Chapter 25

The GMRT Correlator

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25.1 Introduction

Chapters 8 and 9 covered the basics of correlator design and implementation. Recall that there are two popular types of correlators, viz. the FX and XF types. The FX design has a number of advantages including (a) low cost, (b) digital fringe stopping and fractional delay compensation and (c) minimal closure errors. The GMRT correlator is an FX correlator. The integrated circuit (IC) used for performing the FFT and the correlation is an application specific IC (ASIC) designed by the NRAO for the VLBA correlator. This chapter provides an overview of the GMRT correlator and discusses its various modes of operation. The material is meant as a guide the correlator users (i.e. astronomers). For details of hardware implementation see Tatke (1997).

The main considerations while designing the GMRT correlator were the following:

1. *Astronomical requirement :* Briefly, the correlator should have the capability to make continuum radio maps of all the stokes parameters as well as spectral line radio maps.

2. *Radio Frequency interference :* As a low frequency telescope the GMRT is highly susceptible to man made interference. To observe weak celestial sources in the presence of strong radio frequency interference (RFI), the dynamic range of the receiver system and the correlator should be large. If the RFI spectrum is narrow band, it may also be possible to edit it out from the data if the visibility spectrum is measured with sufficiently high resolution.

3. *Cost :* The overall cost of the correlator system should be kept at a minimum.

The last two requirements favor an FX configuration. Since the FX correlator inherently measures the visibility spectrum, any narrow band RFI can be edited out. To improve the dynamic range 4-bit sampling is used.

Recall that the GMRT has 30 antennas and that each antenna provides signals in two orthogonal[1] polarizations. The maximum operating bandwidth at all frequency bands is 32 MHz, which is provided as two 16 MHz wide baseband signals (corresponding to the two sidebands) for each polarization (see Fig. 25.1). From the basic block diagram

[1]All the frequency bands of GMRT except the L band are circularly polarized. At L band two linearly polarized signals are provided.

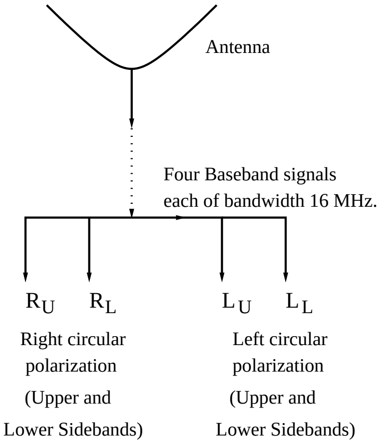

Figure 25.1: Schematic showing the four baseband outputs from each GMRT antenna. Each antenna is dual polarized and each polarization signal (which is of maximum bandwidth 32 MHz) is split into two sidebands, each of maximum bandwidth 16 MHz. At all frequencies of operation, except L band, right (R) and left (L) circular polarizations are measured. At L band two orthogonal linear polarizations are measured. The two sidebands are called the Upper Side Band (U) and Lower Side Band (L) respectively. So R_U is the upper side band of the right circular polarization, and so on.

of an FX correlator (see Fig 9.4 in Chapter 9) it is evident that the GMRT correlator should have 120 $(= 30 \times 4)$ ADCs, integral delay compensation units, number controlled oscillators, FFTs and fractional delay compensation units.

The total number of multiplier units required for the GMRT can be calculated as follows. The total number of cross products for a n element array is $n \times (n-1)/2$. If the self products are also computed then the total number of products is $n(n-1)/2+n = n(n+1)/2$. In an FX correlator these products have to be measured for each spectral channel. Since the GMRT correlator provides 256 spectral channels, the total number of multiplier units required is $n \times (n+1)/2 \times 256$. Further since, as discussed above, there are four baseband signals for each antenna, the number of multiplier units required goes up by a factor of 4. To measure all the four Stokes parameters the cross products between different polarizations need to be measured (see chapter 15), this causes the required number of multiplier units to increase by another factor of 2. Thus for $n = 30$ the total number of multipliers required is 9,52,320. However, to lower the cost and to simplify the hardware design the number of multiplier units in the GMRT correlator is only 2,38,080. To minimize the impact of this reduction in multipliers, the GMRT correlator has a a highly configurable design. Depending on the astronomical requirement the correlator can be configured to minimize the loss of information, for example in may spectral line observations it is not neccessary to measure all four stokes parameters. The following sections give an overview of the GMRT correlator and also discuss these different correlator configurations.

25.2 An overview of the GMRT Correlator

A simplified block diagram of the GMRT correlator is shown in Fig. 25.2. The basic units are the analog to digital converters (ADC), the Integral Delay compensation (Delay-DPC) subsystem, the Fourier transform and fractional delay compensation (FFT) subsystem and the multiplier-accumulator (MAC) unit. The data from the MAC output is acquired

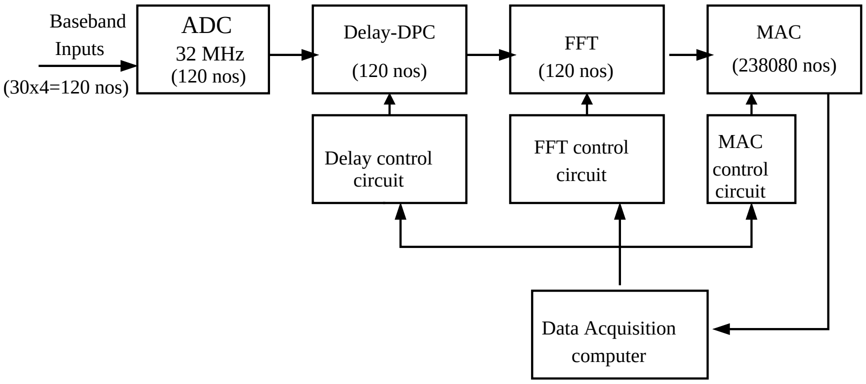

Figure 25.2: A simplified block diagram of the GMRT correlator

using a special purpose PC add on card. All of the subsystems, except the ADC, have DSP (digital signal processor) based control circuits. These control circuits are in turn controlled by the data acquisition computer, (i.e. the same machine which acquires the data via the add on card; see Chapter 26 for more details).

25.2.1 ADC

The GMRT correlator uses 6 bit, uniform quantization ADCs. The ADCs are designed such that a Gaussian random signal of 0 dBm power will have minimum distortion (see Chapter 8) and operate at a fixed clock frequency of 32 MHz. This means that when the input signal has a bandwidth of 16 MHz the digitized signal is Nyquist sampled. However at the GMRT, the input signal could have a bandwidth less than 16 MHz[2], for these signals the Delay-DPC effectively resamples the digitized signal so that down stream of the Delay-DPC unit the signal is Nyquist sampled.

25.2.2 Delay-DPC

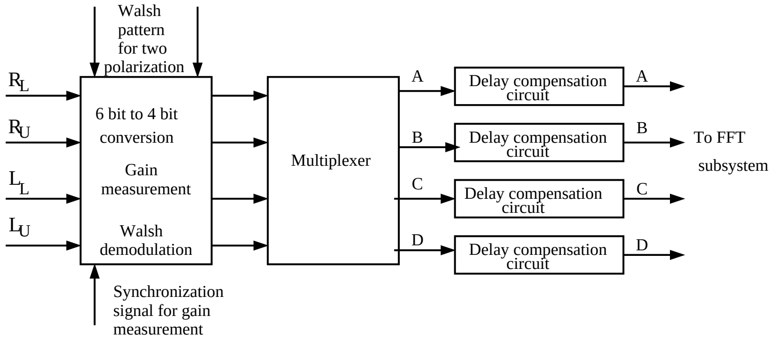

Figure 25.3: Block diagram of the delay-DPC unit of the GMRT correlator

The block diagram of the delay and data preparation card (delay-DPC) is shown in Fig. 25.3. Each basic unit of the delay-DPC takes the four outputs of ADCs corresponding

[2]Available bandwidths go from 64 kHz to 16 MHz in steps of 2, (see also Chapter 23).

to (see Fig 25.1) the signals R_U, R_L, L_U and L_L from a given antenna. These 6 bit quantized signals are rounded off to 4 bits and then sent to a multiplexer. The multiplexer has various modes; for example any one of the four inputs of the multiplexer can be mapped to all four of its outputs (A, B, C, D in Fig. 25.3). Other mappings include (a) $A = R_L$, $B = L_L$, $C = L_L$, $D = R_L$, and (b) $A = R_U$, $B = L_U$, $C = L_U$, $D = R_U$, which are used for polarization observations with the correlator. The multiplexer outputs are passed through a memory based integral delay compensation circuit (see Chapter 9). The delay compensated outputs are then fed to the FFT subsystem.

The rate at which data is written to the memory in the dly-DPC card is tunable. In particular it can be any one of $32/2^k$ MHz, where $k = 0$ to $k = 7$. This rate is chosen to be the Nyquist rate for the input signal bandwidth, i.e. for bandwidths smaller than 16 MHz, the rate is less than 32 MHz. However, the data is always read out at a constant rate of 32 MHz[3]. To maintain the data throughput, data from the memory hence has to be read out in an 'overlapping' fashion. This way of reading the data provides the facility to perform 'overlapping' FFTs (and hence an improvement in the signal to noise ratio) when the input bandwidth is less than 16 MHz.

The two other functions of the delay-DPC system are (a) gain measurement (b) Walsh demodulation.

25.2.3 FFT

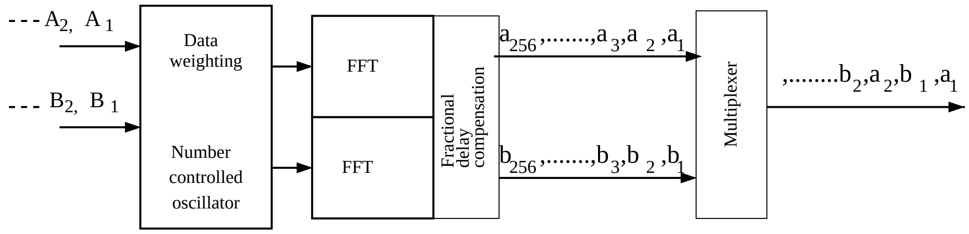

Figure 25.4: Block diagram of the FFT unit of the GMRT correlator

The block diagram of the FFT subsystem is shown in Fig. 25.4. The basic unit of the FFT subsystem takes two data streams (either A,B or C,D in Fig. 25.3) from the Delay-DPC. In the first stage, a weighting function can be applied to the 4 bit time series. The weighting function is software selectable, and can be chosen to be one of the standward "window functions" discussed in Chapter 8. This is followed by a number controlled oscillator (NCO), which does the fringe stopping (see Chapter 9). The two fringe stopped time series are passed through two sets of FFT engines, realized using VLBA ASICs, to perform Fourier transforms. Phase gradients are then applied to the spectrum of the signal to correct for delays smaller than the sampling interval (FSTC).

Each FFT engine can perform a Fourier transforms of maximal length 512 points. This length is software selectable to be 256, 128 or 16 points; it is even possible to bypass the FFT operation altogether. A 512 point FFT gives 256 channels, however in the next stage of the correlator (MAC) there are only enough multipliers for 128 channels per sideband per polarization. In the standard mode of operation, two adjacent FFT channels are hence averaged together in the MAC. A single MAC also acquires data from two FFT engines in a time multiplexed fashion. The data is multiplexed as shown in Fig. 25.4, where a_i and b_i are the spectral channels from the two FFT engines.

[3]In the final correlator it will be at 32.25 MHz.

25.2.4 MAC

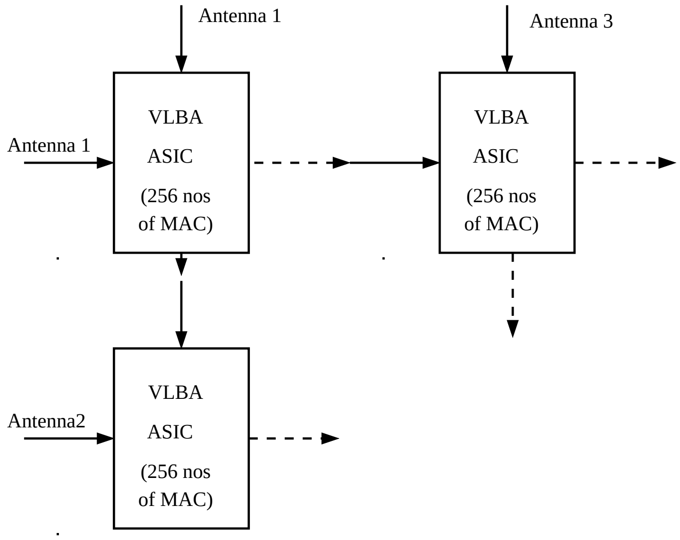

Figure 25.5: Block diagram of the Multiplier-Accumulator (MAC) unit for the GMRT correlator

The Multiplier and Accumulator (MAC) is, hardware wise, the most complex subsystem of the correlator. The MAC takes the FFT outputs computes the cross and self products and accumulates them for a maximum of 128 ms and a minimum of 4 ms. A schematic of the configuration of the multipliers is shown in Fig 25.5. Each MAC unit consists of 256 accumulators. The MAC can be configured in several different modes. As described in more detail below this flexibility allows the GMRT corrrelator to be used to make a wide variety of observations. Data from the MAC unit is read out by the Data Acquisition System (DAS) using a special purpose add on card on a PC (see Chapter 26 for more details).

25.3 Modes of operation of the GMRT correlator

As mentioned above the total number of multipliers available in the correlator is less than that required for the measurement of all four stokes parameters in all spectral channels for all sidebands of all antennas. Instead ,the correlator is configurable in various ways. Some configurations would sacrifice polarization measurements for improved spectral resolution, while others allow the measurement of all four stokes parameters at the expense of total bandwidth. The most commonly used configurations of the correlator are described in some more detail below.

25.3.1 Non-Polar Mode

In this mode of observation the visibility for only one of the two polarizations can be measured in each of 256 spectral channels for all baselines (including self correlations). The maximum bandwidth possible is 2×16 MHz. Thus the observation will have half the total sensitivity of the GMRT.

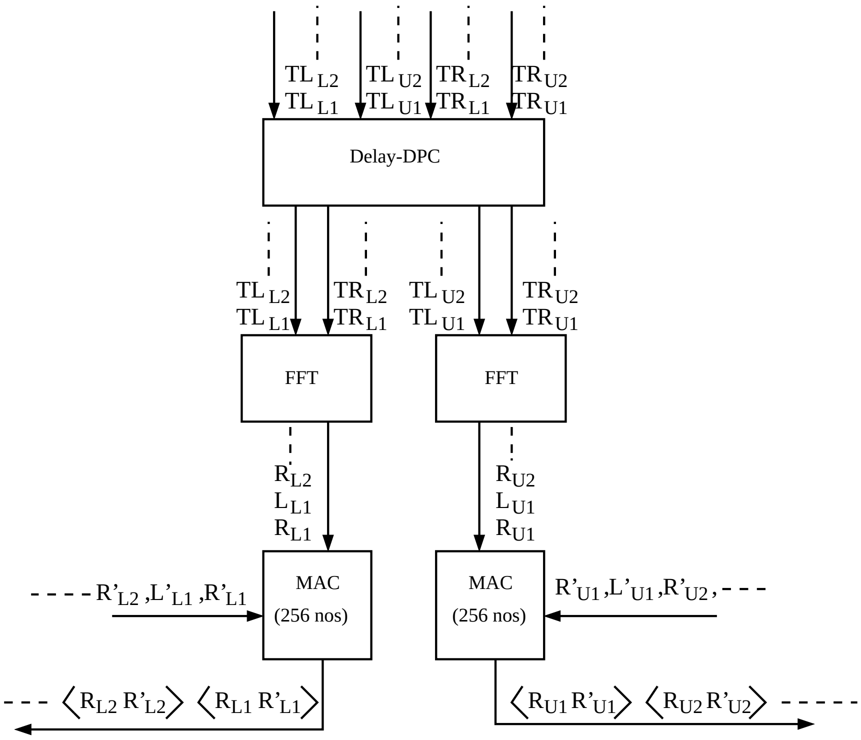

Figure 25.6: The signal flow in the GMRT correlator for the Non-Polar mode. Signal names preceding with a T indicate time series and angular brackets denote time average. Numeric subscripts indicate the sample number for time series data and the frequency channel number for spectral data.

In the non-polar mode the required sampling frequency is selected in the delay-DPC system. The multiplexer in the delay-DPC is configured such that the data flow is as shown in Fig 25.6. $TR_{Ui}, TR_{Li}, TL_{Ui}$ and TL_{Li} are the time series of the four baseband signals for a given antenna. The FFTs of these time series are R_{Ui}, R_{Li}, L_{Ui} and L_{Li} respectively (for $i = 1$ to 256). $R^{'}_{Ui}$, $L^{'}_{Ui}$ are the corresponding signals from a second antenna. The MAC mode is selected such that the 256 channels in one of the sidebands of one of the polarizations (in this case R_{Ui}) is integrated in its 256 accumulators. A second set of MACs integrate the signals from the second sideband of the same polarization (in this case R_{Li}).

25.3.2 Indian-Polar Mode

In this mode the visibility from both polarizations of all 30 antennas is measured but the number of spectral channels per baseline is limited to 128. Thus the spectral resolution is half that of the Non-Polar mode but the maximum bandwidth that can be observed in this mode is 32 MHz. Thus the observation will have the full sensitivity of the GMRT. For a non polarized source, this mode measures stokes I, and it is the most commonly used mode in interferometry.

The Delay-DPC configuration for this mode is similar to that of the Non-Polar mode. The MAC is configured (see Fig 25.7) such that the adjacent channels of the same polarization are averaged together, thus reducing the number of channels from 256 to 128.

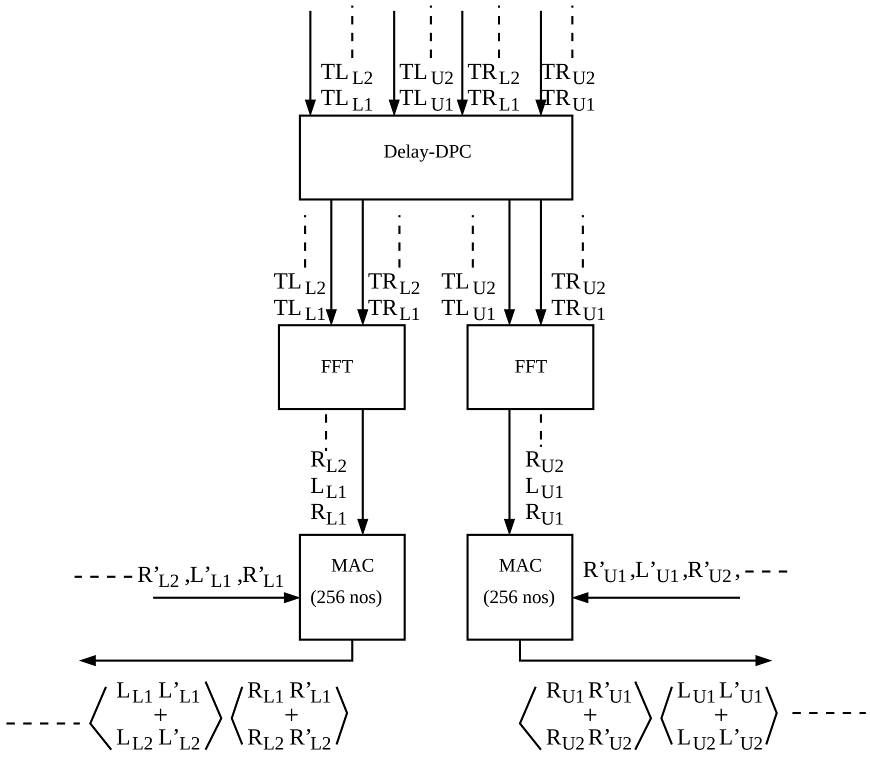

Figure 25.7: Signal flow in the GMRT correlator when it is configured in Indian-Polar mode. See the caption of Figure 25.6 for other details.

Since each MAC unit has 256 accumulators, the other 128 accumulators of the same MAC are used to integrate the data from the second polarization of the same baseline.

25.3.3 Polar Mode

All the cross products needed for measuring the four Stokes parameters (see Chapter 15) are measured in this mode. The number of channels available per baseline is again restricted to 128 and further one sideband from all 30 antennas is processed. Thus the maximum possible bandwidth in the Polar Mode is 16 MHz, as opposed to 32 MHz in the Indian Polar mode (which measures Stokes I for unpolarized sources), and the spectral resolution is also half of the maximum possible in the Indian Polar Mode.

The delay-DPC multiplexer is configured so that the data flow will be as shown in Fig 25.8. The data from one side band for both polarizations (in this case R_{Ui}, L_{Ui}) is multiplexed to get the required data sequences. The MAC is configured in the polar mode such that it measures the cross product of the two polarizations in addition to the cross products of a polarization with itself. Adjacent channels of the cross product of one of the polarizations (eg: $R_{Ui} \times R'_{Ui}$) are averaged and integrated in 128 accumulators of the MAC. Unlike in the Indian-Polar mode, the second set of 128 accumulators integrate the cross product of the two polarizations (eg: $R_{Ui} \times L'_{Ui}$). Similar measurements of the second polarization (i.e. in this case, $L_{Ui} \times L'_{Ui}$ and $L_{Ui} \times R'_{Ui}$) are made in the second MAC. Thus all required cross products are measured, from which, as described in Chapter 15 all four Stokes parameters of the source can be computed.

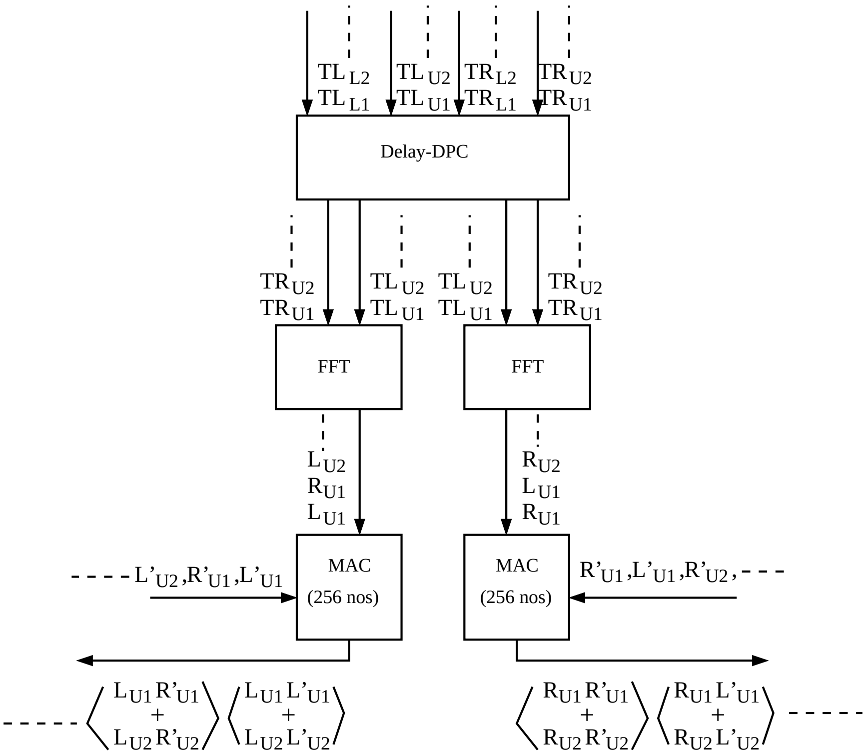

Figure 25.8: Signal flow in the GMRT correlator in the Polar Mode. Signal names preceded by a T indicate time series and angular brackets denote time average. See the caption of Figure 25.6 for other details.

25.4 Further Reading

1. Tatke, V. M., 1997, M.Sc.(Engg) Thesis, Indian Institute of Science, Bangalore.