The Mauritius Radio Telescope

You gather the idea that Mauritius was made first and then heaven and that heaven was copied after Mauritius.

Mark Twain

Chapter 2

THE MAURITIUS RADIO TELESCOPE

The Mauritius Radio Telescope (MRT) [24] is an aperture synthesis instrument built and operated jointly by the University of Mauritius (Mauritius), the Raman Research Institute (India) and the Indian Institute of Astrophysics (India). It is situated at Bras d'Eau (Latitude 20°.14 South, Longitude 57°.73 East) in the north-east of Mauritius. The primary objective of the telescope is to survey the sky at 151.5 MHz in the declination range $-70°$ to $-10°$, covering the entire 24 hours of right ascension with a point source sensitivity of $\sim$200 mJy and an angular resolution[1] of $4' \times 4'.6 \sec(\delta + 20°.14)$.

The MRT is a T-shaped non-coplanar array with 1024 helices in a 2048 m east-west arm, 15 trolleys with 4 helices each on a 880 m south arm and one trolley on a 14.5 m north arm. Figure 2.4 shows the basic layout of the MRT. The helices are mounted with a tilt of 20° towards the south. This tilt allows for a better coverage of the southern sky ($-70° \leq \delta \leq -10°$), including the southern-most part of the Galactic plane. The east-west arm is divided into 32 groups of 32 helices each. All the east-west groups are not at the

[1] FWHM (Full Width Half Maxima) of the synthesized beam is used to define the resolution.

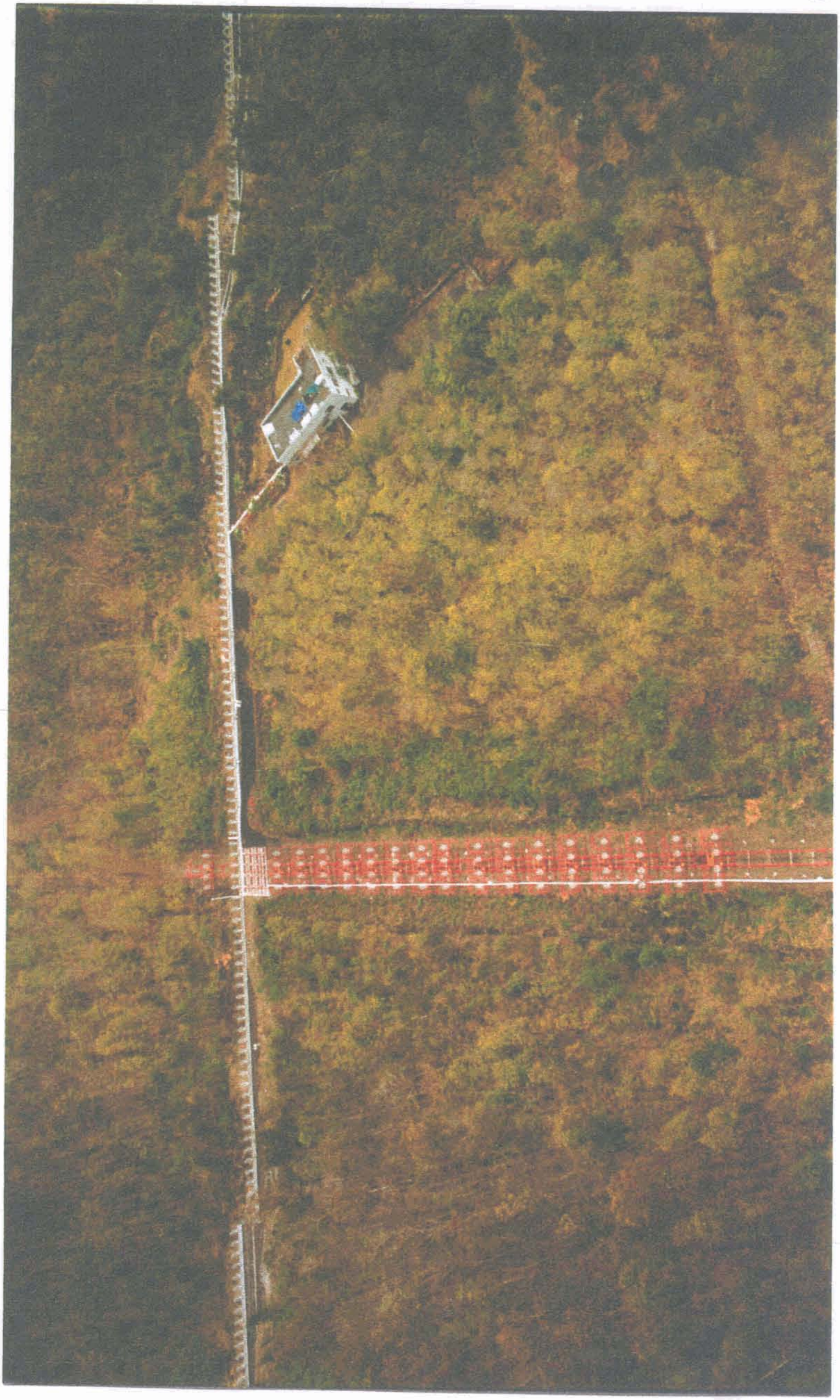

Figure 2.1: An aerial view of the Mauritius Radio Telescope. The observatory building is also seen in this picture.

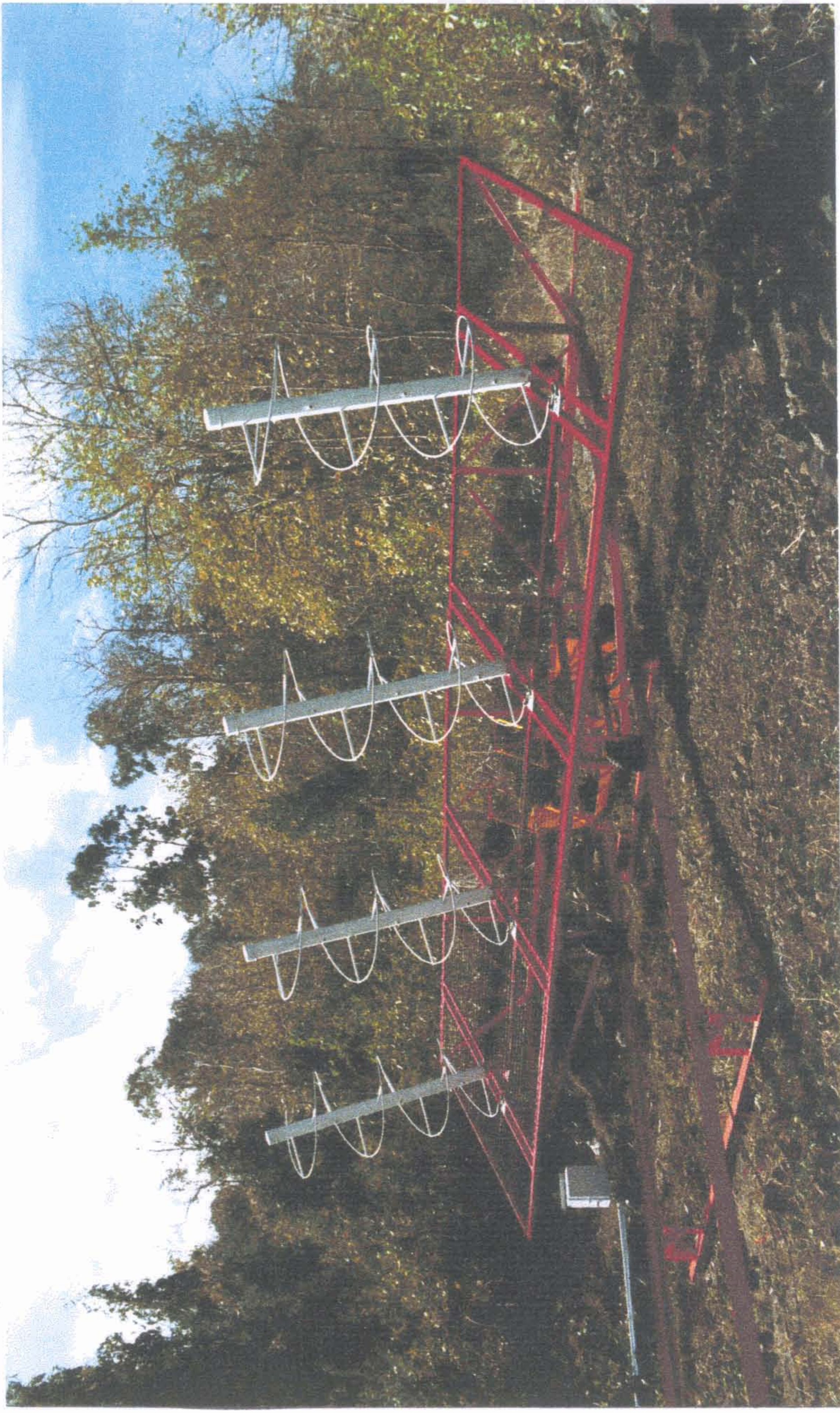

Figure 2.2: A closer view of a north-south trolley.

Figure 2.3: A view of the eastern arm. The non-coplanarity of the array is seen clearly.

same height, a situation imposed by the uneven terrain. Each trolley in the south arm constitutes one south group. Both east-west and north-south group outputs are heterodyned to an intermediate frequency (IF) of 30 MHz using a local oscillator (LO) at 121.6 MHz. The 47 group outputs are then amplified and brought separately to the observatory building via coaxial cables. In the observatory the last group of the east array is split in two for use in calibration (Section 2.2). The 48 group outputs are further amplified and down-converted to a second IF of 10.1 MHz. A 512 channel 2-bit 3-level complex correlation receiver is used to measure the visibility function. At least 60 days of observing are required for obtaining the visibilities up to the 880 m spacing. Table 2.1 summarizes the specifications of the MRT.

2.1 The front-end system

In this section we describe the characteristics of the front-end system of the MRT giving details of the primary element and of the groups in the east-west and the north-south arms along with a description of the field electronics and the local oscillator system.

Latitude	$20^\circ.14$ S
Longitude	$57^\circ.73$ E
Observing frequency	151.5 MHz .
Telescope configuration	T shaped array
East-west arm	2048 m
North-south arm	880 m
Basic element	helical antenna
Polarization	right circular
FWHM of helix	60"
Declination coverage	-70° to -10°
Collecting area of a helix	4 m^2 at 150 MHz
East-west arm	32 groups with 32 helices each
North-south arm	16 trolleys, each with 4 helices
1^{st} IF frequency	30 MHz
2^{nd} IF frequency	10.1 MHz
Instrumental bandwidths	0.15, 1.0, 1.5, 3.0 MHz
Digitization before correlation	2-bit 3-level, 1-bit 2-level
Correlation receiver	32 x 16 complex correlators
No of baselines measured per day	32 x 16
Collecting area per baseline (1 EW x 1 NS)	90 m^2
Sensitivity per baseline	30 Jy(τ=1 s, $\Delta\nu$ =1 MHz)
Minimum and maximum baselines	0, 661 λ
Time to get full resolution image	60 days
Synthesized beam-width	$4' \times 4'.6 \sec(\delta + 20^\circ.14)$
Point source sensitivity	200 mJy (3σ)

Table 2.1: Specifications of the MRT.

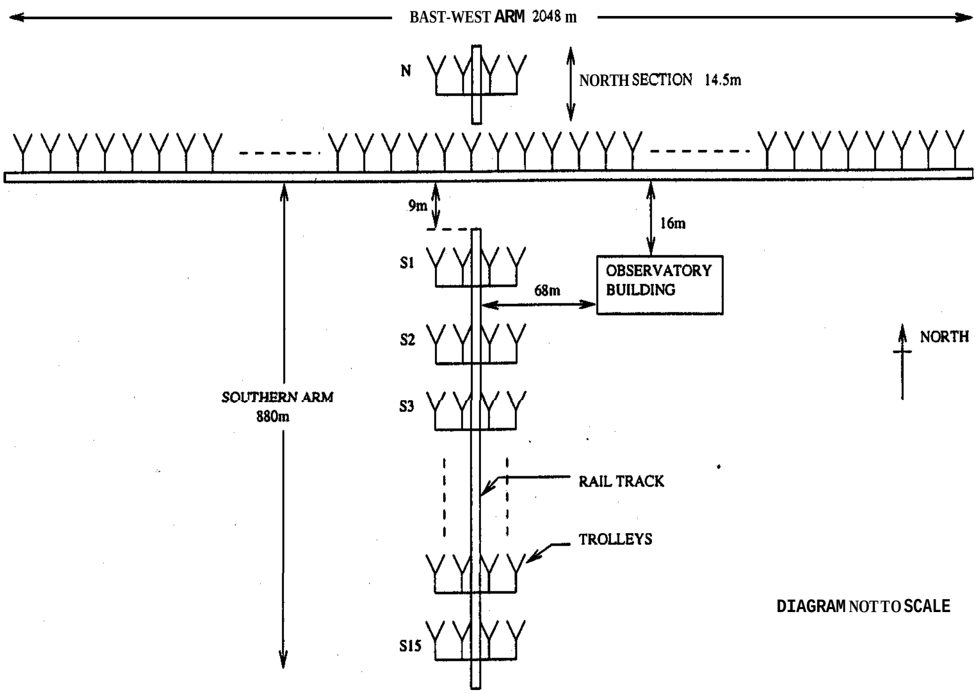

Figure 2.4: Basic layout of the Mauritius Radio Telescope.

2.1.1 The MRT primary element: Helix

The primary element of the array is a helix [25] [26] [27]. Four helices are combined to form the basic unit of the array. A helix was chosen for the MRT because of the following characteristics of this antenna:

a.) It has a large primary beam and would therefore allow imaging of a large declination range.

b.) It has a broadband response (80 MHz - 220 MHz) and therefore gives the option of observing at another frequency in the future.

c.) It has circular polarization and the observed source intensities are unaffected by Faraday rotation in the intervening medium including the local ionosphere.

d.) It is robust and can withstand wind speeds of up to 200 km/hr (required to withstand cyclone conditions in Mauritius).

e.) It is relatively inexpensive to manufacture.

f.) It is easy to install.

The MRT helix is a peripherally fed monofilar[2] axial mode helix of *3* turns with a diameter of *0.75* m and a height of *1.75* m. Figure *2.6* shows the schematic of a MRT helix along with its parameters. The helix is wound using a *1.5* cm diameter round aluminum tubing supported on a central **UV**[3] stabilized **PVC**[4] tube with radial **PVC** rods. It is mounted above a stainless steel reflector mesh of grid size *5* cmx *5* cm which acts as the ground plane. The helix has a broadband response *(80* MHz - *220* MHz). The terminal resistance[5] at *151.5* MHz is about *137* R. The impedance matching of the helix to a *50* R cable can be achieved over a broadband by bringing the last $\frac{1}{4}$-**turn** of the helix parallel to the ground in a gradual manner [29]. However, this tapering has not been done on the MRT helix. We tried matching the helix to a *50* Ω cable by adjusting the distance of the mesh from the last 1/4 turn before the feed. Although this method produced reasonable matching, it was not reliable because, over time, the mesh tends to sag, thereby reducing the matching. Finally, a quarter wave impedance transformer was used which was less sensitive to small variations in the distance of the mesh. However, this limits the use of the helix to a narrow range of frequencies around *151* MHz. The impedance of the quarter-wave transformer (Z_{qw}) required to match an antenna with terminal impedance $Z_{antenna}$ to a cable of characteristic impedance Z_{cable} is given by [27]:

$$Z_{qw} = \sqrt{Z_{cable} Z_{antenna}} \tag{2.1}$$

For matching a helix having a terminal impedance of *137* Ω to a cable

[2]Monofilar=unifilar=single wire=single conductor (terms used to distinguish one-wire helix from helices with 2 or more wires).

[3]Ultra-Violet

[4]Poly-Vinyl Chloride

[5]Given by Baker [28] to within 10% as $\frac{150}{\sqrt{C_\lambda}}$ for helices with peripheral feeds.

with a characteristic impedance of **50** *52,* a quarter-wave transformer of **83** Ω is required. We used a coaxial cable of **75** Ω and empirically trimmed its length until a VSWR of around **1.1** was achieved.

All the helices in the field were tested by measuring the VSWR of the groups of **4** helices which are combined together. A test signal from a Network Analyzer was fed into the 4-way combined output and the return loss was measured. The matching of each helix to **50** *52* was tested by shorting its feed to ground and comparing it to the signature of a group of well matched helices. The VSWR was adjusted by basically adjusting the height of the last quarter-turn of the helix using an insulator stub attached to the feed plate and by improving the soldering in some cases. A typical plot of return loss with frequency is shown in Figure **2.5.** We were able to tune all the helices to have a VSWR of less than **1.4** with most being close to **1.2.**

An approximate normalized far field voltage response in the direction ϕ for an axial mode helix is given by [27]

$$V(\phi) = \left(\left(\sin \frac{90^\circ}{n}\right) \frac{\sin(n\psi/2)}{\sin(\psi/2)} \cos \phi\right) \tag{2.2}$$

where ϕ is the angle from the helix axis, **n** is the number of turns and $\psi = 2\pi[S_\lambda(1 - \cos \phi) + (1/2n)]$, where S_λ is the spacing between the turns in units of wavelength.

The theoretical power pattern $V^2(\phi)$ of the MRT helix, is plotted in Figure **2.7.** The helical antenna is expected to have a collecting area of about λ^2 (**4** m^2 at **151.5** MHz) with a FWHM of about 60°.

2.1.2 The east-west arm

The **1024** helices in the east-west arm are divided into **32** groups, each with **32** helices. Due to the uneven terrain these groups are not coplanar and have a

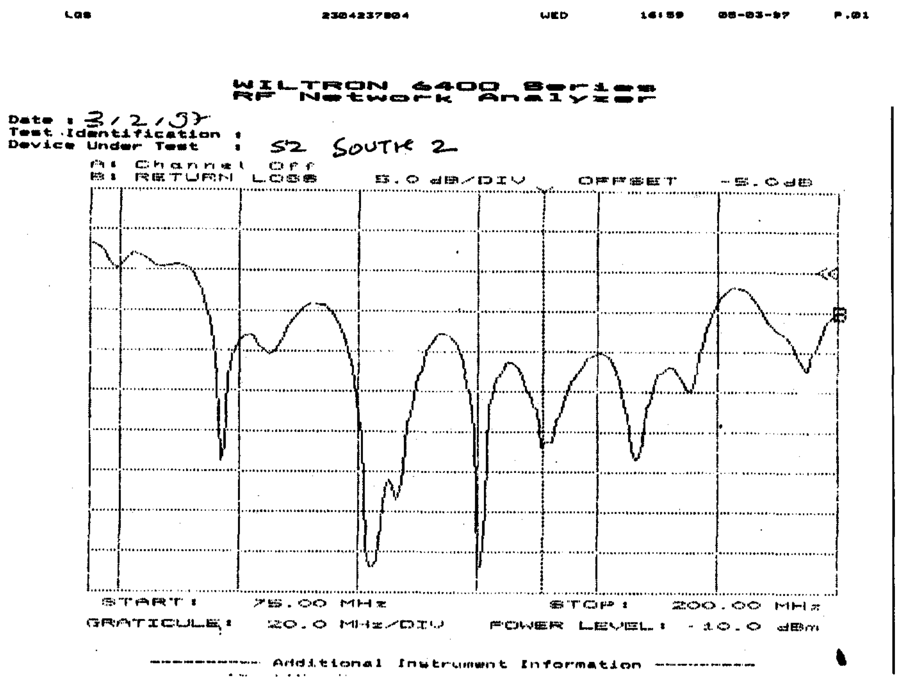

Figure **2.5:** Typical return-loss from a group of four helices. The x-axis represent the RF frequency from **75 MHz** to **200 MHz.** The y-axis ranges from **-45** dB to **+5** dB and represents the return loss.

maximum height difference of 35 m. Figure **2.8** shows the height profile of the east-west arm.

Each group in the east-west arm is 64 m wide and comprises of **32** helices. They are mounted on a **2** m x 64 m ground plane with an inter-element spacing of **2** m. In each group, four helices are combined using a 4-way power-combiner and the output is high-pass filtered and amplified in a pre-filter amplifier unit. The noise temperature of the first amplifier is aoout **270** K. The total attenuation between the helix and the amplifier is about 1 dB (0.1 dB loss in the cable, 0.4 dB insertion loss in the 4-way combiner and **0.5** dB insertion loss in the pre-filter) and therefore the system temperature is deteriorated[6] to about

[6]The noise temperature of the receiver-transmission line, T_{RT} is given *by* [3]:
$T_{RT} = (\frac{1}{\epsilon} - 1)T_{LP} + \frac{1}{\epsilon}T_R$
Where ϵ is the transmission-efficiency coefficient, $0 \leq \epsilon \leq 1$, T_{LP} is the physical temperature of the transmission line. and T_R is the noise temperature of the receiver. For 1 dB

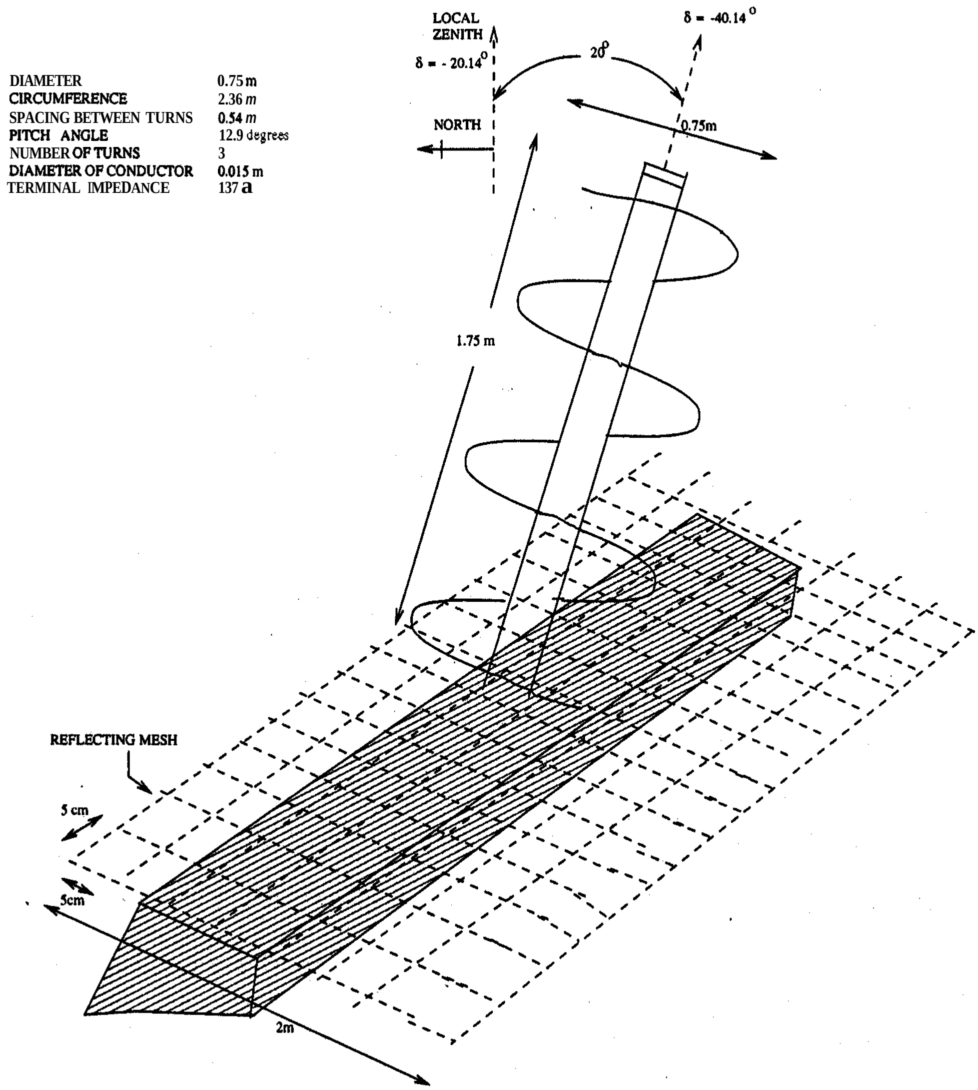

Figure 2.6: A schematic of the MRT Helix: The MRT helix is a peripherally fed monofilar axial mode helix of **3** turns with a diameter of 0.75 m and a height of 1.75 m. The helices are mounted with a tilt of **20°** towards the south.

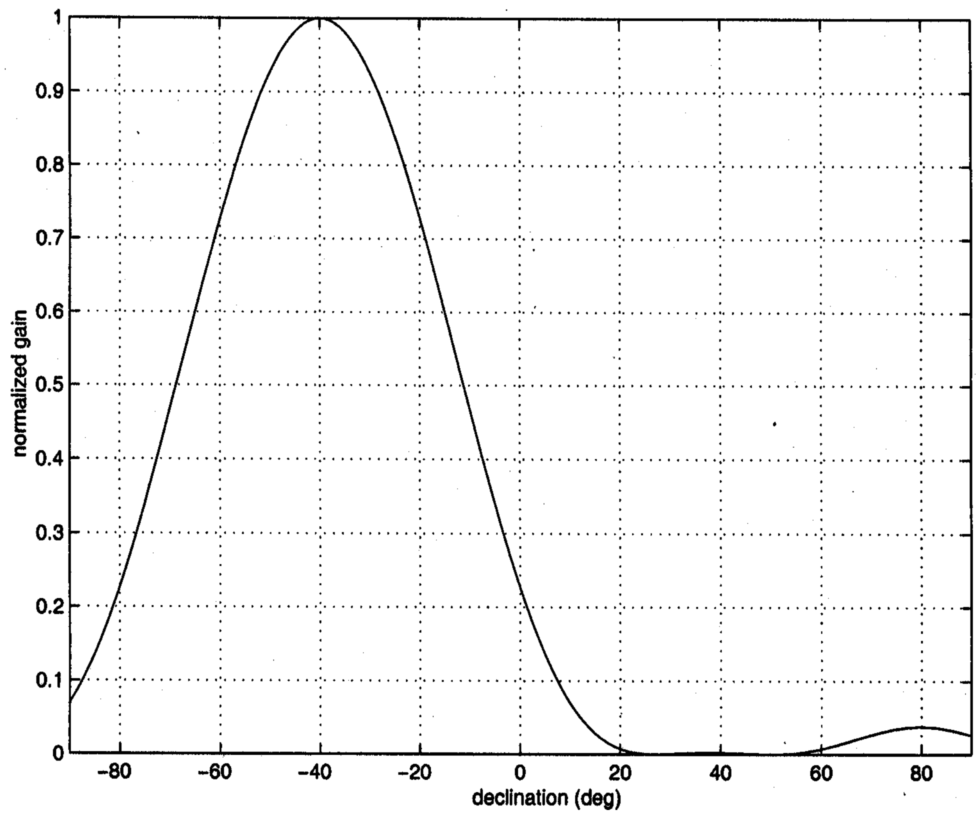

Figure 2.7: The theoretical primary beamshape of the helix. The FWHM is about 60°.

400 K. Eight pre-filter amplifier unit'outputs are further combined in an 8-way power-combiner to produce a combined group output. This signal is then sent to the mixer box wherein after band pass filtering (by a combination of high-pass and low-pass filters), the signal is heterodyned to 30 MHz using an LO of 121.6 MHz. The heterodyned signal is then passed through a bandpass filter centered at 30 MHz and amplified. The net gain of the mixer unit is typically 12 dB. The output of the mixer unit is further amplified by about 36 dB before being transmitted to the laboratory via a 1050 m coaxial cable in the eastern arm and a 1100 m coaxial cable in the western arm with an attenuation of ~35 dB at 30 MHz. Approximately equal lengths of cables have been used

attenuation, $\epsilon = \frac{1}{10^{\frac{1}{10}}} = 0.794$. Therefore, $T_{RT} = (\frac{1}{0.794} - 1) \times 290 + \frac{1}{0.794} \times 270 \approx 414$ K.

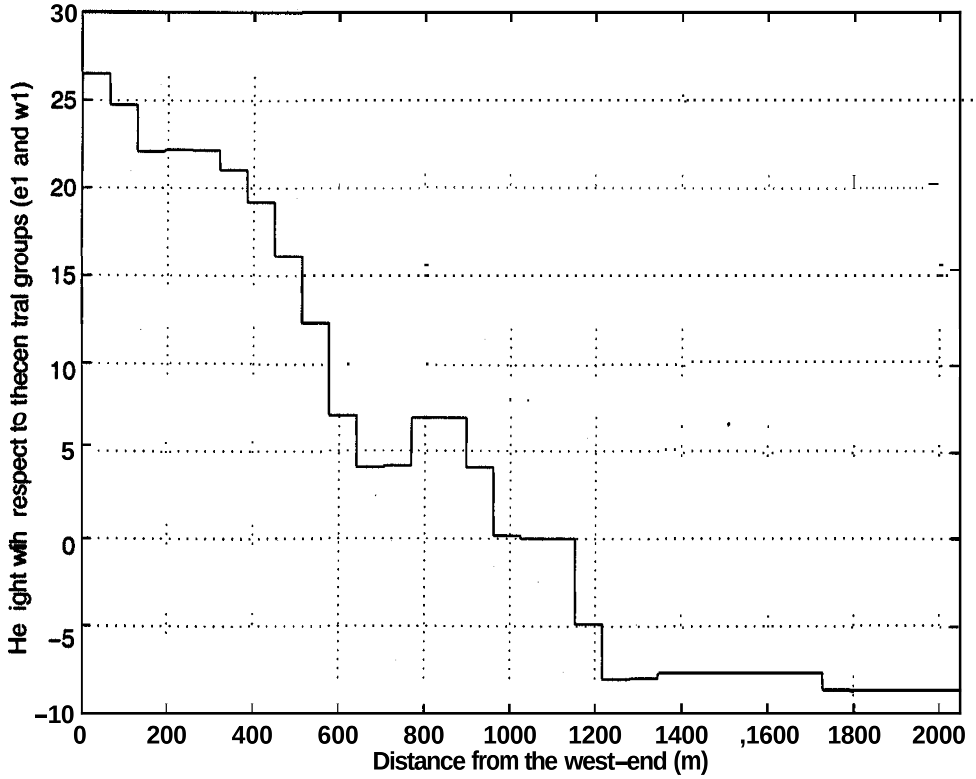

Figure 2.8: The east-west height profile. Due to the uneven terrain, all the groups in the east-west array are not at the same height. The maximum height difference in the east-west arm is 35 m.

for all the groups irrespective of their distance from the observatory. This ensures similar phase variations in all the groups due to change in the ambient temperature. The signal path of an east-west group is shown in Figure 2.10.

The far field voltage pattern of an east-west group in declination is the primary beam voltage pattern of the helix (Equation 2.2) centered at about 6 = $-40°$. In RA, the normalized voltage pattern (shown in Figure 2.9) is given by:

$$V_{EW}(\xi,\eta) = \frac{1}{N}\frac{\sin\left(\frac{N\psi}{2}\right)}{\sin\left(\frac{\psi}{2}\right)}P(\xi,\eta) \tag{2.3}$$

where $\psi = 2\pi\frac{2}{\lambda}\xi = 2\pi\frac{2}{\lambda}\sin \mathrm{H}\cos\delta$, $P(\xi, \mathrm{q})$ is the primary beam response

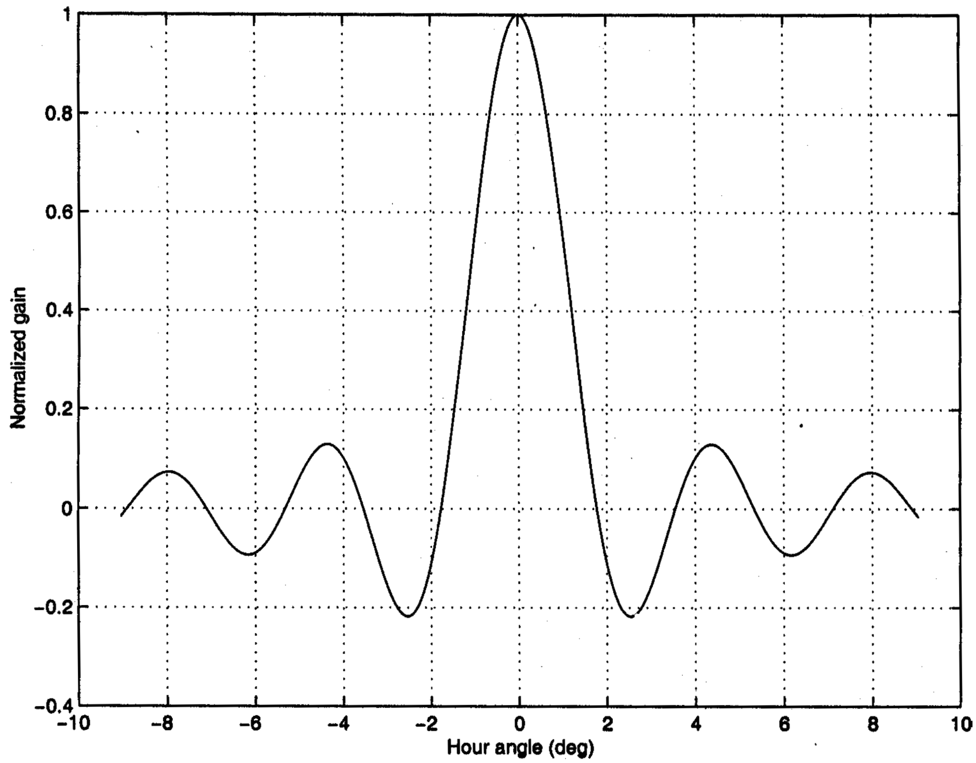

Figure **2.9:** The normalized voltage pattern of an east-west group as a function of hour angle.

of the helix and N = **32.** Thus the far-field primary beam voltage pattern of an east-west group has a FWHM of about **2**" x **60°**.

2.1.3 The north-south arm

The north-south arm consists of **15** movable trolleys. The south track starts at a distance of **9** m from the east-west arm and the closest that the helices on a trolley can get to the east-west arm is 11 m due to the physical size of the trolleys. The south track has a downward slope of $\frac{1}{2}^{\circ}$ till the **655** m mark and from there onwards it has an upward slope of **1°.** Since the south arm cannot approach the east-west array closer than **9** m, the north arm has been constructed which allows measurements down to **2** m spacing. The north rail track is **14.5** m long and is flat. The slope profile of the north-south arm is

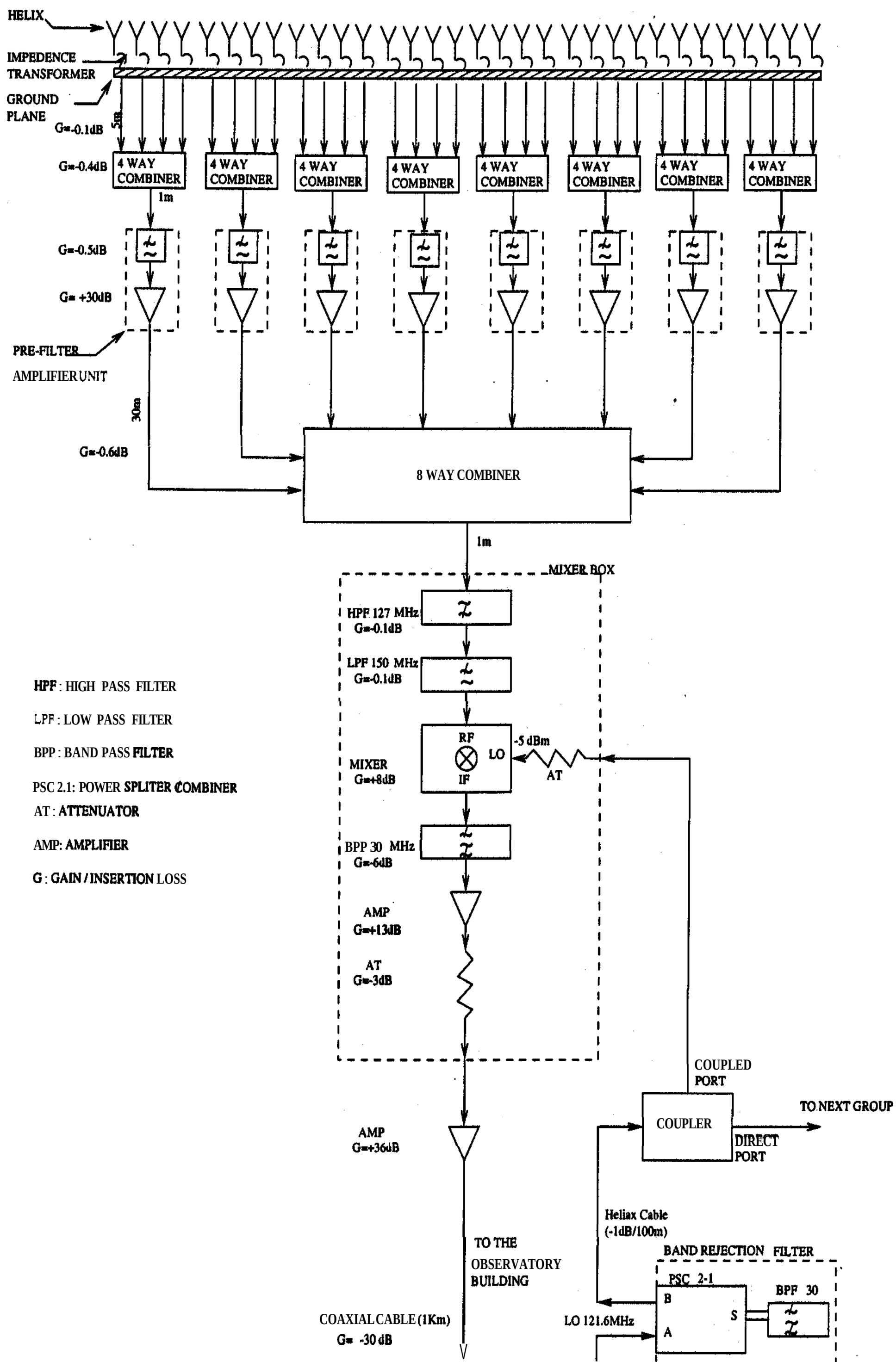

Figure 2.10: Signal path of an east-west group. The north-south trolley has a similar signal path except that there are only 4 antennas and 1 pre-filter unit.

shown in Figure 2.11.

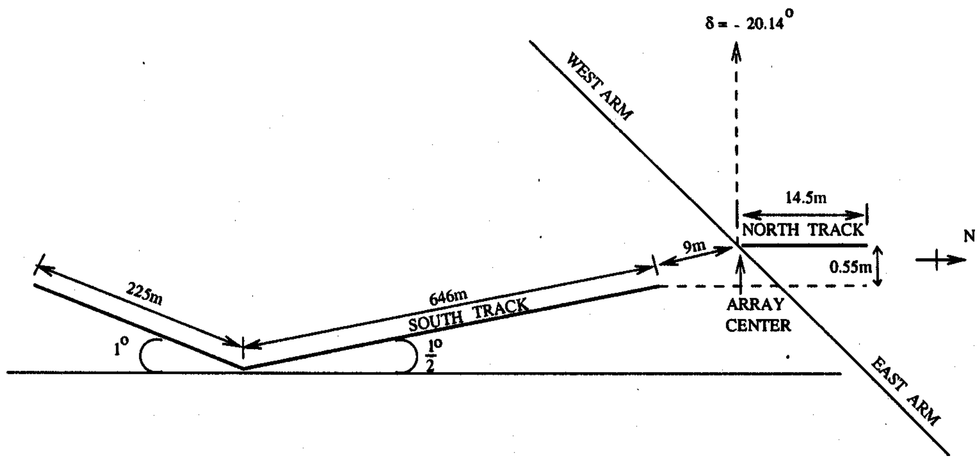

Figure 2.11: North-south slope profile: The south track has a downward slope of $\frac{1}{2}^{\circ}$ till about the 655 m mark and from there onwards it has an upward slope of 1°. The north track is flat.

Four helices mounted on a trolley with a 8 m x 4 m ground plane constitutes a group in the north-south arm. The signals from the four helices are combined using a 4-way power-combiner and the output is high-pass filtered and amplified in a pre-filter unit. With the loss between the helix and the pre-filter unit being around 1 dB the receiver noise temperature is about 400 K. The combined signal is then sent to the mixer unit where it is filtered, heterodyned and amplified in the same way as in an east-west group and is then transmitted to the laboratory using a coaxial cable of about 1000 m. Depending on the distance from the center of the south arm, a part of these IF cables are rolled on to a spool attached to the trolley.

The far field voltage pattern of a north-south group in declination is the same as the primary beam voltage pattern of the helix (Equation 2.2) centered at $\delta = -40^{\circ}$, while in R.A, it is given by Equation 2.3 with N=4. Thus the far-field voltage pattern of a north-south group has a FWHM of about 15° x 60°.

2.1.4 Local oscillator: Distribution and phase switching

Heliax cables running parallel to the east, west and south arms of the array are used to distribute the local oscillator (LO) signal required for heterodyning. Heliax is a low loss cable (-2.4 dB /100 m at 121.6 MHz) and has a better EMI shielding than braided cables like RG 274U. At each group, the LO signal is tapped by using directional couplers. To maintain a power level of typically -5 dBm in all the groups, amplifiers are placed at several places along the heliax cable and suitable attenuators are used in the individual mixer units. .Spectral impurities around 30 MHz from the LO synthesizer and from the LO amplifiers leak to the IF port of the mixers and cause spurious correlations. These effects are minimized by using band-elimination filters centered around 30 MHz at the output of the LO amplifiers[7].

The local oscillator to the three arms are phase switched $(0/\pi)$ to reduce the effects of spurious pickups on the path from the field to the correlator system. Phase switching also eliminates the effects of small threshold offsets in the samplers [30]. The switching period is a reciprocal power of **2** of the integration period. Phase switching eliminates pickups which enter the signal channel at a point after the phase switch and remain constant over the switching period. The demodulation (reverse switching) is done in the samplers in synchronization with the switching in the field. For the signals which enter the signal channel before the first switching, the two phase reversals cancel one another, but the signal components entering the channel after the switching, which reverses the phase only once, are averaged to zero. The switching waveforms required for the channels being correlated must be orthogonal over the

[7]Bandpass filters centered at 30 MHz and power splitters are combined to act as band elimination filters (Figure 2.10).

integration interval. Radamacher functions[8] [16] are used where small number of switching signals are involved, as in the present case, but when a large number of them are needed, Walsh functions are used.

At the MRT, we switch the LO in the south arm with a square wave of period P_s, the LO to the west arm is switched with a period $2P_s$, whereas the east arm is left unswitched, with $P_s \approx 10$ ms.

2.2 I.F. and digital back-end system

In the observatory, the last group of the east array (E16) is fed to the correlator in the place of the 16^{th} north-south input. This gives a set of baselines formed between E16 and all the groups of the east-west arm. This helps to check the repeatability of data. These baselines with each trolley also give 31 independent closure values which are used in the calibration (Section 4.2). This mode of observing reduces the number of usable trolleys to only 15. The 48 channels are amplified, filtered and down-converted to 10 MHz (second IF). The 10 MHz outputs of each of the 32 east-west and 16 north-south channels are digitized to 2-bit 3-level samples and then fed to a 512 channel digital complex correlation receiver. A large part of this system was acquired from the Clark Lake Radio Observatory [31]. We modified and adapted the Clark Lake system for use at the MRT. We have also designed a recirculator system to enhance the capabilities of the correlator system. We will discuss the recirculator system in the next chapter. The signal path at the MRT is shown in Figure 2.12.

[8]Radamacher functions may be derived by quadrature shifts in phase and factors of two in frequency. One antenna can remain unswitched and the ratio of highest to lowest square-wave frequency is then 2^m, where m is the smallest integer that is greater than or equal to $\frac{(\text{number of antennas}-3)}{2}$. For large arrays this factor becomes inconveniently large and Walsh functions are preferred where the highest to lowest square wave frequency is the lowest

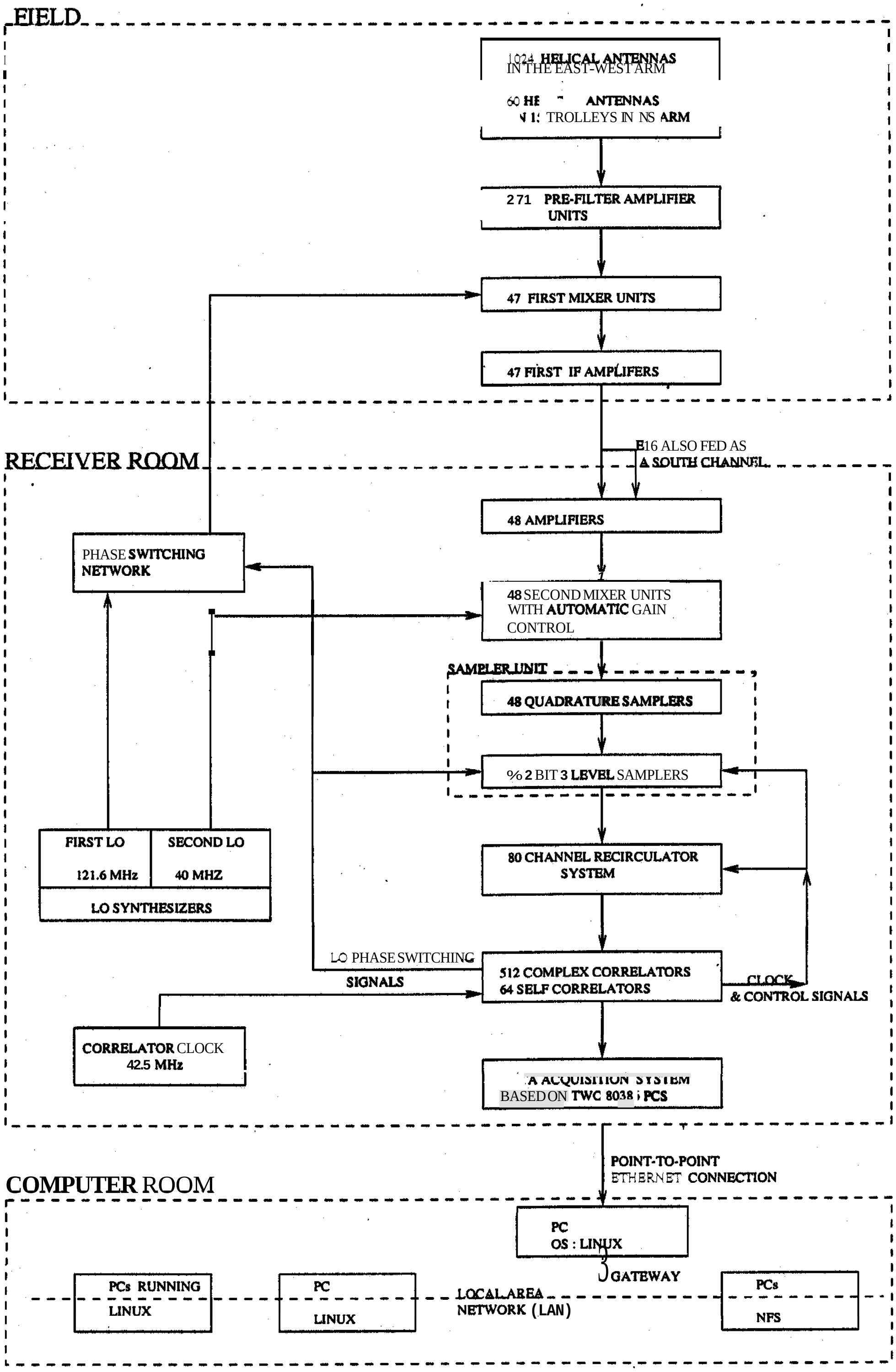

Figure 2.12: The signal path at the MRT: The various subsystems involved and their interconnections are represented here.

2.2.1 I.F. system

The 48 channels are split using a hybrid with one output of each hybrid sent to a monitor port and the other output, to the second mixer unit, via a bandpass filter centered at 30 MHz. In the second stage mixer unit, the signal is further amplified by about 15 dB before being heterodyned using passive mixers and an LO of 40 MHz. The mixer output is then filtered by bandpass filters centered at 10.1 MHz. Four selectable filters of bandwidths 0.15 MHz, 1 MHz, 1.5 MHz and **3.0** MHz are available. The filtered outputs go through an Automatic Gain Control (AGC) unit, which keeps the output level constant. The block diagram for the generation of the second IF is shown in Figure 2.13.

The second-IF outputs of the 32 east-west and 16 north-south groups then go to the sampler unit. In the sampler unit, the IF signal is isolated by a 1:1 transformer from the digital (sampler) ground. This is followed by a broadband quadrature hybrid which splits the signal into quadrature phase channels – the in-phase (cos) and the quadrature-phase (sin) channel outputs. These two channels are then amplified to produce a signal with an RMS of 1 V. The cos and the sin channels are then quantized by comparators with threshold voltages of about $V_{th} = \pm 0.7$ V producing 3-level amplitude quantization. After the comparators, the quantized signal is sampled in subsequent flip-flops (F/F) at the rate of the correlator clock frequency, which can be up to 12 MHz. These are then processed in a 2-bit 3-level correlator. In a 2-bit 3-level correlator, sampling the digitized signal at Nyquist rate, the maximum sensitivity obtainable relative to an analog correlator is 0.81. This is obtained when V_{th}/σ is 0.61. The sensitivity changes by only 5% from this optimal value when the signal power changes by 40% [32].

power-of-two integer that is greater than or equal to $\frac{(\text{number of antennas}-1)}{2}$.

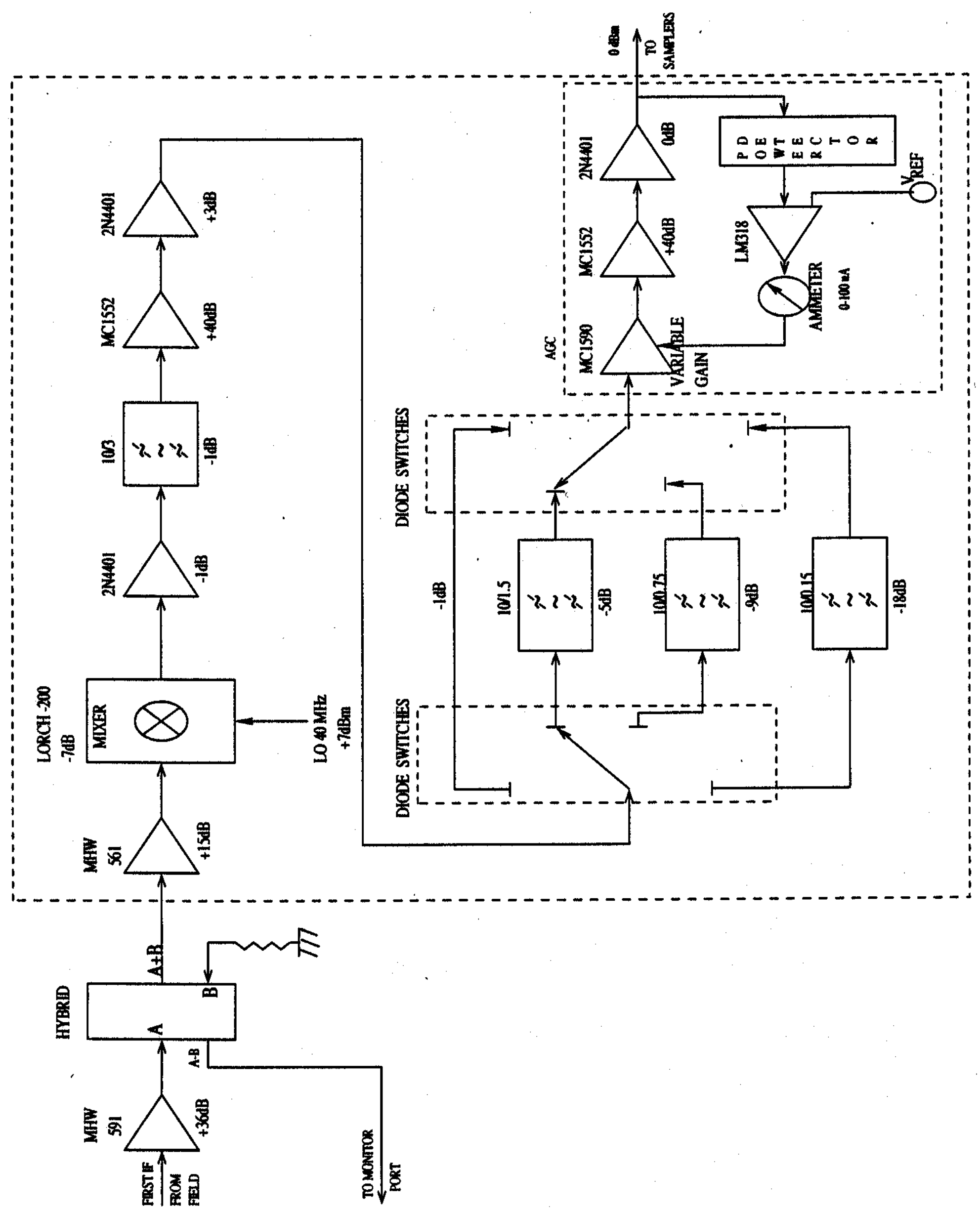

Figure 2.13: Second IF generation: The signal in the laboratory is amplified by about 36 dB and then passed through a hybrid. One output of the hybrid is connected to the monitor port and the other is sent to the second stage mixer unit via a bandpass filter centered at 30 MHz. In the second stage mixer unit the signal is amplified by about 15 dB before being heterodyned using passive mixers and an LO of 40 MHz. The mixer output is then filtered by bandpass filters centered at ~10 MHz. Filters of bandwidths 0.15 MHz, 1 MHz, 1.5 MHz and 3.0 MHz are available and are selectable using diode switches. The filtered outputs go through an *Automatic Gain Control (AGC)* unit which keeps the output level constant at about 0 dBm (1 mW).

2.2.2 The correlator system

The digitized data is sent to the correlator boards via the delay boards in which the delays can be programmed up to ±127 x T_{clk}, in steps of T_{clk} which is the period of the sampling clock.

The correlation receiver provides **512** complex correlators, wherein 32 channels are cross-correlated with 16 channels. Sixty four self-correlators are also provided wherein each channel is correlated with itself with zero delay. The self-correlators of the MRT are wired such that they measure the probability (P) that the input signal amplitude, V, is between the threshold levels used for digitization. This probability for a zero-mean Gaussian signal with RMS fluctuation of a and a symmetric 2-level digitizer with voltage threshold levels $\pm V_{th}$, is given by:

$$P = \frac{1}{\sigma\sqrt{2\pi}} \int_{-V_{th}}^{+V_{th}} e^{-(\frac{V}{\sqrt{2}\sigma})^2} dV = erf(\frac{V_{th}}{\sqrt{2}\sigma}) \qquad (2.4)$$

Knowing P, the $\frac{v_{th}}{\sigma}$ of the signal can be obtained. This provides the necessary information for obtaining the normalized correlation coefficient, ρ, from the measured digital correlation counts using the D'Addario correction given by [30]:

$$\rho = \gamma - \frac{\gamma^3(\alpha_1^2 - 1)(\alpha_2^2 - 1)}{6} \qquad (2.5)$$

where $\gamma = (\pi/2)(N/N_{max})e^{(\alpha_1^2+\alpha_2^2)/2}$. α_1 and α_2 are the V_{th}/σ of the two channels being correlated and N/N_{max} is the ratio of the correlation counts to the maximum value possible out of a 2-bit 3-level system.

The AGCs maintain a constant power level to the samplers even though the brightness distribution of the sky changes. This results in identical correlations for a weak source in a weak background and for a strong source in a correspondingly stronger background. Therefore we do not get the amplitude information of the signal from the sky. To recover the amplitude information while using the AGC there is a need to keep track of the gains. In many telescopes this is done by adding a fixed amount of a known signal at each antenna. At the MRT, however, the variation in the background radiation as seen by the east-west and the north-south groups are measured separately by switching off the AGC, one in each of the east-west and the north-south arms and using the self-correlators to measure the total power output of these groups. Since the east-west and the north-south groups have very broad beams, the power output of these groups do not change much ($<$ 3dB) in the 24 hour period. This results in the variation of S/N over the 24 hour cycle to be less than 5%.

The equivalent analog correlation, ρ_a, is then obtained using the relation

$$\rho_a = \rho \times \sigma_1 \times \sigma_2 \tag{2.6}$$

where σ_1 and σ_2 are the RMS of the signals correlated. σ_1 and σ_2 are obtained from the channels where the AGCs have been switched off.

2.2.2.1 Hardware description

Figure 2.14 shows the schematic of a section of the correlator system. The 1088 correlators are distributed over 64 correlator boards with each board containing sixteen cross-correlators and one self-correlator. The correlator boards are organized in a matrix of 8 rows by 8 columns. The 8 rows are grouped into two halves referred to as the upper half and the lower half. The upper half gets its inputs from the first eight north-south channels and the lower half gets its inputs from north-south channels nine to sixteen. The delays are set using 32 delay boards. Of these, 16 cater to the east-west channels and the other 16 are used for the north-south channels.

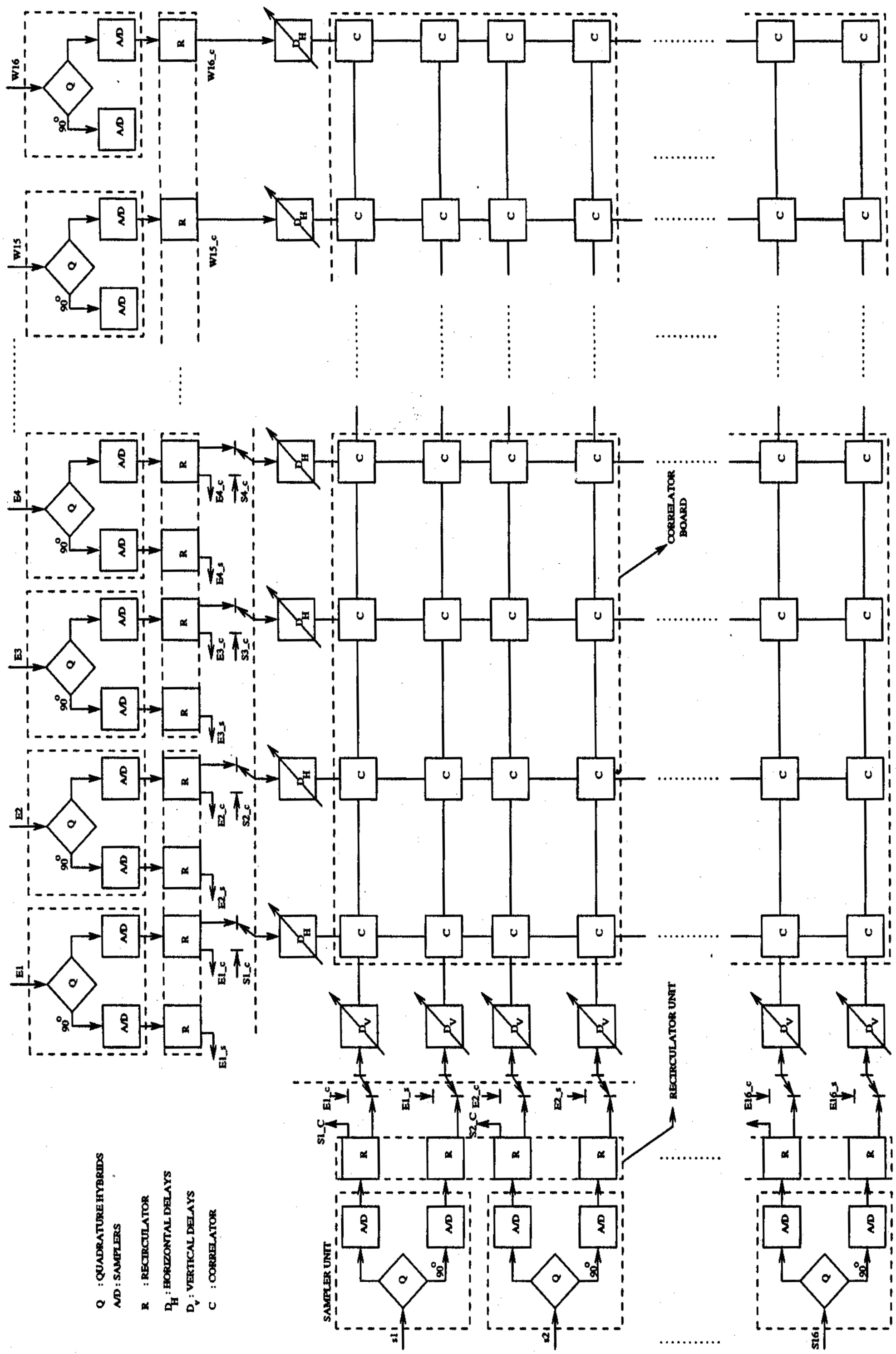

Figure **2.14:** Schematic of **a** part of the MRT correlator system.

Each delay board caters to two channels. A north-south delay board caters to the *cos* and the *sin* channels of a given group. Since the *cos* and the *sin* channels of a given group have to be delayed by the same amount, only one delay setting is provided on the north-south delay boards. The east-west delay boards cater to two separate antenna groups and provide for the delay to be set for each group separately. The delays are implemented using a double bank RAM. Figure 2.15 shows the logic diagram of the delay module. For a given delay interval, the data is written into a 2 x 256 bit RAM and is read from an identical second RAM. In the next delay interval, the RAM's tasks are swapped. The memory swapping cycle is generated by loading a down counter with the actual delay. When the counter reaches –1, the counters are reset to the delay value and the memories are swapped.

Each correlator board is controlled by an on-board 6505 (2 MHz) microprocessor with its program stored on an on-board PROM[9]. The correlator boards are built around a dual multiplier chip (VLA-1) and a unidirectional counter (VLA-2). There are 9 VLA-1s and 17 VLA-2s on each board. The VLA-1 and the VLA-2 together provide 14-bit data integration with 2 bits in the VLA-1 and 12 bits in the VLA-2. The multiplication logic works according to the scheme shown in Figure 2.16. The output corresponds to a multiplication result shifted by a constant offset so that no subtraction is required in the integrator. Hence unidirectional counters can be employed. In order to compensate this offset, one input of the correlator as well as the sign of accumulation in the microprocessor are periodically inverted (see Figure 2.17). The switching signal is called the phase-switch and has a period of 2^{16} cycles which is half of the shortest integration period. As an example, consider sig-

[9]PROM: Programmable Read-Only Memory

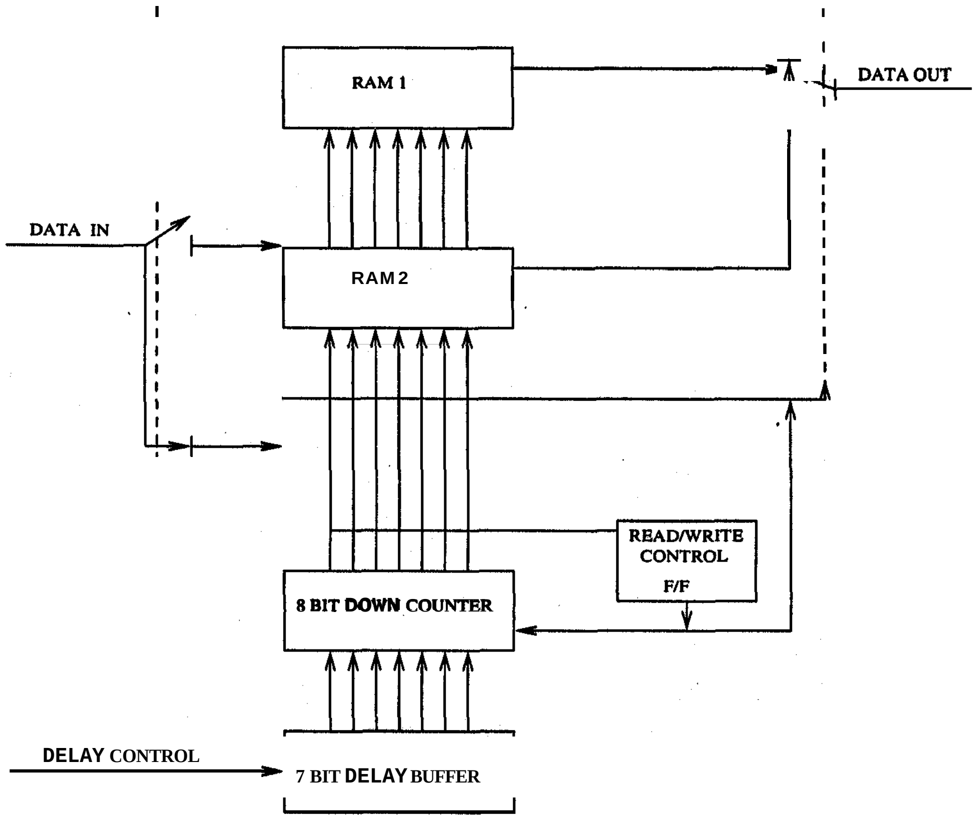

Figure 2.15: A schematic showing the delay logic: For a given delay interval, data is written into one 2 x 256 bit RAM and is read from an identical second RAM. In the next delay interval, the RAM's tasks are swapped

nals between the threshold levels in both the channels being correlated. For half the integration time, the counter adds 1 for each clock cycle, and then for the other half, subtracts one per clock cycle thereby giving zero for the full integration period.

In order to avoid overflow, the VLA counter is loaded into a shift register and is reset after 2^{13} clock periods by a control signal called update. After an update, the counter immediately resumes integration while the data from all the correlators on a board are serially transferred into a microprocessor where they are accumulated into 16-bit ,registers. Of the original 14 bytes, only ten most significant bits are picked up every 2^{13} clock periods by the

CORRELATOR INPUT Y \ CORRELATOR INPUT X	$X < -V_{th}$	$-V_{th} < X < +V_{th}$	$X > +V_{th}$
$Y < -V_{th}$	+2	1	0
$-V_{th} < Y < +V_{th}$	1	1	1
$Y > +V_{th}$	0	1	2

Figure 2.16: The VLA-1 multiplication table with an offset of +1 for a 3-level input.

microprocessor from the SIPO (serial-in-parallel-out) and integrated in a dual memory buffer for a further 2^n clock periods where n = 1, 2, 3. The truncation results in a very small deterioration of S/N of the order of .07%. The flow of data in a correlator board is shown in Figure 2.17.

The correlator system provides for different operations to be run simultaneously. These are

- programming the delays.

  Delay values up to 127 clock periods can be programmed for each group.

- programming the integration period.

  The integration intervals that can be set are 2^n clock periods where n = 17, 18, 19, 20.

- programming the beam configuration.

  The correlator may be configured in any of the following ways:

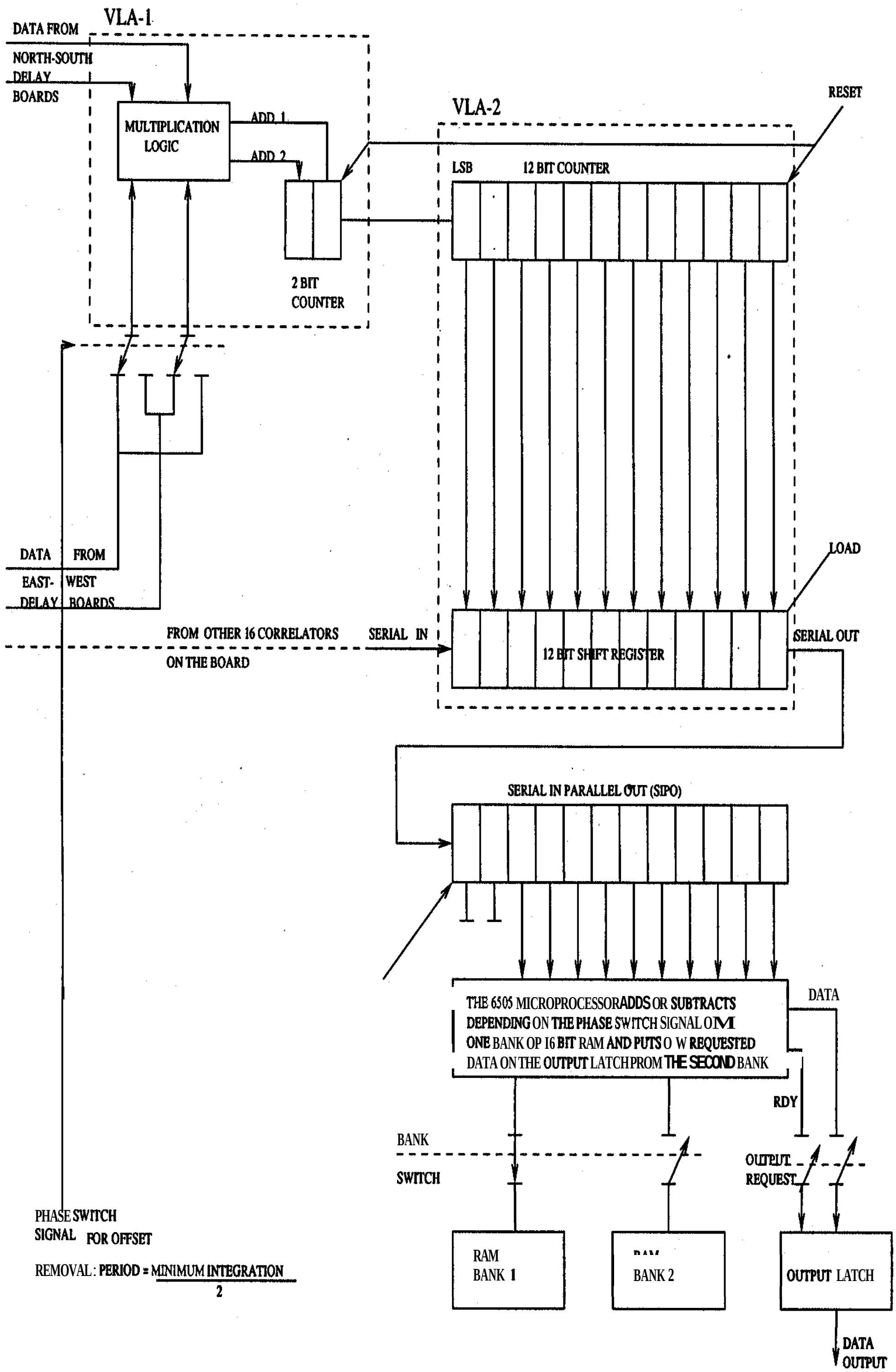

Figure 2.17: The signal path in a correlator board.

Pencil Beam configuration : (E + W) x NS . Each of the east-west groups is correlated with every north-south group.

East-west fan-beam configuration : (NS + W) x NS . This provides correlation of every north-south group with every other north-south group. In this mode, correlations of all the groups of the west arm with all the north-south groups are also provided.

North-south fan-beam configuration : (E + W) x.E. In this mode, all the east-west groups are correlated with all the east groups.

- transfer of data.

  The data can be transfered out of the correlator system continuously, while data is being collected.

Since the system has to be programmed without immediately affecting the current operation, the information has to be pre-stored and is activated by an internally generated signal called the *activate.* The *activate* command is used to activate the new system configuration and the new delays. To avoid integration of transient signals after a change of configuration, the delay outputs are zeroed by a blanking signal at the beginning of the integration interval. This blanking signal is for a period of 10 clocks. The blanking signal is sent every 2^{16} clocks to ensure that the + and − phases (in the phase switching to remove offsets) are equally shortened. For transferring the data out of the correlator system continuously while data is being collected from the VLA chips, a double-bank RAM of size **128** K is employed (only **64** K bytes on this IC are used). While the microprocessor is integrating data on one bank of the RAM, the other bank is available to the the PC based control and data acquisition system (Section **3.2.4)** for reading. The control signal called *integration-bank-select* (i.b.s) which alternates between integration intervals selects the RAM bank from which data is read out.

At the end of each integration period, the correlator system sends an interrupt to the control and acquisition system. The ccquisition system responds by sending in a 11-bit code of which the most significant 5 bits select one of the 17 correlators on all the 64 boards. The 6 least-significant-bits are decoded into 64 enable lines enabling the output latch on the selected board. The microprocessors on all the 64 boards pick up the requested correlator data and put it onto an output latch along with a signal called *Ready* (RDY) indicating that the data on the latch is valid. The acquisition system polls for the RDY signal on each board and collects the data when it finds its RDY signal active. This process is repeated till all the 1088 correlation values (17 correlation data from all the 64 boards) have been acquired. The control and data acquisition system can change the correlator number by sending the correlator number or can increment the correlator number by sending a *data request* (DR) control signal. The acquisition system integrates the correlation values to make them into about 1 s packets before writing into a file onto a hard disk. With the above configuration, 512 complex correlation and 64 self-correlation values are acquired every second.

2.3 Mode of observation:

In the T configuration, we are interested in sampling the baselines with a north-south components from 0 m all the way up to 880 m. The baselines along the 880 m north-south arm are sampled every 1 m. 1 m is $\frac{\lambda}{2}$ at 150 MHz which keeps the grating response at the horizon when observing at 150 MHz, Even though we have shifted the frequency of operation to 151.5 MHz, we continue to sample the visibilities at 1 m intervals. This sampling still keeps the grating response well outside the primary beam response (we discuss the grating response of the MRT in detail in Section 4.3.1).

To measure visibilities up to 880 m with a 1 m spacing using 15 trolleys, we require 60 allocations[10]. In'each allocation, the 15 trolleys are spread over 84 m with an inter-trolley spacing of 6 m. After obtaining data for 24 sidereal hours in one allocation, the trolleys are moved by one meter. Therefore, after 6 consecutive allocations we get visibilities measured over 90 m. We refer to the measurements made over 6 consecutive allocations to fill up 90 m along the north-south track as a ***block.*** The 60 required allocations are therefore obtained in 10 blocks. The positions covered in each block are summarized in Table 2.3. All spacings available in a square aperture are obtained by correlating the east-west arm of the T with the north-south arm.

block-1	6 m-94 m
block-2	2 m-5 m, 95 m-171 m
block-3	172 m-261 m
block-4	262 m-351 m
block-5	352 m-441 m
block-6	442 m-531 m
block-7	532 m-621 m
block-8	622 m-711 m
block-9	712 m-801 m
block-10	796 m-880 m

Table 2.2: The observations over the 880 m north-south track are divided into 10 blocks each covering 90 m.

The T array may be thought of as divided into an east-section, a west section, a south section and a central section as shown in the Figure 2.18

The correlation of the east-west arm with the north-south arm, with the

[10] **Allocation** refers to the placement of all the 15 trolleys on a single day.

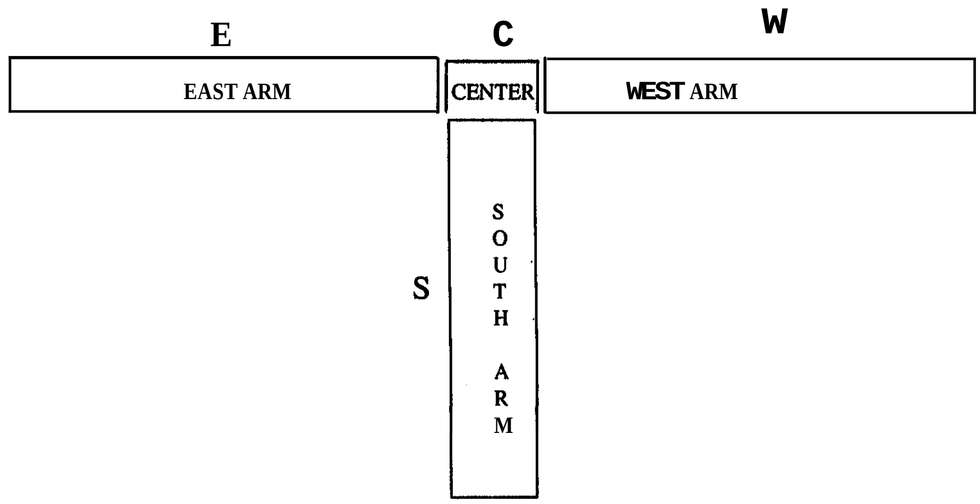

Figure 2.18: T-array composed of east, west and south arms and a central section

central section included in both the arms, may be written as

$$[E+W+C]\times[S+C] = \{[E+W+C] \times S\}+\{E\times C\}+\{W\times C\}+\{C\times C\} \quad (2.7)$$

Using the present arrangement we sample all $[E+W+C] \times S$ except the 1 m spacing from the east-west arm because the trolleys can approach the east-west arm up to a distance of 2 m only. The second and the third terms in the RHS of Equation 2.7 are not normally measured. To measure $E\times C$[11], a special arrangement was made, whereby, the group of 4 antennas from the western arm which is adjacent to the eastern arm, was correlated with all the groups of the eastern arm. The fourth term is measured as the self-correlation of a trolley without the AGC[12]. Thus we have all the spacings except for a trolley position 1 m away from the east-west arm which we cannot measure because the trolleys cannot approach the east-west array closer than 2 m.

Because of interference we measure the visibilities on a given allocation for

[11] For a coplanar array, W x C and E x C are hermitian symmetric and only one of them needs to be measured. However, at the MRT, these are not hermitian symmetric because of different heights of the east and west groups.

[12] This however includes the self-correlation of the amplifier noise.

about 3 sidereal days. It therefore takes 180 days to,obtain data for all the baselines. However, in this time the Sun moves through half the sky (12 hours in right ascension) thereby preventing full sky coverage with the 6 month data. We therefore carry out the observations in two rounds. In the second round we observe the same trolley allocations after about a 6 months interval. This ensures that we have night time observations with all the trolley allocations.

2.4 Sensitivity

The minimum detectable flux density[13], ΔS_{min}, from a point source using an array of N_b baselines and a correlation receiver, is given by:

$$\Delta S_{min} = \sqrt{\left(\frac{\sqrt{2}\,2k_B(\sqrt{T_{sys_{ew}}T_{sys_{ns}}})}{\eta_{eff}\sqrt{N_b}A_e\sqrt{\Delta\nu t}}\right)^2 + S_{conf}^2} \tag{2.8}$$

η_{eff} is the efficiency factor of a digital correlator (which for a 2-bit 3-level quantizations at Nyquist rate is 0.81 [32]).

A_e is the effective collecting area of an interferometer pair. For a correlation receiver the effective area $A_e = 2\sqrt{A_1A_2}$ where A_1 and A_2 are the areas of the two antennas forming the interferometer pair. At the MRT we correlate an east-west group with a north-south group. An east-west group has a collecting area of 128 m^2 and a north-south group has a collecting area of 16 m^2.

N_b is the number of baselines used.

k_B is the Boltzmann constant.

$T_{sys_{ew}}$ and $T_{sys_{ns}}$ are the system temperatures of an east-west group and a north-south group respectively.

[13]Flux density is measured in units of Watts per square meter per unit frequency bandwidth ($Wm^{-2}Hz^{-1}$). It is a measure of power per unit bandwidth falling on a unit area normal to the direction of arrival.

S_{conf} is the confusion noise flux density[14].

The expected variation of system temperature[15] with RA of an east-west group and a north-south group are shown in Figure 2.19a. The variation of the point source sensitivity from Equation 2.8[16] with RA for the entire system, i.e., using all the baselines, is shown in Figure 2.19b. The minimum detectable flux, ΔS_{min}, is lowest, about 50 mJy, at an RA of about 04:00 hours and is highest, about 200 mJy, at an RA of about 17:45 hours. Ideally one should use the T_{sys} variation of a 4' x 60" beam for the east-west and 15" x $4'.6 \sec(\delta + 20^\circ.14)$ beam for the north-south.

The contribution of confusion at 151.5 MHz, for single beam criterion, in the system for different beam-widths is shown in Figure 2.20[17]. At a resolution of 4' x 4' the confusion noise at 150 MHz is estimated to be 12 mJy [34] for 50 beam area criterion. From Equation 2.8, even when the the receiver noise is at its minimum of 50 mJy, $S_{min} = \sqrt{50^2 + 12^2} \approx 51$ mJy. The noise in the image is therefore determined by the system noise, i.e., we are not confusion limited[18].

Ban

[14] Confusion noise : There is a flux density below which there is more than one unresolved source per synthesized beam. These weaker sources are not perceptible individually, but the statistical fluctuations in their number present in each beam cause an apparent increase of noise.

[15] Obtained by convolving the 408 MHz all-sky image with the beams of the east-west group and the north-south trolley. A temperature spectral index, α_T ($T \propto \nu^{-\alpha_T}$) of 2.7 (see Chapter 5).

[16] for 16 second integration (optimal integration for 4' beam) using 1 MHz bandwidth

[17] This plot has been derived from the combined differential source counts given by Pearson [33] which he obtained from the 5C5, 5C2, the Molonglo MCI survey and the Molonglo whole-sky compilation for $S_{408} \geq 10^{25} W m^{-2} Hz^{-1}$.

[18] However, if we were to synthesize the full 2° beam, i.e., have integration time of about 480 s the minimum receiver noise would be about 2 mJy. In this case we would be confusion limited.

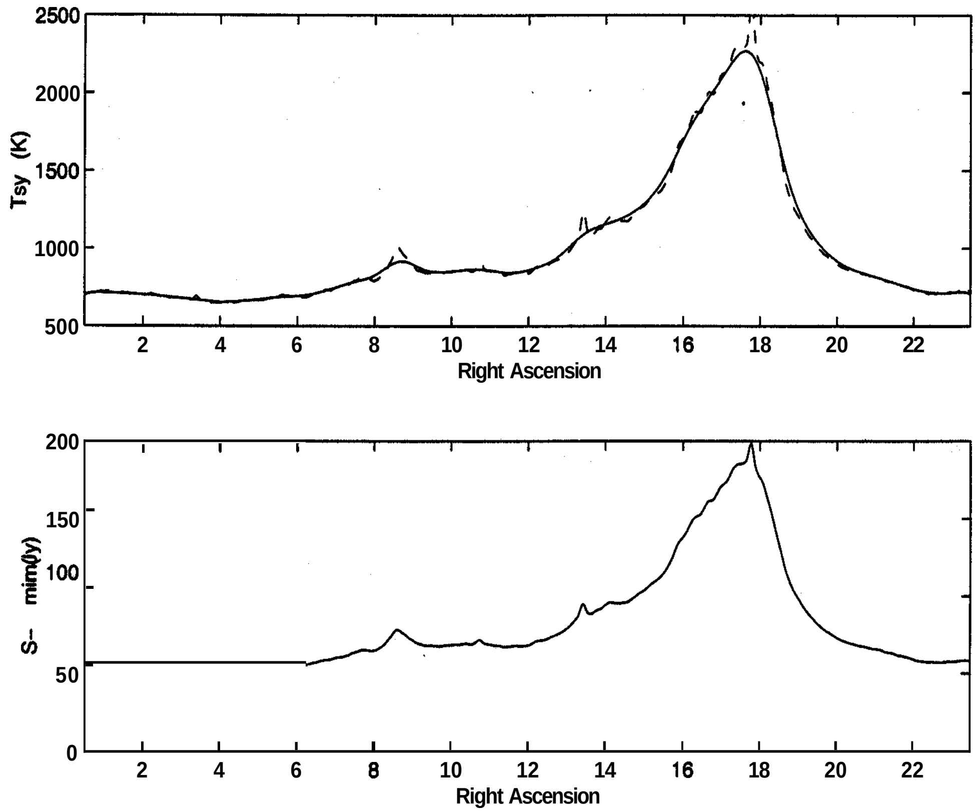

Figure 2.19: (a) The variation of system temperature with RA of an east-west group (dashed line) and a north-south group (solid line). (b) The lower plot gives the variation in sensitivity with RA for all the baselines (880x32) using a bandwidth of 1 MHz and an integration time of 16 seconds.

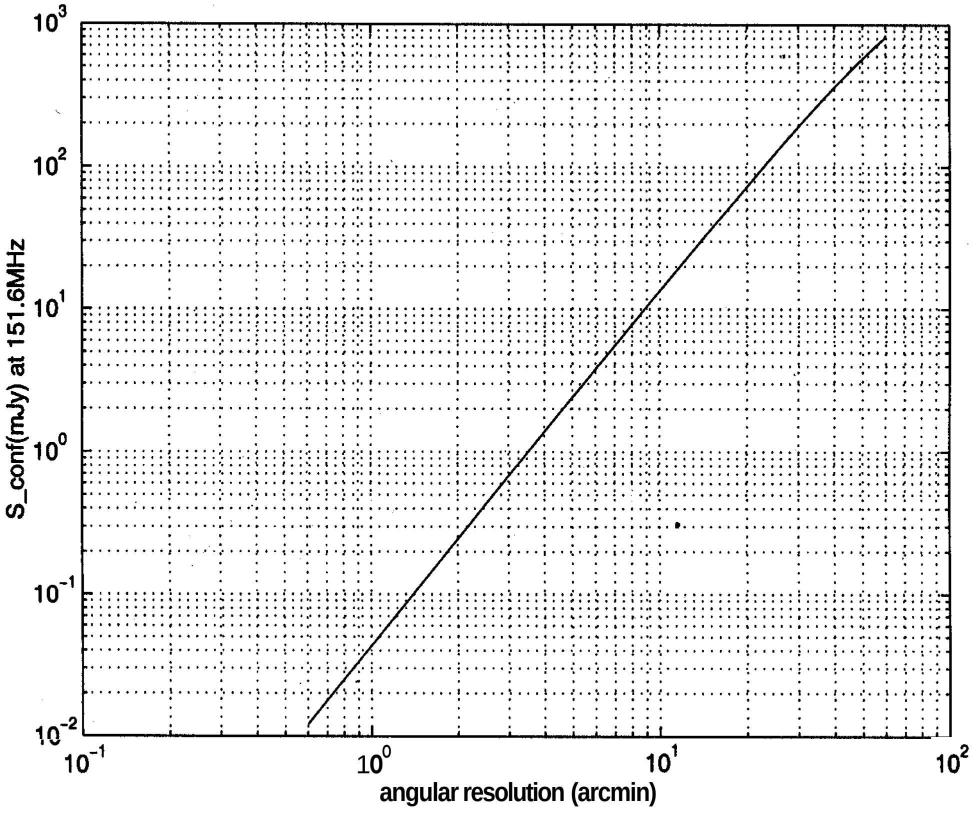

Figure 2.20: The contribution of confusion at 151.5 MHz, for single beam criterion, for different beam-widths