National Centre for Radio Astrophysics

Internal Technical Report
NCRA--GMRT/uGMRT/March 2016

Feedback and recommendations from simultaneous multi-frequency (multi-subarray) observations using GSB & GWB

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Objectives: (1) To test and debug various aspects of pulsar observing modes, and assess sensitivity and RFI situation in the newly released wide-bands of *uGMRT*.
(2) To test and establish the procedure for conducting multi-subarray observations by operating *GWB* and *GSB at different frequencies*.

Revision	Date	Modification/ Change
Ver. 1	March 2016	Initial Version

Feedback and recommendations from the multi-subarray observations using GSB and GWB

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1 Objectives

The studies presented in the report have primarily the following main objectives.

1. To assess the sensitivity of GMRT wide-band systems by carrying out astronomical measurements using the available antennas.
2. To assess the RFI situation in the 130–260 MHz, 300–500 MHz and 1300–1500 MHz bands which are currently usable with the GMRT wideband systems.
3. To test and establish the procedure of conducting multi-subarray observations, by using the individual beams of the GMRT software backend (GSB) and the GMRT wideband backend (GWB) simultaneously at different frequencies.
4. To test and debug various aspects of the pulsar observing modes of current release of the uGMRT.

2 Introduction

The full upgrade of the GMRT will offer a unique opportunity to conduct *simultaneous* flux measurements at densely sampled frequencies within the spectral span of 130–1500 MHz. Astronomical measurements simultaneously across the frequency span of 130–1500 MHz will require using the GMRT dishes in multiple subarrays. Such measurements, utilizing the upgraded GMRT as a *very sensitive and wideband spectrometer*, will be of particular importance to study the spectral complexities of astronomical sources in this frequency range, e.g., spectral breaks and turn-overs exhibited by various radio pulsars. Wider bandwidths and the increased frequency coverage of the uGMRT will also enable much better studies of the interstellar medium, e.g., via its imprints on pulsed signals from pulsars.

uGMRT is a pathfinder for the SKA. Multi-subarray mode is also one of the proposed observing mode of the SKA. Hence, testing the multi-subarray observing mode of the GMRT with the currently released wide-band systems is not only important for making suitable advances towards the fully upgraded GMRT (i.e., the full-fledged uGMRT), but also to understand the obstacles and work-arounds in achieving a similar observing mode for the SKA.

3 Observations and sensitivity tests

A total of 3 observing sessions were conducted, with each of the sessions utilizing 24 (out of 30) GMRT dishes divided into 4 subarrays. The 4 subarrays were used at 150 MHz (once in legacy mode with 16 or 32 MHz bandwidth, and twice with the wideband system), 300–500 MHz (i.e. the wideband system), 610 MHz (in legacy mode with 33 MHz bandwidth), and L-band (once with the 200 MHz wideband system, and twice in legacy mode with 33 MHz bandwidth). The wideband observations utilized a bandwidth of 200 MHz with 4096 channels, while the legacy system observations used 512 channels across the (typically) bandwidth of 33 MHz.

To assess the system sensitivity, on-source as well as off-source (5° away from the source in declination) observations of a number of flux calibrators (like, 3C48, 3C119, 3C468.1, 3C273,

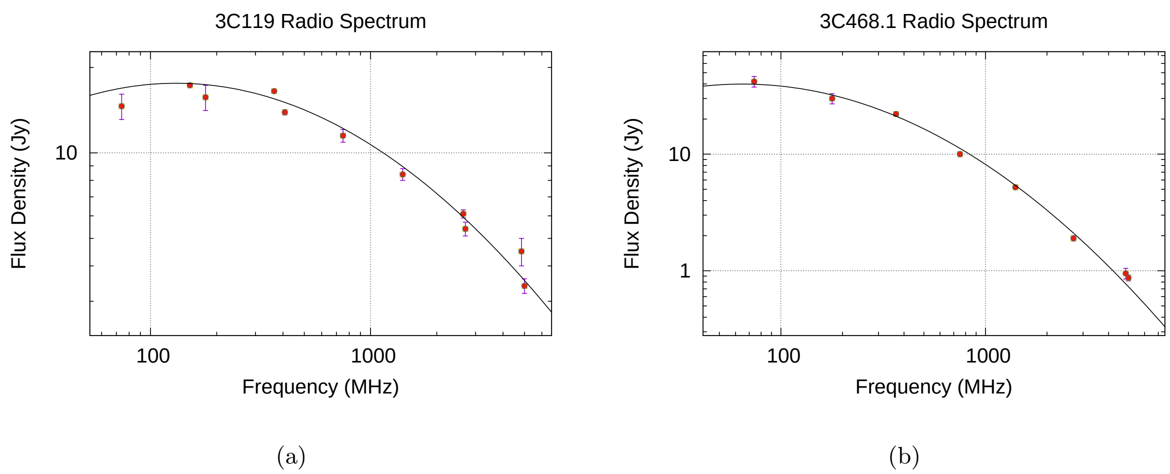

Figure 1 — Flux densities at several frequencies in the range 50–5000 MHz obtained from NED (points with error-bars), and the fitted spectra (continuous lines) for the two calibrators 3C119 and 3C468.1 are shown in the two panels.

etc.) were performed. These observations were used to assess the system sensitivity in terms of ratio of system gain by temperature (G/T_{sys}) given by:

$$\frac{G}{T_{sys}} = \frac{(S/N)}{S\sqrt{2\,\tau\,\Delta\nu}} \tag{1}$$

where, (S/N) is the achieved signal to noise ratio, τ is the observation duration (in sec), $\Delta\nu$ is the bandwidth (in Hz) corresponding to individual measurements, and S is the source flux density (in Jy).

A reasonably accurate flux density spectrum of 3C48 is known from Baars et al. (1977). To estimate the spectrum of 3C119, 3C468.1, 1830−360 and 3C273 across the frequency range of our observations, we used the flux density estimates of these sources at various frequencies in the range 50–5000 MHz available from NED, and fit an expression similar to that used by Baars et al. (1977). The flux densities obtained from NED as well as the fitted spectra for 3C119 and 3C468.1 are shown in Figure 1.

To compute the S/N as a function of frequency, we first computed the average power as a function of frequency integrated for a few seconds (hereafter partially averaged spectra) for on-source as well as off-source data. Using these partially averaged spectra, we computed the median and root-mean-square (RMS) power as a function of frequency towards the source as well as away from the source. As an example, the median spectra obtained for the calibrator 3C48 for the wideband 300–500 MHz are shown in Figure 2. These spectra along with the off-source RMS spectrum is used to compute the S/N as a function of frequency.

Due to prominent radio frequency interference (RFI) in the 150 MHz band (in legacy 33 MHz as well as in the 100–300 MHz wideband), we could not calculate the deflection in power reliably. In the other three frequency bands (300–500 MHz, 610 MHz and L-band) corresponding to the other three subarrays, we used the on and off-source spectra for 3C48, 3C119, 3C468.1, 1830−360 and 3C273 (observed in three different sessions) to compute G/T_{sys}. The frequency channels heavily contaminated by RFI, as indicated by the corresponding median or RMS spectra, were excluded from G/T_{sys} computation. For example, a few channels around 350 MHz, 402 MHz,

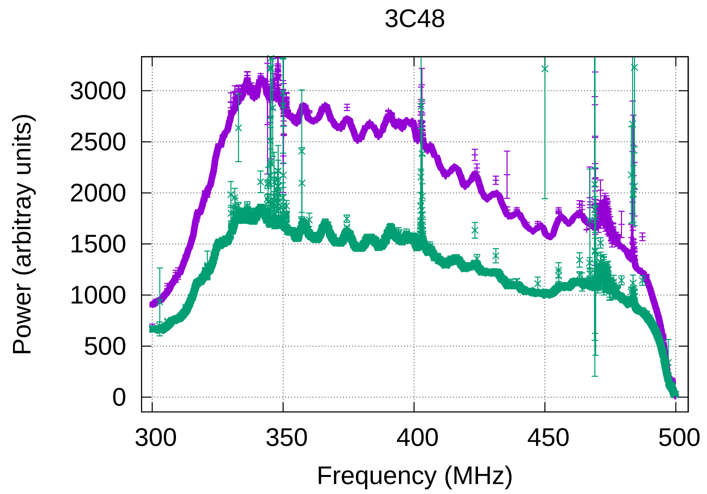

Figure 2 — The violet colored points show the received power towards the calibrator 3C48, while the green points show that from the background sky. The error-bars represent the $\pm 1\sigma$ deviations.

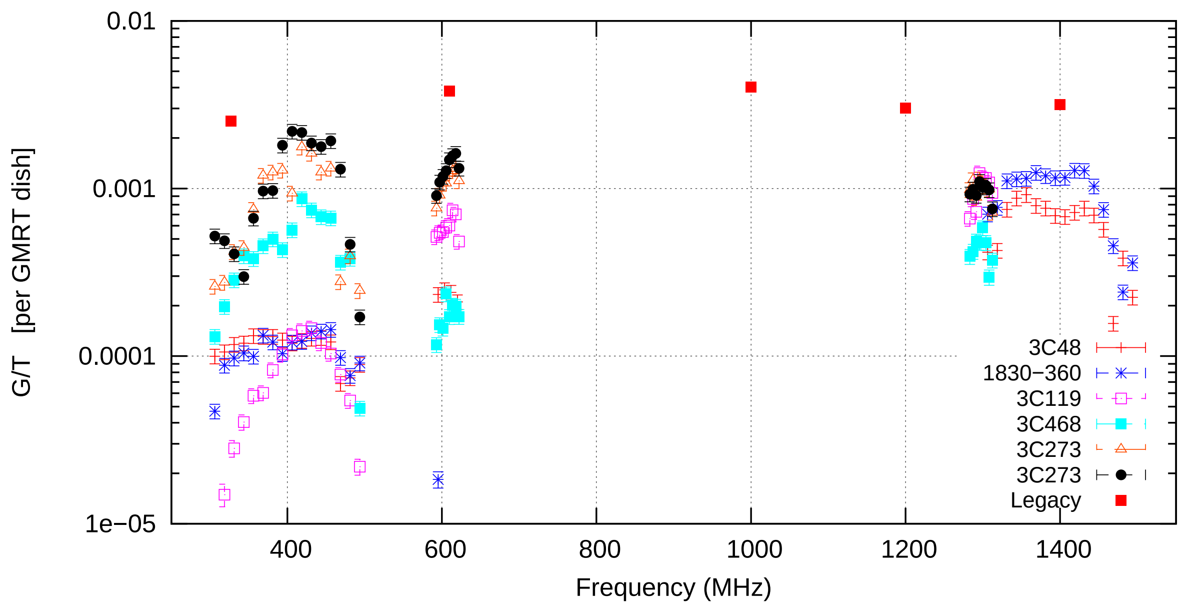

Figure 3 — G/T_{sys} measurements as a function of frequency, using the sources 3C48, 3C119, 3C468.1, 1830−360 and 3C273 (2 measurements), along with the earlier measurements available from the GMRT website (marked as "Legacy" in the list of legends) are shown together.

470 MHz, and 485 MHz show large deviations from the mean spectra in Figure 2, and hence, were excluded. The data were also averaged across frequency such that we got 16 measurement across the 200 MHz wideband and 4 or 8 across the legacy 33 MHz bandwidth. To compute the sensitivities for a single GMRT dish, the G/T_{sys} values at each of the bands were divided by the number of dishes included in the respective subarrays. The estimated values of G/T_{sys} using all the sources in all the frequency bands are shown in Figure 3. For comparison with the existing measurements using the legacy systems (available at `http://gmrt.ncra.tifr.res.in/gmrt_hpage/Users/doc/WEBLF/LFRA/node181.html` and shown as red-dots in Figure 3), the units have been changed to $\mathrm{Jy}^{-1}\,\mathrm{K}^{-1}$. The error-bars represent uncertainties in the computed power deflection and assumed 10% uncertainties in flux densities propagated appropriately.

It is apparent that the G/T_{sys} in 300–500 MHz and 610 MHz bands show large variations from one source to other. These variations are most likely due to variable RFI contamination in different observing sessions. RFI contamination is generally not so much at L-band, and the corresponding small dispersion in G/T_{sys} in this band reassures this fact.

The most reliable estimates of G/T_{sys} in these bands are from our night time observations of 3C273 (2 measurements). The G/T_{sys} from 3C273 are comparable with those from the legacy system. These measurements appear to be smaller than those from the legacy system, on average, by a factor of 2. The most likely reason for this degradation is non-perfect phasing or de-phasing (with time) of the respective subarrays. The 610 MHz band subarray included a few arm antennas, while the L-band subarray was consisted of mainly only the arm antennas. The correspondingly larger deviation in G/T_{sys} (when compared to legacy system) at these two bands supports the argument that the observed degradation is primarily because of issues with phasing the subarrays.

As mentioned earlier, only the RFI contaminated spectral channels were excluded, and no effort was made to exclude any possible RFI contaminated samples (due to, e.g., 50/100 Hz or any spiky/bursty RFI), before computing G/T_{sys}. Existence of any temporal RFI would also have caused underestimating G/T_{sys}.

4 RFI statistics

A total of 13 pulsars were observed during the multi-subarray observations. Data from observations of 10 pulsars were analyzed to determine the typical percentage of RFI-free data one gets. For this purpose, the GMRT data were converted to SIGPROC-format, and the pulsar search and analysis software PRESTO was used to do a RFI analysis. The RFI identification process involved dividing the data into 0.5 s long intervals, and doing a statistical analysis in time as well as frequency domains to find and list the outliers above specified thresholds in the two domains. This analysis results in a mask that can be applied to data to exclude the RFI-contaminated parts, as well as basic statistics of the identified RFI contaminated samples and spectral channels. An example of the mask resulted from the RFI analysis for one of the data files is shown in Figure 4.

Details presented in Table 1 indicate that for the 300–500 MHz and 1300–1500 MHz bands, typical percentage of data contaminated by RFI is 5–10%, however, this fraction can reach to 30–40% during peak RFI times. A major fraction of this RFI is generally the 50/100 Hz interference. All the observations presented in Table 1 were conducted in day time.

The full 200 MHz bandwidth in the 100–300 MHz band is not useful, since the feed is sensitive only in the 130–250 MHz range, and even within this range 20 MHz (∼170–190 MHz) is lost due to a notch filter in the chain. For these reasons, the frequency ranges 100–140 MHz, 170–190 MHz, and 240–260 MHz were manually masked in the above RFI analysis. So, nearly 60% of the 100–

Table 1. Summary of observations and RFI statistics

Sr. No.	PSR Name	Date	Frequency (MHz)	Duration (minutes)	RFI-contaminated (percentage)	Pulsar detected (Yes/No)
1	B0329+54	Dec. 20, 2015	300–500	5	6.1	Yes
			1300–1500	5	2.3	Yes
		Jan. 08, 2016	100–300	5	61.8‡	Yes
			300–500	5	28.8	Yes
			591–624	5	32.4	Yes
2	J0341+5711†	Jan. 08, 2016	100–300	5	61.7	No
			300–500	5	5.9	No
			591–624	5	7.5	No
3	B0531+21	Jan. 08, 2016	300–500	5	2.8	50% Data-loss Recorded in high time resolution — nearly 50% data-slips
			591–624	5	7.3	Yes
4	B1737−39	Dec. 20, 2015	300–500	15	2.1	Yes
			1300–1500	15	2.5	Yes
5	B1911−04	Dec. 20, 2015	300–500	30	2.0	Yes
			1300–1500	30	4.9	Yes
6	B1929+20	Dec. 20, 2015	300–500	33	2.1	Yes
			1300–1500	33	2.4	Yes
7	J2043+7045†	Jan. 08, 2016	100–300	25	62.0‡	No
			300–500	25	6.2	No
			591–624	25	7.6	No
8	J2238+6021†	Jan. 08, 2016	100–300	15	62.0‡	No
			300–500	15	5.0	No
			591–624	15	7.5	No
9	J2302+6028	Jan. 08, 2016	100–300	20	61.8‡	No
			300–500	20	13.1	Yes
			591–624	20	8.0	Yes
10	B2319+60	Jan. 08, 2016	100–300	2	61.2‡	No
			300–500	2	3.5	Yes
			591–624	2	7.3	Yes

†For these pulsars, timing solutions as well as their exact sky-positions are not available. Hence, some or all of these pulsars might get detected in a blind search of these data.

‡The high percentage of RFI contaminated data in the 100–300 MHz band is due to manual masking, see the relevant text for more details.

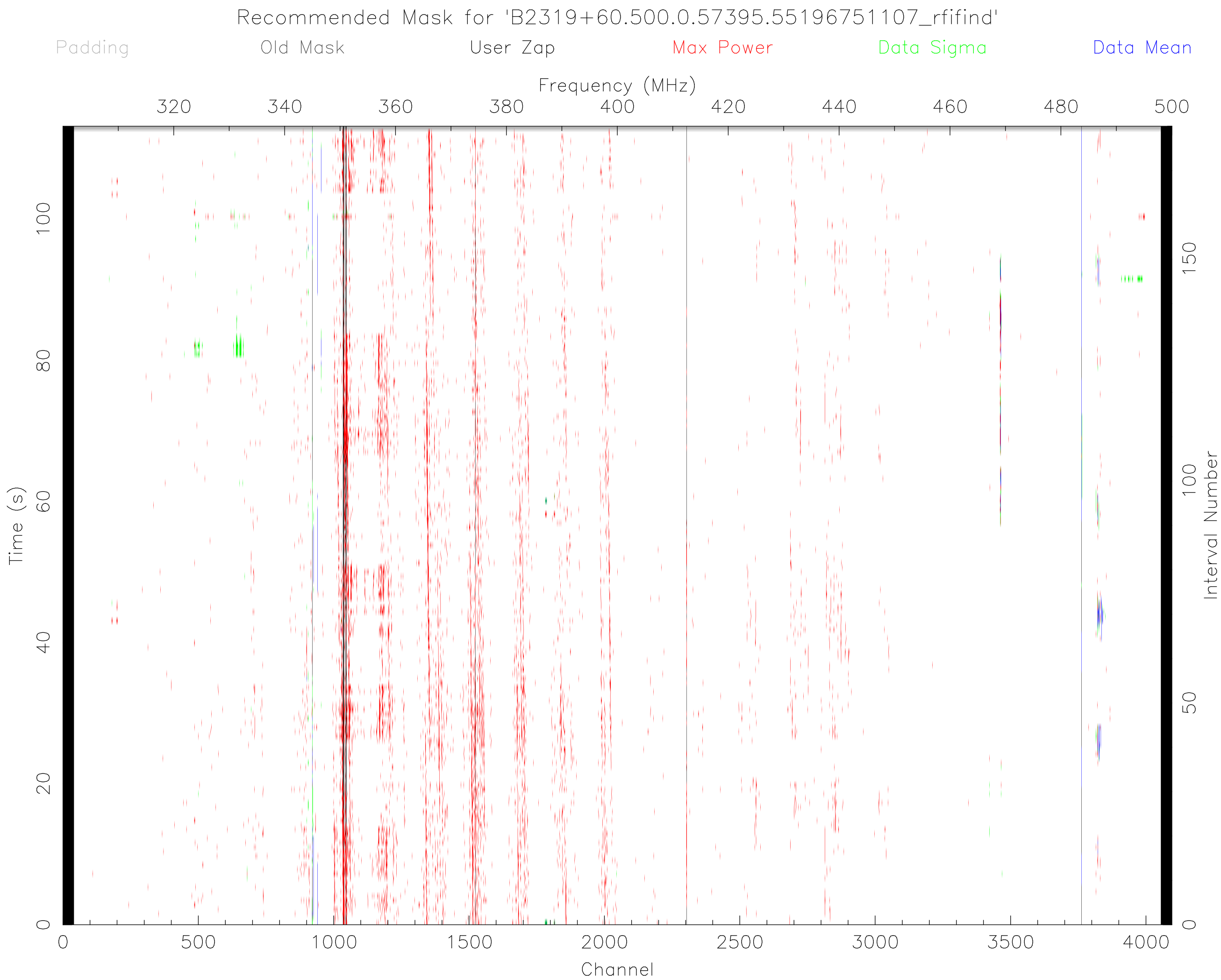

Figure 4 — Example of a RFI-mask to be applied to data. The colored parts in the shown time–frequency domain are identified to be RFI-contaminated. The black color corresponds to user-specified mask, the red color corresponds to 50/100 Hz or similar interference, the green and blue colors correspond to spiky RFIs.

300 MHz band data were manually masked. Hence, the high percentages (more than 60%) of 100–300 MHz band data marked as RFI contaminated in Table 1 is primarily due to the manual masking of the unusable parts of the band. Quantifying the actual RFI-contaminated percentage of data from the rest of the band requires more careful analysis than presented here.

5 Feedback and Recommendations

1. The observatory should develop a **single command interface** for starting pulsar and LTA acquisition in multiple subarrays and GSB and GWB simultaneously (e.g., a command named as "strtnmfsubarr"). This is important primarily because of the following reasons.

    (a) The pointing has to be done "manually", and one by one for different subarrays. The results of pointing scans are analyzed in tax, and then the deduced pointing offsets have to be incorporated "manually", making this process to be quite time consuming.

    (b) More importantly, the above approach which requires a lot of manual interference, is highly prone to human errors, and hence, to reduction in final achievable sensitivity.

    Additionally, the above procedure of manual pointing leads to considerable stress on operators, particularly in the night shift.

2. A similar single command system based on GUI is required for faster simultaneous set up of IF, LO etc.

3. The acquisition client — one of the several GWB client processes (viz., the acquisition client, communication between the online and correlator client, the buffer client and the LTA-file record client) — gets killed on its own many times. It was noted that many of such incidences had followed just after issuing the command either to start dumping data in the buffer or to start recording in the pulsar-observing mode.

4. Power equalize and phasing schemes were tested and work OK and, are generally reasonably fast.

5. A hierarchical system with large acquisition disk space backed by a hierarchy of two level NAS systems with increasing capacities connected by 10 Gigabyte Ethernet network is needed to cope up with the pulsar data in general and multi-subarray observations in particular, which the observatory should procure and commission.

6. Using 2 beams of GWB at different frequencies requires 2 different LOs, if both LOs need to be set below 600 MHz. This setup currently poses limitations in using the 130–260 MHz and 250–500 MHz bands simultaneously. For our observations, a separate signal generator was used to facilitate an additional LO.

7. Using the 2 beams of GWB in 2 different frequency bands constrains to use the same bandwidth and same number of channels in both the bands. This amounts to unnecessary overuse of resources, e.g., when sampling a bandwidth of 200 MHz to utilize the only 80–100 MHz bandwidth usable in the 130–260 MHz band. This limitation can be broadly resolved if a provision of recording only a limited part of the sampled bandwidth can be provided.

8. Phasing of the 130–260 MHz band using the currently available antennas (C10, W01, E02 and S03) is stable hardly up to 10 minutes. An on-the-fly phasing scheme is essential for useful observations involving arm antennas, and especially to use the full potential of the GMRT in phased-array mode.

9. Phasing of 250–500 MHz band was found to be quite stable for approximately 1 hour of time. It is to be emphasized here that only central square antennas were used for this band.

10. From pulsar science point of view, 130–260 MHz wideband feed is important, and could be a priority (compared to 550–900 MHz feed). However, more careful tests are required to assess the RFI situation, and the full sensitivity of the system, especially in this band, will be utilized only when an on-the-fly phasing mechanism becomes operational. An on-the-fly RFI excision will also be of immense importance in this band.

11. Operating the GWB appears to be simpler than operating the GSB.

6 SOP for carrying out simultaneous multi-frequency observations using multiple sub-arrays exploiting the GSB and GWB

```
 This document summarizes the procedure for carrying out simultaneous multi-
frequency observations using the two beams of the legacy system GSB (GMRT
Software Backend) at two different frequencies with 33 MHz bandwidth each
and two beams of the GWB (GMRT Wide-band Backend) at two other frequencies
with 200 MHz bandwidth each.

----------------------------------------------------------------------------
0.  Prepare a list of antennas to be used in each of the 4 sub-arrays.

    The antennas to be used with the GWB are naturally constrained to
 those which have the wide-band feed installed on them already. The maximum
 number of total antennas usable in the two sub-arrays (to be used with GWB)
 is limited to 16. The number of released antennas that have the wide-band
 feeds installed for the 130--260 MHz, 250--500 MHz and 1400 MHz bands
 are 4, 16 and 32, respectively. Prepare a list of antennas to be used in
 4 sub-arrays, keeping in mind the above technical constraints and scientific
 motivations.


----------------------------------------------------------------------------
1. Go to Correlator and GAB room, and make sure that samplers (corresponding
   to the GWB) are connected to correct (i.e, the desired) antennas in this
   room. Update these in edit preference and host machine settings menu of GSB.

----------------------------------------------------------------------------
2. Split avialable antennas in 4 subarrays (subar 2,3,4,5) and do default
   or desired settings for the 150, 325, 610 and 1390 MHz bands.
   Note that settings for two sub-arrays will correspond to the GSB, and
   those for the remaining two sub-arrays will correspond to the GWB.
   Examples of the information that the settings consist of is given below.
   ========================================================================

   Global Settings :
     Project-code : uGA.01

     Subar 2 : 250-500 MHz Wide Band
     Antenna C00 C04 C06 C08 C11 C12 S01 (= 7 antennas)
     RF : 500 MHz WBF, RF ON
     PreGAB filter : 200 MHz ?
     BB : 200 MHz, ALC Off
     Ist LO : 500  MHz
     corr mode : 16 (10s) 200 MHz 4096 TI flipped LSB gain ON fstop ON 8 bit
     GWB mode: beam1: PA  gwbh2 Total intensity  (TI)
         No of chan : 4096   Integration time : 1.3 ms (64 fft-ints)
```

```
  RF Frequency (ch1-ch4096) : 500.0 - 300.0 MHz

  Subar 3 : L Band Wide band
  Antenna C01 W03 W04 S03 S04 E03 E04 (= 7 antennas)
  RF : 1500 MHz WBF, RF ON, NG OFF, SA OFF, RF filter bypass (400 MHz)
  PreGAB filter : 200 MHz ?
  BB : 200 MHz, ALC Off
  Ist LO : 1500
  corr mode : 16 (10s) 200 MHz 4096 TI flipped LSB gain ON fstop ON 8 bit
  GWB mode: beam2: PA  gwbh3 Total intensity  (TI)
      No of chan : 4096 Int time : 1.3 ms (64 fft-integrations)
  RF Frequency (ch1-ch4096) : 1500.0 - 1300.0  MHz

  Subar 4 : 150 MHz Legacy
  Antenna C03 C05 C10 (= 3 antenna)
  RF : 150 MHz, RF ON, NG OFF, SA ON
  IF :  16 MHz, ALC Off, default atten @ 150 MHz
  BB :  32 MHz, ALC Off
  Ist LO : 207  4th LO : 51
  corr mode : Indian Polar total intensity 16s 33.333 MHz
  GSB mode: ONLINE, beam1: PA ON node33 122 us (2 fft-integration) 512 channels
  tpa  150 MHz  :   207 207 156 156 51 51
  RF Frequency (ch1-ch512) : 156.0 - 122.666 MHz

  Subar 5 : 610 MHz Legacy
  Antenna C02 C09 C14 W02 S02 E02 = (6 antenna)
  RF : 610 MHz, RF ON, NG OFF, SA OFF
  IF :  32 MHz, ALC Off, default atten @ 610 MHz
  BB :  32 MHz, ALC Off
  Ist LO : 540  4th LO : 51
  corr mode : Indian Polar total intensity 16s 33.333 MHz
  GSB mode: ONLINE, beam2: PA ON node34 122 us (2 fft-integrations) 512 channels
  tpa  Default for 540 MHz  :   540 540 591 591 51 51
  RF Frequency (ch1-ch512) : 591.0 - 624.3333 MHz
========================================================================
```

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-----------------------------------------------------------------------------
3. Rotate feeds for required 3 subarrays (assuming that one sub-array is
   already in the right frequency)

-----------------------------------------------------------------------------
4. Do pointing (manually using 30'/min scan and using self in tax) for the
   3 subarrays where feeds were rotated

   An alternative approach is to first rotate the feed to L-band for all
   the antennas, do the pointing for all the antennas, and then rotate the
   feeds of antennas in 3 sub-arrays to their desired frequencies.
```

```
------------------------------------------------------------------------------
5. Do/Re-check the required RF, LO, IF and BB settings for all the subarrays.

 ========================================================================
 (a)  Setup legacy GSB, initialise GSB in the required mode,
 (b)  Setup GAC for GSB for the two beams, setup PA mode in two beams, and
 (c)  Setup pulsar data acquistion setup in node33 and node34 for legacy subarrays.
 (d)  Note down which subarray and frequency is connected to which beam and node.
 (e)  Note down no of channels, acq bw and sampling time.
 (f)  Start GSB.


------------------------------------------------------------------------------
6. Do/Re-check required RF, LO, BB settings for wideband subarrays

 ========================================================================
 (a) Setup GWB, initialise GWB in the required mode,
 (b) Setup GAC for GWB for two beams, setup PA mode in two beams, and
 (c) Setup pulsar data acquistion setup in gwbh2 and gwbh3 for wideband subarrays.
 (d) Note down which subarray and frequency is connected to which beam and host.
 (e) Note down no. of channels, acq bw and sampling time.
 (f) Start GWB.


------------------------------------------------------------------------------
7. Check bandshapes Corresponding to frequencies of all the 4 subarrays.


------------------------------------------------------------------------------
8.  Power equalize the antenna-bands for all subarrays -- first for GSB and
    then for GWB (any particular reason for this order ??)


-----------------------------------------------------------------------------
9.  Go to Cal source and check fringes on all subarrays.


-----------------------------------------------------------------------------
11. Do phasing on GSB followed by GWB. (any particular reason for this order ??)

    Remember to start the scan before phasing in each subarray otherwise
    it will not phase. During phasing follow the sequence -- for 2 subarray
    in GSB/GWB, start scan, take some data first in one and then after ~10s
    delay in another. Take some records and run phase script then stop one
    and then another after about 10s.
    Apply phase and then start one and then second subarray. Doing this
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```
    sequence individually can lead to problem. However, GSB and GWB subarrays
    can be phased in parallel.


----------------------------------------------------------------------------
12. Stop scan and start 4 LTA file, one for each of the subarrays.


----------------------------------------------------------------------------
13. Conduct pulsar/calibraor observations.


----------------------------------------------------------------------------
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7 Acknowledgment

We thank the staff of GMRT in making these observations possible. A particular thanks to Nilesh Raskar on some aspects of operating procedure. We thank the members of digital backend team, led by Shri Ajith Kumar. They helped us in understanding the connectivity, required choices of LO and other issues regarding GWB. We thank Yashwant Gupta for discussions on capability of GWB.

References

Baars, J. W. M., Genzel, R., Pauliny-Toth, I. I. K., & Witzel, A. 1977, A&A, 61, 99