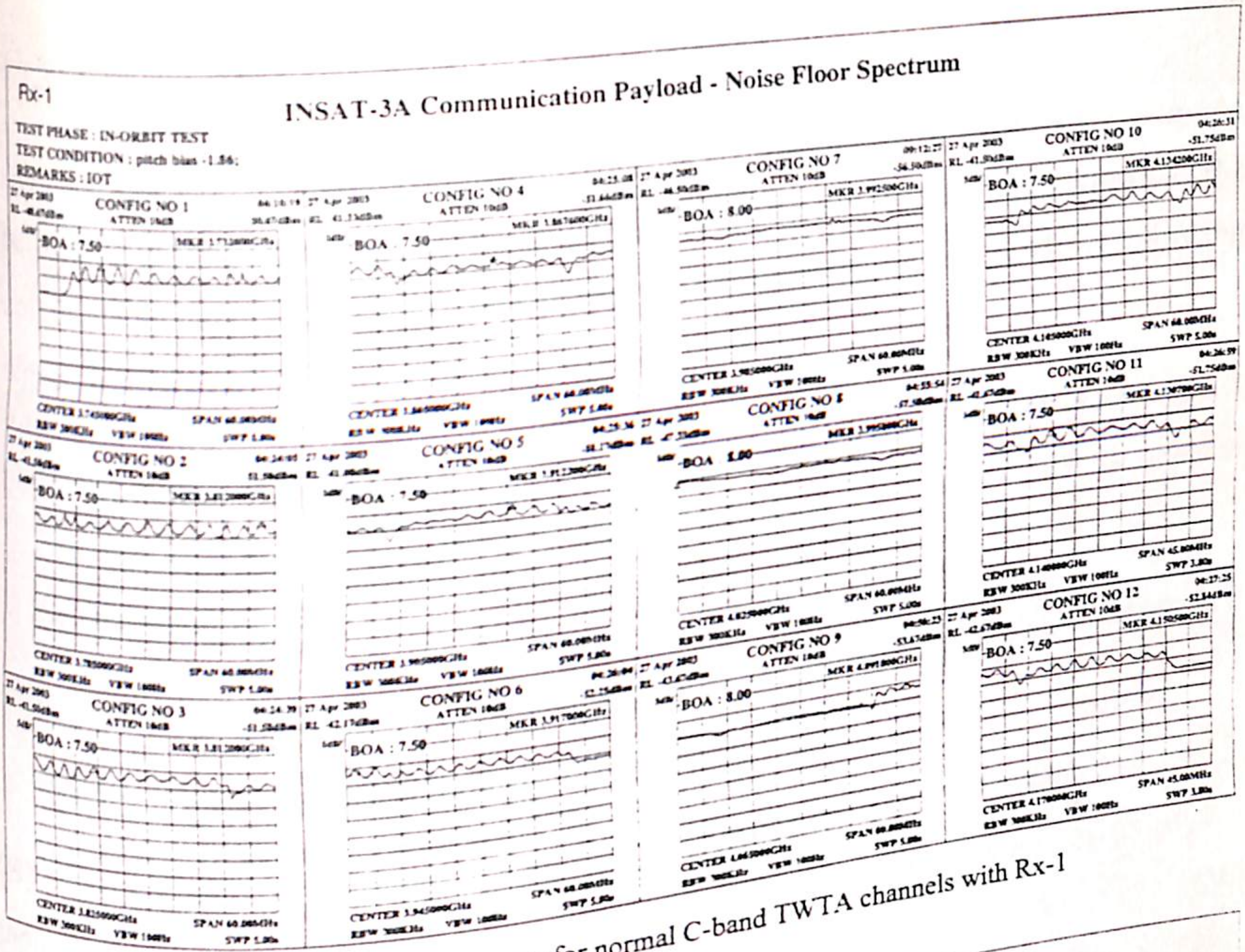
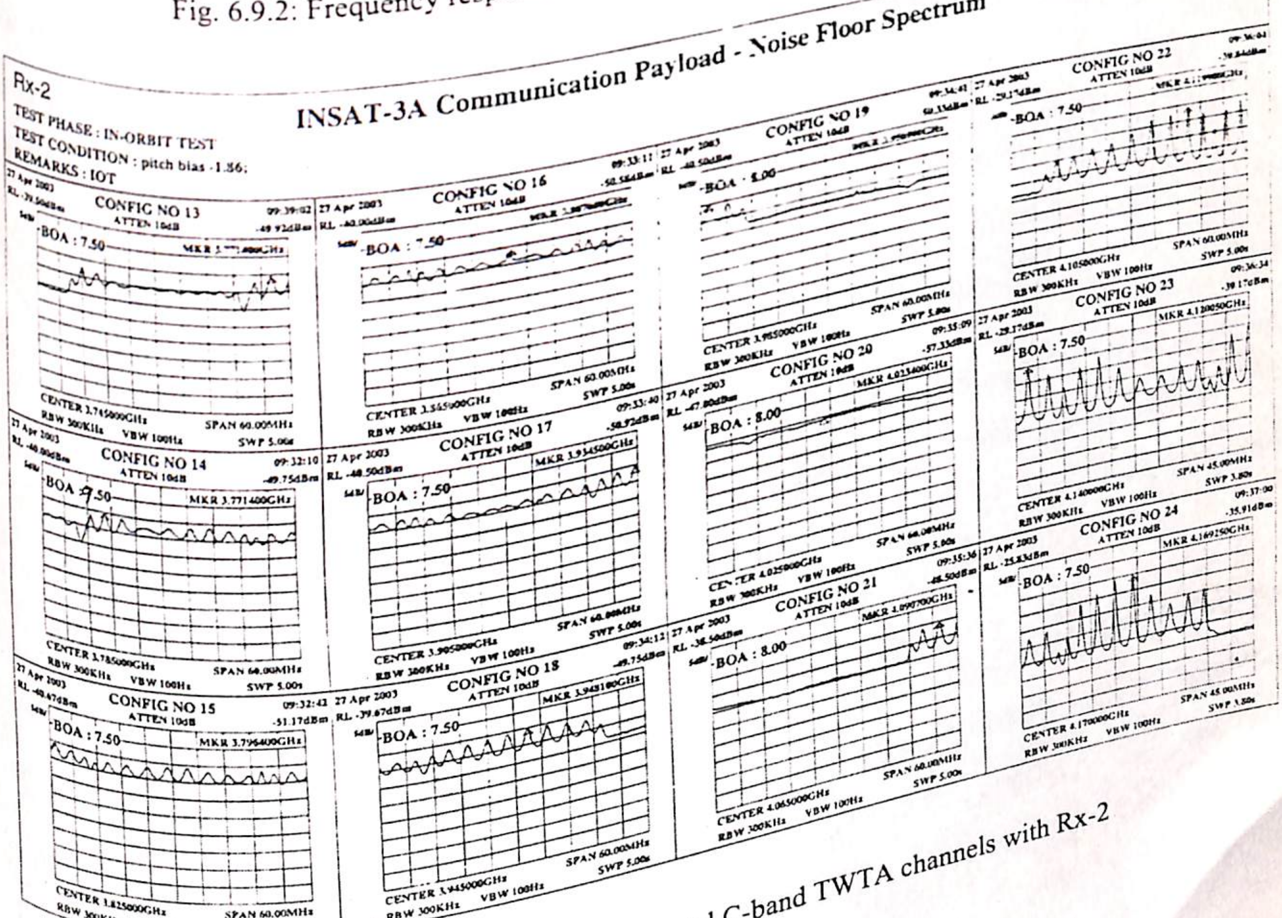


Fig. 6.9.2: Frequency response for normal C-band TWTA channels with Rx-1



ponse for normal C-band TWTA channels with Rx-2

6.9.3 *Initial analysis*

(A) Ripples in the frequency response are generally indicative of feedback coupling between high output signals at the downlink frequencies, and low input signals at the uplink frequencies. The designers verified all the ground test data, and the following inputs were given:

- The ripples in the frequency response were within the specs upto pre-launch phase. The ripples in the pre-launch test were found to be of the order of 2 dB for some of the channels (Fig. 6.9.4).
- The onboard redundant receiver, RX-2, was found to be more sensitive to the radiated field in the subsystem level EMI tests.

(B) Two tests were carried out to verify whether the onboard coupling between input and output was the real cause of the ripples. One was to measure the frequency response at different onboard attenuation values, and the other was to verify whether any one onboard channel was contributing to the ripples. These test results indicated the following:

- The ripple levels reduced with increasing onboard attenuation. This clearly indicated a coupling between input and output signals. A typical plot of the frequency response at different BOA settings is given in Fig. 6.9.5.
- The frequency response and the ripples are measured on channel 1 with all other transponders in the ON condition, and also with all other channels switched OFF one-by-one. This had not changed the ripple values (Fig. 6.9.6). This test had concluded that no single channel was the cause of the ripples.

(C) On review of all the ground tests data and IOT results, it was concluded that the ripples in the frequency response are prominent in the pre-launch conditions, and further aggravated after the launch. This could be due to the shield of the receiver bei
nch and orbit injection process.

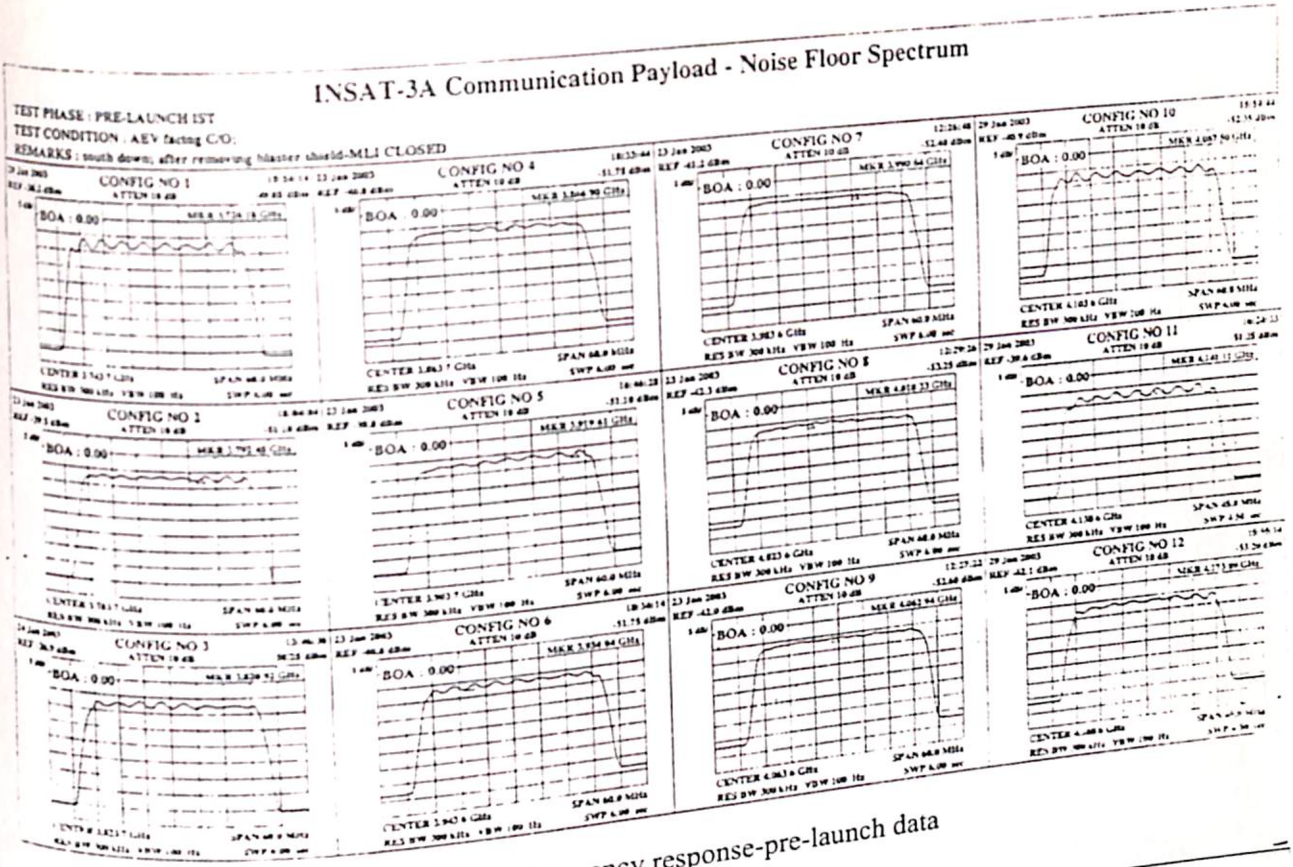


Fig. 6.9.4: Frequency response-pre-launch data

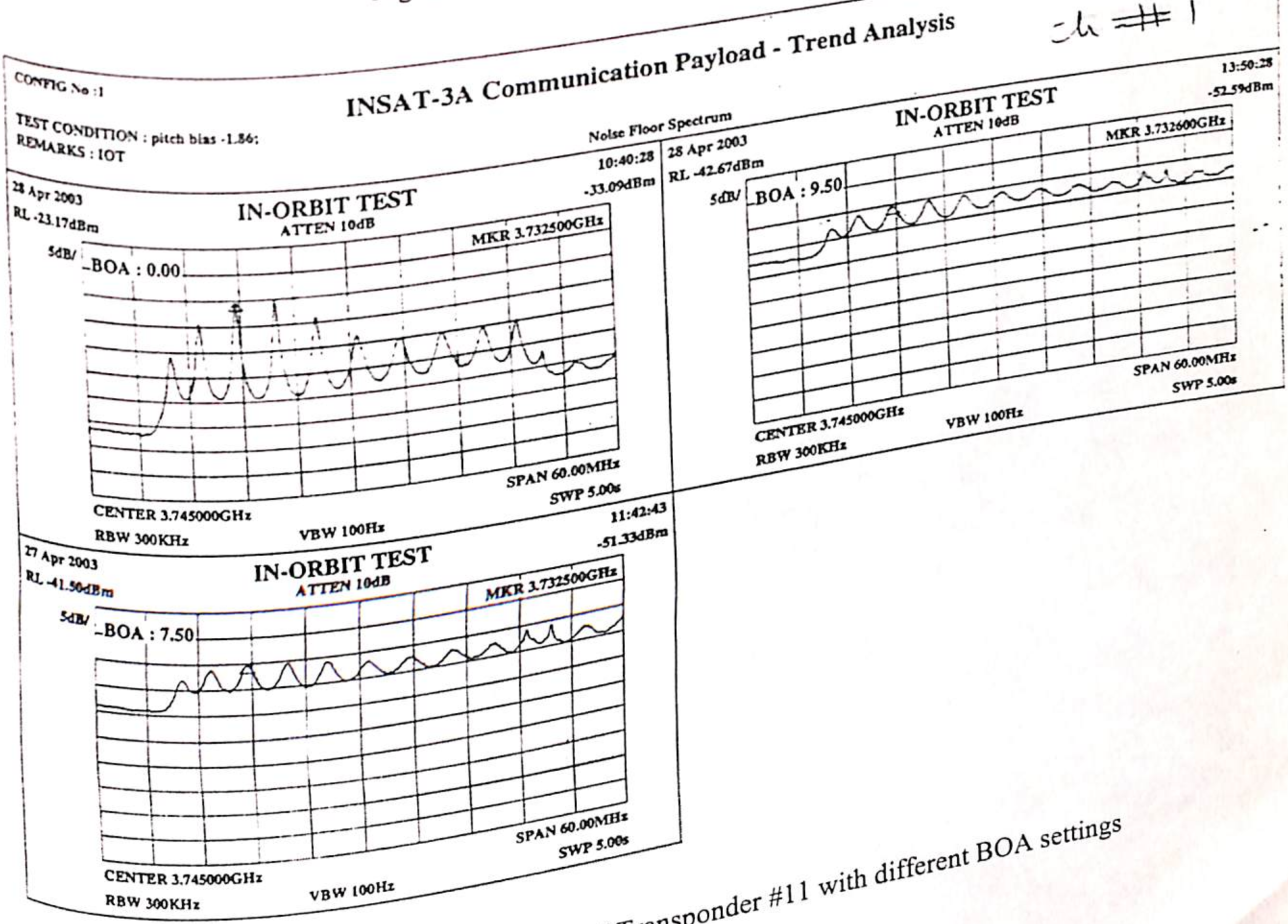
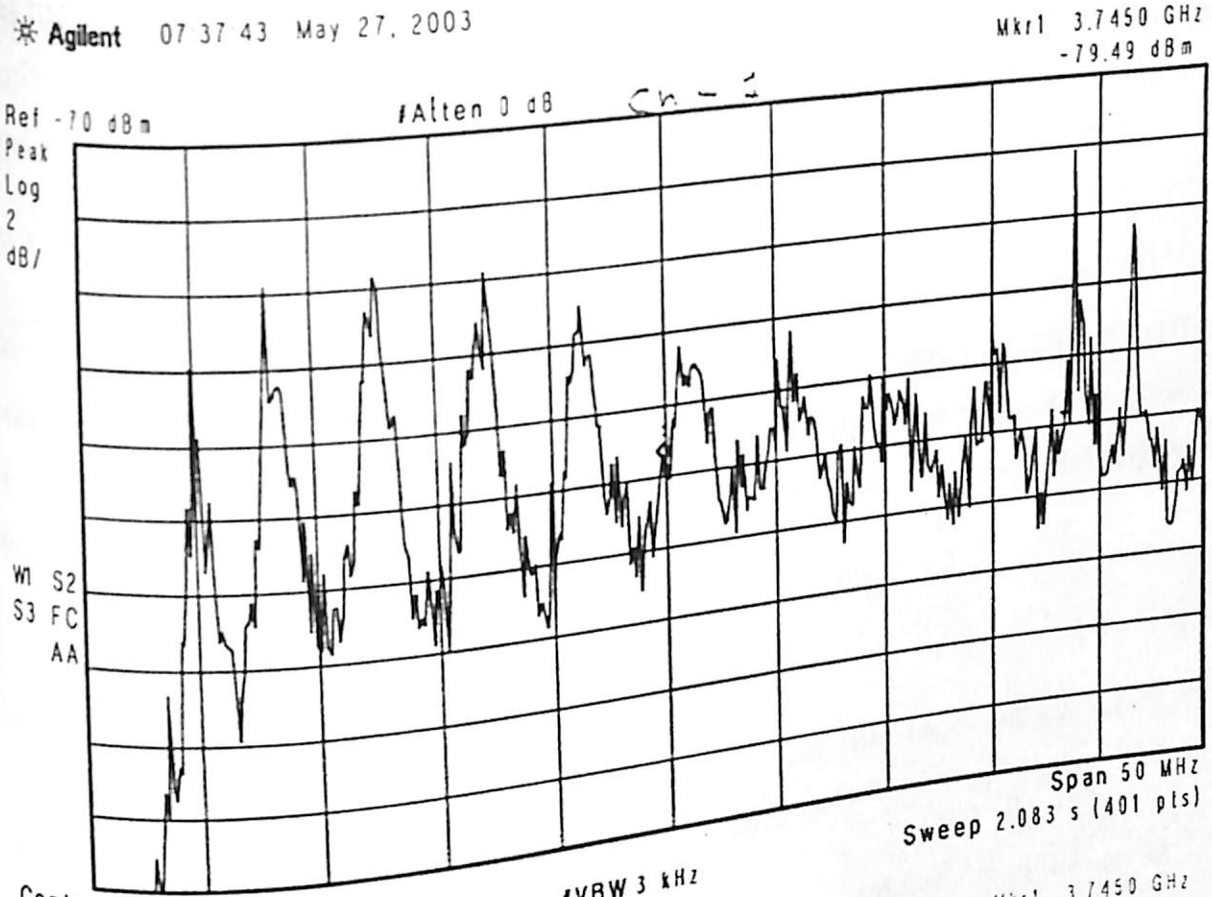
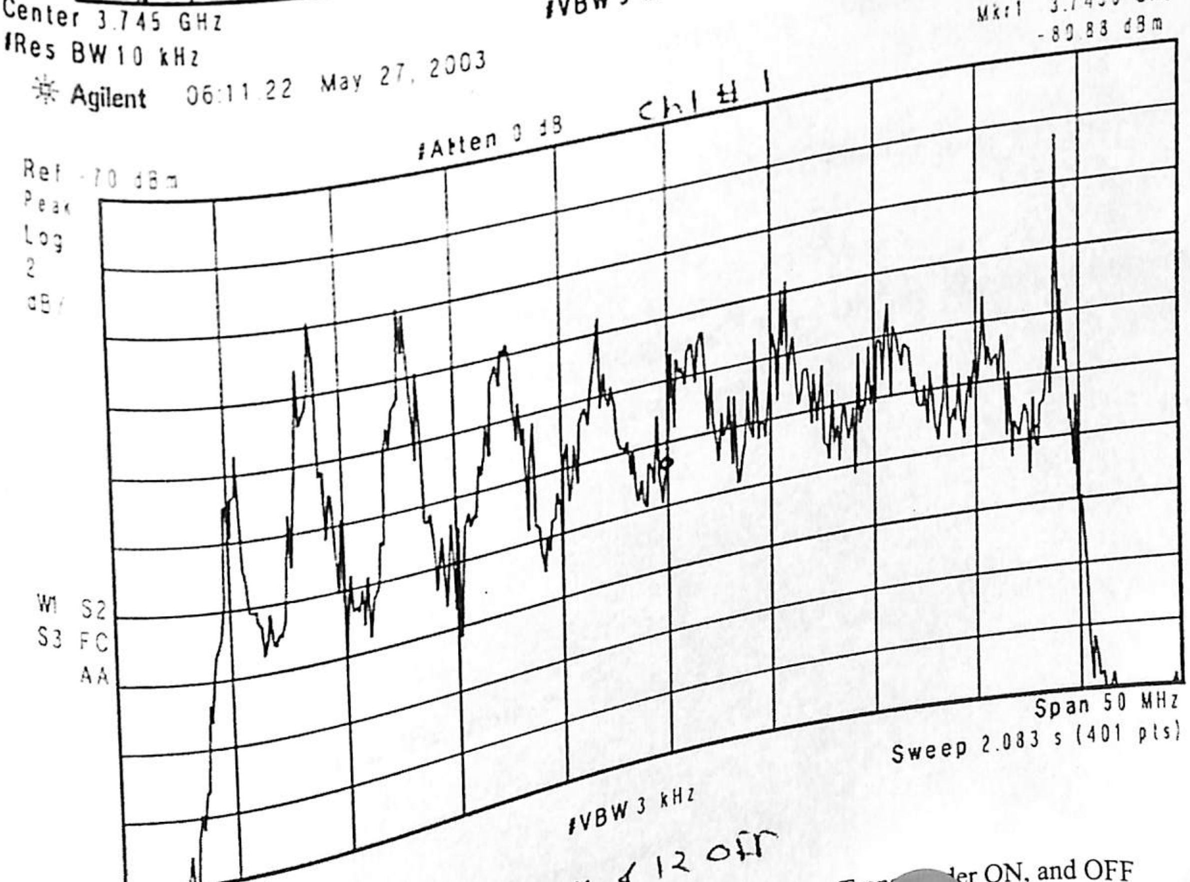


Fig. 6.9.5: Frequency response of Transponder #11 with different BOA settings





4 12 OFF

Tran der ON, and OFF

The most likely coupling mechanism was concluded to be between high-power wave guide runs and the sensitive receiver input, most probably very near to the feed / receiver location.

6.9.4 Analysis on the implications of the coupling

The input / output coupling combined with the non-liner characteristics of TWTAs is ideal for generation of intermodulation products. Hence, it was decided to verify the intermodulation products being generated when multiple carriers were uplinked. Before coming to the results of multiple carrier tests, a brief description of intermodulation interference is given below:

(A) Intermodulation interference

The non-linear amplification produces distortion and intermodulation interference. The TWT Amplifiers exhibit two kinds of non-linearities:

- Non-linearity of the output amplitude vs. input amplitude of the signal (AM – AM conversion).
- Non-constant phase shift between input and output signals as a function of input power (AM-PM conversion).

When a number of signals get mixed in a non-linear device, the amplified output contains intermodulation products at frequencies of: (1)

$$f_x = k_1 f_1 + k_2 f_2 \ldots\ldots + k_N f_N$$

where:

For example, $2 f_1 - f_2$ is one of the third-order products. When the centre frequency of the transponder is large compared to the bandwidth of the transponder, odd-order intermodulation products are the only ones falling in the useful frequency band. This is the case in satellite communications.

(B) Multiple carrier tests

Tests were carried out with two uplink signals at a time, both at saturation levels, and the downlink spectrum are verified. The intermodulation products are clearly observed in many combinations.

To systematically investigate the combination and to verify intermodulation products two further steps were taken:

- Intermodulation products for three input signals were computed through a computer software. Two of the input signals were taken at the downlink frequencies corresponding to uplink excitation, and third signal at the uplink frequency of one of the channels. The computed intermodulation signals could be matched with the additional spectral components observed in the downlinks (Table-6.9.2 and Fig. 6.9.7, Fig. 6.9.8, Fig. 6.9.9 and Fig. 6.9.10).
- Tests, with different combinations of two uplink signals at a time, were carried out. The downlink spectrum was verified for each of the tests. Table-6.9.3 gives the matrix of the two channels chosen for uplinking, and the presence of the intermodulation interference.

(C) A number of intermodulation products were observed whenever either channel
the downlink spectrum with uplinks for
of only two downlink

linked. Fig. 6.9.12 shows heavy intermodulation products in the downlink spectrum plots when channels 1, 2 and 10 were up-linked along with channel 4.

Table-6.9.2: Intermodulation Frequency Analysis

1. Products due to CHL#11 uplink, CHL#11 downlink and other downlink frequencies

Sl. No.	Interfering Channel Frequency (MHz)			Product Type	Order	Product frequency (MHz)	Remarks
	Uplink	Downlink					
1	6365 (CHL#11)	4140 (CHL#11)	3865 (CHL#4)	(-1 -5 8)	14	3855 (in CHL#4)	Reference Fig. 6.9.7
2	6365 (CHL#11)	4140 (CHL#11)	3865 (CHL#4)	(1 5 6)	12	3855 (in CHL#4)	Reference Fig. 6.9.7
3	6365 (CHL#11)	4140 (CHL#11)	3865 (CHL#4)	(-1 -4 7)	12	4130 (in CHL#11)	Reference Fig. 6.9.8
4	6365 (CHL#11)	4140 (CHL#11)	3865 (CHL#4)	(1 6 -7)	14	4150 (in CHL#11)	Reference Fig. 6.9.8
5	6365 (CHL#11)	4140 (CHL#11)	4170 (CHL#12)	(-2 2 2)	6	3890 (in CHL#5)	Reference Fig. 6.9.9 & Fig. 6.9.10

1. Products due to CHL#11 uplink, CHL#11 downlink and other downlink frequencies

Sl. No.	Interfering Channel Frequency (MHz)		Product Type	Order	Product frequency (MHz)	Remarks
	Uplink	LO				
1	4170 (CHL#11)	2225	(2 -2)	4	3890 (in CHL#5)	Reference Plot-12 & Plot-14

Table-6.9.3: Intermodulation Interference test results with two uplinks at a time

	1	2	3	4	5	6	10	11	12
1	-	✓	✓	×	✓	✓	✓	✓	×
2	✓	-	✓	×	✓	✓	✓	✓	×
3	✓	✓	⊗	×	✓	✓	✓	✓	×
4	×	×	×	×	×	×	×	×	×
5	✓	✓	✓	×	-	✓	✓	✓	×
6	✓	✓	✓	×	✓	-	✓	✓	×
10	✓	✓	✓	×	✓	✓	-	✓	×
11	✓	✓	✓	×	✓	✓	✓	-	×
12	×	×	×	×	×	×	×	×	⊗

× - Intermod products occurring in other channels ✓ - No Intermod / Interference ⊗ - 4 &12 when on alone.

- The uplink frequency of channel 4 and 12 were varied within the transponder band. This test was carried out because the intermodulation products which fall within the useful spectrum, depend on the exact carrier frequencies.

lation products disappear if the uplink carrier

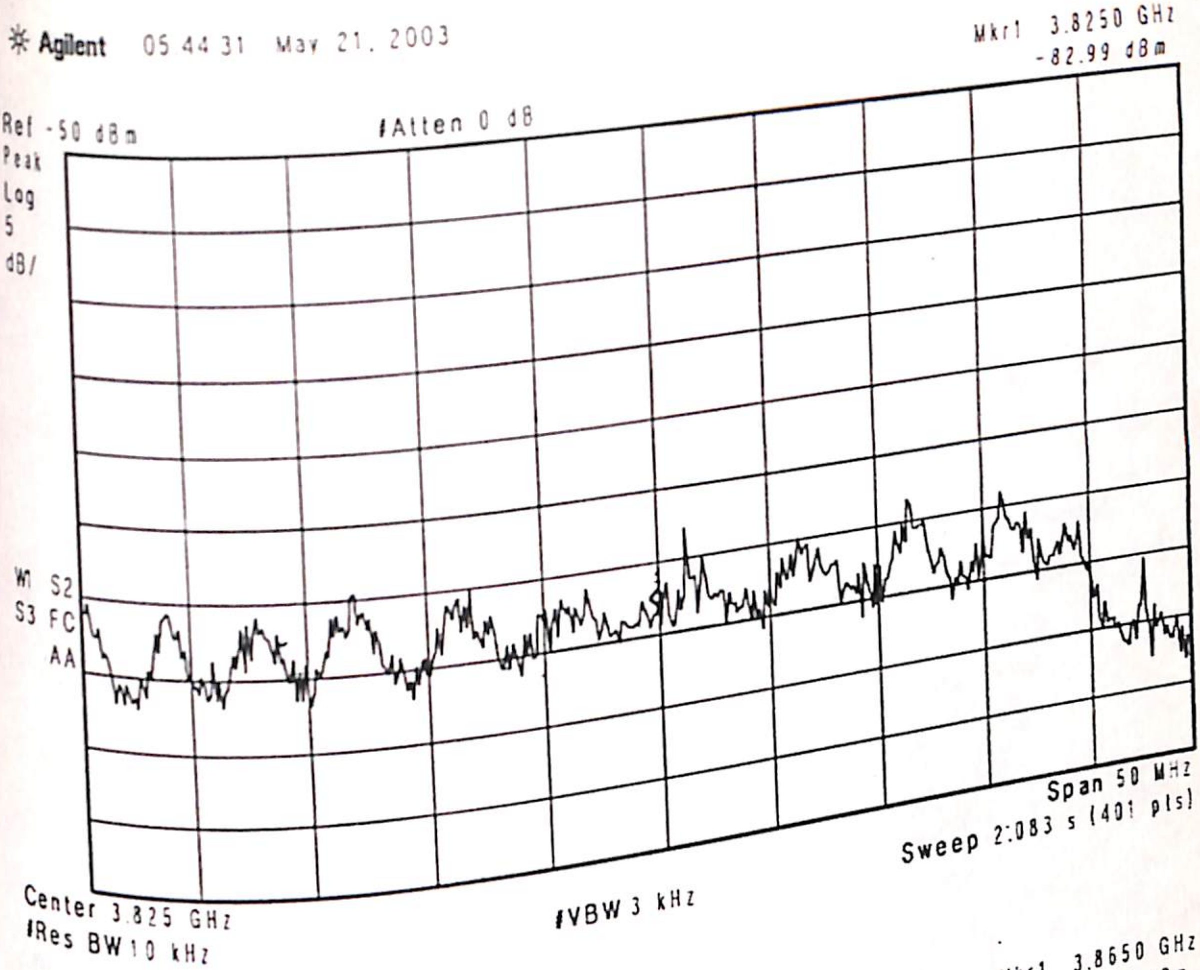
tre frequency of channel 4 or

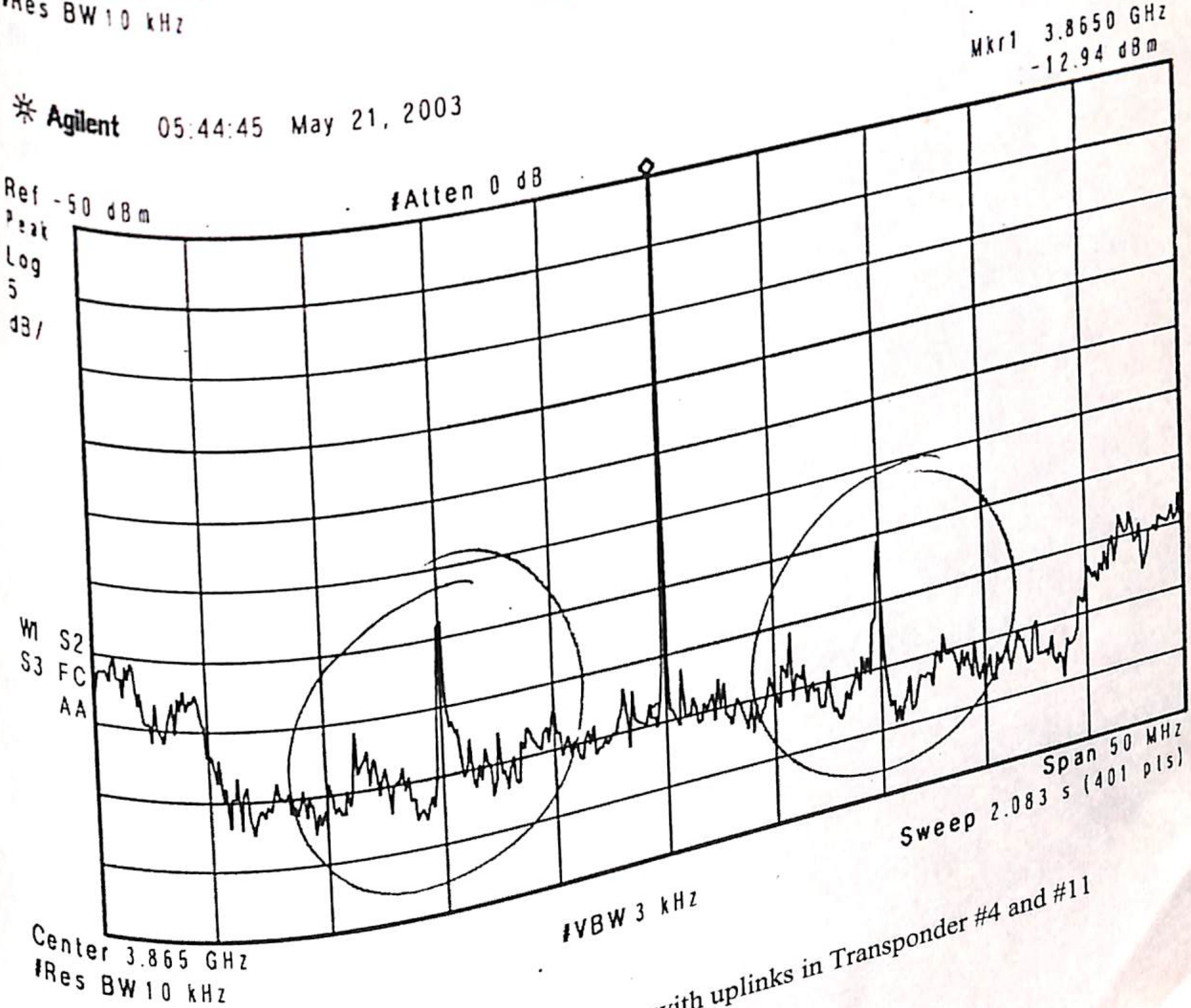
12. However, when the carrier was within this 10 MHz band, the intermodulation products were very bad for some of the combinations.

(D) All the above tests and results were analysed to find an acceptable way of using the payload. It was also noted that channel 4 and 12 were creating the intermodulation problem, specially in a particular frequency range within the transponder. Hence, not using that part of the frequency range was the solution to circumvent the effects of unintentional onboard coupling between input and output, and still use the total payload. However, it was not possible to ensure that a particular part of the spectrum was not used. Even if that part of the spectrum was not allotted, there would always be a possibility that somebody could uplink in the culprit frequency range causing intermodulation products and disturbing traffic in all other transponders. Hence it was decided to switch off channel 4 and 12 permanently.

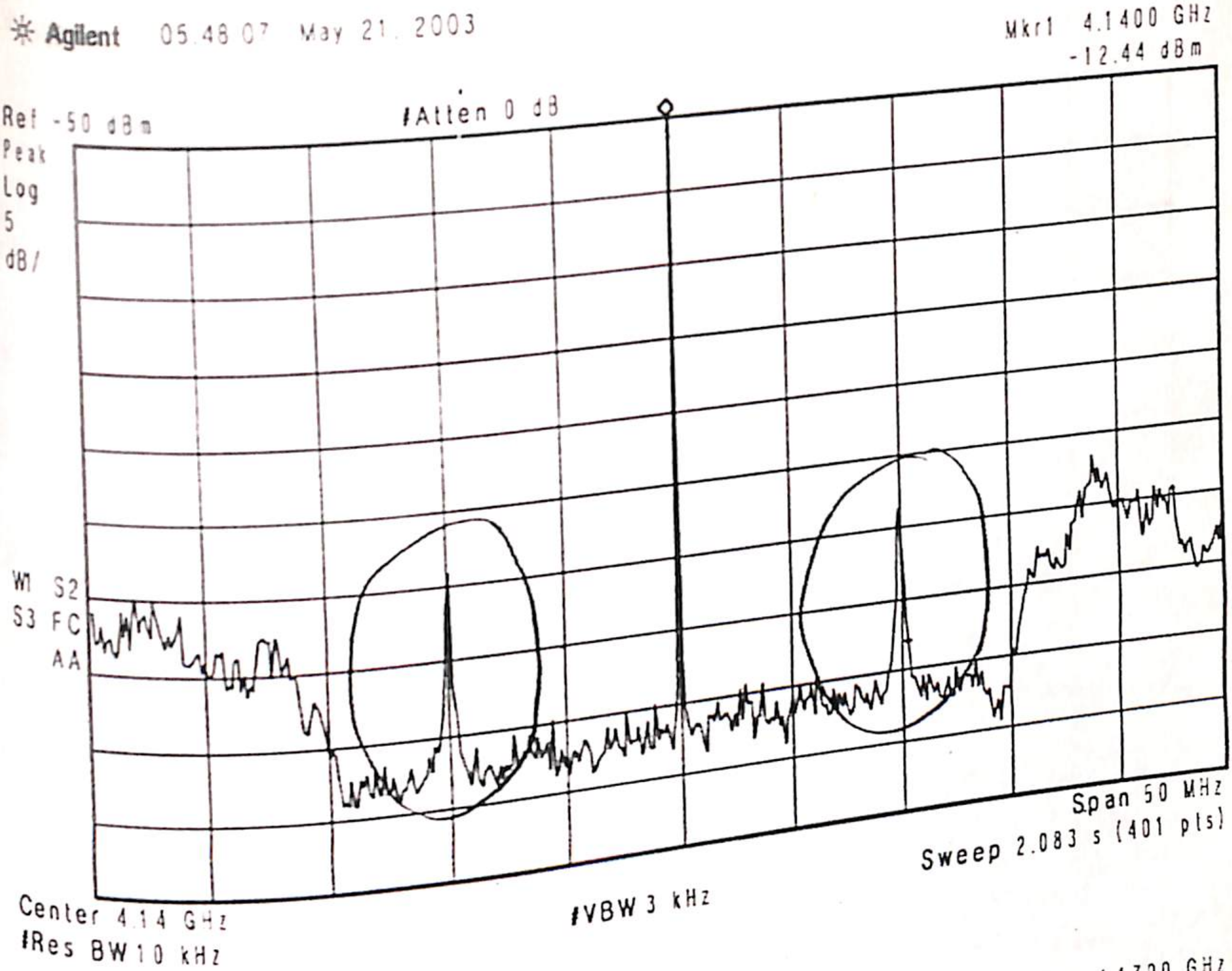
6.9.5 Conclusions

1. A problem of interference involving intermodulation interference was investigated in this case. The interference was generated onboard the satellite due to unintentional coupling between input and output of the normal C-band, and due to the presence of multiple uplink (and corresponding downlink) signals.
2. After theoretically confirming the occurrence of intermodulation interference, the same was verified with a number of multi-carrier tests. Detailed mapping of the combination was carried out to identify the input channels which were causing the intermodulation interference in a dominant manner.
3. It was decided to switch off channel 4 and 12, based on the test results and analysis, and salvage the remaining 10 channels of the normal C-band payload.





with uplinks in Transponder #4 and #11



Agilent 05:48:07 May 21, 2003

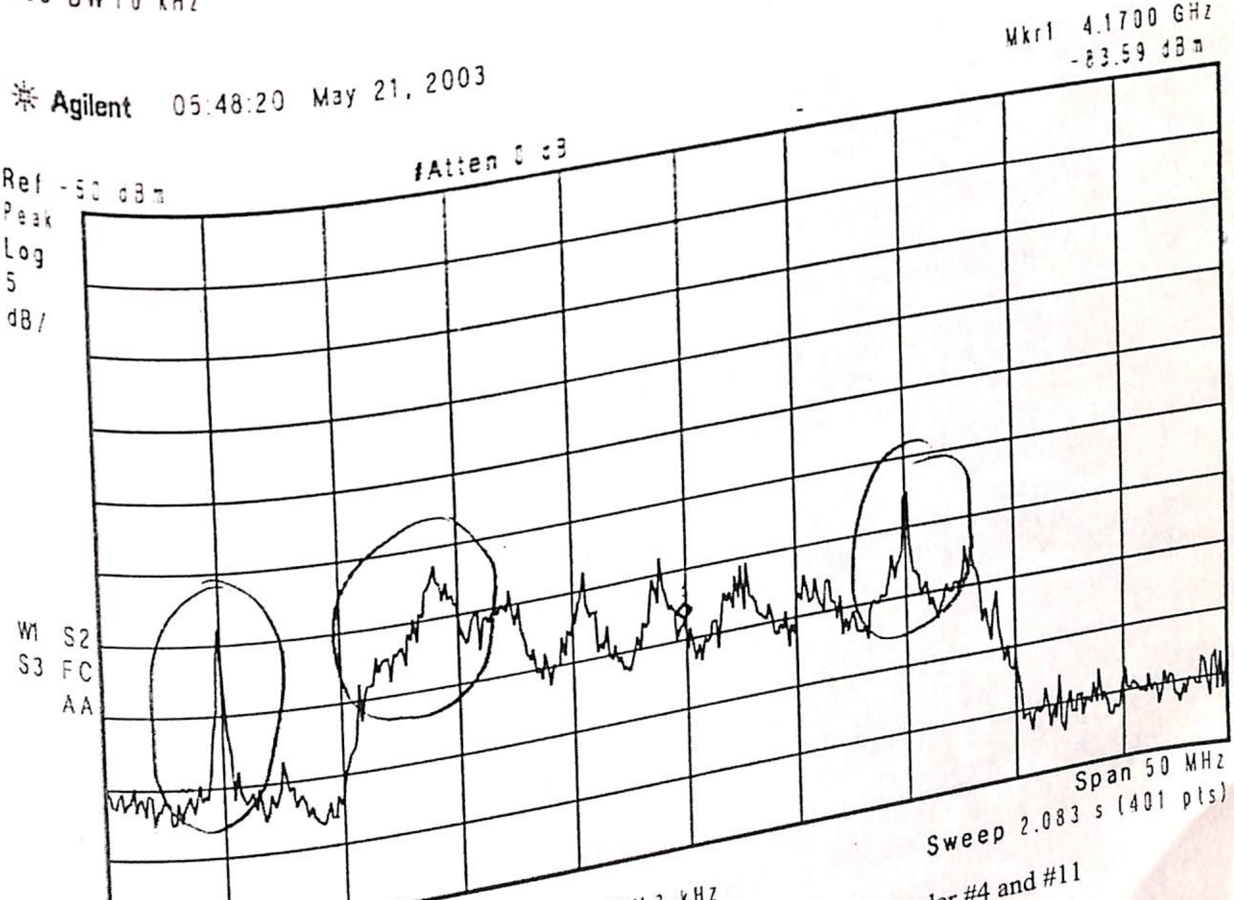
Mkr1 4.1400 GHz
-12.44 dBm

Ref -50 dBm
#Atten 0 dB

Peak
Log
5
dB/

W1 S2
S3 FC
AA

Center 4.14 GHz
#Res BW 10 kHz
#VBW 3 kHz
Span 50 MHz
Sweep 2.083 s (401 pts)



Agilent 05:48:20 May 21, 2003

Mkr1 4.1700 GHz
-83.59 dBm

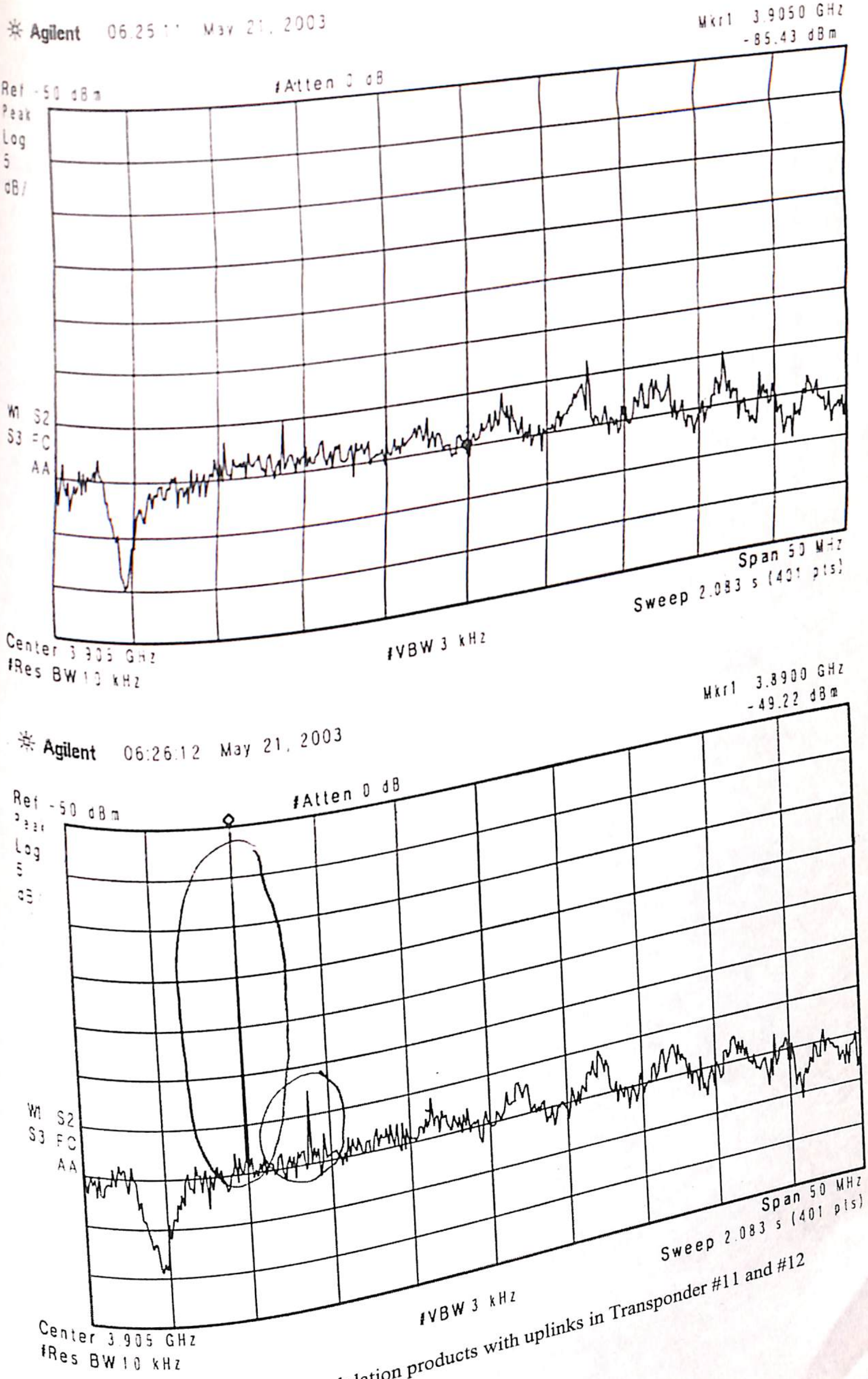
Ref -50 dBm
#Atten 0 dB

Peak
Log
5
dB/

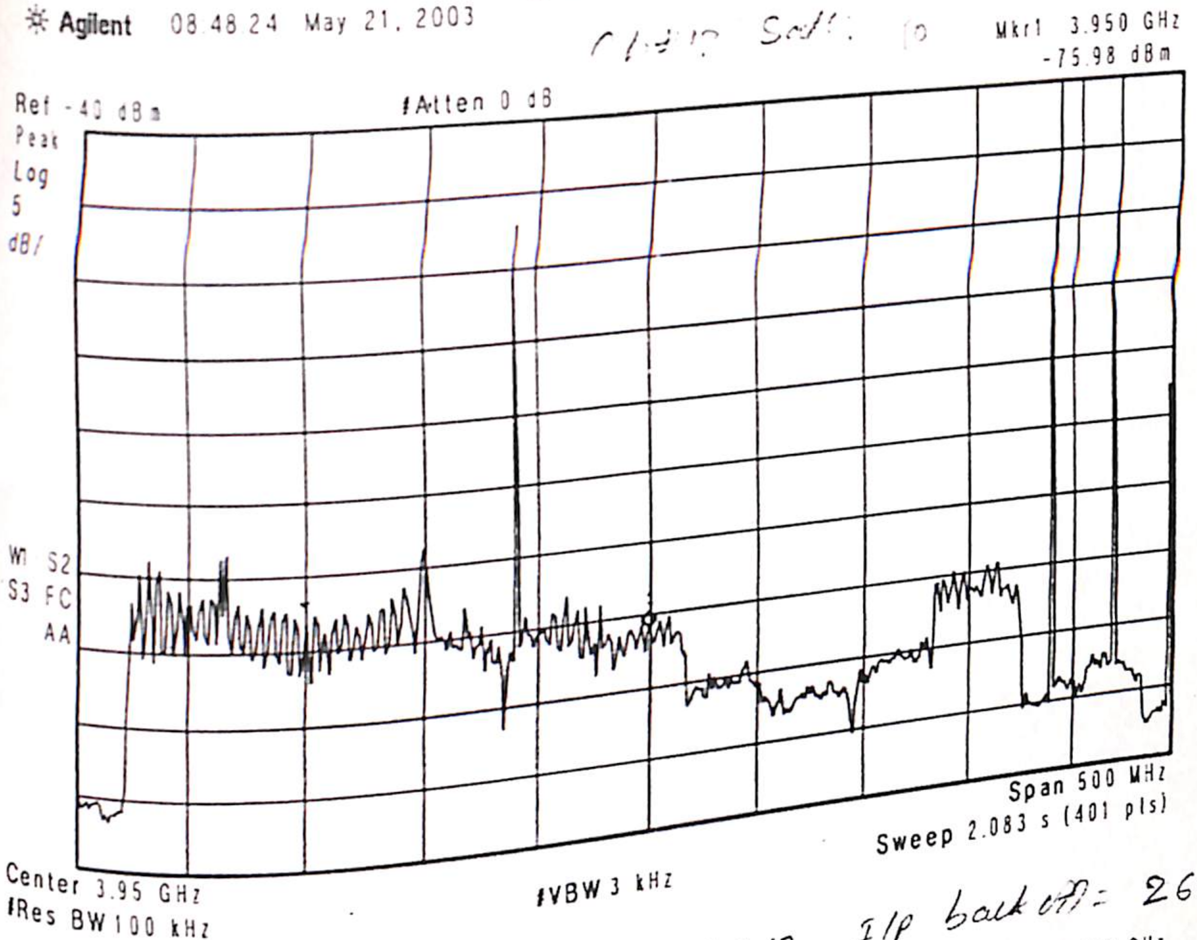
W1 S2
S3 FC
AA

Center 4.17 GHz
#Res BW 10 kHz
#VBW 3 kHz
Span 50 MHz
Sweep 2.083 s (401 pts)

products with uplinks in Transponder #4 and #11



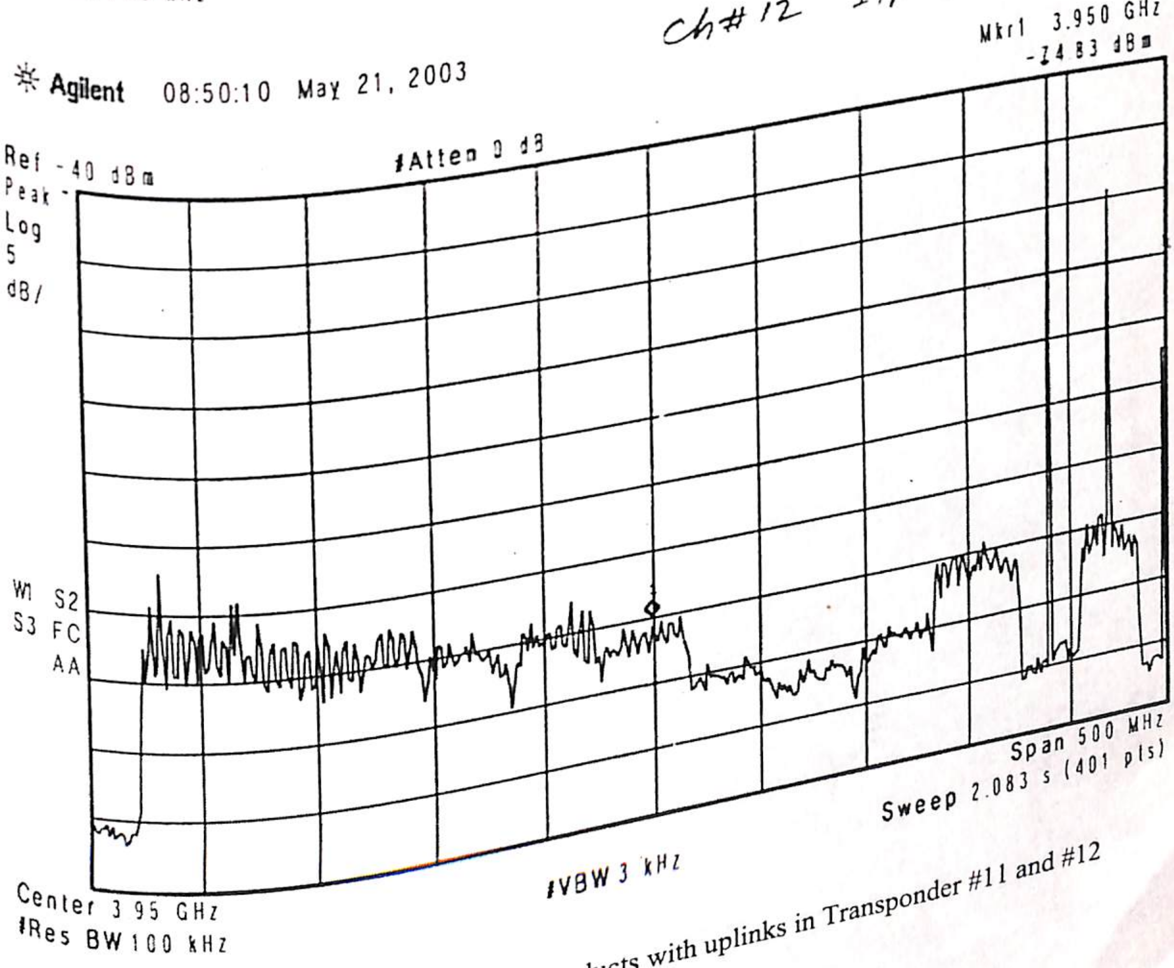
ulation products with uplinks in Transponder #11 and #12



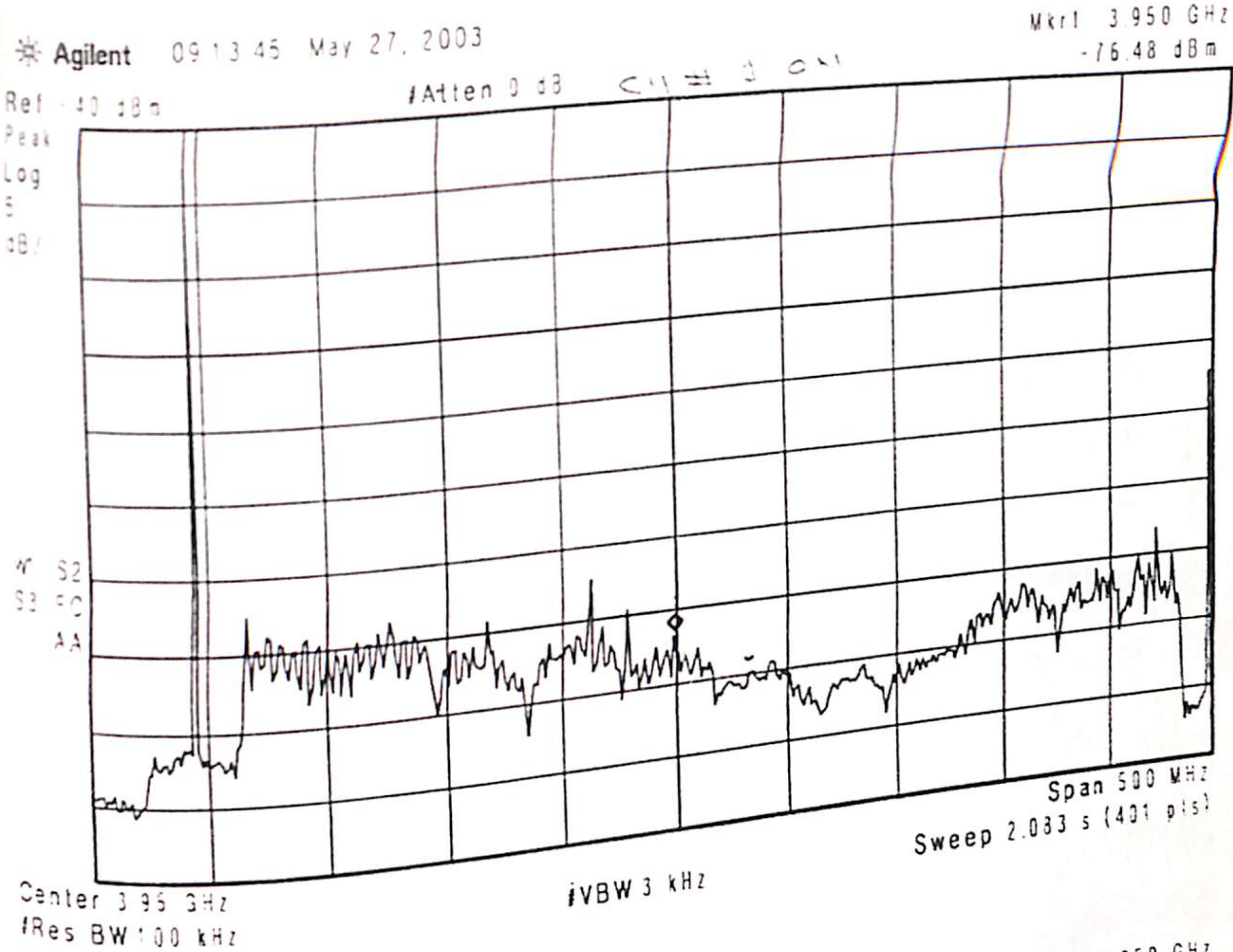
Ch#11 & Ch#12 U/L

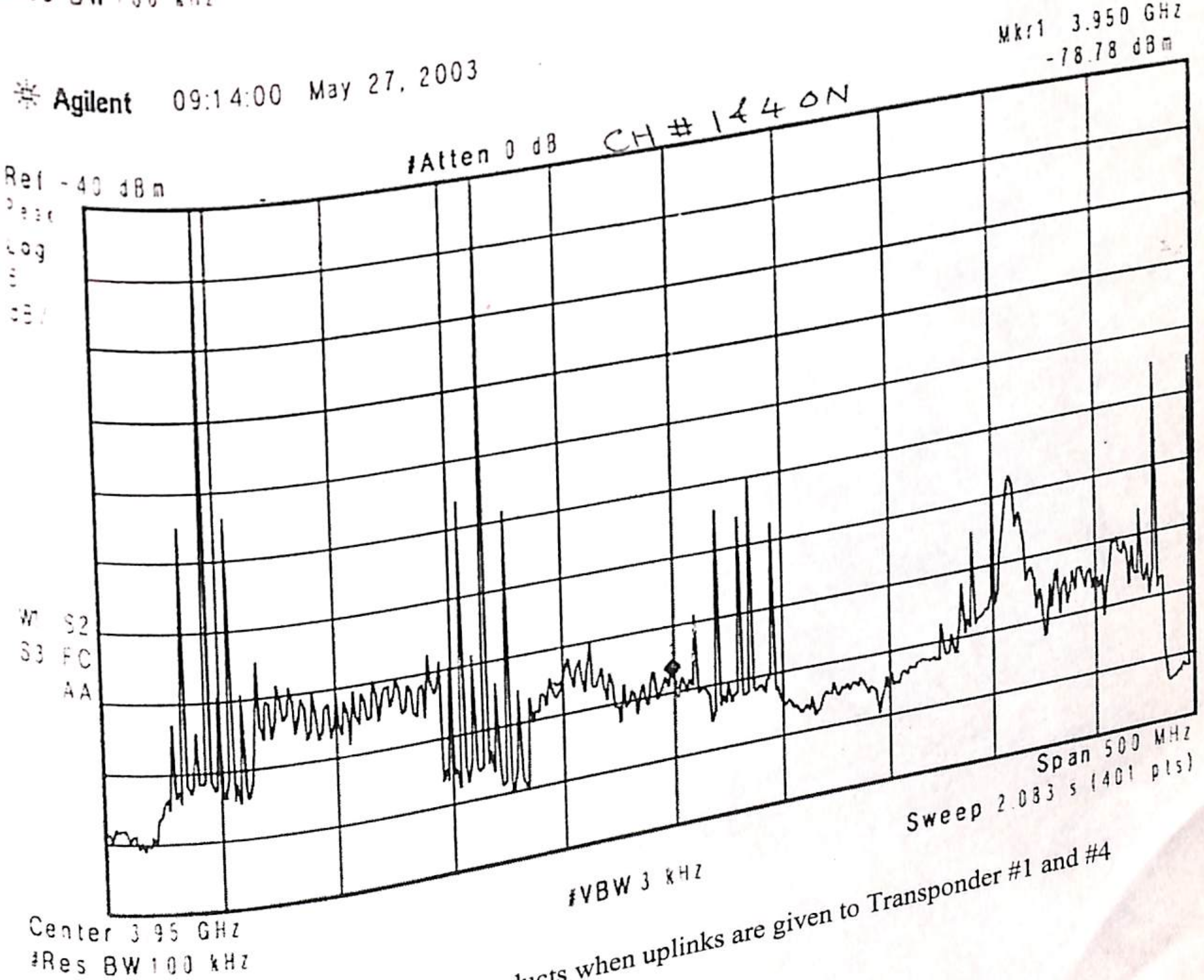
Ch#12 Sat: 10

Ch#12 I/P back off = 26dB



tion products with uplinks in Transponder #11 and #12





products when uplinks are given to Transponder #1 and #4

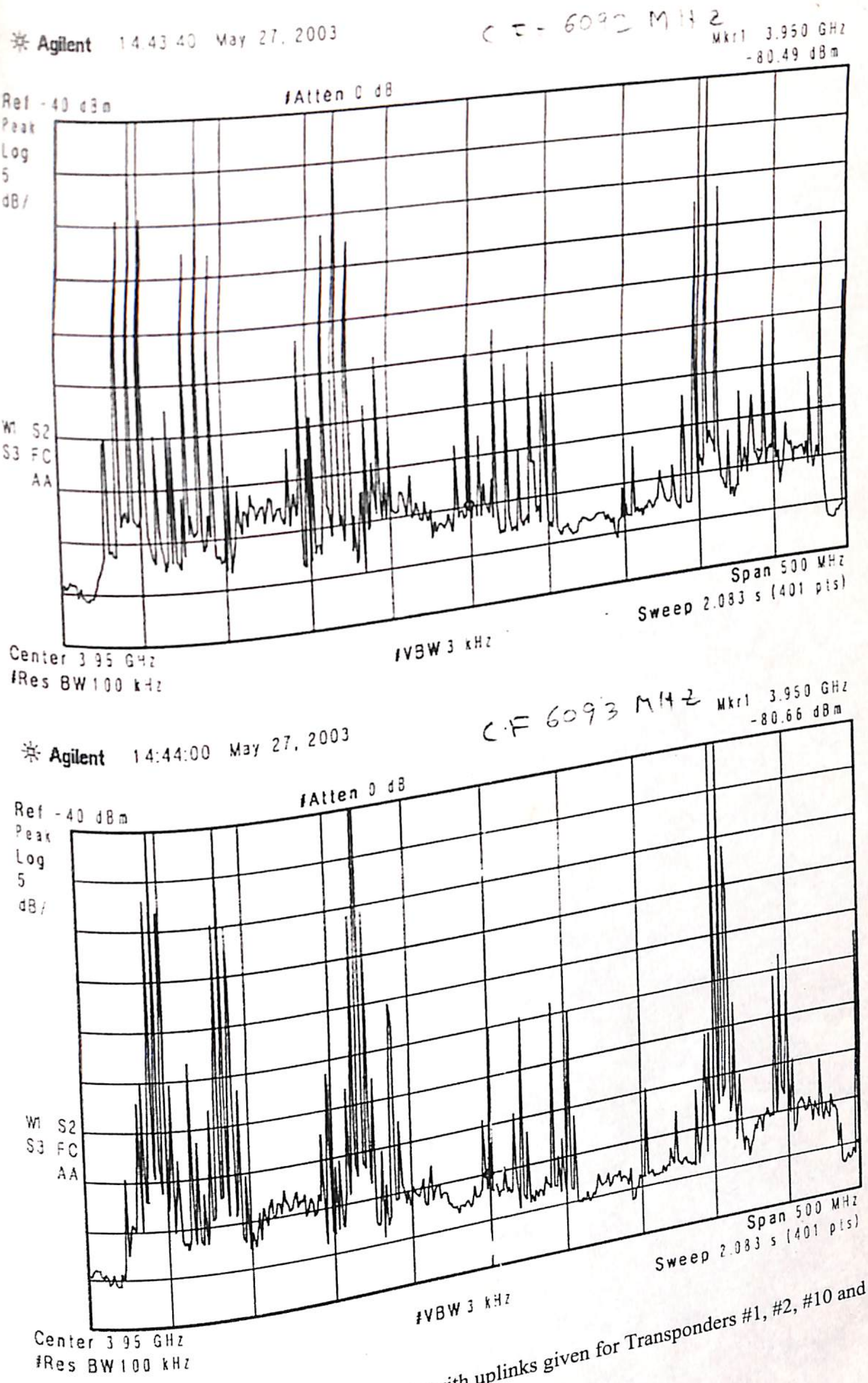


Fig. 6.9.12: Intermodulation products with uplinks given for Transponders #1, #2, #10 and #4

Chapter - 7

Chapter-7

Most important conclusions of the thesis and further work

Introduction to the chapter

This chapter summarizes the important conclusions of the interference cases experienced in the INSAT system and the investigations carried out in each case as detailed in Chapter 6. The summary includes the unique nature of the analysis and experimentation carried out in each case and the general conclusions drawn from the investigations. A generalized approach to characterize and analyze the cases is developed using the approaches employed in each case, and a step-by-step engineering approach is described.

In the outline of further scope of the study, specialized software to translate the step-by-step engineering approach into an automated method; and the possibility of developing a lightweight general test equipment for use by VSAT Operators are described.

7.1 The most important conclusions of Investigations into the Interference problems in INSAT system

The extensive satellite communication network of INSAT system provided an excellent context for investigation of interference problems in satellite communications with special emphasis on Geo-Stationary Orbit. The process involved for investigation of each of the cases was time consuming and required a large number of measurements to be carried out in each case. Most of these tests involved number of Users spread over the country, and required coordinated testing involving Users and NOCC, in addition to MCF. The infrastructure required for investigating these interference problems is very costly, involving many antennae operating in different frequency bands, downlink receiving equipments, specialized equipment like Telecom

Carrier Analyzer and Spectrum Analysers. The uplinking equipment, including High Power Amplifiers, were needed to simulate and estimate the EIRPs involved in the interference cases. All these costly equipments and required expertise of engineers is available only at MCF-Hassan.

The investigations required large amount of discussions among experts and the guidance from highly experienced people in satellite communications. The experts available in ISRO, who specialized in the design of onboard communication payloads and ground networks for various Applications came in handy for the Investigations.

All the Investigations of interference cases were measurement-intensive investigations. The number of cases and types of interference being experienced in the INSAT system (and also by all major satellite Operators in their systems, nowadays) were of varied in nature with severe levels of interference. The understanding of the problems, and solving them were concurrent. The cases of severe interference investigated in this Research work had different sources of interference, different signatures and manifestation on signals, and different coupling mechanisms. In a sense, each case is a typical 'stand-alone' case.

Hence, the major technical approach is on characterization of interference, exactly understanding the interference-coupling mechanism, and devising the right tests to bring out the unique features of the interference signals to aid the identification and localization of the source of interference. The localization of the culprit source of interference required coordinated testing involving many Users and agencies, especially in the cases where the interference affected only one satellite.

The most important contributions and conclusions of this thesis are summarized in the following sections.

7.2 Summary of the investigations and their special nature

The Table-7.2.1 below gives the assessment of the Interference Cases vis-à-vis the available Recommendations on interference reduction / Practices / Regulations. It also gives special nature of these problems not covered in the available literature.

Table-7.2.1: Assessment of interference cases

Case Study	Problem	Special nature of the problem	Assessment
#1	Interference into INSAT-2E form adjacent satellite network of Raduga 1-6	Usually, 2 deg orbital separation, and conformance to ITU Regulation of 580-5 for off-axis radiation pattern of ground antenna should not create interference. However, a strong interference was experienced for almost two years before resolving.	Case of interference between networks of adjacent satellites. Resolved through Coordination based on ITU Recommendations.
#2	Interference from ground radars into transponders of INSAT–2E	Highly skilled maneuvering of spectrum analyser settings was needed to detect and characterize the interference. Signals from ground-based-Radars reaching satellites in GSO was not even comprehensible in the beginning. The use of unknown frequency bands, and frequency hopping by military radars complicated the study and analysis.	The ground radars involved and their operation obviously do not conform to control of spurious signals and power flux density (pfd) limits at GSO. No clear recommendation on radar-type of interference into satellite communications exists.
#3	Wideband noise interference in Ext. C-band channels of INSAT-3B	A single VSAT terminal creating wideband noise, which was able to raise the whole noise floor across 60 to 70 MHz bandwidth, was totally new when the investigation was started.	The cause of the interference was a loop-back in one of the VSAT terminals between uplink and downlink at IF level. This type of problems are not covered in any of the Recommendations / Regulations.
#4	Wideband noise interference in Ext. C-band channels of INSAT-3C	A single bad VSAT terminal caused noise over 240 MHz bandwidth. The investigation required switching off of approximately 3000 VSAT terminals involving 5 transponders. Coordinated tests were difficult, in view of heavy traffic being covered by the networks.	The cause of the interference was a bad connection at ODU in one VSAT terminal. Problem is more related to maintenance than to any design deficiency. Hence, the consideration of ITU Recommendations is not relevant.
#5	FM radio pick-up by VSAT terminals and transmission to satellite.	The coupling mechanism of FM radio signals into satellite uplink transmissions required complete understanding of the ground equipment, and their	This type of interference was addressed only by Intersputnik in its User manuals. However, this type of interference constitutes a

		frequency response characteristics. Detailed database of FM Radio Stations in Indian cities, and the location of individual VSAT terminals in the vicinity of such Stations were needed in the Investigation.	significant percentage of total interference problems currently in the Asia-Pacific region.
#6	Interference during drift orbit phase of satellites	The investigations required understanding of the orbital dynamics of the satellite during the drift orbit phase; and the database on the existing GSO satellites including their operational frequency bands.	No specific guideline exists. The Satellite Operators handle these cases in real time, with intimation on operations on other's satellites received at short notice.
#7	Interference from ground-based radars into MSS SxC channel of INSAT satellites	A number of radars operate in S-band. Theoretically interference should not occur, but the magnetrons involved in the radar transmitters create spurious outputs outside of their bands. Weather radars employ very high power and scan across big range of elevation angles.	Not yet resolved. No clear-cut guidelines for this type of cases exist.
#8	Onboard generated intermodulation interference in INSAT-3A	The problem should not exist theoretically. However, the intermodulation interference occurred due to coupling between input and output signals in the satellite payload.	Intermodulation interference was most widely studied subject in the design of onboard payloads. However, the situations when the EMI shielding are disturbed is not amenable to any analysis or exact computations for the level of interference.

7.3 The most important achievements due to the Investigations of the interference cases

The Investigations into the interference cases, as described in the previous Chapter, required specialized understanding of the satellite communications and ground networks involved. The investigations resulted in the following significant contributions to the INSAT system, and to the current knowledge base.

1. Very complicated interference cases were resolved, sometimes taking about 2 to 3 years time to solve. In two important cases (Case-1 and 2) the problems were resolved and the bandwidth, which was not usable due to interference, was retrieved successfully resulting in recovery of large amount of withheld revenue.

2. The Investigations resulted in detailed understanding of interference-coupling mechanisms resulting in additional input to the knowledge base, and helped to establish a procedure for systematic experimental investigations.

3. The Investigations brought out that violations of ITU Regulations in some cases, or poor maintenance of the equipment in some other cases can result in serious interferences, and manifest with highly complicated signatures of signals. Hence technical guidelines for use by Network Operators are being evolved based on the experience of the Investigations.

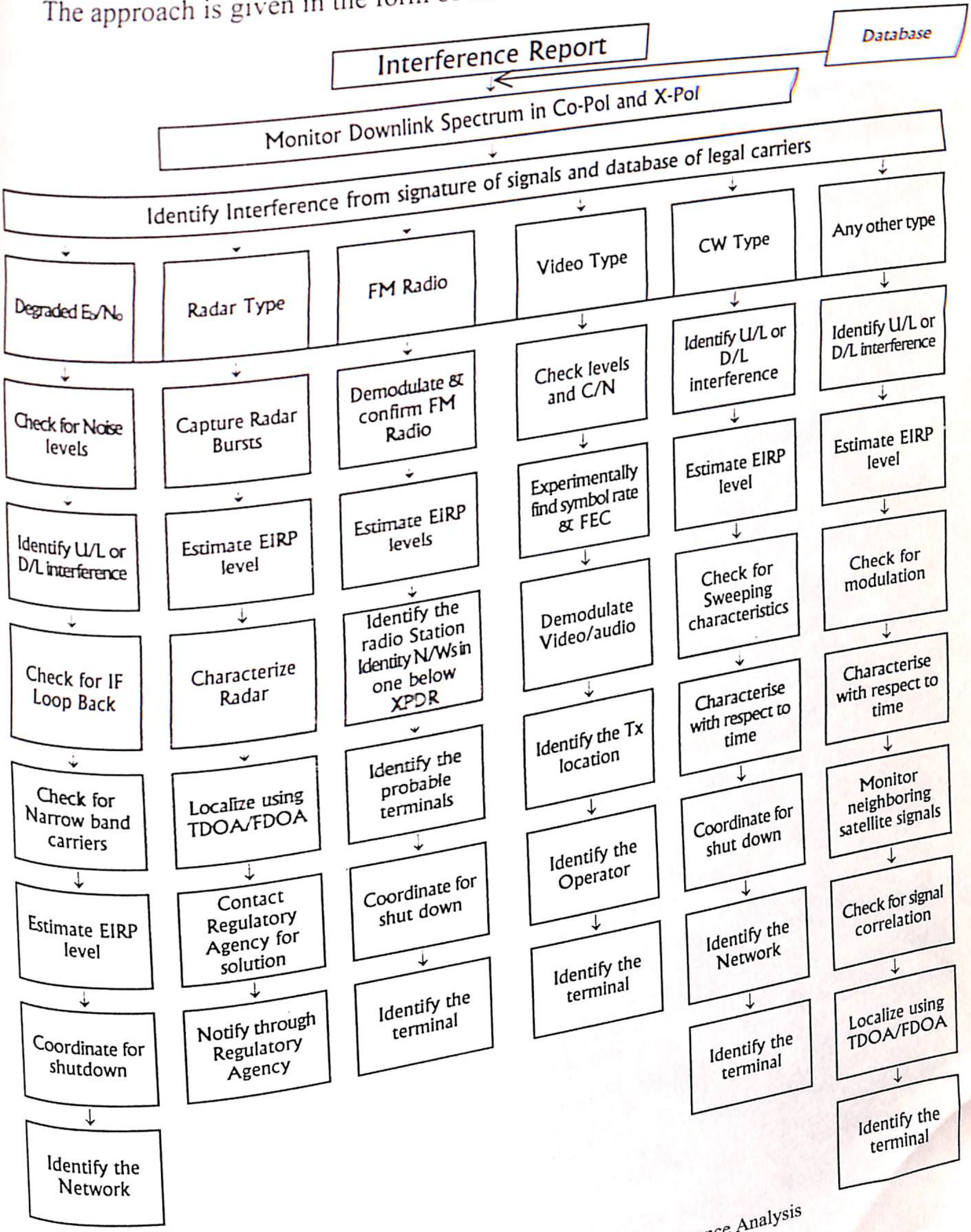
4. The Investigations brought out the importance of Time Difference of Arrival (TDOA) and Frequency Difference of Arrival (FDOA) measurements, which is a standard method reported in the literature. A measurement technique for investigating the interference cases based on TDOA and FDOA principles has been developed, and methodology to approximately locate the geographic area in which the source lies was established.

   Investigations also brought out the limitations of methodology based on TDOA and FDOA principles and their non-applicability for certain cases like interference affecting only one satellite, or misbehaviour of an onboard transponder etc.

5. Issues related to coordinated tests involving large number of Users are brought out during these Investigations, which is expected to bring awareness on interference problems to Network Operators.

6. The Investigations have created a knowledge base and brought out a systematic engineering approach, which can be gainfully put to use by any Satellite Operator who experiences interference problems.

7. The approach used in Investigations of the interference cases is studied carefully, and generalized step-by-step engineering approach is generated for use in future. The approach is given in the form of flowchart in Fig. 7.3.1.



Generalised Engineering Approach for Interference Analysis

The above Generalised approach is now being adopted to study, analyse and resolve interference problems, which is yielding positive results in terms of quick characterization / resolution of the problems. A recent case of interference is analyzed to be due to a loop-back between uplink and downlink in one of the VSATs. This loop-back is characterized within one day, whereas similar characterization in the investigation of Case Study-3 (reported in section 6.4) took about twenty days to identify that the interference was being caused by the loop-back coupling mechanism.

7.4 Further scope of work

The Investigations into interference problems undertaken in this thesis has a great amount of scope for future work. Outline on the future scope of the work is given below:

7.4.1 Automation of the interference measurement / analysis approach

The generalized engineering approach described in the previous section can be used to identify the signature of interference signals, carryout measurements to characterize the interference, and also vary certain parameters during measurements for understanding correspondence and correlation with other test data. This approach utilizes a large amount of database of allotted spectrum and Users, configuration and deployment of the ground terminals, type of signals and modulations involved in the communications etc., to identify and characterise the interference.

A major portion of this generalized engineering approach can be automated, using the database and spectrum monitoring features of equipments like Telecom Carrier Analyzer (TCA) etc., to identify the illegal / interference signals and to characterise them. Features of the Spectrum Analyzers like continuous monitoring of signals, and max-hold monitoring can be used along with specialized software developed to log and analyse the data, for characterizing interference with respect to time. Estimation of the EIRP of the ground terminal causing interference requires measurement of the lar EIRP consumed by the interference signal, and then using the characterise the culprit ground terminal. Estimation of EIRP, can be automated without disrupting the traffic. Various modules as described in the Generalised Approach can be linked together to minimize manual intervention.

Certain blocks in the flowchart of the Approach, like “coordinated shutdown tests” cannot be automated, and they have to be essentially carried out in coordination with the concerned Users only.

7.4.2 Further development of specialized software

The following software was developed during the course of investigation of interference cases:

- Logging of TCA data in external PC (described in section 5.2.4)
- Cross correlation between signals to determine TDOA and FDOA (described in section 5.2.4)
- Approximate geo-location of source of interference using TDOA and FDOA values (described in section 6.3.6.2)
- Identification of interference embedded in the occupied bandwidth. (described in section 5.2.3)

The software can be further enlarged and improved to have more sophisticated analysis and presentation features.

One of the elements in the FDOA is to estimate the drift of the onboard LO frequency from the measured frequency-difference data, and to exactly compute radial range-rate-difference between the two satellites affected by interference. Similarly, computation of the range rate value of the satellites from the known satellite ephemeris data can be integrated into this software.

The digital modulation constellation diagrams, a feature of TCA, was used manually to identify the symbol rate and FEC of the modulations of the interference signals during the Investigations. This feature can be automated and can become one of the modules to analyse the interference signals.

7.4.3 Development of lightweight measurement equipment

The costly measurement / analysis equipments are generally available at the Hub Stations of the VSAT Networks. The VSAT remote terminals lack proper instruments like spectrum analyzer, power meter etc. Moreover, most of the VSATs are installed on the rooftop of the multi-storied buildings, with outdoor units (ODU) being an important element in the configuration. Many a time, the remote VSAT terminals are the source of interference. The ODUs of the terminals often create problems due to lack of proper maintenance.

The RF output at the antenna feed point needs to be monitored in the remote VSAT terminals during the coordinated tests to resolve interference cases. Carrying heavy equipments to the outdoor location of the antenna of the terminal, usually, discourages the technicians to carryout the measurements and supply the data for analysis. Hence, there is a need to develop a lightweight and portable equipment which can log the transmission frequency, RF power (in different polarizations), VSWR at the feed port etc. The portable equipment should operate on battery power, and should be able to download the data to a PC later.

The development of such equipment will be very useful for carrying out interference related investigations at remote sites [51]. Initial work on definition of this type of equipment development is taken up at MCF, which can be further progressed to design and realization phases.

The Investigations into the interference problems revealed that new knowledge keeps on accumulating with every case. Same will be applicable for the scope of future work also – i.e., many more new ideas to improve the efficiency of investigations will be recognized with each experience of interference problems. Hence, the future scope of work, as described above, can only be taken as outline.

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