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Identification of Radio Frequency Interference (RFI), its Characteristics and Mitigation to Optimize Performance of the GMRT

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Identification of Radio Frequency Interference (RFI), its Characteristics and Mitigation to Optimize Performance of the GMRT

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ABSTRACT:

This Report summarizes various sources of RFI that adversely effects sensitivity of the GMRT and makes several suggestions for minimizing its harmful effects, in order to optimize performance of the GMRT, particularly with its current upgrading.

As a first step, it is important to minimize RFI to the antennas of the Central Array caused by the nearby Power lines and also by the GMRT electronics. Further, the proposed "Radio Location Array (RLA)" would be able to identify sources of unauthorized sources of RFI at each of the GMRT antennas on a 24/7 basis. I also suggest making a survey of RFI from electronics located in the Control, Observer, Correlator and Receiver Rooms as described in Section 5.1.2. Minimizing RFI is important that would result in improvement of the sensitivity of the GMRT by a factor of nearly 2 and thus uGMRT to remain competitive to LOFAR, MEERKAT, ASKAP, JVLA, as GMRT has good sensitivity in the frequency range of ~ 130 MHz to 1430

MHz. In due course, the eGMRT proposed by NCRA group in the next plan will further add to its capability.

As many astronomers and engineers of the NCRA and GMRT groups may not read the full report, I am giving a long summary in this Abstract and several recommendations that need to be implemented. A summary is also given in the Introduction.

Even though the Central Array of the GMRT is located about 60 km away from the Pune city (line of sight) with several hills in between, considerable radio frequency interference (RFI) is observed at various antennas of the GMRT. There are several sources of RFI: (a) radiation from several VHF and UHF transmitters particularly at Pune, and also sometimes from transmitters at Mumbai and Ahmednagar; (b) As I recall there are only 4 or 5 authorized transmitters located physically in a radius of ~ 30 km from the central array of the GMRT (GMRT-RFI group to verify by measurements and also by writing to WPC), yet lot of RFI takes place from unauthorized local sources including those from the GMRT electronics that must be minimized; (c) satellite RFI at ~ 138MHz, 150 MHz and in the band of ~ 250-260 MHz, (d) GSM and CDMA mobile towers but these effect only bands near 860 and 950 MHz; (e) till recently, malfunctioning TV boosters in villages around the GMRT that were giving occasional RFI but I have been told that now RFI is taking place from leaky cables and connectors of the Cable TV in villages near the GMRT antennas that are all illegal and action can be initiated against them with help of monitoring wing of WPC at Mumbai ; (e) ***RFI from GMRT electronics*** and (g) ***broadband interference from the 11 kV electrical transmission lines, particularly affecting all antennas of the central array of the GMRT.*** As a result, about ~ 50% data is flagged by radio astronomers during the analysis of their observations in the 150 MHz and 235 MHz bands and more than 20% in the 325MHz band and even in the 610 MHz band, particularly for the Central Array antenna pairs, as is found during flagging. Therefore, it becomes strenuous to analyze the data, although some pipelines have been developed for flagging (e.g. FLAGCAL), and a few also for calibration and imaging by individual users. Because of the local RFI, the theoretical value of sensitivity (rms noise) has not been achieved generally, except in a limited number of cases at a few times the theoretical value.

The RFI group at the GMRT has been doing considerable work in order to identify some of the sources of RFI mentioned above. However, we need to undertake a great deal more effort, particularly in view of the recent broad-banding of the GMRT from ~ 130 MHz to 1430 MHz.

It is important to review the work being done and discuss further steps that must be planned. I also review briefly RFI that may arise due to the intermodulation products by strong RF signals in the observing bands, based on 1 dB compression point and 3rd order intercept point as measured by the RF and optical fibre groups. It is important to carry out a detailed analysis similar to that done by Anish Roshi and Ellingson, to minimize inter-modulation products due to several strong RFI signals and also perhaps a combination of several not so strong sources of RFI in the observing bands. I understand that 8 bit digitization is being done in the new correlator; one should investigate limitations to the generation of any intermodulation products, if any.

I have also summarized several surveys that have been made concerning RFI at the GMRT site during the last 15 years. Some of these are available as Internal Technical Reports. Shri Joardar and Raybole and colleagues have also made many surveys. In the D-space of the NCRA library, a report by Joardar and Banerjee is available describing a survey made in 2004 using the innovative "E plane Omni-directional RFI Monitoring System" by Joardar. GMRT library has many reports of RFI measurement of electronics equipment that I plan to discuss in another report.

I may add that this Report is a bit long as part of it is a tutorial for benefit of young radio astronomers, engineers and technicians.

To summarize, I would like to make following suggestions: *(a) replace the overhead 11 kV lines feeding the Eastern and Southern Y arm antennas by underground 11 kV cables from the 33 kV HT yard up to about few hundred metres away from the C0 antenna, in order to minimize harmful effects of power-line RFI to the antennas of the central array (Shri Swami has suggested supplying powers to all the Y array antennas at 6 kVA (3 or 4 kVA may be better) that will require new transformers and would eliminate power-line RFI from our own 11 kV lines; similarly the 11 kV line from Shiroli up to the 33kV HT yard of the GMRT, for the portion just north of the central array, to be substituted by overhead HT powerline cables. Further, to ensure that powerline RFI is NOT caused to the central array antennas by transformers feeding irrigation pump up to about 0.5 or 1 km distance from the antennas of the central array by making weekly survey; (b) clip the pulsed interference due to the power lines (preferably at each antenna) or soon after the ADC in the GMRT Wideband Correlator (GWB);* (c) *minimize RFI from the RF and digital labs in the Central Electronics Building (CEB) by constructing a fully shielded lab of about 7000 sq. ft. area, with wire-mesh all around, to house all the 6 RF and digital groups, located closer to the existing CEB building, rather than mixing with the proposed auditorium cum multi-purpose building; (d) install GI chicken wire mesh up to ~ 10 m high and then to be plastered in order to minimize RFI from servo systems, UPS and other electronics at the central array antennas, as a second line of defense against RFI from electronic equipment at the base of the antennas; similarly one may consider placing copper wire-mesh on outer walls (not roof) of the control, correlator and receiver rooms, (e) purchase or develop urgently a shielded box with minimum 40 dB rejection for minimizing RFI and installing it in all the PCs located in various rooms in the CEB, as already being planned; (f) urgently make a dedicated mobile RFI van with direction finding as has been suggested several times over the last 15 years (GMRT RFI group has been using a mobile van but it may require further development for allowing rapid surveys with minimum manpower); (g) additionally, to build with high priority a **RFI Location array (RLA)** by installing Discone antennas on poles of say 10 m height near all the 30 GMRT antennas, with signals received brought to a simple correlator in the central electronics building using the existing optical fibres, over another optical band, and thus use the received signals to identify sources of RFI near the GMRT antennas; this scheme would* *require innovative software;* the GMRT RFI group had made a novel proposal last year for locating Discone antennas mounted on ~12 m high poles/towers near only 7 out of 30 antennas of the GMRT. I consider it is important to construct Discone antennas near all the 30 dishes of 45m. (Discone antenna is like a vertical fat dipole with reflector radiating/receiving only towards horizontal direction). Once the RFI group develops one station (ensuring amplifiers that are unconditionally stable like all the GMRT front end amplifiers), the full array could be sub-contracted (mobile RFI van cannot keep 24/7 watch). RLA can use a simple correlator with few thousand channels and thus act as a spectrum analyzer. If a scheme can be developed for calibrating phase of the electronics system of RLA, it can act as an interferometric array that is sensitive by tens of dB lower values than that made by total power measurements and RLA can be named as PARI (Phased Array for RFI Identification); (h) develop an online RFI Mitigation software and **finally (i)** ***it is important to identify at least one full time B.Tech engineer towards a Ph.D. to undertake a detailed study of identification of Radio Frequency Interference (RFI), its characterization and mitigation in order to optimize performance of the GMRT ; also execution of RLA including development of the required software in collaboration with the GMRT-RFI group.***

All the above may seem a tall order but it is important to eliminate RFI from local sources and the GMRT electronics with a high priority in order that the GMRT remains internationally competitive in spite of new facilities, such as, LOFAR, ASKAP, MEERKAT and upcoming SKA.

[May I note that the estimated cost of the GMRT if built today would be > Rs. 300 crores. If we can minimize harmful aspects of the RFI to the GMRT observations by say only 10%, it would be worth Rs. 30 crores! Further, it would allow faster data reduction by research workers and lower achievable rms noise, resulting in more discoveries.]

1. INTRODUCTION

Radio telescopes are highly susceptible to radio frequency interference (RFI) as their minimum detectible signal is million times lower than that of terrestrial radio communication systems. Although GMRT is located about 60 km away from Pune and about 120 km away from Mumbai, with many hills in between, GMRT is still subject to considerable degree of RFI due to signals received by troposcatter communication as discussed in this report. There are only few authorized transmitters (police wireless; irrigation department transmitter in the Kukadi colony and perhaps some others) in area up to 30 km distance from the Central Array of the GMRT, (apart from mobile-communication towers in the bands near 860 and 950 MHz that effect only small part of the GMRT RF bands). However, there arises lot of RFI from several spurious sources closer to the GMRT antennas, such as (a) powerline RFI, (b) spurious radiation by the GMRT electronics and (c) oscillating TV boosters and leakages from poor shielding of cables and connectors of TV cable networks producing RFI of higher power flux density (pfd) values than allowed by the ITU and the WPC and therefore is *illegal*. Actions could be taken against the manufactures and shops who are selling TV boosters subject to oscillations (report by Raybole (2008) lists several manufactures supplying TV boosters) or is it also due to poor connectors of cables that lead to oscillations and hence those carrying out such installations could be prosecuted since there are national and international regulations regarding limits of spurious emission. It is not possible for the GMRT RFI group to continue to modify such TV booster over a large region around the GMRT on a daily basis. Hence I wonder whether a directive by the State Government requesting local authorities (e.g. sapanch of villages within a km of the GMRT antennas in the Junnar Taluka) to get TV boosters certified by the GMRT authorities, after installing a resistor, is a possible solution

During 1985 to 2004 many surveys had been made for measuring RFI at the GMRT site, in which I had participated closely. The details of these surveys were described in two Internal Technical Reports as listed later. Many recent reports are available with the RFI group of the GMRT and with Dr. S. Joardar. The main purpose of the present Report is firstly to summarize various measurements of RFI in which I participated closely and then to make several recommendations for the purpose of minimizing harmful effect of RFI to the GMRT.

RFI surveys use spectrum analyzers that measure total power. Same is true of the *total power pass bands* of the GMRT electronics that are displayed for each polarization from each of the 30 antennas in the control room. However, a 2 antenna interferometer measuring visibility, say with 16 second integration and 125 kHz channel-width measures correlated power that is $(16s \times 125\ kHz)^{0.5} \sim 1400$ times (31.5 dB) lower. Over 10 hour observations much lower rms values are achieved. With measurement of the correlated voltages received by the antenna pairs of the Y array antennas, with other Y array antennas, and with the Central Array antennas, RFI will get integrated and rms noise is suppressed by sq. root of large number of fringes, $n^{1/2}$, that are recorded when a celestial source is tracked over several hours (Thompson et al. 1986). Suppression takes place as each antenna pair produces number of fringes, with phases varying continuously from 0^0 to 360^0, as antennas are tracked for observing a celestial radio source over several hours. ***However, such suppression would be much lower for the pairs of the Central Array antennas alone, since lower number of fringes are recorded since adjacent distances between the pairs is only few hundred m. Hence it is very important to minimize all sources of spurious RFI due to the GMRT electronics arising from the central electronics building and that from the power lines and associated transformers of farmers up to about half or one km from the antennas of the Central Array. I believe that this is practical and will result in considerable improvement in the performance of the GMRT.***

In view of the recent broad-banding of the GMRT with nearly continuous coverage from ~ 130 MHz to 1430 MHz, it is important to review the work being done regarding RFI surveys and further steps planned. I also review very briefly linearity of the broadband RF amplifier and of the optical fibre system of the upgraded GMRT, particularly concerning steps taken to minimize inter-modulation products due to a strong RFI or possibly a combination of several sources of RFI in the 400 MHz band.

In Section 2 are described theoretical sensitivity and harmful effects of RFI for a total power radio telescope as recommended by the International Telecommunication Union (ITU). A radio telescope using interferometers such as the GMRT is less affected by RFI as discussed in Section 3 but still gets seriously affected by various authorized and unauthorized RF signals due to the extremely high sensitivity of the GMRT, that allows observations of celestial sources at tens of micro-jansky levels (1 micro-jansky = 10^{-32} Watts/m^2/Hz) (Swarup 1991).

In Section 4 is summarized power flux density (pfd) of the RF signals (dBWatts/m^2) measured at the GMRT site. An attempt is made to understand the observed pfd values at the GMRT antennas from the estimated power of transmitters located at Pune and Mumbai, and path loss based on troposcatter propagation models.

In Section 5, I discuss RFI from (a) unauthorized spurious RFI from several sources near the GMRT antennas; (b) RFI from the electronics systems at the GMRT antennas. I make a few suggestions to minimize RFI from the RF and digital labs and many PCs in the Central Electronics Building (CEB). It is suggested to construct, next to CEB, a fully shielded lab of about 7000 sq. ft., *with wire-mesh all around it*, and to locate in it all the 6 RF and digital groups. It is also important to develop urgently a shielded box for minimizing RFI from PCs in the CEB, as already planned. A survey should also be made of RFI from the Control, Correlator and Receiver Rooms and also the RF labs at a distance of ~ 10m around the CEB.

In Section 6, I discuss intermodulation products that could arise due to nonlinearities of the RF amplifiers, the optical fibre system and in the digital correlator. The concerned engineers have measured values of 1 dB compression point and 3rd order intercept. These measurements are used in Section 6 to analyze any intermodulation products by various strong signals in the wide band receivers of the upgraded GMRT (uGMRT). My preliminary analysis indicates that intermodulation products are not likely to arise from any RFI with pfd value of < - 10^{-9} dBW/m^2, but it would be advisable to make measurements of the entire electronics by placing Front End electronics at the base of the antenna, connected to the optical fibre system and CEB electronics and applying input signals using 2 signal generators.

In Section 7 is summarized *power-line RFI* as has been measured by me in 1999 at the antennas of the GMRT. As is known, a high level of pulsed interference is observed in the antennas of the Central Array from the overhead 11kV HT lines feeding the east and southern GMRT antennas and also from the nearby 33 kV line feeding the GMRT 2 MVA transformer at the HT yard. There is also a 22 or 33 kV (?) power line near the E3 antenna and a High Voltage DC (HVDC) line passing in between the E5 and E6 antennas. Further, HT lines supply power to the irrigation pumps of farmers in the nearby regions and have often poor interconnections at the transformers that convert 11 kV to 440 V AC power. Our measurements show that pulsed interference is observed every 10 ms when the voltage of the HT lines exceeds roughly about +/- 6 kV, every 10 ms of the 3 phase 50Hz supply. These pulses have rise-time of tens or hundreds of nanosecond and duration of many microseconds. Therefore, these narrow pulses result in broadband RFI to the GMRT even up to 600 MHz and beyond (with far away peaks proportional to $1/x^2$, with x = tens/hundreds of nanoseconds $(\sin x/x)^2$ spectrum). It is also suggested in Section 7: (a) to replace the two overhead 11 kV lines feeding the Eastern and Southern Y arm antennas from the 33 kV HT yard up to few hundred away from the C0 antenna, by two underground 11 kV cables, in order to minimize harmful effects of power-line RFI to the antennas of the Central Array, and (b) clip the pulsed interference soon after the ADC in the GSB and in the new GMRT wideband backend correlator (GWB) as suggested in Section 7. **I emphasize that powerline RFI must be eliminated for the antennas of the Central Array as discussed above We should be conservative rather than optimistic.** We should also plan clipping sub-millisecond pulses (to disable clipping for pulsar observations), particularly for the antennas of the Y array (apart from continuation of surveys of harmful powerline RFI by the GMRT RFI group).

In Section 8, I make brief comments on the valuable ppt talk by Pravin Raybole in 2008, "TV Booster Interference and Power Line RFI around GMRT". The report gives peak values of RFI measured in dBm with a spectrum analyzer but those values need to be calibrated and also multiplied with the effective area, A_{eff} of the log-periodic antenna of gain ~ 8 dB (A_{eff} = $(\lambda^2 /4 \pi)$ so as to give measured power flux density in units of dBW/m^2 That report also discusses RFI by TV Boosters and leaky transformers of irrigation pumps.

In Section 9, I discuss briefly some aspects of a mobile RFI van that has been suggested over the last 15 years. GMRT RFI group has been using a mobile Van. It would be useful to improve it so that it becomes possible to identify any spurious sources of RFI near the GMRT antennas on a routine basis, e.g. spending an hour near each of the GMRT antennas and thus doing measurements at all 30 antennas in a week or 10 days.

In Section 10**,** I discuss importance of building, with a high priority, a RFI Location Array (RLA), by installing Discone antennas on ~ 10 m high poles near *all the 30* GMRT antennas, connecting to a broadband amplifier and then to bring the received signals to a baseband receiver and finally to a correlator and thus use the data to identify sources of unauthorized RFI near each of the GMRT antennas.. However, for determining coordinates of a source of RFI, it is required that the relative phase of the amplifiers and transmission lines from the Discone antennas is measured with respect to a reference antenna. As discussed in Section 9, it may be practical do round trip phase measurement, particularly for the Central Array antennas, whence RLA could be named as "Phased Array for RFI Identification (PARI)". I may stress that a mobile van cannot keep 24/7 watch**.**

In Section 11, I have given 3 references concerning RFI Mitigation. It is desirable to develop online Mitigation software, apart from off-line software FLAGCAL, recently developed for flagging the GMRT observations.

In Section 12 are given concluding remarks. I would like to suggest that NCRA should identify a full time B.Tech. Engineer for a Ph.D. programme, who would undertake detailed study of the following, (a) identification of Radio Frequency Interference (RFI), (b) its characterization and mitigation, in collaboration with astronomers and the existing RFI group at the GMRT, and (c) developing RLA that is a very challenging task. Innovative solutions need to be developed for mitigation of the observed RFI, e.g. using the capability of the new GMRT wideband backend (GWB).

In Section 13 are given references and are also listed various Reports regarding RFI that are available in the D-space of the NCRA library.

Acknowledgements are given in Section 14. Figures are given in Section 15. Appendix 1 gives several other figures, particularly it gives expected transmission loss suffered by authorized RF signals received at the GMRT antennas from Pune and Mumbai due to transmission by irregularities of the refractive index of the moist layers of upper atmosphere, called troposcatter communication. Appendix 2 gives data sheet of the laser diode being used currently.

2. SENSITIVITY OF A RADIO TELESCOPE

As shown below, the sensitivity of a radio telescope is extremely high compared to that of a communication receiver. Voltage received from a celestial radio source is a random noise. A radio astronomer measures the difference between the received noise power for the case when antenna is pointed towards a celestial source and when it is pointed away from the source. Therefore, the sensitivity of a radio telescope is dependent upon the root mean square (rms) fluctuations of the receiver noise.

The power output, p (Watts) of receiver is given by

$p = kT_s \Delta f$ W,

where k = Boltzman's constant = 1.38×10^{-23} Joules/Kelvin (W/Kelvin)/Hz), T_s is the system temperature and Δf (Hz)is the bandwidth of the receiver.

The rms value of, $\Delta p_{rms,}$ of the receiver noise with integration time Δt (s):

$$\Delta p_{rms} = kT_s \Delta f /(\Delta t \, . \, \Delta f)^{1/2}, \quad (2.1)$$

As per the recommendation by the International Telecommunication Union, ITU RA 769.1, the harmful level of RFI, Δp_H, is taken as 10% of the receiver rms fluctuations. Hence,

$$\Delta p_H = 0.1\, \Delta p_{rms} \text{ W} \quad (2.2)$$

The relation between the harmful noise power, Δp_H , and the power flux density (pfd), ΔP_H (W/m^2), of the harmful radiation incident on the antenna of a radio telescope with effective aperture area, A_{eff} (m^2) = G. $\lambda^2/4\pi$, (corresponding to the gain of the sidelobes of the antenna of the radiation towards the horizon and ground) at a wavelength λ (m) is given by

$$\Delta p_H \text{ (W)} = \Delta P_H \text{ (W/m}^2) \, . \, A_{eff} \text{ (m}^2) = \Delta P_H \, . \, (G. \, \lambda^2/4\pi) \quad (2.3)$$

Hence from (2.1), (2.2) and (2.3), the pfd of the harmful radiation ΔP_H (W/m^2) is:

$$\Delta P_H = (0.4\pi / G. \, \lambda^2). \, kT_s \Delta f /(\Delta t \, . \, \Delta f)^{1/2} \quad (2.4)$$

Since $\lambda = c/f$, where c = velocity of light, we may write (2.4) as

$$\Delta P_H = (0.4\pi f^2 / G. c^2) . kT_s \Delta f /(\Delta t . \Delta f)^{1/2} \quad (2.5)$$

The spectral power flux density ΔS_H is given by ($\Delta P_H / \Delta f$). For calculating the RFI levels, ITU R769.1 recommends for protection of radio astronomy observations from RFI that the gain G of the antenna sidelobes towards the horizon and ground may be taken as unity; Δf is bandwidth of allocated protected bands for protection of radio astronomy and Δt = 2000 seconds (although currently radio astronomers are observing with much larger bandwidth and integration over tens of hours. Values of ΔS_H and $\Delta S_H / \Delta f$ are given in Tables 1 and 2 of ITU RA 769.1 for continuum and spectral observations at various frequencies protected for radio astronomy observations (see following Table that is extracted from Table 1 and 2 of ITU RA 769.1).

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

As can be seen from the Table that the harmful level of RFI = -194.5 dBW/m^2 at a frequency of 150 MHz and -189 dBW/m^2 at 325MHz. The minimum detectable signal of a communication receiver is ~ -130 dBW/m^2, nearly 10 times the receiver noise. *Thus, it is seen that a radio telescope is about 60 dB more sensitive than a radio communication service and therefore radio telescopes are located far away from cities and RFI from the associated electronics is minimized..*

3. RFI SURVEYS AT THE GMRT

In Section 3.1 are discussed severe limitations of RFI surveys that are made using a spectrum analyzer, as the power levels measured by such surveys is ~ 30 dB higher compared to that of the sensitivity of a total power radio telescope with bandwidth of several MHz and time constant of few seconds or that of a 2 antenna interferometer with only 16 seconds of integration and bandwidth of 125 kHz (e.g. for a baseline of 2 antennas out of 435 pairs [n (n-1)/2] of the GMRT for each polarization. In Section 3.2, we discus attenuation from a source of RFI located at a height of h_T above the ground to the power received by an antenna with a height of $h_{R.}$ and located at a distance D. It is shown that attenuation is proportional to D^4 and not as inverse square law if $[(h_{T\,+}\ h_{R/D}{}^2]$ is <<1. Hence, measurements of RFI may not be carried close to the ground and preferably may be carried out at several m above the ground. In Section 3.3, we discuss required level of protection to radio astronomy as per ITU. In Section 3.4 are discussed troposcatter propagation of radio emission from authorized transmitters located far away in Pune and Mumbai.

3.1. Relative Sensitivity of RFI Surveys Using a Spectrum Analyzer and by a 2-Antenna Interferometer.

In view of extremely high sensitivity of radio telescopes, International Telecommunication Union (ITU) has allocated several bands to radio astronomy service worldwide for protection from manmade radio emission. Please see several Reports by ITU in the NCRA library, giving details of protection against manmade transmissions and also ITU recommendation 769.1, etc. The ITU reports also give upper limits of out-of-band emission of transmitters. For general electronics, such as PCs, switched mode power supplies etc., ITU advises national administrations to specify acceptable level of spurious emission. I find from Google search, that Federal Communication Commission (FCC) of USA has specified that level of spurious emission of electromagnetic field by digital and other electronic systems, etc., should be less than E = 150 μV/m at a distance of 3 or 10 m (depending on class A or B with lower or higher level of spurious emission) with power flux density, $P = E^2 / 377 = (150 \times 10^{-6})^2 / 377 = 0.5 \times 10^{-10}\ W/m^2$ at a distance of 3 or 10 m and therefore at 10 m , maximum level of spurious emission should be less than, $\mathbf{P_{rfi\text{-}rad} = 4\pi R^2 \times P_{rfi} = 6.28 \times 10^{-8}\ W/m^2}$.

The Wireless Planning Coordination (WPC) of the Government of India has allocated the following bands for radio astronomy (RA) observations with the GMRT (with no manmade transmitter in these bands up to ~ 600 km away from the GMRT): (a) 37.5-38.25MHz, (b) 322-328.5 MHz, (c) 608-614 MHz and (d) 1400-1427 MHz. (e)The band 150.05-153 MHz has additional allocation to the radio astronomy service in India, as a result of a footnote protection by ITU, but is also allocated to some other services. WPC has coordinated it for use for observations with the GMRT (Swarup, ITR in preparation that will give correspondence with the WPC), (f) in coordination with the JPEC group of the Ministry of Defense, WPC has also allocated an additional band of 230-234 MHz for the GMRT. However, it seems that the band 230 MHz to 399 MHz, with random selection of the frequencies of transmitters is being used by certain aircrafts of the Indian defens**e** during their exercises (as part of aeronautical mobile). Attempts are being made by the GMRT group for ensuring no transmissions by these aircrafts in the band 322-328.5 MHz that is internationally protected for RA as a primary service.

In order to observe celestial radio sources with a high sensitivity (lower values of rms noise of radio telescopes), radio astronomers are building antenna feeds and receivers with *much wider bandwidths* (as well with integration up to 10 hours), connected to a complex digital correlator using modern high performance digital devices. Hence RFI monitoring and developing RFI mitigation techniques become very important.

We discuss briefly in Section 3.1.1 sensitivity of RFI survey using a spectrum analyzer (SPA) and in Section 3.1.2 sensitivity of 2 antenna interferometer.

3.1.1. **Power Measured by a Spectrum Analyzer.** Power received by the spectrum analyzer is given by $P_{spa} = A_{eff}$. (k T_{sys} $\Delta f + P_{rfi}$) watts, where A_{eff} is collecting area of the log periodic antenna, $A_{eff} = G_{lpa}.\lambda^2 /4\pi$, $T_{sys} \sim 1000$ K (estimated noise figure of the spectrum analyzer to be verified) and Δf = 3 kHz, 10 kHz, 30 kHz, 100 kHz , 300 kHz or 1 MHz depending on the resolution Bandwidth (RBW) of the spectrum analyzer selected by the engineer for making RFI survey *over a selected frequency range* and P_{rfi} is the power flux density (Watts/$m^{2)}$ of RFI in its bandwidth Δf_{rfi}. Typically, RFI is measured using a spectrum analyzer and a log periodic antenna (LPA) at a height of only 2m or 3m, at distances of several metres from the source of RFI of the GMRT electronics being tested and at distances of tens of metres or higher from the RFI sources in the villages close to the GMRT Y array antennas. As discussed in Section 3.3, if the source of RFI (and/or or the measurement antenna are located close to the ground), one should consider radiation from not only from the source of RFI but also its image that has -180 degree phase. I ignore that for the present.

Gain of a typical LPA being used at the GMRT is about 8. Thus, $A_{eff} = G_{lpa}.\lambda^2/4\pi = 2\lambda^2/\pi$ is $\sim 8/\pi$ m^2 at 150 MHz, $\sim 2/\pi$ m^2 at 300 MHz, $1/2\pi$ m^2 at 600 MHz and $1/11.33\,\pi$ m^2 at 1420 MHz.

The RFI group of the GMRT detects sources of RFI that are few dBs to tens of dB *above the baseline of the spectrum analyzer* P_{spa} (dBW) and then generally records values of RFI only as (A_{eff} P_{rfi}) dBW. What is of importance is to determine values of P_{rfi} (dBW/m^2), as follows: by dividing the observed values in the spectrum analyzer (A_{eff} P_{rfi}) by dividing by A_{eff} and adding the value of the baseline of the spectrum analyzer: i.e.

P_{rfi} dBwatts/m^2) = (A_{eff} P_{rfi}) dBwatts – 10logA_{eff} + P_{spa} dBWatts

Also it is desirable to record measurements in a Technical Note to be submitted to the library at the GMRT in Dspace, even if it is informal; hand written notes can be scanned and recorded.

Assuming that the receiver and the spectrum analyzer has $T_{sys} \sim 1000$ K at 300 MHz (λ =1m) and selected resolution bandwidth, RBW = Δf of 100 KHz, using a log periodic antenna with gain of 8, the sensitivity limit of the observed RFI is given by (taking $A_{eff} = \lambda^2$ G / 4 π with

G=8 and λ =1 for 300 MHz) as P_{spa}= k T_{sys} Δf / A_{eff} W/ m^2 = 1.38 x 10^{-23} x 10^3 x 10^5/ (A_{eff} = 2/π) = - 152.2 dBW/m^2 at 300 MHz. With RBW = 1 MHz, we get P_{spa} = -142.2 dBW/m^2, that is 50 dB above harmful level to a radio telescope. A lower value of RBW say 10 KHz and integration over 100 scans of the spectrum analyzer, it would be able to detect lower level of RFI.

The system temperature of GMRT at 300 MHz is ~ 100K. The sidelobes of the GMRT antennas have gain, G ~ 1 (Swarup RT 00191, Appendix A, 2001). GMRT correlator has 256 channels over 32 MHz. Hence resolution of each channel is 125 KHz. Hence, we have

$P_{baseline}$ = k T_{sys} Δf /A_{eff} W/ m^2 = 1.38 x 10^{-23} x 10^2 x 1.25 x 10^5/ (A_{eff} = 1/4 π) = -146.6 dBW/m^2 . For a total power measurements with a single antenna, rms noise is 60 dB lower with Δf = 32 MHz and integration over 8 hours.

As described in Section 2, ITU recommends (RA769.1; Swarup 2001, R0091) that to ensure sensitivity of a radio telescope the flux density of the RFI should be less than in the protected bands as follows -194 dBW/m^2 in 150.1- 153 MHz, -189 dBW/m^2 in 322-327.4 MHz, -185 dBW/m^2 in610-614 MHz and -180 dBW/m^2 in 1400-1427 MHz. ITU considers a single antenna with sidelobes G ~ 1, T_{sys} ~ 40 K, and integration over 2000s.

For 30 antennas and integration over 10 hours GMRT has rms sensitivity of < 30 μJy (micro-Jansky) at 325 MHz. For a bandwidth of 32 MHz, 30 μJy, we get,

P = 32 x 10^6 x 30 x 10^{-32} = -230 dBW/m^2.

For spurious emission, we may consider the effective collecting area of sidelobes ~ 1 m^2. Also, rfi will give rise to fringes over 10 hours and will get integrated by sq. root of number of fringes (see Section 3.1.2). However, number of fringes that will occur for close by antennas, such as C5, C6 C9 and C3, C4 would be < 100 at 325 MHz. Considering above aspects, I suggest that it is desirable that no unauthorized signals of pfd > ~ - 200 dBW/m^2 are received by the sidelobes of the central array antennas of the GMRT. This level is nearly 50 dB below the $P_{baseline}$ of the receiver pass band that is seen on spectrum analyzer in the receiver room or in the control room display.

We have to live with the RFI from *authorized* transmitters near the GMRT and those from Pune, Mumbai, etc (see Section 3.4). BUT we must ensure that RFI does not take place from the GMRT electronics and any other unauthorized sources up to 30 km radius from the Central Array of the GMRT.

3.1.2. With an interferometer consisting of 2 antennas of the GMRT, we record RFI received by the sidelobes of the primary feeds of the GMRT antennas that have gain G ~ 1 (-10 db below the maximum radiation of the primary feed towards the centre of the parabolic dish). Hence, A_{eff} of sidelobes is ~ λ^2 /4 π.

Power received by GMRT antennas is given by

$P_{sidelobe}$ (W) = A_{eff} (sidelobe) x PFD_{rfi} W/m^2

Where PFD_{rfi} is power flux density of rfi in W/m^2 and A_{eff} (sidelobe) ≡ A_{eff} (m^2) is area of distant sidelobes of the GMRT antenna **towards the horizon and ground**. ITU 769.1 considers that Gain, G of distant sidelobes = 1.

Power received by a radio telescope is given by

P (W) = ½ S A Δf

Where S = flux density of a celestial radio source ($W/m^2/Hz$), factor ½ is for one polarization, A is effective aperture area of the radio telescope and Δf is receiver bandwidth. We equate

P (W) = k T_a Δf,

T_a is labeled as antenna temperature. This is done because output of the antenna is connected to an amplifier with receiver temperature (including background sky and other contributions) labeled as T_{sys} and corresponding power being $P_{sys} = k\, T_{sys}\, \Delta f$.

If we integrate for time constant τ with bandwidth Δf, rms of receiver noise for a single antenna is

$\Delta T_{rms} = T_{sys} / [\tau\, \Delta f]^{0.5}$ K

And corresponding power (W) is given by

ΔP_{rms} (W) = $k\, T_{sys}\, \Delta f / [\tau\, \Delta f]^{0.5}$ K

The 2 antenna interferometer measures

ΔP_{rms} (W) = $k\, T_{sys}\, \Delta f / [n\, (n-1)\, \tau\, \Delta f]^{0.5}$ K, where n = 2.

At 325 MHz and 610 MHz, T_{sys} = 100 K, Δf = 125 kHz for the present correlator with input bandwidth of 16 MHz and time of integration τ = 16.8 seconds.

Hence we get value of the receiver noise, ΔP_{rms} of a 2 antenna interferometer as,

$\Delta P_{rms} = k\, T_{sys}\, \Delta f / [2\tau\, \Delta f]^{0.5}$ K. $= 1.38 \times 10^{-23} \times 10^{2} \times 1.25 \times 10^{5} / (2 \times 16.8 \times 1.25 \times 10^{5})^{0.5}$

= -190.7 dB.

At 325 MHz, A_{eff} (sidelobe) ~ **2 / π**

Hence, $P_{sidelobe}$ (minimum detectable RFI) = PDF_{rfi} = ΔP_{rms} dB +10 log A_{eff} = (-190.8 -2 dB) = - 192 dBW.

In a synthesis radio telescope, such as the GMRT, we multiply voltage received by each pair of antennas. The GMRT antennas track a radio source and therefore value of the projected baseline changes giving rise to fringes with phase varying from 0^0 to 360^0. In the correlator, phases of output of each pair of antennas are corrected to become a constant value so that one can then determine brightness distribution of radio emission of celestial sources. However, since the source of RFI is fixed, fringes will arise with phase varying from 0^0 to 360^0. Therefore, if RFI is present in a 2 antenna interferometer, its amplitude will get decreased by sq. root of n fringes observed while tracking a celestial source. Many antennas in the central array are located within 100m or 200m. Hence at 150 MHz, only 50 to 100 fringes will be recorded and rejection in say 10 hour observations will be only by a factor of less than 10. As discussed in Section 3.1.1, it is important that RFI received from the GMRT electronics should be less than -200 dBW/m^2 in order to achieve theoretical sensitivity of the GMRT (at present astronomers have generally managed to achieve sensitivity (rms noise in the final maps) ten times worse than theoretical value.

3.2. Attenuation between a source of RFI located at a height of h_T above the ground and a receiver located with a height of h_R at a distance D (see Fig. 2)

We discus attenuation from a source of RFI located at a height of h_T above the ground to the power received by an antenna with a height of $h_{R.}$ and located at a distance D. It is shown that attenuation is proportional to D^4 and not as inverse square law *if* $[(h_{T+}h_{R/D)}{}^2]$ is <<1. For D being small as is the case for measurement from the GMRT electronics equipment, the attenuation can be calculated from Eq. 3 below.

Consider a Transmitter (source of RFI) with voltage, $V_{T,}$ and power P_T with its antenna located at a height of h_T above the ground. It will have an *image* below the ground at h_T with phase = 180^0. Voltage, V_R , received at the Receiver located at distance D with its antenna at a height of h_R is given by

$$V_R = V_T [- \cos (\omega t + \beta R_1) + \cos (\omega t + \beta R_2)] \qquad \text{Eq.1}$$

where $\beta = 2\pi/\lambda$ and R_1 is distance between image to the receiver and R_2 between the transmitter and the receiver (Fig. 2).

Since (cos A – cos B) = - 2 sin ½ (A + B). sin ½ (A- B), we get

$$V_R = -V_T [\sin \{ \omega t + \pi/\lambda (R_1 + R_2)\}] \sin \{\pi/\lambda (R_2 - R_1)\}, \qquad \text{Eq. 2}$$

the amplitude of the received voltage being,

$$I\, V_R\, I = \sin \{\pi/\lambda (R_2 - R_1)\},$$

and the power received is given by,

$$P_R = G_T A_R P_T [\sin \{\pi/\lambda (R_2 - R_1)]^2 , \qquad \text{Eq. 3}$$

Where G_T is gain of the antenna of the transmitter (~ 1 for a typical source of spurious unauthorized RFI, e.g. of the GMRT electronics and leaky cables of village TV network) and A_R is the effective area of the receiving antenna (log periodic or GMRT sidelobes).

The distances between the receiver located at a distance D, at height h_R , from the transmitter at a height of h_T and image below the ground at height h_T is given by R_2 and R_1 (see Fig 2),

$R_2 = [D^2 + (h_R - h_T)^2]^{1/2}$ and $R_1 = [D^2 + (h_R + h_T)^2]^{1/2}$, Eq. 4

We now consider two cases: 2.2 (a) when h_R and h_T are nearly equal, e.g. for the case when RFI measurements are made of an electronic equipment with the measurement antenna (e.g. log periodic antenna) of nearly same height; and 3.2 (b) when D is large so that $(h_R + h_T)/D^2 << 1$.

In either case $(h_R - h_T)/D^2$ and $(h_R + h_T)^2/D^2$ are << 1, it is easily shown (since $(1-b)^{1/2} = (1- ½ b)$ for $b <<1$),

$R_1 = D + ½ (h_R + h_T)^2/D^2$ and $R_2 = D + ½ (h_R - h_T)^2/D^2$,

Hence, we get h

$(R_1 – R_2) = 2 h_R h_T / D^2$,

If $2h_R h_T / D^2 << 1$ and since $\sin \theta = \theta$ for $\theta << 1$, we have from Eq. 3 that,

$P_R = G_T A_R P_T (\pi/\lambda \, 2 h_R h_T / D^2]^2$

i.e. $P_R = 4 (\pi/\lambda)^2 G_T A_R P_T (h_R h_T)^2 / D^4$ Eq. 5.

Thus, it is seen that the received power gets attenuated by D^{-4} (rather than inverse square law being D^{-2}) for a source of radiation located close to the ground when $(h_R - h_T)/D^2$ and $(h_R + h_T)^2/D^2$ are << 1.

The actual calculations based on Equations 1 to 4 may be considered when measuring RFI from the GMRT electronics. However, in the above calculations, I have assumed good conductivity of the ground. It is possible that the expected image below the ground may have much lower amplitude due to the poor conductivity of the ground. It is important that a calibration is done by the GMRT- RFI group by using 2 log-periodic antennas, one connected to a signal generator and 2nd to a 20dB LNA followed by a spectrum analyzer. The heights of h_T and h_R may be varied from 1 to 3 m and of D from 3, 5 and 10m. RBW of only 10 kHz and VBW < 300 Hz may be used. Measurements may be made at 6 or more frequencies from 130 MHz to 380 MHz. Log periodic antennas may be firstly oriented vertically and later horizontally. It would be useful to coordinate with the antenna group and thus it would be possible to assess harmful effect of RFI from PCs, SMPU, UPS etc. when measurements are made using the above test range. I have studied many reports by the RFI group but I am not able to quantify power radiated (power flux density as Watts/m^2) by a typical or worse PCs, UPS, switched mode power supplies etc. in order to estimate level of RFI from the GMRT electronics to the antennas of the central array. I may add that level of RFI measured by the GMRT-RFI group seems ~ 20 to 30 dB lower compared to that measured by Millenaar & Steppel (2004) at WSRT in which they have measured RFI from many equipment in a report titled “On self-generated RFI at Radio Astronomy Sites”.

4. **Power Flux Density (pfd) of the RF Signals (dBWatts/m^2) measured at the GMRT site**

In Section 4.1, I summarize the NCRA technical report: R00191 particularly with an objective to describe methods used for measurement of RFI and broadly indicate Power Flux Density (dbWatts/m^2) of strongest RF signals measured (e.g. from Pune TV) as ~ -90 dBW/m^2 and of majority of other signals from transmitters in Pune and Mumbai lying in the range of ~ -110 to -150 dBW/m^2. Our measurements indicated lot of discrete RF signals (unauthorized) seems to arise within ~ 30 km radius of the Central Square. Further discussions are given in Section 5. In Section 4.2, brief discussion is made of measurements made by Joardar and colleagues during early 2000.

4.1. In this section I summarize the NCRA technical report: R00191 (G. Swarup, 2001): "Surveys of Radio Frequency Interference (RFI) at the GMRT site from Terrestrial transmitters"**:** http://hdl.handle.net/2301/137. It is an extensive report (about 180 pages) in which I had summarized RFI measurements made by me and by T.L Venkatsubramani (TLV) at the GMRT site on several occasions during 1995 to end 2000. Using equations described in Appendix A of that Report, I had calculated power flux density (PFD) in units of dBW/m^2.

RFI signals observed with the GMRT in the 150-156 MHz and 230-245 MHz bands were tabulated in the Table 4-7 of R00191. Sensitivity of baseline of the recorded output of the spectrum analyzer connected in the receiver room to the output of the optical fibres corresponded generally to pfd -140dBW/m^2 based on $kT\Delta f$ (T ~ 100 K and Δf ~ 6 MHz); (~ -170 dbW/m^2 was obtained when a resolution of only 3 KHz was used on a few occasions to determine the modulation of the observed RF signal). Most of the observed and tabulated RFI signals had pfd values varying from – 145 dBW/m^2 to about -110 dBW/m^2. The received pfd of the TV signal from Pune was observed with pfd = -90 dBW/m^2. On the other hand, t*he harmful level of RFI for a radio telescope as per ITU Recommendation R769 for the protection of radio astronomy vary from pfd -180 to -194.5 dbW/m^2 for the 1420 MHz band to the 150 MHz band (see Section 2 and Table 3 of R00191).* Further, as discussed in Section 3.1.1, , it is desirable that no unauthorized signals of pfd > ~ - 210 dBW/ m^2 arise near the GMRT antennas particularly near antennas of the Central Array in order to achieve rms sensitivity of 20 micro-Jansky at 325 MHz.

Ten years ago, the spectrum analyzers available at the GMRT had only 400 point resolution and if I recall, Resolution bandwidth (RBW) of either 3 or 10 or 30 or 100 or 300 kHz. Thus if we decide to make measurements, say over 40 MHz, our resolution (RBW) could be only 100 kHz, whence we could measure RFI signals of power flux density, pfd, of only $kT\Delta f/A \approx$ -150 dBW/m^2. Now, I understand that Spectrum Analyzers are available at the GMRT with 10000 point resolution and hence, it should be possible to make surveys with sensitivity of -170 dbW/m^2 by observing over only 200 MHz bandwidth rather than 500 MHz or 2000 MHz as is being done by the GMRT RFI group. It is important that the RFI group of the GMRT must tabulate measured values of RFI in units of power flux density (pfd) dBW/m^2 rather than simply tabulating values noted from the Spectrum Analyzer. S. Joardar has also tabulated values of pfd (see also Manna, J. 2006 in the D-space of NCRA Library)

I discuss here only some highlights. During 1998-2000, we used the primary antenna feeds of the GMRT antennas pointed towards the horizon in four different directions. The 130 MHz IF outputs of the antennas in the Central Electronics Building were connected to a HP 8590 spectrum analyzer. Most of the measurements which were made during April 1998-September 2000 used resolution bandwidth (RBW) of 10 kHz or 30 kHz, video bandwidth (VBW) of 1 kHz, and averaging of 10 or 20 scans. Surveys had been made at the GMRT site mostly in the bands 152-154 MHz, 230-234 MHz and 322-328.6 MHz and also at adjacent frequencies of ± 16 MHz. For measurements made during the period April 1998-September 2000, scans had been taken only periodically during the day and night on several days, but more detailed measurements were made in December 1996-January 1997 and later in 1999 by T. L. Venkatasubramani for several days continuously. Sensitivity of the survey was only about - 155 to – 160 dBW/m^2. Thus, only the strong sources of RFI which are likely to be located within about 100 to 150 km distance from the GMRT site have been identified. More sensitive RFI surveys on a 24 Hrs. basis for several days should be made periodically using the GMRT radio interferometric system, with sensitivity of ~ - 170 dBW/m^2.

In Section 2 of Report R00191, are described RFI measurements made at the GMRT site and also near Alephata, Sangamneer, Junnar, Pune and Lonavala/Khandala during April 1998-September 2000 to identify the operating frequencies, power flux density and approximate directions of various radio transmitters producing severe RFI to GMRT, particularly in the bands 152-154 MHz and 230-234 MHz (see Figures 10 and 11 of that Report, reproduced in the present Report on pages 43 and 44 (see Appendix A). **These measurements showed that many more RF signals were seen in the measurements made at the Central Array than at Pune and other places indicating that a great deal of RFI is generated by the GMRT electronic**s. Results were summarized in Section 3 of the NCRA-R00191, discussions in Section 4 and conclusions in Section-5. **In Appendix-A of R00191 are summarized various methods which have been used for RFI surveys and the analysis procedure used.** Sensitivity of a radio telescope and required protection levels are summarized in Appendix-B of R00191. In Annexure A to the present Report are reproduced a few of the Figs. given in R00191.

4.2. Joardar and Banerjee (2004) have tabulated values of discrete RF signals measured by them using the innovative “E-plane Omnidirectional RFI monitoring System” near the CEB developed by Joardar (2004). There are large no. of plots in the report. They have plotted power of RF signals observed in units of dBJansky (1 Jy = 10^{-26} W/m^2/Hz). In that report, Resolution Bandwidth (RBW) used is not indicated. Assuming RBW ~ 30 kHz, I estimate that their data indicate pfd of -90 dBW/m^2 for Pune TV ~ 175 MHz and most other discrete signals in the range of -110 to -150 dBW/m^2 , similar to that summarized Section 4.1.
(see also “Absolute Calibration of RFI detection System at GMRT”by Manna, J. 2006 in D-space of NCRA Library and report by Banerjee and Joardar 2005)

5. RFI from Authorized and Unauthorized transmissions and by the GMRT Electronics particularly from the Central Electronics Building (CEB).

In Section 5.1 general comments are made regarding RFI surveys. In Section 5.2, are discussed authorized transmitters within ~ 30 km radius of the central array. In Section 5.3 are discussed transmission loss by troposcatter communication from authorized transmitters in Pune and Mumbai. In Section 5.4 a brief discussion is made suggesting the need to develop **RFI-Matrix** software that could distinguish between the RFI from authorized transmitters located far away, say Pune and Mumbai (should appear in most of the GMRT antennas) and spurious RFI from the GMRT electronics (only in nearby antennas). In Section 5.5 is proposed construction of a RFI shielded building of ~ 7000 square feet with priority to house all of the RF, optical fibre and digital electronics in order to minimize RFI from the central electronics building**.**

5.1.1. **RFI surveys**: As described in Sections 2, 3 and 4, the harmful RFI to the GMRT is lower by a factor of ~30 to ~40 dB (~ 1/1000 to 1/10000) than that measured by the GMRT RFI group using a spectrum analyzer connected to a log periodic antenna. The loss between the Central Electronics Building and the nearest GMRT antennas has to be considered. I also suggest that the GMRT RFI group may further develop a mobile van and particularly a Radio Location Array as are discussed in Section 9 for the purpose of daily monitoring of RFI.

5.1.2. Survey of RFI from Electronics located in the Control, Observer, Correlator and Receiver Rooms: During early 1990s, copper wire-mesh had been fixed on the inside walls of the above rooms. I strongly advise that a RFI survey may be made during 2 or 3 days during maintenance period with a Log Periodic Antenna (LPA) + 20 dB LNA and a spectrum analyzer with 10000 points across the Sweep, so that RBW of only 10 kHz is selected. Measurements may be made at distances of ~ 3 m and 10 m at 8 locations next to the above rooms with all PCS and electronics in other areas of CEB switched off. Electronics in the above rooms may be switched off sequentially and finally all electronics switched off. Measurements could be expatiated if 2 LPAs are used same time at 2 locations. It would be preferable if height of LPAs is made at least 2m above the ground, better 3m. Further, it would be advisable to measure the effect of shielding by radiating a RF signals at 150 MHz, 230 MHz and 325 MHz from a LPA at a height of ~ 1 m or 1.5 m inside the above rooms, sequentially and making measurements from outside. If there is not adequate shielding, an additional wire mesh on outer walls (not roof) of the above rooms should be installed.

5.2. RFI from authorized transmitters within ~ 30 km radius of the Central Array.

As I recall that there are very few transmitters authorized by the WPC within a radius of 30 km from the central array, apart from several GSM and CDMA towers near GMRT. *Most of the RFI at the GMRT antennas are likely to arise by troposcatter communication from transmitters located near Pune, Mumbai, Sangameer and Ahmednagar*

The band 149.05-150.05 MHz is used by a RN (radio navigation?) satellite. The police wireless has all India allocations in the bands of 157.5-159.5 MHz and 162.5-164.5 MHz. However, near Narayangaon they have fixed transmitters at ~ 158.45 MHz and 163.5 MHz. (GMRT RFI group may have a better record of the exact frequency and bandwidth that is likely to be < 75 kHz as typical for a frequency modulation: FM). Their mobile vans may be transmitting occasionally at some other frequencies. Irrigation Department has also a transmitter to communicate with their field workers opening and closing gates of the canals. I do not know whether the two sugar factories near W5 and S6 antennas have any allocations. A decade ago, P&T had an allocation for paging service but I am not sure whether that is still used. It is likely that P&T vans use radio transmitters at allocated frequencies in the 140-170 MHz region (GMRT RFI group may have information).

There are many mobile towers within a radius of 30 km or so from the GMRT antennas. These are transmitting in the bands ~ 850-880 MHz and ~ 950 MHz (exact bands have been measured by the GMRT-RFI group).

5.3. Transmission loss by the Troposcatter Communication from Authorized Transmitters in Pune and Mumbai to the GMRT antennas

There are large numbers of transmitters that are allocated by the WPC to various agencies in the frequency bands of ~120 MHz to ~ 500 MHz, in and around the city of Pune and Mumbai. There is no direct line of sight from the above cities to the site of the GMRT antennas. However, the signals from these transmitters are received at the GMRT antennas by troposcatter propagation. The troposcatter propagation depends on variations of the refractive index of parts of the upper layers of the earth's atmosphere lying at heights of about a km or two. It also depends on the moisture content that varies during the day and night and through the year. In Figure 12 of R00191 is given path profile between Mumbai and the GMRT site. In Figure 13 of R00191 and reproduced as Figure A5 in the present Report are given predicted transmission loss between a transmitter at Mumbai and the GMRT site based on a model by the National Physical Laboratory, New Delhi (NPL). In Figures 15 and 16 of R00191 reproduced as Figure 12c of the present Report are given predicted transmission loss between a transmitter at Pune and the GMRT site (Figure A6 and A7). To summarize, transmission loss is expected to be greater than 150 dB ~ 65% of time between Mumbai and the GMRT site and > 130 dB ~ 90 % of time. Between Pune and the GMRT site > 150 dB for ~ 83% of time and > 139 dB ~ 90 % of time. I may note that I expect troposcatter loss could be larger towards Mumbai and therefore I consider those values only as indicative. In Figure 16 of R00191 (A7 of present Report) is given predicted average transmission loss at various frequencies as calculated by T. L. Venkatasubramani in 1989 using National Bureau of Standard (N.B.S Tech Note 101). *To summarize, I expect loss between Pune and Khodad to be in the range of 140 dB - 150 dB in the frequency range of ~ 150MHz - 500 MHz most of time, with loss being about 10 dB lower at 150 MHz compared to that at ~ 500 MHz.*

In Table 8 of R00191 are given Power Flux Density (PFD) measured during 1995-1997 of several RF signals received at the Central Array in the frequency range of ~130 MHz to 183 MHz. Strongest signals measured were three: (a) we measured PFD of signal from Police Wireless transmitter at ~158.45 MHz and ~163.5 MHz (frequency to be measured more accurately) with PFD ~ -104 dBW/m^2. According to a letter that I received from the office of Police Wireless office in Pune on my request, the Police transmitter at Narayangaon radiates 40 W at 158.50 MHz and there is a repeater at Peth transmitting 25 W at 163 MHz. Assuming that Narayangaon police station is transmitting 40 W *isotropically*, and has a distance of ~ 10 km from the central array to Narayangaon, we would expect PFD ~ $P/4\pi R^2$ = [40 /4 π $(10000)^2$] = - 75 dBW/m^2 assuming loss as R^2 but -115 dBW/m^2 if we consider loss as R^3. The measured value of PFD ~ -104 dBW/m^2 for the police wireless signal is in between; (b) a signal was also measured at 146.65 MHz with PFD ~-108 dBW/m^2 and its source is not clear; (c) RF signal at the GMRT from the Pune TV at the carrier frequency of 175.25 MHz was measured ~ - 90 dBW/m^2 by us in 1996; assuming that the power of 6 kW (log 6 kW = 38dBW) was transmitted isotropically by the Pune TV , we deduce path loss from the 300 m tower at Singhgad hills near Pune to the GMRT site as follows: 38 dBW - 128 dB/m^2 = - 90 dBW/m^2. Considering the height of the TV tower, this value is comparable to the expected transmission loss between Pune and the GMRT site by troposcatter of about -140 dB (see previous para). I have assumed that the loss has units of m^{-2} as it is proportional to R^{-2}.

Most other signals received at the GMRT site according to the Reports R00186 and R00191 had PFD values between ~ -120 dBW/m^2 to -150 dBW/m^2. If we assume that these are by typical transmitters radiating 25 watts near Pune, the expected troposcatter transmission loss is in the range of ~ -140 – 160 dB, as predicted. However, we again note that these RF signals are 50dB to 60 dB larger than the sensitivity of a 2 antenna interferometer and hence it is important to develop suitable mitigation techniques.

In a 2 page Note that I found recently in my papers, it is summarized as follows: " Tentative estimates of RFI in the frequency range of ~155-210 MHz, 210-560 MHz and 560-1700 MHz: to summarize: there are likely to be scores of signals, a few of -90 dBW/m^2 and many in the range of -120 to -150 dBW/m$^{2.}$; (i) In the range of about -156 MHz to 176 MHz, there are many signals with power flux density (PFD) of about -110 dBW/m^2 to -140 dBW/m^2….the TV at Pune has PFD of about -90 dBW/m^2. Also TV signals from Mumbai and Ahmednagar were observed at the GMRT up to ~ 210 MHz"

It is highly desirable to make recent surveys giving a summary of the PFD levels of RF signals observed at the GMRT antennas. To summarize, I believe that there are likely to be seen a few signals at the GMRT in the frequency range of ~ 130 MHz to 530 MHz with PFD levels of greater than -110 dBW/m^2. *These should be measured during the month of June or July on days of high winds when antennas are parked and therefore the GMRT Feeds can be rotated towards the horizon in various bands on different days and PFD levels calculated taking account of A_{eff} of antenna feeds (see R00191, Appendix-A)*. For RFI signals > -100 dBm or -110 dBm filters may be planned at the front end boxes or base of all the GMRT antennas to avoid intermodulation products by the optical fibre system. Any case we should evaluate intermodulation products for signals with PFD in the range of -90 dBW/m^2 to -120 dBW/m^2.

5.4. Proposal for RFI-Matrix Software to distinguish between Authorized and Un-authorized narrow band Transmitters.

The GMRT telescope operators (including S.N. Katova) have developed useful software (RFI statistics) that plots observed RFI, *separately for each antenna and for 2 polarizations,* during the GMRT observing session of 6 or 10 hours by plotting *intensity* as grey scale, *time* along the y axis and *frequency* along the x axis. I suggest development of one more software named **RFI-Matrix** that plots RFI by grey scale for *antennas* 1 to 30 along the y axis and *frequency* along the x axis, with selectable time of integration, say 1 minute or tens of minutes (separate plots for 2 polarizations). **Thus it would be possible to distinguish readily between (a) RF signals from far-away places, such as Pune or Mumbai or Ahmednagar that should be seen in majority of antennas (but not all the antennas as troposcatter communication will have *multipath* losses) and (b) local RFI from the GMRT electronics or TV boosters or cable TV or from spurious equipment of the sugar mill near the W5 antenna**. Further I suggest that the GMRT RFI group may locate source of RFI being generated by the electronic equipment at the sugar factory and help them to install suitable shielding. I may note that ITU and WPC have limits of permissible spurious emissions, exceeding those limits is illegal.

5.5. Proposed Construction of a RFI-shielded Building of ~ 7000 square feet with priority to house all of the RF, optical fibre and digital electronics.

As described in Section 4, RFI arises from unauthorized spurious RFI from several sources near the GMRT antennas. It is important to minimize RFI to antennas of the Central Array arising from the RF and digital labs and also by many PCs in the Central Electronics Building (CEB), I recommend that NCRA should construct, (a) a fully shielded lab of about 7000 sq. ft., next to CEB, *with wiremesh all around* and to locate all the RF, control and Monitor and digital groups (see Fig. 3) and (b) also install urgently a shielded box for minimizing RFI from all the PCs, even those that are in the control room etc. I understand that a shielded box has been developed by the RFI group of the GMRT and also a commercial shielded box has also been identified. It may be noted that Jodrell Bank group has been using shielded boxes with 40 dB attenuation.

6. INTERMODULATION PRODUCTS OF RFI SIGNALS

6.1: Due to non-linearity the GMRT receiver system spurious RF ('RFI') signals may arise in the presence of narrow band RF signals being received by the GMRT antennas. Intermodulation arises if the output, y, is not related linearly to input values, x, such that it has finite values of 'b" and "c" in the relation: $y = a.x + b.x^2 + c.\ x^3$ ……. Generally higher order terms are negligible, where,

$$x = v_1.\cos 2\pi f_1 + v_2.\cos 2\pi f_2 + v_3.\cos 2\pi f_3 + v_4.\cos 2\pi f_4 + \dots\dots\dots$$

Generally the observing band is less than an octave in bandwidth, whence the term $b.x^2$ does not give intermodulation products. The 3rd order intermodulation products are given by the finite value of the coefficient c. The RF and optical fibre group measure the 3rd order intermodulation value (OIP3) by applying two strong RF signals. As I have described in Section 4, the strongest RF signal observed is from Pune TV at 175 MHz with pfd value of ~ -90 dBW/m^2. At ~ 350 MHz, narrowband RF signal seems to be often present quiet with pfd value ~ -110 dBW/m^2. Besides many RF signals are observed in the frequency bands of 130-

250 MHz and 250-500 MHz with pfd in the range of -120 dBW/m^2 to-150 dBW/m^2 (sensitivity limit of RFI surveys done so far at the GMRT).

Since the expected rms of the GMRT in the 300-400MHz band, as an example, is ~ 30μJy, it is advisable to make a detailed analysis to ensure that the *products due to the term* (c. x^3) of the input RF signal of power flux density, pfd ~ -110 dBW/m^2 with several weaker signals in the range -120 dBW/m^2 to - 150 dBW/m^2 do not produce intermodulation products of weaker levels up to ~ -210 dBW/m^2 as even such weak signals would be detrimental to the achieving rms sensitivity of the GMRT at 30 microJansky. It would be possible to make such an analysis after the value of c in the term c. x^3 is determined by the GMRT electronics group. Sensitive measurements by the GMRT electronics group may be able to measure lower levels of intermodulation products. At 300 MHz, the effective area of sidelobes with expected gain G =1 of the GMRT antennas is $A_{eff} = G.\lambda^2/4\pi = 0.08\ m^2 = -11\ dBm^2$. Hence pfd of -110 dBW/m^2 of RFI at the GMRT antennas corresponds to input power at the LNA of the frontend box = -110 dBW/m^2 -11 dBm^2 = -121dBW = -81 dBm. As described earlier, weakest level of intermodulation at the frontend amplifiers (LNA) of the GMRT should be < - 210 dBW/m^2 -11 dBm^2 = -221 dBW = -189dBm. GMRT group has sensitive spectrum analyzers that may allow such measurements using RBW of 1 kHz or 3 kHz near the expected products of two input RF signals of -81 dBm applied to the input of RF amplifier (LNA) using 2 signal generators and using integration to ensure that no products are seen >-189 dBm.

6.2. In this Section, I discuss 3 major systems of the GMRT receiver chain that could give rise to spurious RF signals due to non-linearity: (a) RF amplifiers at each of the GMRT antennas, (b) non-linearity of the laser diodes of the optical fibre system and (d) digital correlator.

6.2.1. RF amplifiers:

A detailed report titled "Complete signal flow analysis of 325 MHz frontend system" by Gaurav Parikh & Anil Raut (GMRT/FES/001-Feb 2014) has tabulated as follows: (http://www.gmrt.ncra.tifr.res.in/gmrt_hpage/Upgrade/signal_flow_analysis-325MHz.pdf)

As the Report describes, selectable filters are placed after the LNA. Thus the 250 - 500 MHz band has 4 sub-bands of 100 MHz each: (240 -340), (300 - 400), (360 - 460) and (420 - 520 MHz). Full Band gives 250 MHz bandwidth.

As is a standard practice, RF group measures values that indicate maximum values of input and output powers due to any RFI that would not give rise to harmonic products. The measured values are 1db compression at *input* = -52.2 dBm for 100 MHz bandwidth and - 44.6 dBm for 400 MHz; 3rd order OIP3 at *input* = -39.1 dBm for 100 MHz bandwidth amplifier chain and -23.3 dBm for 400 MHz amplifier chain (see report by Parikh and Raut).

For system temperature of ~ 100^0 K and Δf = 100 MHz , the input rms noise power is given as: $kT\Delta f = 1.38 \times 10^{-23}. 100. 10^8 = 1.4 . 10^{-13}$ W and $5.6 .10^{-13}$ W for Δf = 400 MHz. The strongest RF signal ('RFI') seen at ~350 MHz (Section 5.3) with pfd value ~-110 dBW/m^2 - 11 dBm^2 = -121 dBW = -81 dBm. Even conservatively, I estimate that the input power at the RF amplifier for assumed bandwidth of the 'RFI' of 10 kHz is ~ -81 dBW = -51 dBm which is lower than OIP3 at *input* = -39.1 dBm . *Therefore, we do not expect any **strong** non-linear components caused by the RF amplifier of the 250-500 MHz system of the uGMRT. However, one needs to determine whether **weaker** intermodulation products could arise as discussed in Section 5.1.*

(Occasionally very strong RFI is caused by certain airplanes of the Indian Air Force in this band. They would not give nonlinearity unless the strength of the signal received by the GMRT antennas is much greater, say 50 dB higher than that of the receiver noise caused by its noise temperature of 100^0 K and could be filtered in principle elsewhere in the receiver system (coordination is being done and must be ensured that these airplanes MUST not radiate in the protected band of 322-328.6 MHz).

6.2.2. Optical Fibre system:

As described above, the output of the frontend RF amplifiers is applied to a set of switchable filters followed by the 'common box' placed near the focal point of the 45 m dishes. The received signal is brought to the base of each antenna and is applied to a set of switchable attenuators followed by the laser diode connected to the optical fibre that transmits the received RF signals by each of the GMRT antenna to the receiver sub-system and digital correlator at the Central Electronics building.

6.2.2. 1: The basic parameters of the optical fibre system are given below (private communication by Shri Suresh Kumar):
Bandwidth of the input signal to the optical fibre depends on the filters placed in the RF Front end system of the input part of the receiver: (a) The Bandwidth for 130 -260 MHz band is 130 MHz . (b) The 250 - 500 MHz band has 4 sub-bands of 100 MHz each. (240 -340 MHz), (300 – 400MHz), (360 – 460MHz) and (420 - 520 MHz). Full Band gives 250 MHz bandwidth. (c) 550 - 900 MHz band has 4 sub-bands of 100 MHz each (550 – 650MHz), (635 – 735MHz), (720 – 820MHz) and (800 - 900 MHz). (d) L-Band with 4 sub-bands each of 120 MHz Bandwidth each. Full Band gives 400 MHz bandwidth

The RF input power to the laser diode for any of the bands and bandwidth is ensured as -28 dBm by the laser diode group by using a variable attenuator: the variable RF attenuator before the laser is adjusted depending on the RF Band, full-band and sub-band. The laser's input P1dB saturation is + 19 dBm. The operating point is getting fine tuned with a variable attenuator between the frontend and fiber optic system so that the RF operating power of the laser diode is constant for all the RF bands and for all bandwidths and thereby ensuring constant RF power to the backend system).

6.2.2. 2. Analysis : (I make below an analysis for the laser diode of the uGMRT, following the analysis described in the M.Tech thesis (1994) by D. Sivaram; pp. 47-48). It should be noted that laser diode is a non-linear device (Fig. 3.2). The test data sheet of the laser diode used for uGMRT (Model #: 1754C-34-BB-SC-10) (see Appendix 3) has specified the threshold current as 11.89 mA. Although it specifies peak current as 120 mA, I find that 1 dB compression corresponds to ~ 60mA (see (b) below).

(a). Input Power -28dBm -30 = - 58dBW = 1.584×10^{-6} W = $(i_{rms})^2$ x 50 ohms. Hence, i_{rms} = 0.178 mA.
(b). P1dB saturation = + 19 dBm = -11dBW = 0.079W = $(i_{rms})^2$ x 50ohms). Hence, i_{rms} = 39.75 mA and therefore I_{peak} = 1.414 x 39.75 = 56.3 mA. I assume it as 60 mA corresponding to 10 mW output power of the laser diode.
(c). From Fig. 3.2, the maximum permissible value of peak to peak current of a RFI is the difference between peak current and the threshold current of the laser diode = (60 - 11.89) = ~ 48 mA and therefore its rms value is $i_{rms} = \{48/ (2 \times\sqrt{2})\} \times 10^{-3}$ A, that I equate to $\sqrt{P/50}$ ohms).

Hence $P = 50 \times [\{48/ (2 \times\sqrt{2})\} \times 10^{-3}]^2$ = 0.0144 W = - 18.4 dBW = 11.6 dBm.
Since P = 11.6 dBm = (P_{rfi} + Font end amplifier noise) = (P_{rfi} - 28 dBm). we get maximum allowable value of RFI as
P_{rfi} = (11.6 dBm + 28dbm) = 39.6 dBm = 9.6 dBW

The input signal to the laser diode in absence of RFI is ensured as -28 dBm. Hence, the narrowband RFI signal will not give rise to non-linearity if its power P_i is the difference between 11.6 dBm and -28 dBm. = 39.6 dBm

At the input of the RF amplifier for Tsys = 300 K and 100 MHz filter of the 130-250 MHz band we get, $P = kT\Delta f = 4.14 \times 10^{-13}$ Watts = -123.8 dBW = -93.8 dBm and therefore P at input of laser diode = -27.8 dBm for a gain of ~ 66 dB between inputs of LNA and laser diode. A 40 dB margin implies no intermodulation if the pfd value of RFI < -123.8 + 40 = ~ - 83.8 dBW = A_{eff} x pfd. Since $A_{eff} = \lambda^2 .G/ 4\pi = 1/ \pi$ (for G =1 and λ =2 at 150 MHz) = -5 dBm^2, the maximum allowable power flux density, pfd, of RFI = - 78.8 dBW/m^2 at 150 MHz. If observations are made with a filter of 5.6 MHz, maximum allowable pfd of RFI = -91.3 dBW/m^2

Since maximum observed value of RFI observed at the GMRT antennas is -90 dBW/m^2 (Pune TV), we may conclude that nonlinearity of the laser diode may not produce intermodulation products.

6.3. Non-linearity of the Digital Correlator: I understand that 8 bit digitization is being done in the new correlator; one should investigate and record its limitation to the generation of any intermodulation products, if any. For the hardware correlator built during 1990s, a 4 bit digitization was done and as I recall it had only 34 dB margin against intermodulation. The present correlator group may have examined the margin against intermodulation;. I suggest a 100 dB margin so that narrow band RF signals seen at the pfd level of ~ -110dBW/m^2 do not produce any spurious intermodulation products of -210 dBW/m^2. This aspect requires discussion in a technical note by the GMRT correlator group.

7. POWER-LINE RFI RECEIVED BY THE GMRT.

7.1. Central array antennas.

A great deal of pulsed interference is observed from the overhead 11 kV HT lines feeding the GMRT antennas, as well other 11 kV HT lines and transformers supplying power to the irrigation pumps of a large number of farmers in the nearby regions to the GMRT antennas. Pulsed interference is observed every 10 ms, when the voltage of the HT lines exceeds about +/- 5 kV in every 10 ms of the 50 Hz power supply (20 ms period) particularly from the dirty and/ or cracked insulators, poor grounding of poles, poor wire connections etc. These pulses have rise time of several nanoseconds and duration of < tens of microseconds. Consequently it results in *broadband RFI* to the GMRT even up to 300 MHz (with far away peaks proportional to $(1/x)^2$ of $(\sin x/x)^2$ spectrum. (Swarup, ITR R233, 2008). These sharp pulses give rise to harmful interference to the GMRT observations. This broadband RFI affects the sensitivity of the antennas of the Central Array of the GMRT due to their close spacing, whence the observed numbers of inteferometric fringes, n, even in observations made over several hours, are limited in number. As pointed in Section 2, RFI gets suppressed as $n^{1/2}$ and hence suppression is considerably lower if n is small. Therefore, the rms noise increases considerably due to the powerline RFI and the theoretical sensitivity and dynamic range of the large collecting area of the GMRT is not achieved.

The GMRT RFI group has been making considerable effort to identify 11 kV poles with defective insulators and also transformers supplying power to farmers in nearby regions of the GMRT antennas. It is not possible to do daily monitoring over the large area covering the GMRT array. It is therefore very important to take major steps to minimize power-line RFI as suggested below.

Firstly, for reasons described above, we must eliminate all sources of powerline RFI up to distance of ~ half or one kilometer from the Central Array antennas. I had written a letter on 9th September 1998 (copy available with me) to the late Prof. Kapahi urging "it is important that the 11kV power lines from the 2 MVA transformer to East and South lines be replaced …by 11kV HT underground cable running through our premises …to a distance of about 200 or 300 metres to the east of the C0 antenna)".

I consider that it is very important (essential) to avoid low level broadband RFI to the GMRT. In 1998 I had made sensitive measurements using a FM receiver and a digital meter across the loudspeaker and found that RFI was observed from almost half the poles of the 11 kV lines lying north of the Central Array. As has been described in ITR ROO191 (Swarup, 2001) and ITR 233 (Swarup, 2008), pulsed RFI is observed in the data of most of the GMRT antennas. Measurements by B.C. Joshi using pulsar observations have also shown that. Recently, the GMRT-RFI group has noted considerable broadband RFI for several southern antennas of the Central Array. This could be arising from connections of the transformers of some of the irrigation pumps towards the south of the Central Array.

Pulsed RFI is also observed from the poles of the 33 kV lines supplying power to the GMRT and we may consider replacing the portion by 4 wire cable up to 300 m away from the HT yard at the Central Array. The GMRT RF group has been regularly monitoring RFI from the connections etc. of the transformers in the HT yard.

Sometime ago, Shri Swamy had suggested that we consider supplying HT power to the Y array antennas at 6 kV (I prefer 4 kV) rather than 11 kV. It will increase losses in the line supplying power to the 14 antennas of the Y array increasing in the electricity cost for the Y array. Perhaps, it may increase the cost of power supplied to the E and S arrays by only 10% or so, but needs to be calculated by Shri Swamy. Also the cost of a transformer at the Central 33kV yard and 12 transformers at the Y array antennas needs to be evaluated. This suggestion needs serious consideration. In that case we need not replace the overhead 11 kV HT lines supplying power to the East and Southern antennas of the Y array next to the Central array by underground 11 kV HT cable as suggested above by me.

I reproduce below abstract of a NCRA Technical Report R 00233 (by Swarup 2008) discussing in detail origin of RFI from High Tension power-lines particularly of 11kV that supply electrical power to the GMRT antennas and also to numerous farmers within several hundred m from the GMRT antennas.

High tension (H.T.) power-lines in the vicinity of the GMRT antennas produce harmful pulsed radio frequency interference (RFI) to radio astronomy observations, particularly in the 150 MHz band. Measurements show occurrence of groups of pulses occurring every 10 ms (half cycle of 50Hz), with each pulse of tens to few hundred micro-second duration. The intensity of the pulses is often 10 or 20 dB above the system temperature of the GMRT receiver adversely affecting the achievable sensitivity of the GMRT at 150 MHz. Power-line RFI is also present at higher frequency bands of the GMRT but of lower intensity. The power flux density of the pulses decreases with increasing frequency as f^{-2} or f^{-3}, including consideration of the gain of the side-lobes of the primary antenna feed. It would be interesting to estimate frequency dependence of the power-line RFI by taking Fourier transform of the pulsar observations at 150 MHz, 235 MHz and 325 MHz on a given day and finding the intensity of the 50 Hz pulses and of harmonics.

Measurements made by me and Raybole on 9th April 2008 indicate that the power- line RFI seems to be much higher now than that recorded by me in 1998 (we also found that the observed power-line RFI at the E2 antenna is extremely high, perhaps from the nearby 22 kV or 33 kV line (to be checked now).

Brief comments on the extensive Power Point (PPT) Report regarding Power line interference by transformers by Pravin Raybole and colleagues are given in Section 7.

Although it would become possible to clip these sharp pulses at the input of the new software correlator, it is also important to carry out electrical and electronic solutions to minimize the power-line RFI, particularly for antennas of the Central Array of the GMRT. Clipping at the antennas is desirable in order to minimize any inter-modulation products due to the limited dynamic range of the laser diode of the optical fibre transmission system. This clipping at the antennas will be particularly important for the proposed 40 MHz - 60 MHz feed for the GMRT.

It is known that severe radio noise (RFI) is generally caused by *corona discharges* on the HT lines of voltage > 65 kV. For lines of lower voltage, say of 11 kV and 33 kV, *gap discharges* at the insulators located at the electrical poles, poor grounding of the support arms and loose contacts in the joints gives rise to severe RFI. Similarly, RFI is also observed near the transformers of the irrigation pumps located near the antennas of the GMRT due to poor connections to the 11kV lines.

I discuss here various solutions for minimizing power-line RFI at the GMRT antennas. These concern electrical, electronics and software solutions. I have incorporated some of the comments that I got when I gave a talk at GMRT on 10th April 2008. I summarize here some of my recommendations, supplementing the efforts being made by the GMRT group.

(a) Electrical solutions: Shri Swamy has tentatively proposed replacing the 11kV lines with the 6 kV lines. Swamy considers that using 11 kV insulators on the 6 kV line (and changing 11 kV/ 400 V transformers to 6kV/400V at each of the Y array antennas) may offer higher resistance to the surface contaminants and any defects on the insulators that may result in lower RFI. It is not clear whether that would minimize power-line RFI appreciably since the gap discharge is a high impedance occurrence. However, I consider that gap discharge takes place only when the powerline voltage exceeds ~ 5kV or 6 kV (Swarup 2008, ITR 233). This can be experimented either at the GMRT site by purchasing a 11kV/6kV transformer and experimenting with poor insulators. Alternatively, one may consult the Central Power Research Institute (CPRI) at Bangalore, next to RRI (Prof Udayshankar may have contacts).

(b) Identification of defective connections on the 11 kV and 33 kV HT lines. GMRT staff is periodically locating defective connections and insulators on the electric poles of the HT lines and also loose connections at the irrigation pump transformers using an ultrasonic devise, consisting of a small dish and an ultrasonic detector. Additionally, I would like to recommend building a compact portable battery operated amplifier with a gain of about 60 or 80 dB and , with a small whip antenna at the input, a filter of about 1 MHz bandwidth. The amplifier may be tuned to a VHF frequency, say in between 60 or 70 MHz (where no strong CW signals may be seen at the GMRT). The output of the amplifier is to be connected to a diode detector followed by a sensitive 3 digit voltmeter. This will provide quantitative measurements near the electric poles and as a function of distance. If an FM receiver is used, it would be important to add a RF amplifier of about 20 dB gain at the input to improve the sensitivity. The GMRT group may also consider buying a standard radio noise measuring equipment using the European CISPR standard (it has also been adopted by the Indian Standard Institution, ISI).

(c) Electronic solutions: It is planned by the correlator group to clip the narrow pulses caused by power-lines using the new software correlator. The clipping may be done for a fraction of 1 ms whenever sharp pulses are detected with a time constant of about 50 microseconds at the input section of the software correlator (durations to be experimented).

Ideally one may clip the pulses at each antenna, just before the laser diodes of the optical fibre system, in order to avoid any inter-modulation products due to the limited dynamic range of the laser diodes. This would also minimize RFI during thunderstorms. For pulsar observations or observations for celestial transient sources, such clipping would be disabled using the existing Monitoring and Control Modules (MCM). Noise generator calibration would be required to measure the period for which the voltage signals are clipped in order to calibrate the gain of the antenna. I may add that observations in the frequency band of ~ 40-60 MHz with the new feed being developed by the Raman Research institute (RRI) for the GMRT are likely to be very seriously affected, unless sharp pulses of power-line RFI are clipped at each antenna. (It may not be possible now to install RRI low frequency feeds due to installations of the Cone Dipole: I may add here that I have suggested to G. Shankar an alternate possibility of installing an innovative Feed system operating ~ 60 MHz using pairs of short dipoles around four sides of the L Band feed).

(d) Software solutions: In addition to the clipping as described above, it should be possible to locate readily all the defective electrical poles and irrigation pump transformers, using the proposed RLA and PARI (Section 8). It would use a search technique similar to that developed by Pathak, Swarup, Chatterjee and Kale (2005) and uLi Pen et al. (2009). If differential GPS positions are determined for all the electric poles and irrigation pump transformers within a region of ~ 1 km surrounding the Central Array of the GMRT, it would be possible to locate harmful sources of power-line RFI expeditiously within ~ one hour. Thus MSEB can then take corrective steps readily within a few days in one go.

8. **PPT PEPORT BY RAYBOLE DATED 2008**

In a detailed report Pravin Raybole and colleagues titled: "TV Booster Interference and Power Line RFI around GMRT", pravin2.ppt, 2008, http://hdl.handle.net/2301/395 (please see NCRA, Library D-Space), a detailed summary is given of random visits made during a period of 3 years from ~ 2005-2008, in order to survey RFI by (a) TV boosters and (b) 11kV/ 440 V transformers of the MSEB power-lines.

8.1. RFI by TV Boosters: In 16 villages next to the antennas of the GMRT, 1699 TV boosters were noted. RFI was noted from a large fraction of these TV boosters and many were modified by improving the RF amplifiers, in many by simply adding a resistor. The report lists 21 manufactures. Measurements were made using a log Periodic antenna, RF amplifier and spectrum analyzer. Unfortunately, no attempt was made to estimate power radiated by a mal-functioning TV boosters at their output in units of dBmV as measured at a distance of ~ 10m and also power flux density (dBW/m^2) of RFI by TV boosters at a distance of say 300m to the closest GMRT antennas. As I have noted earlier that *it is illegal* to operate defective electronic equipment that produces spurious radio emission more than permissible limits of radio emission.

There are detailed recommendations by ITU regarding levels of spurious emission from general electronics equipment (check from ITU documents in the NCRA library, contact WPC and search Google). The level depends on the telecommunication service. As I recall that there is a general limit of – 60 dBm in a 100 kHz band for spurious and out of band emission at the output of the electronic equipment (GMRT group to consult WPC). Any equipment radiating more than specified limit is illegal and will be banned by WPC. I strongly recommend that a senior radio astronomer from NCRA and an RF engineer should visit WPC regarding oscillating TV booster, **as well leaky coaxial cables by Cable operators in villages close to the GMRT antennas.**

I and Ramesh Sinha had ordered several reports of the International Telecommunication (ITU) in early 1990s that are available at NCRA library. It is possible that general limits of RFI are given in one of those reports. A search in Google would also provide such information.

8.2**. Survey of 11kV/400V Transformers**. In the ppt report by Raybole et al. (2007), latitude and longitude of 58 transformers near the GMRT antennas of the West arm, 32 of East Arm and 24 of South arm are given. Extensive work has been done. I may note that only occasional visits are possible to transformer of irrigation pump of farmers near the GMRT antennas. Hence, I would like to suggest that a better method has to be evolved than is being carried out. As discussed elsewhere in Section 9, it is important to develop RLA (and PARI for the Central Array) that will be able to monitor quickly on a daily basis any malfunctioning TV booster, leaky coaxial cables and mal-functioning 11kV/440 V transformers and pulsed RFI from 11 kV poles of power lines. Locating powerline RFI using software developed by u-li Pen et al or Sachin et al using the GMRT antennas is not an easy solution.

9. MOBILE VAN FOR RFI DETCTION

Over the last 15 years, importance of a mobile van for locating sources of unauthorized and spurious emissions has been discussed many times (I have several reports; please see R233; Figs 5 and 6). The GMRT RFI group has also used a mobile van for the purpose of locating sources of RFI. It would be useful to upgrade the present set up so that it could *survey and locate sources of local RFI near each of the 30 antennas within 7 or 8 working days* in an automatic way. Further, I suggest a mobile van with 6 Discone antennas placed at a height of 0.5 m or higher above the roof of the mobile Van in the form of a rectangular or hexagonal array, operating in the frequency band of ~ 130 MHz to 700 MHz, and each connected to a RF amplifier, LO, Mixer, IF amplifier, ADC and finally to a digital correlator (a standard PC may provide thousands of channels). RFI group may evolve a suitable design using visiting students and project trainees. To begin with only one Discone antennas may be put on the roof of a Van or the CEB and electronics developed. I may add that many observatories have developed suitable RFI Vans (e.g. by the Sardonia group).

10. RFI LOCATION ARRAY (RLA).

I would like to suggest constructing with high priority a RFI Location Array (RLA) by installing Discone antennas on poles of say 10 m height near all the 30 GMRT antennas. Signals received by these antennas would be amplified and brought to a correlator installed in the Central Electronics Building (CEB) using the existing optical fibre and if required another optical band. Thus, we can readily identify sources of unauthorized RFI close to the GMRT antennas. It would require innovative software. The GMRT RFI group had made a novel proposal last year for locating Discone antennas mounted on ~12 m high poles/towers near only 7 out of 30 antennas of the GMRT. I consider that it is important to install Discone antennas near all the 30 dishes of 45m. Once the RFI group develops one station (ensuring amplifiers that are unconditionally stable like all the GMRT front end amplifiers), the full array could be sub-contracted, e.g. Dr Vishwas Udpikar may be interested. I may add that the mobile RFI van cannot keep 22/7 watch. RLA can use a simple correlator with few thousand channels and thus act as a spectrum analyzer. If a scheme can be developed for calibrating phase of the electronics system of RLA, it can act as an interferometric array that would be sensitive with tens of dB lower values than that made by total power measurements of RLA. Mobile van is required when an unauthorized RFI is observed near any of the GMRT antennas**.**

If a scheme can be developed for calibrating phase of the electronics system of RLA, it can act as an interferometric array that is sensitive by tens of dB lower values than that of total power measurements of RLA. For celestial observations with the GMRT, point/compact celestial radio sources are observed as 'phase calibrators' for determining phase of each of the frequency channels of the RF electronics of each of the GMRT antennas. That would not be possible for the RLA as discone antennas have small effective area as these have gain ~1 and $A_{eff} = G. \lambda^2/4\pi$ being only ~ 0.3 m^2 at 150 MHz and even smaller at higher frequencies compared to A_{eff} ~ 900 m^2 of the GMRT antennas.

For the central array antennas, we could in principle calibrate the phase of electronics by radiating a narrow pulse of a 5 MHz oscillator that will have harmonics every 5 MHz. As described below, it may be sufficient to transmit only tens of mW from the oscillator just before and after RFI survey is made, say on the weekly maintenance day. This pulsed oscillator is to be connected to a wideband Discone antenna, mounted on a pole at a height of ~ 15m and located at the northern side of the Central Array or at the GMRT housing colony (accurate positions of all the poles to be determined using a differential GPS receiver). Comparison of the voltage signal received by the Discone antennas of the RLA with that of the transmitted signal will provide round trip phase measurements. It may be noted that the round trip measurement is extremely sensitive because it has rms of only $kT\Delta f$, with $\Delta f = 1/\tau$ with τ being time constant of the measurement being few seconds (Swarup and Yang 1961). Thus with a receiver of system temperature of say 100K, it is possible to make measurements with round trip loss of ~ 200 dB in principle. Hence it may be sufficient to transmit only tens of mW signals (please see D. L. Narayana's thesis regarding LO link of OSRT). Thompson, Moran and Swenson (1986, Section 7.2) discuss several practical round trip schemes. If the above scheme is found practical by firstly experimenting using 2 stations, RLA can be named as PARI (Phased array for RFI identification). For the Y array antennas, a round trip measurement of phase can be considered in principle but it would be cumbersome.

In principle, the concept of RLA and PARI using a circular array could be important to locate unauthorized signals, e.g. by terrorists around major cities (I wonder whether the concept would be patentable once it is executed).

11. RFI MITIGATION

A number of reports are available in the literature for RFI mitigation on line as well post analysis as listed in the following reports (see Section 13: References); (1) Baan et al. 2004 and 2010, RFI mitigation at WSRT… ; and (2) a detailed report: ITU-R, RA (09-2013) : Techniques of Radio Frequency Interference in Radio Astronomy". Subhashish Roy is one of the authors of Baan et al. 2010. He and others should provide guidance for development of online RFI mitigation, prior to correlation in the GWB.

12. CONCLUDING REMARKS

Even though the GMRT is located about 60 km away from the Pune city, considerable radio frequency interference (RFI) is observed at various antennas of the GMRT. There are several sources of RFI: (a) radiation from many VHF and UHF transmitters at Pune and Mumbai; (b) 3 or 4 transmitters located within a radius of ~ 30 km from the central array of the GMRT and radiating in frequency bands authorized by the WPC and (c) satellite RFI in the band of 137-138 MHz, 150-150.05 MHz and in a band of about 248-260MHz; (d) GSM and CDMA mobile towers; (e) **RFI from the GMRT electronics,** (f) till recently, mal-functioning TV boosters in villages around the GMRT were giving occasional RFI but now RFI is taking place from leaky cables and connectors and (g) broadband interference from the high power 11 kV electrical transmission line and its connections to transformers 11 kV/440 V of irrigation pumps.

As a result, about 30 to 50 % data is flagged by radio astronomers during the analysis of observations made with the GMRT particularly in the 150 MHz and 240 MHz bands and more than 20 % in the 325 MHz and even in the 610 MHz band. Therefore, it becomes strenuous to analyze the data, although some pipelines have been developed for flagging, calibration and imaging. Recently we found that the FLAGCAL software has flagged 70 % of the data of the planet Venus observed on March 26, 2004 in the 240 MHz band. Because of RFI, the theoretical value of sensitivity (rms noise) value is not achieved.

The harmful effect of RFI will be much more serious in the wide band capability of the upgraded GMRT. Hence, it is very important to ensure that (i) no spurious radiation takes place by the GMRT electronics; (ii) to construct a fully shielded building (wiremesh all around) of about 7000 or 8000 sq. ft., adjacent to the present Central Electronics in which all RF and digital Labs and adjacent offices of the concerned engineers are located; (iii). *replace overhead 11 kV lines by underground 11 kV cables feeding the Eastern and Southern Y arm antennas from the 33 kV HT yard up to~ 300 m away from the C0 antenna in order to minimize harmful effects of power-line RFI to the antennas of the Central array; (iv) clip the pulsed interference soon after the ADC in the GSB and GWB as per the scheme suggested in this Report,* (v) urgently make a *mobile RFI van* as has been suggested over the last 15 years,

(vi) *additionally*, to build with high priority a Radio Location Array *by installing 30 poles with Discone antennas near all the 30 GMRT antennas* and use its data to identify sources of RFI next to and up to several km away from the GMRT antennas. At the Central Array, RLA could can be upgraded in due course as a *Phased Array for RFI identification (PARI).*

Reference 6 describes a Ph. D. thesis by Langat from South Africa: "Power-line sparking noise characterisation in the SKA environment". It quotes my ITR233, http://hdl.handle.net/2301/431. However, our efforts have been very limited.

I would like to suggest strongly that NCRA may interest/identify at least one full time B.Tech. Engineer for a Ph.D. programme for carrying out a detailed study of the **i**dentification of radio frequency interference (RFI), its characterization and mitigation. A detailed study would allow optimizing the performance of the GMRT. Over the last 10 years several workers at NCRA have investigated various schemes for RFI detection, filtering and automatic flagging of the GMRT data (list of various reports in the D-Space is given in References in this Report). Particularly FLAGCAL software has been built by Jayram Chengalur and colleagues for automatic flagging of the GMRT data. In view of the broad band of uGMRT, further innovative solutions need to be developed for mitigation of the RFI particularly using the wideband backend (GWB) of the GMRT. I understand that it would provide few thousand channels. It would be useful to carry out RFI mitigation prior to MUX in the correlator . Apart from guidance by one or more of the NCRA astronomers, one may be able to interest a Professor from one of the IITs (I understand that a Professor at COEP (Sutane) may be interested in certain aspects of the problem, particularly RFI Characterization). There are also several references in the literature concerning mitigation strategies.

In conclusion, minimization of harmful effects of RFI to the GMRT is of great importance, particularly with the new capability of the upgraded system.

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13. REFERENCES AND LIST OF RFI REPOTS IN D-Space OF NCRA LIBRARY

Atre, A. V., and Swarup, G., "Note on direction finding equipment for RFI", 18 pages, NOO111, 1999

Baan, W. A., Friedmann, P. A., & Millenaar, R. P., " Radio Frequency Mitigation at the Westerbork Radio Telescope, Algorithms, Test Observations, and System Implementation", Astron, J. 128, 933-949, 2004.

Baan, W. A., Friedmann, P. A., Subhashish Roy, & Millenaar, R. P., " Radio Frequency Mitigation at the Westerbork Radio Telescope", RFI Mitigation Workshop, RFI 2010, March 28-31, 2010, Proceedings of Science.

ITU-R, R.A., 2126-1 (09-2013): Techniques of Mitigation of Radio Frequency Interference in Radio Astronomy." (this report has many references").

Jog, R., Sutaone, M.S., and Badawe, V.V., "Investigation of Radiated Emissions from GPS Based "Vehicle Tracking System Board and it's comparison with different EMI /EMC

Standards and Remedies to reduce the Radiations" *International Journal of Computer and Electrical Engineering, Vol.4, No.2, April 2012*. Copy available with G Swarup [Comments by GS: Authors are in COEP and have developed a shielded box for GPS receivers; Prof Sutaone is Head of Electrical Eng Dept. They could be interested to collaborate including interesting a bright student for M.Tech thesis for some of the aspects an2d also to develop an Al box for minimizing RFI from PCs at the GMRT].

Langat , Philip Kibet , "Power-line sparking noise characterisation in the SKA environment" Dissertation presented for the degree of Doctor of Philosophy in the Faculty of Engineering at Stellenbosch University"; http://hdlhandle.net/10019.1/17970.

Joardar, S. and Banerjee, Arijit, 2004, 60 pages, http://hdl.handle.net/2301/356, under Student Reports

Pathak S., Swarup G., Chatterjee A., Kale V., "Location of Radio Frequency Interference using GMRT," in URSI General Assembly, New Delhi, 2005.

Prasanna, R. "Study of RFI Filtering Algorithms for the GSB", 2009, http://hdl.handle.net/2301/557 (Student Reports).

Raybole, Pravin, "TV Booster Interference and Power Line RFI Around GMRT", pravin2.ppt, 2008, http://hdl.handle.net/2301/395, Appears in Collections: Talks/Presentations of the GMRT Group.

Swarup, G., "Radio frequency coordination interference measurements and mitigation techniques regarding the Giant Metrewave Radio Telescope Part- I", R00186, 98 pages, 1998, http://hdl.handle.net/2301/134

Swarup, G., "Surveys of radio frequency interference (RFI) at the GMRT site from terrestrial transmitters Part IV", 178 pages, ROO191, 2001, http://hdl.handle.net/2301/137

Swarup, Govind, "Power-line radio frequency interference at the GMRT", " 55 pages, R233, 8-Dec-2008, http://hdl.handle.net/2301/431.

Swarup, G. and Yang, K.S. 1961, IRE Trans. Antenna s Propagation, AP9, 75-81, 1961.

Thompson, A. R., Moran, J.M., and Swenson, G.W., "Interferometry and Synthesis in Radio Astronomy", 1986, John Wiley & Sons, New York.

List of some of RFI reports in D Space of NCRA

Issue Date	Title	Author(s)
2003	NCRA Annual Report (2002-2003)	-
1992	Result of the RFI survey in 100-600 MHz band at GMRT site	*Venkatasubramani, T. L.; Somsekar, R; Phakatkar, S*
1996	Report on RFI Survey at GMRT	*Venkatasubramani, T. L.*
2003	Automatic RFI identification and flagging	*Urvashi, R. V.*
1999	Note on direction finding equipment for RFI	*Swarup, G.; Atre, A. V.*
2001	Surveys of radio frequency interference (RFI) at the GMRT site from terrestrial transmitters Part IV	*Swarup, G.*
2002	Study on 150 MHz band RFI and detect usable band	*Sureshkumar, S.; Ajit Kumar, B.*
2000	Technical report on RFI testing	*Somashekar, R.*
2004	Modified 150MHz Front-End System Incorporating Filters for RFI Mitigation	*Choudhari, Sandeep*
2006	Absolute Calibration of RFI Detection System at GMRT	*Manna, Jharna*

1 2 3 next

Issue Date	Title	Author(s)
2004	Preliminary RFI survey at GMRT site using the omnidirectional RFI monitoring system	*Joardar, S; Banerjee, Arijit*
2004	E-Plane Omnidirectional RFI Monitoring System	*Joardar, S*
2003	RFI Rejection Filters at 150 MHz	*Toshniwal, Vinod*
2005	Data analysing software tool for the omnidirectional RFI spectrum monitoring system of GMRT	*Banerjee, A; Joardar, S*
2008	TV Booster Interference and Power Line RFI Around GMRT	*Raybole, Pravin*
2006	Absolute Calibration of RFI Detection System at GMRT	*Manna, Jharna*
8-Dec-2008	Power-line radio frequency interference at the GMRT	*Swarup, Govind*
28-Jul-2010	Identifying and filtering RFI based on its polarised nature	*Nityananda, Rajaram*
28-Jul-2010	Effects of SVD RFI filtering on a weak signal	*Nityananda, Rajaram*
28-Jul-2010	Recovering RFI contributions to visibilities between sky pointing antennas from correlations with and between reference antennas	*Nityananda, Rajaram; Pen, Ue-Li*

previous 1 2 3 next

Issue Date	Title	Author(s)
14-Oct-2011	RFI qualification using CASPER tools (11.40 am - 14th October 2011)	*Malan, Sias*
14-Oct-2011	Sifting for fast radio transients using the modulation index in a high RFI environment (12.00 pm - 14th October 2011)	*Spitler, Laura*
2009	Study of RFI Filtering Algorithms for the GSB	*Prasanna, R*
Apr-2013	Development of MAD based spectral domain RFI filtering techniques	*Baburaj, Nishit*

previous 1 2 3

Issue Date	Title	Author(s)
Apr-2013	Development of MAD based spectral domain RFI filtering techniques	*Baburaj, Nishit*
14-Oct-2011	RFI qualification using CASPER tools (11.40 am - 14th October 2011)	*Malan, Sias*
14-Oct-2011	Sifting for fast radio transients using the modulation index in a high RFI environment (12.00 pm - 14th October 2011)	*Spitler, Laura*
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bands and had to operate on lesser bandwidth and lower number of channels. The present exercise has been carried out in the same spirit of spectrum sharing coordination and coexistence.

3.11. **Review of 800/900 MHz Band**

(a) Equipment capability for cellular operation (GSM based in 900 MHz) is in the frequency band 890-915 MHz / 935-960 MHz (25+25 MHz) which is known to be extendable to 880-890 MHz/925-935 MHz.

(b) Equipment capability for WLL technologies is in the frequency band 824-849 MHz / 869-894 MHz (25+25 MHz).

(c) National coordination was effected to make available about 12.5+12.5 MHz spectrum for cellular operations by relocating existing operations of other users in the remaining 12.5+12.5 MHz spectrum to the extent possible.

(d) Upto 4.5+4.5 MHz have been given to each of the two cellular operators depending on their justified needs. In metro cities (Delhi, Mumbai, Chennai and Calcutta) spectrum has been enhanced upto 6.2+6.2 MHz depending on the availability and justification.

(e) As regards WLL technologies for fixed applications for basic services, spectrum upto 20+20 MHz has been coordinated in 800 MHz band which varies from location to location depending on existing usage. Appropriate spectrum has been earmarked/given to two basic service operators.

14. ACKNOWLEDGEMENTS

I thank Kaushal Buch for extensive comments on this report that has resulted in its revision. I also thank Dr. Nimisha Kantharia for many comments. I also thank Shri Suresh Kumar for providing information regarding the Laser Diode system.

15. FIGURES

Figure 1: (a) Proposed Layout of Underground 11kV lines feeding power to the Eastern and Southern arms; (b) Emergency alternate 11 kV line from a junction near E2 antenna by MSED to the 33kV-11kV HT yard at the Central Square (I do not know whether that line is still operating) and (c) overhead 33 kV cable replacing the 3 phase overhead open lines up to ~ 300m away.

Appendix 1: RFI survey

Appendix 2: Emerson from NRAO regarding RFI protection to Radio Astronomy.

Appendix 3: Laser Characteristics.

Appendix 4: About 70 percentage data flagged as per FLAGCAL for observation of Venus in the 240 MHz band made on 26 March 2004.

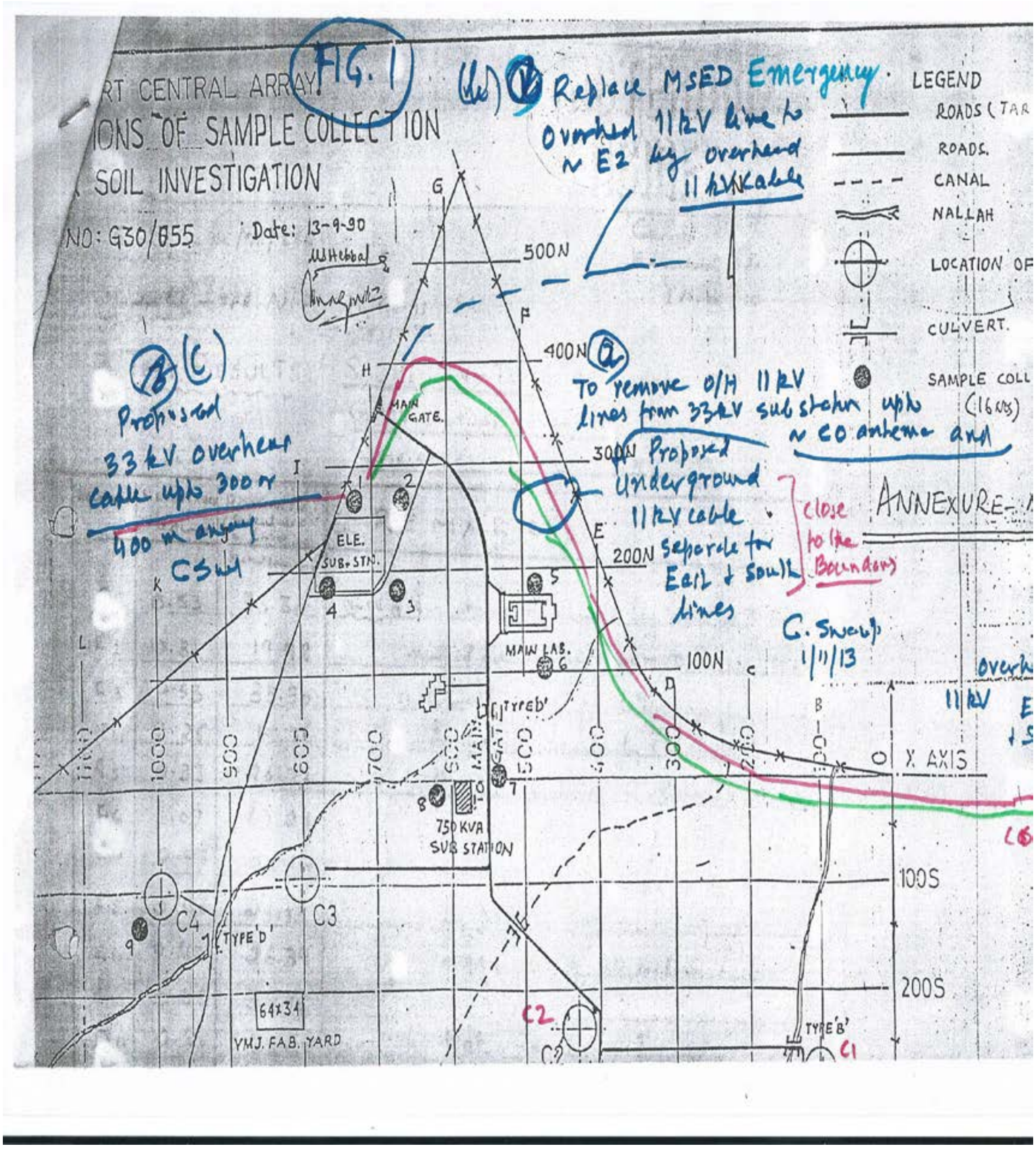


FIG. 1
RT CENTRAL ARRAY
IONS OF SAMPLE COLLECTION
SOIL INVESTIGATION
NO: G30/055
Date: 13-9-90
(b) Replace MSED Emergency Overhead 11kV line to E2 by overhead 11kV cable
LEGEND
ROADS (TAR
ROADS.
CANAL
NALLAH
LOCATION OF
CULVERT.
SAMPLE COLL (16 nos)
(a) To remove O/H 11kV lines from 33kV substation upto CO antenna and
300N Proposed underground 11kV cable separate for East + South lines
close to the Boundary
C. Swarup 1/11/13
(c) Proposed 33kV overhead cable upto 300 m
400 m away CSW
ANNEXURE
MAIN GATE.
ELE. SUB-STN.
MAIN LAB.
750 KVA SUB STATION
TYPE'B'
TYPE'D'
YMJ. FAB. YARD
64x34
500N
400N
200N
100N
X AXIS
100S
200S
C1
C2
C3
C4

$$R1 = [D^2 + (h_R + h_T)^2]^{1/2}$$

$$R2 = [D^2 + (h_R - h_T)^2]^{1/2}$$

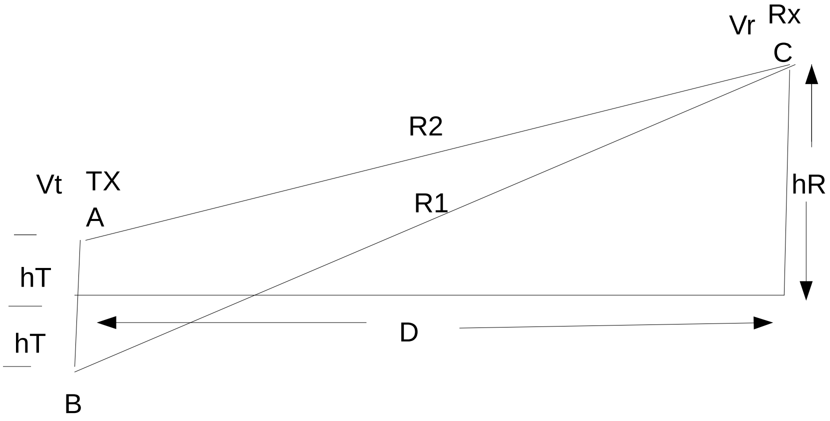


Fig. Voltage Vr received at receiver Rx at a distance D is sum of direct signal Vt from transmitter Tx AND a signal –Vt from the image below the ground (see Section 2.2).

Figure 2.Voltage V_r received at a receiver Rx at a distance D from transmitter Tx.

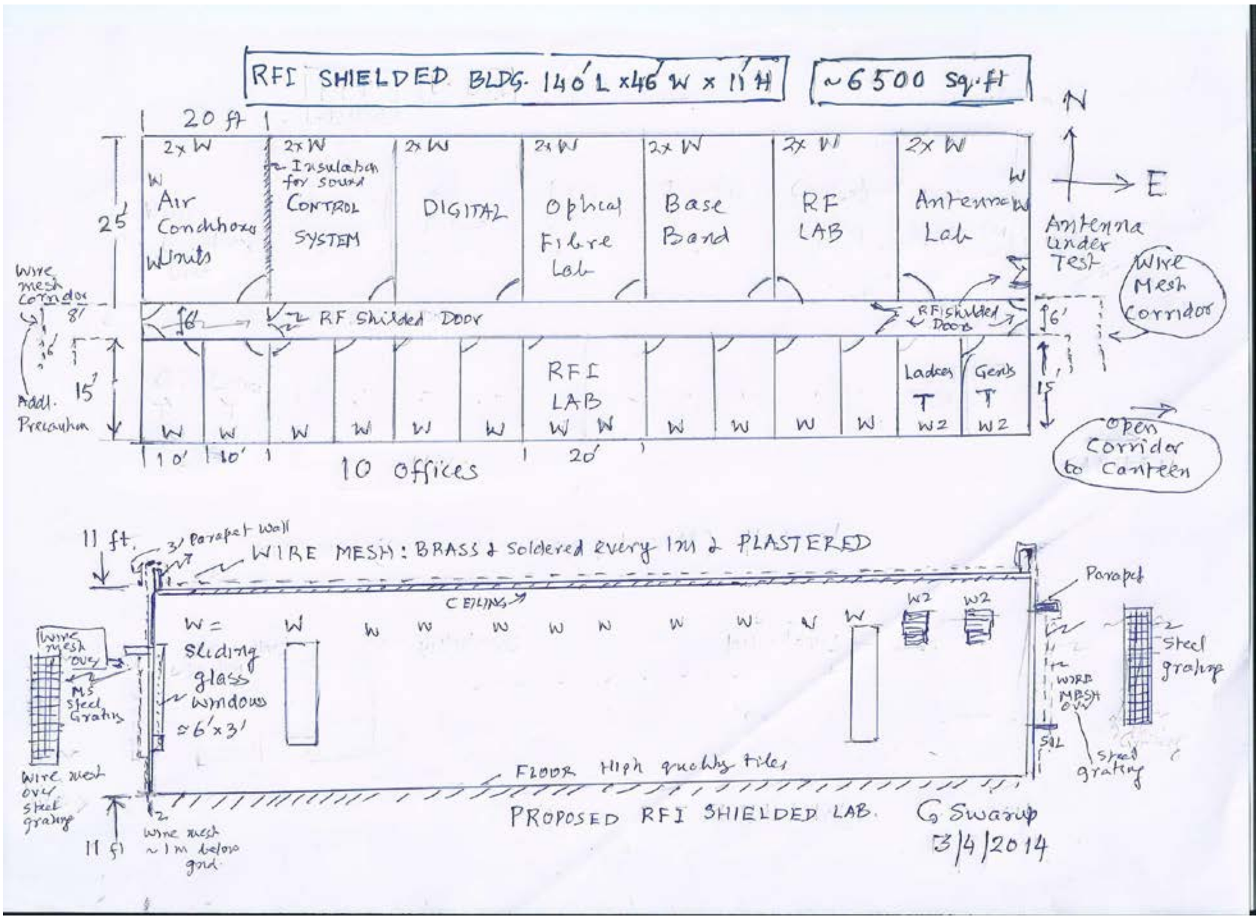


Figure 3.1. Proposed fully shielded building of ~ 7000 sq. ft, ADJACENT to the present building to allow good interaction. The proposed auditorium should not be mixed with this shielded building. In my personal view, instead of auditorium, a lager lecture hall can be set up in the present digital lab next to the library. Auditorium can be part of the purposed Visitor's Centre.

Figure 3.2. Laser Diode modulation (a) without RFI (normal operation) and (b) with narrowband RFI); threshold current ~12ma and 1dB compression ~ 60 ma.

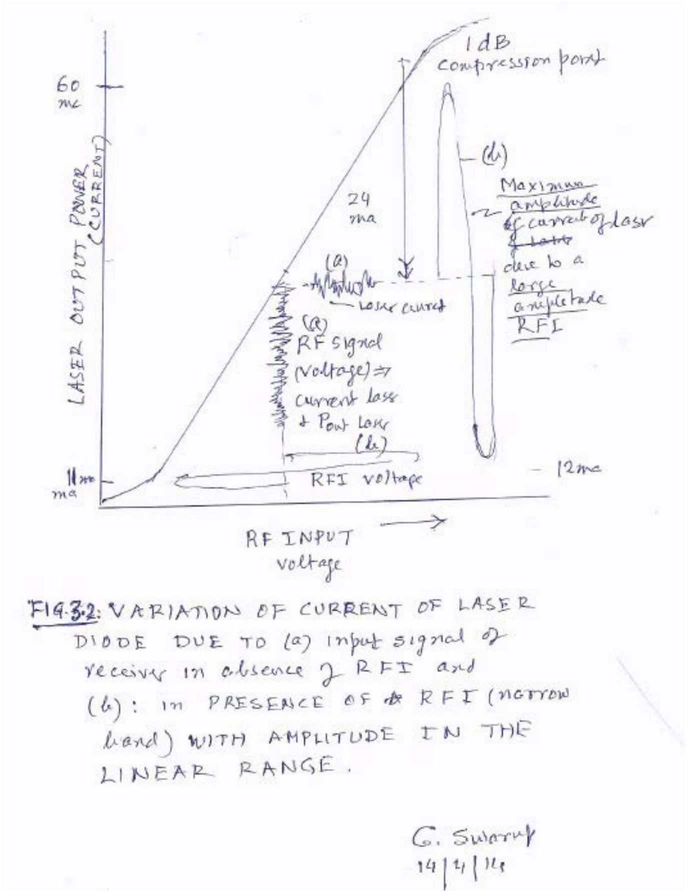
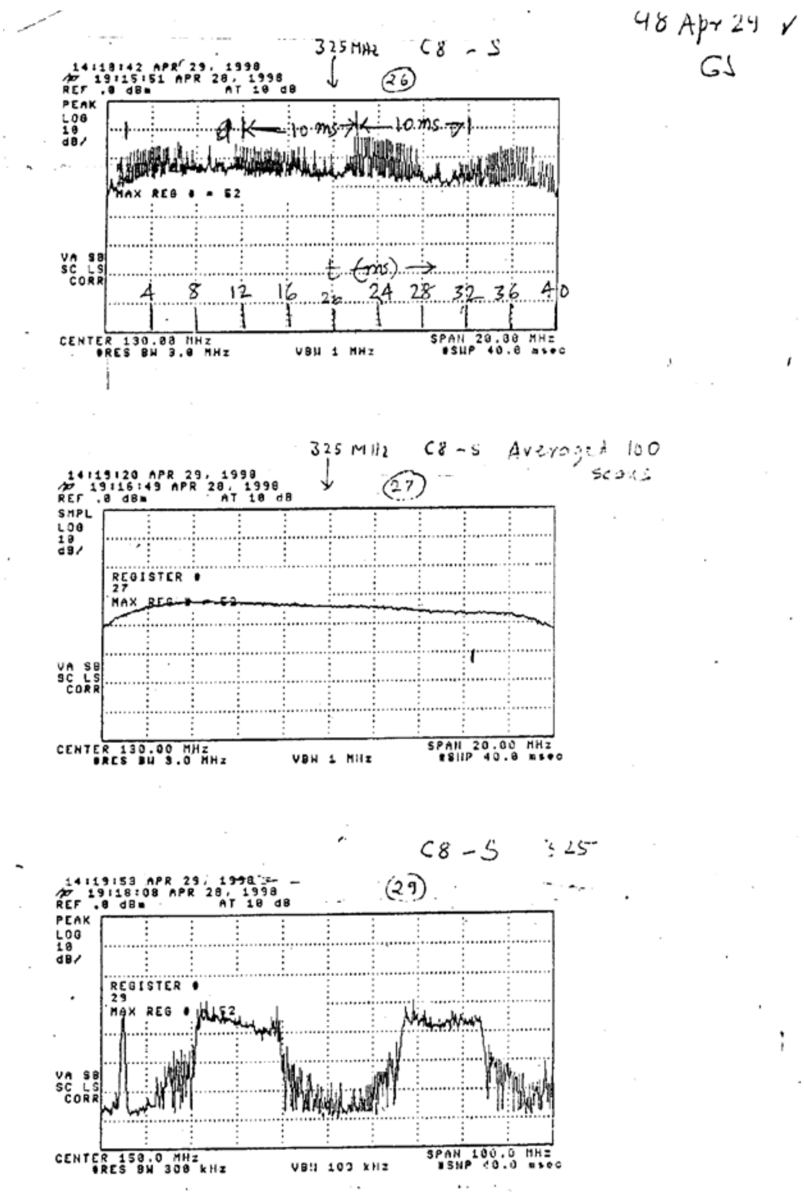


Figure 4: RFI from Power-line: Some Figs. reproduced from NCRA Internal Technical Report R233 by G. Swarup

(a) Measured by G. Swarup on 29 April 1998.



58

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

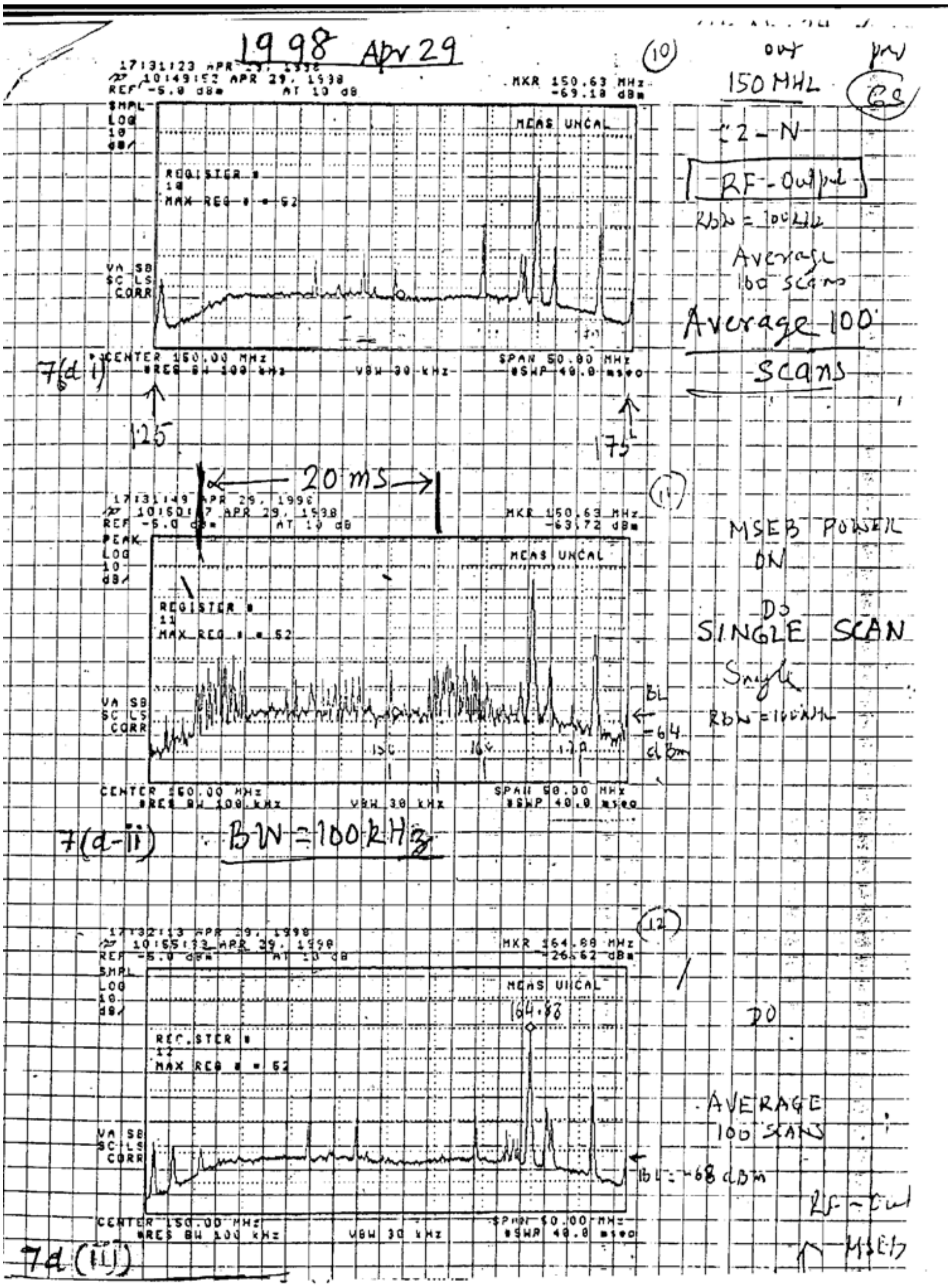


FIG. 7(d) Plot showing RFI at GMRT antennas due to 11 kV power lines. 150 MHz feed was towards horizon. HP 8590 Spectrum Analyzer was used with RBW=100 kHz and span of 20 MHz. In Fig. 7(d-i) and 7(d-iii), 100 scans were averaged. But in Fig 7(d-ii) only a single scan was made and show sharp spikes, perhaps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

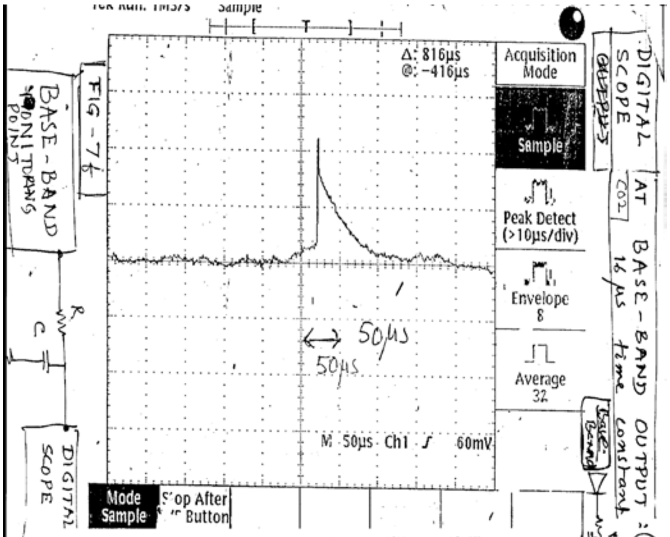


FIG. 7(f) Digital oscilloscope output at the base-band output of C02 antenna of GMRT showing sharp pulses due to 11kV pulsed RFI. Measurements were made by Swarup and Srinivasan on 23-4-98 by placing a diode followed by an RC integrating circuit with time constant of 16 microsec between the 16 MHz base-band 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 mircosec (see Fig 7(h).

GMRT consists of 12 dishes of 45 m diameter located in a Central Square of about 1km x 1 km, just outside and other 16 along 3 arms of a Y shaped array (selected for easy access by road and for connecting the antennas by optical fibre network and also supplying power to the antennas using 11 kV power lines.

Appendix 1: RFI survey

Appendix 2: Emerson from NRAO regarding RFI protection to Radio Astronomy.

Appendix 3: Laser Characteristics.

Appendix 4: About 70 percentage data flagged as per FLAGCAL for observation of Venus in the 240 MHz band made on 26 March 2004.

Appendix 1:

In this appendix are reproduced only few illustrative RFI plots measured by G Swarup and T. L. Venkatsuramani during 1996-2000 as summarized in the NCRA technical reports (R00186 98 pages 1998, http://hdl.handle.net/2301/134) and 178 pages, ROO191,2001, http://hdl.handle.net/2301/137). I would like to suggest that concerned radio astronomers and engineers may study the full report to understand characteristics of the observed RFI.

On the next page is reproduced Fig. 1 (c) from above report.

Fig. A1: RFI observations at the GMRT at 150 MHz. It may be noted from the spectral outputs plots, that I had estimated value of the power flux density, pfd, of the baselines of the spectral plots = $kT_{sys}\,\Delta f/A_{ef}$, where T_{sys} is the receiver system temperature for the concerned plot, Δf = 125 kHz being the bandwidth of each output of the correlator = 32 x 10^6 / 256 channels and $A_{ef} = \lambda^2/4\pi.G$, where G = 1 corresponding to gain of sidelobes of the GMRT antennas towards the horizon.

FIG. 1(c) : [continuation of Fig. 1(a)] shows results of RFI observations made when 4 of the GMRT 150 MHz antenna feeds were pointed towards South on 28th September 1999 (same as right band side of Fig. 1(a) but the Figure is somewhat enlarged). Antennas used are noted in the Figures. It is seen that strong RFI is observed mainly when the feeds are pointed to the South. For antennas, C5-E, E2-E, W2-S, C11-W, C8-W and W3-N RFI is observed every ~ 920 kHz apart and is likely to arise from the GMRT electronics. In this Figure 1(c), the Right hand side plots of Fig 1(a) for antenna feeds to the South are enlarged for better display.

Fig. A2; same cption as A1.

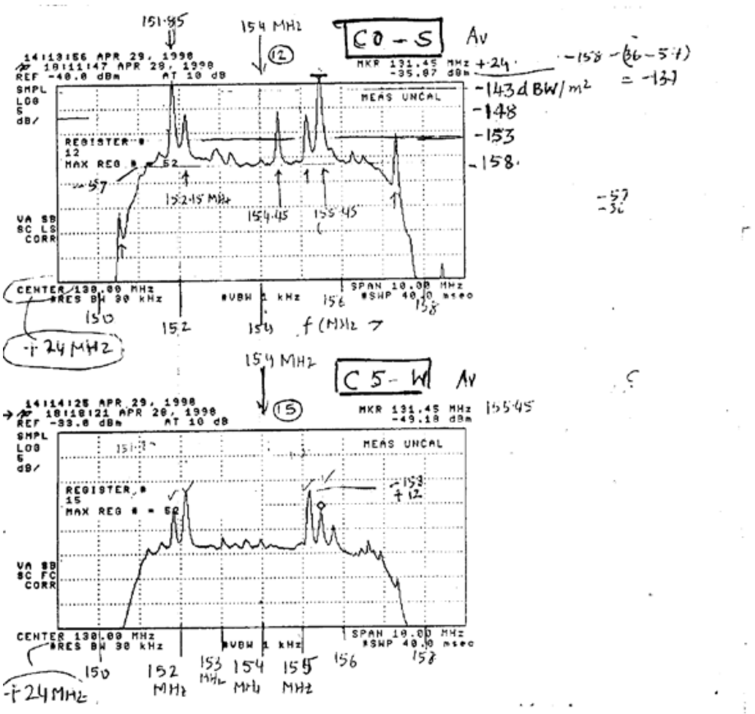


FIG. 1(k) : Same caption as for Fig. 1(g) for C0-S and C5-W antennas.

RFI by Defective TV boosters: Measurements made by G. Swarup at 1603 hrs on the output of the W3 antenna with its 240 MHz feed pointed towards the northern horizon showed a strong RFI with its frequency varying from 242.255 MHz to 241.575 MHz (` 0.9 MHz) in only 2 minutes; a clear sign of an oscillating amplifier, such as that of a defective TV booster.

(see Report R0091)The proposed Radio Location Array (RLA) (Section 9 of this Report will be able to detect such defective TV boosters many days before detected by the RFI team)

Figure A3. Summary of RFI measurements in the band 152-154 MHz, made in 1999 by GS, Joardar, and others at Sangammer, Kukdi, GMRT Site, Pune, Lonavala and Khandala. It is clear that RFI considerable RFI occurs from the GMRT electronics. Measurements were made using a log periodic antenna mounted on a jeep and connected to an amplifier (?) and a spectrum analyzer. A diesel generator was used. (reproduced from Fig. 10 of R00191)

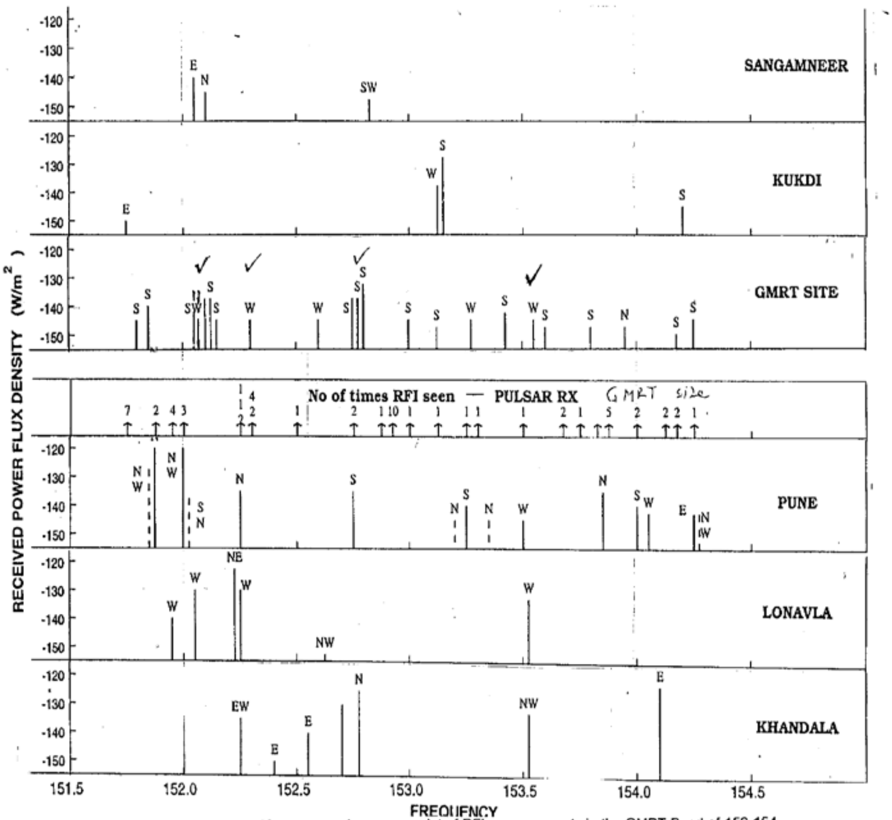


Fig. 10 : A summary plot of RFI measurements in the GMRT Band of 152-154 MHz based on observations made at Sangamneer, Kukdi, GMRT site, (Pulsar Rx : see text), Pune, Lonavala and Khandala Ticks are marked on the GMRT site data for those frequencies for which there seems to be some correlation between RFI at (a) the GMRT site and

Figure A4. Summary of RFI measurements in the band 229-235 MHz, made in 1999 by GS, Joardar, and others at Alephata, Junnar, Lonavala, Khandala, GMRT Site and at NCRA-, Pune,. It is clear that RFI considerable RFI occurs from the GMRT electronics. Reproduced from Fig 11 of ROO191 by Swarup 2001).

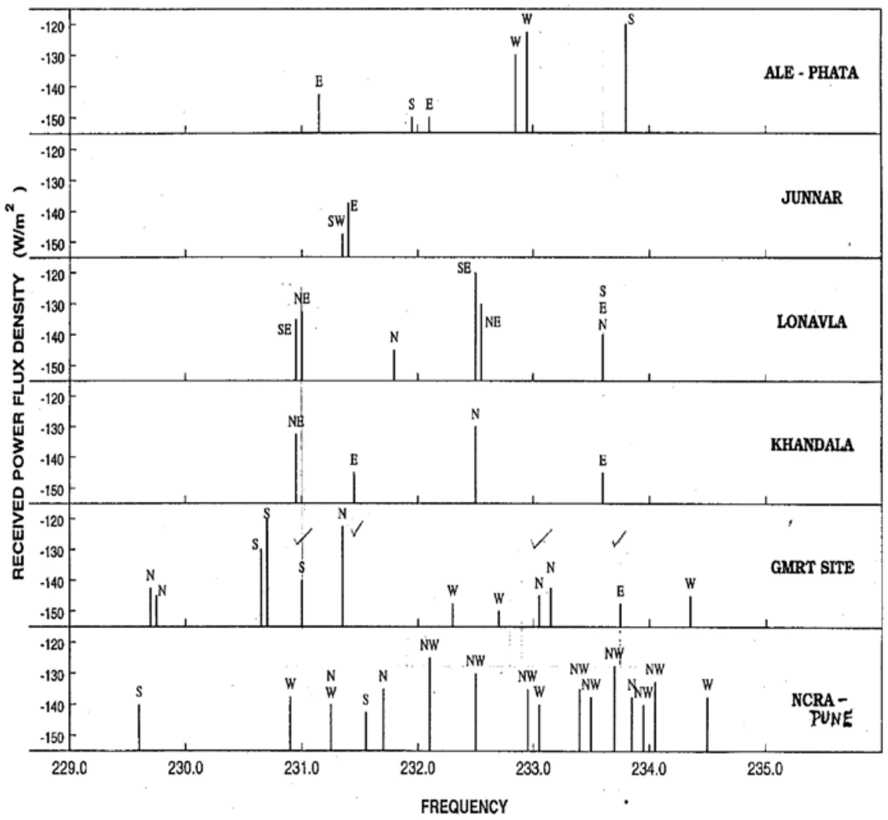


Fig. 11 : RFI measurements in the GMRT Band of 230-234 MHz at (a) Alephata (b) the GMRT site, (c) Junnar, (d) NCRA-Pune, (e) Lonavala and (f) Khandala.

Fig. A5. From Report by G Swarup 00186, 1998 and 00191 Swarup 2001

FIG. 12 : **PREDICTED PROBABILITY DISTRIBUTION**

For loss between GMRT site and Pune and Mumbai. Predictions were made in 198' so by the National Physical Laboratory, New Delhi using "NPL Troposcatter Model" were based on (I) Height profile between above stations and (ii) Statistics of Refrac Gradient of Air Measured by India Meteorological Department.

FIG. 12(a) : Predicted percentage probability of loss between Pune and the GMR' 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 alon 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 GM 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)

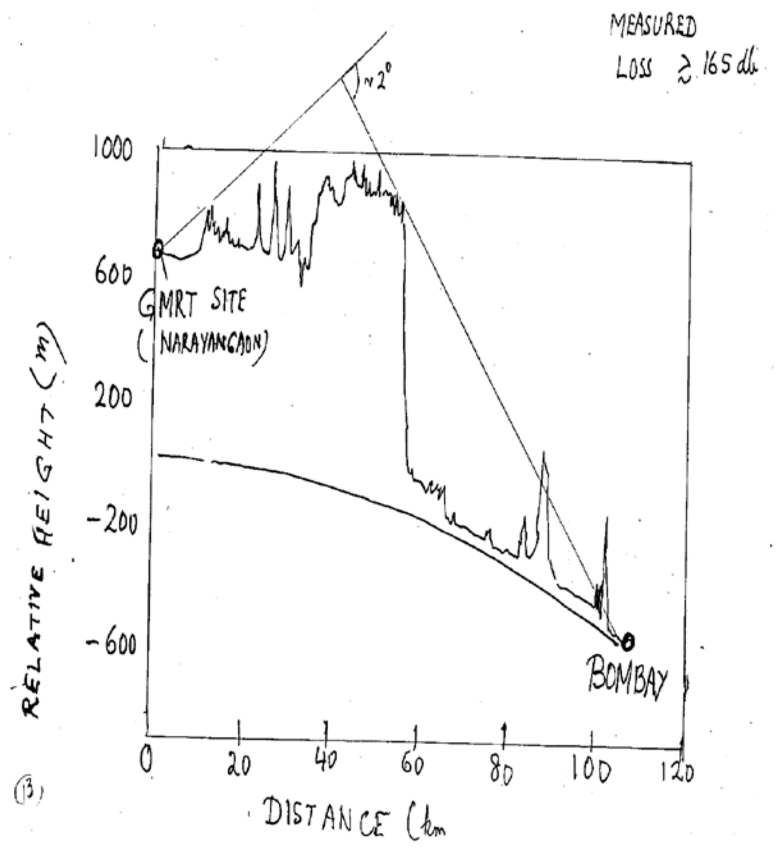


FIG. 13 : Height path profile between Bombay and GMRT site. The plots were made using survey of India maps along the line of site from the GMRT site to the central part of Bombay.

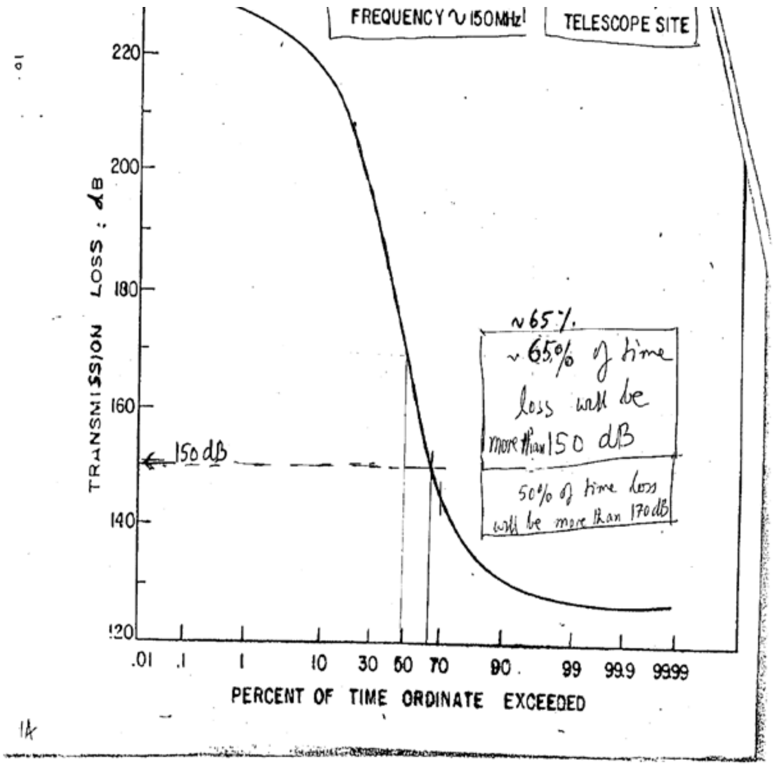


FIG. 14: The calculations of Tropo-Scatter path as shown in Fig. 13 show transmission loss by NPL. The absissa percent of time ordinate exceeded at different values of losses. For e.g. it may be noted that 65% of the time will be lost at the 150 dB between Bombay and GMRT site.

Figure Shows that the Troposcatter Loss is expected to be greater than -150 dB between Pune and the GMRT site at 150 MHz.

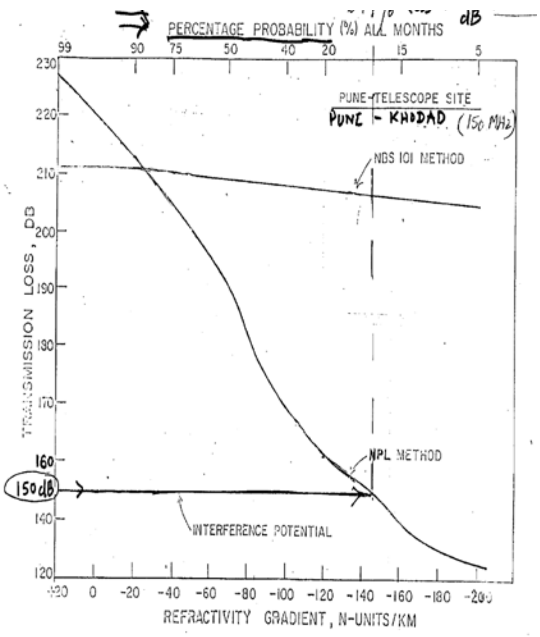


FIG. 15: The percentage probability at Pune and GMRT site will lost at 150 dB for 17% of time.

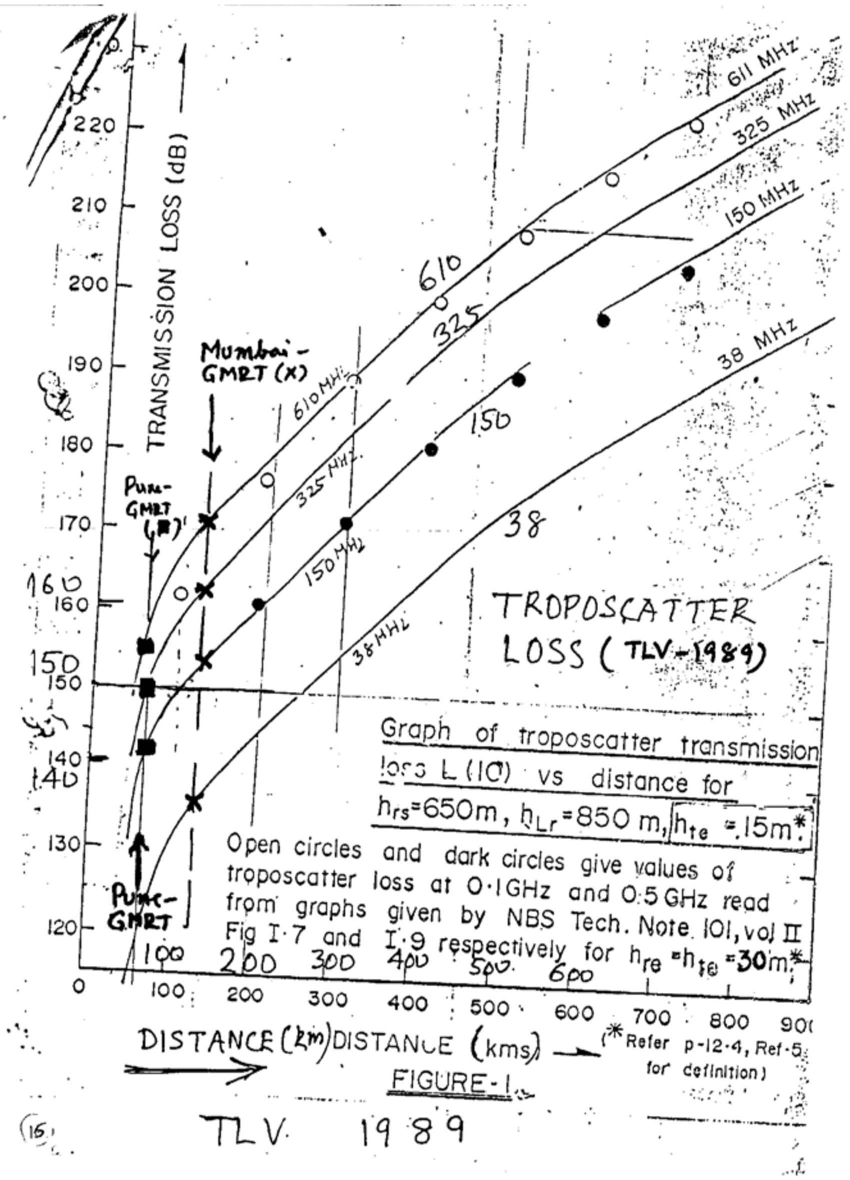


FIG. 16 : Tropscatter loss estimated by T.L. Venkatasubramani from NBS Tech. Note 101, Vol. II (see RFI Report-Part XII)

Appendix-2

Extracts from an informative talk (PDF) : "International Spectrum Management"
By **Darrel Emerson**, **NRAO, Tucson**. (Google: **International Spectrum Management** - Green Bank www.gb.nrao.edu/sd03/talks/sdspecman_cut.pdf)

•

"Spectrum Management: Radio Frequency Management Is Done by Experts Who Meld Years of Experience With a Curious Blend of Regulation, Electronics, Politics and Not a Little Bit of Larceny. They Justify Requirements, Horse-trade, Coerce, Bluff and Gamble With an Intuition That Cannot Be Taught Other Than by Long Experience
Vice Admiral Jon L. Boyes
U.S. Navy"

"Why does Radio Astronomy need Protection?
Radio Astronomy deals with such extremely weak signals. •Received terrestrial communications signals are typically 10^6 to 10^{12} (i.e. 60 dB to 120 dB) stronger than the flux from cosmic sources •Communications engineers like received signals to be 60 dB above the noise • Radio astronomers typically work with signals that are 60 dB below the noise • "A garage door opener on the moon would appear on the earth as the brightest radio source in the sky"• Radio observatories are usually put in remote locations to avoid man-made interference – but this alone isn't enough protection.
• Satellite interference is the worst of all – no terrain shielding, line-of-sight propagation, can cover nearly a hemisphere of the earth, moving & multiple sources of interference, permitted levels of unwanted emission are very high."

Appendix 3: Laser Characteristics

Max = (0.21 × 120 = 25.2 mW ?) (1)

0.21 × 62.25 ≃ 10.59 mW

TEST DATA SHEET

emcore empower with light	TDS-409427 Rev E Sheet 1 of 2 Date: 06-30-11		Ref: PS-1754C
	S/N: CAD1453		Test Station: 12
Model #: 1754C-34-BB-SC-10	Connector Options: FC/APC: SC/APC: X Pigtail - no connector:		DATE: 2012-6-22 Operator: LCM

TEST PARAMETERS	TEST TITLE	CONDITIONS	MIN.	MAX.	MEAS. VALUE	UNITS
Fianl LIP Data	Iop	-	Ith	120	62.25	mA
	Threshold Current	-	-	20	11.89	mA
	Slope Efficiency	T=Top	Note 2		.21	mW/mA
Optical Power	Optical Power	T=Top, Iop=Ibb+Ith (1)	Note 2		10.59	mW
Spectral	Optical Spectrum Peak Wavelength, Iop=75mA (6)	Iop=75mA, T=Top	Note 3		1550.13 (ITU-34)	nm
	Laser Operating Temperature, Top	-	18	35	21.29	Deg C
Chirp	Chirp	-	40	100	68.8	MHz/mA
CNR ?	CNR	-	Note 2	-	57.1	dB
CSO	CSO	-	-	Note 2	-65	dBc
CTB	CTB	-	-	Note 2	-70	dBc
MPD Current Slope	MPDI Slope	-	0.01	0.2	.03	mA/mW
MPD Current	MPD Current	Iop=Ibb+Ith	0.06	2.4	.32	mA
Frequency Response (4, 7)	50-Ohm Flatness	T=Top, Iop=Ibb+Ith (1)	-	4.0	Pass	dBp-p Pass/Fail
Input Return Loss (4, 7)	50-Ohm Return Loss	T=Top, Iop=Ibb+Ith (1)	10	-	Pass	dB Pass/Fail

Notes:

1. Ibb is the bias point at which simultaneously the laser at its best linearity and the optical power is within specification.
2. Consult Section 2.1 of PS-1754C.
3. Consult PS-1754C for channel wavelengths.
4. Measure on a resitively matched 50-ohm to 25-ohm loss pad.
6. ITU-T_GRID.
7. Measured from 47 MHz to 2600 MHz.

0.21 × 11.89 mA = 2.4969 mW ≃ 2.5 mW

Appendix 4: FLAGCAL: Percentage data flagged (~70 %) in the 240 MHz band 5.6 MHz bandwidth observations Venus on 26March 2004.

File: /home/nithinisro/Documents/A....05BBA01_VENUS26_240_FG.fcs.log   Page 1 of 6

```
>>flagcal version 0.988 compiled on astro4.gmrt.ncra.tifr.res.in Apr 25 2013 14:14:53

Input file 05BBA01_VENUS26_240.FITS
Channel 0  Start_Chan       8
Channel 0  Num_Chan         4
Channel 0  Frequency        243.0625           (MHz)
Channel 0  Bandwidth        500.0000           (kHz)
Src     3C48 Flux set to    5.3572e+01 +-     0.0000e+00 (Jy)
Src 0318+164 Flux set to    5.4915e+00 +-     9.3761e-01 (Jy)
Src    3C147 Flux set to    6.0975e+01 +-     0.0000e+00 (Jy)
Total vis and flg frac
3C48                        1614720        0.51
0318+164                    5790720        0.61
VENUS-26                    28118400       0.72
3C147                       946560         0.45
```

VENUS OBSERVATIONS
March 26, 2004
240 MHz

FLAGCAL

Flagged Fraction varies from 66 % to 81 % !!

Nithin Mohan / G. Swarup
Dharm Vir ~ 25/3/14

```
>>> Scan    0 Src 3C48
Number of recs in scan        : 58
HISTORY                       : read_scan usr_flag scan_stats flag_ant flag_base
HISTORY                       : flag_chan flag_rec flag_vis print_flag_summary
HISTORY                       : compute_chan0 setjy solve_chan0 calibrate
Mean Vis Amp (Jy)             :  5.8235e+01 (6.5e+00)
Flagged fraction per stokes : 0.51
Antennas flagged per stokes :   4/30
Baselines flagged per stokes: 147/435
Records flagged per stokes  :   0/58
Channels flagged per stokes :   0/64
Antennas flagged in Stokes 0: 6  (C06) 13 (C14) 24 (W01) 28 (W05)

>>> Scan    1 Src 0318+164
Number of recs in scan        : 14
HISTORY                       : read_scan usr_flag usr_flag scan_stats flag_ant
HISTORY                       : flag_base flag_chan flag_rec flag_vis
HISTORY                       : print_flag_summary compute_chan0 solve_chan0 getjy
Mean Vis Amp (Jy)             :  8.2059e+00 (1.9e+00)
Flagged fraction per stokes : 0.57
Antennas flagged per stokes :   4/30
Baselines flagged per stokes: 157/435
Records flagged per stokes  :   0/14
Channels flagged per stokes :   0/64
Antennas flagged in Stokes 0: 2  (C02) 4  (C04) 24 (W01) 28 (W05)

>>> Scan    2 Src VENUS-26
Number of recs in scan        : 79
HISTORY                       : read_scan usr_flag compute_chan0 gain_transfer
HISTORY                       : bpass_transfer calibrate scan_stats flag_ant
HISTORY                       : flag_base flag_chan flag_rec flag_vis
Mean Vis Amp (Jy)             :  1.3552e+00 (5.6e-01)
Flagged fraction per stokes : 0.66
Antennas flagged per stokes :   7/30
Baselines flagged per stokes: 232/435
Records flagged per stokes  :   0/79
Channels flagged per stokes :   0/64
Antennas flagged in Stokes 0: 2  (C02) 4  (C04) 6  (C06) 7  (C08) 13 (C14)
                            : 24 (W01) 28 (W05)

>>> Scan    3 Src 0318+164
Number of recs in scan        : 14
HISTORY                       : read_scan usr_flag usr_flag scan_stats flag_ant
HISTORY                       : flag_base flag_chan flag_rec flag_vis
HISTORY                       : print_flag_summary compute_chan0 solve_chan0 getjy
Mean Vis Amp (Jy)             :  5.5946e+00 (2.1e+00)
Flagged fraction per stokes : 0.68
Antennas flagged per stokes :   5/30
Baselines flagged per stokes: 180/435
Records flagged per stokes  :   0/14
Channels flagged per stokes :   0/64
Antennas flagged in Stokes 0: 4  (C04) 11 (C12) 21 (S03) 24 (W01) 28 (W05)
                            :

>>> Scan    4 Src VENUS-26
```

END REPORT: RFI Characteristics and Mitigation by G. Swarup