RFI REPORT : PART-I

(Part-I of 13 Reports)

RADIO FREQUENCY COORDINATION, INTERFERENCE MEASUREMENTS AND MITIGATION TECHNIQUES REGARDING THE GIANT METREWAVE RADIO TELESCOPE

AN OVERVIEW

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Keywords: Giant Metrewave Radio Telescope (GMRT): International-Telecommunication-Union-(ITU)-Frequency Coordination; WPC-Govt. of India; RFI Measurements; RFI-Narrow Band; RFI-Broad Band, RFI - Automobiles; RFI-Power Line; RFI-Thunderstorm; RFI-GMRT site; Radio Frequency Interference to Radio Telescope; RFI Terrestrial-Transmitters; RFI-Satellite-Transmitters.

SUMMARY

Over the last few years many surveys have been made at the GMRT site for measuring Radio Frequency Interference (RFI) in the frequency bands allocated to the Giant Metrewave Radio Telescope (GMRT). A great deal of work has also been done concerning radio frequency coordination. GMRT consists of 30 nos. of parabolic dish antennas of 45-m diameter placed along a 25 km Y-shaped array. GMRT is located about 70 km north of Pune (line of sight) in Western India. The purpose of this series of 13 reports on RFI, as listed below, is to describe the work done so far and to make certain recommendations, particularly for the follow up work which needs to be done urgently.

This report (Part-I) gives an overview of the work done so far by various members of the GMRT group regarding radio frequency coordination, interference measurements and development of mitigation techniques for the purpose of minimizing harmful interference to the operation of GMRT. Detailed surveys made over the last few years have shown that the level of RFI at the GMRT site is relatively low compared to the receiver noise in the frequency bands of 322-328.6 MHz; 608-614 MHz and 1400-1427 MHz, which have been allocated by the Govt. of India for operation of GMRT. The level of RFI in the adjacent parts of the frequency bands 325 ± 16 MHz; 611 ± 16 MHz and 950-1427 MHz which are covered by the GMRT receiver system is also relatively low but continues to increase every year. Further a great deal of very harmful RFI is observed in the frequency band of 152-154 MHz and also at relatively unacceptable levels in the 230-234 MHz band. Frequencies of some of the strongest RFI signals observed in these two bands are listed in Report No. IV. In order to locate unauthorized transmissions in these bands, it is important to develop suitable monitoring and direction finding

equipment. In this report are described some suggestions and schemes for developing relatively simple direction finding equipment for locating the sources of RFI in the protected bands of GMRT.

In Part-II and Part-III of this series of technical reports, is described the frequency coordination carried out and several allocations obtained for the Giant Metrewave Radio Telescope (GMRT). Coordination carried out at the World Radio Conferences (WRC) of the International Telecommunication Union (ITU) is discussed in Part-II. India has played a significant role for protection of radio astronomy at the ITU conferences. The Govt. of India has allocated a number of frequency bands (Table-I) for operation of GMRT, viz. 37.5-38.25 MHz, 152-154 MHz, 230-234 MHz, 322-328.6 MHz, 608-614 MHz and 1400-1427 MHz. (Part-III). Recently allocations have also been requested for the bands 408-414 MHz; 1610-1613.8 MHz and 1660-1670 MHz.

RFI surveys for the narrow band terrestial signals (< about 100 kHz) have been made at the GMRT site during 1985-2000 and a summary of these measurements is presented in Parts-IV & V. Surveys have also been made at several locations within about 60 to 80 km of the GMRT site. The sensitivity limits of these RFI surveys is about -150 to -160 dBW/m^2. However, this level is about 30 to 40 dB higher than the level of harmful interference recommended by the ITU. More sensitive surveys using several pairs of radio interferometers of GMRT have also been done for certain bands. For some of the RFI signals, possible sources of RFI have also been identified as described in Report-Part-IV of this series.

In Report Nos.VI & VII is summarized the results of RFI measurements for automobile interference and powerline interference from 11 kV HT lines. In Report-VIII is given a summary of the expected RFI by coronal discharges from high power HT AC lines of > 66 kV; a similar summary for high power DC line of 400 kV which passes near the top end of the Eastern Arm of the GMRT antennas (between E05 & E06 antenna) is given in Report-IX.

RFI from satellites, which could be a serious source of interference to GMRT and the required coordination carried out is described in Reports X & XI. Coordination by the Indian delegations at ITU as well as coordination provided by WPC with the satellite agencies have assured suitable protection to the GMRT. However, in view of increasing satellite communication, it is important that we have to be very vigilant, particularly from the broad-band digital transmissions by the Low-Earth Orbiting (LEO) satellites at frequencies in the VHF and UHF range. Similarly, it is important to make careful coordination with the Medium-Earth orbiting and Geo-Synchronous Satellite Systems in the frequency range of 1.45 to 1.7 GHz. We should electronically scan ITU circulars which announce newly proposed communication satellites.

Part-XII describes a summary of the expected propagation losses from Pune, Bombay, etc. to the GMRT site. A summary of some relevant ITU reports is given in this report.

Part-XIII describes various mitigation techniques for which some preliminary work has been done, as well a summary of the work being done internationally.

Although the level of RFI observed at metre wavelengths at the GMRT site is much lower than that seen at many other observatories, say in USA and Europe, it is extremely important to ensure adequate protection to the GMRT in several frequency bands which have been allocated by the Government of India, considering the high sensitivity of GMRT and its great potential for important contributions to Radio Astronomy.

1. INTRODUCTION

It is known that the sensitivity of a radio telescope is more than a million times than that of a radio communication receiver. Considering the same, the International Telecommunication Union (ITU) has provided EXCLUSIVE, PRIMARY or secondary allocations for the "radio astronomy service" in the frequency bands from about 13.5 MHz to greater than 300 GHz. Only a limited number of these bands have EXCLUSIVE allocation. All the other bands allotted to the radio astronomy service have either PRIMARY or secondary status, shared with other services, such that PRIMARY has a higher degree of protection for the radio astronomy service if a suitable coordination is made. Hence it becomes necessary for radio astronomers to seek coordination from the National frequency coordinating agencies so that no transmitters are permitted upto certain specified distances from a sensitive radio telescope. Further it becomes essential to make sensitive surveys for RFI at the site of the radio telescope and to ensure that any sources of RFI are identified and coordination done with various telecommunication agencies in order to minimize harmful interference to the radio telescope. Finally radio astronomers should also develop suitable mitigation techniques for suppressing or minimizing harmful effects of any RFI in the allocated bands or for astronomical observations which become necessary in other frequency bands.

The Giant Metrewave Radio Telescope consists of 30 parabolic dish antennas, each of 45-m diameter placed in an array of 25 km extent. Appendix-A summarizes the relevant features of GMRT.

In Section-II of this Report (Part-I), we present a brief summary of the 13 RFI Reports, viz. Part-II to Part-XIII of this series of RFI Reports on Radio Frequency Coordination, Interference Measurements and some preliminary work done concerning mitigation techniques. The Wireless Planning & Coordination Wing (WPC) of the Government of India has been very supportive and appreciative of the radio astronomy research being carried out in India and has provided the required coordination both nationally and internationally. However, with the increasing telecommunication activity, there does arise considerable RFI in the bands allocated to GMRT as discussed in Part-IV and Part-V. Also, there arise interference from automobiles and Power Lines as discussed in Parts-VI to IX.

In Sections 3 to 7 of this Report (Part-I), I have made several suggestions for further work to be done for the purpose of identifying sources of RFI in the frequency bands allocated for operation of GMRT. We need to carry out more sensitive and periodic RFI surveys at the GMRT site, including those to be made using the GMRT interferometric system, as discussed in Section 4. Further, we need to develop suitable radio direction finding equipment (Sections 5 and 6). Industrial development is progressing rapidly in and around Pune. Even though there exist many hills between the GMRT site, Pune and Mumbai, we also need to ensure that no transmitters are located in and around Pune and Mumbai in the GMRT bands upto the coordinating distances of 200 to 600 km as agreed by WPC and as per ITU recommendations. It is very important to note that such protection would be possible only if we develop a suitable monitoring as well as direction finding equipment.

In Section 7 we briefly discuss possibilities for minimizing the harmful effects of power-line interference. Recommendations are finally summarized in Section 8.

I may add that it has not been easy to compile all the above reports adequately due to the coverage of wide ranging topics and also work done over many years, in which many colleagues have participated. The reports are often sketchy and repetitive. I hope that the readers will understand the difficulties and will find the reports useful nevertheless. I have also not been able to summarize work done by various members of the GMRT Group over the last one year.

2. BRIEF SUMMARY OF PART-II TO PART-XIII OF THE "GMRT RFI REPORT" ON THE RADIO FREQUENCY COORDINATION, INTERFERENCE MEASUREMENTS AND SUPPRESSION / MITIGATION TECHNIQUES REGARDING THE GIANT METREWAVE RADIO TELESCOPE

2.1. PART-II (ITU) :

In order to ensure adequate protection to the sensitive radio astronomy observations, it is important to seek the required national and international frequency coordination. As described in Part-II, the International Telecommunication Union (ITU) makes allocations of different frequency bands (as well as rules and regulations concerning the same) to a large number of different active radio services (which produce radiation) as well as to passive services such as radio astronomy and space exploration of earth's resources. ITU consists of over 160 member countries of the World, with each country having one vote. The allocations are discussed periodically in the World Administrative Radio Conferences (WARC) which are now simply called as World Radio Conferences (WRC). India has played an active role in these conferences for the protection of radio astronomy, particularly for the frequency bands upto 1.4 GHz. Further, India has supported proposals made by various countries in all the bands of interest to radio astronomers. The first allocations of frequency bands to radio astronomy were made in WARC-1959. I am told that the leader of the Indian delegation chaired the Working Group which allocated the band 1400-1427 MHz to radio astronomy on an EXCLUSIVE basis. Next WARC took place in 1979. I attended it for eight weeks and convassed support by several developing countries for

India's proposal for allocation of the band 322-328.6 MHz on a PRIMARY basis in all the three regions of the world as defined by ITU. All the Western countries strongly opposed India's proposal as the band was being used by their Defence services but we finally got the allocation approved at the Plenary General Assembly with 43 Votes in our favour and 37 Votes against - although all the countries with active research in radio astronomy such as USA, Europe, Japan, etc. opposed India's proposal. This was as a result of my writing to scientists of many countries before WARC 1997 and intensive convassing to delegates of many developing countries at WARC-79.. Our proposal for Giant Eqatorial Radio Telescope (GERT) made in 1977 was helpful. Shri T. Srirangan, Wireless Adviser, Govt. of India played a major role for getting the above proposal approved. I am highlighting this here to show that India should continue to take active interest in those World Radio Conferences in which proposals are discussed that may affect radio astronomy. At WARC 1979 Indian proposals for PRIMARY allocation of the bands 150.05-153 MHz and 608-614 MHz in India were also approved by the Conference (several neighbouring countries such as Malaysia and Singapore had opposed allocation of the band 150.05-153 MHz to radio astronomy in India but I managed to get Indian proposal approved at the Working Group level itself). At WARC-1992, myself and R.P. Sinha managed (after lot of effort and support by the Indian delegation) to get approved a foot note for the protection of the radio astronomy bands 150.05-153 MHz and 322-328.6 MHz against digital modulation of the Low Earth Orbiting Satellites (LEO). At WRC-1995 & WRC-1997 S. Ananthakrishnan ensured better protection against any spurious emissions from LEO satellites, apart from several other important contributions. There are several such issues which still need to be pursued and have been partially addressed at WRC-2000, which was attended by A.P. Rao and T.L. Venkatasubramani. In Part-II, we also summarize the very important role of the International Union for Allocation of Frequencies (IUCAF) for protection of radio astronomy and space passive services by providing the necessary coordination. IUCAF is a non-statutory body supported by I.A.U., U.R.S.I. and COSPAR.

2.2. PART-III (WPC)

The WPC has provided the necessary coordination both nationally and internationally for the protection of various radio telescopes in India including GMRT. Allocations made to GMRT are given in Table-I There have been numerous correspondence as well as many meetings at Delhi for seeking allocation of various frequency bands for operation of GMRT. WPC has also helped on many other occasions, such as protection from the unauthorized satellite transmissions near 324 MHz by an agency in USA; proposal by MOTOROLA for mobile terrestial services near 320 MHz which we managed to get withdrawn after tests on their mobile sets made at NCRA; coordination with IRIDIUM, WORLD-SPACE and some other satellite systems. Some of these efforts are described in Part-III, in which is also reproduced in our letter to WPC dated 20th June 1998 and of November 1999 (original correspondence with WPC re: frequency bands protected for GMRT and summarizing various licences that have been issued for the frequency bands allocated for GMRT operation). Part-III also describes brief ly RFI observed in the bands 152-154 MHz and 230-234 MHz and also characteristics of Cable TV transmissions.

2.3. PART-IV and PART-V (RFI Surveys) :

In Part-IV is discussed in detail several RFI surveys made in the bands 152-154 MHz and 230-234 MHz at the GMRT site as well as at several nearby locations upto a distance of about 60 kms, such as Sangamneer, Alephata, Kukdi, Junnar, NCRA-Pune, Lonavala & Khandala. Surveys made at 322-328.6 MHz are also briefly described. A summary of surveys by T.L. Venkatasubramani in various radio astronomy bands allocated to GMRT in various frequency bands in the frequency range of about 150-1427 MHz are also presented and further details are given in Part-V. Various methods used for the above surveys are discussed in Appendix-I of Part-IV. The sensitivity of these surveys is about -150 to about -160 dBW/m^2. In Appendix-II of Part-IV is described the levels of harmful radio interference as recommended by the ITU. For continuum observations these are about -190 to -200 dBW/m^2 for the GMRT bands Table-III. In Part-V we present a summary of RFI measurements made by various groups at the GMRT site during 1985-2000.

In Fig. 1 of this Report we present some of the several figures given in Part-IV of this series of reports in order to illustrate that a great deal of RFI is being observed in the frequency band of 152-154 MHz at the GMRT site. In Table-I of Part-IV are listed frequencies of several narrow band signals seen in the above frequency range. To summarize, RFI has been observed quite frequently near 152.06-152.08; 152.11-152.12; 152.13-152.15; 152.78-152.80; 152.90; 153.53-153.61 and near 154.0 MHz Some of the above frequencies have errors of measurements, but the signals are broadly near the above frequencies. Signals in the GMRT protected band of 152-154 MHz have also been observed at several locations within about 60 km of GMRT, particularly at Lonavala (Fig1(d). As discussed elsewhere in this Report, it is important to locate these sources of RFI so that harmful interference does not take place in the protected bands of GMRT.

Some RFI is also seen at GMRT in the band 230-234 MHz (Fig.2). In Table-5 of Part-IV are listed frequencies and PFD of signals seen in this band, which are frequently at 229.70, 230.65, 231.0, 232.3, 233.1 and 233.8.

The level of radio frequency interference in the higher frequency bands allocated to GMRT is relatively low (Figs. 3 & 4). In Figs 5(a) and 5(b) are given RFI measurements made by T.L. Venkatasubramani in July 1999. As described in Section-IV of this report we need to make more sensitive measurements using the interferometer and correlator system of GMRT.

2.4. PART-VI (Automobile Interference)

In Part-VI are described measurements by Venkatasubramani and Saini for spark induced broad-band RFI from a two wheeler vehicle. From Fig.6 it is seen that there occurs sharp pulsed RFI with rise time of less than one micro-sec. Discussions and some data regarding automobile interference from the book by Skomel (1978) are also summarized in Part-VI in order to estimate decrease of system sensitivity for those antennas which are close to road (e.g. Fig. 6C). As is well known that a resistive wire is placed in the ignition circuit in all the automobiles manufactured in the Western countries to minimize RFI from the spark plug discharge. This is generally not done in vehicles made in India. Also, our measurements have shown that diesel jeeps & trucks which do not have spark plugs also produce RFI, due to carbon brushes in the Dynamos. It would be useful to place a resistive wire in these circuits. The resistive wire which may be available from wholesale automobile shops or may be imported. A report by LRDE, Bangalore for installation of filters in GMRT vehicles for minimizing automobile interference is also included in Part-VI.

2.5 PART-VII (RFI from gap discharges in the 11-kV lines)

In Part-VII are presented measurements of pulsed broad-band interference due to gap discharges in the 11 kV power-lines as measured at GMRT. In Figs. 7(a) to 7(c) are shown typical measurements made with the GMRT 150, 235 and 327 MHz and feeds pointed towards the horizon in different directions. These measurements were done using the Zero span mode of the HP-5890 Spectrum Analyzer(SpA), for which case the SpA acts as a receiver with the selected resolution bandwidth (RBW) of the SpA. The SpA was internally triggered by the 230 Volts single phase 50 Hz A.C. power and with the sweep (SWP) of the SpA scan being typically 40 milli-sec. Measurements were made with RBW of 100 kHz, 1 MHz, 3 MHz and 5 MHz. The power-line RFI seems to be maximum for a 3 MHz bandwidth. In Fig. 7(e) is shown a plot of power spectrum of total power received output for one of the 45-m antennas of GMRT which was obtained by the Pulsar group with about 1ms time constant; it is seen that considerable power is observed at several harmonics of 50 Hz. It is seen that there occurs considerable RFI from the 11 kV power-lines to the GMRT receivers. If RFI takes place due to faulty insulators or poor junction connections or poor grounding at or a given pole of the 11 kV lines, we should expect RFI to occur when the A.C. voltage rises to about + 11 kV or - 11 kV (perhaps even as it rises to more than ±5 or 6 kV). For the three phase lines which supply 11 kV voltage to GMRT, we should then expect to see RFI at multiples of 3.33 ms for the 50 Hz frequency in India (Fig.8). It is interesting to note that for most of the antennas of the GMRT, RFI was seen soon after line trigger at either 3.3 or 6.6 or 10 ms (starting often at 1 or 2 ms earlier to the above periods). Sometimes, RFI was observed only every 20 ms apart indicating that sparks occur only when the voltage rises to + 5 or 6 kVA or -5 or 6 kVA and not for both cases. Thus in my view the RFI arises often due to faulty connections or insulators and poor grounding at only one or two of the poles of the 11 kV power-line within a few hundred m of the GMRT antennas. Recently it has also been found by M.R. Sankararaman and colleagues that there takes place considerable RFI from the 2-MVA sub-station supplying power to GMRT, which is located adjacent to the Central Array, and the results will be described elsewhere. According to measurements made by me in 1998, it seems that power-line RFI also arises at the GMRT antennas from 11 kV power lines or transformer connections at the irrigation pumps in agricultural fields close to the GMRT antennas, perhaps upto several hundred mtrs. away. We need to develop a hand-held RFI measurement setup for detecting power-line RFI from HT lines as discussed by me in Part-VII.

The power line RFI is likely to adversely affect the dynamic range of GMRT as discussed in Appendix-B of this Part-I.

2.6 PART-VIII (RFI from corona discharges in the 110 & 220 kV A.C. lines)

It is known that HT lines of more than 65 kV give rise to RFI at VHF frequencies due to Corona discharges. During selection of the GMRT site in 1985, the Central Power Research Institute was requested to measure RFI from the 110 kV and also a 400 kV A.C. line in the Narayangaon region. We also made a detailed study of the literature and it was decided that the RFI from the 110 kV A.C. HT lines will be negligible if the Central Array is located more than about 7 km away. The 400 kV line is passing about 6 or 8 km north of Ojhar and therefore the locations of W5 and W6 were selected to be well away from the 400 kV line. However, E4 antenna passes close to a 220 kV line. Further, recently a 220 kV line has been erected from Ale-Patha to Narayangaon which passes between W3 and W4 antennas. Although RFI from the above lines may not be correlated for far away base lines of the GMRT array, we need to measure the degree of degradation to the sensitivity of GMRT. In Report-VIII is summarized the expected power levels (dBW/m^2) of RFI due to Corona discharge by HT lines as a function of frequency and distance from the lines.

2.7. PART - IX (RFI from 400 kV DC line)

In 1997, while returning from a technical visit to E6 antenna, S. Ananthakrishnan noted that a few tall steel towers had been erected recently along a line which passes close to E6 antenna. Although M.S.E.B. were aware of the need for the protection of GMRT, they had not made the required coordination with us. I visited I.I.Sc. library at Bangalore and obtained several papers discussing corona discharges from the High-Tension D.C. lines. A detailed report was written by me as given in Part-IX. S. Ananthakrishnan, myself and N.V. Nagarathnam had detailed discussions with M.S.E.B. who referred the problem to a Consultant in Canada, who agreed with our assessment. It was finally decided by M.S.E.B. to realign the line (the tall towers were shifted) at their cost so as to pass roughly half-way between E5 and E6 antennas.

2.8. PART-X (RFI from LEO satellites)

At the Satellite Mobile Conference in 1987 and later at W.A.R.C.-1992, the I.T.U. approved a new satellite communication service, called Non-Geo-Stationary Non-Voice service (NG-NVS), with allocations in the bands 137-138 MHz and 387-400 MHz. Its propose is to provide low-cost message communication. The satellites are placed in Low Earth Orbits of about 700 to 1000 km away from the Earth. In 1991, the Belgian Administration had issued a notification for launching a mobile satellite named as MLMS which was published in the weekly circulars of ITU. This ITU circular came to my attention and I was very surprised to note that this service planned to use the simple BPSK (Binary phase-shift Keying) modulation, which was known to produce considerable spurious emission upto far away frequencies from the Carrier frequency of the transmitter (Fig. 9). A report by Swarup and Sinha (1992), discusses the expected level of spurious emission in the radio astronomy bands of 150.05-153 MHz and 322-328.6 MHz from the LEO satellites for different modulation schemes and is included as an Appendix in Part-X of the RFI Reports (also see Fig.9). We had circulated this Report widely. Later in the report submitted to the ITU by the U.S. administration (7D/25) it was concluded that RFI from LEO's can be kept below the harmful level for radio astronomy as per ITU-R RA 769 by suitable design of the satellite system as carried out by certain Firms (these US report also referred to Swarup & Sinha report). However, there were some mistakes in the US report (a much smaller value of bandwidth for the 150 MHz band was assumed in the US report than is applicable as per ITU-R-RA769.1) as was noted by me. An addendum to the above report was submitted by me to WPC and later by T.L. Venkatasubramani but some or how the above report has not been taken note of by the ITU Working Groups. India should consider submitting a new report in this connection incorporating the above material and ensure its adoption.

2.9 PART-XI (RFI from IRIDIUM, World-Space and other satellite systems)

2.9.1. IRIDIUM

It is well-known that the IRIDIUM system consisting of 66 satellites and operating in the frequency band of 1613.8 to 1622 MHz, as per allocations made at WARC-92, gives rise to a considerable degree of RFI in the radio astronomy band of 1610-1613.6 MHz. The band is used for important spectral-line observations of the OH cosmic masers. After considerable negotiations (as coordinated by WPC), NCRA-TIFR entered into a MOU with IRIDIUM who agreed to restrict the traffic density of their service during the period from 00 Hrs. to 0600 Hrs. IST so that the planned observations of GMRT in the above band are not adversely affected. Although IRIDIUM service has been curtailed considerably due to their financial problems, our efforts (myself, Ananthakrishnan and Sankararaman) as well as by many other countries (USA & particularly Europe) and by IUCAF regarding GLONASS has hopefully sent a message to the satellite communication agencies to take adequate precautions for minimizing spurious emissions of the satellite transmitters when operating close to the radio astronomy bands. But, it must be noted that the commercial considerations are over-riding considerations for the satellite communication agencies and hence radio astronomers need to be very vigilant. Although local RFI can be minimized by a careful selection of the site of a radio telescope, RFI from satellites can be minimized only by international coordination.

2.9.2 **WorldSpace** :

A broad-band (nearly 3 MHz) Digital Audio Broadcasting Service (DBS) was approved at WARC-92 for broadcasting high quality music (CD quality). After considerable discussions, the frequency band of 1452-1492 MHz was allocated for the above service. It was hoped that suitable modulation scheme will be used by the satellite communication agencies for adequate protection of the important 1400-1427 MHz band. S. Ananthakrishnan came to know at WARC-97 that ALCATEL in France is designing a satellite transmitter system for the above service for the “WorldSpace” agency. At first, we had considerable difficulty in obtaining full details. I made a detailed study of the potential RFI from the above service based on a report of ALCATEL obtained by Ananthakrishnan, a report obtained by me from Space Application Centre of ISRO, Ahmedabad and a detailed note written about DBS by Ponsonby some years ago (see Part XI). With the help of French radio astronomers, we finally obtained test results from ALCATEL which showed that the level of spurious emission in the 1400-1427 MHz is likely to be below the harmful level as per ITU recommendation 729.1.

It may be noted that the WorldSpace has placed three Geo-Stationary satellites for the DBS service for providing high-quality music as well as data communication. The CARIBSTAR provides coverage over South-America, AFRISTAR over Africa and ASIASTAR over Asia. Regarding ASIASTAR, WPC has coordinated with the Australian Administration which is coordinating ASIASTAR for World Space. Some of the ex-ISRO officers occupy senior positions in the World Space organizations at Bangalore and Washington D.C. The Australian Administration has assured adequate protection of GMRT in the 1400-1427 MHz band (Fig. 10). However, the power levels from the ASIASTAR is quite high near 1492 MHz. Therefore, the 21-cm receiver of GMRT may get saturated if pointed in a direction close to the ASIASTAR in view of the high collecting area of GMRT 45-m dishes. Detailed measurements need to be made in this connection.

2.9.3 (RFI from an orbiting Satellite at 328.234 MHz).

It was noted in 1996 that a Polar orbiting satellite produced very high level of interference at a frequency of about 328.234 MHz in the Ooty Radio Telescope and also in the GMRT. RFI level is about 30 dB above the receiver noise even when satellite passes for away from the main beam of the telescopes. This satellite had been transmitting at 328.234 MHz in the 322-328.6 MHz which is allocated by I.T.U. to Radio Astronomy on a PRIMARY basis by ITU, along with Fixed and Mobile terrestial services, but with no allocations to the aeronautical or satellite services. The satellite produced pulsed radio emission every 72 seconds which was seen for a period of about 5 to 15 minutes whenever the satellite was above the horizon (Fig. 11). After considerable correspondence by India and Netherlands, it was identified that the signals were due to a US Navy satellite, who agreed to turn it off on a request by NSF. However, it still turns on occasionally which has been attributed to defective equipment. Details are given in Part-XI.

2.9.4 PART-XII (Propagation Losses)

In this Report-XII is summarized estimates of propagation losses between the GMRT site and Mumbai and also Pune (Figs. 12). These are based on estimates made by the National Physical Laboratory, New Delhi and also based on our measurements of power flux-density received at the GMRT site for signals from T.V. transmitters and paging transmitters. References are also given to ITU reports. A Report written by T.L. Venkatasubramani in 1987 which calculated Coordination Distances for the 152-154 MHz band is also included.

2.9.5. PART-XIII (Mitigation Techniques).

Although we must identify sources of RFI in the protected bands of GMRT, weak levels of RFI may be unavoidable. Also, for certain astronomical observations, it becomes necessary to observe over a wider band. Hence, several radio astronomy groups have been developing possible mitigation techniques for partially or fully suppressing the harmful effects of RFI to a radio telescope. In the observed band. In PART-XIII are summarized several schemes and also some preliminary work done by O.Frezot during his stay in India under my guidance.

3. FURTHER WORK TO BE DONE

The problem of frequency coordination, identifying sources of unauthorized or spurious RFI signals in the frequency bands allocated for operation of GMRT, stopping/minimizing their transmissions and also development of mitigation techniques is an important job and will last as long as GMRT is operational. The task will become more and more challenging with the rapid development of high speed electronics and also increase of the wireless communication by both terrestial and satellite transmission systems. In the next few Sections is highlighted the work which needs to be done over the next year or two, in order to exploit the potential of GMRT, particularly for the frequency bands of 152-154 MHz and 230-234 MHz. These bands are unique to GMRT and are very important for several important programmes such as Pulsar work, Galactic research, studies of solar radio emission and especially for searching for HI emission/absorption at high redshifts (z = 5 & z = 8). In Section 7, I have listed several recommendations. It is clear that the protection of the GMRT requires a dedicated group effort. Although I have made several recommendation/s, I would like to suggest that a group discussion be held on one or preferably two half days so that priorities can be agreed to and the work schedule monitored thereafter every six months.

4. RFI SURVEYS AT THE GMRT SITE (NARROW BAND RFI)

As described in Reports IV & V, several RFI surveys have been done over the last fifteen years at the GMRT site for detecting narrow band signals from transmitters or faulty equipment radiating in the GMRT bands. Based on the work done so far by various persons of the group, I would like to make the following suggestions for further work.

4.1. As described in Reports IV & V, the sensitivity of RFI surveys done so far is about -150 to -160 dBW/m^2. Even this has also been possible by pointing the feeds of the GMRT, which have a gain of about 8 to 10 dB, towards the horizon. I understand that it is planned by the GMRT engineering group to install four log-periodic antennas with a gain of about 8 to 10 dB, on a 20-m high tower, and to carry out periodic RFI surveys. The measurements and their analysis (frequencies and power levels) in the RFI bands should be automated. On the other hand the harmful level of radio interference to a radio telescope is about -190 to -200 dBW/m^2 for continuum observations over the allotted bandwidth and a time constant of 2000 sec. (ITU-R- RA-769.1 and also Annexure-II of Report Part-IV). Hence it is recommended that we undertake more sensitive searches in various frequency bands using the GMRT correlator. There are three suggestions :-

a) During the data reduction of the GMRT observations, various astronomers are able to identify interference in different channels of the correlator based on BPASS or SPFLG tasks of AIPS or a task for examination of GMRT data before AIPS, written by S. Bhatnagar. It is important that they inform the frequency of the channel, antennas, time-range and approximate power level of the observed RFI signals to an identified concerned Engineer or observer of GMRT, who should keep a data-base of the RFI observed in a standard format.

b) Recently the bandpass of each antenna is plotted approximately every 30 seconds using the self output of the correlator (and recently also for cross-products) and is generally displayed throughout the GMRT observations. It would be very valuable if this data is stored in a file and given to the astronomers who can use it for identifying the time-range and frequency channels whenever RFI is seen. In-fact, it would also be useful if similar data (say every one minute or two) is stored for the correlated outputs for all the frequency channels, say for (a) one of the Central Array antennas, say C2, C5, C6 or C9 versus all the other Central Array antennas, (b) one of the E-array antennas versus all the E-array antennas and (c) & (d) similarly for the West and South Arrays. This data for 27 outputs should be plotted on a Grey Scale Plot with frequency as abscissa and time as vertical axis but with about one inch plot for covering 10 hours data for the vertical axis for each antenna or baseline. A similar Grey Scale Plot made by O-Frezot is shown in Fig. 13 but the software of this plot requires considerable improvement. Since the correlator output with a time constant of about 1 or 2 minutes will provide a fairly high sensitivity (about -180 dBW/m^2), we should be able to identify weak levels of RFI which is also important, when observing in the 150, 235, 325, 610 or 1427 MHz bands. The above recommendation is also made recognizing that there seems to occur occasional local RFI near the East, West and South array antennas in the above bands (Fig.13 (c))We should also identify harmful effects of any local RFI from GMRT electronics, including that from the Central Electronics Building. This should be done urgently.

c) For identifying weaker sources of RFI from far-away directions, we may firstly point the feeds of all the GMRT antennas for several antennas in the same direction and then combine the self output of the correlator for all the frequency channels by scalar averaging and then plotting the measurements on a grey scale plot. Similarly the plots suggested in Para 4.1 (b) will also be valuable. Pulsar group and GMRT Observers have developed suitable software for making such grey scale plots giving frequency and time as coordinates. We may make such plots separately for the Central array and for each of the three arms. This should allow us to identify any local sources of RFI. The above surveys may also be carried out periodically, say every month or so, by pointing the GMRT antenna feeds in different directions, such as N, E, S & W.

5. RADIO DIRECTION FINDING EQUIPMENT

Commercial direction finding equipment for signals in the frequency range of VHF & UHF are generally expensive. Recently, during his visit to NCRA, Sanat Kumar of the Nehru Planetarium at New Delhi pointed to me the availability of low-cost direction finding equipment used by radio amateurs. I have downloaded the description of one of such equipment. Ananthakrishnan and Sankararaman had also done some, internet searches two years ago. We should further pursue the matter. Nevertheless, in addition to our own requirement of such equipment for locating sources of RFI to the GMRT, it would be valuable to many other agencies in India such as Police and Defence if we can develop a low cost direction finding equipment using the expertise of the radio astronomy group of NCRA-TIFR..

5.1 Direction finding equipment using four or six dipoles connected to a receiver and a correlator.

Two years ago, I guided thesis of two B.Tech students viz. S.M. Kulkarni and N.A.Nangare of the Govt. College of Engineering, Pune, for developing a direction finder using four dipoles. Measurement of amplitude and phase of different pairs of dipoles provides us information about the direction of the incoming radio signal (Kulkarni & Nangare 1999). Based on the preliminary work done by the above authors, Swarup and Atre (1999) made a proposal in March 1999 for the fabrication of a direction finding equipment for the VHF range using four dipoles, each connected to amplifiers, narrow band filters, local oscillator and mixer with output of about 1-100 kHz to be applied to a DSP processor card or a correlator (Fig. 14). A PC may also be used for cross-correlation of the outputs of 4 dipoles. Due to a shortage of manpower it has not been possible to develop the proposed Direction Finder so far. I do hope that we would be able to undertake work on such an equipment over the next year or so.

5.2 A simple direction finding equipment using a pair of dipoles and a Spectrum Analyzer

In this section I propose a simple direction finder which uses a pair of crossed-dipoles (vertical and horizontal), each with a reflector rod, with the two crossed dipoles separated by about half wavelength. The signals from the two dipoles are added in-phase and also out-of-phase. The two outputs are followed by amplifiers and filters and connected to a HP Spectrum Analyzer (SpA) which has two simultaneous input channels. The two dipoles with reflector rods are supported on a vertical tube mounted on a jeep (Fig. 15). The tube is rotated such that one of the two channels of the SpA shows maximum and the other minimum. By straddling around the minimum, say by 3 dB, it should be possible to locate the direction of the incoming radio signal to 5 or 10 degrees, particularly for the stronger signals. Thus, it may be possible to drive the jeep right upto the source of RFI signal, whether arising due to spurious signals or due to unauthorized transmissions.

It should be possible to fabricate the above setup within a few months as it requires mostly mechanical fabrication. Detailed drawing for the set-up of Fig. 15 have been are now being released to the NCRA workshop. The amplifiers and filters which were fabricated in connection with the work done by Kulkarni and Nangare and also surveys by Swarup & Shirlakar are already existing with us (at the GMRT site) But we need to make 4 amplifiers and filters for each of the 150 and 235 MHz bands. This setup is described in Fig. 16.

We plan to take the jeep firstly to about 20 or 30 points around the GMRT and make measurements in various directions to identify any local sources of RFI, say from GMRT electronics receiver room and electronics at various antennas as well as various electronic equipment in the Junnar Taluka. (As may be seen from Part-IV of RFI Report, we were able to identify RFI to arise from local regions for a few cases based on measurements which were carried out using the jeep two years ago at Alephata, Kukdi and Junnar). We should then take the jeep to several places upto about 100 km from GMRT, particularly a few places around Pune and Lonavala.

6. DIRECTION FINDING USING GMRT ANTENNAS

6.1 Locating the source of RFI using the GMRT correlator data.

It may be possible to find the direction of the source of RFI by measuring the amplitude and phase of the RFI signal in a given frequency channel for several base lines of GMRT, particularly those of the Central Array (Swarup 2001). If the measured complex amplitudes (after calibration for correcting the phase due to GMRT electronics including optical fibre) are added for N antennas for an assumed position of the RFI transmitter/radiator, the signal to noise ratio will be sq. root (N) times higher than if the position is assumed wrongly. By adding suitable values of phase in the measured correlated outputs, one may be able to get a maximum or null, whence the signal to noise ratio will be enhanced. This is the basic concept. For testing this idea, I had proposed transmission from the Narayangaon Housing Colony of GMRT at, say at 153.0 and later at 153.5 MHz and taking measurements using the GMRT correlator system, without tracking the antennas. Recently Prof. S. Ananthakrishnan had arranged to get such measurements done and A. Sarkar has done preliminary processing the data but has not been able to calibrate the data . If preliminary results are promising, an optimization software (assuming thousands of locations and choosing the location which gives maximum output). will have to be developed for using this technique.

6.2 Locating the direction of RFI signal and possibly its position by installing an 8 element dipole array along one of the 16 rim trusses of the 45-m diameter dishes of the GMRT, particularly for the 153 and 233 MHz bands of GMRT.

Unfortunately, GMRT dishes have an elevation limit of about 15 to 20 degrees above the horizon. Hence we have used primary feeds of GMRT rotated towards horizon for RFI surveys. Since the primary feeds of GMRT antennas (located at a height of about 40m above the ground) have a rather broad beamwidth of about 60 degrees, it has been difficult to locate the source of RFI from the surveys made at the GMRT site. Hence, we may fabricate a dipole array which would provide a narrow beam. We could then place the array on one of the 16 nos. of Rim Trusses which exist at the outer periphery of the GMRT antennas of 45 m diameter which can be readily rotated in Azimuth for finding the direction of RFI. These rim trusses are quite stiff and consist of tubular steel members of 80 and 60 mm diameter (wall thickness 4.5 mm) and the trusses have a size of about 1.2 m x 1.2 m x 1 m. Each truss has a length of about 8.8 m. When the antenna is in the zenith position, one of the three faces of these trusses is vertical so that dipoles would point towards the horizon.

Hence it should be quite practical to mount a light-weight array of 8 broad-band dipoles, covering a frequency range of 150 to 350 MHz, on one of the 16 rim trusses of GMRT (Fig. 17). One may also consider placing an array of 4 or 8 log periodic antennas to cover a wider frequency range. Such an array of dipoles could have crossed-dipoles for receiving vertical and horizontal polarization or we may fabricate two arrays to be put on two different rim trusses of a 45 m dish, preferably on two trusses on diagonally opposite side of the dish. One of the two arrays should be broad-side (parallel dipoles) such that it would receive vertical polarization and the other being a co-linear array which would receive horizontal polarization. Signals from all the dipoles are to be combined using a Christmas tree branching system. However, at the final junction, the two halves of the array are to be added in-phase and out-of-phase. The two outputs are connected to two channels of the Spectrum Analyzer. If the 45-m antenna is rotated in azimuth so that the rim truss is perpendicular to the direction of the incoming RFI signal, one of the outputs will give a maximum and the other will produce a null signal. Fig. 18 illustrates the proposed scheme. At 150 MHz, the 8 m long dipole array will have a 3 dB bandwidth of about 15 deg. Further, as described above, by straddling around the null direction, we may be able to determine the direction of RFI to a few degree accuracy, say 3 degrees or better, which is about 1 part in 20. Thus, we could determine the source of RFI to about a km at a distance of 20 km and then use a mobile set-up for finding the faulty equipment or unauthorized transmission. As a further sophistication, may cross-correlate signals from groups of dipoles for measuring phase difference and thus determining the direction of RFI. If such arrays are put on three GMRT antennas separated by about a kilometer, it may be possible to triangulate the sources of RFI to an accuracy of few hundred meters at a distance of about 50 km at an observing wavelength of about 2 m (150 MHz) and similarly for other locations and frequencies. Better precision may be possible by placing the above arrays on three GMRT antennas separated by several kilometers. However, the accuracy of location of RFI may be limited by multi path propagation effects. To begin with we should plan to construct one dipole array of 8 dipoles, of the same design as the 150 MHz dipole but centered at, say, 230 MHz in order to provide a frequency coverage from about 150 MHz to 330 MHz. Alternatively we may also consider using Vivaldi antennas but that would be time-consuming for the required R & D effort. The dipoles may be separated by about half-wavelength at 180 MHz (~ 0.83 m).

7. SUPPRESSION OF AUTOMOBILE AND POWER LINE INTERFERENCE.

7.1 As described in Reports (Part-VI & VII), a great deal of broad-band pulsed interference is being observed at each of the GMRT antennas from nearby 11 kV lines. Our measurements show that these pulses have a bandwidth of a few MHz. The bandwidth was measured by me by verying the Resolution Bandwidth (RBW) of the Spectrum Analyzer from 100 KHz to 3 MHz and noting the increase in the amplitude of pulses. Similarly, there arises considerable interference from the automobiles, including two wheelers (scooters and motor cycles) four wheelers (cars & vans) and trucks (even from diesel engines, perhaps from battery chargers). Interference from power lines is more serious than automobiles as it arises at almost all the time, though it varies with seasons, due to dust or moisture or water on insulators. RFI may reach more than one antenna from a single insulator, particularly for the Central Array. Faulty insulators, and poor grounding are responsible for creating spark based RFI which takes place when voltage rises towards ± 11 kV. Similarly, poor connections at periodic junctions on the overhead lines and/or 11 kV/440 V transformers on 11 kV power lines supplying power to GMRT antennas or nearby farmers are also likely to be creating considerable interference. The State Electricity Board is being requested to improve these lines. We should also monitor RFI from 11 kV lines and transformers close to the GMRT antennas. However, this task is not easy. In my view it is very important to develop a low cost mobile radio equipment for detecting such interference, as is described in Report-VII. A few years ago I used a sensitive battery operated commercial radio receiver (with an RF amplifier) tuned to about 28 or 30 MHz where there were no radio stations to which was connected externally a digital multi meter across the loudspeaker. I was able to detect RFI from faulty 11 kV potes easily.

There also arises considerable RFI due to corona discharges from 110 & 220 kV lines but most of the antennas except a few are located several km away from these AC-HT lines. There also exist a 400 kV DC line lying between E5 and E6 of the GMRT antennas but the estimated RFI is relatively low. Estimates of RFI from these lines is discussed in Reports-VIII & IX.

7.2 A simple scheme for minimizing the harmful effects of broad-band RFI:-

Although we would continue to improve the 11 kV HT powerlines and decrease the RFI arising from them, as discussed above, it is not quite practical to eliminate RFI caused by HT powerlines as there are large nos. of these powerlines criss-crossing the area around GMRT antennas. Hence, I would like to suggest that we install a diode detector and a switch/clipper in the IF electronics at the Base of each of the GMRT antennas, which will detect sharp pulses of the broad-band RFI interference caused by automobiles or power-lines and suppress them or minimize their harmful effect. It is desirable to do some clipping at the base of each antenna so as to not get laser diode for optical fibre transmission get into a non-linear region during the power-line pulses. Further clipping can be done in the delay-line unit of the correlator for each antenna in the Central Electronics Building. Measurements made in 1995 by Venkatasubramani and Saini (Part-VI) show that the automobile ignition gives rise to a sharp pulses of about 10 or 20 micro seconds (Fig.6). Measurements by myself made in 1998 show a similar characteristics for power line interference (Fig.17(a)). These sharp pulses have a rise time of about 10 or 20 microseconds and a tail of several hundred microsecond, occasionally upto about a few milli-secs. A simple scheme for minimizing the pulse interference is sketched in Fig.19 and is discussed in more detail in Report-VII.

8. RECOMMENDATIONS

8.1 Recommendations

Over the last few years, the engineers and scientific teams of GMRT have been very busy in debugging GMRT and as a result GMRT is now running well. It is now important that urgent steps be taken to identify various sources of RFI in the frequency bands protected by the Government of India for operation of GMRT. The task is not easy it but seems to be much simpler than the very complex electronics built by the GMRT electronics group. The following recommendations are listed below, not necessarily in order of priority. It is suggested that a plan of action be chalked out after a group discussion. The Government of India has provided protection to GMRT such that no transmitters should operate in the 230-234 MHz band upto 200 km, in the 152-154 MHz band upto 400 km (Fig. 20) and in the 322-328.6 MHz, 608-614 MHz and 1400-1427 MHz bands upto 600 km. However, RFI seems to arise from unauthorized transmitters or faulty equipment in the above bands either in locations such as

Pune, Lonawala, Mumbai etc. or in local places such as near East, West or South arms and in some cases GMRT electronics (Fig. 21). A dedicated team effort is required to identify these sources of RFI urgently as well as we need to undertake continuous monitoring over years to come.

8.1.1. Audio & Digital Monitoring

It seems likely that some of the RFI signals are voice or data signals, e.g. the RFI around 152.10 ± 0.05 MHz; 152.78 ± 0.02 and 153.58 ± 0.02 MHz. It is recommended that in addition to making measurements on a Spectrum Analyzer, we should also carryout audio and digital monitoring. It is suggested that the above radio signals be received by the AM/FM/(FSK ?) receiver which has been imported by us and the signals be recorded on a tape recorder or on a suitable digital data recording equipment. We should purchase another receiver (not as sophisticated as the above imported receiver) and put it in the Control Room so that the Observers or Engineers or Scientists making astronomical observations with GMRT can check whether signals have voice transmission. If the RFI signal is due to a faulty equipment such as an oscillating Booster amplifier connected to T.V. antenna, etc, the signal would have a very narrow bandwidth (say < 1 kpc) and may give rise to a steady hiss in the AM/FM receiver.

8.1.2. A simple Direction Finding or Monitoring Mobile Equipment in a Jeep

It is important to develop a simple direction finding equipment within a few months as suggested in Section 5. In fact, even the mobile set-up which I got developed in May 1998 for measurements at several locations around GMRT with the help of Shiralkar, Atre and Joardar should be able to locate sources of RFI in the GMRT bands of 152-154 MHz near Pune and Lonavala, provided we concentrate for two or three weeks. Once a few sources are identified, we should request the Monitoring Cell of WPC to bring their sophisticated direction finding equipment to Pune and GMRT site and locate sources of RFI.

8.1.3 JCEC :

The band 153-154 MHz and 230-234 MHz has been coordinated for operation of GMRT with JCEC. It is important to contact them through WPC and seek their cooperation in ensuring that no transmissions take place by the concerned agencies within the agreed coordination distance.

8.1.4. GMRT Electronics

It is known that GMRT electronics also gives rise to RFI. However, I am clear that most of the RFI in the 152-154 MHz arises from either unauthorized transmissions or defective equipment. As discussed by me in Report V-B, most of the RFI observed in bands 152-154 MHz and 230-234 MHz is unlikely to arise from harmonics of transmitters at Pune and elsewhere. When we had contacted an ex-employee Engineer of the Monitoring Cell of WPC, he made some measurements at the GMRT site and told us that we should first eliminate RFI from GMRT electronics. A direction finding equipment as discussed in 8.1.2 should allow us to identify any defective oscillators at various GMRT antennas.

8.1.5. Copper Fingers

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In order to minimize radiation from GMRT electronics, we should urgently install the Copper Fingers which have been imported 5 or 6 years ago on all the doors at the earliest. This should be quite straight-forward and should be carried out at the earliest. Also, doors of all Racks which have been designed for RFI suppression should be kept closed; magnetic latches may be installed in these doors.

8.1.6 Grounding of Cables entering GI rooms

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RF and data cables from or to the antenna electronics near the focus of the GMRT antennas, enter the GI rooms at each antenna but their shields have not been grounded due to the lack of a decision about the brass-plates which were proposed several years ago. Also, Praveen Kumar had proposed using a special connector incorporated with RFI suppression devices, for the cable carrying digital signals to the electronics near the focal point. A design should be finalized at an early date and job carried out on at least one or two antennas every week. The copper pipes connecting compressor of air-conditioners placed outside to the fan-units located inside also need to be grounded. A simple and practical scheme needs to be evolved.

8.1.7 RFI Monitoring Tower

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I understand that it is planned to develop a RFI monitoring set up using 4 log periodic antennas pointed in 4 different direction mounted on a 15-m or 20-m high tower. Although it would be useful for periodic mounting of the entire spectrum, the development of a Direction Finding Equipment seems to me to have a higher priority. Over the last 5 years we have spent hundreds of man-days in RFI monitoring but have not managed to identify any source of RFI from unauthorized transmitters/radiators except several cases of RFI from GMRT electronics. It is quite likely that transmissions (intentional or unintentional or by ignorance) are being made in the 152-154 MHz and 230-234 MHz band of GMRT by various agencies. Once we identify a few of these transmitters, it may be relatively easy to stop others making transmissions in the above bands. We may also consider developing the low cost direction finding equipment as described in Section 5.1 and installing on 4 towers, one at the above Monitoring tower and

3 others near one of the antennas of each of the 3 Y-array arms. The increasing level of RFI is alarming, e.g., I have been told by a Radio Amateur in Delhi that one can buy in Delhi market illegally manufactured and imported "long range cordless phones" which look similar to cellular handheld devices, but operate in the frequency bands of 130 to 170 MHz ! We need to investigate such aspects (are they also called "soft radios" and see to it that they are not used in the Pune District.

8.1.8. A dipole Array to be mounted on the Rim Trusses

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The suggestion for developing a dipole-array for detecting the direction of RFI, as discussed in Section 6.2 needs to be discussed and should be carried out over the next year or so.

8.1.9 RFI monitoring using the correlator output

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____ ____We should seriously consider making RFI measurements using both self and correlated outputs of GMRT. Since a spectrum analyzer measures RFI in a given resolution bandwidth of 10 or 30 kHz for only (1/400) of the sweep time for each scan, its sensitivity is Ö 400 or at least Ö 20 times smaller than that of the self of the GMRT correlator. Further, outputs of several antennas pointed in the same direction can be combined if the correlator data is used for monitoring. GMRT has the advantage that the primary feeds can be pointed towards the horizon. Finally it may be noted that the cross or correlated products of the correlator is likely to give much higher sensitivity.

8.1.10 Power-line RFI

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The GMRT operational Group has proposed a number of steps to improve the 11-kV power-lines supplying power to GMRT. I strongly recommend that we should purchase a hand-held mobile radio with an RF stage and tunable upto 30 MHz or so and then connect a digital meter at its output for detecting poor contacts and joints and defective insulators. Such radios are available from Kenwood, Sony, Sangean (ATS-803A; ATS-903A) etc. Further, we should also install in the IF output of each antenna at its base a circuit for clipping spark-induced RFI as discussed in Reports, Part-VI and Part-VII.

8.1.11 RFI Mitigation

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Lot of work is being done by radio astronomers in USA, Netherlands and Australia concerning Mitigation/Suppression of RFI. Although the GMRT group is heavily man-power constrained, suitable action needs to be taken to develop suitable mitigation techniques for GMRT, over the next 2 or 3 years, particularly in view of the rapidly increasing telecommunication activity even in India.

9. CONCLUSION

Considering the high sensitivity of GMRT and its great potential for important contributions to Radio Astronomy, it is very important to ensure adequate protection in the bands allocated by the Govt. of India for operation of GMRT. We are extremely fortunate that WPC and other agencies have given us strong support and have coordinated use of several bands for GMRT. Most of the recommendations made in this report are quite practical. Although RFI protection to GMRT is a continuous exercise, a dedicated effort is required to be carried out by a FULL time engineer and a technical assistant/lab. assistant under the guidance of senior engineers over the next two years in order to identify and provide protection to the 152-154 MHz and 230-234 MHz frequency bands. We may also give a project to IIT, Powai to help us develop RFI mitigation techniques. It is to be appreciated that it has become very difficult to make quality observations in the 152-154 MHz band. Also it becomes necessary to do lot of editing of RFI for the 230-234 MHz observations. RFI also seems to arise from local sources near 315-317 MHz 323 MHz and 335-337 MHz or so. RFI monitoring and suppression will considerably improve the quality of the data and also minimize the time of our small group of astronomers in data editing.

10. ACKNOWLEDGMENT

Over the last 15 years, many engineers and scientists of the GMRT group have made many very valuable contributions for providing frequency coordination at ITU and W.P.C. and also for RFI measurements. In particular, S. Ananthakrishnan, T.L. Venkatasubramani and M.R. Sankararaman have coordinated efforts of the various members of the GMRT group in the above task. We are also very grateful to the W.P.C. for allocation of various radio frequency bands for operation of GMRT. It is noteworthy that during the last 40 years all the Wireless Advisers (W.P.C.) and their colleagues have taken keen personal interest for protection of the radio astronomy work in India from harmful radio interference. Their contributions at the ITU for protection of the radio astronomy service has also been of great value.

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TABLE - 1

FREQUENCIES ALLOCATED FOR GMRT BY WPC, MINISTRY OF COMMUNICATIONS, GOVT. OF INDIA *

	Frequency Bands	Allocation Status (ITU)	
1.	37.75 - 38.25 MHz	Secondary	Internationally
2.	152 - 154 MHz	Primary	Several countries including India
3.	230 -234 MHz	Coordination	(Nationally)
4.	322 - 328.6 MHz	Primary	Internationally
5.	608 - 614 MHz	Primary	Several countries including India
6.	1400 - 1427 MHz	Exclusive	Internationally
7.	1610 - 1613.8 MHz	Primary	Internationally
8.	1660 - 1670 MHz	Primary	Internationally

* For further details, please see Part-II and Part-III of this series of reports on RFI.

TABLE-2 FREQUENCY RANGE AND BANDWIDTH OF GMRT RECEIVERS

Sr. No.	GMRT Protected Bands	Redshift for HI Observation	Frequency Range of GMRT Front End	Probable Usable Bandwidth for which RFI level is low
-	MHz		MHz	MHz
1.	37.5 - 38.25	-	40 - 60 *	~ 1 MHz
2.	152-154	8	153 ± 16	2.0 (4)
3.	230-234	5	233 ± 16	4 (8)
4.	322-328.6	3	325 ± 16	32
5.	608 - 614	1.3	611 ± 16	32
6.	1330 -1400	0.1	1000-1400	32
7.	1400 - 1427	~ 0		32
8.	1610 - 1613.8		**	3
9.	1660 -1670		**	10

* To be installed during 1999-2001

** RRI has modified the frequency range of the 21-cm feed to 1150-1700 MHz by optimizing the ortho-mode polarizer. They will try to make it to operate from 1000-1700 MHz. Another possibility is to make a small horn and an amplifier to cover only from 1600-1700 MHz only and use the present 50 MHz port of the Common Box for the 1.6 GHz band and to bring down signal of the 50 MHz ± 10 MHz from the focus to the ground through separate cables.

TABLE - 3

Sensitivities and harmful interference levels for radio astronomy continuum observations with 2000s integration time

(extracted from Table 1. Rec. 769 page 22 of ITU-R Recommendations, 1994 RA Series Volume)

Centre Frequency (1) fc (MHz)	Assumed Bandwidth Δf MHz	Antenna & Receiver Noise temperature T_R (K)	Harmful Interference Levels	
			Power flux-density $\Delta P_H = S_H \Delta f$ (dB(W/m^2))	Spectral Power flux-density ΔS_H (dB(W/m^2 Hz))
151.5	2.95	300	-194	-259
325.3	6.6	140	- 189	-258
611	6.0	115	- 185	-253
1413.5	27	30	- 180	-255
1665	10	30	- 181	-251

Calculated values for other bands (headings see above)

38	0.5	7000	-195	- 252
50	1	5000	- 193	- 253
233	4	200	- 190	- 256

FIG. 1 : **RFI IN THE PROTECTED BAND OF 152-154 MHz FOR OPERATION OF GMRT**

FIG.1 (a) : [Also Fig. 1(b) detailed characteristics of RFI (FM or FSK modulation) observed in the frequency range of about 152.000 to 152.200 MHz. It seems that there may be present 3 different transmitters centered at 152.06, 152.10 and 152.116 MHz (see also Table-4).

FIG. 1 (b) : Same caption as for Fig. 1(a) for CO-S and C5-W.

FIG. 1 (c) : shows results of RFI observations made when 4 of the GMRT 150 MHz antenna feeds were pointed towards East (E) and another 4 towards South (S) on 28th September 1999 (Fig. 1(b) shows the same for feeds towards W & N). Antennas used are noted in the Figures. It is seen that strong RFI is observed mainly when the feeds are pointed to the South. Further, it may be noted that RFI is observed every 922 kHz apart. For antennas, C5-E, E2-E, W2-S, C11-W, C8-W and W3-N and is likely to arise from the GMRT electronics. In particular see W3-N and C8-W scans.

FIG. 1(d) : RFI measurement in a 4 Mhz band around the protected GMRT band of 152-154 Mhz near Lonavala using a log periodic antenna at a height of about 3-m above ground connected to MAR amplifiers with 60 dB gain and HP 8590 spectrum analyzer.

Fig. 1(e) : Measurements in the Band 151.7-154.2 MHz (a) at the GMRT site using GMRT receiver, (b) at the GMRT site using Pulsar receiver, (c) at Kukdi, (d) Sangamneer, (e) NCRA, Pune, (f) Lonavala and (g) Khandala

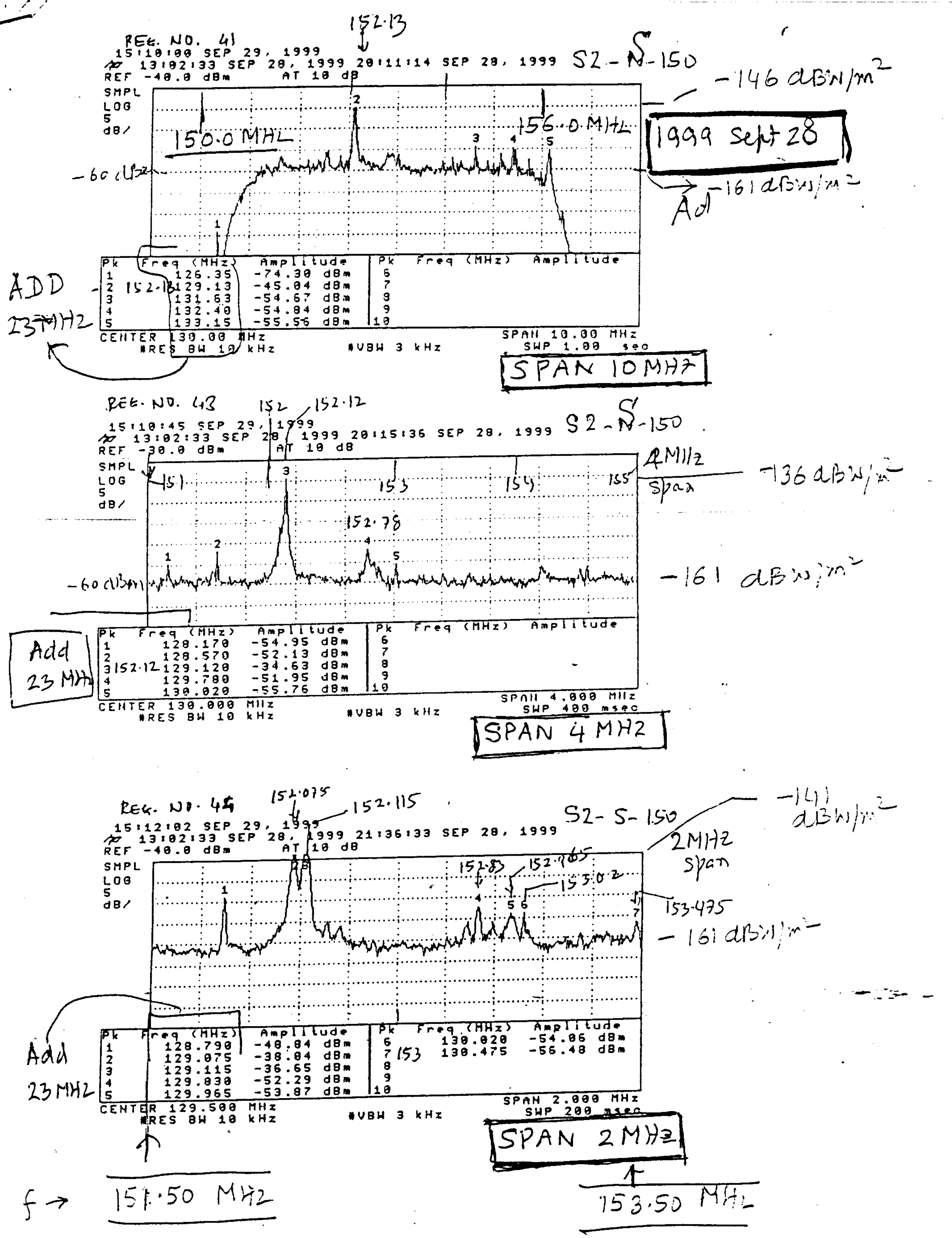

FIG.1 (a) : [Also Fig. 1(b) detailed characteristics of RFI (FM or FSK modulation) observed in the frequency range of about 152.000 to 152.200 MHz. It seems that there may be present 3 different transmitters centered at 152.06, 152.10 and 152.116 MHz (see also Table-4).

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C5-W

CO-S

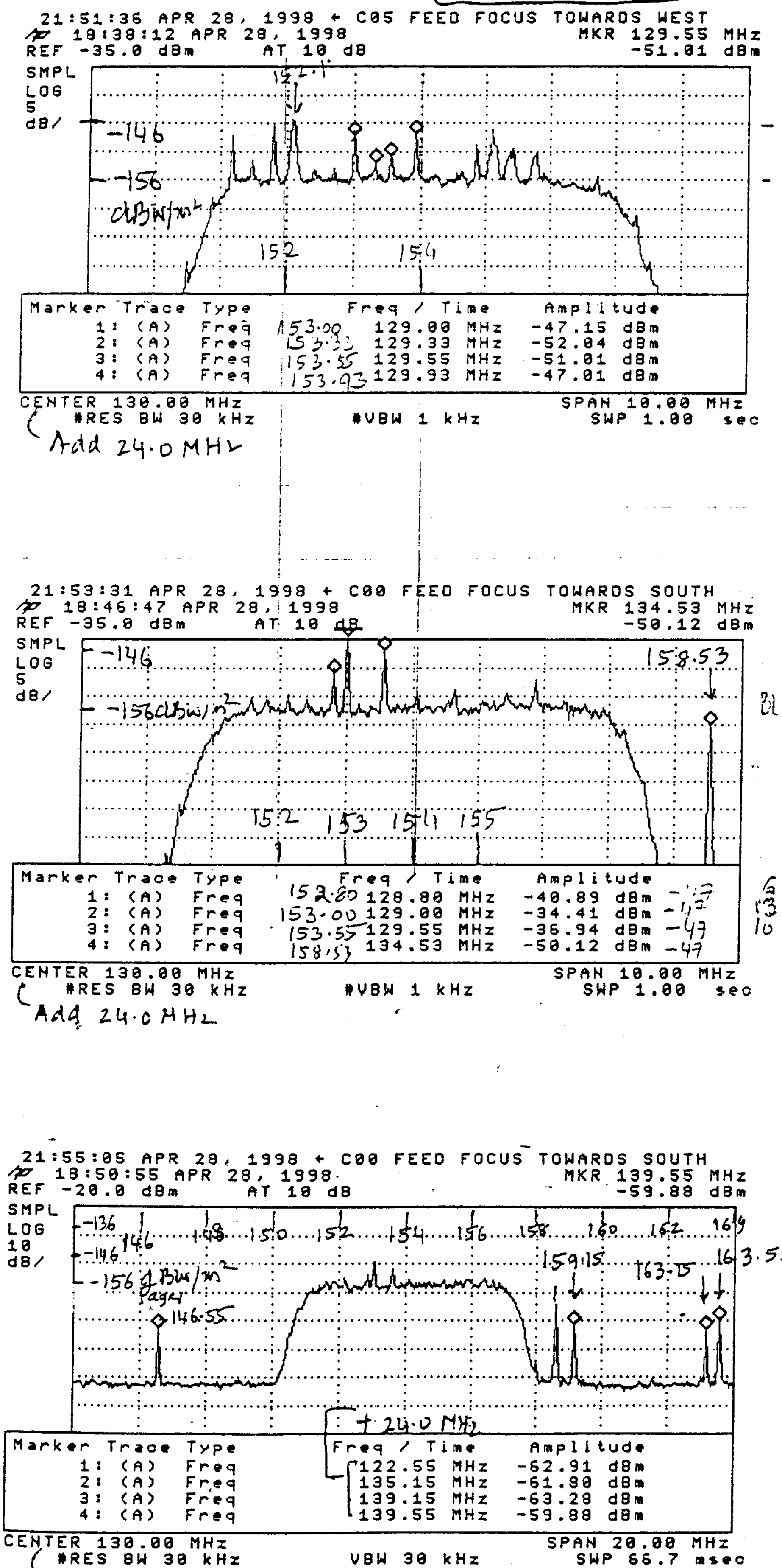


FIG. 1 (b) : Same caption as for Fig. 1(a) for CO-S and C5-W.

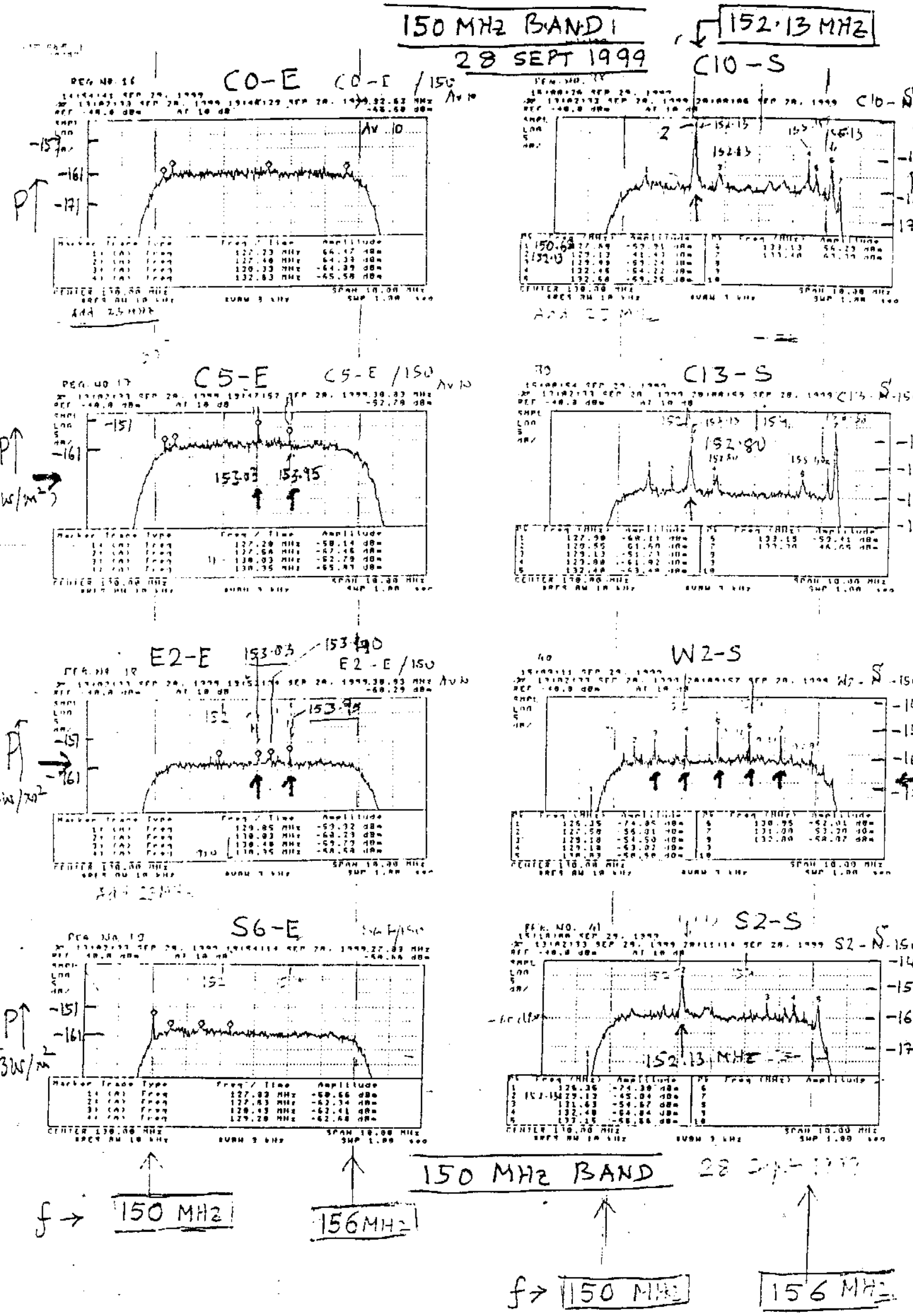


FIG. 1 (c) : shows results of RFI observations made when 4 of the GMRT 150 MHz antenna feeds were pointed towards East (E) and another 4 towards South (S) on 28th September 1999 (Fig. 1(b) shows the same for feeds towards W & N). Antennas used are noted in the Figures. It is seen that strong RFI is observed mainly when the feeds are pointed to the South. Further, it may be noted that RFI is observed every 922 kHz apart. For antennas, C5-E, E2-E, W2-S, C11-W, C8-W and W3-N and is likely to arise from the GMRT electronics. In particular see W3-N and C8-W scans.

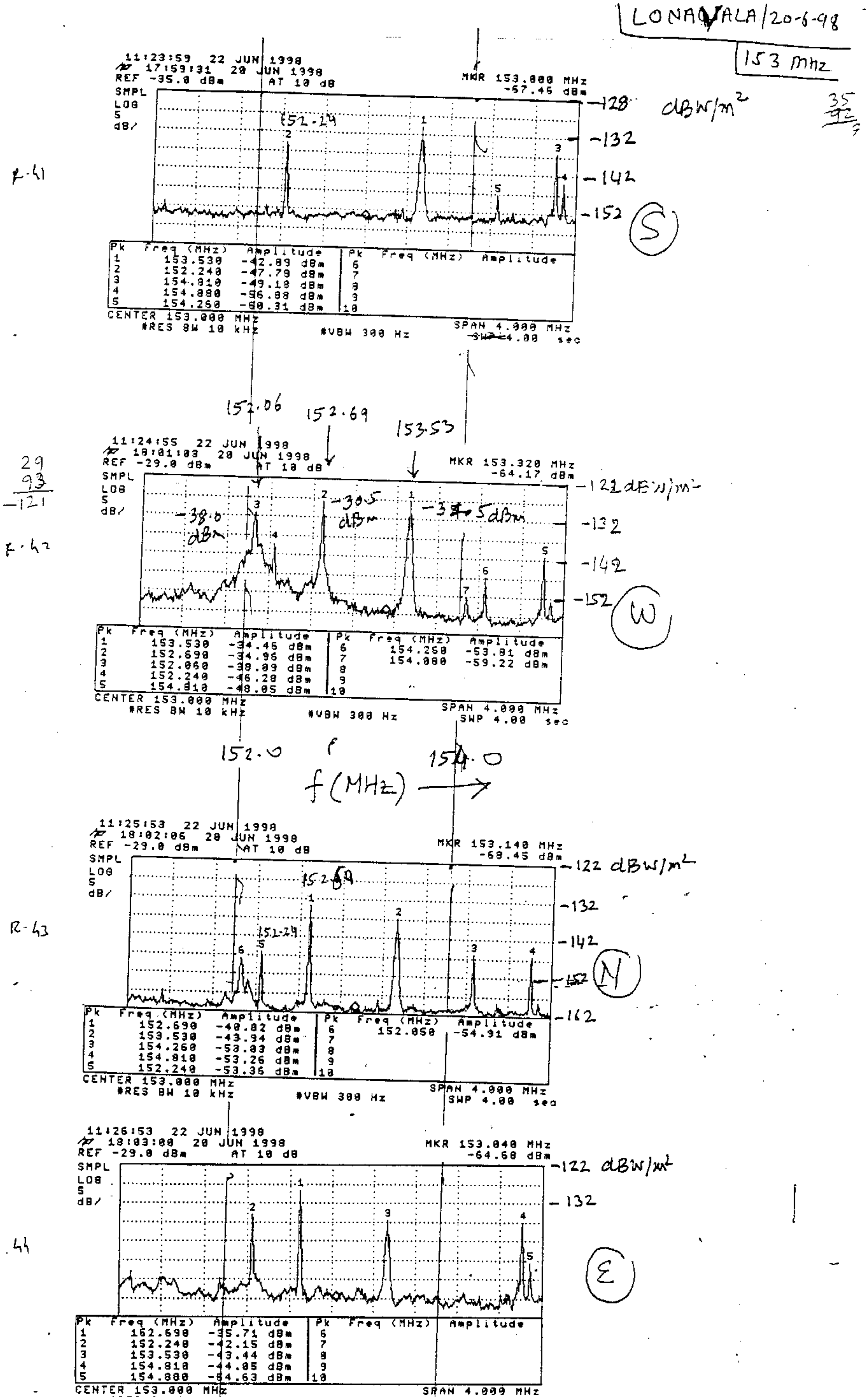


FIG 1(d) : RFI measurement in a 4 Mhz band around the protected GMRT band of 152-154 Mhz near Lonavala using a log periodic antenna at a height of about 6 m ...

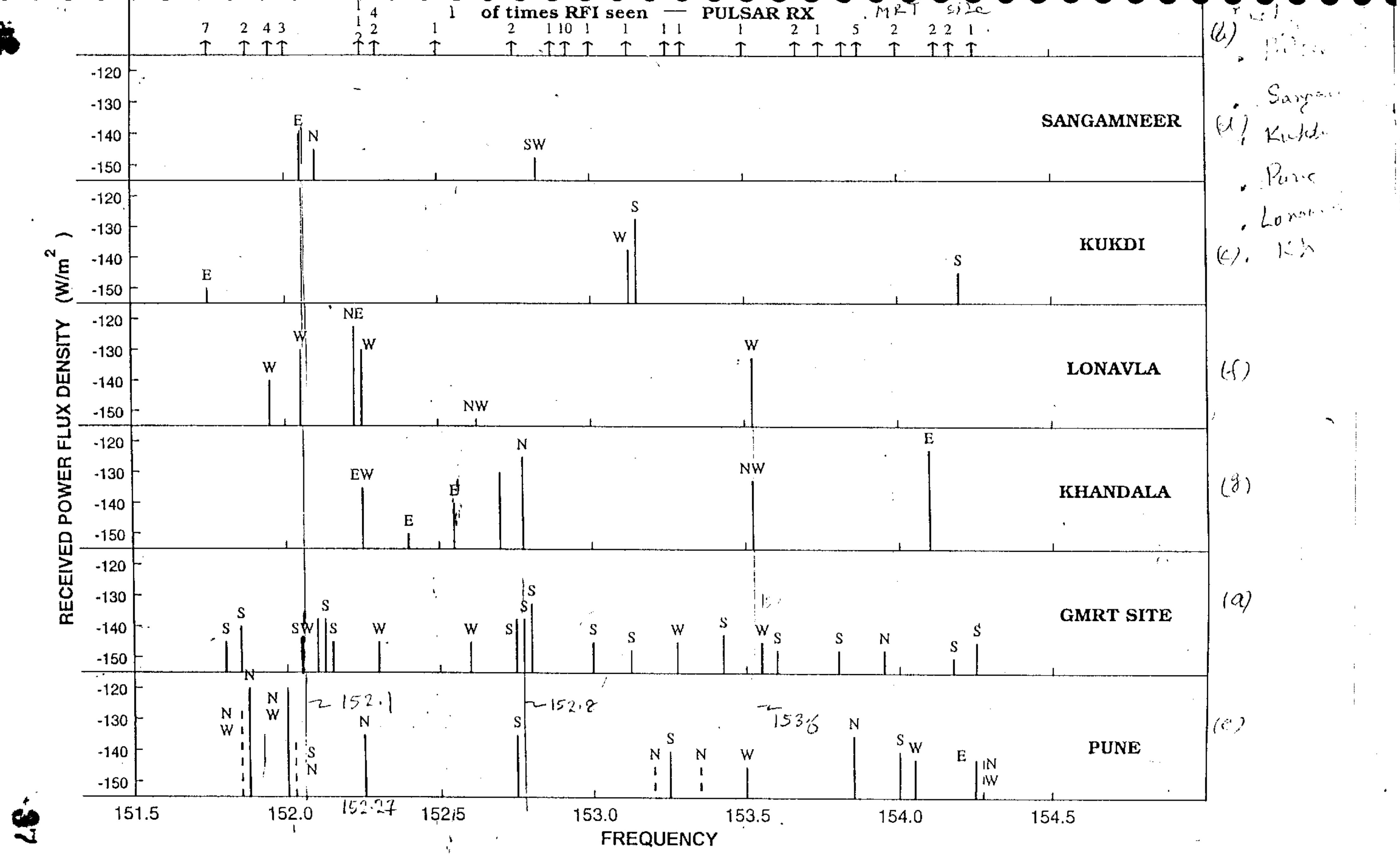


Fig. 1(e): Measurements in the Band 151.7-154.2 MHz (a) at the GMRT site using GMRT receiver, (b) at the GMRT site using Pulsar receiver, (c) at Kukdi, (d) Sangamneer, (e) NCRA, Pune, (f) Lonavala and (g) Khandala

FIG. 2 : **RFI IN THE CORDINATED BAND OF 230-234 MHz FOR OPERATION OF GMRT**

FIG. 2(a) : Shows Spectrum Analyzer scans for the RFI Survey made on 29th May 1998 in the band 235 MHz ± 8 MHz with the W3 235 MHz antenna feed pointed towards North (labelled as W3-N). Several strong narrow-band RFI signals were observed.

FIG. 2(b) RFI measurement in the 4 Mhz protected band of 230-234 MHz near Lonavala using 230-234 MHz using a log periodic antenna at a height of about 3-m above ground, connected to MAR amplifiers with about 60 dB gain and HP 8590 spectrum analyzer.

FIG. 2(c) RFI measurements at the base of E3 antenna with 235 MHz Feed to horizon on West, South and East directions.

FIG. 2(d) Same as Fig. 2(c) with 235 MHz Feed to West.

FIG. 2(e) : RFI measurements in the GMRT Band of 230-234 MHz at (a) the GMRT site, (b) Ale-Phata, (c) Junnar, (d) Lonavala and (f) Khandala.

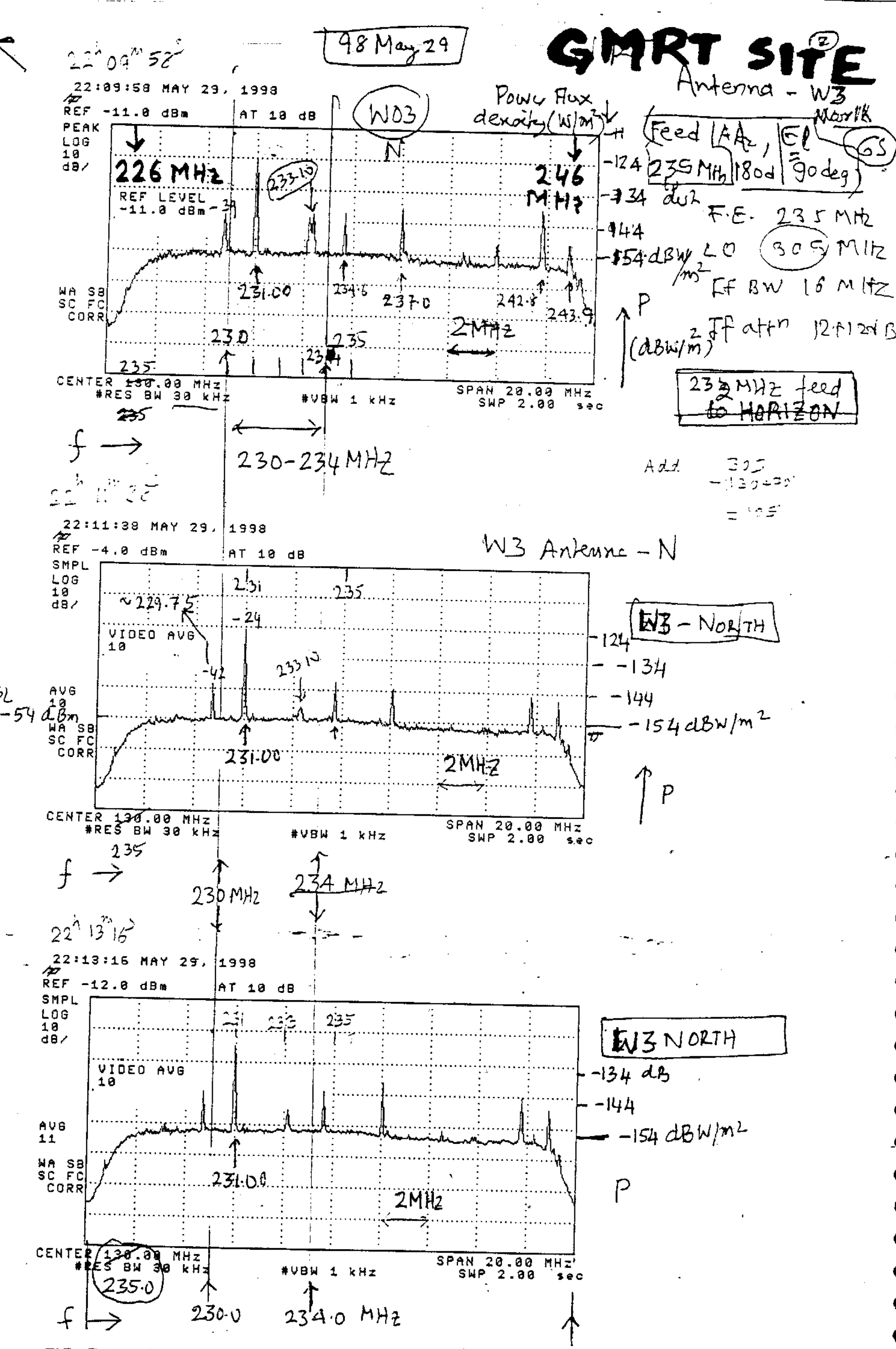


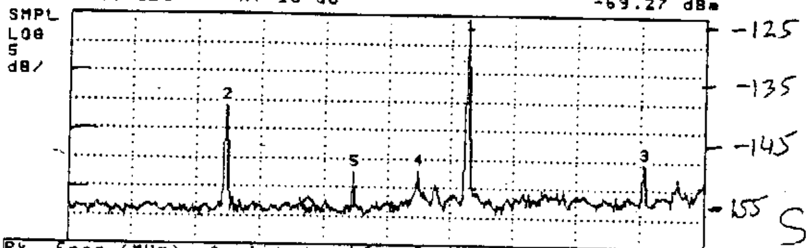
FIG. 2(a) : Shows Spectrum Analyzer scans for the RFI Survey made on 29th May 1998 in the band 235 MHz ± 8 MHz with the W3 235 MHz antenna feed pointed towards North (labelled as W3-N). Several strong narrow-band RFI

20-6-98/ LONAWALA

232 MHz

R-6

11:08:54 22 JUN 1998
15:41:43 20 JUN 1998 17:38
REF -35.0 dBm AT 10 dB
MKR 231.500 MHz
-69.27 dBm

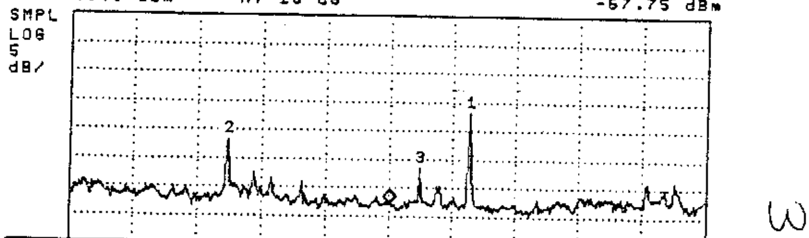


Pk	Freq (MHz)	Amplitude	Pk	Freq (MHz)	Amplitude
1	232.510	-37.65 dBm	6		
2	230.980	-50.91 dBm	7		
3	233.620	-60.69 dBm	8		
4	232.190	-62.08 dBm	9		
5	231.780	-62.33 dBm	10		

CENTER 232.000 MHz SPAN 4.000 MHz
#RES BW 10 kHz #VBW 300 Hz SWP 4.00 sec

R-7

11:09:52 22 JUN 1998
17:40:09 20 JUN 1999
REF -35.0 dBm AT 10 dB
MKR 232.000 MHz
-67.75 dBm

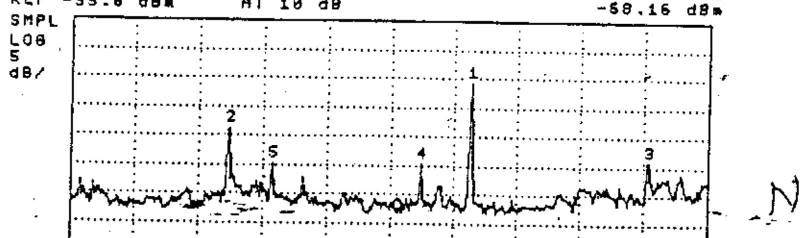


Pk	Freq (MHz)	Amplitude	Pk	Freq (MHz)	Amplitude
1	232.510	-51.74 dBm	6		
2	230.990	-56.85 dBm	7		
3	232.190	-61.47 dBm	8		
4			9		
5			10		

CENTER 232.000 MHz SPAN 4.000 MHz
#RES BW 10 kHz #VBW 300 Hz SWP 4.00 sec

R-8

11:10:30 22 JUN 1998
17:41:09 20 JUN 1998
REF -35.0 dBm AT 10 dB
MKR 232.040 MHz
-68.16 dBm



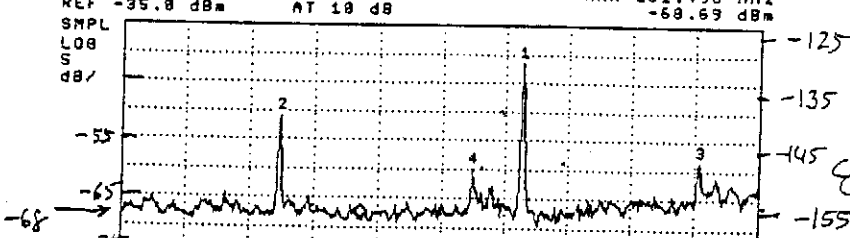
Pk	Freq (MHz)	Amplitude	Pk	Freq (MHz)	Amplitude
1	232.510	-45.78 dBm	6		
2	230.990	-53.85 dBm	7		
3	233.630	-59.21 dBm	8		
4	232.190	-59.80 dBm	9		
5	231.260	-59.89 dBm	10		

CENTER 232.000 MHz SPAN 4.000 MHz
#RES BW 10 kHz #VBW 300 Hz SWP 4.00 sec

* 230.99 strong ~~weak~~ ~~Med~~
232.13 ~~Med~~ weak
* 232.51 v. strong
233.63 weak

R-9

11:12:24 22 JUN 1998
17:42:47 20 JUN 1998
REF -35.0 dBm AT 10 dB
MKR 231.490 MHz
-68.69 dBm



Pk	Freq (MHz)	Amplitude	Pk	Freq (MHz)	Amplitude
1	232.510	-41.53 dBm	6		
2	230.990	-51.09 dBm	7		
3	233.630	-58.62 dBm	8		
4	232.190	-60.24 dBm	9		
5			10		

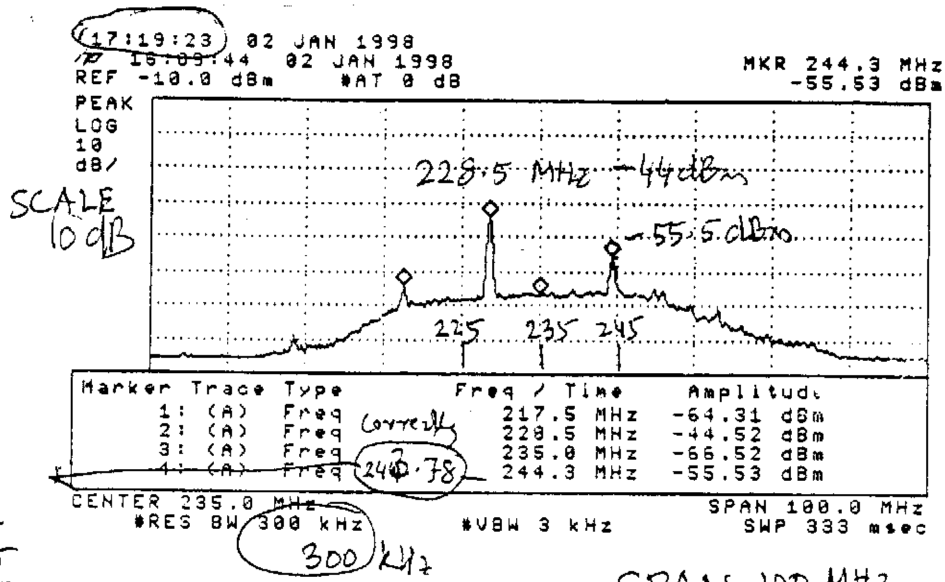
CENTER 232.000 MHz SPAN 4.000 MHz
#RES BW 10 kHz #VBW 300 Hz SWP 4.00 sec

- 68
- 87
-155

2(b) RFI measurement in the 4 Mhz protected band of 230-234 MHz near Lonavala using 230-234 MHz ~~near Lonavala~~ using a log periodic antenna at

235 feed towards West.

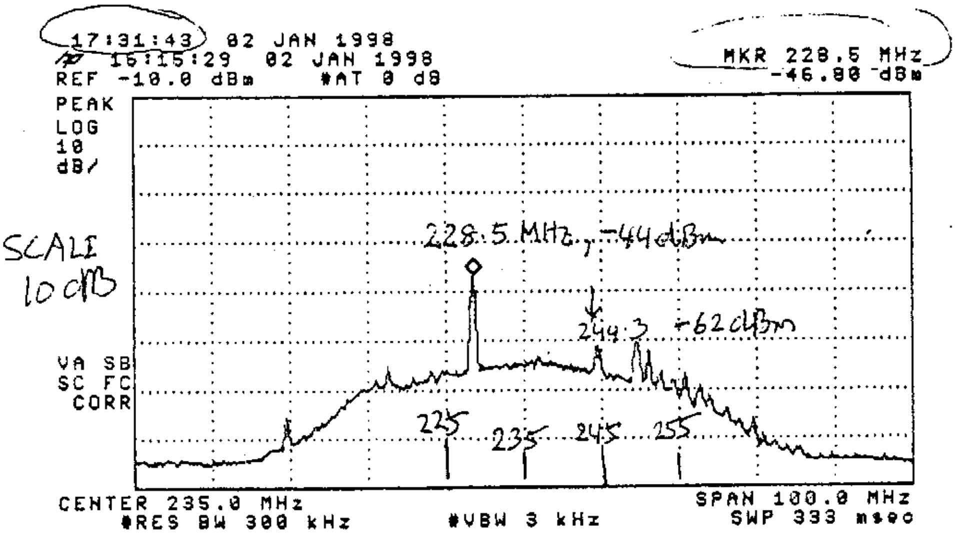
2nd JAN 98
E3 RF OUT (BASE)
Feed W, S, E
OBS (MS)



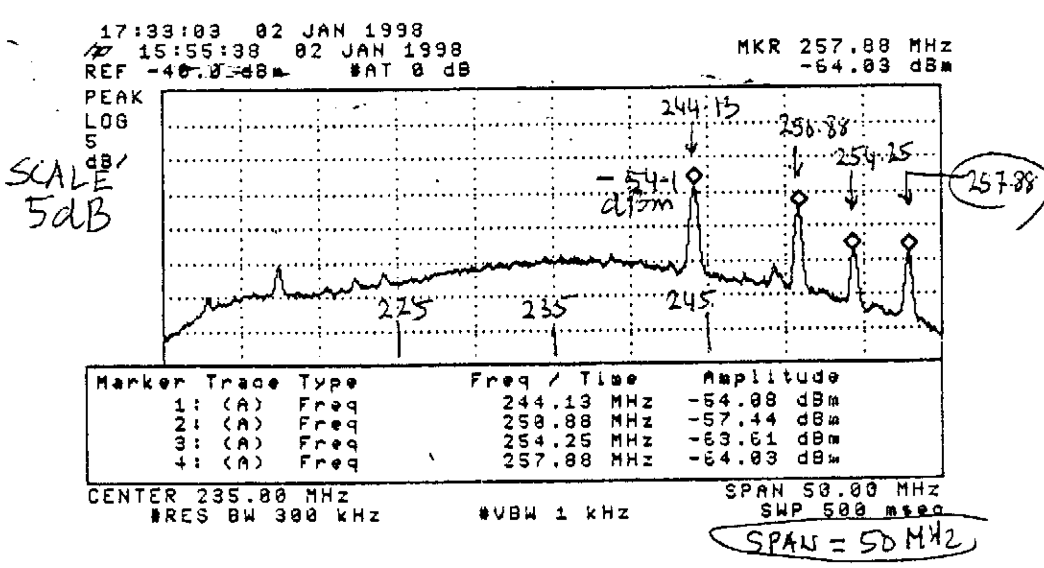
RFI's in 235 MHz Band

WEST

SPAN 100 MHz



Now, 235 feed to South (Az ~0°)



235 feed to East

Page 4.

FIG. 2(c) RFI measurements at the base of E3 antenna with 235 MHz Feed to horizon on West, South and East directions.

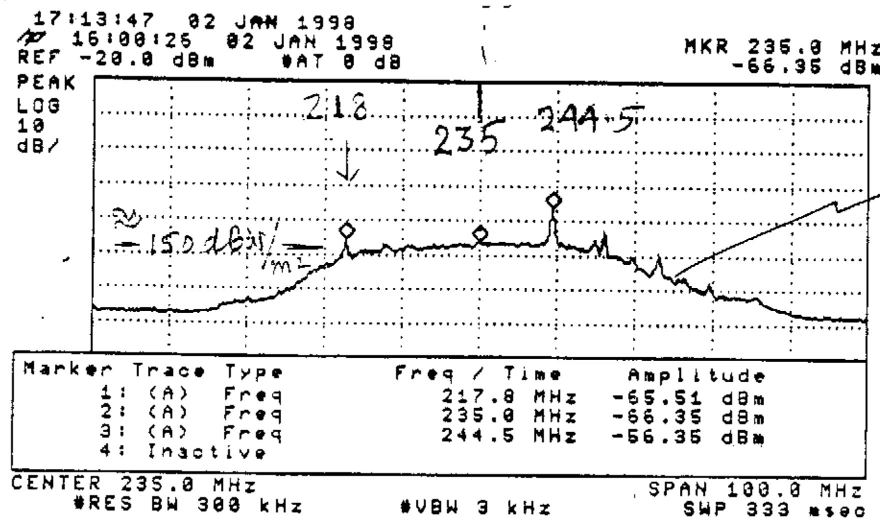
Ref: G Swarup

02 Jan 98

E3 BASE

235 MHz RF o/p

Meas with HP8590

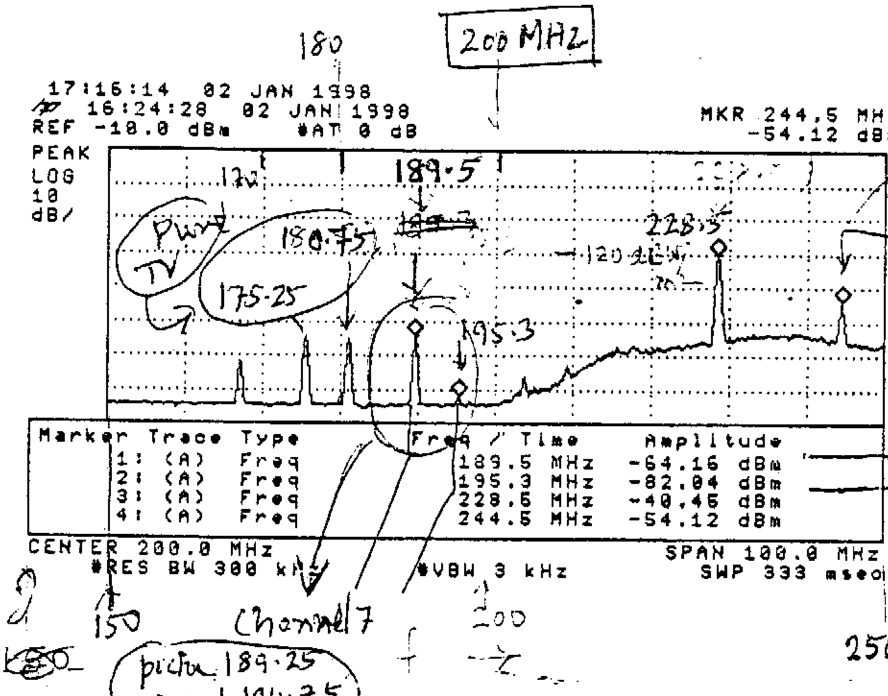


PASSBAND OF FRONT END (Dipole + Amp + filter)

235 Feed facing ~ West (Junnar)

Az: ~ 95°
El: 90°

E3 – W (Junnar TV is absent) was to be shifted to Ch. 10 210.25/215.75 MHz



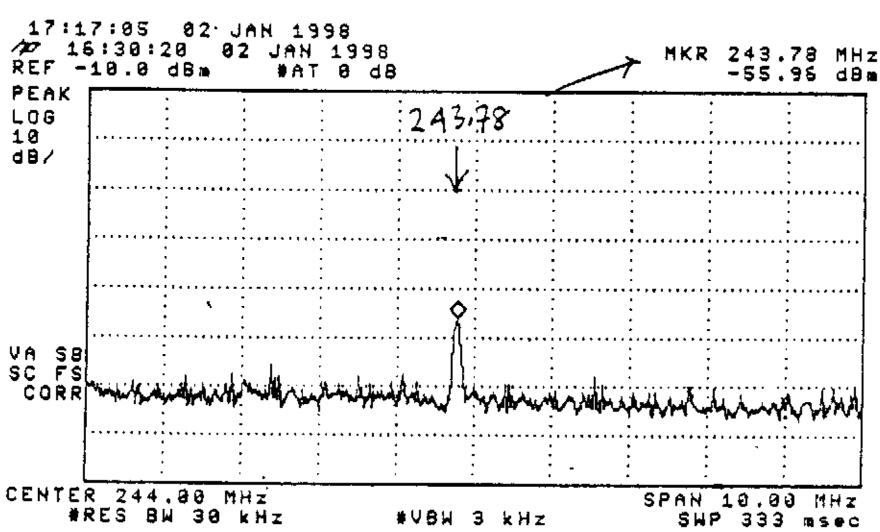
measured E3-W 244.5 MHz with 100 MHz span

Actual 243.78 MHz (see chart below)

WEST

~ -150 dBW/m²

Junnar TV ?



E3-W

This line has varying power levels

RBW = 30 kHz

Page 1

FIG. 2(d) Same as Fig. 2(c) with 235 MHz Feed to West.

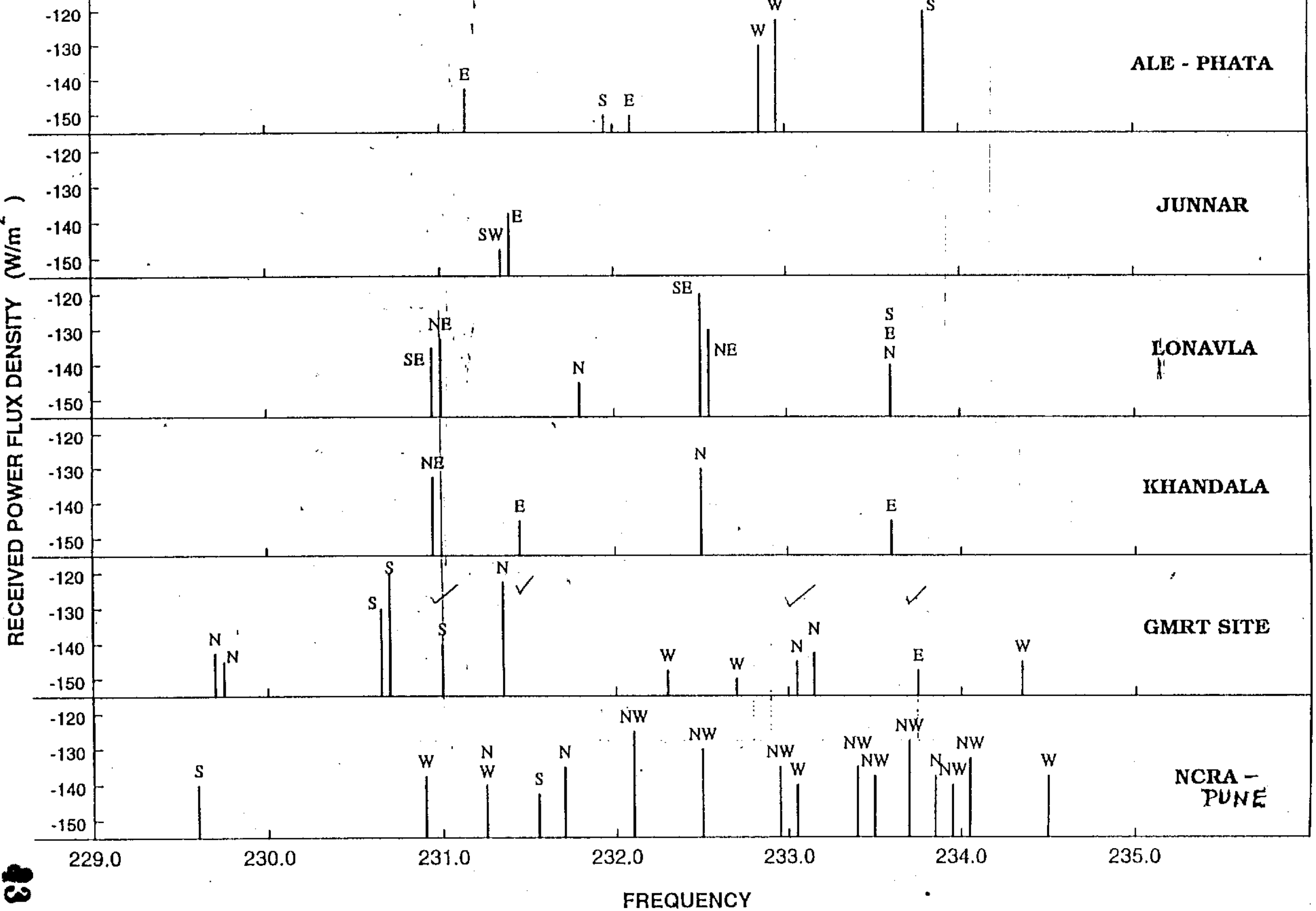
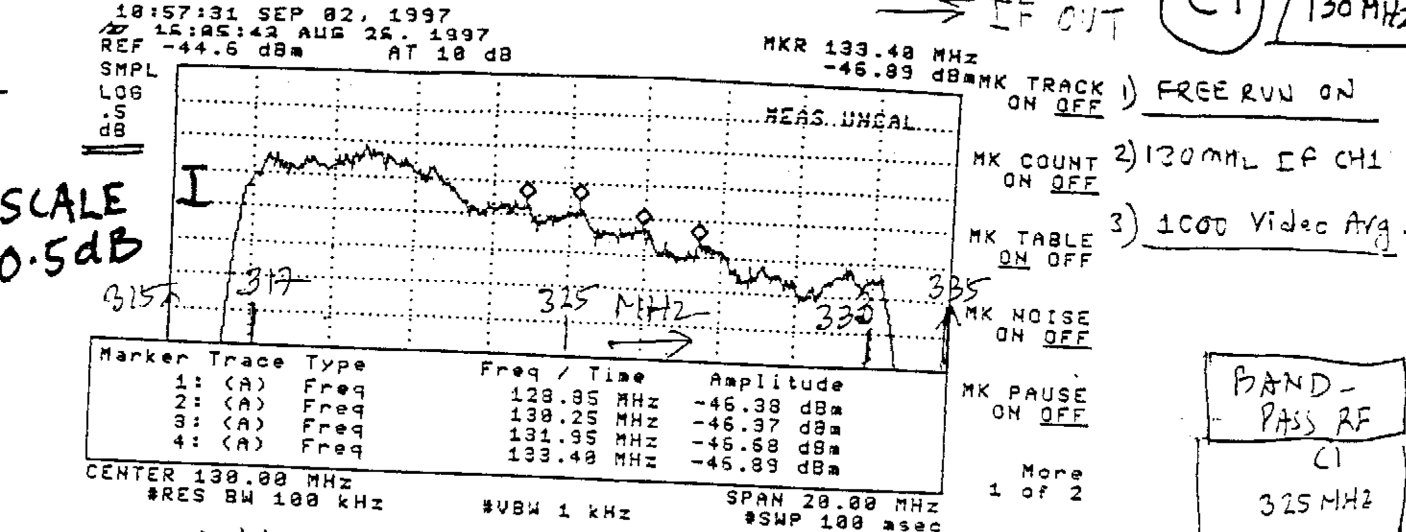


Fig. 2(e): RFI measurements in the GMRT Band of 230-234 Mhz at (a) the GMRT site, (b) Ale-Phata, (c) Junnar, (d) Lonavala and (f) Khandala

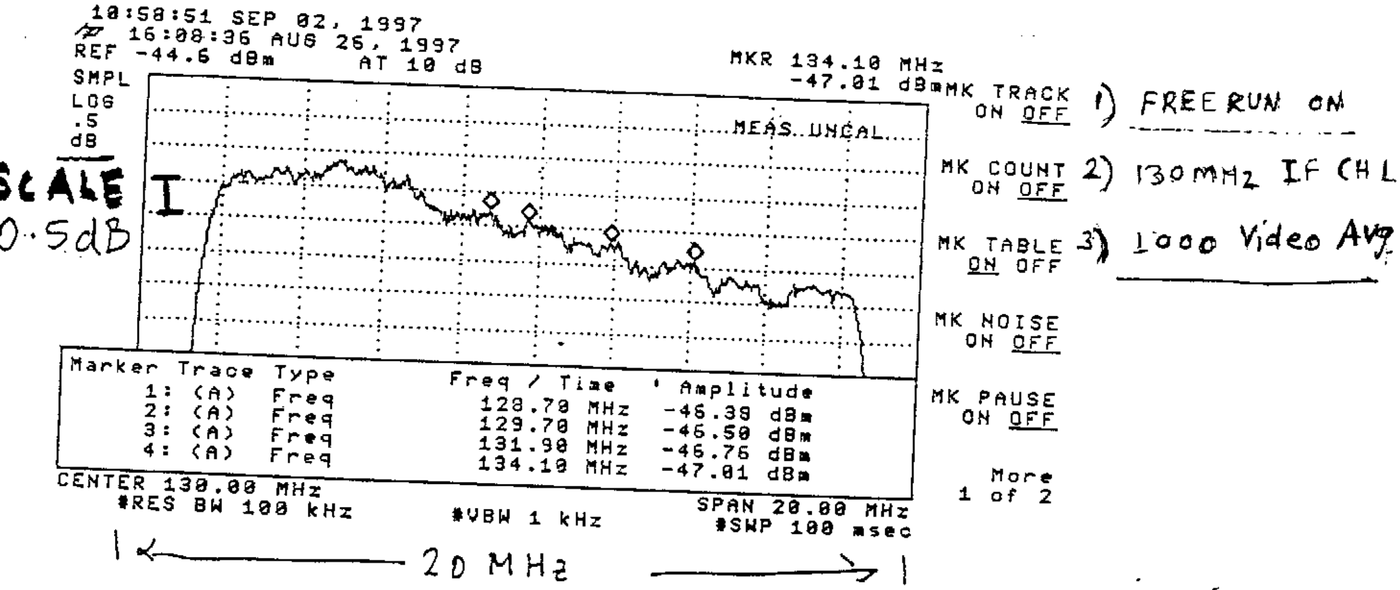
FIG. 3 : Scans across the band 315-335 MHz for C1 antenna of GMRT at the output of the optical fibre in the receiver room for 130 MHz IF channel. No RFI is observed above 0.2 dB of (5%) of the receiver noise (1.05 $kT\Delta f$ = 1.05 x 1.38 x 10^{-23} x 120 x 10^{5} Hz = -157.6 dB.

C1 325 RF ABR → IF OUT C1 130 MHz



Add 105 MHz

Repeated



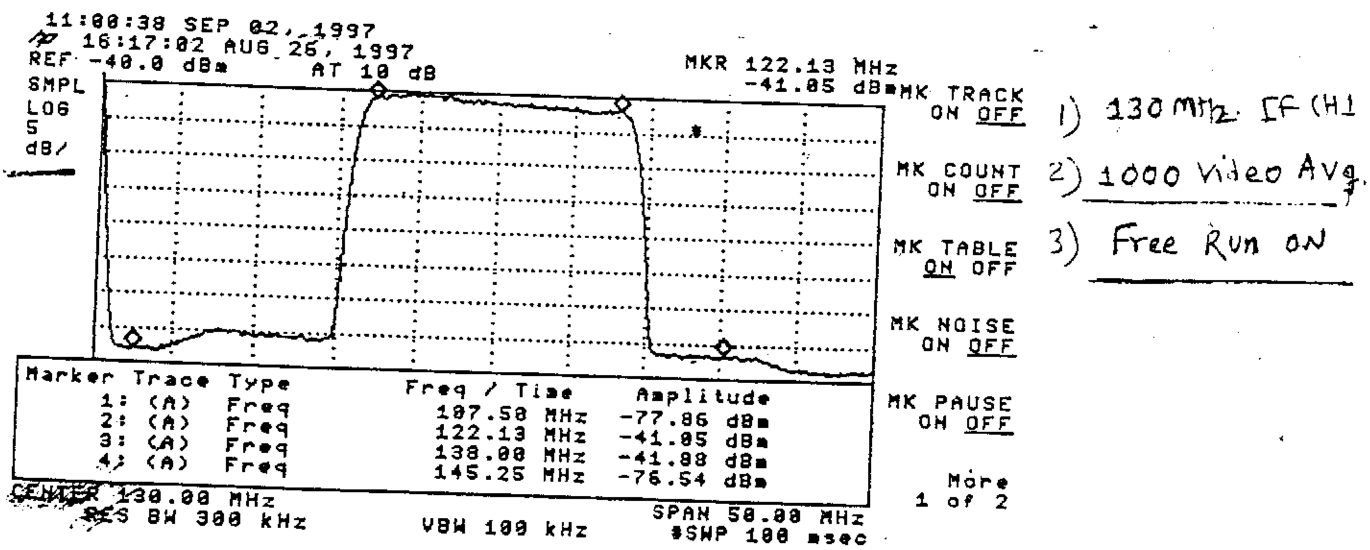


FIG. 3 : Scans across the band 315-335 MHz for C1 antenna of GMRT at the output of the optical fibre in the receiver room for 130 MHz IF channel. No RFI is observed above 0.2 dB of (5%) of the receiver noise (1.05 kTΔf = 1.05 x 1.38 x 10^{-23} x 120 x 10^{5} Hz = -157.6 dB).

FIG. 4 : **SUMMARY OF RFI SURVEYS MADE BY VENKATASUBRAMANI FOR SEVERAL RADIO ASTRONOMY BANDS PROTECTED FOR GMRT FROM 152 MHz to 1427 MHz.**

FIG : 4(a) : Summary of RFI surveys made by T.L. Venkatasubramani in early 1997 by pointing primary antenna feeds of GMRT towards the horizon. Azimuth of the W3 antenna was rotated from + 180° to 180° in steps of 45° with dwell time of 15 minutes. RF outputs at the base of the antenna were connected to a Spectrum Analyzer and recordings made of the maximum and minimum received power over a period of about 8 hours. For the resolution and video bandwidths of the spectrum analyzer used, the difference in maximum & minimum values is expected to be about 7 dB (± 2.5 standard deviation). It is seen that level of RFI was low in the GMRT protected bands except for the 152 MHz band.

4(b) : Same as Fig. 4(a) but for measurements made in late evenings and night time.

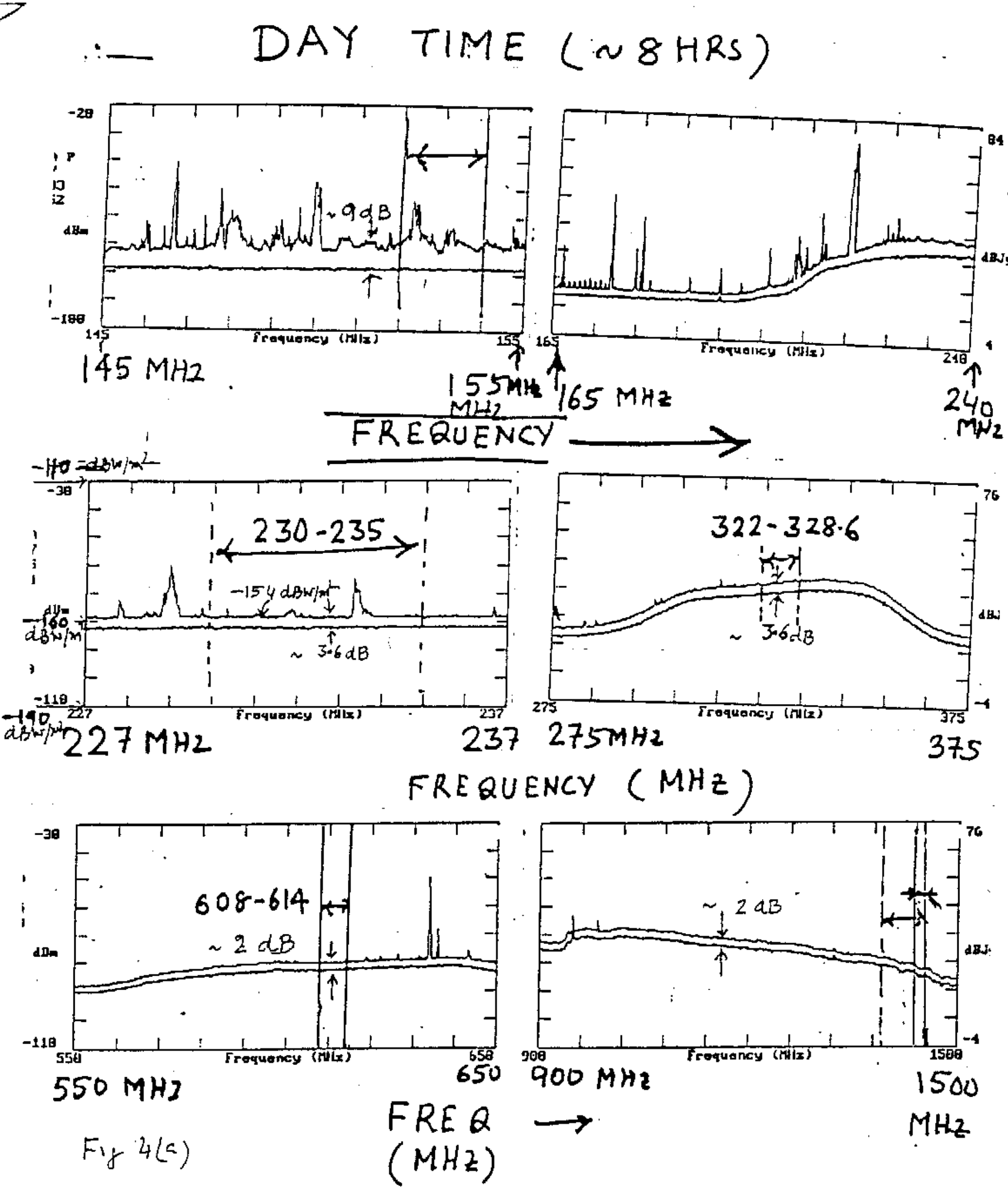


Fig. 4(a) DAY TIME
RFI AT THE GMRT SITE

RFI IS LIKELY TO INCREASE A GREAT DEAL OVER THE NEXT DECADE

: 4(a) : Summary of RFI surveys made by T.L. Venkatasubramani in early 1997 by pointing primary antenna feeds of GMRT towards the horizon. Azimuth of the W3 antenna was rotated from + 180° to 180° in steps of 45° with dwell time of 15 minutes. RF outputs at the base of the antenna were connected to a Spectrum Analyzer and recordings made of the maximum and minimum received power over a period of about 8 hours. For the resolution and video bandwidths of the spectrum analyzer used, the difference in maximum & minimum values is expected to be about 7 dB (± 2.5 standard deviation). It is seen that level of RFI was low in the GMRT protected bands except for the 152 MHz band.

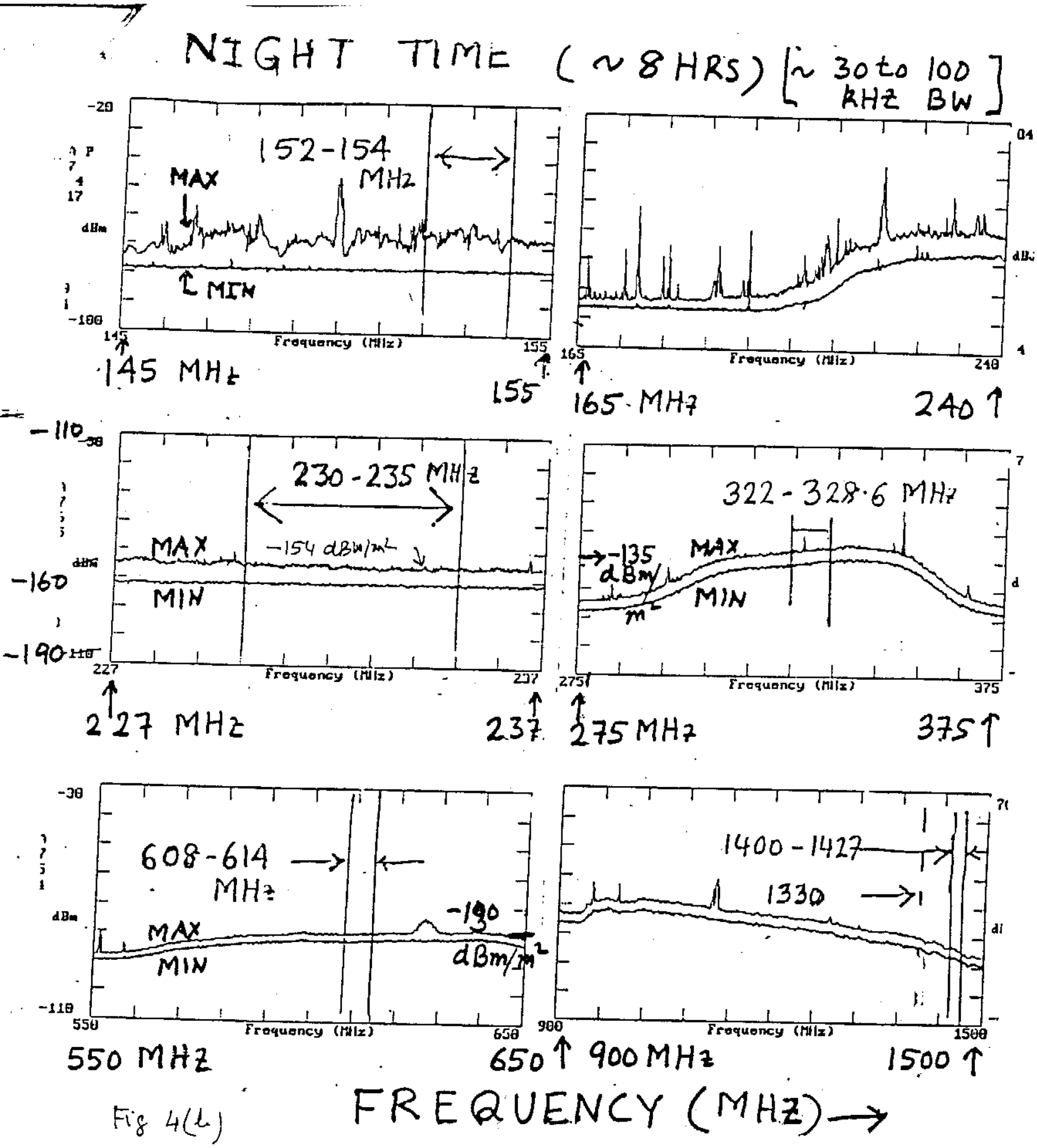
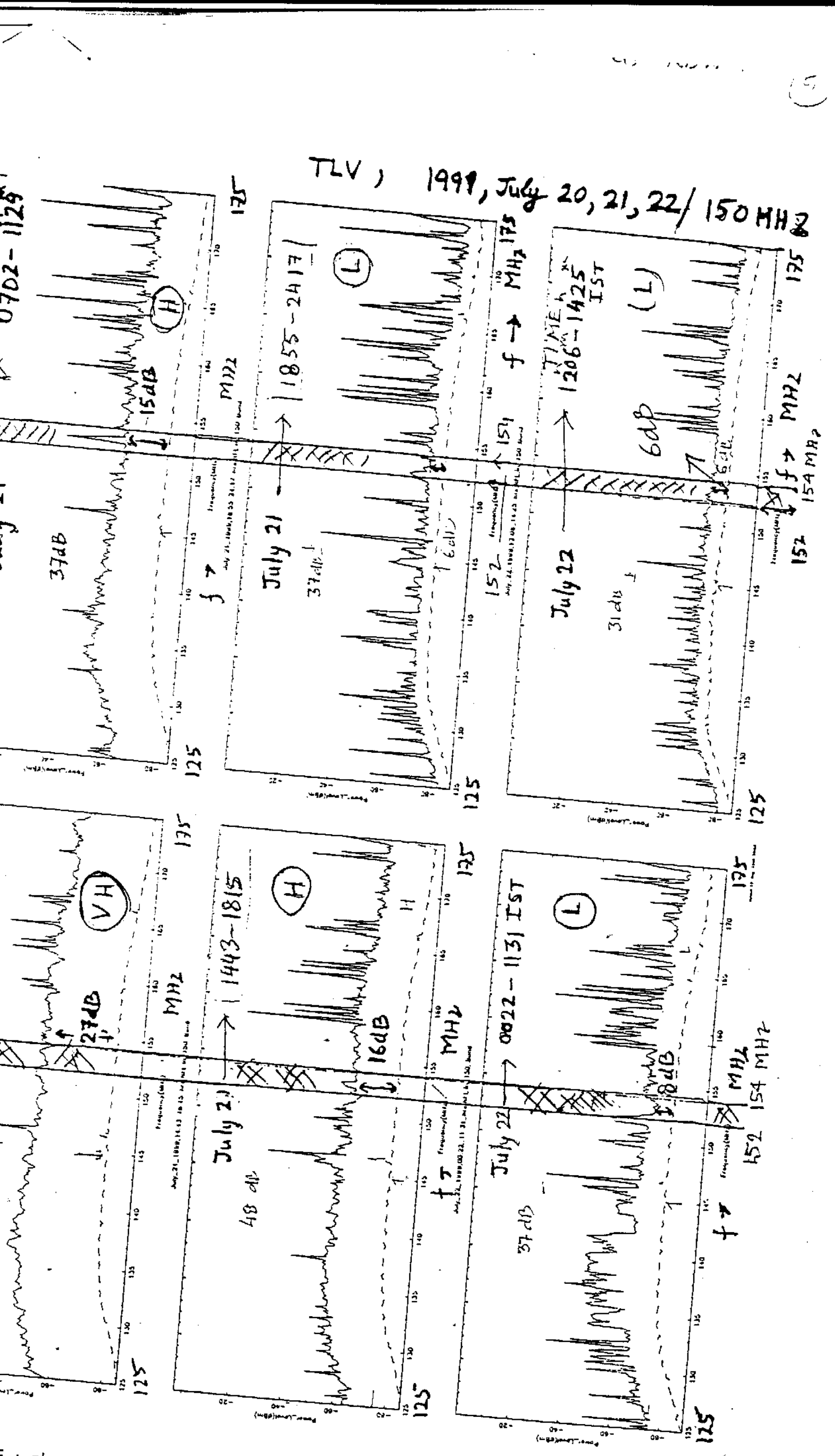


Fig 4(b)

RFI AT THE GMRT SITE IN AND NEAR RADIO ASTRONOMY BANDS ~ 150 MHz to 1500 MHz

4(b) : Same as Fig. 4(a) but for measurements made in late evenings and night time.

FIG. 5 : shows some typical RFI plots made by T.L. Venkatasubramani for several hours during the month of July 1999. Hatched portions show the bands 152-154 MHz protected for operation of GMRT. The difference between Maximum & Minimum shows Very High (VH), high (H) or relatively low (L) levels of RFI (125-175 MHz)



5 : shows some typical RFI plots made by T.L. Venkatasubramani for several during the month of July 1999. Hatched portions show the bands 152-154 MHz ted for operation of GMRT. The difference between Maximum & Mini (VH), high (H) or relatively low (L) ...

FIG. 6 : **AUTOMOBILE INTERFERENCE**

Fig. 6(a): Shows digital oscilloscope output for pulsed RFI produced by NCRA office Jeep, as measured by Saini and Venkatasubramani at NCRA in 1993, at the output of a 150 MHz receiver with a dipole antenna placed just outside the window of the Electronics Lab. on 1st Floor and the jeep about 40 m away on the NCRA road towards north.

Fig. 6(b) : Same as Fig. 6(a) but for pulsed RFI caused by a Moped.

Fig. 6(c) : Typical current waveforms caused by unsuppressed (Fig. 2-2-a and suppressed (Fig. 2-2-b) spark-gap discharges in an automobile (figure 2-2 is reproduced from "Manmade Radio Noise" by SKOMEL).

Use calibration of Y axis for subsequent plots markers

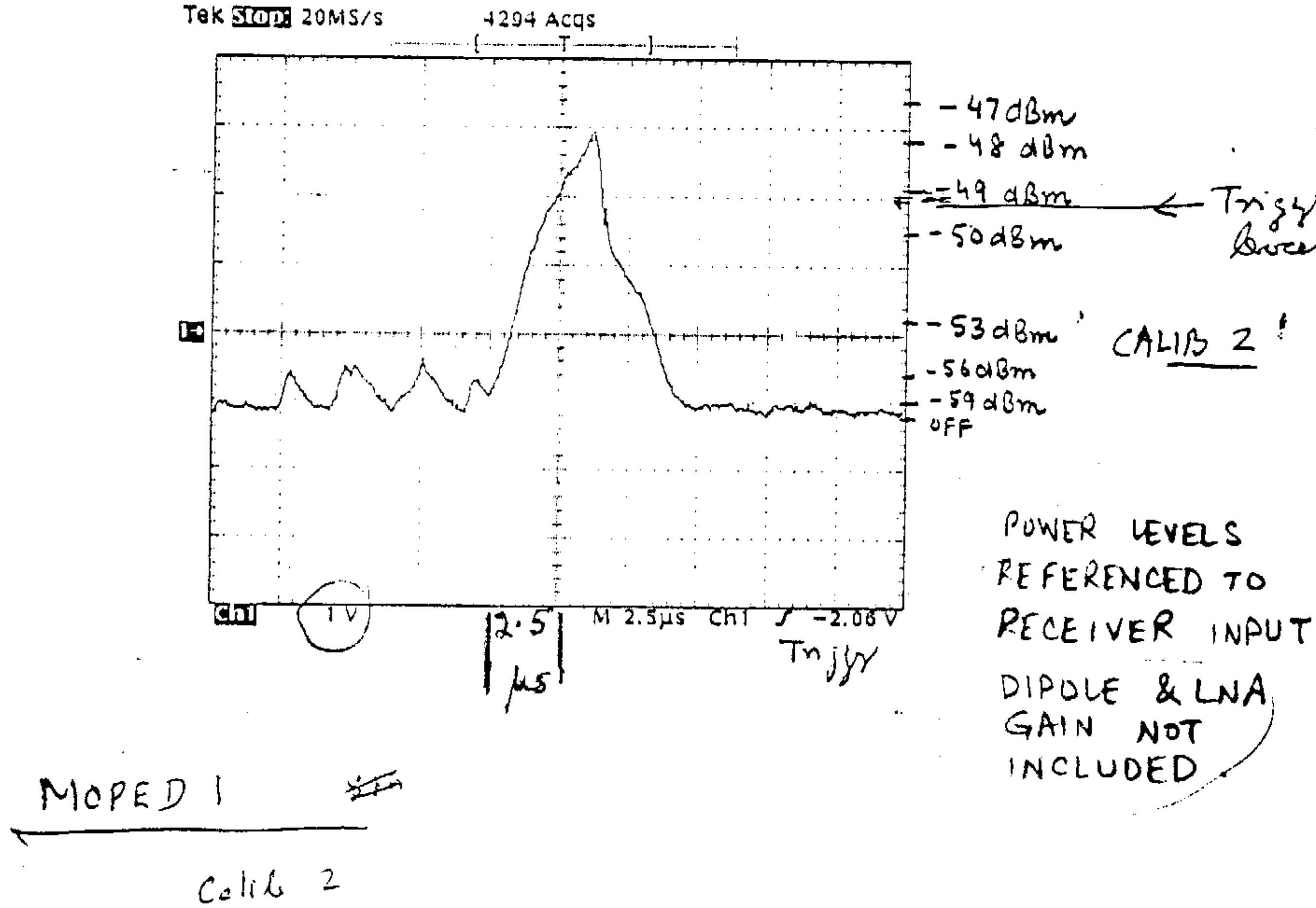
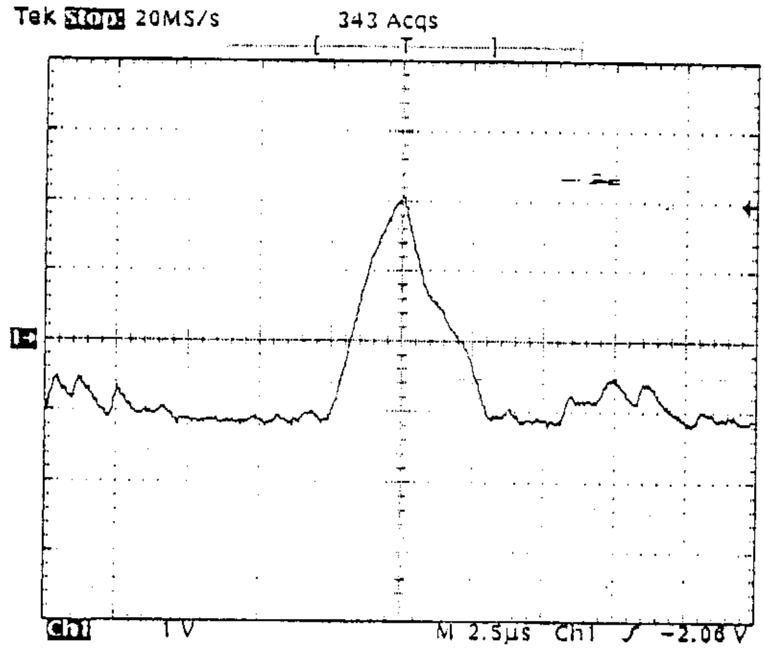


Fig. 6(a): Shows digital oscilloscope output for pulsed RFI produced by NCRA office Jeep, as measured by Saini and Venkatasubramani at NCRA in 1993, at the output of a 150 MHz receiver with a dipole antenna placed just outside the window of the Electronics Lab. on 1st Floor and the jeep about 40 m away on the NCRA road towards north.



other jeep

Fig. 6(b) : Same as Fig. 6(a) but for pulsed RFI caused by a Moped.

AS PER
CALB NO 2

SPARK PLUGS

charge a weak radiated field emanating from the wiring, as secondary-circuit voltages are now insufficient to sustain an arc discharge.

Ignition Waveforms

SHARP SPIKE 5 nsec or less

Figure 2-2 shows the conducted current pattern produced by an unsuppressed secondary-ignition circuit at, and subsequent to, initiation of the spark-plug discharge.[1] The time-base increments represent 10 nsecs. The sharp spike lasting 5 nsec or less arises from the discharge of the coaxial capacitor of the spark plug and is known to be readily suppressable by inserting an in-line center conductor resistor near the plug tip, at the gap end, without detracting from engine performance.[2] One may observe in Fig. 2-2(a) the oscillations impressed upon the radiated field by the secondary-circuit resonances that follow the capacitive spike. In Fig. 2-2(b), a larger fraction of the

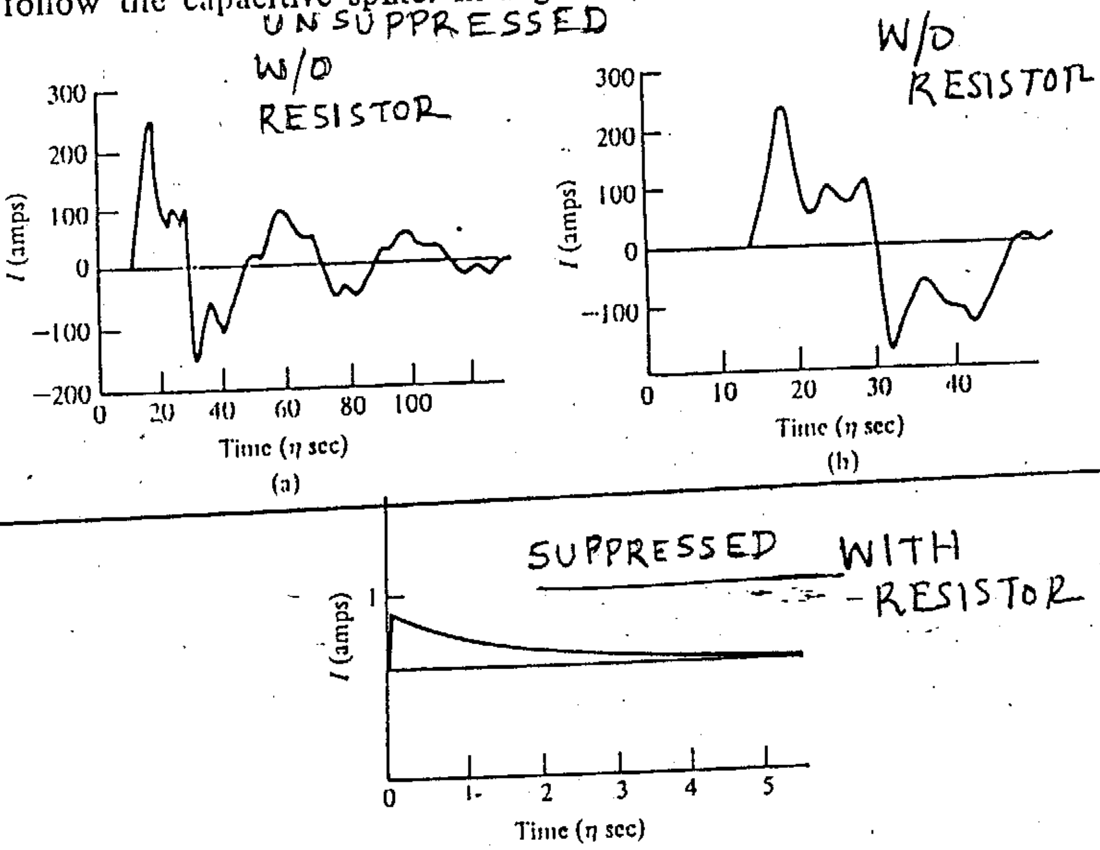


Fig. 2-2. Secondary ignition circuit current waveforms, 12-Kv applied peak potential. (*a*) and (*b*) Unsuppressed resistor located at the spark plug. (From Ball and Nethercot, *Proc. Inst. of Mech. Eng.*, London, 1952)

Fig. 6(c) : Typical current waveforms caused by unsuppressed (Fig. 2-2-a and suppressed (Fig. 2-2-b) spark-plug discharges in an automobile (figure 2-2 is reproduced from "Manmade Radio Noise" by SKOMEL).

FIG. 7 : **RFI FROM 11 kV POWER LINES DUE TO GAP DISCHARGES**

FIG. 7(a) :Plot showing RFI at GMRT antennas due to 11 kV power lines. 150 MHz antenna feed was pointed towards horizon and measurements made using HP 8590L Spectrum Analyzer in Zero Span Mode, which acts as a total power receiver with Resolution Bandwidth (RBW) as indicated below the plot and time constant inverse of VBW. Please see Report-VII for more outputs.

FIG. 7(b) Same as Fig. 7(a) but at 235 MHz.

FIG. 7(c) Same as Fig. 7(a) but at 325 MHz.

FIG. 7(d) Plot showing RFI at GMRT antennas due to 11 kV power lines. 150 MHz feed was towards horizon. HP 8590 Spectrum Analyzer was used with RBW=100 kHz and span of 20 MHz. In Fig. 7(d-i) and 7(d-iii), 100 scans were averaged. But in Fig 7(d-ii) only a single scan was made and show sharp spikes, perhaps due to spark induced RFI by power lines.

FIG. 7(e) Power Spectrum of the pulsar receiver output showing peaks at 50 Hz and odd multiples (power spectrum outputs are different on other days).

FIG. 7(f) Digital oscilloscope output at the base-band output of C02 antenna of GMRT showing sharp pulses due to 11kV pulsed RFI. Measurements were made by Swarup and Srinivasan on 23-4-98 by placing a diode followed by an RC integrating circuit with time constant of 16 microsec between the 16 MHz base-band amplifier output and the oscilloscope. The antenna feed of 150 MHz was pointed towards north. It is seen that pulsed RFI reaches a peak in less than one microsec (see Fig 7(h).

FIG. 7(g) (h): Same as Fig. 7(f) with 1 ms and 500 ns respectively.

FIG. 7(i) Same as Fig. 7(f) with 2.5 ms

FIG. 7(j) and 7(k) : Same as Fig. 7(f) with 250 ms.

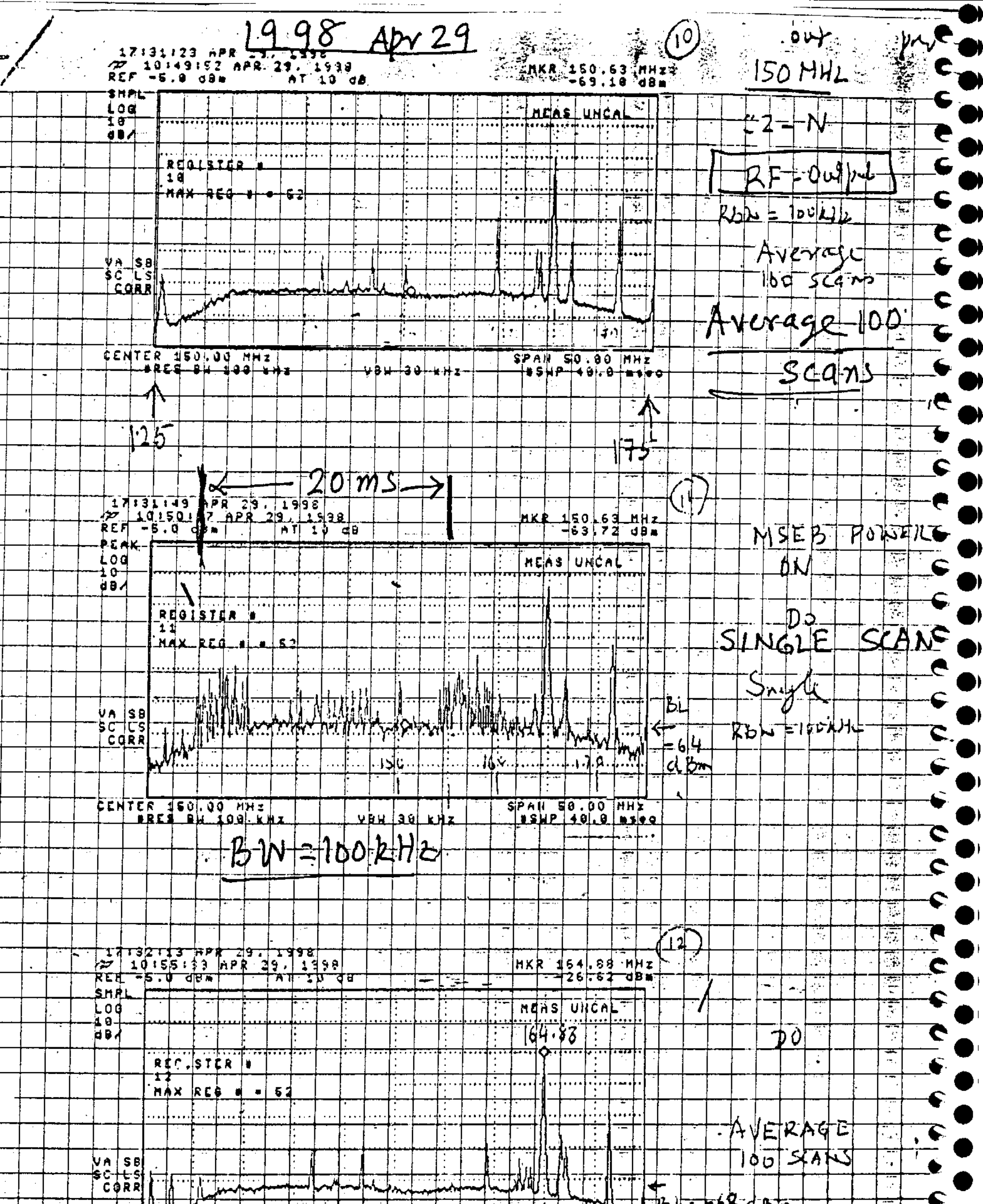
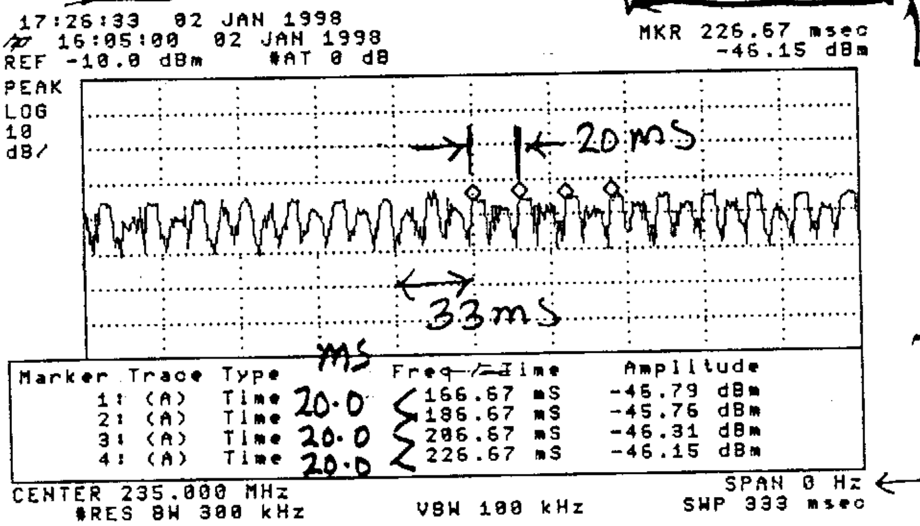


FIG. 7(a) :Plot showing RFI at GMRT antennas due to 11 kV power lines. 150 MHz antenna feed was pointed towards horizon and measurements made using HP 8590L Spectrum Analyzer in Zero Span Mode, which acts as a total power receiver with Resolution Bandwidth (RBW) as indicated below the plot and time constant inverse of VBW. Please see Report-VII for more outputs.

2nd JAN 98

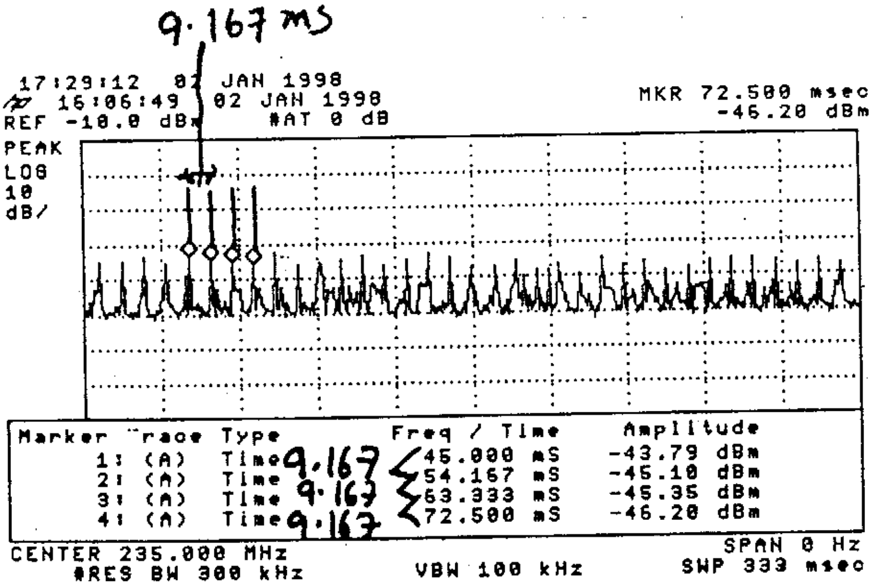
235 MHz feed to WEST



Time Domain Plot at 10 μs integ. times

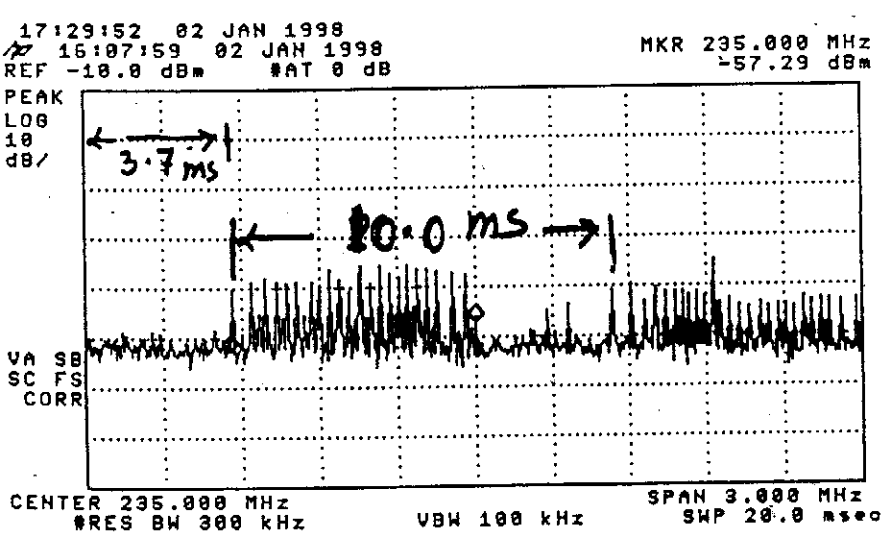
ZERO SPAN

Sweep 333 msec



(" ")

= 54.5 Hz



Freq. Domain Plot

→ 3 MHz BW around 235 MHz.

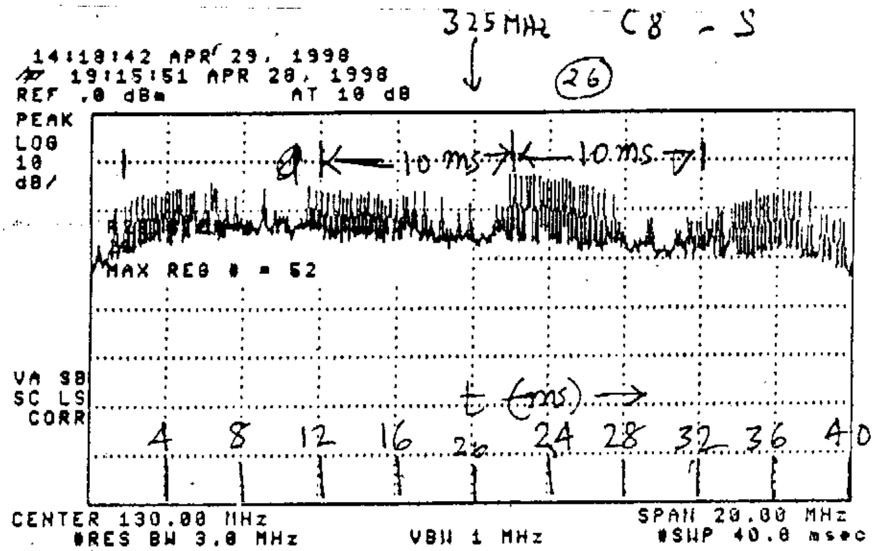
RFI Burst seen with 10 μs integ. time.

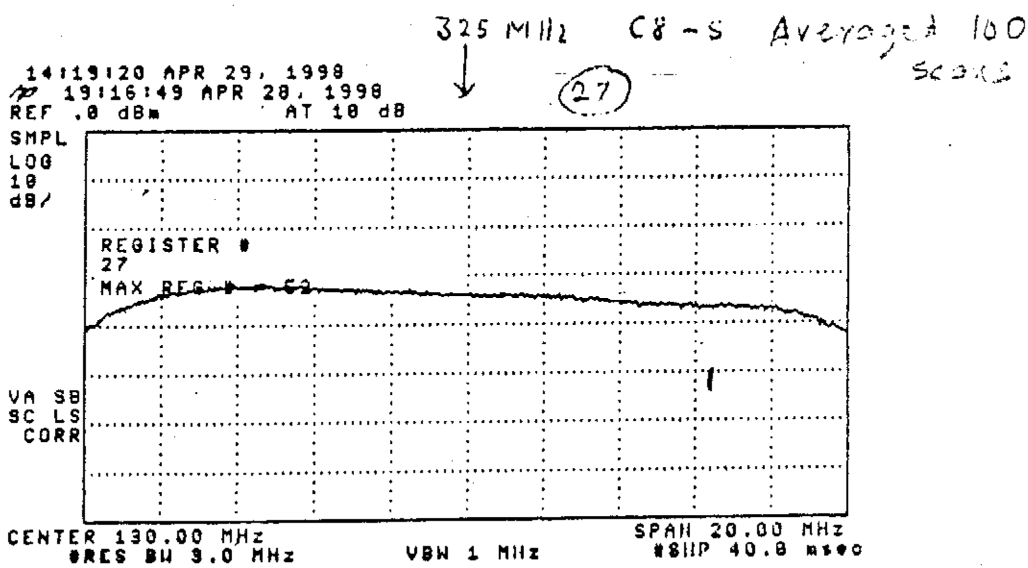
BW 300 kHz

SWEEP TIME 20 ms.

FIG. 7(b) Same as Fig. 7(a) but at 235 MHz.

48 Apr 29 ✓
GJ





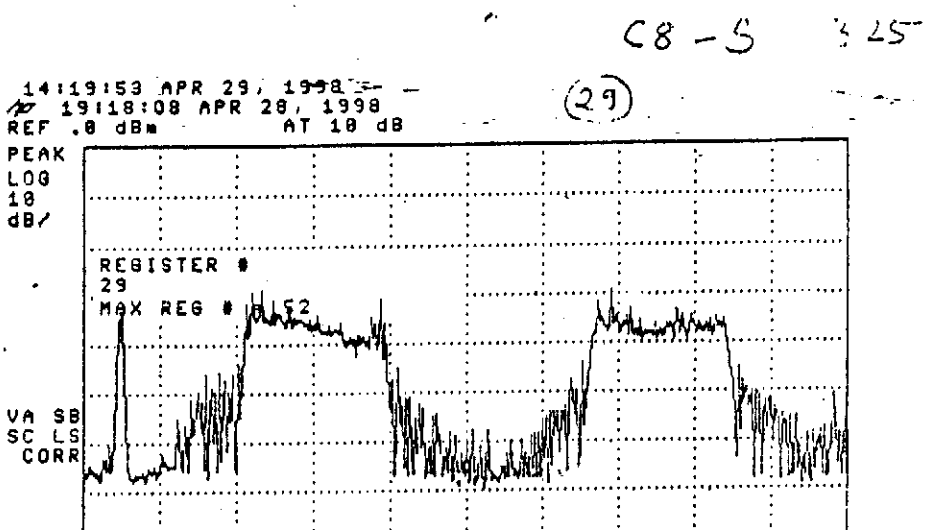


FIG. 7(c) Same as Fig. 7(a) but at 325 MHz.

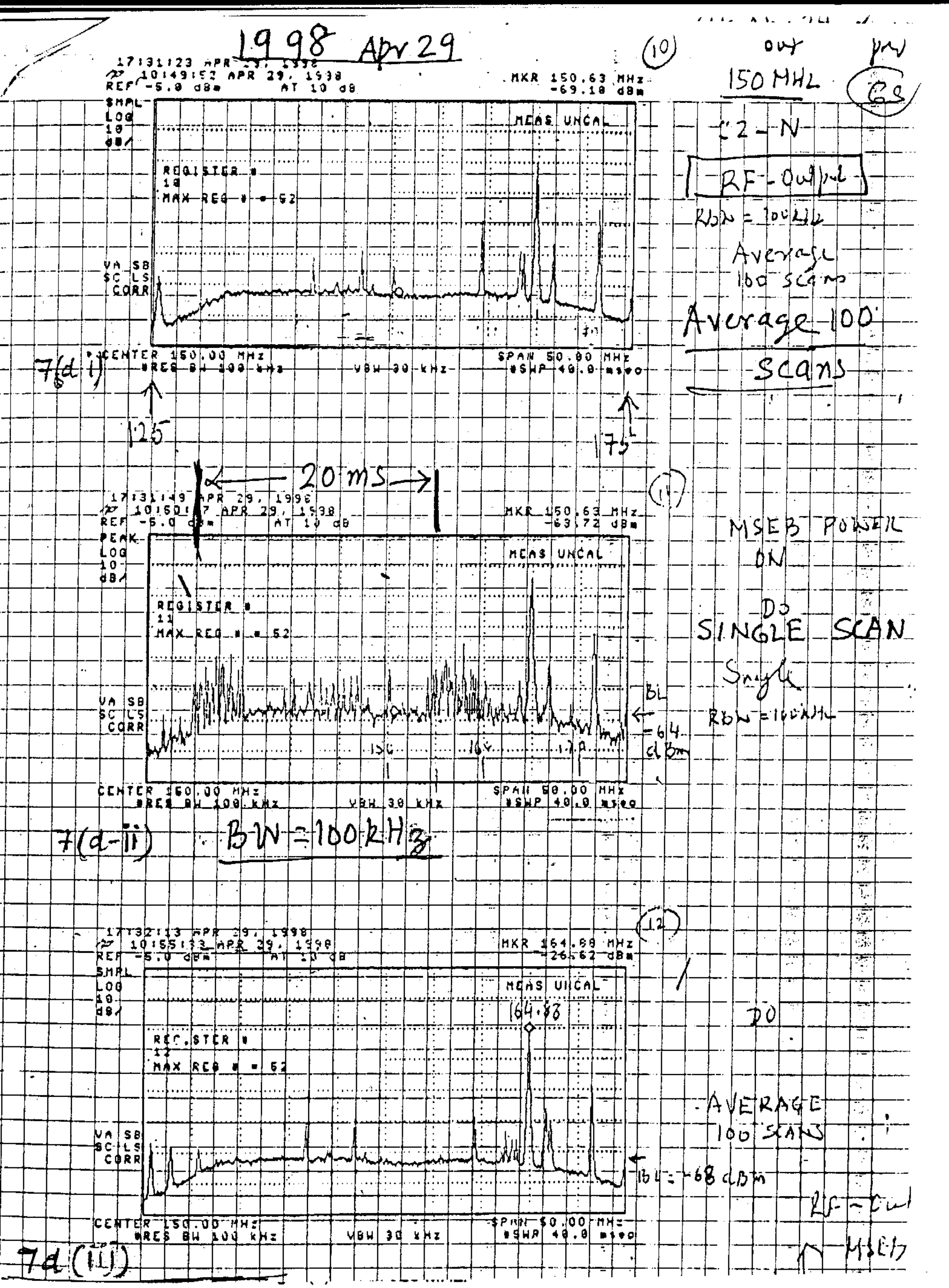


FIG. 7(d) Plot showing RFI at GMRT antennas due to 11 kV power lines. 150 MHz feed was towards horizon. HP 8590 Spectrum Analyzer was used with RBW=100 kHz and span of 20 MHz. In Fig. 7(d-i) and 7(d-iii), 100 scans were averaged. But in Fig 7(d-ii) only a single scan was made and show sharp spikes, perhaps due to spark induced RFI by power lines.

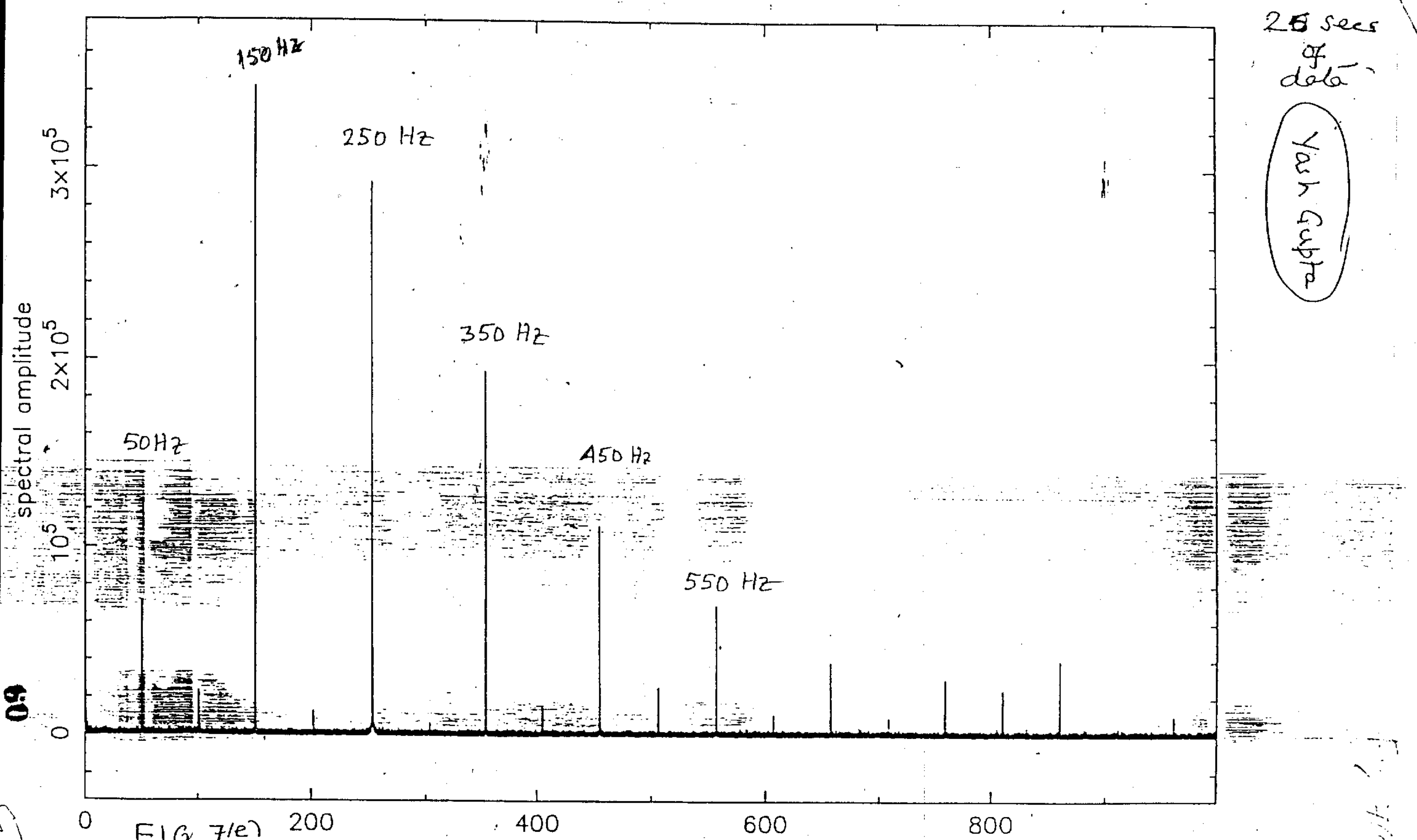


FIG. 7(e) Power Spectrum of the pulsar receiver output showing peaks at 50 Hz and odd multiples (power spectrum outputs are different on other days).

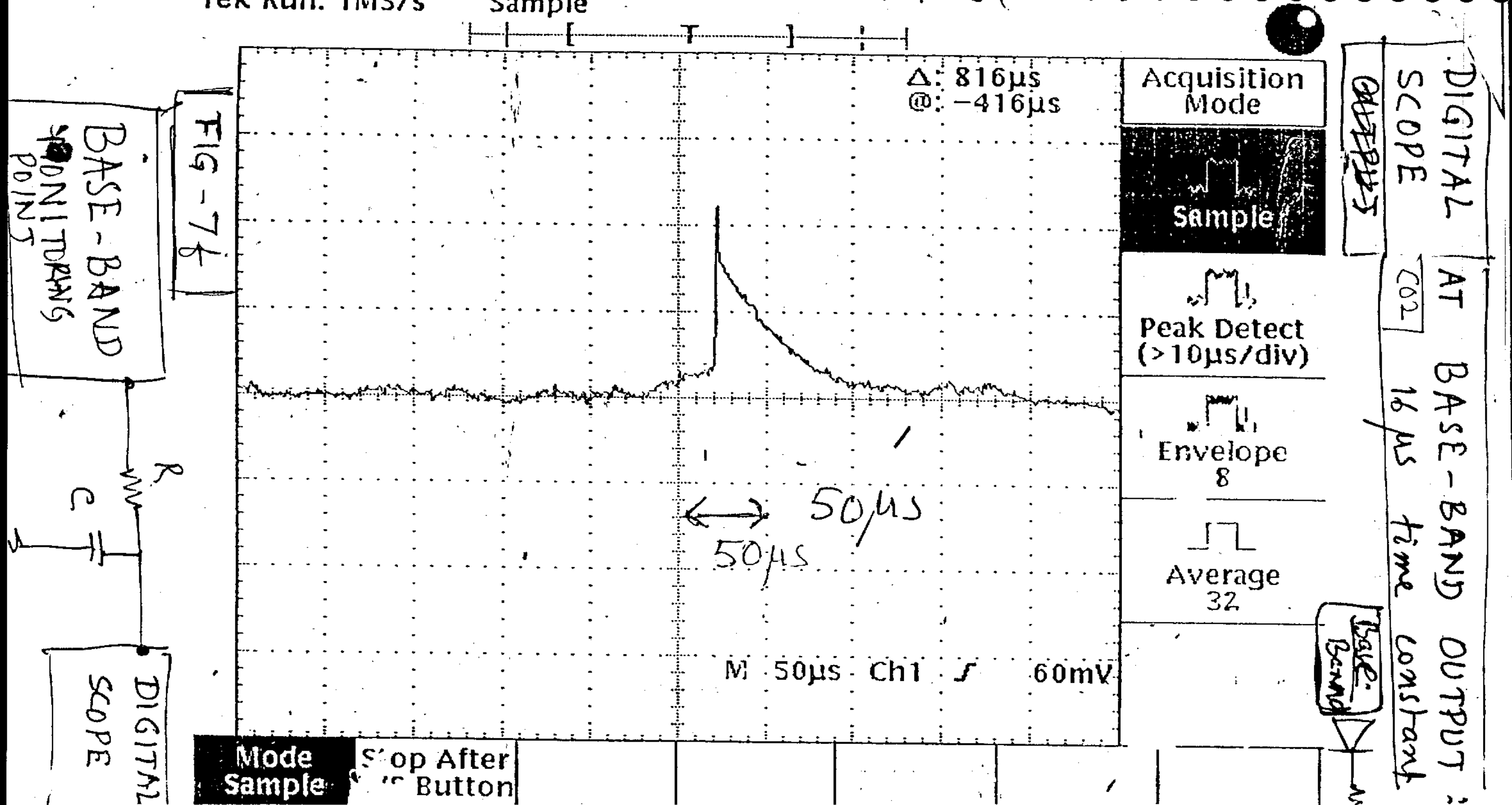


FIG. 7(f) Digital oscilloscope output at the base-band output of C02 antenna of GMRT showing sharp pulses due to 11kV pulsed RFI. Measurements were made by Swarup and Srinivasan on 23-4-98 by placing a diode followed by an RC integrating circuit with time constant of 16 microsec between the 16 MHz base-band amplifier output and the oscilloscope. The antenna feed of 150 MHz was pointed towards north. It is seen that pulsed RFI reaches a peak in less than one mirosec (see Fig 7(h).

C-2 24104
4:05

GS+MS

C-2 24/4/98

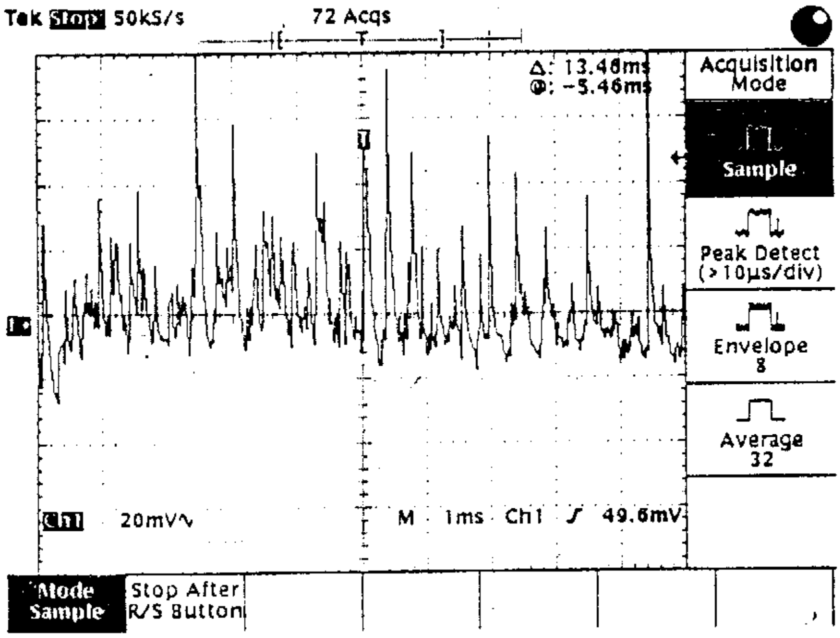


Fig. 7 (g)

C-2

4:08

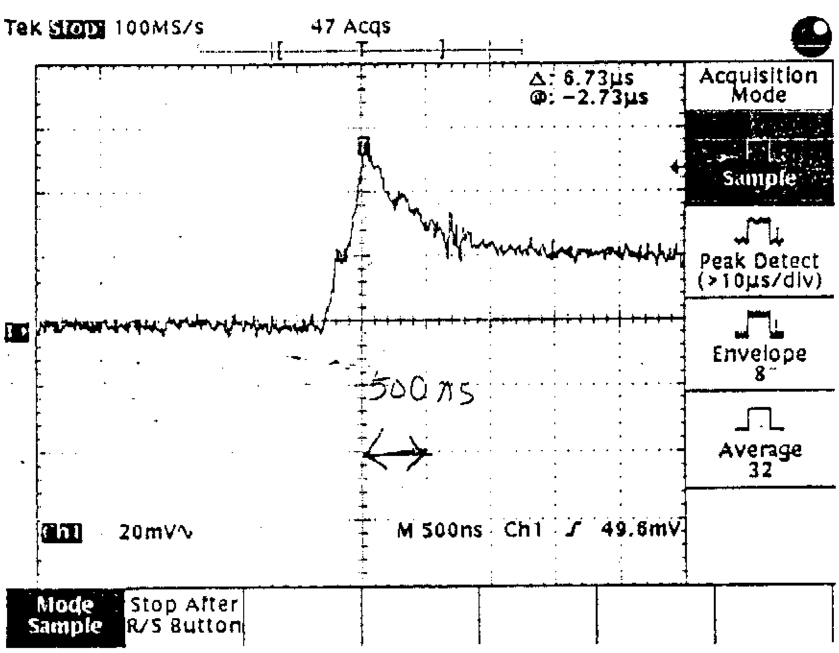


FIG. 7(g) (h): Same as Fig. 7(f) with 1 ms and 500 ns respectively.

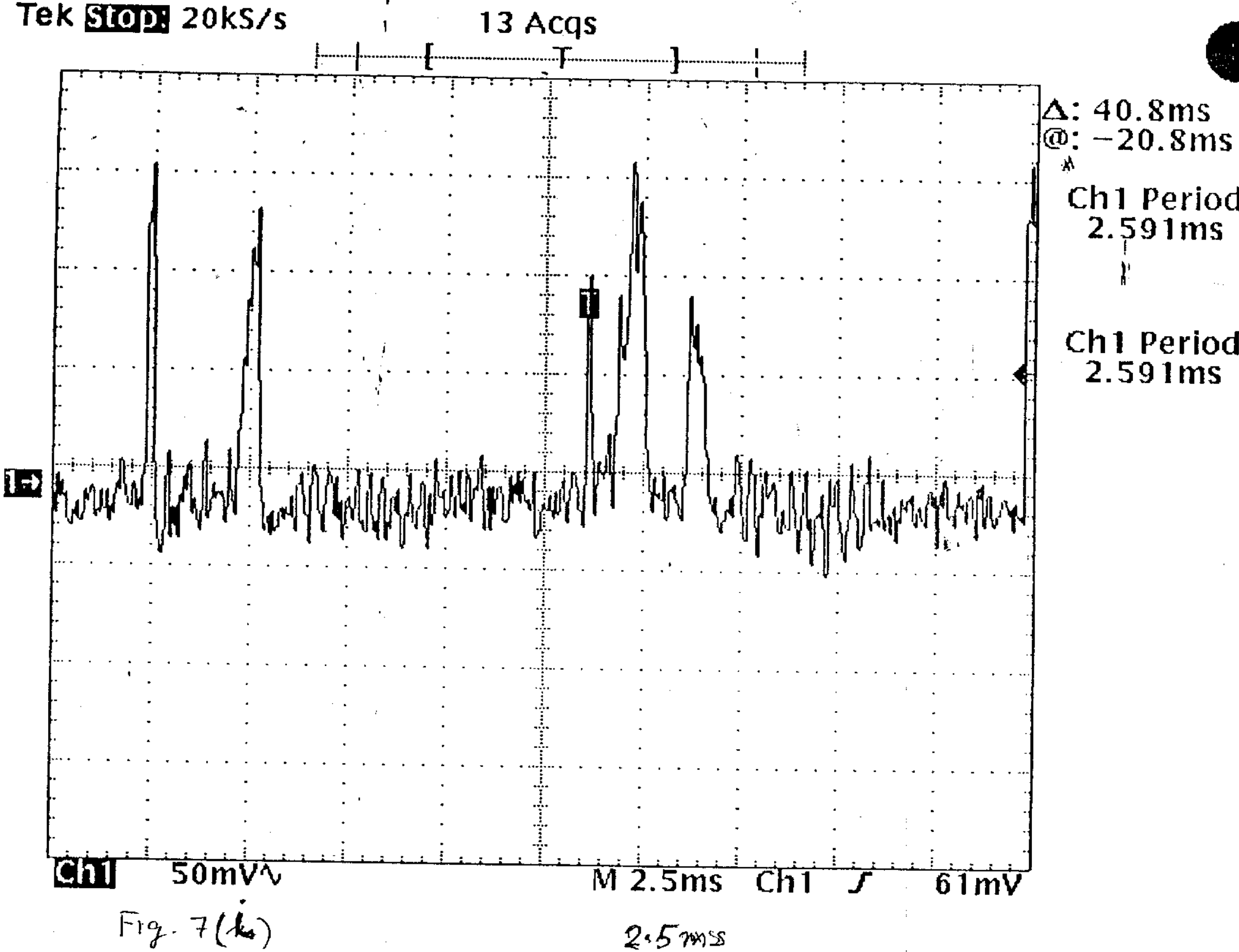
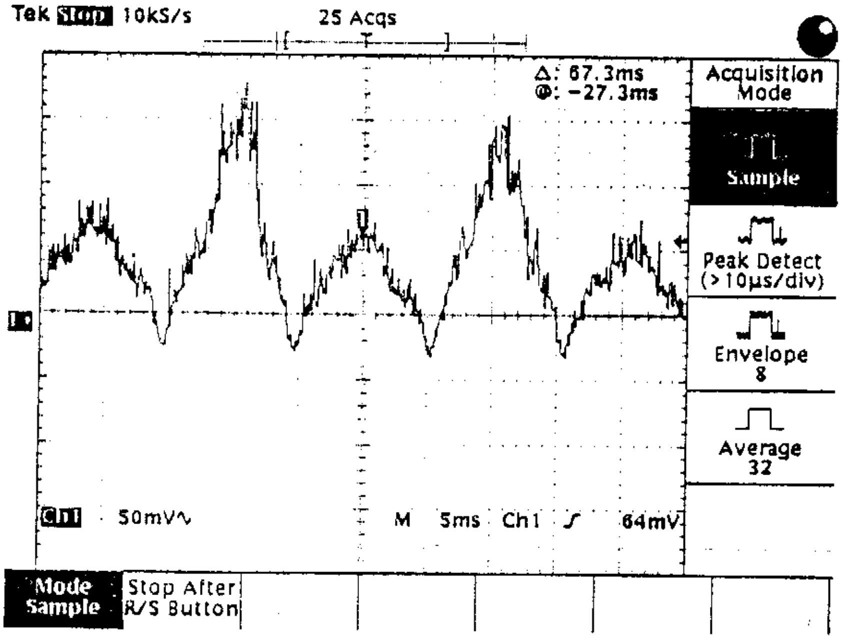


FIG. 7(i) Same as Fig. 7(f) with 2.5 ms

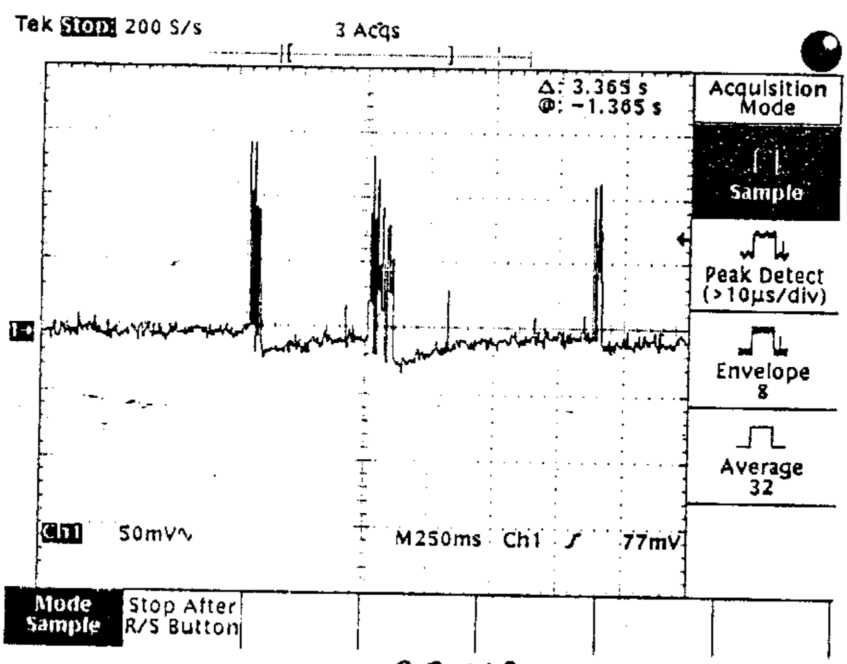
S-2

24/04/98
3:50
GS +



5 ms

Fig. 7(j)



250 ms

FIG. 7(j) and 7(k) : Same as Fig. 7(f) with 250 ms.

FIG. 8 : A schematic showing three-phase A.C. 11 kV HT supply. RFI due to gap discharge may occur, when Voltage rises to more than about 50% or 60% of 11 kV or thereabout on any of the three phase lines. It is noted from Fig. 7(a) 7(c) that pulsed RFI seems to occur on several occasions only every 10 ms, which indicates that only one of the three phases of 11 kV line shows RFI on a given day and RFI occurs only when voltage rises to + 11 kV or -11 kV (further measurements are required). The particular phase can be identified by measuring the time difference between the line trigger phase of the spectrum analyzer and the occurrence of pulsed RFI near the measured antenna of GMRT. In case of defective insulators or poor connections or poor grounding. It may be possible to identify the defective line by making RFI zero span meansurements spectrum analyzer with trigger using power line voltage (not UPS) & identifying the phase.

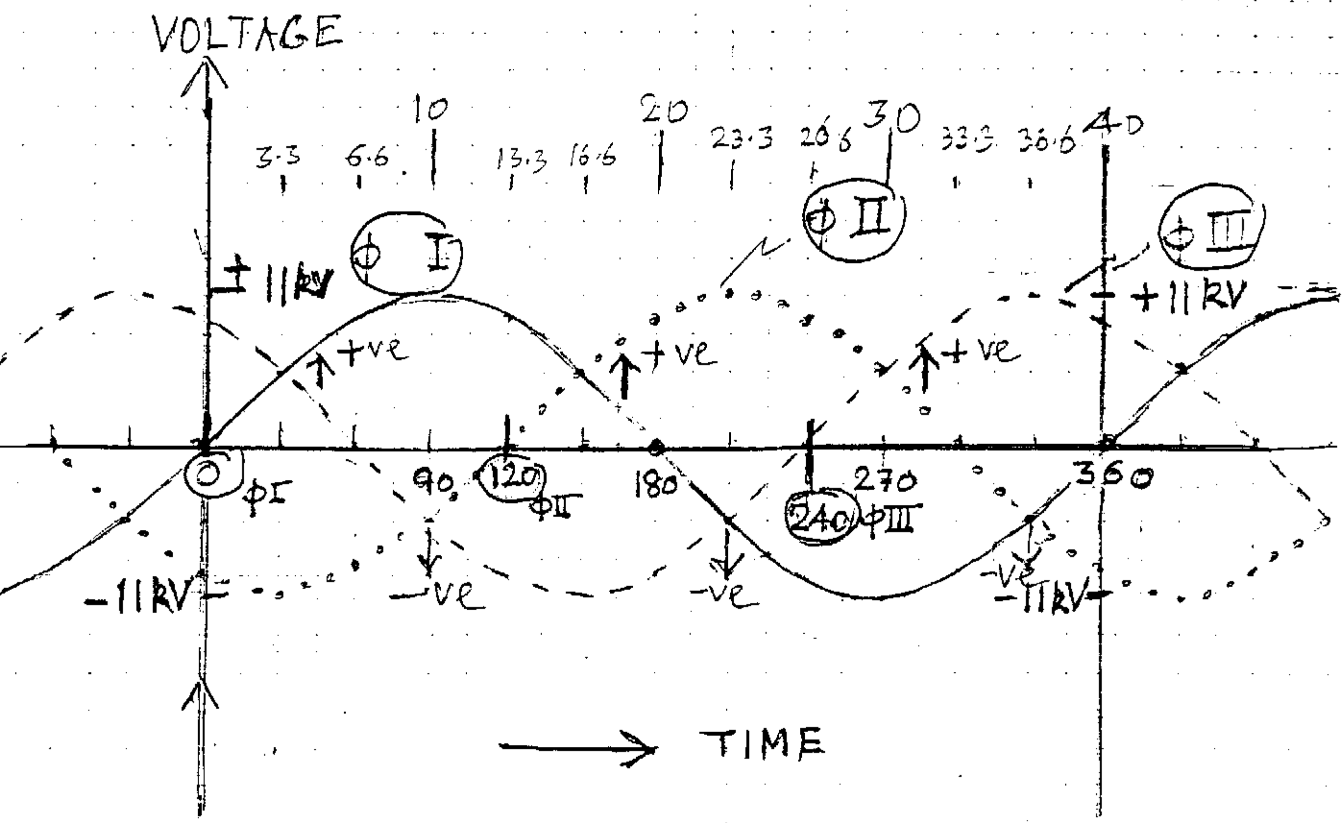


FIG. 8 : A schematic showing three-phase A.C. 11 kV HT supply. RFI due to gap discharge may occur, when Voltage rises to more than about 50% or 60% of 11 kV or thereabout on any of the three phase lines. It is noted from Fig. 7(a) 7(c) that pulsed RFI seems to occur on several occasions only every 10 ms, which indicates that only one of the three phases of 11 kV line shows RFI on a given day and RFI occurs only when voltage rises to + 11 kV or -11 kV (further measurements are required). The particular phase can be identified by measuring the time difference between the line trigger phase of the spectrum analyzer and the occurrence of pulsed RFI near the measured antenna of GMRT. In case of defective insulators or poor connections or poor grounding. It may be possible to identify the defective line by making RFI zero span ~~means~~ measurements using spectrum analyzer with trigger using power line voltage (not UPS) & identifying the phase.

Fig. 9 : **LEO SATELLITE SPURIOUS EMISSION**

Spectral roll off (spurious emission) of different modulation schemes. Figure is reproduced from Swarup and Sinha (1992). It is seen that a satellite transmitter at 137 MHz with power output of one watt, connected to an antenna with a gain of about one, placed in a Low Earth Orbit (LEO) (at a height of about 800 km from the earth) will produce RFI which is 90 db above the sensitivity of radio astronomy service as per ITU-RA-769.1, if the usual BPSK or QPSK modulation is used. However, a GMSK (gaussion mean shift keying) modulation as used in Cellular radio will produce negligible spurious emission away from the transmitting frequency.

MODULATION SCHEMES

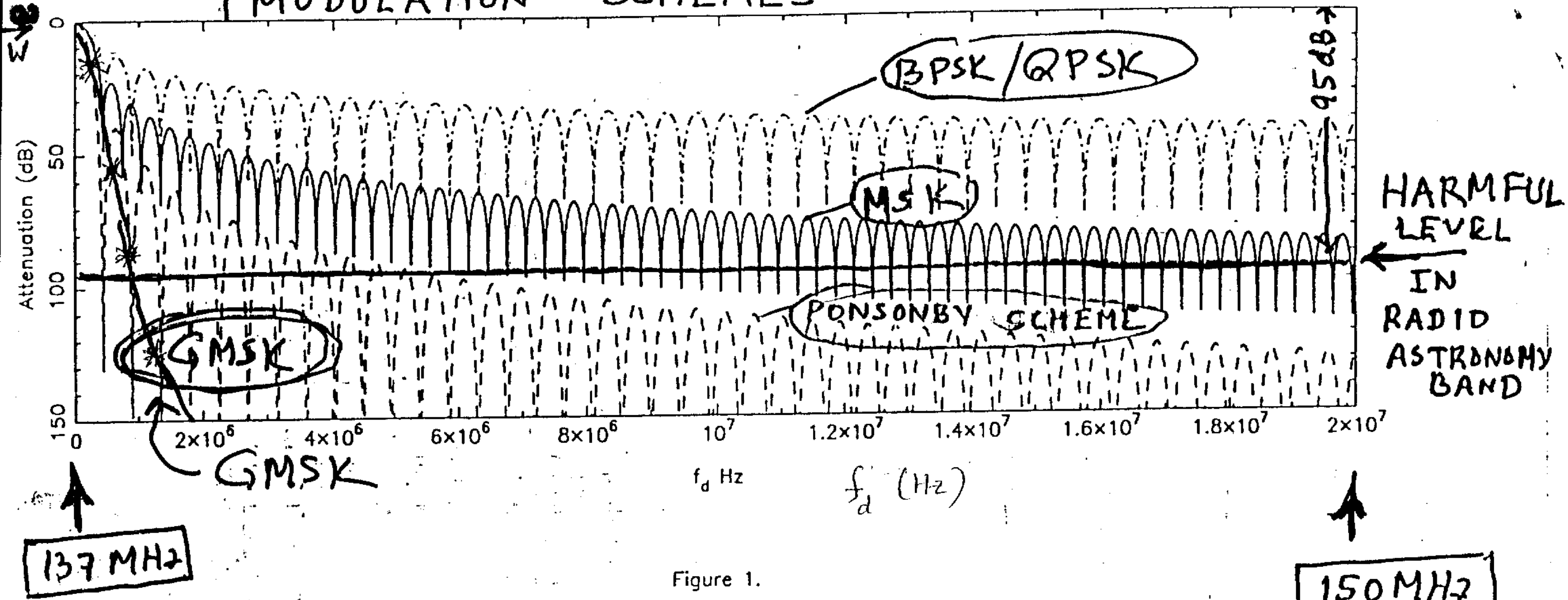


Figure 1.

Spectral Roll off of different modulation schemes
Where f_d is the offset from the carrier frequency

Dashed–dotted curve:	BPSK/QPSK
Solid curve:	MSK
Dashed curve:	Ponsonby
Dotted curve:	95dB line, the desired limit
Star:	GMSK

(Fig 9)

FIG. 10 : **PREDICTED SPURIOUS EMISSION**

In the 1400-1427 MHz Band from the "ASIASTAR" which is a Geo-stationary Satellite for Digital Audio Broadcast at 1492 MHz. The predicted signal is below ~~the~~ rms noise of a radio astronomy receiver as per ITU-R-RA-769.1.

WORLDSTAR

... Measurement
Supplied by Australian Admin

ASA DISPLAY

ASIABSS

From: M.R.Sankaranarayanan N. Delhi

ALCATEL TELECOM

FM2 : TOB2.1 DX3 STEP 25 DOWN 15

19/5/99

Configuration CU :

02/04/1998 a 12h 08mn 24s

START 1.400 0 GHz

STOP 1.427 0 GHz

ATTEN 40 dB

REF 30.0 dBm

10 dB/

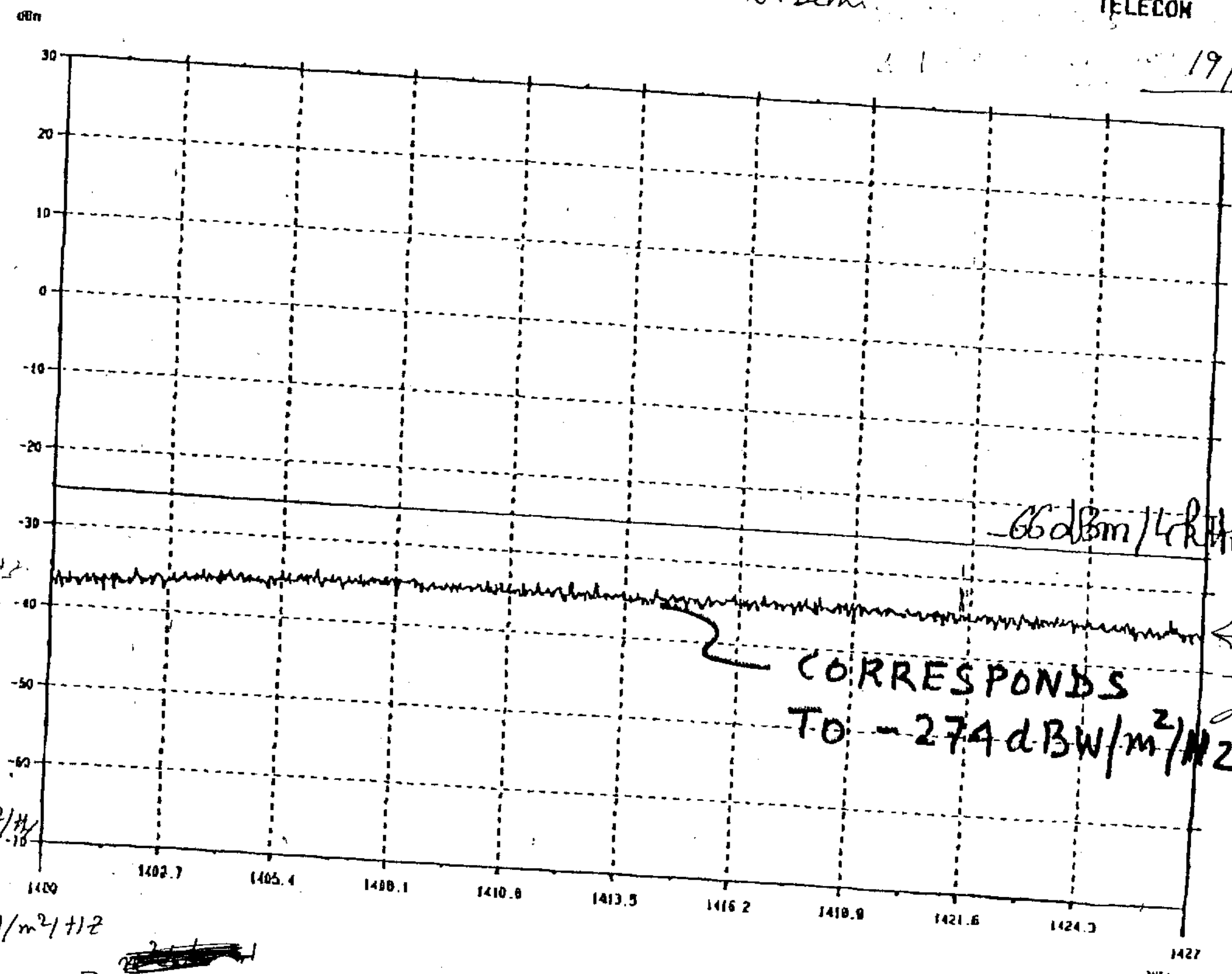
RES BW 100 kHz

VBW 1 kHz

SWP 810 msec

Amp. Mark. : -34.6

Freq. Mark. : 1413.88



ITU RA 769 Limit : -270 dBW/m²/Hz

Spread loss : 162.5 dB

-107.5 dBW/m²/Hz

Boresite antenna gain 30.5 dB

-138 dBW/Hz ⟹ -102 dBW/4kHz ⟹ -72 dBm/4kHz. Measurement shows -76 dBm/4kHz

FIG. 11 : **RFI FROM AN AMERICAN SATELLITE IN THE PROTECTED RADIO ASTRONOMY BAND OF 322-328.6 MHz.**

Fig. 11(a): Shows strong RFI from a satellite which occurred every 72 s at 328.2343 MHz, in channel 69 of the correlator output for the baseline of C2 and C9 antennas of GMRT.

FIG. 11(b): Same as Fig. 10(a) plotted on a grey scale.

FIG. 11(c) Same as Fig. 10(a) as a function of channel nos. It is seen that RFI level is 35 dB above the receiver noise, even when the satellite passes towards far away sidelobes of GMRT antennas.

FIG. 11(d) A typical record of the Ooty Radio Telescope (ORT) showing satellite RFI (same as Fig. 10-a). Hundreds of such occurrences were recorded at ORT during 1994 to 1997.

FIG. 11(e) Date and time of occurrence of RFI from the 328.23 MHz satellite wing which Gupta and Swarup calculated the orbital period.

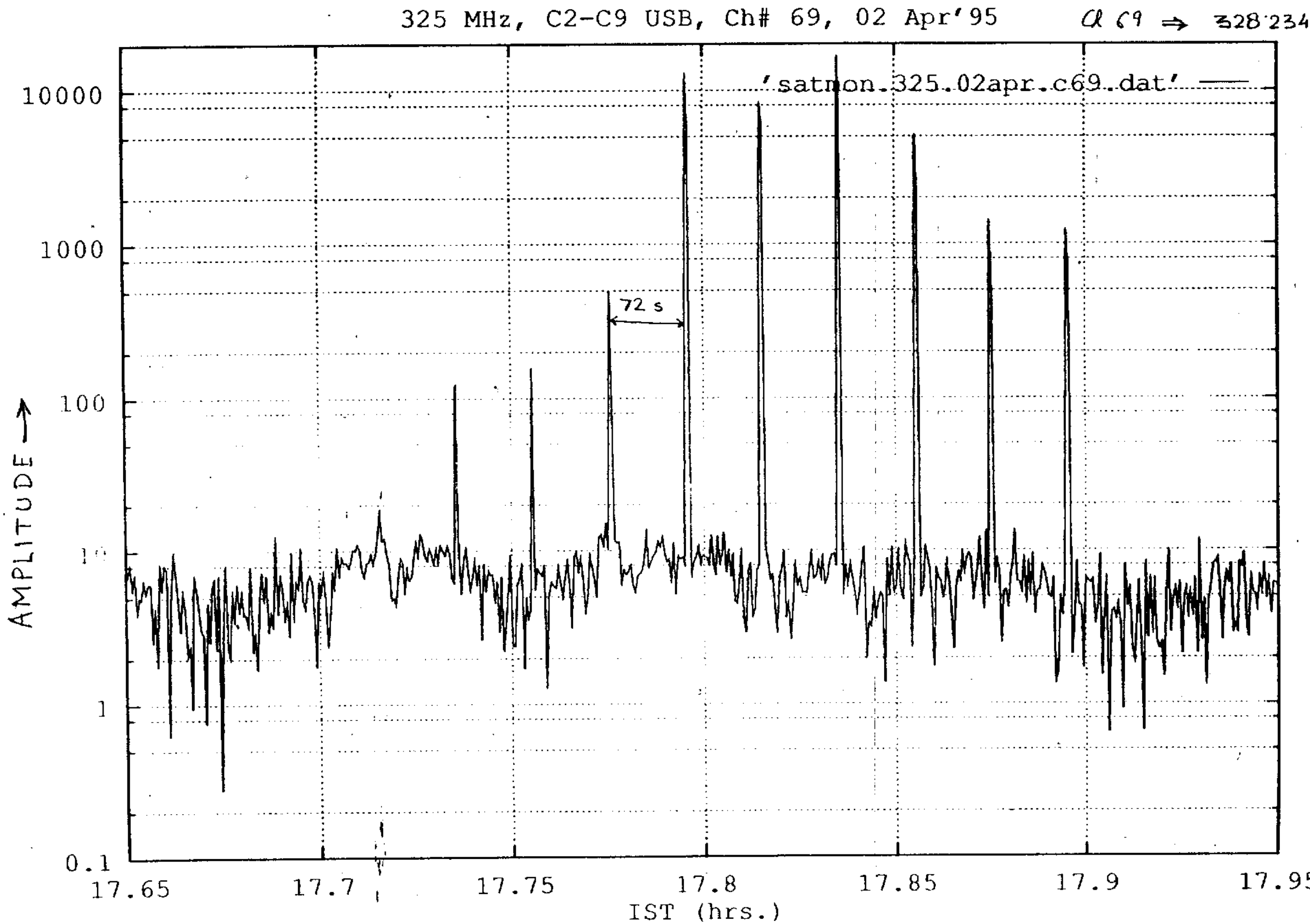


Fig. 11(a): Shows strong RFI from a satellite which occurred every 72 s at 328.2343 MHz. in channel 69 of the correlator output for the baseline of C2 and C9 antennas of

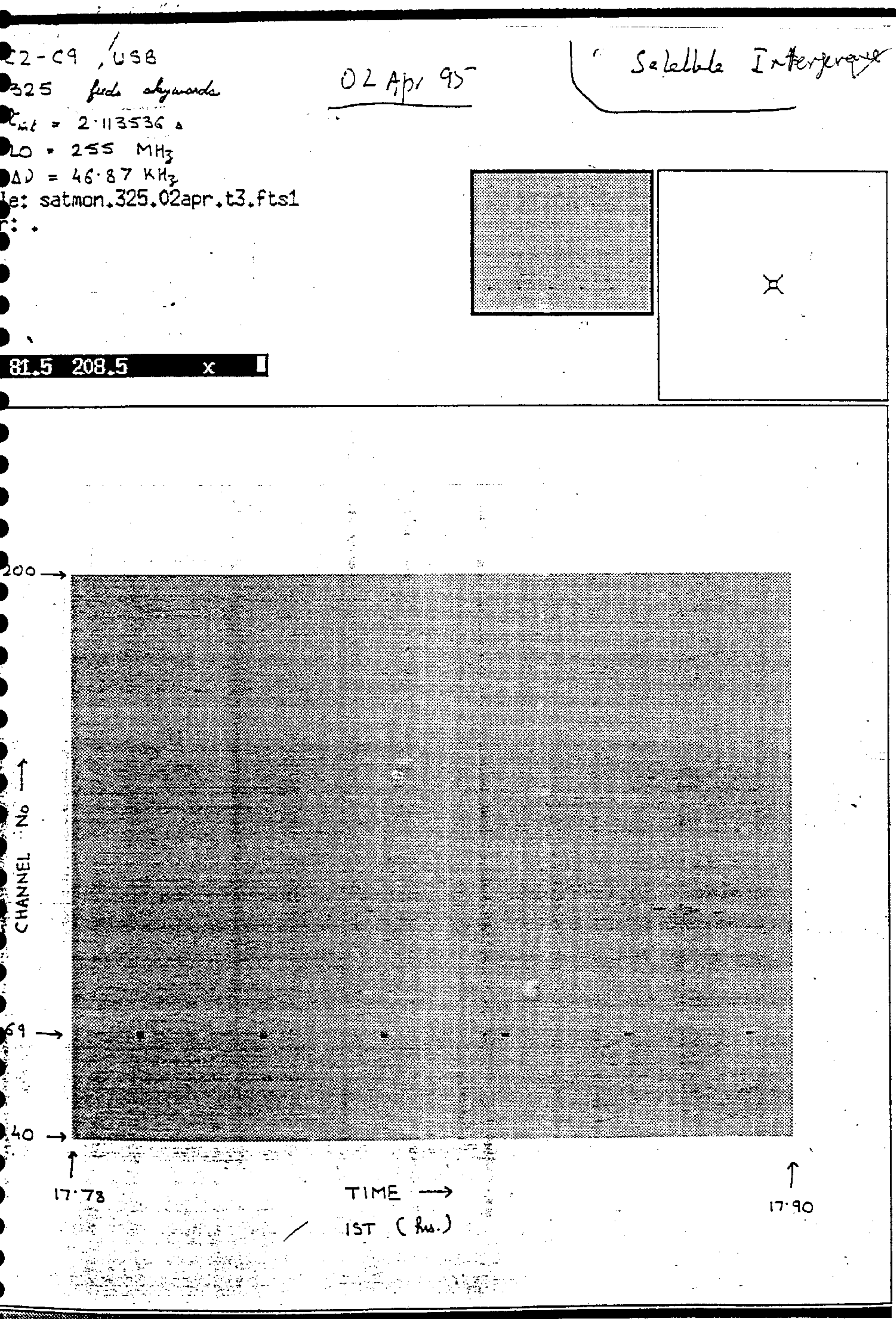


FIG. 11(b): Same as Fig. 10(a) plotted on a grey scale.

FIG. 11(c) Same as Fig. 10(a) as a function of channel nos. It is seen that RFI level ... when the satellite passes towards far away

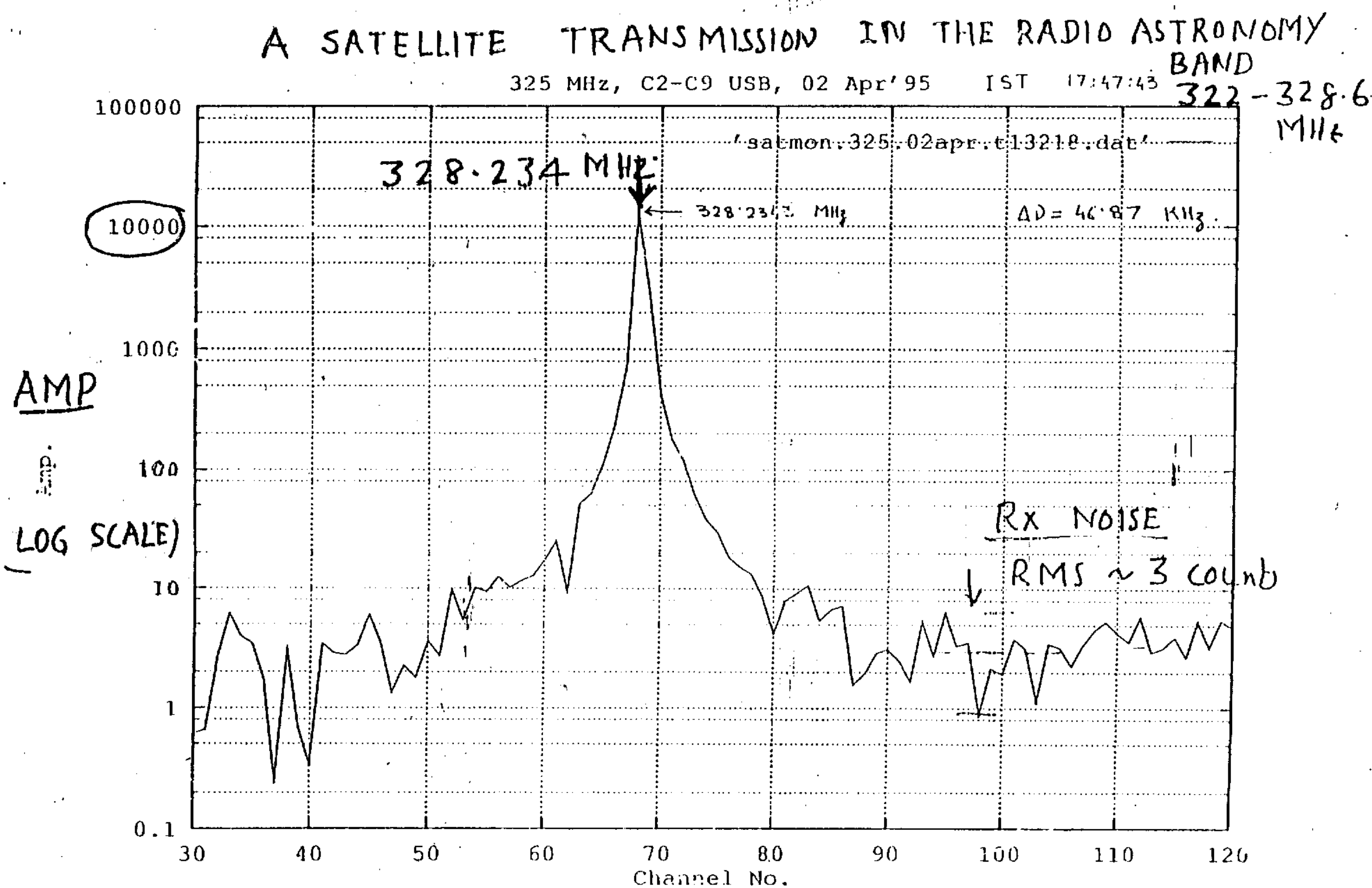


Fig 3: scan along frequency channel at 17:47:43 IST

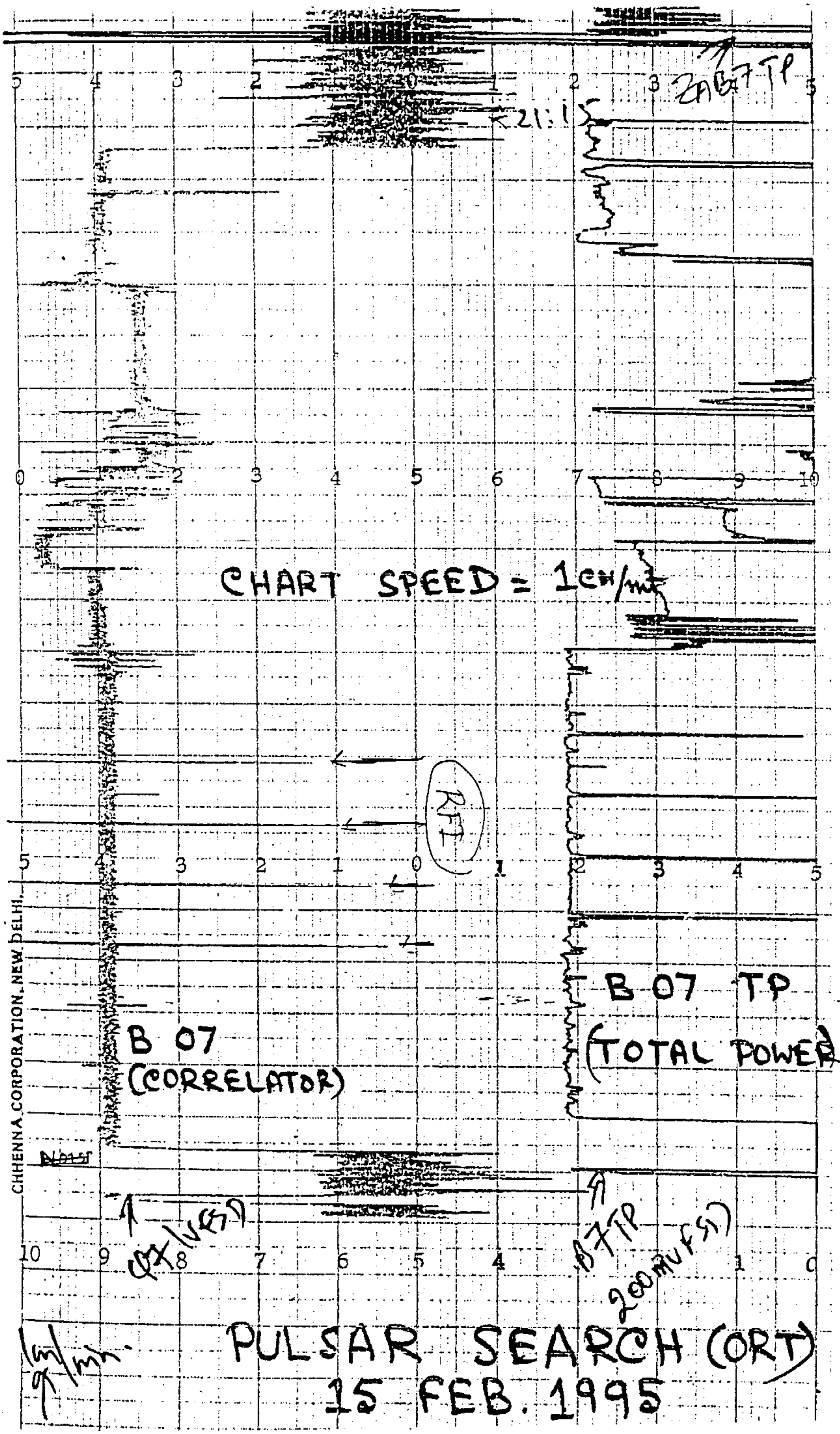


FIG. 11(d) A typical record of the Ooty Radio Telescope (ORT) showing satellite RFI (same as Fig. 10-a). Hundreds of such occurrences were recorded at ORT during

DATE

in ~~seconds~~ minutes

Difference in satellite transit times (wrt October 18, 1994) for 40 transits:[2]

		1994 Oct	d	h m
1	0	~~94 10~~	18	0431
2	~~94~~ 6		18	0607
3	1480		19	0511
4	2861		20	0412
5	2958		20	0549
6	4203		21	0234
7	4337		21	0448
8	5590		22	0141
9	5819		22	0530
10	8575		24	0326
11	8676		24	0[illegible]7
12	10055		25	04[illegible]6
13	10154		25	0545
14	12916		27	0347
15	13013		27	0524
16	15772	1994 Oct	29	0323
17	15873		29	0504
18	54512	1994 Nov	25	0103
19	54612		25	0243
20	57469		27	0220
21	58850		28	0121
22	58949		28	0300
23	64567	1994 Dec	2	0038
24	64667		2	0218
25	66046		3	0117
26	66144		3	0255
27	67525		4	0156
28	67625		4	0336
29	70385		6	0136
30	166590	1995 02	10	2101
31	166691		10	2242
32	173734		15	2055
33	175270		16	2141
34	185322		23	2113
35	185957		24	0748
36	187434		25	0825
37	188179		25	2050
38	189660		26	2131
39	192516		28	2107

G Swarup

[2] ~GSwarup/satellite.tex

FIG. 11(e) Date and time of occurrence of RFI from the 328.23 MHz satellite wing which Gupta and Swarup calculated the orbital period.

FIG. 12 : **PREDICTED PROBABILITY DISTRIBUTION**

For loss between GMRT site and Pune and Mumbai. Predictions were made in 1987 or so by the National Physical Laboratory, New Delhi using "NPL Troposcatter Model" and were based on (I) Height profile between above stations and (ii) Statistics of Refractive Gradient of Air Measured by India Meteorological Department.

FIG. 12(a) : Predicted percentage probability of loss between Pune and the GMRT site, showing loss will be more than 150 dB for 83% of time.

FIG. 12(b) : Height path profile between Mumbai and GMRT site. The plots were made by Ganamurthi using Survey of India maps along the line of site from the GMRT site to the central part of Mumbai.

FIG. 12(c) : Predicted percentage probability of loss between Mumbai and the GMRT site, showing loss will be more than 150 dB 65% of time.

FIG. 12(d): Troposcatter loss estimated by T.L. Venkatasubramani from NBS Tech. Note 101, Vol. II (see RFI Report-Part XII)

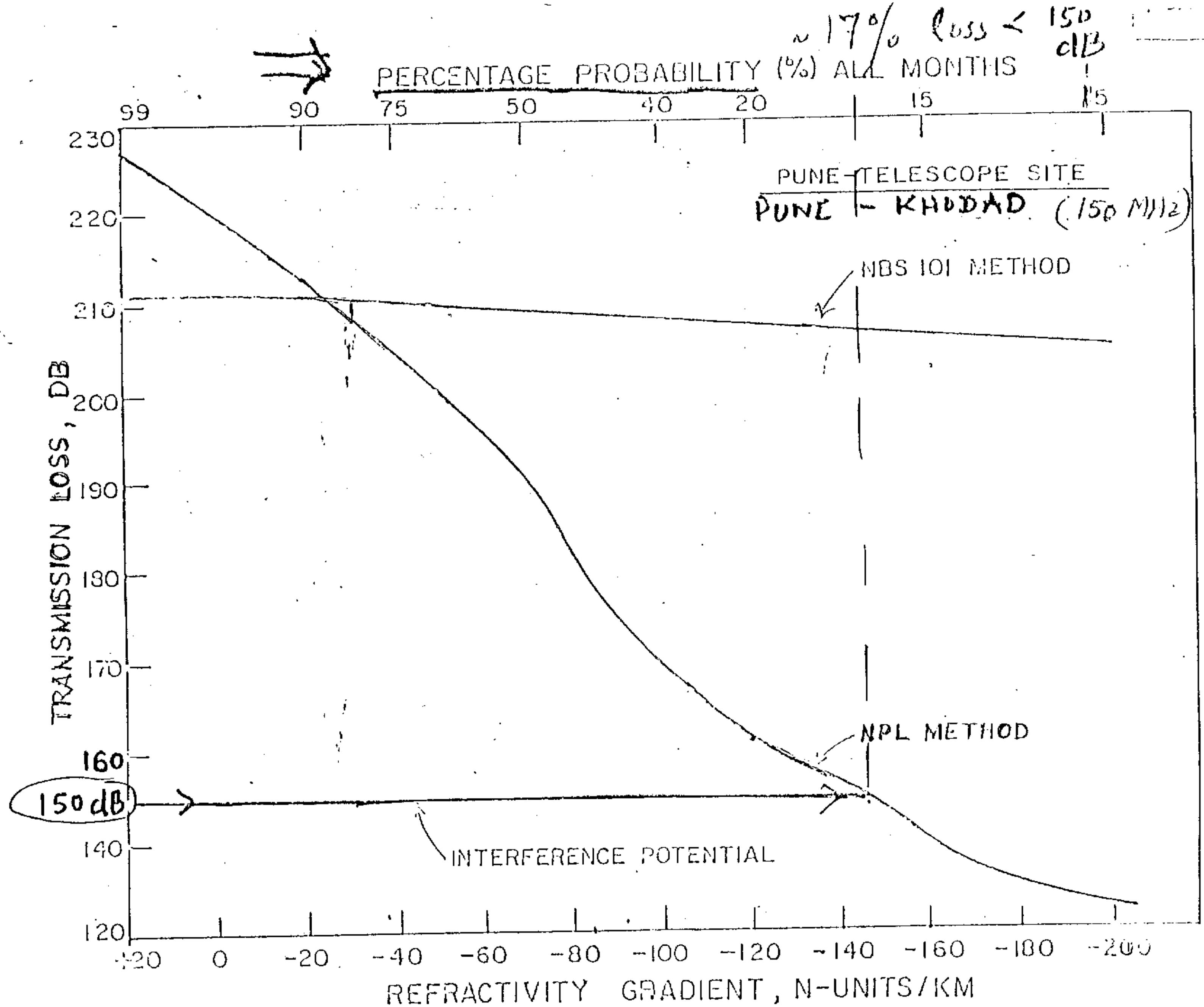


FIG. 12(a) The percentage probability of loss between Pune and GMRT site will lost at 150 dB for 17% of time.

HEIGHT PATH PROFILE BETWEEN BOMBAY AND GMRT SITE

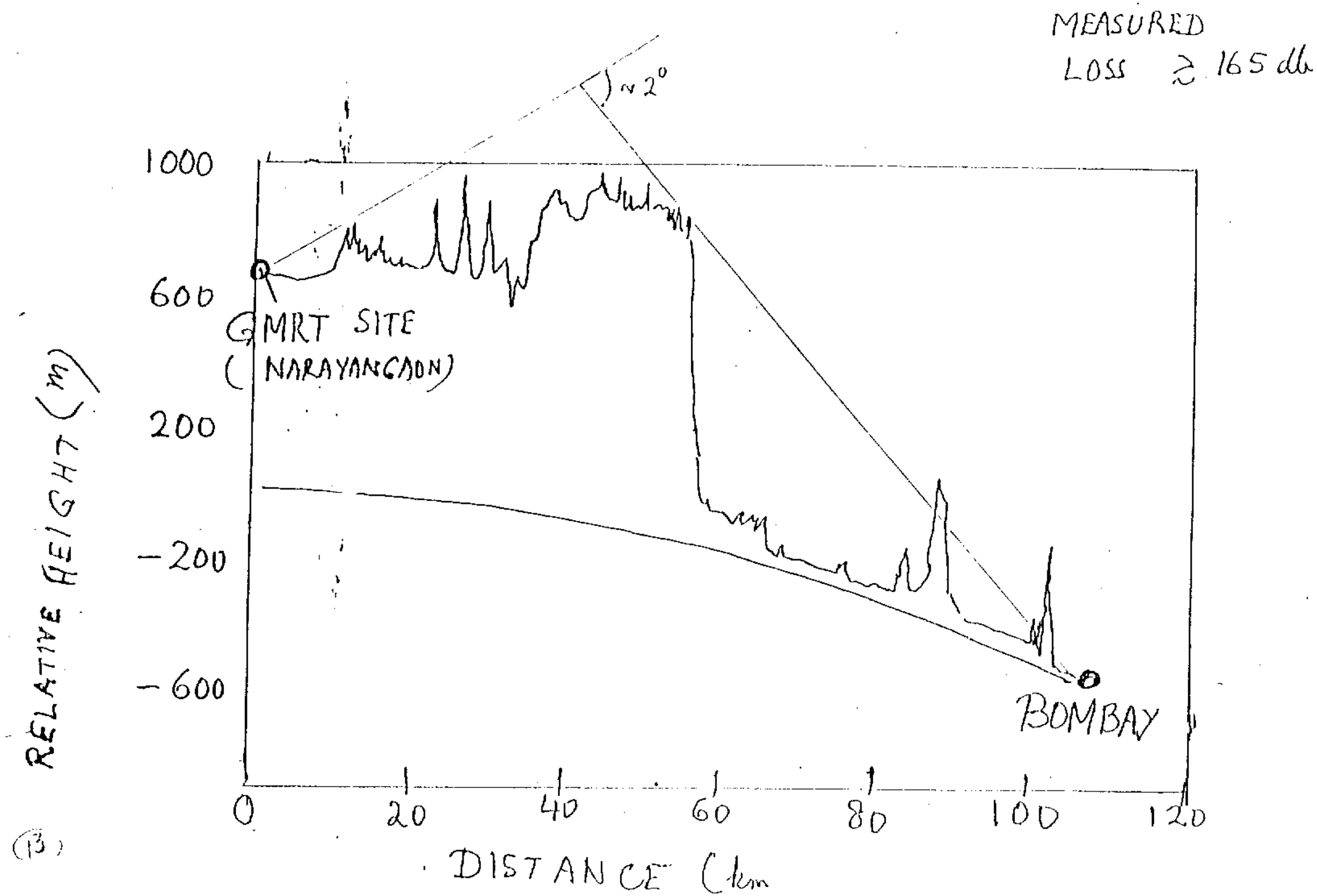


FIG. ~~13~~ 12(b) : Height path profile between Bombay and GMRT site. The plots were made using survey of India maps along the line of site from the GMRT site to the central part of Bombay.

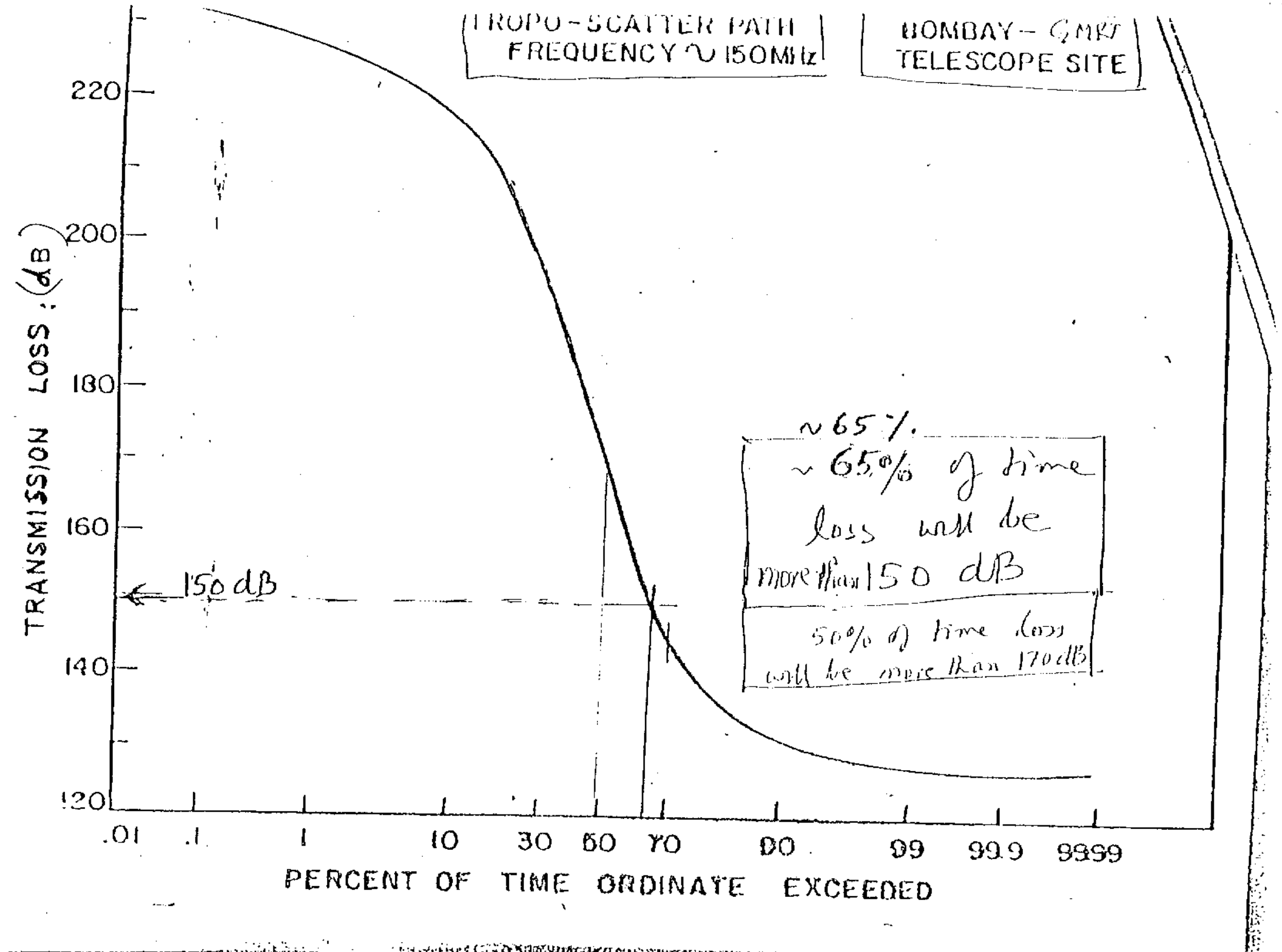


FIG. ~~14~~ 12 (c) The calculations of for Tropo-Scatter path as shown in Fig. ~~13~~ 12(b) ~~show~~ transmission loss by NPD. ~~The absissa~~ gives ~~percent of time ordinate exceeded at different values of losses. For e.g.~~ It may be noted that 65% of the time ~~will be lost at the~~ loss is expected to exceed 150 dB between Bombay and GMRT site.

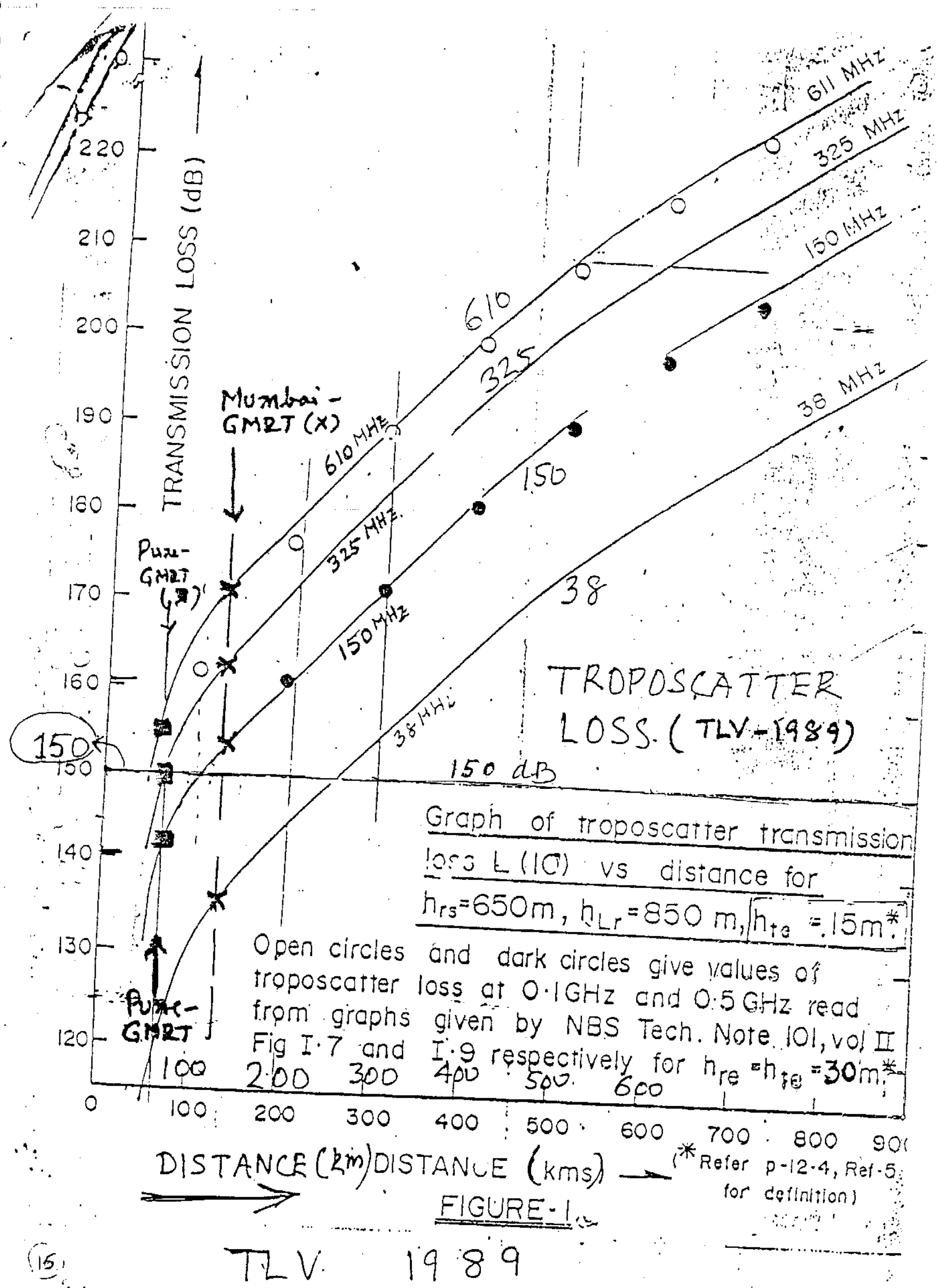


FIG. ~~16~~ 12(d) Tropscatter loss estimated by T.L. Venkatasubramani from NBS Tech. Note 101, Vol. II (see RFI Report-Part XII)

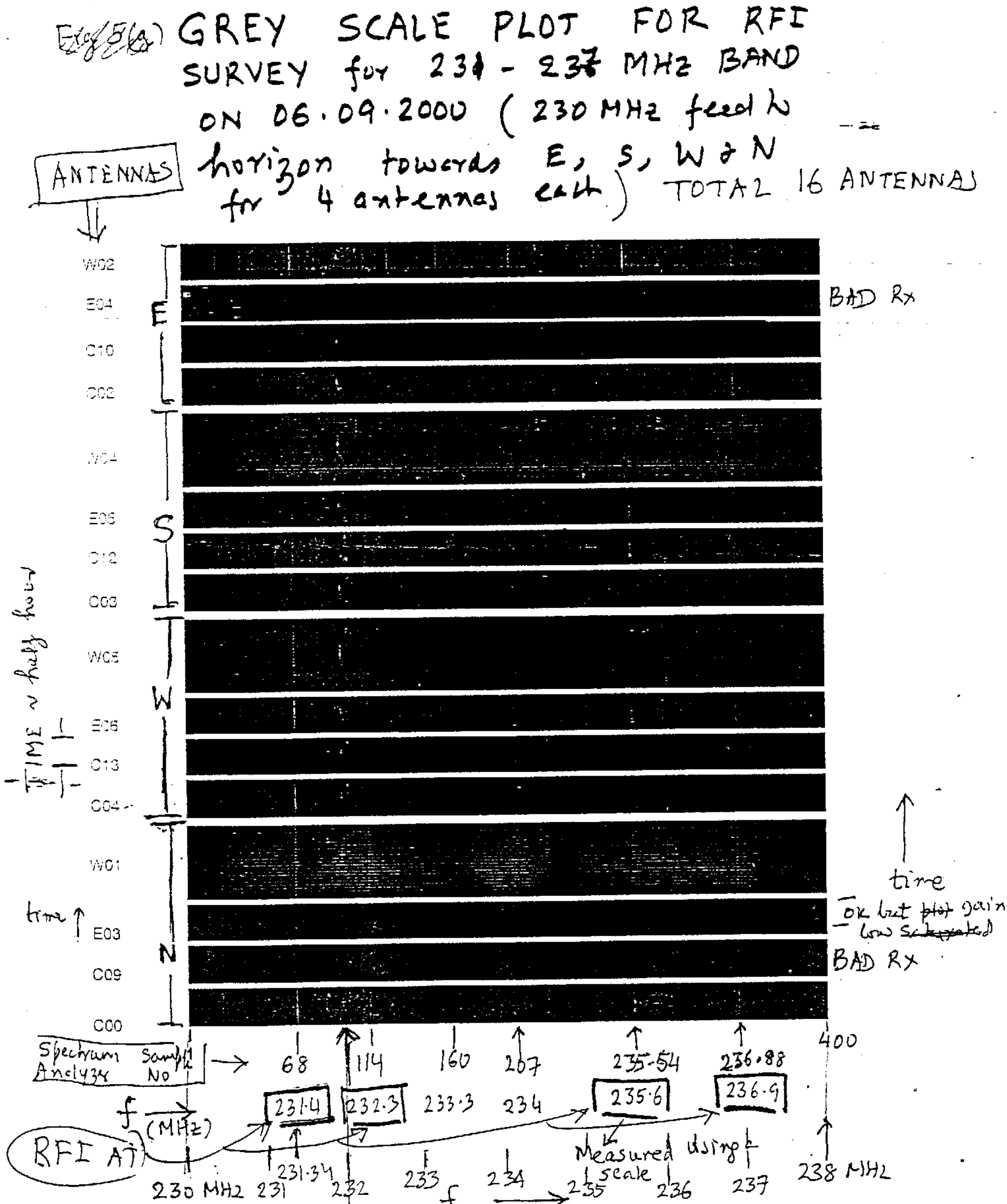
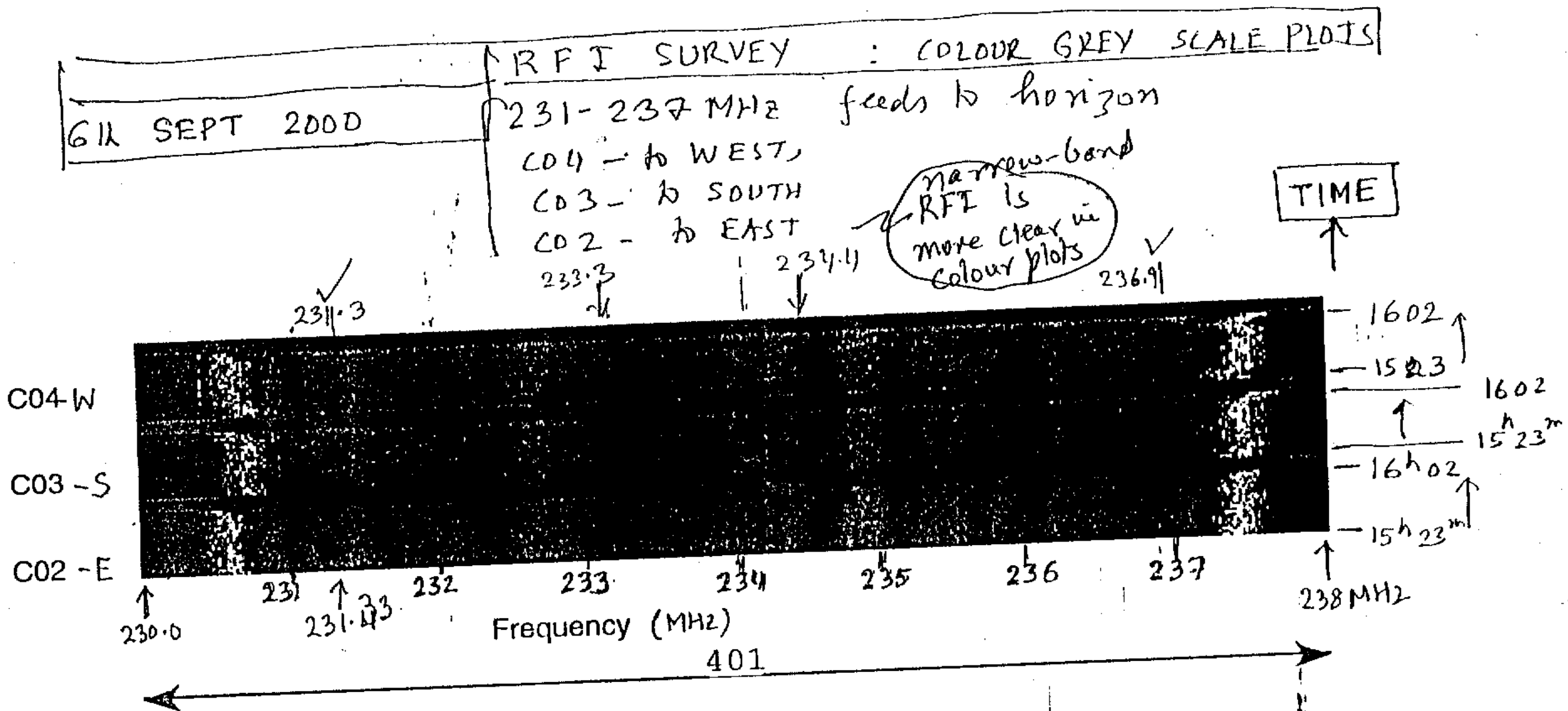


FIG. 13: Gray Scale Plot for RFI survey made over the 231-237 MHz band on 6th September 2000 with 230 MHz feed to the horizon towards E, S, W and N for 4 antennas in each direction. Horizontal axis is frequency and vertical ... although of



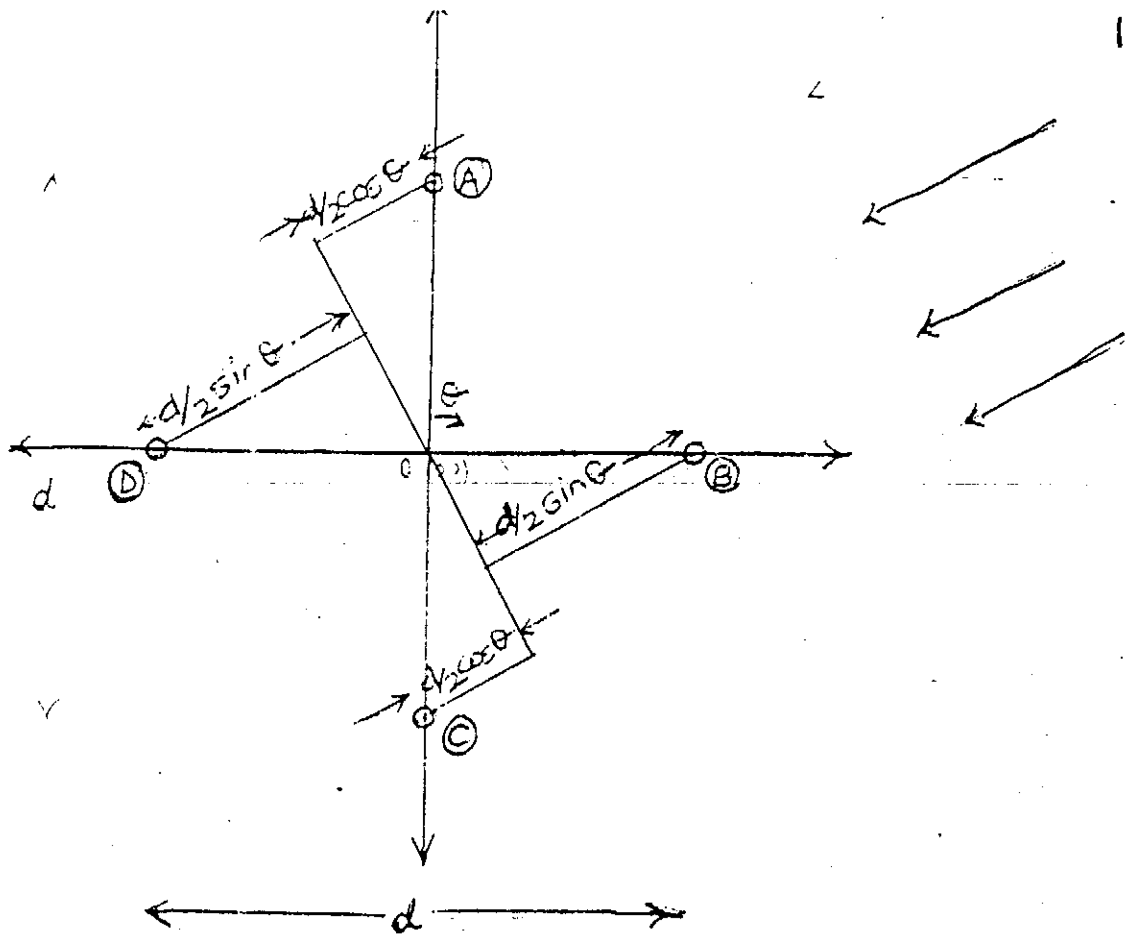
13(l.)
FIG. ~~5(h)~~ : Colour gray scale plot similar to Fig. 5(g) but for C04-W, C03-S and C02-E antennas only. The presence of RFI signals are much better seen in this ~~plot~~ colour plots

RFI Survey
OBS, Somsekhar, Sircard
Frezot
Transmitted 234/235 MHz from housing colony at N.Gaon.
(176 mm = 8 MHz)
Plots by Olievere Frezot 80 4
41 2
Expt suggested by G. Swarup

FIG. 14 : Proposed mobile Direction Finding Equipment using a set of four vertical monopoles/dipoles (broadband) separated by about 0.7λ in the mid-frequency range followed by set of amplifiers, filters, baseband unit and a digital correlator and a PC (correlations could be done in the PC) for measuring phase differences of the received RFI signals and thus ~~the~~ determine direction.

FIG. 14(a) Schematic showing four dipoles.

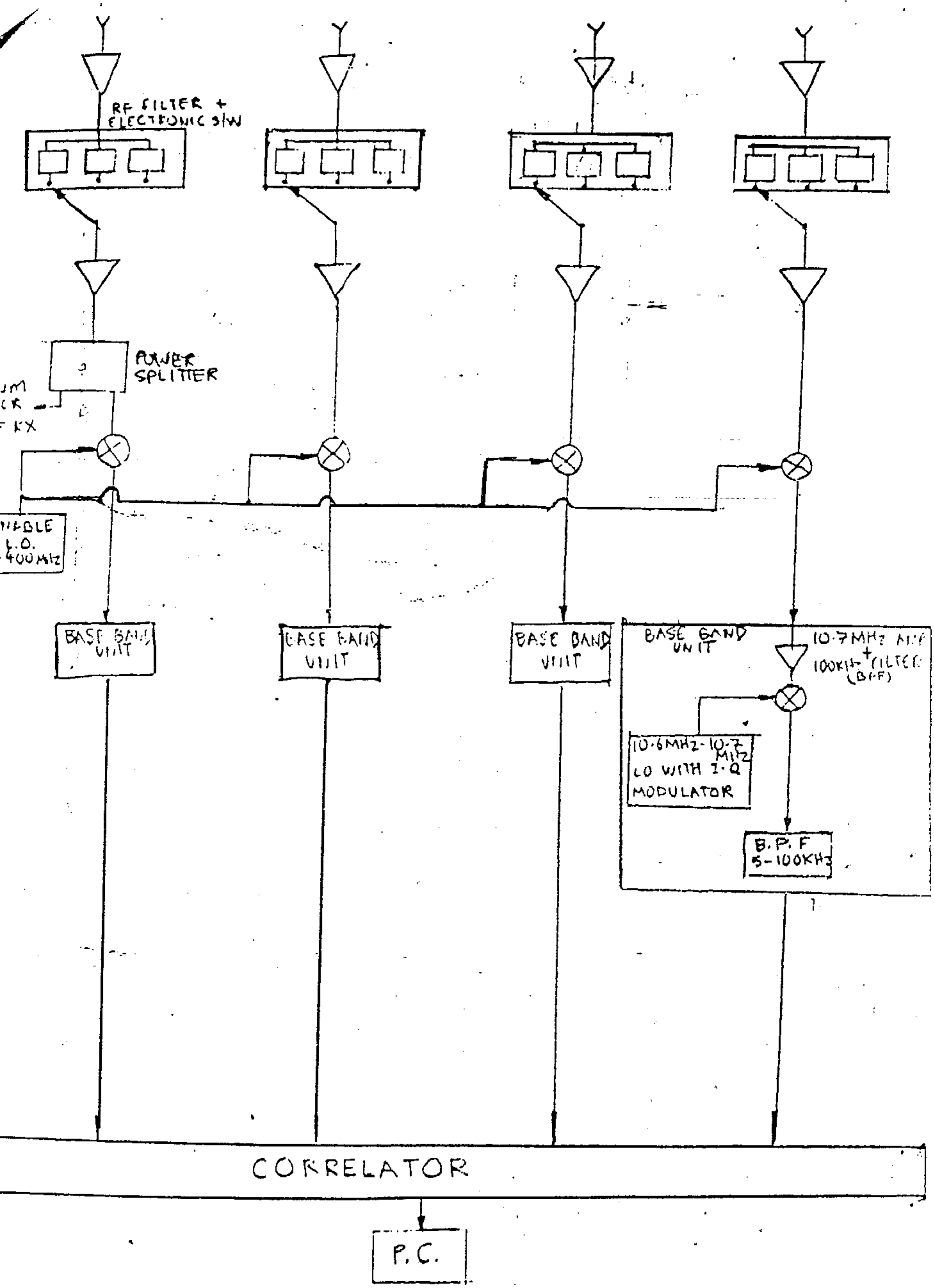
Fig. 14(b) : Schematic of receiver system.



~~Fig. 14~~

~~DIRF~~

Fig 14(a) Schematic Showing four dipoles



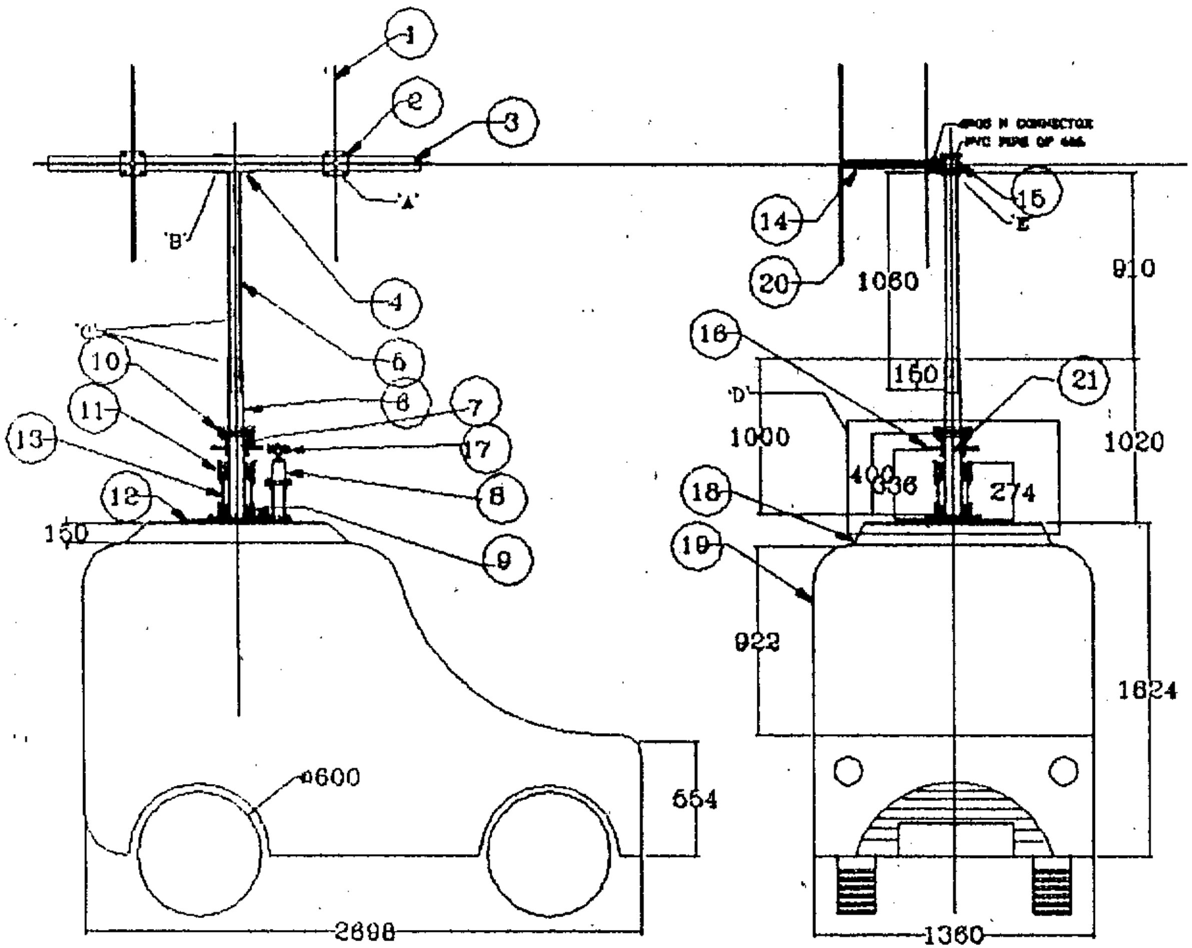
Schematic of Receiver System

Fig: 1

14 (h)

LOCK DIAGRAM OF PROPOSED DIR$^{N.}$ FINDING DEVICE

FIG. 15 : Schematic showing a Jeep-Mounted mobile direction finder under fabrication at NCRA for RFI in the 150 MHz and 235 MHz bands, using both horizontal and vertically polarized dipoles with reflector rods. Broad band Log periodic antennas can also be mounted.



SR.NO.	DESCRIPTION	SIZE	MAT'.	QTY.
21	SHAFT M/C'D	50 O.D. 48 I.D.	M.S.	1
20	TUBE	10 O.D.X6 I.D. X 80 LG	AL	16
19	GMRT JEEP	1526 X 2698	M.S.	1
18	CARRIER	200D. SQ.PIPES	M.S.	1
17	PINNION	16 TEETH X 4 MOD.	M.S.	1
16	GEAR	40TEETH X 4 MOD.	M.S.	1
15	U-BOLTS	10 DIA. X 70	M.S.	4
14	DIPOLE PIPE	16 O.D. X 465 LG.	AL	8
13	PIPE	100 NBX200 LG.	G.I.	4
12	PLATE	350X 350X8MM	M.S.	1
11	BEARING	NO.6010		1
10	FLANGE	55 I.D. X 210 O.D	M.S.	2
9	BEARING	NO. 6010 -SKF		1
8	STEPPER MOTOR	40 OZ.IN. X16 RPM		1
7	M/C'D PIPE	55 O.D.X50 I.DX400 LG	M.S.	1
6	PIPE 50NB	~~55 O.D.~~ X 50 I.D.X600 LG	G.I.	1
5	PIPE OD	48 ~~NB~~ X 1060 LG.	G.I.	1
4	PLATE	100X100X8MM	M.S.	2
3	PIPE	65MM O.D. 1800 LG.	PVC	1
2	PLATE	115X115X8MM	AL.	4
1	DIPOLES ROD	6MM O.D. X 480 LG.	AL.	16

OD

NATIONAL CENTRE FOR RADIO ASTROPHYSICS
TATA INSTITUTE OF FUNDAMENTAL RESEARCH, PUNE-07

DESIGN		TITLE
DRAN		RFI DIRECTION FINDER
CHECKED		ASSEMBLING
APPROVED		
DATE	9.4.2001	DRG:SA/TIFR/1 OF 10
SCALE	1:0.023	

FIG. 15 : Schematic showing a Jeep-Mounted mobile direction finder under fabrication at NCRA for RFI in the 150 MHz and 235 MHz bands, using both horizontal and vertically polarized dipoles with reflector rods. Broad band Log periodic antennas can also be mounted.

FIG. 16 : A block diagram showing the receiver set up for the RFI measurement equipment in a mobile jeep of Fig. 15. A similar set up is required for horizontal and vertical dipoles but a toggle or diode switch may be used for connecting to a single (SPA). A PC may be added for storing the data. Also required is a digital analog direction indicator using a magnet connected to a 360° potentiometer OR preferably a low cost GPS receiver costing about US $ 150.

FIG. 17 : Schematic showing the mounting of the proopsed Array of 8 broadband dipoles (140-350 MHz) on one of the 16 Rim trusses of 45-m antennas of GMRT which comes close to the ground when antenna is rotated to about 18 degrees to horizon. Broad details of mounting of dipole array and of the transmission will be suggested by G. Swarup if the scheme is approved in principle and can be worked out in full detail by a RF engineer. Transmission line consists of standard Al channel which is supported on 3 or 4 transverse tubular supports which are clamped to the RIM TRUSS using GI Bolts.

FIG. 18 : Block diagram suggesting a possible scheme for measuring the direction of RFI by installing 8-element dipole array on one of the 16 RIM Trusses of GMRT (See Fig. 17). Such arrays may be installed on 3 antennas of the Central Array seperated by about 1 km.

FIG. 19 : A schematic Block Diagram showing the required clipping/suppression action for minimizing the harmful action of RFI due to gap discharges on 11 kV or corona discharge of 110 kV/220 kV AC HT lines. Power output of AGC unit of the IF chain at the base of each GMRT antennas is amplified, so as to allow clipping using diodes to about +/- four standard deviation, each time a pulsed RFI is detected, and attenuated afterwards so that RMS remains same, in the absence of RFI. One may also consider suppressing data during the period of pulsed RFI. (See discussions Part-VII of this series of report).

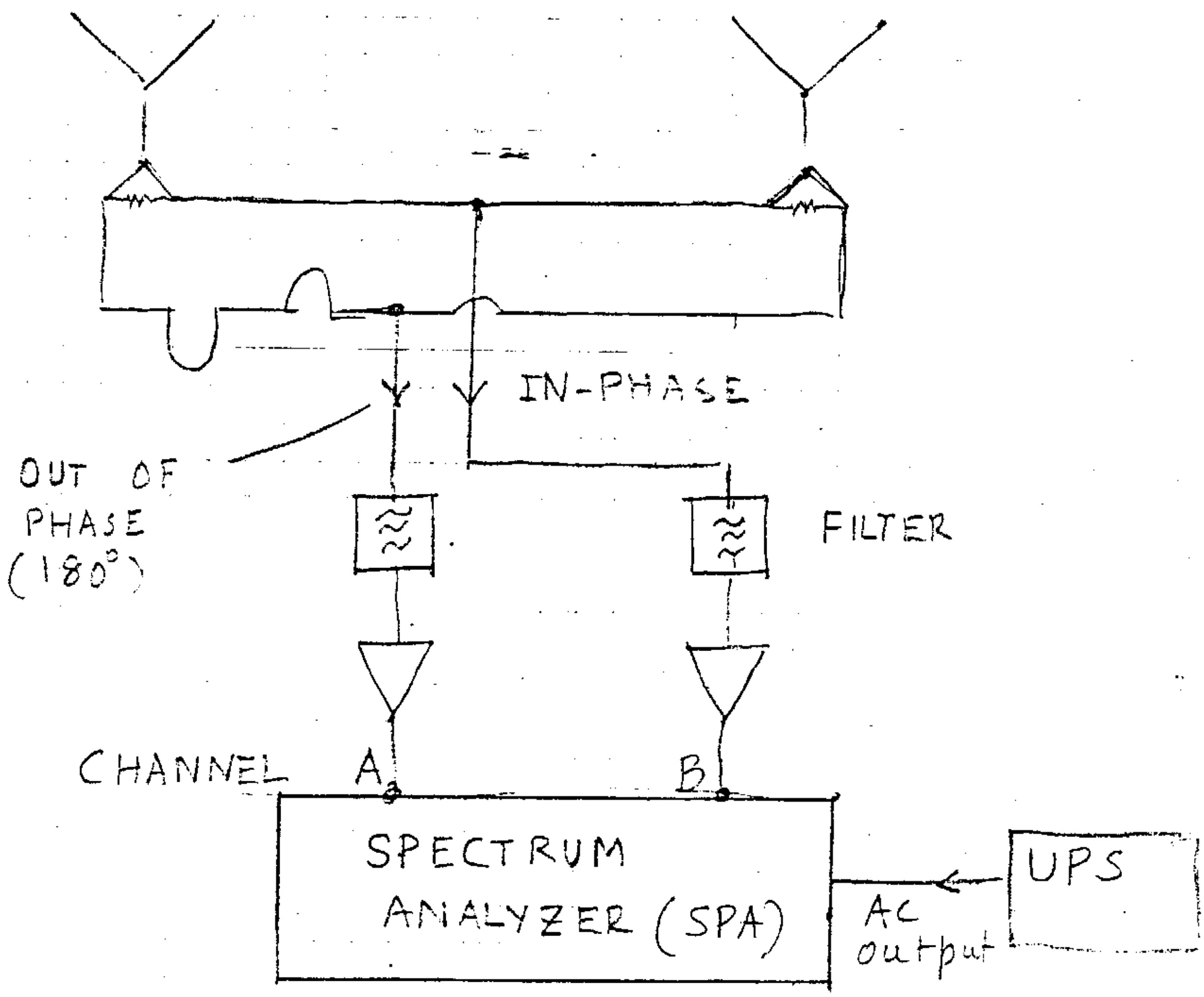


FIG. 16 : A block diagram showing the receiver set up for the RFI measurement equipment in a mobile jeep of Fig. 15. A similar set up is required for horizontal and vertical dipoles but a toggle or diode switch may be used for connecting to a single (SPA). A PC may be added for storing the data. Also required is a digital analog direction indicator using a magnet connected to a 360° potentiometer OR preferably a low cost GPS receiver costing about US $ 150.

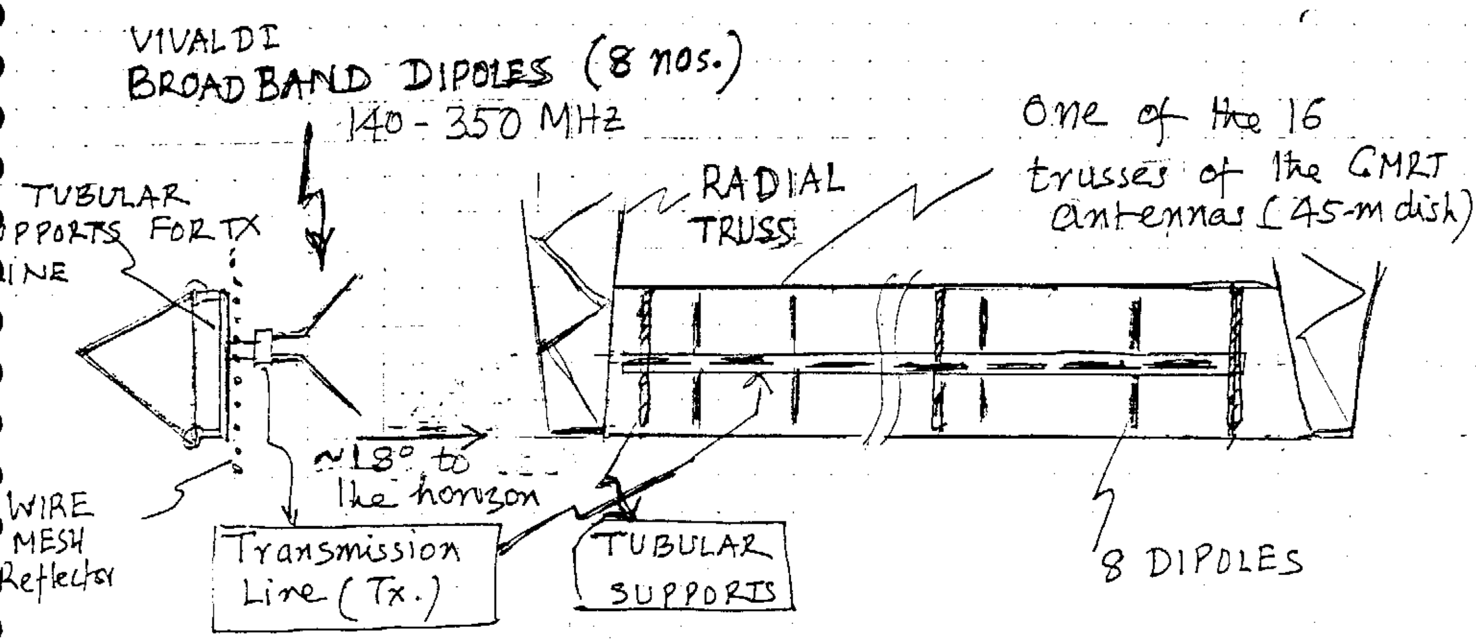


FIG. 17 : Schematic showing the mounting of the proopsed Array of 8 broadband dipoles (140-350 MHz) on one of the 16 Rim trusses of 45-m antennas of GMRT which comes close to the ground when antenna is rotated to about 18 degrees to horizon. Broad details of mounting of dipole array and of the transmission will be suggested by G. Swarup if the scheme is approved in principle and can be worked out in full detail by a RF engineer. Transmission line consists of standard Al channel which is supported on 3 or 4 transverse tubular supports which are clamped to the RIM TRUSS using GI Bolts.

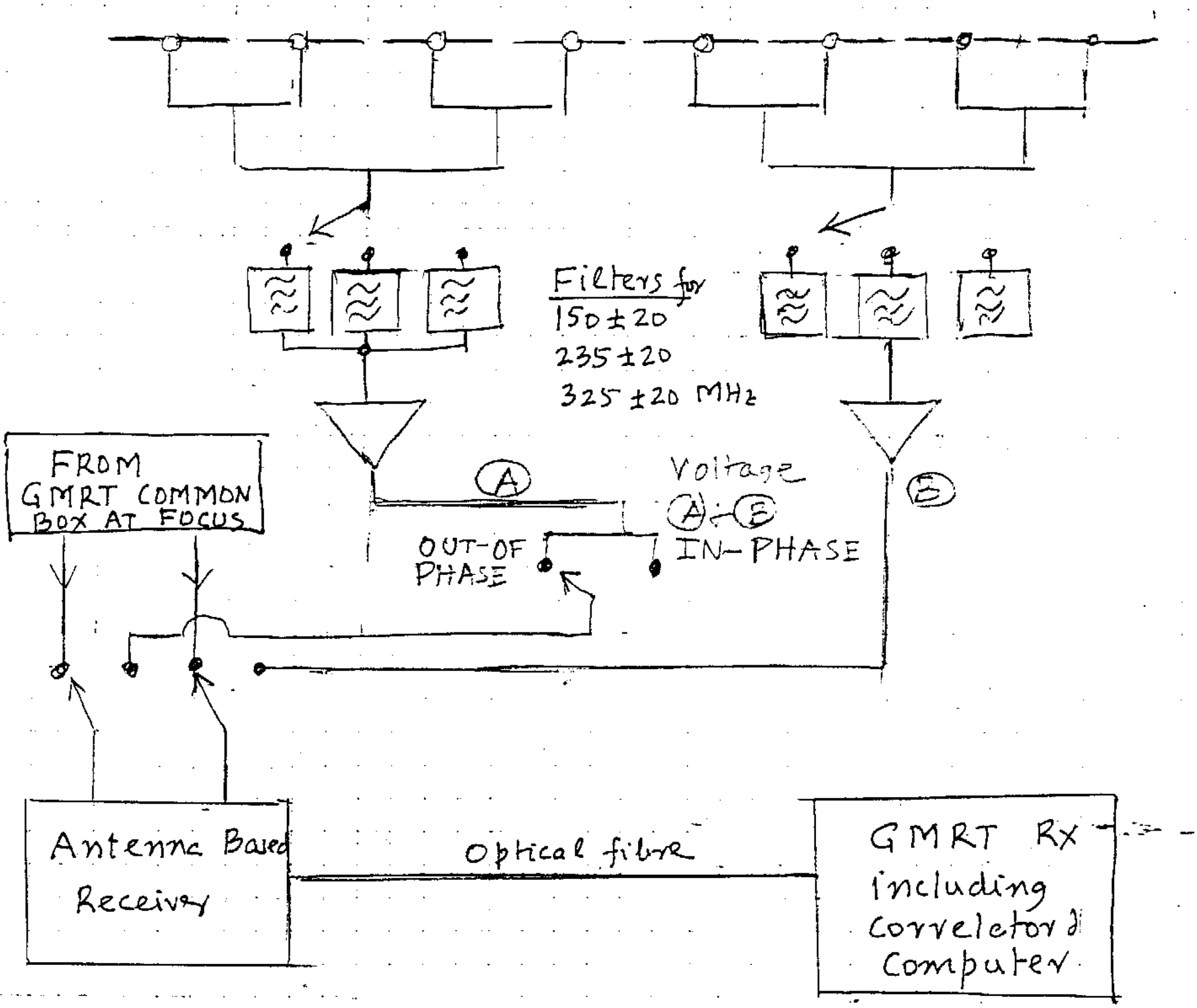


FIG. 18 : Block diagram suggesting a possible scheme for measuring the direction of RFI by installing 8-element dipole array on one of the 16 RIM Trusses of GMRT (See Fig. 17). Such arrays may be installed on 3 antennas of the Central Array seperated by about 1 km.

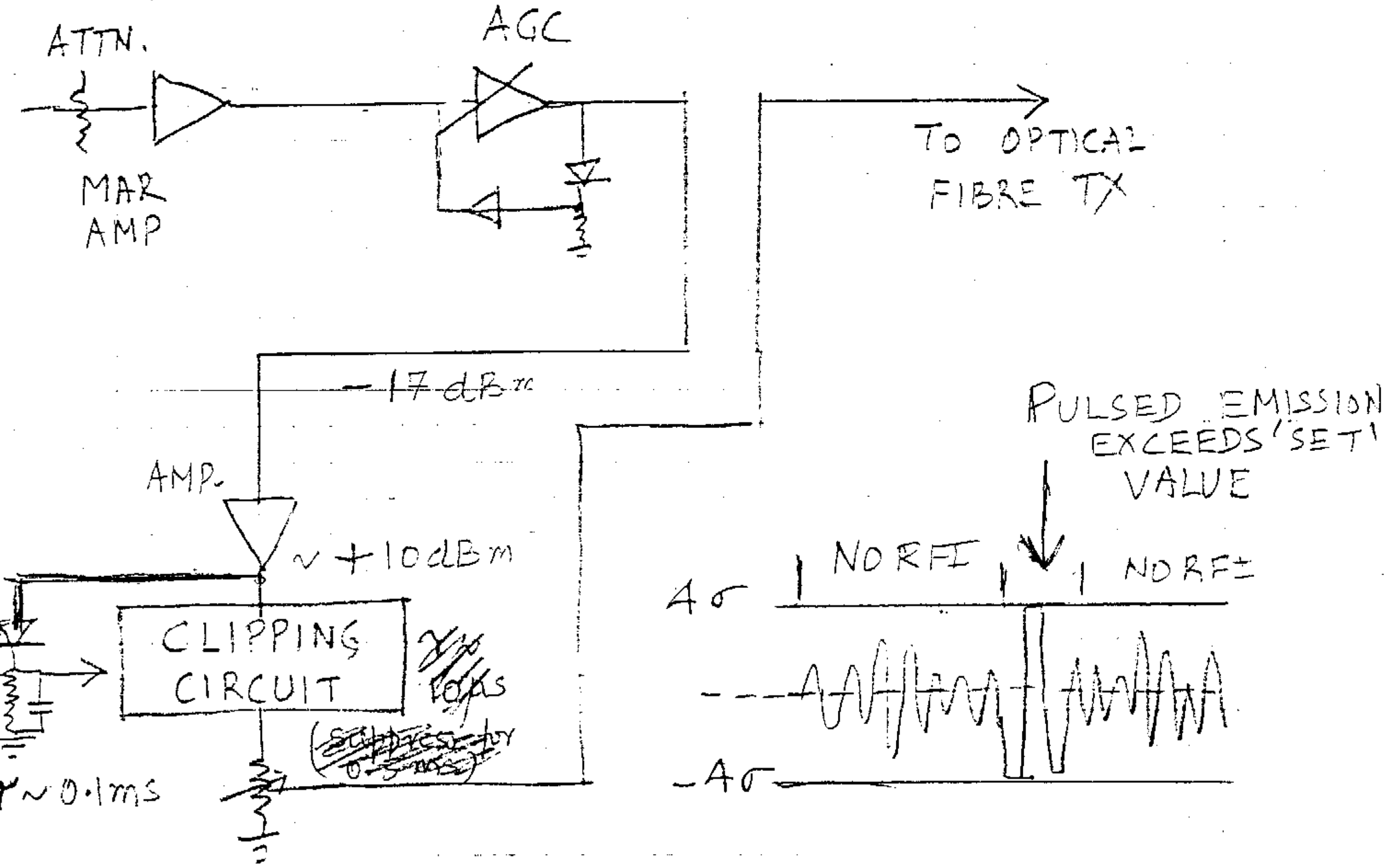


FIG. 19 : A schematic Block Diagram showing the required clipping/suppression action for minimizing the harmful action of RFI due to gap discharges on 11 kV or corona discharge of 110 kV/220 kV AC HT lines. Power output of AGC unit of the IF chain at the base of each GMRT antennas is amplified, so as to allow clipping using diodes to about +/- four standard deviation, each time a pulsed RFI is detected, and attenuated afterwards so that RMS remains same, in the absence of RFI. One may also consider suppressing data during the period of pulsed RFI. (See discussions Part-VII of this series of report).

FIG. 20 : Circles giving Protection Zones for GMRT on a map of Western India.

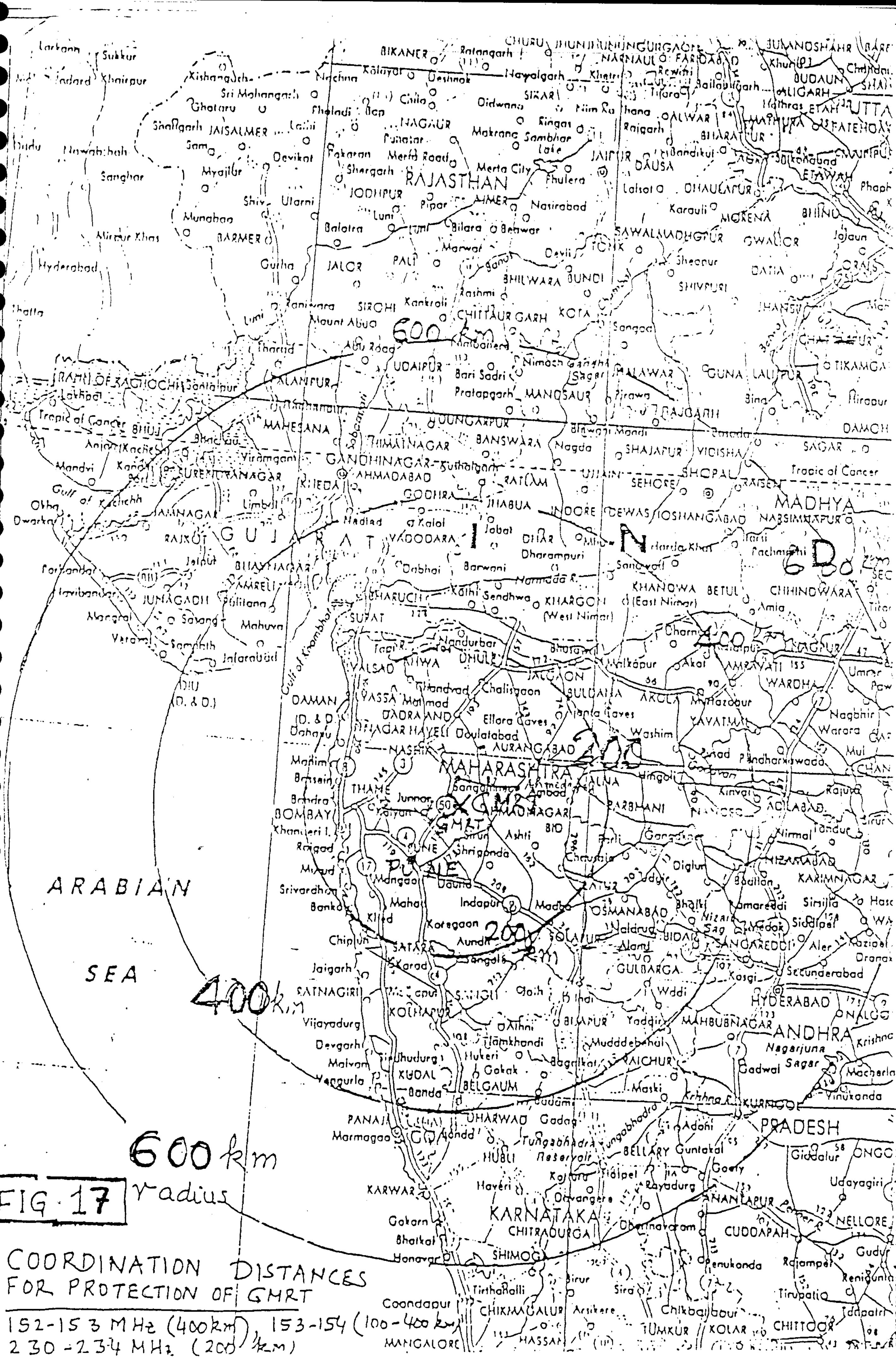


FIG. 20 : Circles giving Protection Zones for GMRT on a map of Western India.

FIG. 21 : Map showing locations near GMRT site (Alephata, Kandali, Jambut, Kukdi & Junnar) Sangamneer, Pune, Khandala and Lonavala where RFI measurements were made in 1998 by Shiralkar and others as coordinated by G. Swarup (See Figs. 1(e) and 2(e)).

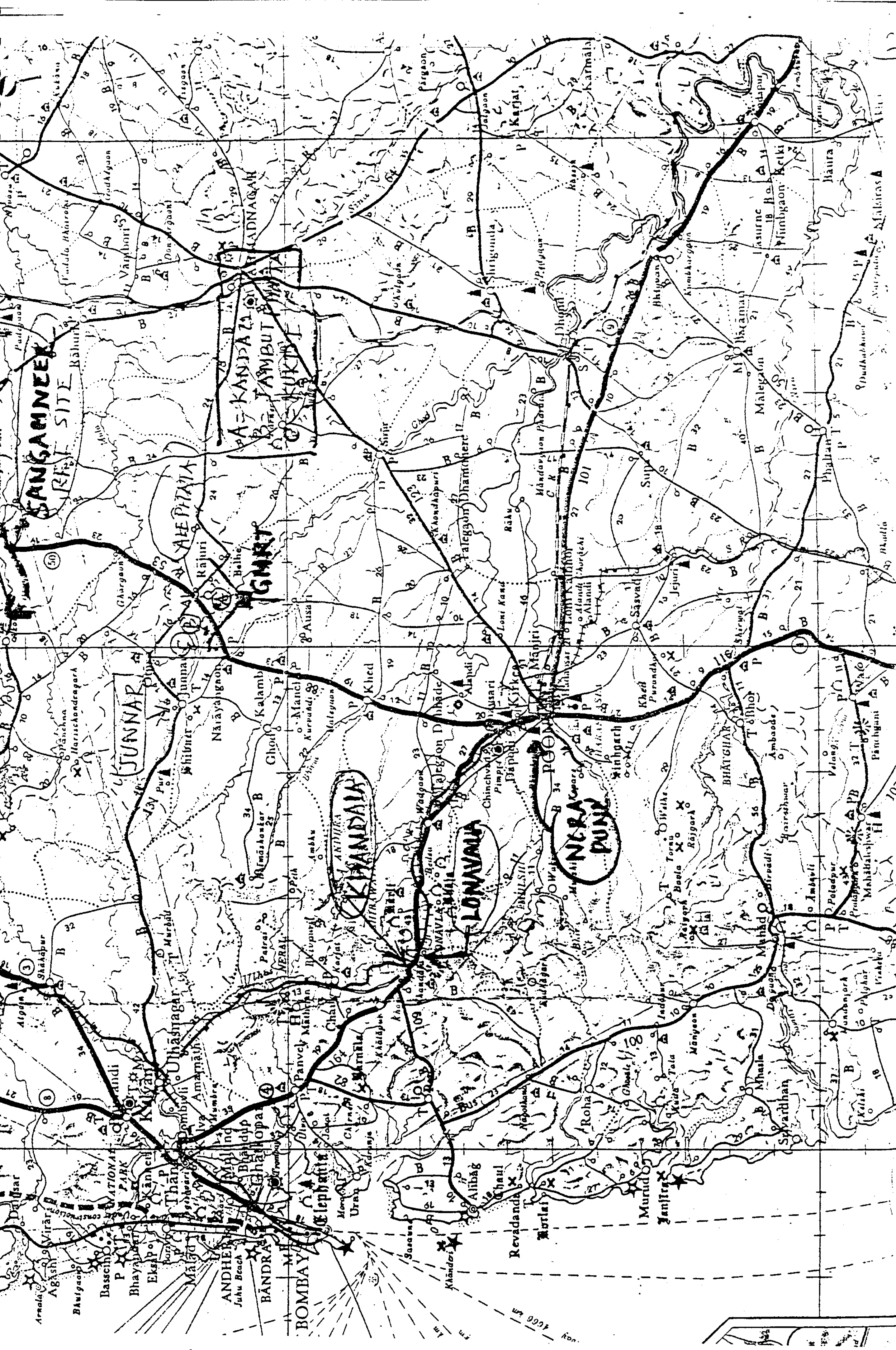


FIG. 21 : Map showing locations near GMRT site (Alephata, Kandali, Jambut, Kukdi & Junnar) Sangamneer, Pune, Khandala and Lonavala where RFI

The Giant Metrewave Radiotelescope

By G. SWARUP, S. ANANTHAKRISHNAN,
C. R. SUBRAHMANYA, A. P. RAO,
V. K. KULKARNI AND V. K. KAPAHI

National Centre for Radio Astrophysics, TIFR
Pune University Campus, Pune 411 007, India.

The Giant Metrewave Radio Telescope (GMRT) under construction in India is a major new facility in the field of radio astronomy. GMRT consists of 30 fully-steerable parabolic dishes of 45-m diameter each. Twelve of the dishes are located in a central array of about 1 km $\times$ 1 km in size and the other eighteen along three arms of an approximately Y-shaped array, providing a maximum baseline of $\sim$ 25 km. Signals received by the 30 antennas are brought together to a central laboratory using coherent local oscillators and optical fibre links. GMRT will operate in the following frequency bands protected for radio astronomy in India : 37.75-38.25 MHz, 152-155 MHz, 230-235 MHz, 322-328.6 MHz, 608-614 MHz and 1400-1427 MHz. However, the front-end amplifiers have bandwidths varying from about 20 MHz to 40 MHz for the above frequency bands but cover 1000-1430 MHz for the highest frequency range. Narrower bandwidths can be selected in the IF and baseband systems. It has been possible to build the light weight 45-m dishes quite economically using a novel concept, nicknamed SMART (Stretched Mesh Attached to Rope Trusses).

One of the important scientific objectives of GMRT is to search for neutral hydrogen clouds prior to the formation of galaxies and clusters in the Universe. The signals are expected to be extremely weak and may occur somewhere in the frequency range of 150-600 MHz. GMRT will, however, be a versatile instrument for investigating a variety of other astrophysical problems concerning the sun, radio stars, pulsars, HII regions, supernova remnants, the Galactic centre, nearby galaxies, radio galaxies, quasars and cosmology.

Twenty-four of the thirty dishes have been taken over by TIFR after the installation of the mechanical drives; the remaining antennas are expected to be completed by May 1996. Astronomical observations, calibrations, on-line programming and debugging have been done using four antennas since September 1993. Electronics systems have been installed on eleven more antennas recently and it is hoped that the first astronomical maps will be available within a couple of months. The full telescope is expected to be ready by late 1996.

1. Introduction

The Giant Metrewave Radio Telescope is being set up in India by the National Centre for Radio Astrophysics (NCRA), Pune, which is a part of the Tata Institute of Fundamental Research. It will provide a large collecting area over a wide frequency range of about 38 to 1430 MHz. The two most important scientific objectives that have been kept in mind while designing GMRT are (a) to detect the highly-redshifted 21-cm line of neutral hydrogen from protoclusters or protogalaxies, and (b) to search for and study a large number of rapidly-rotating pulsars in our Galaxy. However, the specifications of GMRT will make it a highly versatile instrument for investigating a variety of other astrophysical problems concerning objects in our solar system, the Milky Way, nearby galaxies, clusters of galaxies and the very distant radio galaxies and quasars.

GMRT consists of thirty fully-steerable parabolic dishes of 45 m diameter each, located over a region of about 25 km (Swarup et al. 1991). It is now in an advanced stage of completion and is expected to become operational by end-1996. The array configuration of GMRT is briefly described in Section 2 and the major design features of the GMRT

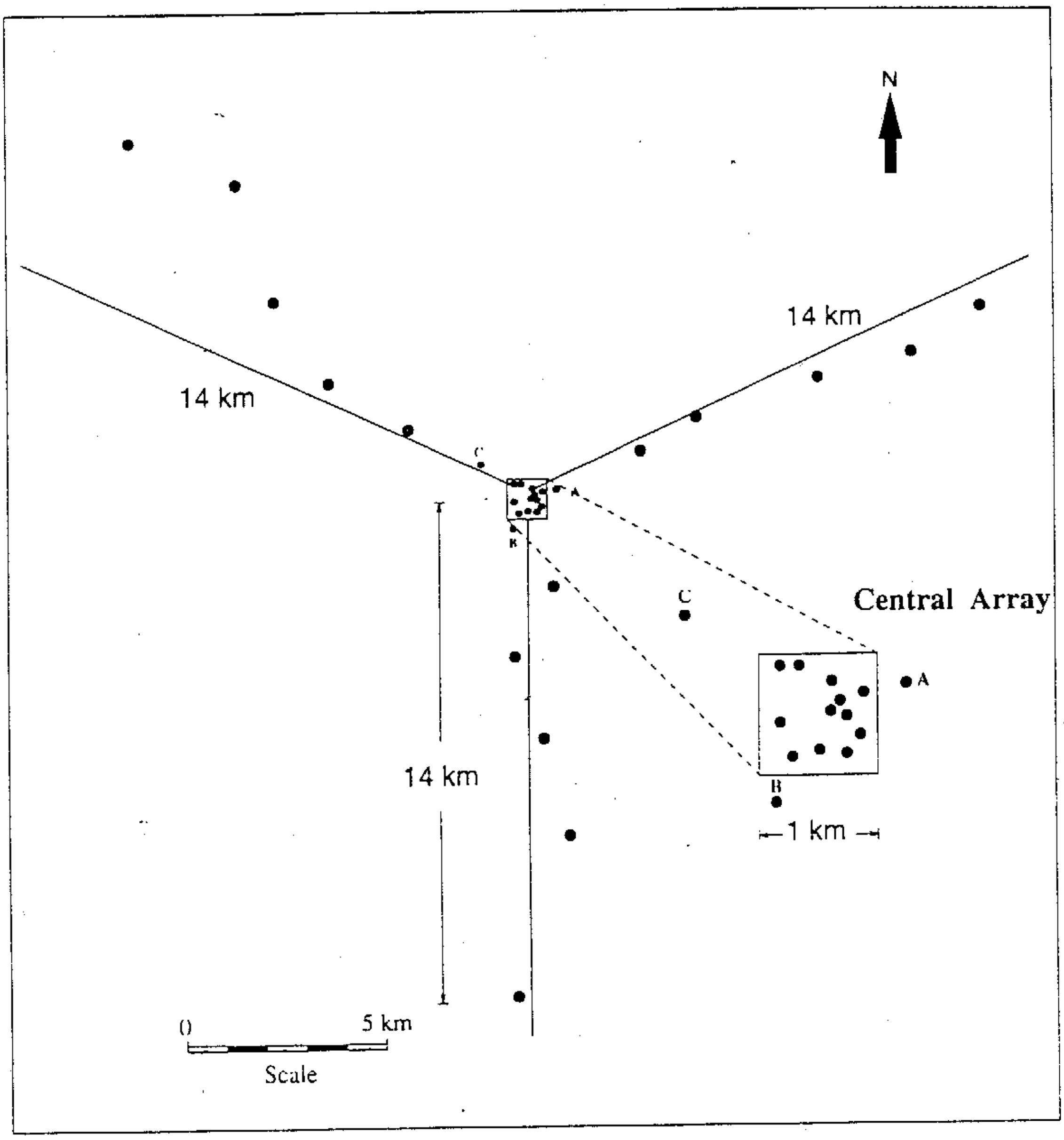


FIGURE 1. Array Configuration of the thirty 45 m diameter dishes of GMRT

dishes and of the electronics system are summarised in Sections 3 and 4 respectively. In Section 5, we give the expected system parameters and results of some recent performance tests. A few examples of the astronomical capabilities of GMRT are mentioned in Section 6.

2. Array Configuration

GMRT operates as an "Earth Rotation Aperture Synthesis Radio Telescope" (Thompson et al. 1986). Its array configuration has been chosen so as to be sensitive to both compact and broad features of celestial radio sources. Twelve antennas are placed somewhat randomly in a central array with a maximum baseline of about 1.1 km. The other 18 antennas are distributed along the three 14-km-long arms of a Y-shaped configuration (Fig. 1). With its 30 antennas, GMRT would measure 435 Fourier components of the brightness distribution across a radio source at any given instant and roughly a million components in about a 12-hr period of observation.

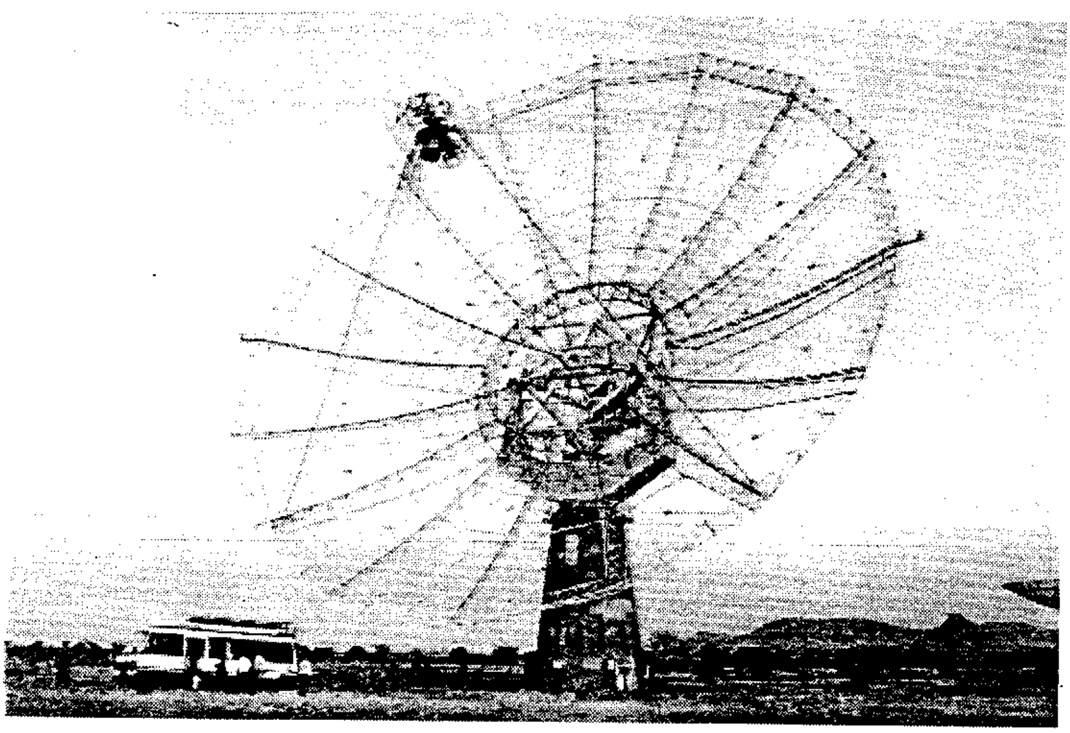


FIGURE 2. A photograph showing a 45-m diameter GMRT dish

3. Design Features of the GMRT Dishes

The antenna system forms a major part of the cost of a radio telescope. Since the galactic background temperature at high latitudes varies as $\sim 50\ \lambda^{2.7}$ K, where λ is the wavelength in metres, the system temperature of a radio telescope is dominated at the longer wavelengths by the Galactic background temperature rather than the receiver temperature. Hence it becomes necessary to construct a large collecting area for a sensitive metrewave radio telescope. After investigating many alternative possibilities, a novel concept was developed, nicknamed SMART (Stretched Mesh Attached to Rope Trusses), resulting in considerable economy in the cost of the 45-m-diameter dishes (Swarup, 1990; Swarup et al. 1991). In this concept, the reflector surface of the antenna is made of low solidity wiremesh, which is supported by rope trusses attached to the backup structure of the dishes. This design cuts down forces due to wind load on antennas. A 45-m-diameter parabolic dish was preferred for the elements of the GMRT, rather than a more economical parabolic cylindrical antenna or a cluster of several smaller dishes, say 4 dishes of 22.5-m diameter, in order to avoid complexity of the electronics system and also to have a relatively small primary-beam size to minimize the effects of the non-isoplanaticity of the ionosphere.

The backup structure of the 45-m parabolic dish consists of 16 radial parabolic frames made of tubular steel and connected to a 12-m-diameter central hub (Fig. 2). The outer edges of the radial frames are connected to a triangular rim truss and are also interconnected using guy ropes for rigidity. Circumferential stainless steel wire rope trusses of 4 and 2.5-mm diameter are connected to anchor blocks of adjustable height which are welded to the parabolic frames at spacings of 1.2 metre (Fig. 3). These rope trusses are suitably adjusted and tensioned to give a roughly parabolic curvature to the top wire ropes. Wiremesh panels made of 0.55-mm-diameter thin stainless-steel wires are then stretched on the rope trusses to form a series of plane facets approximating the paraboloidal reflecting surface. The mesh has a size of 10 mm × 10 mm in the central

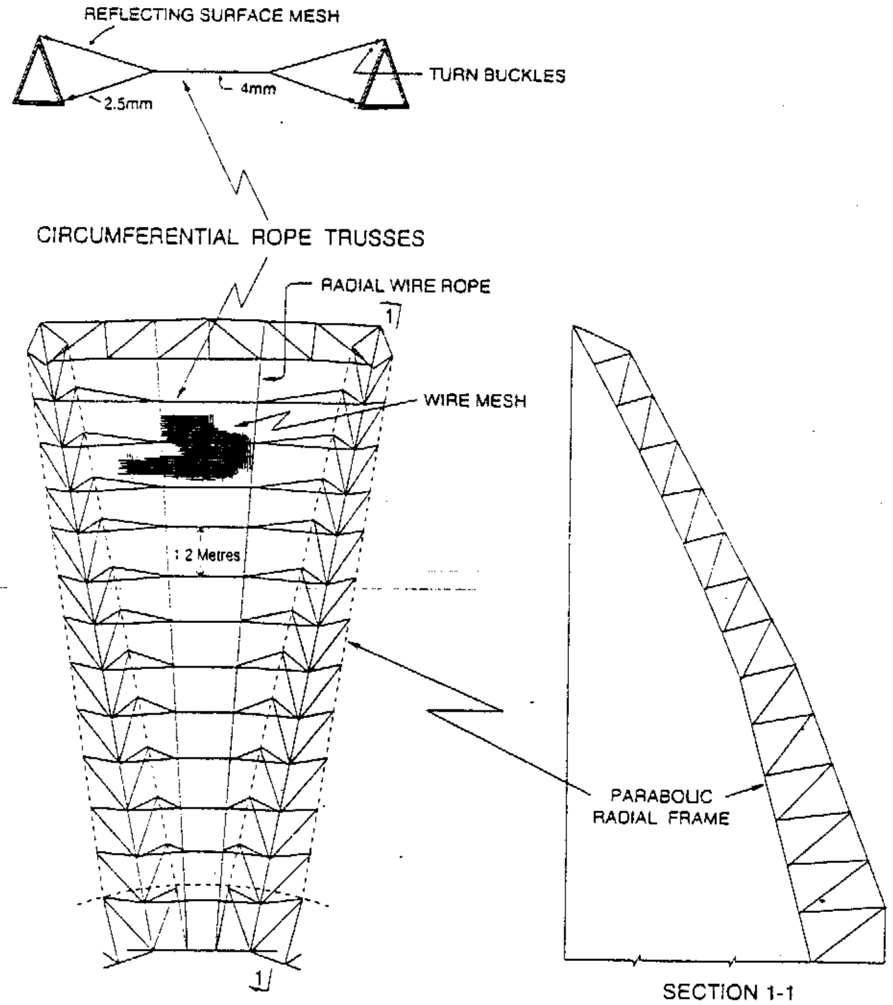


FIGURE 3. A section of the GMRT dish illustrating the SMART (Stretched Mesh Attached to Rope Trusses) concept

one-third, 15 mm × 15 mm in the middle one-third and 20 mm × 20 mm in the outer one-third aperture of the dish. The expected reflectivity of the wire mesh at 1420 MHz is about 95 per cent and the contribution of the ground radiation is thus only about 5 per cent. The measured value of the root-mean-square deviation of the surface from a true paraboloid is about 10 mm for the completed 45-m dishes.

The central hub of the parabolic dish is connected to a cradle at 4 points. The cradle is supported by two elevation bearings on the top of a U-shaped yoke. A bullgear is connected to the cradle which allows rotation of the 45-m dish in elevation from about 17 deg to 110 deg from the horizon. The yoke is placed on a 3.6-m-diameter slewing ring bearing, with a built-in gear-wheel which forms part of the azimuth drive system. The slewing ring bearing is supported on a concrete tower of 12-m height. A counter-torque system, consisting of a pair of 6-hp servo motors each, is connected to the elevation bull-gear and similarly for the azimuth slew-ring gear through a pair of planetary gear boxes, providing a total gear reduction of about 25000:1 and 18000:1 respectively. Seventeen-bit encoders are connected to both elevation and azimuth axis. Measured rms tracking accuracy of the antennas is about 20 arcsecond which is negligible compared to the antenna beam-width at 1420 MHz.

The total weight of the parabolic dish including yoke is only about 85 tonnes. This is much lower than the typical weight of about 250 tonnes for the structural parts of a 25-m dish, operating at cm and decimetre wavelengths.

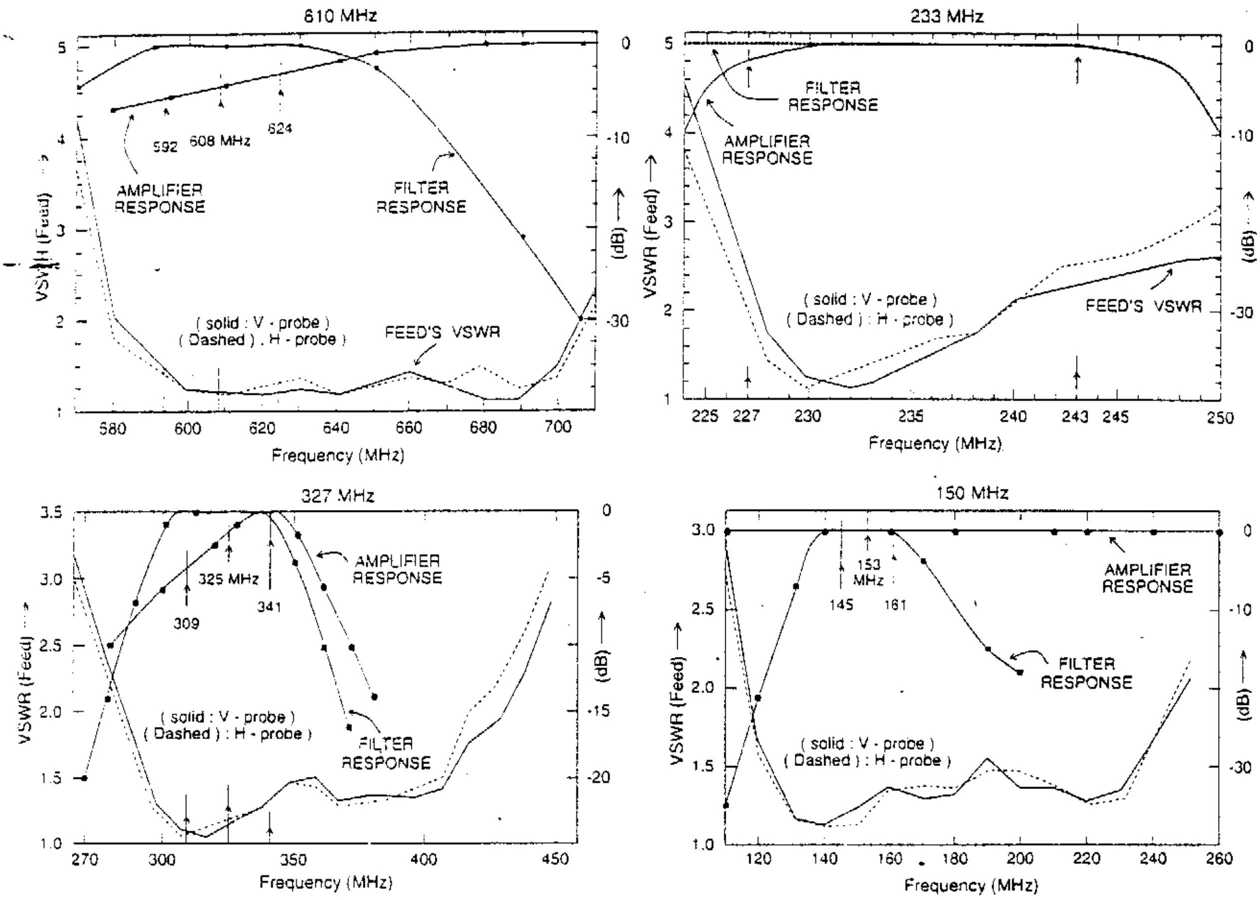


FIGURE 4. Voltage Standing Wave Ratio (VSWR) for two linear dipoles or probes and amplifier and filter responses for feeds operating at 150, 233, 327 and 610 MHz.

4. Electronics System

GMRT is to operate in six different frequency bands as follows : 50 ± 13, 153 ± 16, 235 ± 8, 325 ± 16, 610 ± 16, and 1000-1430 MHz. The 50 and 150-MHz primary feeds consist of two orthogonal pairs of dipoles at spacings of $0.5\,\lambda$, placed in a quad-formation. However, while the 150-MHz feed is placed above a ground plane, the 50-MHz feed is backed-up by linear rod-reflectors. All the primary antenna feeds, except the 50-MHz feed, are mounted near the focus of the 45-m dish on a rotating cage supported by a quadrupod structure. The 50-MHz feed is permanently fixed to the quadrupod structure. The 325-MHz feed consists of 2 orthogonal half-wave dipoles in a cross formation with a beam forming ring placed above a ground plane having a diameter of about one wavelength (Kildal 1982). Dual concentric coaxial feeds are used at 235 and 610 MHz. A broad-band horn has been developed by the Raman Research Institute to cover the frequency range of 1000-1430 MHz.

The performance of the 150, 235/610 and 325-MHz feeds are shown in Figs. 4. It is seen that the 150-MHz feed provides frequency coverage over a bandwidth of about 1.8:1 but the bandwidth of the other feeds is limited. Over the next few years, it is proposed to replace some of these feeds with broadband feeds in order to provide a near-continuous frequency coverage from about 130 MHz to 1430 MHz.

The outputs of all the feeds (except the 1.4-GHz feed) are connected to polarisers giving Right-handed (RH) and Left-handed (LH) signals. The 1000-1430 MHz feeds provide two orthogonal linear polarizations. The feeds are followed by low-noise amplifiers with RF filters. The RF outputs are brought to a LO-IF system placed at the bottom of the concrete tower of each antenna.

The local oscillators (LOs) are phase-synchronized to a master oscillator placed in the central electronics building (CEB) located near the centre of the GMRT array. The RF signals received by each antenna are down-converted to 32-MHz wide IF signals at 70 MHz using the above LO. The IF signals for the two polarizations are then frequency translated to 130 and 175 MHz using a set of second LOs. The two IF signals are then combined and transmitted to the CEB on optical-fibre links. The optical-fibre links are also used for transmitting reference signals at 106 MHz, 201 MHz and 97.5 ± 1 MHz from the CEB to the different antennas for the purpose of phase synchronization of the local oscillators, and also for sending the telemetry signals required to control and monitor all the GMRT antenna and receiver systems. At the CEB, a third Local Oscillator translates the 130/175-MHz IF signals (of 32 MHz bandwidth each) back to 70 MHz and these are then down-converted using a 4th LO giving two 0-16 MHz baseband signals for each of the two polarizations. The receiver bandwidth can be restricted using saw filters placed in the IF chain at the antennas to either 5.5, 16 or 32 MHz and finally in 9 binary steps from 64 kHz to 16 MHz in the baseband system. Attenuators are placed in both the RF and IF systems to allow observations of the Sun and other strong sources.

The baseband outputs from each of the four outputs of the 30 antennas are then digitised by a 4-bit sampler. A 4-bit system has been chosen, rather than the usual 2-bit sampler, in order to ensure that any narrow-band interference signals from man-made transmitters, after being sampled, do not produce intermodulation products in the passband higher than -45 dB of their input levels. The samplers are followed by delay lines and Fast Fourier Transform machines giving 256 complex spectral outputs over a bandwidth of 16 MHz for each of the two sidebands and two polarizations for each antenna. The dynamic range of FFT for intermodulation is expected to be about 35 dB.

The signals from the FFT machines of the two side-bands are fed to two separate multiplier and accumulator (MAC) systems, since correlation between the sidebands is not required. Each of the MAC systems forms all the cross products between the 256 channels in each of the polarizations of the 30 antennas giving a maximum of $(30\times 31/2)\times 256\times 2 = 238{,}080$ RR and LL products including self-products. The MAC system supports a polarization mode which gives the RR, LL, RL and LR products but with half the frequency resolution (128 frequency channels). Each of these products can be averaged in an accumulator for integration times selectable from 64 ms to 10 s. The correlator system uses about 1500 VLSI chips developed by the National Radio Astronomy Observatory for the Very Long Baseline Array (VLBA).

5. System Parameters

The expected system parameters of GMRT are summarised in Table 1. The antenna efficiency and system temperatures have been measured for several completed GMRT antennas and these have been found to be close to those given in Table 1. The measured antenna efficiency including cable losses is about 55 per cent at 327 MHz and 38 per cent at 1420 MHz. Further measurements are being made to verify various system parameters.

6. Astronomical Objectives

The design of GMRT has been motivated by a need to set up a powerful facility in radio astronomy to investigate a variety of astrophysical problems that are either exclusive to the metrewave region or which will complement the existing facilities at

TABLE 1. Some estimated system parameters for GMRT

	Frequency (MHz)					
	38	150	233	327	610	1420
Primary beam (deg)	13	3.1	2.0	1.4	0.8	0.32
Synthesized beam :						
Total array (arcsec)	80	20	13	9	5	2
Central compact array (arcmin)	28	7	4.5	3.2	1.7	0.7
System temperature (K), Total T_{sys}	10,280	580	250	110	100	70
RMS noise in image (μJy)†	1,420	55	24	11	10	12

†For assumed bandwidth of 16 MHz, integration time of 10 h, and natural weighting and 2 polarizations

shorter wavelengths. As already mentioned, one of the important scientific aim of GMRT is to search for the 21-cm line from primordial clouds of neutral hydrogen in the redshift range of about 3 to 8, in an attempt to determine the epoch of galaxy formation. Such a discovery would be of fundamental importance to our understanding of the formation of structure in the Universe. Attempts will be made also to determine the variation of HI content of clusters of galaxies with redshift by observing in the frequency range of 1000-1430 MHz.

Pulsars would form another very important topic of study with GMRT. Apart from detailed studies of individual pulses for elucidating pulsar emission mechanisms, GMRT would be a powerful instrument for undertaking a search for hundreds of new pulsars. The optimum frequency for carrying out such searches is 327 MHz but searches towards the galactic plane may be carried out also at 600 and 1400 MHz. Particularly important would be searches for pulsars with milli-second periods, those in binary systems and in globular clusters. Timing of milli-second pulsars can be an effective probe of the theories of gravitation and also of internal structure of the neutron stars. Observations of pulsar scintillations can provide valuable information about the interstellar medium.

Apart from the above-mentioned observational programmes, the special features and capabilities of GMRT will make it a powerful tool for undertaking a variety of other astrophysical studies, a few of which are mentioned below:

- HI studies of our Galaxy and of external galaxies out to cosmological distances through emission as well as absorption.
- Relic radio sources and ageing effects from observations of the steep-spectrum diffuse emission associated with the population of old relativistic electrons.
- Non-thermal halos around spiral galaxies and in some rich clusters of galaxies.
- Large-scale deep surveys of the sky at metre wavelengths, to catalogue millions of radio sources for a variety of statistical and cosmological studies.
- Search for the Deuterium line at 327 MHz which is of considerable cosmological interest.
- Studies of a variety of objects in our Galaxy and nearby galaxies such as HII regions, supernova remnants, transient radio sources, etc.
- Study of recombination lines from our Galaxy as well as from external galaxies.
- High-time-resolution studies of solar radio bursts and studies of solar wind through interplanetary scintillations.

7. Conclusion

GMRT will provide high sensitivity, good spectral and polarization capability, excellent sky coverage and reasonably good angular resolution at six different frequency bands from 38 MHz to 1430 Hz. Its sensitivity will be comparable to that of the VLA at 21 cm but is expected to be about 4 to 8 times better at 327 MHz. Further, it will be operating at several decimetre and metrewave bands. GMRT's sensitivity will be comparable to that of the Arecibo Radio Telescope, but with much higher angular resolution and declination coverage. GMRT is likely to be completed by late 1996. It will be used for investigating a variety of astrophysical problems which are best studied at the longer radio wavelengths.

8. Acknowledgements

Successful near completion of the challenging project of GMRT is due to the sustained and dedicated efforts of a large team of engineers and scientists of the Tata Institute of Fundamental Research. The engineering teams have been led by S.C. Tapde, M.K. Bhaskaran, N.V. Nagarathnam, M.R. Sankararaman, T.L. Venkatasubramani, A. Praveen Kumar, R. Balasubramanian, G. Sankarasubramanian and A. Dutta. V. Balasubramanian and A.J. Selvanayagam of RAC, Ooty, have also made valuable contributions. The Raman Research Institute is building the 21-cm front-end receiver system and a major part of the pulsar back-end. The engineering design of the 45-m dishes has been done by M/s. Tata Consulting Engineers. The project has also benefitted from discussions and contributions by many other scientists in India and abroad.

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APPENDIX-B

Effect of transiet RFI, such as power line RFI on GMRT maps

1. For gain calibration of GMRT correlator, the cross-correlated outputs are being divided by system temperatures at present because the continuous noise generator calibration system is not yet installed. Hence, in presence of uncorrelated pulsed RFI, we get

$$V_{mn} = \frac{< G_m V_{mc} G_n V_{nc} >}{< G_m^2 (T_{sm} + T_{im}) G_n^2 (T_{sn} + T_{in})^{1/2} >} \qquad \text{Equ. (1)}$$

where G_m, G_n are voltage gains for mth and nth antennas ;

V_{mc}, V_{nc} are correlated voltages, T_{sm}, T_{sn} are system temperatures and T_{im}, T_{in} are pulsed interference of duration less than one second whence the AGC system would not alter the gains of the amplifier system.

If T_{in} is much less than T_{sn}, we get from Equation (1)

$$V_{mm} = \frac{< V_{mc} V_{nc} >}{< T_{sm} T_{sn} >^{1/2}} \left(1 \frac{1}{2} \frac{T_{im}}{T_{sm}} - \frac{1}{2} \frac{T_{n}}{T_{sn}} \right) \qquad \text{Equ. (2)}$$

Thus, it is seen that we would effectively corrupt the measured visibility as a function of time. In fact, the situation could be worse if $T_{im} > T_{is}$ for various frequency channels.

It is expected that the gain calibration using noise generators at each antenna (which are there right from beginning) would become functional when the new Delay Units get installed in some months from now.

Any case, we should take all steps to minimize pulsed RFI due to gap discharges on 11 kV lines. Also, one may make some maps without dividing by T_s and finding gains by frequent noise generator calibrations, say every 10 or 30 minutes.