NCRA - TIFR

National Centre for Radio Astrophysics

Internal Technical Report

Characterizing Polarization Isolation of the GMRT Antennae

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Objective: Characterizing polarization isolation of the GMRT antennae for different bands across the entire bandwidth.

Document History:

Revision	Date	Modification / Change
Ver.1	13 May 2013	Initial Version

1 OBJECTIVE

Located ~ 80 kilometers North of Pune, near the village of Khodad, The **G**iant **M**eterwave **R**adio **T**elescope (GMRT) is a synthesis radio telescope operating presently at five different bands in radio frequencies, namely 150 MHz, 230 MHz, 325 MHz, 610 MHz and 1420 MHz. The GMRT has 30 fully steerable parabolic antennae, each of 45 meters diameter, arranged in a shape of the English letter "Y". At present it operates at a maximum bandwidth of 32 MHz with a maximum of 512 spectral channels and four polarizations.

In the full polar mode of operation, it is useful for the observer to have a rough understanding of the polarization isolation characteristics of the GMRT antennae across the bandwidth of observations. As a part of the **P**ost Maintenance **Q**uality **C**heck (PMQC), polarization isolation test is regularly carried out at the GMRT (at least once in a week). The test was started in the year 2000. Initially only three channels were used to to access the isolation characteristics of the antennae. Moreover, only a text file was made available as the final output. During GMRT cycle 21 some modifications were made to map the isolation characteristics across the entire bandwidth of observation. We describe this new implementation here.

In the next section we shall analytically describe two different estimators for the polarization isolation. Polarization isolation will be characterized in terms of the gains and couplings of different stages of the hetero-dyne receiver in section (3) and we shall see which of the two estimators described here does a better job. In section (4) we shall describe the implementation of the estimators as a software interface and finally in section (5) and (6) we shall discuss initial observations and possible future improvements of the program.

2 METHOD

Every antenna at the GMRT can record two different modes of polarizations, namely the Right Circular ("**R**") or Left Circular ("**L**") mode. We write the voltage recorded by the antenna A for **R** mode of polarization as

$$\tilde{v}_{\mathrm{A}}^{(\mathbf{R})}(t,\ \nu) \ = \ \tilde{G}_{\mathrm{A}}^{(\mathbf{R})}(t,\ \nu)\ \left[\tilde{S}_{\mathrm{A}}^{(\mathbf{R})}(t,\ \nu) + \tilde{R}_{\mathrm{A}}^{(\mathbf{R})}(t,\ \nu)\right], \tag{1}$$

where t and ν corresponds to the time and frequency, $\tilde{G}$ stands for antenna gain, $\tilde{S}$ is the signal (electric field) and $\tilde{R}$ stands for the RFI. They symbol "tilde" ($\tilde{}$) signifies that all these signals are complex in nature. The superscripts "(**R**)"(or "(**L**)") are notations for the corresponding polarization recorded. Here, we are interested with sources or astronomical signals which are time stationary, frequency independent over the bandwidth of observation and is unresolved by the array (have same signal for all the antenna, *eg* a point source) and at the phase centre of the primary beam of the antenna. In such a case, **eqn.** (1) reduces to

$$\tilde{v}_{\mathrm{A}}^{(\mathbf{R})}(t,\ \nu) \ = \ \tilde{G}_{\mathrm{A}}^{(\mathbf{R})}(t,\ \nu)\ \left[\hat{S}^{\ (\mathbf{R})} + \tilde{R}_{\mathrm{A}}^{(\mathbf{R})}(t,\ \nu)\right], \tag{2}$$

The "hat" ($\hat{}$) sign is a reminder of the stochastic character of the astronomical signal.

Visibilities, characterizing the signal from a pair of antennae, is the correlation of the voltages measured by them. Hence, the visibilities measured by the baseline consisting of antenna A and B would be

$$\begin{aligned} \mathcal{V}_{\mathrm{AB}}^{(\mathbf{RR})}(\nu, t) \quad &= \quad \langle\left[\tilde{v}_{\mathrm{A}}^{(\mathbf{R})}(t,\ \nu)\right]^{*}\ \tilde{v}_{\mathrm{B}}^{(\mathbf{R})}(t,\ \nu)\rangle \\ &= \quad \langle\ \left[\tilde{G}_{\mathrm{A}}^{(\mathbf{R})}(t,\ \nu)\right]^{*}\rangle\langle\tilde{G}_{\mathrm{B}}^{(\mathbf{R})}(t,\ \nu)\rangle \\ & \qquad \left(\mathcal{S}^{\ (\mathbf{RR})}\ +\ \mathcal{R}_{\mathrm{AB}}^{(\mathbf{RR})}\right), \end{aligned} \tag{3}$$

where $\mathcal{S}^{\ (\mathbf{RR})} \ = \ \langle\left[\tilde{S}^{\ (\mathbf{R})}(t,\ \nu)\right]^{*}\tilde{S}^{\ (\mathbf{R})}(t,\ \nu)\rangle$ and $\mathcal{R}_{\mathrm{AB}}^{(\mathbf{RR})} \ = \ \langle\left[\tilde{R}_{\mathrm{A}}^{(\mathbf{R})}(t,\ \nu)\right]^{*}\ \tilde{R}_{\mathrm{B}}^{(\mathbf{R})}(t,\ \nu)\rangle$.

Here, we have assumed the followings

- that the antenna gains are not correlated with the astronomical signals,
- that the antenna gains are not correlated with RFIs,
- that the antenna gains from different antennae are not correlated,
- astronomical signal and RFI are not correlated.
- ensemble averages we perform here are over time and gains do not change over that time.

At the GMRT antennae, the horizontal ("**H**") and vertical ("**V**") polarizations are directly measured by the 150, 230, 325 and 610 MHz feeds and then converted to Right Circular ("**R**") or Left Circular ("**L**") polarizations. For the 1420 MHz band (i.e all it's sub-bands), the two linear polarizations ("**X**") and ("**Y**") are measured. We exclude this band for the discussion that follows here. We shall mention about the 1420 MHz band polarization isolation later. In the electronics receiver chain that measures the two polarizations, because of leakage originating from different reasons (will be discussed later) "**R**" and "**L**" polarizations do not remain entirely isolated. Hence, $\mathcal{S}^{\,(\mathbf{RR})}$ as in the previous equation, are not astronomical signal, but contaminated by polarization leakage. This is why, even for a point source, the signals $\mathcal{S}^{\,(\mathbf{RR})}$ depends on the respective antenna pairs and we reintroduce the antenna index from now on. For the "**RR**" or "**RL**" polarizations, we may write omitting the time dependence,

$$\mathcal{V}_{\rm AB}^{(\mathbf{RR})} = \left[\tilde{G}_{\rm A}^{(\mathbf{R})}\right]^{*} \tilde{G}_{\rm B}^{(\mathbf{R})} \left(\mathcal{S}_{\rm AB}^{(\mathbf{RR})} + \mathcal{R}_{\rm AB}^{(\mathbf{RR})}\right), \tag{4}$$

and

$$\mathcal{V}_{\rm AB}^{(\mathbf{RL})} = \left[\tilde{G}_{\rm A}^{(\mathbf{R})}\right]^{*} \tilde{G}_{\rm B}^{(\mathbf{L})} \left(\mathcal{S}_{\rm AB}^{(\mathbf{RL})} + \mathcal{R}_{\rm AB}^{(\mathbf{RL})}\right). \tag{5}$$

Similar expression can be written for "**LL**" or "**LR**" polarizations. We have not written the ν dependence explicitly here for simplicity.

At this point let us take a little diversion and consider a signal without any RFI. For such a case, if there is perfect isolation in between the two polarization signals we shall have the cross visibilities ($\mathcal{V}_{\rm AB}^{(\mathbf{RL})}$) identically equal to zero. In a general case the following gives an estimate of the isolation characteristics of the antenna B with respect to antenna A:

$$\mathcal{I}_{\rm B}^{(\mathbf{RL})} = -20 \log \left[\frac{\mid \mathcal{V}_{\rm AB}^{(\mathbf{RL})} \mid}{\mid \mathcal{V}_{\rm AB}^{(\mathbf{RR})} \mid}\right] \tag{6}$$

The term $\mathcal{I}_{\rm B}^{(\mathbf{RL})}$ gives qualitative idea about how much separated or isolated the two different polarization channels stays across the electronic chains. We shall use the term "isolation parameter" to refer to the above quantifier henceforth. Note that we have defined as a twenty times the negative logarithm of the ratio of the cross to the self visibilities. Hence, this quantity is usually expressed in units of decibels. At the GMRT antennae the maximum expected isolation is ~ 30 dB. Clearly this depends on the different isolation parameters of the antenna. Note that it is a function of the antenna number and frequency channels (frequency dependence is not written explicitly here). A little investigation shall reveal that the above expression has a dependence on the antenna gains $\tilde{G}_{\rm A}^{(\mathbf{R})}$ etc and has to be taken out. The antenna gains can be calculated and calibrated out. We shall describe two different schemes here to eliminate the effect of antenna gains [1], (1) visibilities are normalized by self and (2) visibilities normalized by gains:

(1) Normalizing by self

The visibilities can be normalized by the self correlations at each antenna. Amplitude of such normalized visibilities will be

$$\mid^{[\mathrm{N}]} \mathcal{V}_{\rm AB}^{(\mathbf{RR})} \mid = \frac{\mid \mathcal{S}_{\rm AB}^{(\mathbf{RR})} + \mathcal{R}_{\rm AB}^{(\mathbf{RR})} \mid}{\left[\mathcal{S}_{\rm AA}^{(\mathbf{RR})} + \mathcal{R}_{\rm AA}^{(\mathbf{RR})}\right]^{1/2} \left[\mathcal{S}_{\rm BB}^{(\mathbf{RR})} + \mathcal{R}_{\rm BB}^{(\mathbf{RR})}\right]^{1/2}}. \tag{7}$$

Here the superscript [N] in the visibility signifies that these visibilities are normalized by the self correlations. In this case the isolation parameter can be given by

$$^{[\mathrm{N}]}\mathcal{I}_{\rm B}^{(\mathbf{RL})} = -20 \log \frac{\mid \mathcal{S}_{\rm AB}^{(\mathbf{RL})} + \mathcal{R}_{\rm AB}^{(\mathbf{RL})} \mid \left[\mathcal{S}_{\rm BB}^{(\mathbf{RR})} + \mathcal{R}_{\rm BB}^{(\mathbf{RR})}\right]^{1/2}}{\mid \mathcal{S}_{\rm AB}^{(\mathbf{RR})} + \mathcal{R}_{\rm AB}^{(\mathbf{RR})} \mid \left[\mathcal{S}_{\rm BB}^{(\mathbf{LL})} + \mathcal{R}_{\rm BB}^{(\mathbf{LL})}\right]^{1/2}}. \tag{8}$$

(2) Normalizing by Gains

A more rigorous way is to estimate the gains of the antennae by observing a calibrator source and then calibrate the visibilities accordingly. We shall denote the visibilities calibrated for gains with a superscript [C], hence,

$$\mid^{[\mathrm{C}]} \mathcal{V}_{\rm AB}^{(\mathbf{RR})}(\nu) \mid = \mathcal{S}_{\rm AB}^{(\mathbf{RR})} + \mathcal{R}_{\rm AB}^{(\mathbf{RR})}(\nu). \tag{9}$$

The isolation parameter in this case is

$$^{[\mathrm{C}]}\mathcal{I}_{\rm B}^{(\mathbf{RL})}(\nu) = -20 \log \frac{\mid \mathcal{S}_{\rm AB}^{(\mathbf{RL})} + \mathcal{R}_{\rm AB}^{(\mathbf{RL})}(\nu) \mid}{\mid \mathcal{S}_{\rm AB}^{(\mathbf{RR})} + \mathcal{R}_{\rm AB}^{(\mathbf{RR})}(\nu) \mid}. \tag{10}$$

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[1] By antenna gain we mean the overall antenna gain here, the leakage terms shall be discussed later.

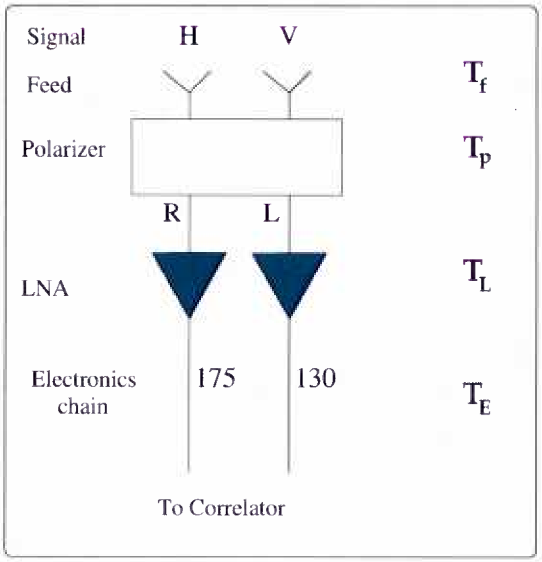

Figure 1.

Here, we are interested in quantifying the polarization isolation characteristics of the antennae. We shall keep the RFI identifications separate from this program. We assume here that we have already identified the RFI's at different antenna and are characterizing the polarization characteristics of the RFI free portion of the data. Hence, we drop the RFI terms from the **eqn.** (8) and **eqn.** (10) and get

$$^{[N]}\mathcal{I}_{\rm B}^{\rm (\mathbf{RL})}(\nu) \;=\; -20\log\frac{\mid \mathcal{S}_{\rm AB}^{\rm (\mathbf{RL})}\mid \left[\mathcal{S}_{\rm BB}^{\rm (\mathbf{RR})}\right]^{1/2}}{\mid \mathcal{S}_{\rm AB}^{\rm (\mathbf{RR})}\mid \left[\mathcal{S}_{\rm BB}^{\rm (\mathbf{LL})}\right]^{1/2}} \tag{11}$$

and

$$^{[C]}\mathcal{I}_{\rm B}^{\rm (\mathbf{RL})}(\nu) \;=\; -20\log\frac{\mid \mathcal{S}_{\rm AB}^{\rm (\mathbf{RL})}\mid}{\mid \mathcal{S}_{\rm AB}^{\rm (\mathbf{RR})}\mid}. \tag{12}$$

In case of an unpolarized source, $\mathcal{S}_{\rm BB}^{\rm (\mathbf{RR})}$ and $\mathcal{S}_{\rm BB}^{\rm (\mathbf{LL})}$ are expected to be equal, hence **eqn.** (11) and **eqn.** (12) are identical. In real world though, there is always some polarization leakage and we shall end up with different values for the isolation if we use the above two expressions. In the next section we discuss how these two estimators are related to different electronics gains and cross gain terms.

3 CHARACTERIZING THE POLARIZATION ISOLATION

It is now left to calculate what the values of the various terms in the right hand side of the **eqn.** (11) and **eqn.** (12) are for a given receiver chain with various gains and leakages. Here we shall not write the frequency dependence of different terms explicitly for simplicity, we shall discuss it later. Figure 1 shows a block diagram of the GMRT hetero-dyne receiver chain and notes the possible transfer functions (**T**) for the different parts of it. Here we briefly describe the individual transfer functions. Note that all the transfer matrices are different for different antennae and hence while considering cross or self visibility terms, we should put in the antenna index.

Feed : $\mathbf{T}_f$

The GMRT antennae have cross dipole feeds, which collects the "horizontal" (H) and the "vertical" (V) polarization of the incoming signal. These feeds can have different gains (complex) and because of mis-alignment, one polarization may leak to the other. Here we model the feed transfer function T_f as,

$$\mathrm{T}_f \;=\; \begin{bmatrix} \tilde{g}^{\,(\mathbf{H})} & 0 \\ 0 & \tilde{g}^{\,(\mathbf{V})} \end{bmatrix} \begin{bmatrix} 1 & \epsilon\, e^{i\phi} \\ \epsilon\, e^{i\phi} & 1 \end{bmatrix}. \tag{13}$$

We have assumed the leakage is symmetrical between H and V polarizations.

Polarizer : $\mathbf{T}_p$

Polarizer is used to convert the “**H**” and “**V**” polarization to the “**R**” and ‘**L**” polarization.

$$\mathrm{T}_p = \begin{bmatrix} 1 & i \\ 1 & -i \end{bmatrix} \tag{14}$$

LNA : $\mathbf{T}_L$

The “**R**” and “**L**” polarized voltages has to now pass through the electronics chain. A pre-amplification is done using a Low Noise Amplifier (LNA) for both the channels (R and L). The LNA can be represented as

$$\mathrm{T}_L = \begin{bmatrix} \tilde{p}^{\,(\mathbf{R})} & 0 \\ 0 & \tilde{p}^{\,(\mathbf{L})} \end{bmatrix} \tag{15}$$

Electronics Chain : $\mathbf{T}_E$

The final part of the signal chain have different local oscillators (LO), optical fiber chain and base-band system. Here also, in principal, there are two types of transformations that the signals can go through; the leakage and gain.

$$\mathrm{T}_E = \begin{bmatrix} \tilde{g}^{\,(\mathbf{R})} & 0 \\ 0 & \tilde{g}^{\,(\mathbf{L})} \end{bmatrix} \begin{bmatrix} 1 & \eta\, e^{i\psi} \\ \eta\, e^{i\psi} & 1 \end{bmatrix} \tag{16}$$

The right most matrix in the right hand side represents the leakage where the left matrix is for the gains. Hence, if the horizontal and vertical polarization of the electric fields produced at the feed by the astronomical signal are $\tilde{S}^{\,(\mathbf{H})}$ and $\tilde{S}^{\,(\mathbf{V})}$ respectively, then the voltages measured in “**R**” and “**L**” polarizations can be given by

$$\begin{bmatrix} \tilde{v}^{\,(\mathbf{R})} \\ \tilde{v}^{\,(\mathbf{L})} \end{bmatrix} = T_E\, T_L\, T_p\, T_f \begin{bmatrix} \tilde{S}^{\,(\mathbf{H})} \\ \tilde{S}^{\,(\mathbf{V})} \end{bmatrix} \tag{17}$$

In the GMRT system, the main contributor to the leakage is expected to be T_f, i.e, the feed transfer function and we can safely assume that there is no leakage in the electronics chain (private communication with Govind Swarup and A. Praveen Kumar) and hence, $\eta = 0$. In such case, T_E and T_L behaves like an overall gain term and we can write

$$\begin{bmatrix} \tilde{G}^{\,(\mathbf{R})} & 0 \\ 0 & \tilde{G}^{\,(\mathbf{L})} \end{bmatrix} = T_E\, T_L. \tag{18}$$

Writing

$$\begin{bmatrix} \tilde{S}^{\,(\mathbf{R})} \\ \tilde{S}^{\,(\mathbf{L})} \end{bmatrix} = T_p\, T_f \begin{bmatrix} \tilde{S}^{\,(\mathbf{H})} \\ \tilde{S}^{\,(\mathbf{V})} \end{bmatrix}, \tag{19}$$

we can rewrite **eqn.** (17) as

$$\begin{bmatrix} \tilde{v}^{\,(\mathbf{R})} \\ \tilde{v}^{\,(\mathbf{L})} \end{bmatrix} = \begin{bmatrix} \tilde{G}^{\,(\mathbf{R})} & 0 \\ 0 & \tilde{G}^{\,(\mathbf{L})} \end{bmatrix} \begin{bmatrix} \tilde{S}^{\,(\mathbf{R})} \\ \tilde{S}^{\,(\mathbf{L})} \end{bmatrix}, \tag{20}$$

which mimics **eqn.** (2) assuming there is no RFI. We have discussed how to normalize against the overall gain factors $\tilde{G}^{\,(\mathbf{R})}$ and $\tilde{G}^{\,(\mathbf{L})}$ in the previous section. Here we shall focus on writing the $\tilde{S}^{\,(\mathbf{R})}$ etc. in terms of the leakage parameters and the astronomical signals $\tilde{S}^{\,(\mathbf{H})}$ etc. Using **eqn.** (13) and **eqn.** (14) in **eqn.** (19) we get,

$$\begin{bmatrix} \tilde{S}^{\,(\mathbf{R})} \\ \\ \tilde{S}^{\,(\mathbf{L})} \end{bmatrix} = \begin{bmatrix} \left(\tilde{g}^{\,(\mathbf{H})} + i\epsilon\tilde{g}^{\,(\mathbf{V})}e^{i\phi}\right)\tilde{S}^{\,(\mathbf{H})} \; + \; i\left(\tilde{g}^{\,(\mathbf{V})} - i\epsilon\tilde{g}^{\,(\mathbf{H})}e^{i\phi}\right)\tilde{S}^{\,(\mathbf{V})} \\ \left(\tilde{g}^{\,(\mathbf{H})} - i\epsilon\tilde{g}^{\,(\mathbf{V})}e^{i\phi}\right)\tilde{S}^{\,(\mathbf{H})} \; - \; i\left(\tilde{g}^{\,(\mathbf{V})} + i\epsilon\tilde{g}^{\,(\mathbf{H})}e^{i\phi}\right)\tilde{S}^{\,(\mathbf{V})} \end{bmatrix}. \tag{21}$$

For an unpolarized source, $|\ \tilde{S}^{\,(\mathbf{H})}\ |^2 = |\ \tilde{S}^{\,(\mathbf{V})}\ |^2 = \ \mathcal{S}$. Clearly, we can calculate the terms like $\mathcal{S}_{\rm AB}^{(\mathbf{RL})} = \langle \tilde{S}^{\,(\mathbf{R})}\tilde{S}^{\,(\mathbf{LR})}\rangle$ etc. using **eqn.** (20). Hence, **eqn.** (11) and **eqn.** (12) becomes to the leading order of ϵ,

$$ {}^{[\mathrm{N}]}\mathcal{I}_{\rm B}^{(\mathbf{RL})} \ = \ -10\log\left[\epsilon_{\rm A}^2 \ + \ \epsilon_{\rm B}^2 \ + \ 2\epsilon_{\rm A}\,\epsilon_{\rm B}\ \cos(\phi_{\rm A} + \ \phi_{\rm B})\right], \tag{22} $$

and

$$ {}^{[\mathrm{C}]}\mathcal{I}_{\rm B}^{(\mathbf{RL})} \ = \ -20\log\left[\left(\epsilon_{\rm A}^2 \ + \ \epsilon_{\rm B}^2 \ + \ 2\epsilon_{\rm A}\,\epsilon_{\rm B}\ \cos(\phi_{\rm A} + \ \phi_{\rm B})\right)^{1/2} \frac{|\ \tilde{g}^{\,(\mathbf{V})}\ |}{|\ \tilde{g}^{\,(\mathbf{H})}\ |}\right]. \tag{23} $$

Clearly, "normalization by self" in this case directly measures the isolation parameters, whereas ${}^{[\mathrm{C}]}\mathcal{I}_{\rm B}^{(\mathbf{RL})}$ have in it the ratio of the horizontal to the vertical gain. Considering the difference between **eqn.** (23) and **eqn.** (24), we can estimate the amplitude ratio between the vertical and horizontal gains.

$$ {}^{[\mathrm{C}]}\mathcal{I}_{\rm B}^{(\mathbf{RL})} \ - \ {}^{[\mathrm{N}]}\mathcal{I}_{\rm B}^{(\mathbf{RL})} \ = \ -20\ \log\left[\frac{|\ \tilde{g}^{\,(\mathbf{V})}\ |}{|\ \tilde{g}^{\,(\mathbf{H})}\ |}\right] \tag{24} $$

However, to the accuracy this gain ratio can be determined depends strongly on the accuracy to which the antenna gains $\tilde{G}$ are determined. Hence, whether or not we can comment on the vertical and horizontal gain ratio has to be checked more thoroughly. This is out of the scope of the present work and is not discussed further. From the structure of the **eqn.** (22) it is clear that ${}^{[\mathrm{N}]}\mathcal{I}_{\rm B}^{(\mathbf{RL})} \ = \ {}^{[\mathrm{N}]}\mathcal{I}_{\rm B}^{(\mathbf{LR})}$. This symmetry in the result is a direct consequence of the symmetry we have assumed in the leakage part of the transfer function T_f. Instead, if we consider the feed transfer function to be

$$ \mathrm{T}_f \ = \ \begin{bmatrix} \tilde{g}^{\,(\mathbf{H})} & 0 \\ 0 & \tilde{g}^{\,(\mathbf{V})} \end{bmatrix} \begin{bmatrix} 1 & \epsilon_H\, e^{i\phi_H} \\ \epsilon_V\, e^{i\phi_V} & 1 \end{bmatrix}, \tag{25} $$

we shall arrive at the modified expressions for ${}^{[\mathrm{N}]}\mathcal{I}_{\rm B}^{(\mathbf{RL})}$ and ${}^{[\mathrm{N}]}\mathcal{I}_{\rm B}^{(\mathbf{LR})}$ and also they will not be equal. Hence, the general form of the isolation parameter will be

$$ \begin{aligned} {}^{[\mathrm{N}]}\mathcal{I}_{\rm B}^{(\mathbf{RL})} \quad = \quad & -10\log\left[\{\epsilon_{\rm A}^{(\mathbf{H})}\cos(\phi_{\rm A}^{(\mathbf{H})}) \ + \ \epsilon_{\rm B}^{(\mathbf{V})}\cos(\phi_{\rm B}^{(\mathbf{V})})\}^2\right. \\ & \left. + \ \{\epsilon_{\rm A}^{(\mathbf{H})}\sin(\phi_{\rm A}^{(\mathbf{H})}) \ + \ \epsilon_{\rm B}^{(\mathbf{V})}\sin(\phi_{\rm B}^{(\mathbf{V})})\}^2\right]. \end{aligned} \tag{26} $$

One can easily obtain the expression for ${}^{[\mathrm{N}]}\mathcal{I}_{\rm B}^{(\mathbf{LR})}$ by exchanging **H** and **V** in the right hand side of the above equation. If from the data we find that ${}^{[\mathrm{N}]}\mathcal{I}_{\rm B}^{(\mathbf{RL})} \neq {}^{[\mathrm{N}]}\mathcal{I}_{\rm B}^{(\mathbf{LR})}$, it indicates that the leakage is not symmetric.

Notes on 1420 MHz band

As we have mentioned before, for the 1420 MHz band (i.e, all the sub-bands at 1420 MHz band), the "X" and "Y" polarizations are measured. We define isolation parameters similar to those in **eqn.** (11) and **eqn.** (12) as follows:

$$ {}^{[\mathrm{N}]}\mathcal{I}_{\rm B}^{(\mathbf{XY})}(\nu) \ = \ -20\log\frac{|\ \mathcal{S}_{\rm AB}^{(\mathbf{XY})}\ |\ \left[\mathcal{S}_{\rm BB}^{(\mathbf{XX})}\right]^{1/2}}{|\ \mathcal{S}_{\rm AB}^{(\mathbf{XX})}\ |\ \left[\mathcal{S}_{\rm BB}^{(\mathbf{YY})}\right]^{1/2}} \tag{27} $$

and

$$ {}^{[\mathrm{C}]}\mathcal{I}_{\rm B}^{(\mathbf{XY})}(\nu) \ = \ -20\log\frac{|\ \mathcal{S}_{\rm AB}^{(\mathbf{XY})}\ |}{|\ \mathcal{S}_{\rm AB}^{(\mathbf{XX})}\ |}. \tag{28} $$

It is straight forward to express these quantities in case of an unpolarized source as before. We note to the fact that T_p is not present in the receiver chain for this band and the transfer matrix is due to T_f only. Hence, we can write the isolation parameters in the leading terms of ϵ as

$$ {}^{[\mathrm{N}]}\mathcal{I}_{\rm B}^{(\mathbf{XY})} \ = \ -10\log\left[\epsilon_{\rm A}^2 \ + \ \epsilon_{\rm B}^2 \ + \ 2\epsilon_{\rm A}\,\epsilon_{\rm B}\ \cos(\phi_{\rm A} + \ \phi_{\rm B})\right], \tag{29} $$

and

$$ {}^{[\mathrm{C}]}\mathcal{I}_{\rm B}^{(\mathbf{XY})} \ = \ -20\log\left[\left(\epsilon_{\rm A}^2 \ + \ \epsilon_{\rm B}^2 \ + \ 2\epsilon_{\rm A}\,\epsilon_{\rm B}\ \cos(\phi_{\rm A} + \ \phi_{\rm B})\right)^{1/2} \frac{|\ \tilde{g}^{\,(\mathbf{V})}\ |}{|\ \tilde{g}^{\,(\mathbf{H})}\ |}\right]. \tag{30} $$

Interestingly, the form of the above equations are exactly same as the **eqn.** (23) and **eqn.** (24). Hence we use same procedure and implementation for all the bands at the GMRT.

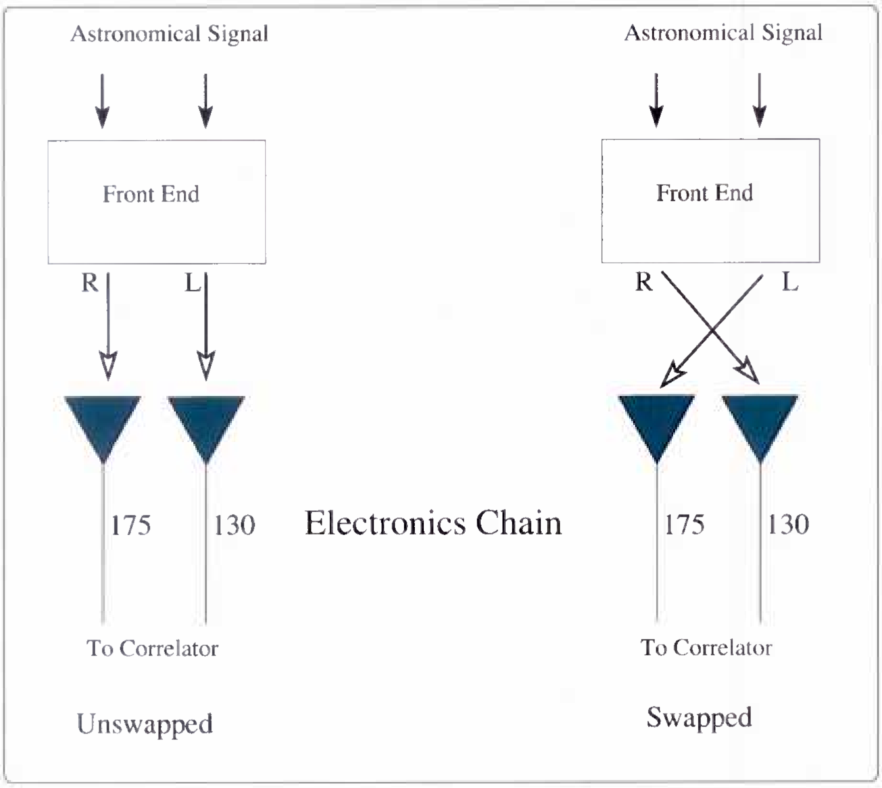

Figure 2. Left panel of the above plot shows the unswapped and right panel shows the swapped mode. See text for details.

4 IMPLEMENTATION

4.1 Observation procedure

The GMRT has two frequency channels centered at 130 MHz and 175 MHz which are used to bring the two polarized voltage signals from each of the antennae to the control room. Usually the 175 MHz channel is used for the "**R**" mode of polarization and 130 MHz channel is used for the "**L**" mode. However, there exists a polarization switch at the antennae, by means of which this choice can be reversed. Moreover, it has been checked (A. P. Rao, 1991) that the isolation switch itself does not introduce a considerable amount of leakage in the system. We use this swapping feature to measure the isolation characteristics of the GMRT antennae through the following procedure:

- Two antennae. one preferably from the central square and another from one of the arms, with good sensitivities are identified. These are referred to as the reference antennae and isolation values are measured for all the other antennae with respect to these two antennae.
- A five minute scan on one of the flux calibrator is taken in the usual mode, i.e, for all the antennae 175 MHz channel chosen for "**R**" polarization and 130 MHz channel chosen for the "**L**" polarization. This is shown schematically in the left part of the Figure 2. This scan is usually referred to as 'unswapped' scan. The visibilities recorded in this scan corresponds to visibilities given by **eqn.** (4).
- In the next step, the paths to the "**R**" and "**L**" polarization are reversed for one of the reference antennae, i.e, the 130 MHz channel is used for "**R**" and 175 MHz channel is used for "**R**' mode of polarization. This is shown schematically in the right part of the Figure 2). All antennae other than the reference antenna are kept in the 'unswapped' configuration. A five minute scan is taken. This scan is referred to a 'swaped' scan. The visibilities recorded in this scan with respect to the reference antenna corresponds to visibilities given by **eqn.** (5) for all the other antennae. Same as above is repeated for the second reference antenna.

These visibilities in the 'swapped' and 'unswapped' scans are used for the further analysis.

4.2 Software Implementations

At GMRT, raw data is stored in the observatory standard binary data format "lta" or "ltb". These data format is directly used while performing the software implementation. Implemented software is named as "PLEAK" and we shall refer to it by this name from now on. PLEAK requires the following programs/libraries:

(i) **xtract**: An observatory software developed by Sanjay Bhatnagar which can be used to read the binary data from the "lta/b" files and ASCII data table can be generated.
(ii) gnu c/c^{++} compiler.
(iii) pgplot library C implementation.
(iv) Linux bash shell environment.

PLEAK operates in the following main steps:

- **USER input**: User has to give input regarding the reference antennae and channels (130/175) of observation and path to the data file.
- **Extracting the binary data**: Based on the user input, PLEAK extracts the required data from the binary data file using 'xtract' and writes it to an ASCII file.
- **Calculating isolation parameters**: PLEAK utilizes two 'C' codes to calculate the isolation parameters, one for all the channels and another for three channels across the band. It writes the isolation values in a ASCII file.
- **Plot:** PLEAK finally generates a color coded isolation plot which can be examined by the investigator. We discuss the format of the plot later.

This software implementation is available in the astro6 computer at GMRT [2]. We have used a comprehensive naming convention for the output files generated by this program. This makes their identification easy. Here we give an example, for the following observation:
DATE: *05Jan2012*
IST: *14-27-59*
MJD: *55931.374*
BandWidth: *33 MHz*
Band: *610 MHz*
Refant: *C08*
Channel: *175 MHz*
Data type: *Multichannel data*
The file name convention is
POLTEST_05Jan2012_14-27-59_55931.374_33_610_C08_175_MCH

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[2] We make version (soft-copy) of this software available with this report. Installation instructions
software. Contact NCRA SRIC for details

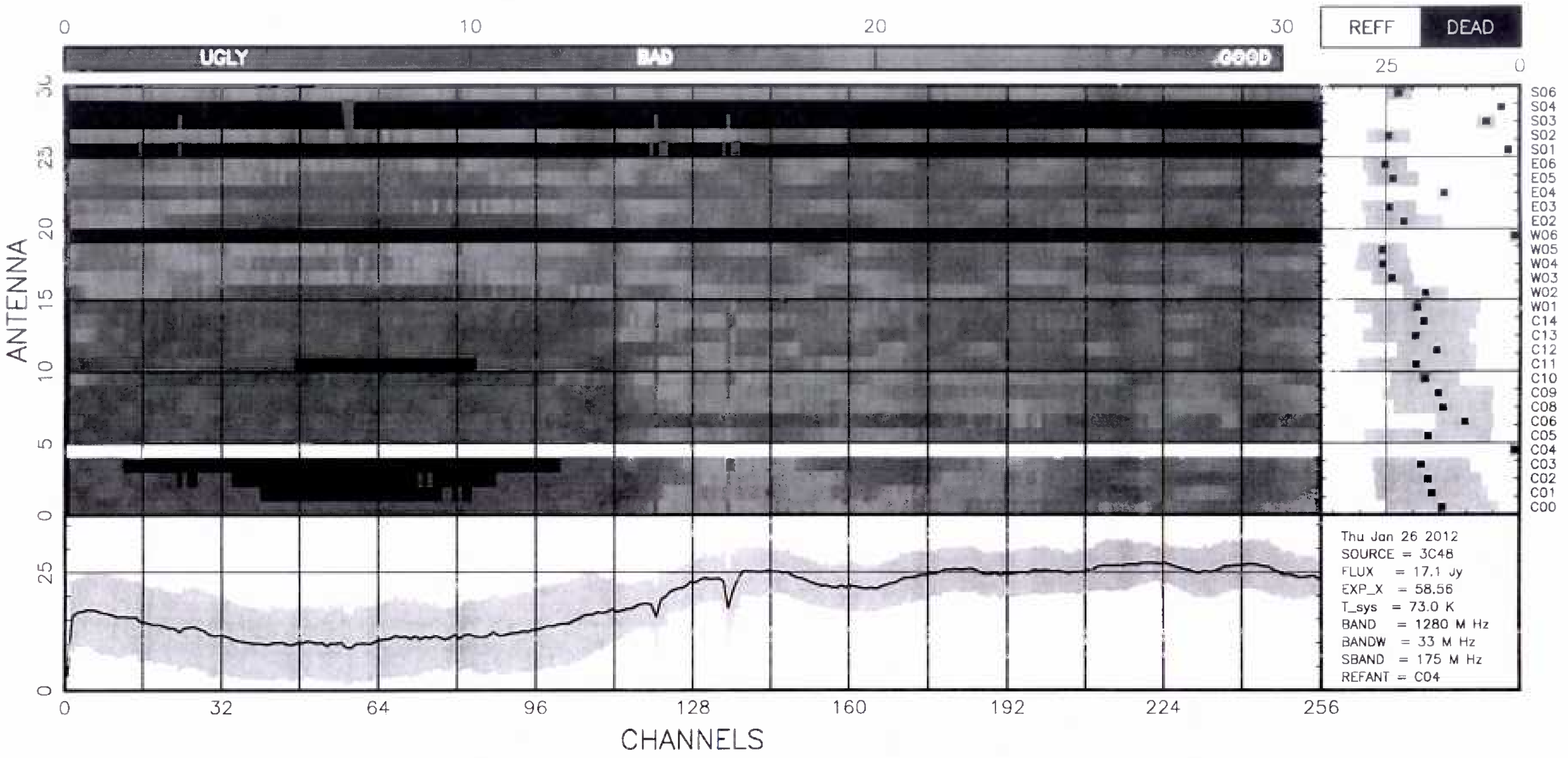

Figure 3. Isolation plot for 1280 MHz band

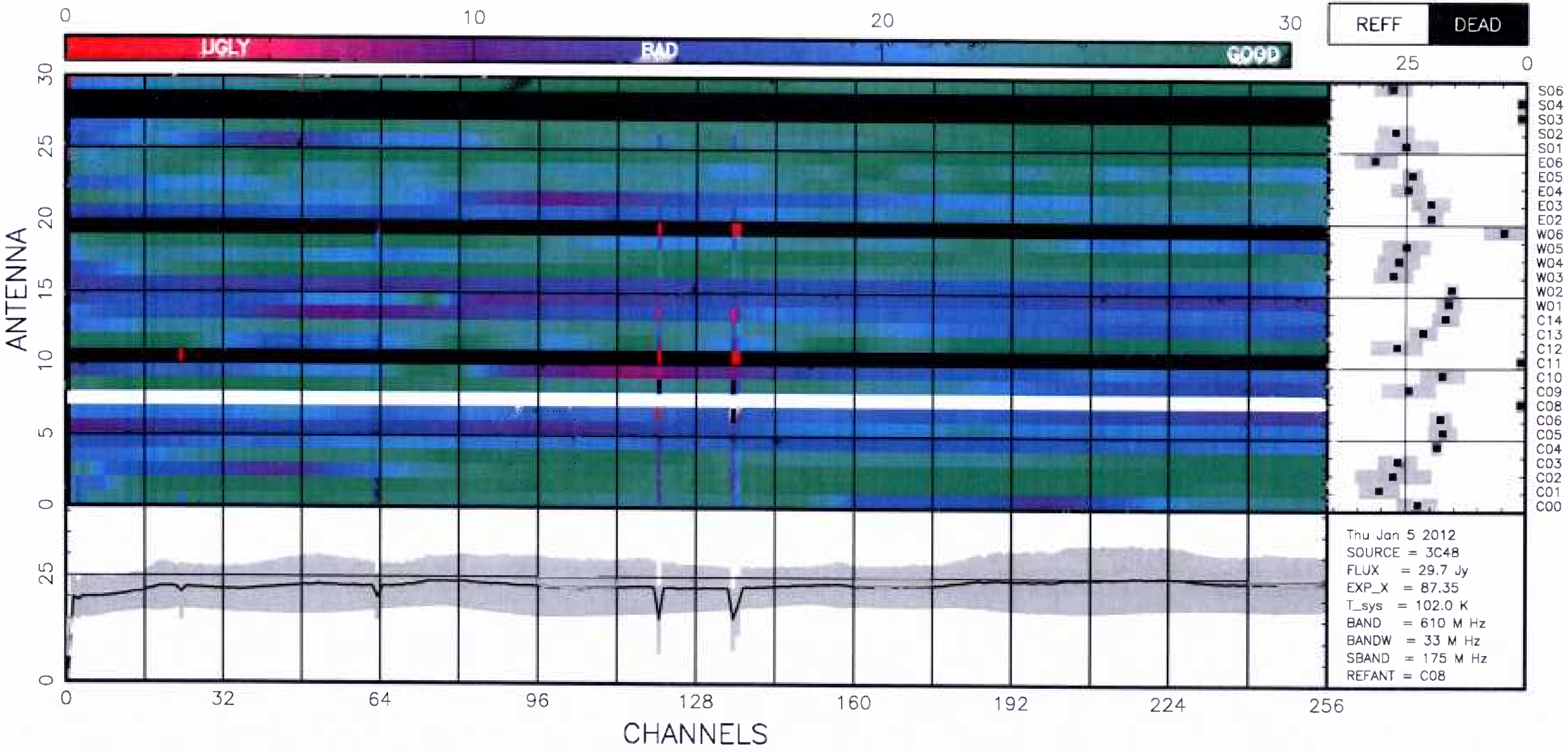

Figure 4. Isolation plot for 610 MHz band

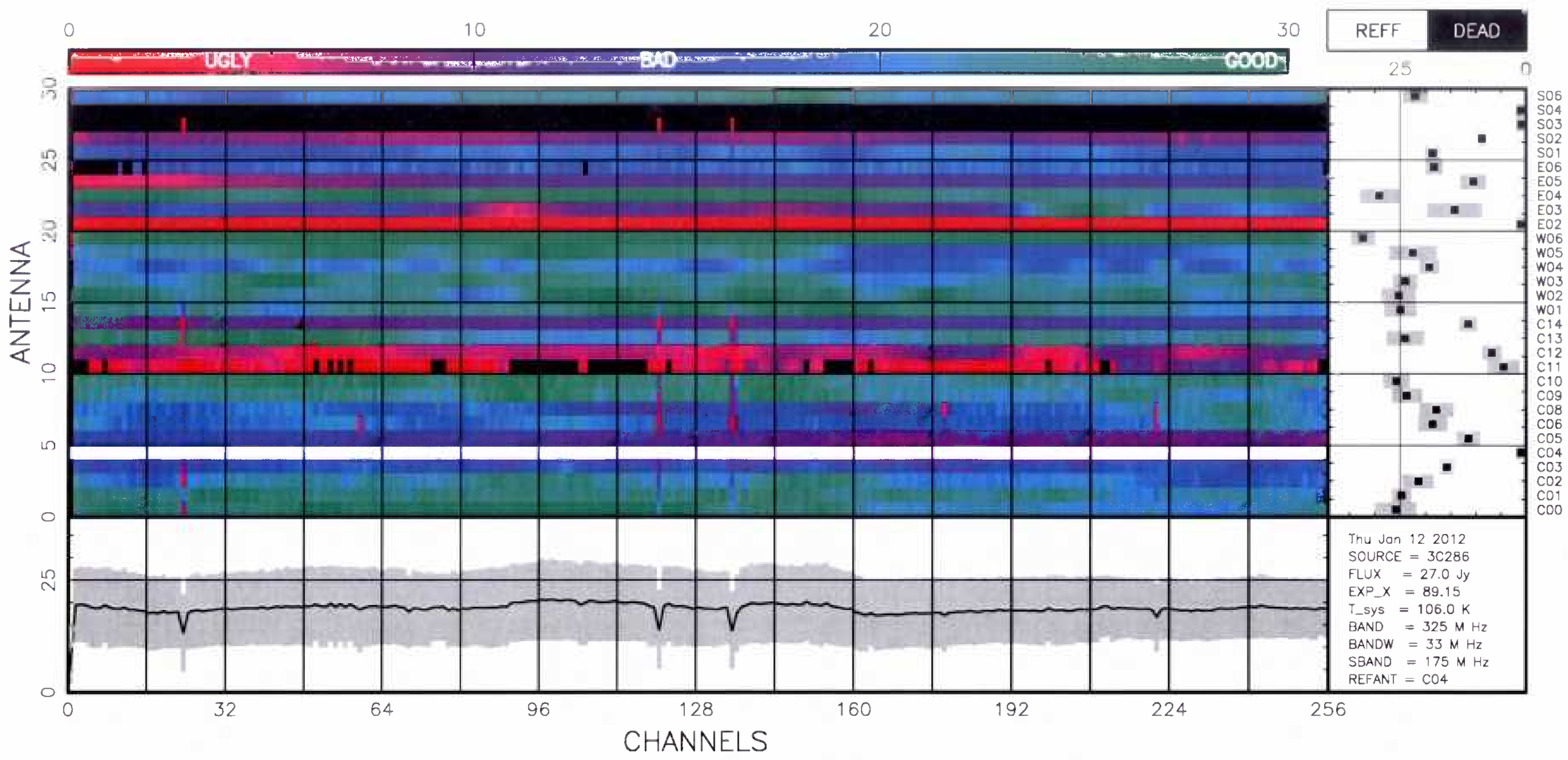

Figure 5. Isolation plot for 325 MHz band

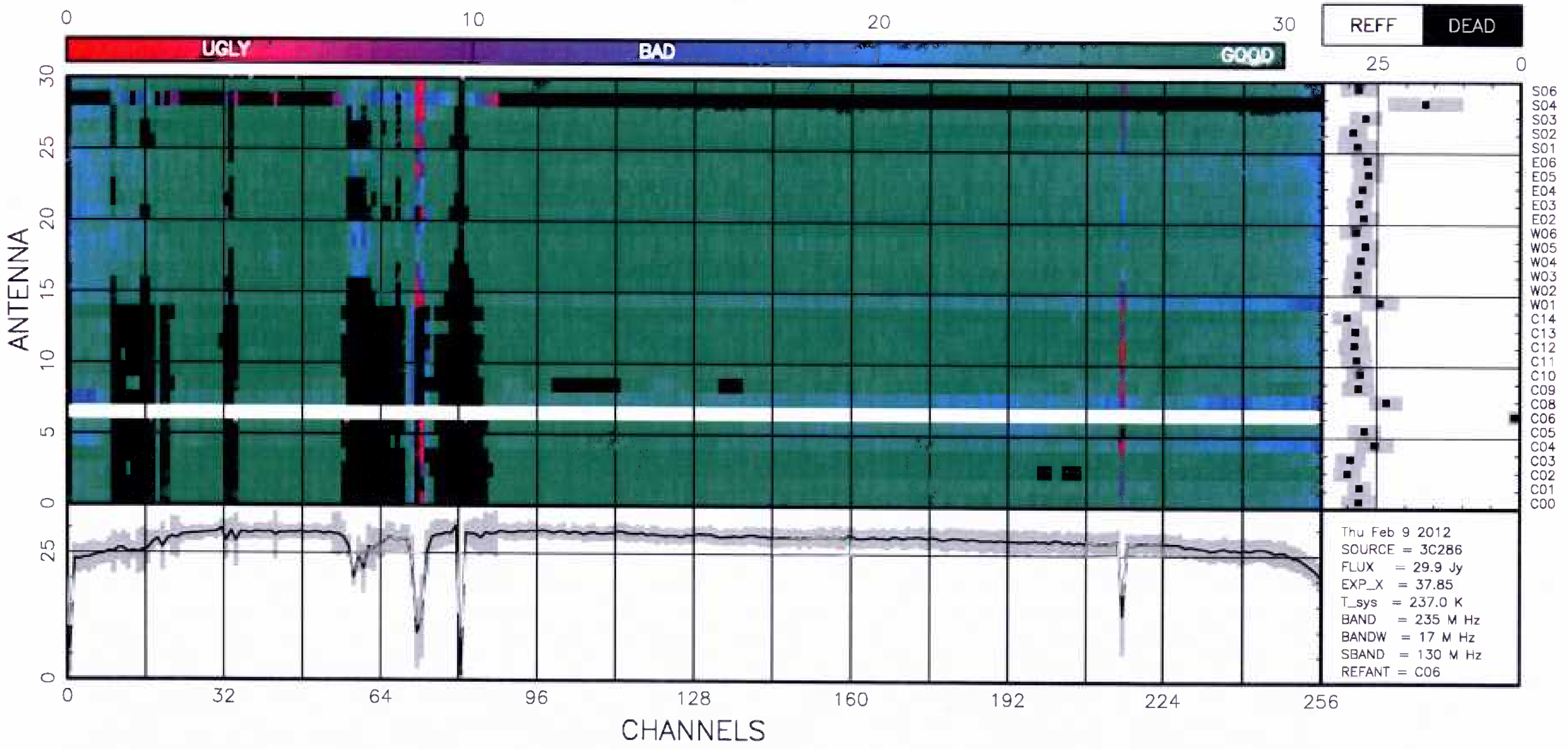

Figure 6. Isolation plot for 235 MHz band

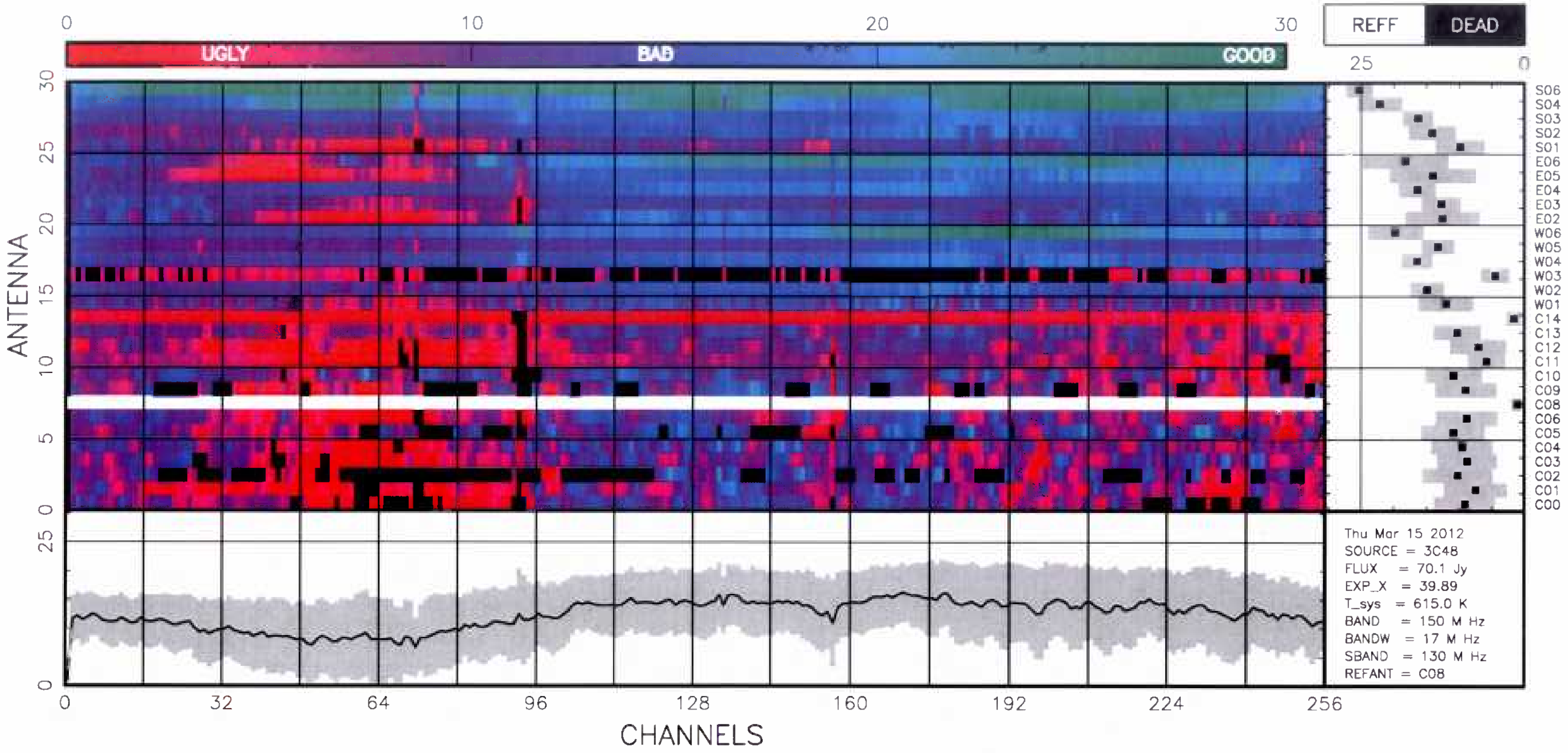

Figure 7. Isolation plot for 150 MHz band

4.3 Isolation Plot

We have implemented a particular representation of the isolation parameters using a color coded plot that can be easily understood. Figure 4 gives the Isolation Plot corresponding to a test made on 05th January 2012 in the 610 MHz band with C06 as the reference antenna. Title bar in the plot shows the color representations of the isolation parameter in terms of dB. We consider a given isolation value ugly if this parameter has a value less than 5 dB. These antennae/channels requires immediate attention from the maintenance team. In between 5 dB to 15 dB the isolation is considered bad and values above 15 dB are labeled as good. The main color box in the figure corresponds to the color coded isolation values across the antennae (antenna names can be found in the right hand margin and the channel numbers at the bottom) and channels. The bottom plot shows the antenna averaged isolation values (and standard deviation) across the channels while the plot at the right hand side shows the channel averaged isolation values (and standard deviation) for a given antenna. Black points in the main color coded plot corresponds to either RFI or dead antennae. The reference antenna is coded with white. The small box at the bottom right corner of the figure corresponds to the observation parameters.

This plot is so designed that one glance at it tells us about the overall quality of isolation across the bandwidth of observation for all antennae. Thus if the plot is mostly green, then the polarization isolation for the most antenna are good whereas if it is mostly red, then something was either wrong during the observation or the isolation characters are bad. A look at the bottom graph gives an idea about how different channels are behaving. Similarly a glance at the right hand margin plot gives the status of different antennae. In the next section we shall discuss a few findings regarding the isolation characteristics of the GMRT antennae utilizing these plots.

5 DISCUSSIONS

Here we have attached four different plots from PMQC test observations. Each plot covers one frequency band from 1280, 610, 325, 235 and 150 MHz. First three plots are from the 175 MHz channel and the next two are from 130 MHz channel. Here we briefly discuss our general observations [3].

(i) We observe, in general, polarization isolation at 1280 (Figure 3)and 610 MHz (Figure 4) is quite good at GMRT. Most of the tests yields plots with mostly green shades indicating more than 25 dB isolation. As we go to the lower frequency bands, the overall isolation decreases. At 150 MHz the isolation is fairly at about 10 to 15 dB. However, 235 MHz (Figure 6) band seems to show good isolation characteristics.

(ii) In the Isolation plots, we have color coded the non working antennae (‘bad antennae’) as black, Apart from this, there are usually some black regions in the plot, these area mostly indicates RFI. Like polarization isolation, 150 MHz (Figure 7) band is affected by large number of RFI’s. Though the overall isolation at 235 MHz band (Figure 6) is appears to be good, as we can see from the plot near to the channels 16 to 80 we see large RFI. Similarly, a red patch in the bottom left part of the plot for the 1280 MHz plot (Figure 3) shows that all the antennae in the central square were affected by a broadband RFI during the time of the test.

(iii) We observe, for the channels corresponding to 5 MHz offset in either side from the central frequency channel, there is always a dip in the isolation value. This is seen for all the frequency bands and can be seen most prominently in all the sub-bands of 1420 MHz band and the 610 MHz band. This is probably coming from (private communication with operators) the LO1 (local oscillator 1). We recommend further investigations regarding this.

(iv) We observe periodic increase and decrease in the isolation values across the frequency channels for most of the antennae. This effect is most pronounce at all the sub-bands of the 1420 MHz band. Frequency of this oscillation (periodic increase and decrease) is roughly ~ 4 MHz which corresponds to a wavelength of 75 meters. We notice that the GMRT antennae have a focal distance of 18.5 meters, roughly $1/4^{th}$ of the wavelength of the oscillations as given above. This prompt us to think that these may be result of some standing wave formation in the antennae. More investigations are necessary to find out what these oscillations are.

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[3] Polarization test plots are regularly updated in the PMQC section of the GMRT website *http://gmrt.ncra.tifr.res.in/ pmqc/Pol_Isolation_results/*

6 FUTURE SCOPE

We propose two steps that can be taken to further improve this program.

- Instead of using three different scans, we may use the full polar mode of the GMRT antenna which at a go measures all the four (RR, LL, RL, LR) polarizations. Based on the full polar mode observations a methodology can be developed to access the short term variation of the isolation parameters.
- Based on the tests done every week a database of the parameter values can be made and used to check if there is any systematic variation of these parameters across different epoch (weeks apart). **At present we are trying to figure out systematic variations in the polarization isolation characteristics of the GMRT antennae over time. We shall present that in a later version of the report.**

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