The Decameter Wave Radio Telescope at Gauribidanur: Antenna Arrays and Control System

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The Raman Research Institute and the Indian Institute of Asrtophysics in a joint collaboration program constructed a large decameter wave radio telescope at Gauribidanur, Karnataka, India (Latitude: 13°36′ 12″ and Longitude 77° 26′ 07″) which is in operation for several years now. This Decameter-wave Radio-Telescope, operating at 34.5 MHz, consists of 1,000 broad band dipoles arranged in the form of the letter "T". In this paper, we present technical details of the antenna arrays, the declination scanning system and the tracking system in hour angle.

Indexing terms : Radio telescope, Decameter

GROUND based radio astronomical observations cover a range of frequencies extending from a few megahertz to a hundred or more gigahertz. The absorption by water and oxygen, and the refraction in the ionosphere limit the observations at the high and low frequencies respectively. The decametric ($\lambda \approx 10$ meters) region of the radio spectrum is relatively unexplored due to difficulties arising out of absorption, refraction and scintillation in the ionosphere and the very limited bandwidth which can be found free of man made interference. In this wavelength range synchrotron radiation is the dominant type from both galactic and extragalactic sources and synchrotron self-absorption becomes important. Free-free absorption in ionised hydrogen regions also becomes very significant and its study would contribute greatly to our understanding of the density and temperature structure of these regions. Diffraction in both interstellar and interplanetary media is very strong and can be used for studies of these media and also as a powerful tool in determining the angular size of compact sources.

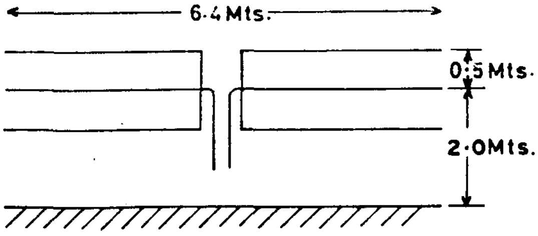
This Radio Telescope at Gauribidanur (Latitute 13° 36′ 12″ and Longitude 77° 26′ 07″) is in operation for several years now. We have made radio maps of the Sun [1,2], galactic supernova remnants [3,4], HII regions [5,6] and extragalactic sources [7]. The telescope has also been used for observations of pulsars [8,9], low frequency radio recombination lines [10] etc.

In this paper we present technical details of the antenna arrays, the declination scanning system and the tracking system in hour angle.

THE ANTENNA CONFIGURATION

The Decameter-wave Radio-Telescope at Gauribidanur, operating at 34.5 MHz, is essentially a meridian transit instrument. The telescope consists of 1,000 broad band dipoles arranged in the form of the letter "T". Various characteristics such as resolution, sensitivity etc of unfilled apertures like T and other configurations are discussed in detail elsewhere [11]. A schematic of the dipole and its characteristics are shown in Fig 1*a*. The outputs of four such dipoles along the East-West (EW) direction are combined in a Christmas tree fashion using open wire (balanced) transmission lines, and transformers to form a "basic array element" as shown in Fig 1*b*. Such basic elements, numbering two hundred and fifty, are arranged to form a 1.38 Km long EW array along the EW direction and a 0.45 Km along South (S) array extending southwards from the centre of the East-West array as shown in Fig 1*c*.

The EW array consists of ten groups of sixteen basic elements each. In each of such groups, the 16 basic elements are arranged in the form of 4 × 4 matrix. The



Imedance → 600Ω, V.S.W.R.→1.1 to 1.5
Bandwidth →10 MHz around 32 MHz
Polarization → linear in E-W direction

Fig 1*a* Schematic of the dipole

Paper No. 70-A; received 1989 September 5; revised 1989 December 12;

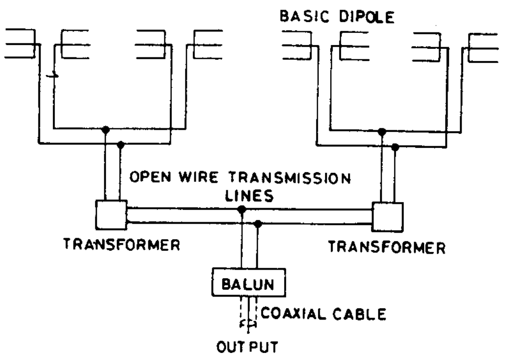


Fig 1*b* The basic array element

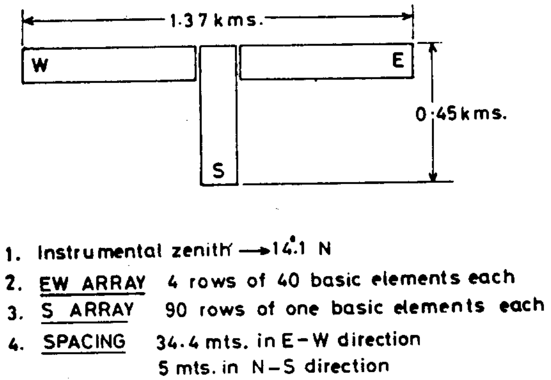


Fig 1*c* The 'T' array at Gauribidanur

outputs of the basic elements are combined as shown in Fig 2*a* to produce a "group" output. FET amplifiers and phase shifters are used at appropriate stages (Fig 2*a*). Five group outputs, available from each of the East and West arms, are combined separately with equal delay and amplitude in the form of a Christmas tree. The East and West arm outputs are amplified and are brought to the receiver room (Fig 2*b*).

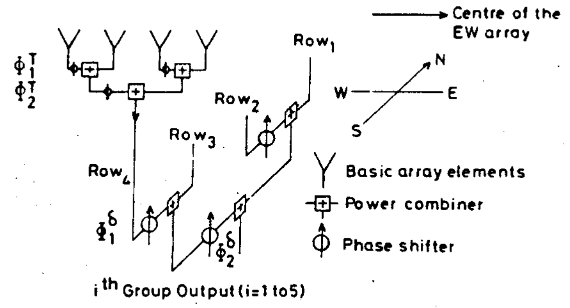


Fig 2*a* Configuration within each EW group

The S array consists of ninety basic elements arranged along the North-South direction. The output of each element is amplified using a FET pre-amplifier. These amplified outputs are then combined together in Christmas tree fashion using diode phase shifters, power combiners and amplifiers at appropriate stages as shown in Fig 3. This final output is brought to the receiver room.

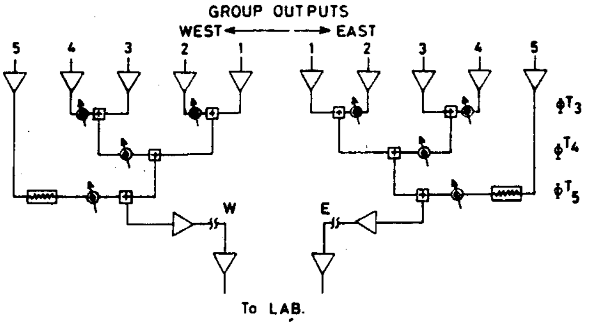


Fig 2*b* Combination of the groups in the EW array

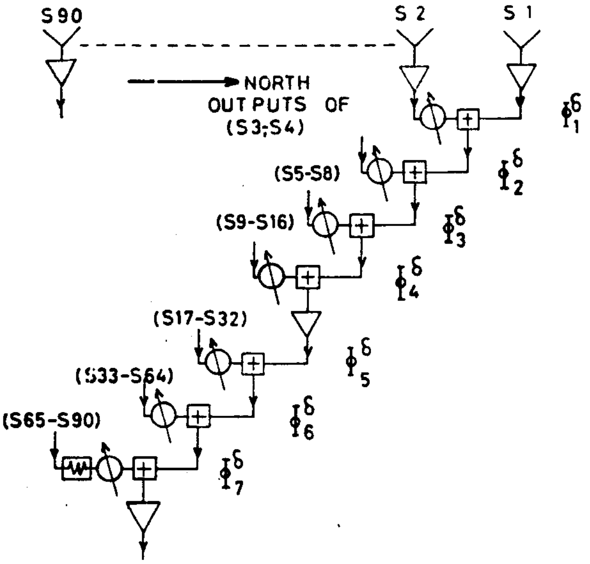


Fig 3 Configuration in the South array

When the outputs of the EW and S arms are correlated in phase, a pencil beam of half power width $26 \times 40 \sec(Z)$ arc minutes is obtained, where Z is the zenith angle.

The effective aperture size in the correlation mode is $240\lambda^2 \cos(Z)$ where Z is the zenith angle and λ is the wavelength of operation. The maximum available interference-free bandwidth is about 1 MHz. In the case of continuum observations the integration time in transit mode is about 25 seconds. The system noise is dominated by the contribution from the sky background at such low radio-frequencies and it can vary from 10,000 K to 40,000 K. For a system temperature of 20,000 K, the minimum detectable flux in the correlation mode is about 0.5 J_y ($1\ J_y = 10^{-26}$ w m^{-2} Hz^{-1}).

BEAM STEERING USING DIODE PHASE SHIFTERS

The beams of both the arrays can be steered in Declination (N-S direction). The beam of the E-W array can be steered in Hour angle (E-W direction) also. As is well known, according to the Nyquist sampling criterion it suffices to sample the brightness distribution in the sky in a given direction at discrete angular intervals equal to half the resolution. However, in order to be able to point the beam to any desired direction it is often necessary to steer the beam at intervals finer than the half power beam width. This would enable one to point the beam closest to the required direction without loss in sensitivity.

The electronic steering is ideally achieved by introducing appropriate delay gradients across the aperture. However, one could use phase gradients instead of delay gradients if the resultant decorrelation due to uncompensated delays [12] can be tolerated. The degradation factor η in sensitivity due to such decorrelation for a N element array is given by

$$\eta = \frac{1}{N} \sum_{i=1}^{N} \mathrm{sinc}\,(\Delta\nu\,\tau_i) \tag{1}$$

where $\mathrm{sinc}\,(x) = \sin\,(\pi x)/(\pi x)$

$\Delta\nu$ = the bandwidth

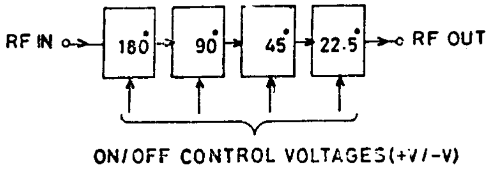
and τ_i = the uncompensated delay for ith element

For uniform excitation the factor is approximately given by

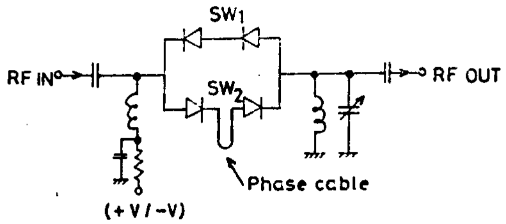
$$\eta = \mathrm{sinc}\,(\Delta\nu\,\hat{\tau}) \tag{2}$$

where $\hat{\tau}$ is the root-mean-square uncompensated delay and it is assumed that $\Delta\nu\hat{\tau} << 1$. The maximum bandwidth in the present case is restricted to $\sim$ 1 MHz due to the use of phase shifters. However, this is not a serious limitation since the usable bandwidth in this frequency range is usually not more than 1 MHz due to terrestrial interference.

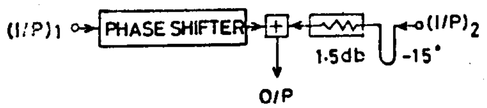
The required phase gradients can be introduced across the aperture using suitable phase shifter modules in the feeder system of the arrays. These phase shifters must be able to produce any phase shift between 0 to 360° at the centre frequency with sufficient accuracy. Figure 4 shows the design of a phase shifter module chosen to meet our requirement. This module consist of four sections. Each section consists of two RF diode switches (SW1, SW2) which are controlled by a DC voltage (+/−). Atleast two diodes are necessary for SW2 in order to isolate the effects of the additional cable length when SW2 is open (and SW1 is closed). To make both the paths similar in terms of delay and attenuation, two diodes are used in SW1 also. Using 180°, 90°, 45° and 22°.5 phase cables in the four sections and by using suitable control voltages represented by 4 control bits, any phase shift ϕ ($0 \leqslant \phi < 360°$) can be introduced with a maximum error of ±11°.25. The resulting phase distribution would have in general a random phase error of the same order over the aperture and would result in an equivalent rms beam pointing error of about 6% of the HPBW. Therefore, incrementing the phase shift in steps of 22°.5 is quite acceptable. It should be noted that the corresponding phase errors due to the refraction introduced by the ionosphere, at this frequency and latitude, are often larger than the errors due to the least count of the phase shifters.



(*a*) Four section phase shifter



(*b*) Individual section



(*c*) Phase and attenuation compensation

Fig 4 The phase shifter module

The response time of this 4 section module is less than 1 msec. The variable capacitors are used to match the input and output impedances to 50 ohms. The module has an average insertion loss of about 1.5 dB and the loss varies by not more than ±0.5 dB as a function of the phase shift. The input to output offset phase difference is about −15° at 34.5 MHz.

The phase shifter module accepts two array element outputs such that one of them [(*i*/*p*) 1] is passed through the variable phase shifter and then added to the other [(*i*/*p*) 2] (Fig 4*c*). The [(*i*/*p*) 2] is compensated for the average insertion loss and offset phase of the variable phase shifter as shown in Fig 4*c*. This procedure makes sure that all the outputs suffer on the average the same attenuation and phase shift which is not accounted for by the set phase gradient.

The phase errors introduced due to the minimum step of 22°.5 in the phase shifts also cause distortion of the beam pattern. The shape of the actual beam deviates from that of the ideal beam pattern (*ie* sinc) by about 5% of the peak beam gain due this effect.

DECLINATION (NS) SCANNING SYSTEM

Design consideration

(*i*) It is required that one should be able to point the array beams to any given NS direction within a range of ±60° of the zenith. Since the beamwidth of the T array is always greater than 40 arc minutes, it suffices to choose discrete direction spaced along NS direction by 12 arc minutes. These two considerations imply that a system having an ability to point the array beam to about 600 predetermined directions can span the required range in declination with adequate sampling.

(*ii*) It is necessary to switch the direction of the beam through a range of declinations (at intervals of 12 or 24 arc minutes) rapidly to cover a large angular region in one day. Therefore it should be possible to time-division multiplex observations of different directions in declination.

Control system

The phase gradients are introduced taking the northern most elements of both the arrays as the reference. The phase shifts required for producing the necessary phase gradients are introduced using diode phase shifter modules (Fig 4) which are incorporated in the feeder system of both the arrays. The phase shifter modules are controlled by a special purpose control systems. The declination control system (Fig 5) accepts the declination value through a set of thumb wheels and generates a suitable address to an EPROM in which 600 sets of control bits for phase shifts are stored. For any given declination, the corresponding bits are read and are stored in a RAM. A maximum of $N = 16$ such sets corresponding to any 16 declinations can be stored in the RAM. A special "Auto" mode is provided to select a set of declinations that are uniformly spaced. In this mode, given the southern most declination value in the set of N directions and the angular spacing the system automatically generates the appropriate addresses for the EPROM. The antenna response can be switched through the N directions by selecting the RAM contents sequentially at a rate of 50 millisecond per direction or slower. The RAM output is used to generate suitable voltage levels, on the control lines used for declination control in both the arrays. Thus with this system it is possible to observe broad sources upto an angular size of 6° in the fast scanning mode. However, it should be noted that due to the time multiplexing the signal-to-noise ratio is worsened by a factor of $\sqrt{N}$ compared to that without scanning.

THE TRACKING SYSTEM

The sensitivity of this telescope is limited by "confusion" (for a discussion of "confusion" in radio telescopes see [13]) due to poor angular resolution for continuum observations, although the minimum detectable flux is quite small. However, for observations of generally weak pulsar signals, low-frequency recombination lines and interplanetary scintillations, the sensitivity attainable with the meridian transit telescope is not adequate. Therefore, a suitable tracking facility is added to the existing set-up, to make the telescope suitable for the above mentioned studies.

Design considerations

The amount of time over which a point source can be

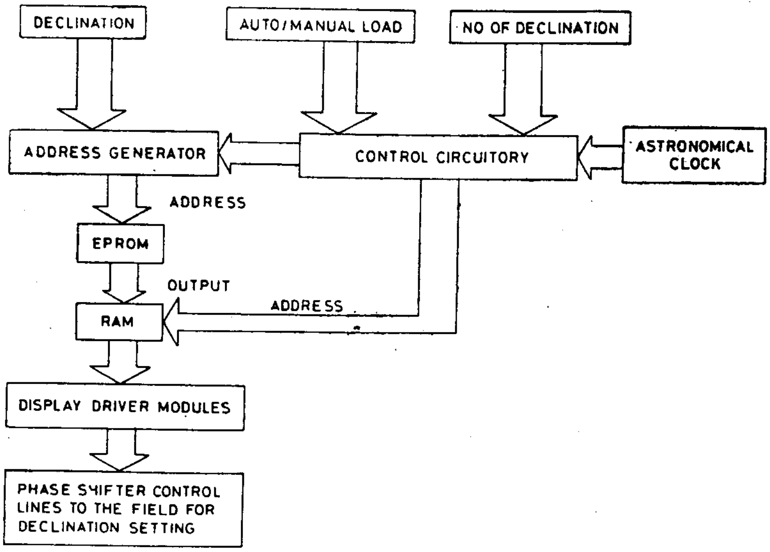


Fig 5 Declination control system

observed, can be increased by tracking the source as it moves from East to West. Ideally, for tracking a source, the beams of both, the EW and the S, arrays should be steerable in the EW direction. However, the EW beam of the South array is 40 times wider than that of the EW array. Therefore, if the beam of the EW array can be tilted sequentially in Hour angle (HA) within the HA beam of the south arm, it is possible to obtain sufficient increase in the observing time.

In general the phase shifter modules should be introduced at the output of each dipole in the EW array. But it suffices to introduce them at the outputs of the basic elements, considering that the response of the basic element in the E-W direction is similar to that of the south array. This reduces the required number of phase shifters and hence the complexity of the system. However, the price for this simplification is paid in terms of the appearence of unwanted "secondary" (grating) responses. Although the grating response may not have very serious effects in the case of pulsar observations, it is of concern for the following reasons. The gain of the primary response reduces when tilted away from the meridian, as both primary and secondary responses are weighted by the EW power response of the basic elements, *ie* by a function sinc² (θ_m/θ_b). Secondly, the grating response can cause confusing contributions from unwanted directions in the case of some observations (*eg* scintillation observations). It can be shown, that the ratio $R(\theta_m)$ of the secondary response to the main response is given by

$$R(\theta_m) = \left[\frac{\mathrm{sinc}\,[(1-\theta_m/\theta_b)]}{\mathrm{sinc}\,[(\theta_m/\theta_b)]}\right]^2 \qquad (3)$$

where θ_m=Angular tilt from the meridian and θ_b=Angular separation between the peak and the first null of the EW response of the basic element. This ratio increases with θ_m. Therefore, the value of the maximum angle (θ_{max}), to which the EW beam should be tilted away from the meridian, needs to be optimized with respect to the grating response. We have chosen a value for θ_{max} of ~5°, such that the grating response contribution on the average is less than 10% of the contribution due to the main response although the peak contribution is about 25%. The angular step by which the sequential EW beams should be separated is chosen to be 10 arc minutes, such that the sequential beams overlap at 95% gain points of the correlation beams. Smaller values of the angular step are not advantageous considering the subsequent increase in the number of sequential beams and the complexity of the system. Thus, by introducing 63 phase gradients sequentially along the E-W direction in the EW array alone, it is possible to track a source over a total span of 10°.5 centered around the meridian. This corresponds to 42. Sec (δ) minutes of observing time for a source at a declination δ. With this basic idea, we will now consider some important aspects of the linear phase gradients required to be introduced in the EW array.

Firstly, we do not want to disturb the phase centre of the *EW* array which is at the physical centre of the array. This means that there will be an inverse symmetry between the phases to be introduced in the E and W arrays with respect to the centre, for any E-W phase gradient.

If a phase shifter is introduced at the output of each basic element, we would need to generate, and transmit to the field, 40 independent sets of control signals for the phase shifters. But if these phase shifters are introduced by making use of the Christmas tree connections as shown in Fig 2, only 10 sets of control signals will be required. Also, as the four rows along the N-S direction are combined within each group, the number of phase shifter modules needed will be reduced to 120 from 160 in the earlier case. As shown in Fig 2*a*, 4 basic elements in each of the four rows of a group can be combined with phase shifts Φ^{T_1} and Φ^{T_2}. The four rows in each group are combined with the declination phase shifters to produce a group output. Five such group outputs in each of the *E* and *W* arms can then be combined using phase shifts Φ^{T_3}, Φ^{T_4} and Φ^{T_5} (Fig 2*b*).

Control system

For the implementation of the basic scheme discussed in an earlier section, a suitable control system is required to generate appropriate control voltages/signals for the remotely controlled phase shifters at appropriate times. We have designed and built a special purpose control system to meet the requirement. For time-keeping in this tracking operation we use a controller which runs at sidereal rate. The controller decides the start and the end times, for the operation over 63 beam positions, depending on the Right-Ascension (RA) and the declination (δ) of a source to be tracked. A source at a declination of δ takes 40 Sec(δ) sidereal seconds to cross 10 arc minutes of a beam. This time interval (Beam Flipping Time 'BFT') corresponds to the observing time in each of the 63 beams.

Given the RA and BFT of a source, the start time (t_s) and the end time (t_e) can be expressed as

$$\begin{aligned} t_s &= \mathrm{RA}-(63/2).\mathrm{BFT} \\ t_e &= \mathrm{RA}+(63/2).\mathrm{BFT} \qquad (4) \end{aligned}$$

These times, t_s and t_e, are calculated using digital counters, where a set of digital counters are preset to a given value of RA. Then (63/2) BFT pulses are counted DOWN or UP, before reading out t_s or t_e respectively. The worst case error, Δt, in such calculations is

$$\Delta t = (\Delta\mathrm{RA}+31.5\,\Delta\mathrm{BFT}+1)\ \text{seconds} \qquad (5)$$

where ΔRA, ΔBFT are the absolute quantization errors in representing RA and BFT respectively. By using the RA value rounded off to the nearest second and the BFT value to the nearest 0.1 second, this worst case error, Δt,

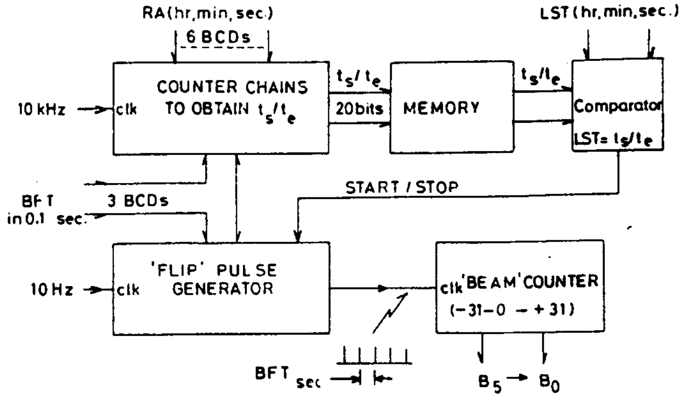


Fig 6 Controller for tracking system

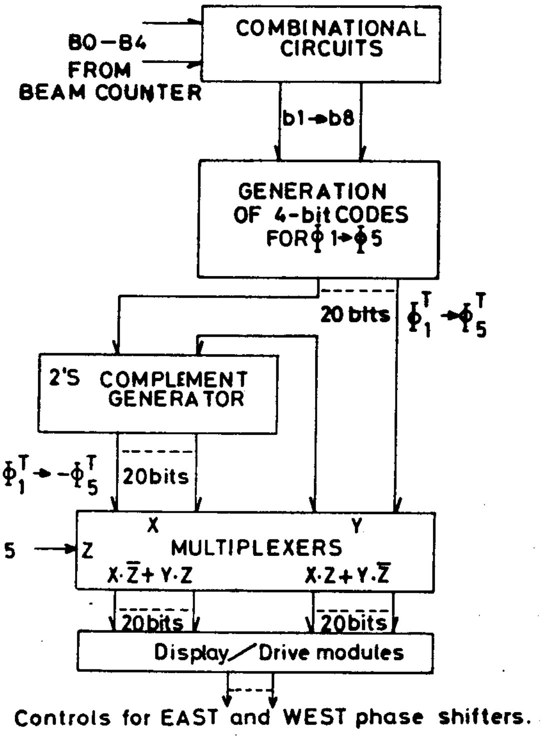


Fig 7 Generation of all the required control sets from the output of the Beam Counter

is 3.075 sec. This error in time will manifest itself in an equivalent beam pointing error of about 0.75 arc minutes in the worst case. Once the t_s and t_e are calculated, they are stored in memory. In most radio astronomical observations, it is required to obtain an off-source baseline observation in a direction as close to the source as possible. To enable the baseline observations off the source at the same declination and at an earlier but near RA, the EW beam is positioned at the extreme East direction (31E) of the tracking cone, well before the start time. When the t_s becomes equal to the local sidereal time (LST) obtained from an existing Astronomical clock [14], the tracking operation is started. At this time, the source will be in the correlation beam at the 95% gain point on the east side. Every BFT seconds after this time the EW beam is flipped to a westerly adjacent position 10 arc minutes away. The total number of available positions is 63. A simplified block diagram of this controller is shown in Fig 6. The binary output of this counter is used to obtain appropriate control signals for the tracking phase shifters. By using this binary information (B5 → B0), we generate 40 bits of information to control the phase shifters as shown in Fig 7.

The control system, which consists of the timing controller and the control sets generator described here, has been built using CMOS integrated circuits.

ACKNOWLEDGEMENT

We thank V Radhakrishnan for his advice and encouragement in all phases of this work. We would also like to thank Manohar Modgekar, S G Siddesh, M N Ramanuja, K R Subramanian, R Nandakumar, K S Dwarakanath, N Udayashankar and A T H Abdul Hameed for their significant contribution at various stages of this work. G N Rajasekhara, C Nanje Gowda and H A Ashwathappa assisted in the construction and maintainance of the entire system. We would also like to thank many other people whose names are too numerous to be listed for their help and co-operation.

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