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A Digital Correlation Receiver for the GEETEE Radio Telescope

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Abstract. A 128-channel digital correlation receiver has been built for the GEETEE[1], the low-frequency radio telescope situated at Gauribidanur, South India, (latitude 13°36′12″ N). The receiver uses a modified double-sideband (DSB) technique. The quadrature samples required for a DSB system are obtained by sampling the digitized intermediate frequency (I.F.) signals by two clocks which are separated in time by one quarter of the period of the I.F. The visibilities required for one-dimensional synthesis are measured using one-bit correlators. A technique to measure amplitude information for the signal using a threshold detector and a one-bit correlator has been developed. The receiver has been successfully used for continuum, spectral-line and pulsar observations. The antenna system of GEETEE and its configuration for one dimensional synthesis are also described in this paper.

Key words: DSB system—one-bit correlator

1. Introduction

The GEETEE is a low-frequency radio telescope operating at 34.5 MHz. It is situated near Gauribidanur, about 80 km north of Bangalore, South India (longitude 77°26′07″ E and latitude 13°36′12″ N). The antenna system is a T-shaped array with 1000 dipoles, 640 in the 1.4-km long East-West array (EW) and 360 in the 0.45-km long South array (S). The basic dipole, its characteristics and the geometry of the array are shown in Figs 1a and b. This array can be phased in a Christmas-tree fashion to form a single beam with a resolution of $26' \times 42'$ Sec $(\delta - 14°.1)$ (Dwarakanath, Shevgaonkar & Sastry 1982; Sastry 1989; Deshpande, Shevgaonkar & Sastry 1989).

To survey a wide field, a single-beam instrument needs a large amount of observing time thus reducing the surveying sensitivity compared with a multi-beam system. Also, at low frequencies, ionospheric effects can cause time-variable shifts in the apparent positions of radio sources. This makes it desirable to observe a large area of sky in a short time, which is not possible with a single-beam telescope. Another problem with low-frequency observing is man-made interference. This can be very destructive at decametre wavelengths and reduces the useable observing time. To obtain long periods of interference-free observing one should be able to change the frequency and the bandwidth of operation both quickly and easily.

[1] This telescope is jointly operated by the Indian Institute of Astrophysics, Bangalore and the Raman Research Institute, Bangalore.

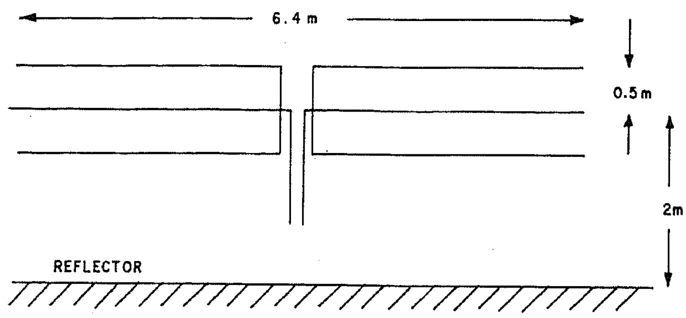

Figure 1a. Four fat dipoles (one of which is shown in this figure) are combined along the EW direction through open-wire transmission lines and appropriate impedance transformers to form a basic unit. Characteristic impedance of the dipole: 600 Ω, Bandwidth: 25–35 MHz with a VSWR of 1.1–1.5, Polarization: linear, oriented along EW.

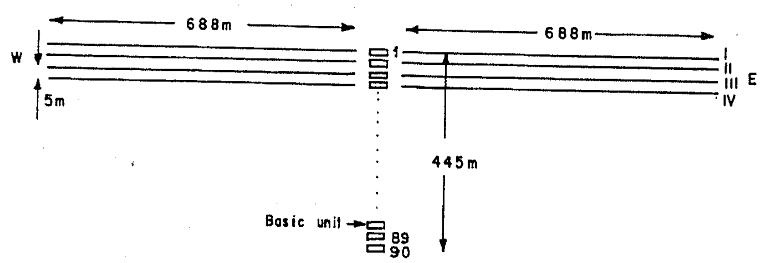

Figure 1b. The Gauribidanur radio telescope (GEETEE). Collecting area: EW array $\approx 12{,}000\ \mathrm{m}^2$, S array $\approx 7{,}000\ \mathrm{m}^2$, EW × S in correlation mode $\approx 18{,}000\ \mathrm{m}^2$.

This paper describes a 128-channel digital correlation receiver (Fig. 2), the main design emphasis of which was to obtain long periods of interference-free observing over as large an area of sky as possible in a given time. The receiver system can be configured for both one-dimensional synthesis and spectral-line observations. A companion paper by Dwarakanath & Udaya Shankar (1990; DU) describes a large-scale continuum survey made at 34.5 MHz using this receiver system. Results of spectral-line observations made with the receiver are briefly described in Section 4.2 of the present paper. Results of pulsar observations using the receiver can be found in Deshpande (1987).

2. Array configuration for one-dimensional synthesis

For one-dimensional synthesis, a single row of the EW array (row III of Fig. 1b) is used in the meridian transit mode (Fig. 3). The S array consists of 90 rows of dipoles placed 5 m apart (Fig. 4). Each row of dipoles in the EW array and each row in the S array have primary beams which cover essentially the whole range of elevations along the meridian, allowing synthesis of a very-large region of the sky in a single day. Since row III of the EW array was chosen for observations, only 88 visibilities along NS were measured. After amplification in the field, the outputs from the rows of the S array are carried to the observatory in 23 open-wire transmission lines using time-division

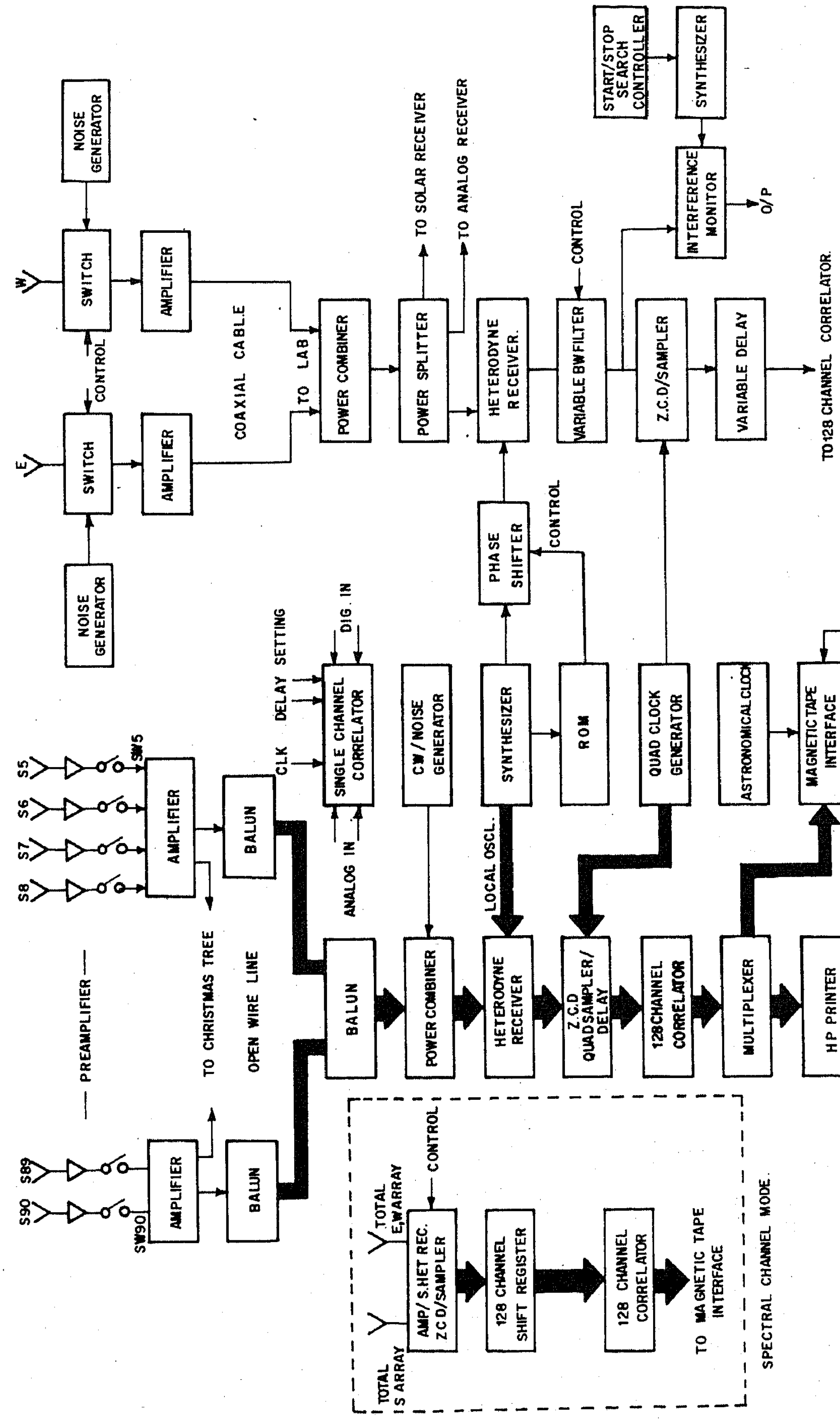

Figure 2. Block diagram of the 128-channel digital correlation receiver.

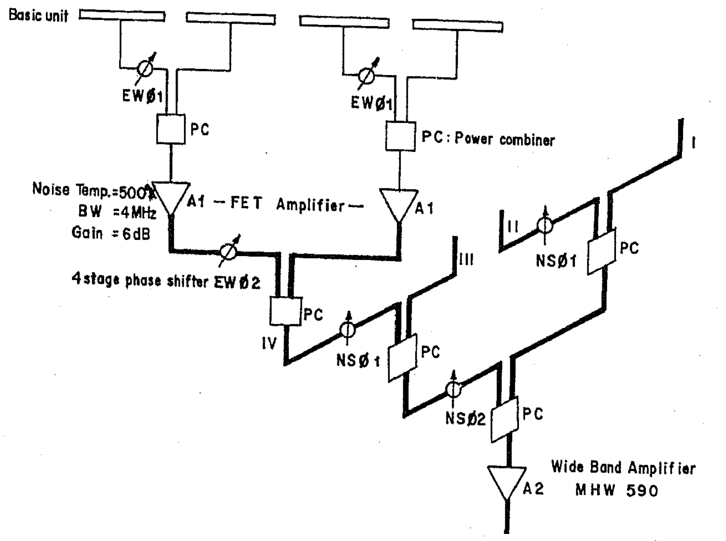

Figure 3. The Christmas-tree configuration of the EW array consisting of 4 basic units in each row is shown in detail.

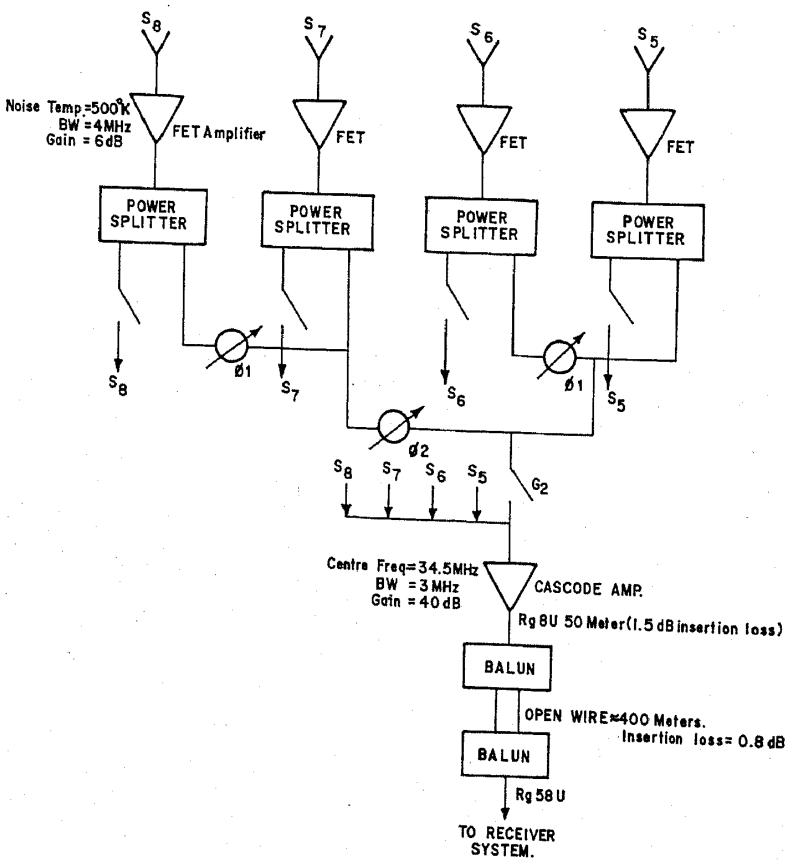

Figure 4. The configuration used in the S array for the sky survey. S_5, S_6, S_7, S_8 refer to rows of basic units in the S array.

multiplexing (Fig. 2). The dipoles at the centre of the array are included in both the EW and the S arrays (Fig. 5) so that the antenna responds to all spatial-frequencies up to those corresponding to its maximum extent. In particular, the zero spatial-frequency component of the brightness distribution is recorded.

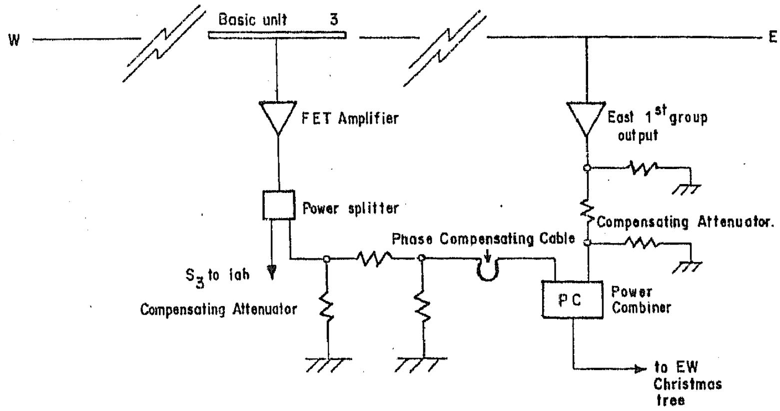

Figure 5. This figure illustrates the inclusion of the zero-spacing into the interferometer.

The above configuration uses only a quarter of the collecting area of the EW array. However, this is not a serious disadvantage since the telescope is essentially confusion limited (DU). The advantages of this configuration are that it

1. reduces the hardware requirements,
2. gives maximum sky coverage for a given observing time, and
3. does not disturb the existing Christmas-tree configuration.

This last consideration permits utilization of the single-beam configuration which is preferred for both spectral-line and pulsar observations.

In the observatory building, the signals from the EW and S arrays are further amplified and then down-converted to an intermediate frequency of 4 MHz. At the front end, only 23 super-heterodyne receivers are used in a time-multiplexed mode to obtain 88 I.F. outputs from the S array. Each of these outputs is correlated with the EW-array I.F. output using one-bit correlators. This gives 88 visibilities sampled at 5 m intervals along the NS direction. The Fourier transform of these visibilities gives the one-dimensional brightness distribution of the sky along the meridian over a zenith angle range of $\pm 47°$, without any grating response (DU).

3. Important design features of the receiver system

3.1 *Double-Sideband* (*DSB*) *System*

The receiver system uses a DSB technique (Read 1963; Radhakrishnan *et al.* 1972; Fomalont & Wright 1974; Udaya Shankar 1986; Thompson, Moran & Swenson 1986). A conventional DSB system for continuum observations is shown in Fig. 6a. In such a system, the sidebands are folded together before correlation. When observing in directions far from the zenith, a DSB system allows coarse delay steps to be used for delay compensation without introducing phase jumps and leaves the phase calibration unchanged. To obtain the same signal-to-noise ratio (S/N) for continuum observations as with a single-sideband (SSB) system, a DSB system requires twice the number of correlators since sidebands have to be unfolded. A conventional DSB system for spectral line observations is shown in Fig. 6b. In spectral line observations the extra

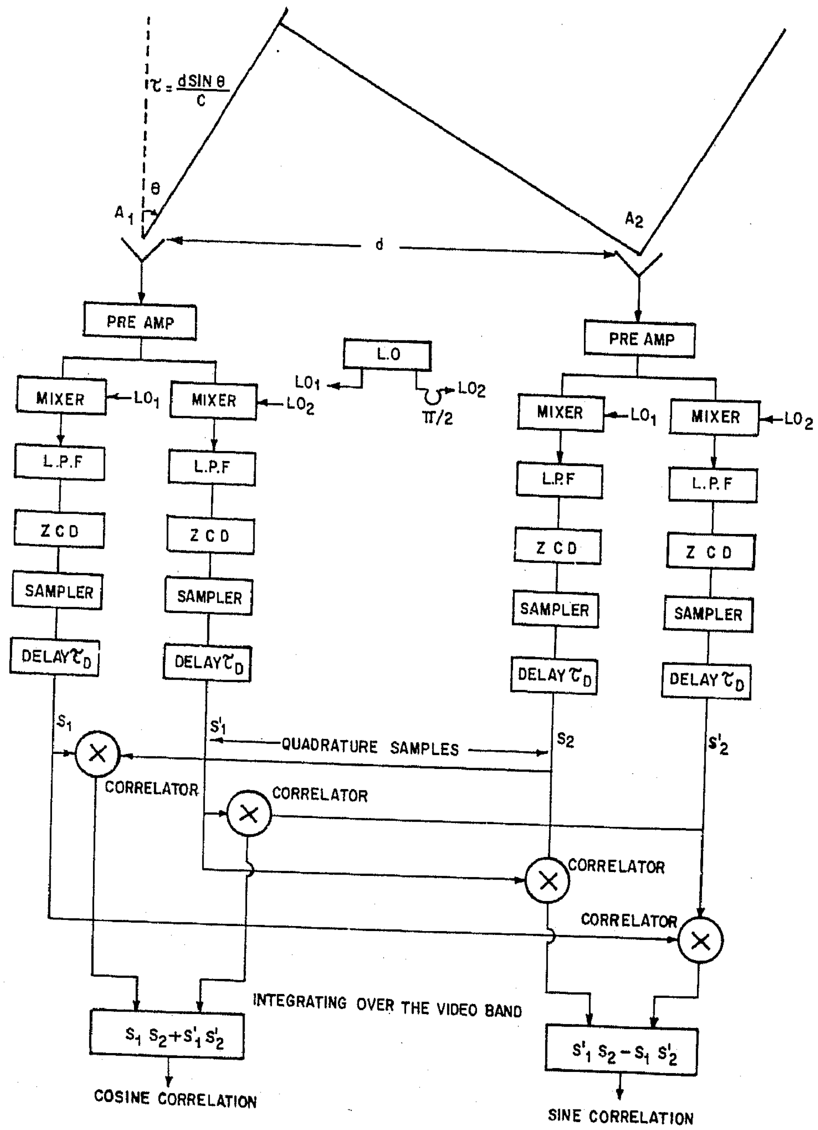

Figure 6a. The scheme for obtaining quadrature samples and correlation coefficients in a conventional DSB system for continuum observations.

correlators provide a reference spectrum without any conventional switching (such as frequency, beam or load switching). In these switching schemes observing time has to be split between on line and off line measurements thus reducing S/N.

A DSB system also requires the generation of quadrature samples of the signal without any significant deterioration of S/N. This is implemented in the present system by obtaining the quadrature samples after digitization. At our frequency, even a conventional DSB system does not suffer from a loss of S/N, as the system temperature is dominated by the contribution from the sky.

In a conventional DSB system, quadrature samples are obtained using two local oscillators shifted in phase by 90° (Fig. 6a). However, the present receiver system obtains the quadrature samples by sampling the digitized I.F. signal ($\Delta f = 400$ kHz, $fc = 4$ MHz) by two clocks which are separated in time by a quarter of the I.F. period (62.5 ns) as shown in Fig. 7. The folding of the two sidebands is achieved by using a sampling frequency (2 MHz) which is a subharmonic of the I.F. This scheme reduces

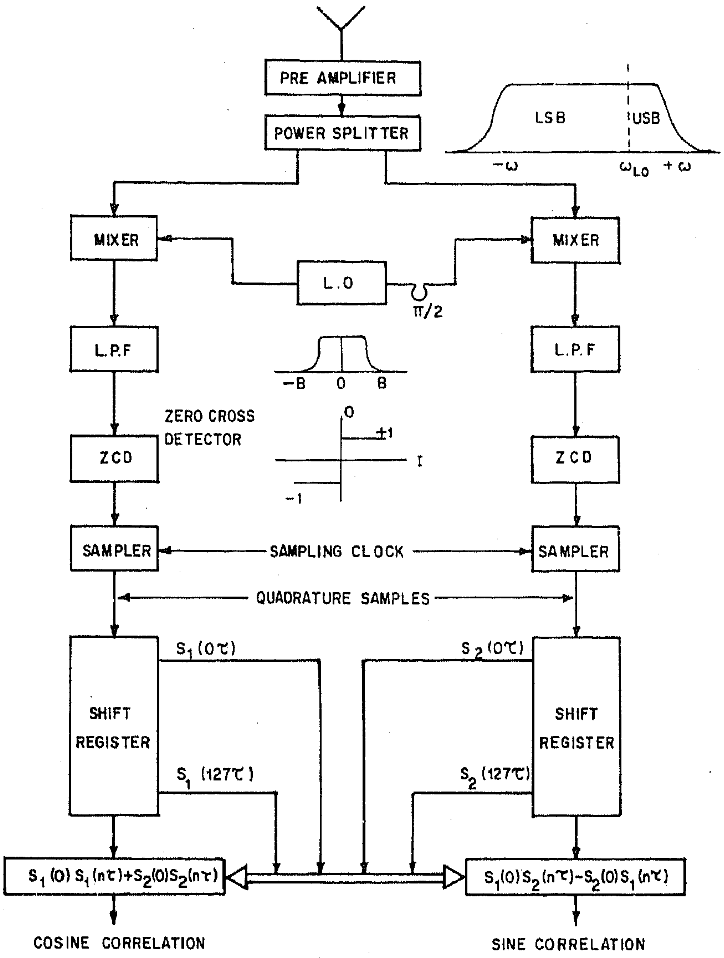

Figure 6b. The scheme for obtaining quadrature samples and correlation coefficients in the conventional DSB system, employed for spectral-line observations in the present receiver. Cosine transform of cos correlator output gives the sum of the two sidebands (USB + LSB). Sine transform of sine correlator output gives the difference between the two sidebands (USB − LSB).

the number of mixers, filters and digitizers required for a DSB system. Since matching the phase characteristics of these filters and equalizing reference voltages for digitizers are very difficult, the reduced hardware results in improved system performance. Correlation of the quadrature samples obtained at slightly different instants of time (62.5 ns) causes bandwidth decorrelation. This is less than 0.2 per cent as 62.5 ns is very small compared to the reciprocal of the I.F. bandwidth (2.5 μs). This method of obtaining the quadrature samples does not permit filtering after digitization. Thus the final observing bandwidth is equal to the I.F. bandwidth. For spectral-line observations it is preferable to retain the facility for altering the bandwidth after heterodyning. Thus, the conventional DSB scheme of Fig. 6b was employed for the spectral-line receiver.

Bandwidth decorrelation and the amount of hardware required for a DSB system could have been reduced further by digitizing directly at 34.5 MHz. However, in such a system, a jitter of even 1 ns in the sampling clock would have caused phase errors of $\sim 15°$. Hence such a scheme was not attempted.

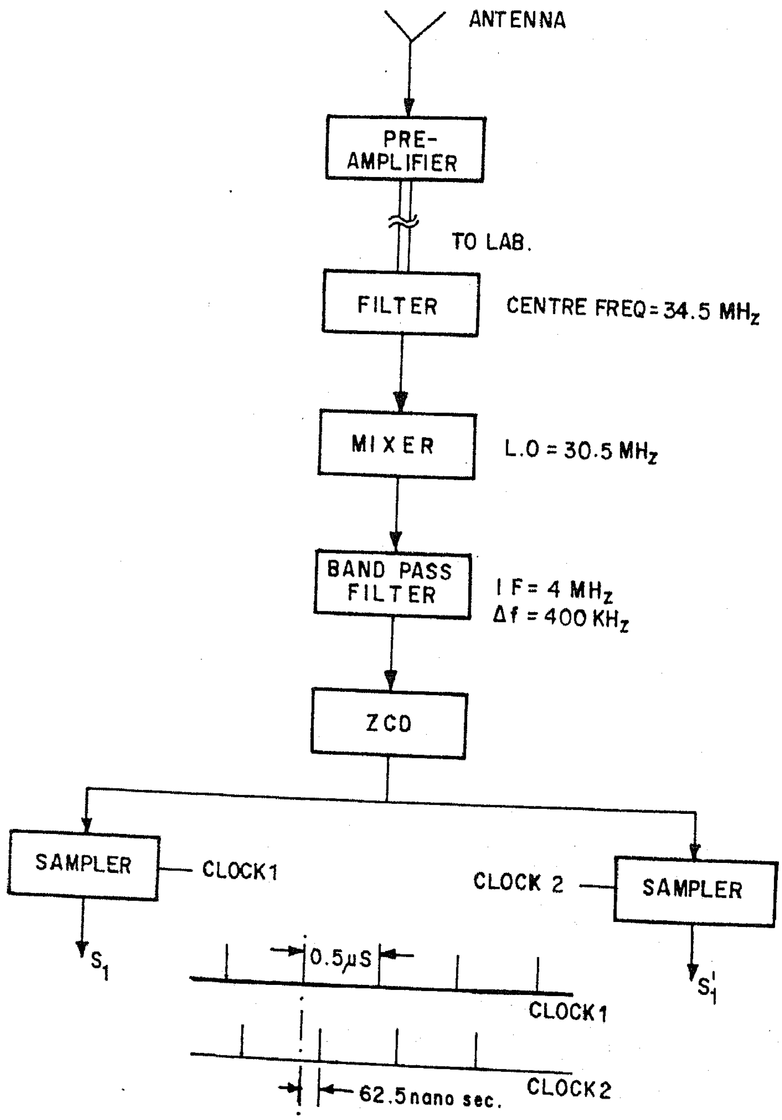

Figure 7. The technique employed in the present receiver system to obtain the quadrature samples of a band-pass signal.

3.2 *Variable-Bandwidth Receiver*

Since the operating frequency of the telescope is very close to the broadcast and communication bands, man-made interference could be high. Two facilities are built into the system to increase the interference-free time for observations (Fig. 2).

Firstly, by tuning the L.O. the centre frequency of observation can be changed over a 2-MHz band. Since the EW array is ~1 km longer than the S array, a small change in the centre frequency alters the instrumental phase calibration and this could change by different amounts for different rows of the S array. To overcome this difficulty, a large delay in the form of a long chain of shift registers is included in the path of the S array signal. A variable-delay shift register is incorporated in the EW signal path and adjusted to maximize the correlation. Further, the lengths of the cables bringing the outputs from the various rows of the S array to the observatory building are equalized to within a wavelength. This makes the R.F.-phase change by the same amount in all channels when the centre frequency changes. To retain the advantages of DSB operation, a hardware scheme using a R.O.M. and a phase shifter is incorporated in the EW L.O. path to retain the phase calibration, independent of the centre frequency.

Interference-free observation can be increased by having variable-bandwidth filters in all channels. Interference monitoring indicated that the cost and complexity of the hardware required for such a system is not commensurate with the increase in observation time obtainable. However, to tackle low-level interference, a variable-bandwidth filter has been included in the EW array alone (Fig. 2). A variable-bandwidth filter in only one of the signal paths of a cross correlator changes the effective observing bandwidth. A filter present in the EW array introduces both a group delay and a phase which is a function of the frequency. Therefore, it is necessary to delay the S-array signals and also pass them through a phase-compensating network to retain the correlation value. However, this increases the complexity of the hardware. To simplify the hardware, the variable-bandwidth filters in the EW-array signal path are designed to have linear phase characteristics. The gross delay in the S-array signal path and the variable delay in the EW channels are then sufficient to maximize the correlation.

When two unequal bandwidth signals are correlated in a one-bit correlator, the correlation coefficient decreases. We note that if the scheme is implemented properly, the signal-to-noise ratio does not decrease below that expected for narrower bandwidth signals in both the signal paths of a cross correlator. The true correlation coefficient can be recovered by knowing the bandwidths of the signals correlated. A detailed description of the scheme used and the detailed S/N calculation may be found in Udaya Shankar (1986).

3.3 *The One-bit Correlator*

The correlator system uses one-bit quantization. A one-bit correlator using Nyquist sampling suffers a loss in sensitivity of 37 per cent (Van Vleck & Middleton 1966; Weinreb 1963). This system samples a 400-kHz I.F. band centred around 4 MHz at five times the Nyquist rate and thus reduces the loss of sensitivity to 20 per cent (Bowers & Klingler 1974). This is very close to the performance of a two-bit three-level correlator employing the Nyquist rate. The correlator is shown schematically in Fig. 8. The addition of correlations required for a DSB system is performed using two phased clocks and an up-counter. The input to the up-counter will be at a rate which is twice the sampling rate. At this rate, which is 4 MHz, a 20-bit counter gets filled in 256 ms. The system employs a variable-length counter (13 to 20 stages) enabling the pre-integration time to be varied from 2 ms to 256 ms. Independent of the integration time, only the eight most-significant bits of the counter are latched out and recorded on an incremental magnetic tape. To avoid loss of information, only these eight bits are reset following each integration and the lower-order bits are allowed to accumulate correlation for the next integration period (Ravindra 1983). It is for this reason that these correlators, unlike superheterodyne receivers, could not be time multiplexed. Thus 88 correlators are used to measure the 88 visibilities.

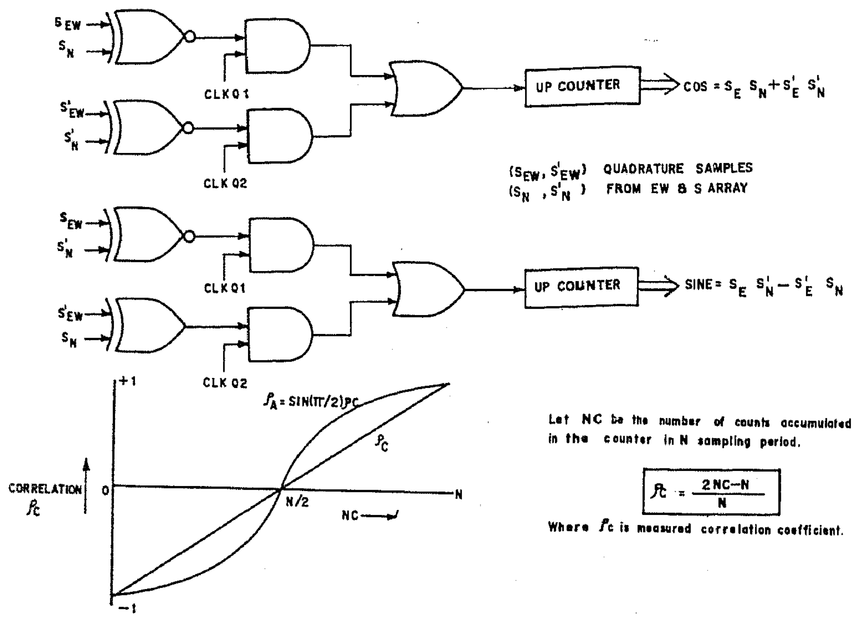

Figure 8. This figure illustrates a scheme for addition of correlations required for a DSB system. A DSB system needs four multipliers to obtain the desired correlation counts N_C. The equation and the graph describe the relation between the desired correlation coefficient ρ_A and N_C.

3.4 *Amplitude Information of the Signal Using One-bit Correlators*

The amplitude information of the signal is lost in one-bit quantization. This results in identical correlations for a weak source in a weak background and a stronger source in a correspondingly-stronger background. The normalized correlation coefficient (ρ_C) measured in a one-bit correlator is related to the analog correlation (ρ_A) by the relation

$$\sin[(\pi/2)\,\rho_C] = \frac{\rho_A}{\sqrt{p_1 p_2}}, \tag{1}$$

where p_1 and p_2 are the powers of the two signals correlated. Thus, in observations made using one-bit correlators to obtain the brightness distribution of the sky, it is necessary to measure the power output of each interferometer element being correlated. To measure the power, we have employed a scheme using a threshold detector and a one-bit correlator. This measures the probability that the signal amplitude is below a certain threshold V_{th} (Fig. 9). For a Gaussian signal with zero mean this is given by

$$P = \frac{NC}{N} = \frac{1}{2} + \frac{1}{\sqrt{\pi}} \int_0^{V_{th}/\sqrt{2}\sigma} \exp[-x^2]\,dx. \tag{2}$$

Knowing this, the RMS fluctuation σ of the signal can be obtained. The power then is simply equal to σ^2.

Even though 88 one-bit correlations are measured for one-dimensional synthesis, only the EW total power and the total power of one of the S array rows are required to reconstruct the brightness distribution of the sky. This is as all the S-array rows are

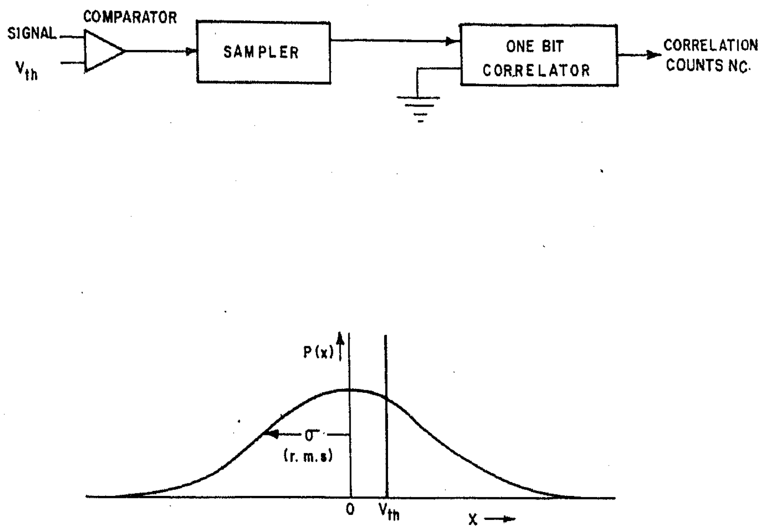

Figure 9. A schematic of the technique used to measure the power of a signal using a one-bit correlator and the threshold detector.

similar and the one-bit correlations are not affected by gain differences in the heterodyne receivers.

3.5 *Miscellaneous Circuits*

The philosophy adopted in the system design was to build circuits which could be used for testing the receiver and make it a stand-alone system. A single-channel one-bit correlator with a six-digit readout has been built which can accept both analog and digital inputs. Delays and phases can be measured accurately using this instrument. A noise generator and a crystal oscillator with a 32-channel power splitter is used to couple the correlated signals into the receiver system (Fig. 2). It is also possible to feed a sub-harmonic frequency of the sampling clock directly to the digital system. This helps ensure that the digital section of the receiver is functioning without adding sampling noise of its own. In the spectral-line mode, such a signal results in a triangular-shaped autocorrelation function. This helps to check the delay shift-register chain. A Hewlett-Packard printer interface in the receiver system helps to check the status of the system instantly. An interference monitor to locate an interference-free band has also been designed. This works on the principle that the autocorrelation function of band-limited noise which is free of narrow band inteference is very small at large delays. A general-purpose astronomical clock (Udaya Shankar & Selvamani 1981) providing solar and sidereal times and Julian date has been incorporated in the receiver system.

4. Observational results

4.1 *Continuum Observations*

The results of the continuum observations are discussed in DU. The receiver and antenna performances are also detailed in that paper.

4.2 *Recombination-line Observations*

With the installation of the digital correlation receiver, confirmation of the presence of recombination lines of carbon in the direction of Cas A (Konovalenko & Sodin 1981; Anantharamaiah, Erickson & Radhakrishnan 1985) and a search for low-frequency recombination lines in the direction of Cyg A, Tau A and the Galactic centre were attempted. The S array was used for these observations, phasing it to the source declination. The S array has a smaller collecting area than the EW array. The observing time obtainable per day using the tracking facility of the EW array and making transit observations with the S array are comparable. However, the measurements made using the S array do not require the beam-flipping logic that is used for tracking the beam of the EW array and hence simplify the observations. The L.O. and sampling frequencies were chosen to have a harmonic relation to avoid any harmonic of the sampling frequency giving rise to an in-band product (except at D.C.).

Between the two possibilities of observing a single spectral line with higher resolution or two spectral lines with lower resolution, the latter was preferred because

1. it gives a higher S/N and thus enables more rapid detection, and
2. interference can be ruled out beyond doubt if two spectral lines, one in the upper sideband and the other in the lower sideband can be detected simultaneously.

We were successful in detecting the C574α and C575α lines in the direction of Cas A. The observed spectra for an integration time of 860 minutes are shown in Fig. 10. We obtained a ratio of line-to-continuum temperature, $T_L/T_C=0.002$, confirming the

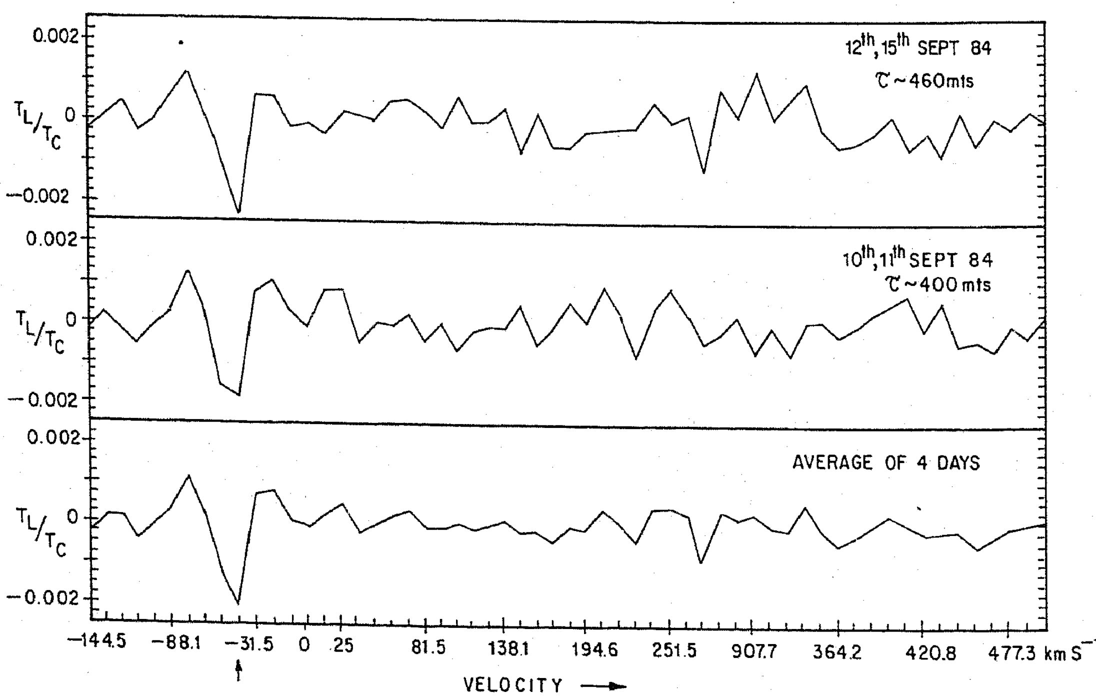

Figure 10. The summed profile of the carbon recombination lines C574α and C575α detected in the direction of Cas A at 44 km s^{-1}. Since the emission of Cas A dominates the system temperature, the optical depth (τ) is very close to the measured ratio of line-to-continuum temperature (T_L/T_C).

results of the earlier observations. No line with $T_L/T_C \geqslant 0.002$ was detected in the direction of Cyg A for a similar integration time. The observations of Tau A and the Galactic centre were partly corrupted by interference and no lines were detectable.

5. Conclusions

The digital correlation receiver we describe has made the Gauribidanur telescope a versatile instrument for decametre-wave observations. The receiver uses one-bit correlators for measuring visibilities. A new scheme for measuring the amplitude information of the signal using one-bit correlators, plus the inclusion of the zero spacing in the synthesis, has enabled us to measure the total sky brightness. The receiver uses a DSB system. A new method of obtaining the quadrature samples of signals required for such a system has been developed. This technique requires less hardware than the conventional DSB technique and also achieves an improved system performance. The receiver offers the facility to correlate two unequal bandwidth signals in a one-bit correlator to maximize the interference-free observing time. On-board test equipment has made the instrument a stand-alone unit.

Using this system, a wide-field survey of the sky at 34.5 MHz has been completed. The system is capable of surveying the entire sky in a single day. It has opened up the possibility of detecting pulsar signals which are highly dispersed (even for DM$\sim$35 cm^{-3} pc) at low radio frequencies.

The spectral-line receiver uses a conventional DSB technique. This measures spectral-line temperatures without any conventional switching. This receiver can serve as a prototype for a bigger system which can be used to survey low-frequency recombination lines.

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