APPLICATION OF DIGITAL TECHNIQUES TO RADIO ASTRONOMY MEASUREMENTS

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DECLARATION

I declare that the work presented in this thesis has been conducted by me in the Raman Research Institute, Bangalore, India. No part of this work has been submitted for the award of any other degree, diploma, associateship, fellowship or any similar title.

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Radio Astronomy Measurements

SYNOPSIS

This thesis describes the design and development of instrumentation for a low frequency decameter wave synthesis radio telescope situated at Gauribidanur, about 100 Km from Bangalore. It is a T shaped array with a 1.38 km East-West and a **0.45** km North-South arm.

In an earlier existing receiver, the East-West and North-South arms were phased in the field by remotely controlled phase shifters. The outputs of each arm were carried by coaxial cables to the observatory building, where the sum of the East and West signals was correlated with that of the North-South arm. This produced a single beam of 26 **x 40** arc minutes (at the zenith) at a frequency of 34.5 MHz. Such a single beam instrument uses only a part of the total available time to observe each beamwidth of the sky and thus reduces surveying sensitivity. Also, in a low-frequency telescope, ionospheric effects can cause an apparent and time variable shift in the position of radio sources. Both these make desirable the observation of a large patch of sky in a short time, and a single beam telescope simply cannot meet this requirement. Another problem is man-made interference which can be very high at decametric wavelengths. This reduces useful observation time. To obtain long periods of interference-free observation one should be able to change easily and quickly the frequency of operation within some given band. The narrow bandwidth of the existing receiver does not permit such large changes in the observation frequency.

This thesis describes a multiple beam forming receiver for the Gauribidanur telescope designed to overcome the above difficulties. The main emphasis in the present receiver system design is to obtain long periods of interference-free observation over as large a patch of sky as possible in a single observation schedule.

For this receiver, the **N-S** array is divided into 23 groups. After amplification in the field, the signals are carried on open wire transmission lines to the observatory building. The signals are amplified and then down converted to an intermediate frequency (IF) of 4 MHz in a heterodyne receiver. Each one of the 23 IF outputs from the N-S arm is correlated with the E-W arm IF output using one bit correlators. Each correlator extracts the in-phase (Cos) and the quadrature (Sin) correlations which are recorded on Magnetic tape.. The Fourier transform of these visibility data yields the brightness distribution of the sky along the meridian.

This new receiver permits observation of a 15° patch of sky (in the **N-S** direction) with **46** beams. The resolution is 26 x 40 sec ZA arc mins (where ZA is the zenith angle). The sensitivity is around 20 Jansky. The frequency of observation can be switched to an interference free window by changing the local-oscillator (LO) frequency within a 2 MHz band. A variable bandwidth filter in the E-W array signal path helps to eliminate narrow band interference when present, by cutting down the bandwidth.

The receiver system consisting of the subsystems described below has been designed, built and tested at the Raman Research Institute and is now installed at Gauribidanur.

Front End Amplifiers:- These are high gain, low noise amplifiers designed for low receiver noise temperature and low intermodulation distortion. The brief specifications are:

Centre Frequency = 34.5 MHz
Gain = 40 dB
3dB Bandwidth ≈ 4 MHz
Noise Temp. = 600 K
Third Order Intercept = +2 dBm

32 Channel Heterodyne Receiver:- Signals from the antenna are down converted to 4 MHz in this part of the receiver system. The IF bandwidth of the receiver is 450 KHz. It has a synthesized signal generator for its LO. The LO frequency can be varied from 29.5 to 31.5 MHz; this permits changing of the observation frequency over a 2 MHz band to obtain interference-free observation. An EPROM in the LO system, controlling the phase shifts at different frequencies ensures identical RF phase for all frequencies

of observation.

32 Channel Quadrature Samplers:- One-bit digital correlators are used to measure the complex visibility function. The IF signal in each channel is infinitely clipped and sampled in two samplers. The sampling clocks are separated in time by 62.5 nanoseconds to obtain quadrature samples. This digital technique is an economical way of obtaining quadrature samples for a . Double Sideband system.

E-W Receiver System:- This has three selectable bandwidths of 425, 275 and 100 KHz, allowing a choice for interference-free observations. After sampling, the signal passes through a variable delay shift register. This allows one to compensate for time delays introduced by the narrow-band filters and to compensate for the delay difference between E-W and N-S signals, thus reducing bandwidth decorrelation.

This thesis also describes a digital technique to reduce the bandwidth of a signal after infinite clipping.

Magnetic Tape Interface:- An incremental magnetic tape recorder is used to record the visibility function. The interface enables an observer to load in the details of the observation and to control writing speed and record lengths.

Astronomical Clock:- Accurate sidereal time information is essential in astronomical observations. A precision Solar/Sidereal clock using Cos/Mos IC's was specially designed and built. The system contains the necessary interface circuits for use with the telescope.

Test Correlator:- This measures and displays the auto/cross correlation function for any fixed delay (Selectable by a Thumb Wheel Switch) and is useful for the measurement of the phase mismatch between any two amplifiers or samplers. It can also be used to measure the delay between two signals.

Antenna and Field Test Equipment:- Antenna testing is essential before a long stretch of observation. A special instrument has been designed to replace the signal generator, vector Voltmeter and counter normally required for the purpose. This self-contained instrument also avoids the need for a power inverter which would otherwise be required to power the standard instruments in the field.

Interference Monitor:- A simple and inexpensive instrument to detect interference and indicate interference free bands has been designed.

Testing and Observation:- Various tests using CW and noise were conducted in the laboratory. The performance of the system was found satisfactory. The receiver system was then installed at Gauribidanur and actual astronomical sources were observed using the receiver system. Initial results have been satisfactory. This thesis includes a description of the testing procedures and the results of some astronomical observations.

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CHAPTER 1

INTRODUCTION

1.1 EARLY YEARS OF RADIO ASTRONOMY

The science of Radio Astronomy had its beginnings in the experiments of Karl G. Jansky in 1931. He was studying the direction of arrival of thunderstorm static. Using this information Bell Telephone Laboratories intended to design beam antennas for transoceaonic radio-telephone circuits, with minimum response in the direction in which thunderstorm static was predominant. For this purpose Jansky built an antenna which was about 100 ft. long and 12 ft. high operating at a wavelength of 14.6 m. The antenna was connected to a sensitive receiver. Jansky was able to identify three groups of static: 1. From local thunderstorms, 2. From distant thunderstorms, 3. A steady hiss type static of unknown origin. It was after a series of observations that he was able to detect the origin. Jansky wrote a paper in the I.R.E. proceedings (1935) in which he said "radiations are received any time the antenna is direted towards some part of the milky way system, the greatest response being obtained when the antenna points towards the centre of the system. This fact led to the conclusiqn that the source of these radiations is located in the stars themselves or in the interstellar matter distributed throughout the milky way. Jansky was well aware of the astronomical importance of his discovery. But he did not obtain support from his employers for his plans to further investigate this radiation. It was many years later in 1944 that Reber, a radio engineer living in Illinois, published the firt maps of the radio sky. ·These maps show the background radiation at 1.87 m. Prof. J.H. Oort, director of the Leiden Observatory, read Reber's article and was quick to perceive that the radiation Reber and Jansky had observed must be a continuum in radiation extending over a broad spectral region from wavelengths less than 1 meter to many meters. He suggeted that if some monochromatic line radiation existed in this radio spectrum significant advances could result. In 1944 his student Van de Hulst reported that neutral Hydrogen in interstellar space was a likely source. It had a natural frequency of 1420 MHz (21.1 cms) corresponding to a transition between two closely spaced energy levels of the ground state related to the relative orientations of the electron and nuclear spin. Ewen and Purcell of Harward university ,Muller and Oort at Leiden and Christiansen at Sydney observed this line in 'emission around the same time in the year 1950. Since then, Hydrogen line observations have been of immense value particularly in mapping the structure of our galaxy. Since these discoveries, radio astronomy has rapidly beome a major branch of astronomy. The main reason is that the Radio window extends from about 1 mm to 10 m. (about 13 octaves). Atmospheric molecular absorption and ionospheric reflection decide the wavelengths limits for ground based observations.

Radio waves are about one hundred thousand times longer than light waves and regions of space that are opaque to light waves are frequently transparent to radio waves and vice versa. But this long wavelength also makes it difficult to see much detail. To obtain high resolving power, huge mechanical structures which are scaled up versions of optical devices have been built. New devices which had no optical analogue have therefore been invented for use in radio astronomy.

1.2 **RADIO-TELESCOPES**

A radio-telescope in its simplest form consists of three elements, 1. An antenna that selectively collects radiation from a small region of sky, 2. A receiver that amplifies a restricted frequency band from the output of the antenna, 3. An indicator that registers the radiometer output so that it may be recorded by the observer.

1.2.1 Antennas

A variety of antennas of different forms have been built to suit the large range of wavelengths over which radio observations are made. Quasi-optical antennas such as the parabolic refletor are most appropriate for milli- meter wavelengths. At the other end of the radio spectrum, multielement arrays of elementary dipole antennas are suitable for decameter wavelengths. Conceptually, it is simpler to consider first antennas as radiators rather than receivers of radio waves.

The general characteristics of an antenna are:

Input impedance (Z_i), polarization, radiation pattern $P(\theta,\phi)$ gain or directivity $D(\theta,\phi)$, effetive collecting area $A_e(\theta,\phi)$, bandwidth and pointing accuracy.

A few important relations between these characteristics are: The power pattern of the antenna is defined as the effective area in any direction normalised to unity in the direction of' maximum response

$$P(\theta,\varphi) = A_e(\theta,\varphi)/A_{max} \tag{1.1}$$

Directivity is defined in terms of radiated power $P(\theta,\phi)$ per unit solid angle and the total power radiated (P_T) by the antenna as:

$$D = P_{Max}(\theta,\varphi)/(P_T/4\pi) \tag{1.2}$$

Where

$$P_T = \iint_{4\pi} P(\theta,\varphi)\, d\Omega \tag{1.3}$$

$$\therefore D = 4\pi / \iint_{4\pi} P_n(\theta,\varphi)\, d\Omega \tag{1.4}$$

$$D = 4\pi / \Omega_A \tag{1.5}$$

where $P_n(\theta,\varphi)$=normalised power pattern.

Ω_A is known as the beam solid angle. From thermodynamical considerations it can be shown that the product of the effective aperture of the antenna and the antenna beam solid angle is equal to the wavelength squared:

$$\lambda^2 = A_e \Omega_A \tag{1.6}$$

when the antenna is used as a receiver in radio astronomy, the power received by the antenna depends upon the radio brightness of the sky. This desribes the flux density per unit solid angle of the sky as a function of the direction.

$$B(\theta,\varphi) = \Delta S / \Delta \Omega \quad (\text{watts}|\text{m}^2|\text{Hz}|\text{Ster}) \tag{1.7}$$

The polarised component of the radiation matched to the antenna polarisation has the radio brightness:

$$B_m(\theta,\varphi) = \Delta S_m / \Delta \Omega \tag{1.8}$$

For a randomly polarised source: $B_m = B/2$ (1.9)

The total power per unit bandwidth due to radiation received from the sky is given by:

$$P = \frac{1}{2} \iint B(\theta,\varphi) P(\theta,\varphi) \, d\Omega \tag{1.10}$$

$$P = \frac{1}{2} A_e \iint B(\theta,\varphi) P_n(\theta,\varphi) \, d\Omega \tag{1.11}$$

P is often equated to the thermal noise power available from a resistor at a temperature T_a, with the resistor replacing the antenna at the input of the receiver. The temperature T which corresponds to a power per unit bandwidth P is given by the nyguist formula:

$$P = KT \text{ watts/Hz} \tag{1.12}$$

K = Boltzmann constant.

The temperature T_a of the fictitious resistor is called the antenna temperature. In an analogous way radio brightness (B) can also be expressed in terms of a temperature (T_B). At radio wavelengths the relation between B and T_B is given by Rayleigh's classical approximation:

$$B = 2KT_B/\lambda^2 \tag{1.13}$$

The thermal radiation from a black body is randomly polarised; thus:

$$B_m = KT_B/\lambda^2 \tag{1.14}$$

and

$$T_a = (A_e/\lambda^2)\cdot\iint T_B(\theta,\varphi)\,P_n(\theta,\varphi)\,d\Omega \tag{1.15}$$

Let the antenna be terminated by a matched resistor and the whole system placed in a black body at a real temperature T. The system reaches equilibrium and $T_a = T_B(\theta,\phi) = T$

Thus we find:

$$\iint P_n(\theta,\varphi)\, d\Omega = \lambda^2/A_e \qquad (1.16)$$

1.2.2 Radio-Telescope Receivers

The receiver system selects and amplifies the signal received by the antenna and provides an output signal to a recording device. The radiation coupled to the receiver by the antenna has the same statistical properties as the noise originating in the receiver. Figure 1.1 shows* the block diagram of a typical superheterodyne receiver. This is the most common type of receiver used in radio-telescopes. If the R.F (Radio Frequency) amplifier is tuned to receive only the sum or difference frequencies of Local oscillator (L.O) and intermediate frequencies (I.F), it is known as a single sideband (SSB) receiver. A receiver which responds to both the frequencybands is known'as a Double sideband (DSB) receiver. The input power level to the receiver is quite small and is of the order of 10^{-15} to 10^{-20} Watts. Typical bandwidths vary from a few hundreds of KHz for decameter wave observations to tens of MHz for mm wave observations. Output integration times used vary from a few msecs. to tens of minutes. The most important characteristics of a receiver are:

1. It's ability to measure the amplitude and spectral characteristics of the input signal.

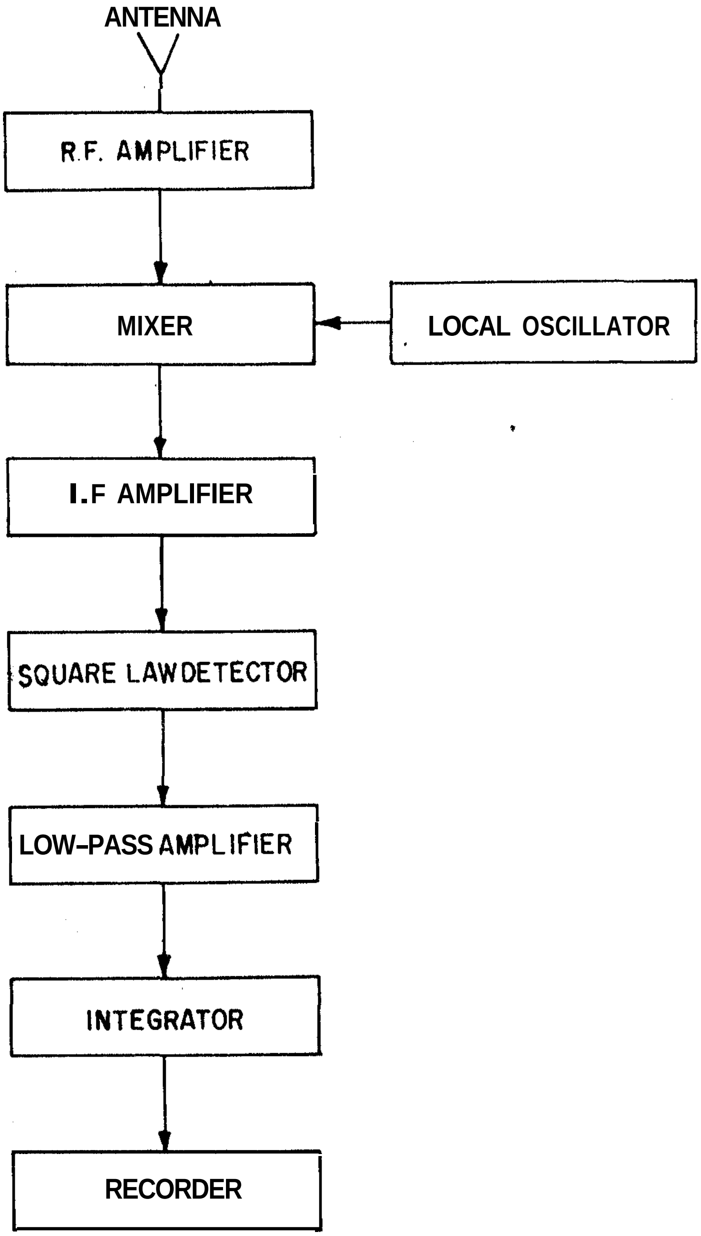

FIG. 1·1. A SUPERHETERODYNE RADIO-TELESCOPE RECEIVER.

2. It's linearity when operated over a wide dynamic range.

3. It's ability to add minimum noise to the signal being amplified.

The receiver noise temperature T_n is a figure of merit for a receiver. This represents the output that would be obtained even if a matched load at absolute zero were connected to the input terminals. The temperature is referred to the input terminals of the receiver 'to make it independent of the gain.

A radio-telescope pointed towards a source results in a system temperature T_{sys} which is the sum of the following contributions:

1. Antenna temperature attributable to the observed source, T_a

2. background radiation and the power received through the sidelobes, T_B

3. and the receiver temperature T_n,

$$T_{sys} = T_a + T_B + T_n \tag{1.17}$$

In order to predict the performance of a system and compare different types of systems the concept of a minimum detectable signal has been established, It is the signal that causes a deflection at the receiver output equal to the standard deviation of the output fluctuations about the mean. From statistical considerations it can be shown to be

$$\Delta T = T_{sys}/\sqrt{B\tau} \tag{1.18}$$

T_{sys} = Total system temperature, B = Noise equivalent rectangular bandpass, τ = True integration time at the receiver output.

In practice three to five times ΔT is considered a reliable value for detection of a weak source. Also, gain (G) and bandpass (B) changes, (receiver instabilities) can set the limit on the system sensitivity. Then we have

$$\Delta T = T_{sys} \left[\frac{1}{B\tau} + \left(\frac{\Delta G}{G}\right)^{2} \cdot \frac{T_G}{\tau} + \left(\frac{\Delta B}{B}\right)^{2} \cdot \frac{T_B}{\tau} \right]^{\frac{1}{2}} \tag{1.19}$$

T_G and T_B are the time scales of the gain and bandwidth fluctuations

Several types of switching receivers like Dicke receiver, Grahm's receiver and gain modulation receivers are used in radio astronomy to overcome the gain instabilities of the receiver. (Dicke, 1946; Graham, 1958; Orhaug and Waltman, 1962).

1.2.3 Confusion

The system sensitivity sometimes gets limited by the response of the radio telescope to multiple unresolved sources in its beam. Such a response has similar statistical properties as receiver noise and is known as "confusion':. However confusion noise cannot be reduced by increasing the integration time, and/or the observing bandwidth since it repeats in successive observations. It can be decreased only by increasing the resolution. Sensitivity at decameter wavelengths is more often limited by confusion, due to the difficulty of obtaining a high enough resolution at large wavelengths.

1.2.4 SURVEYING SENSITIVITY

When a telescope is used to survey a region very much larger than the angular size of its beam, the time taken to complete the survey should be included in a broad definition of sensitivity. Such a definition brings out the advantage of the technique used for surveying.

Surveying sensitivity is defined as the flux density of the weakest source that can be detected with confidence in a survey of a particular region of sky when the whole survey is completed in a total time t.

1.3 INTERFEROMETRY

Because radio wavelengths are relatively long compared to optical wavelengths, the resolving power of single antenna radio-telescopes is not as good as those of their optical counterparts. The resolution of large optical telescopes is limited by atmospheric disturbances. The resolution of a single antenna radio-telescope is limited by its diffraction pattern. From the early days of Radio astronomy,astronomers have looked for ways of increasing their resolving power.By 1963 fan beams of the order of 1 minute of arc were obtained by the use of interferometer techniques, (eg. Swarup et al 1963). A radio interferometer consists of two antennas separated by a distance d and having the outputs multiplied in a correlator. It is designed to give an output proportional to the average product of the voltages from the two antennas. The interference between the voltages from the two antennas causes a modulation of the normal power pattern(Fig 1.2). This interference pattern occurs only when the source is not large compared with the angular distance λ/d between the adjacent fringes. Such an interferometer is insensitive to radio waves from directions for which the phase difference has the value given by:

$$\phi = \pi/2 + i\pi, \; i = 0,1,2 \cdots \qquad (1.20)$$

A receiver with this response may be called a cosine receiver. Another receiver which responds to waves in these directions can be built by adding an extra quarter period delay in front of one of the two inputs, and may be called a sine receiver. The output of these two receivers together provide the "complex visibility". Interferometers with spacings, d,2d.......result in responses:

$\cos\phi + j\sin\phi$, $\cos 2\phi + j\sin 2\phi$, ...

Where $\phi = (2*\pi/\lambda) * d * \sin\theta$

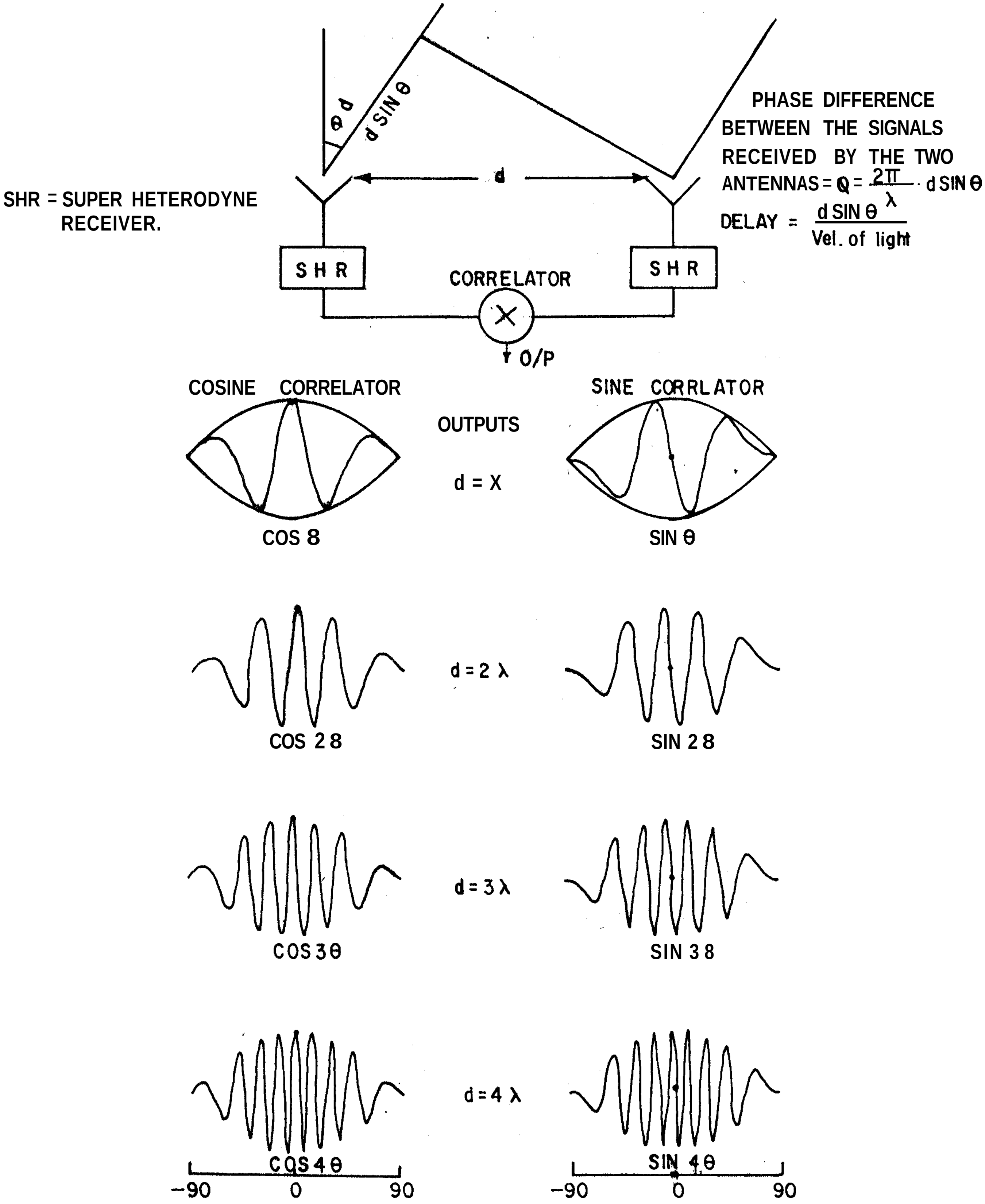

FIG.1·2 INTERFERENCE PATTERNS OF A TWO ELEMENT INTERFEROMETER.

θ =Zenith angle

Thus each interferometer spacing can be thought of as measuring a Fourier component of the brightness distribution in the sky. Telescopes which produce maps of the radio brightness of the sky by Fourier synthesis of the measured values of the complex visibilities are known as "synthesis telescopes". They have a multibeam forming capability . Their advantages are discussed in Section 2.1.

In an interferometer, the signals do not in general reach the two elements at the same instant of time. Thus the signal at one of the inputs of the correlators is a delayed version of the other input. Since the input has a finite bandwidth, the interference fringes are not only modulated by the normal power pattern of the two elements . but also by the "Auto correlation" function of the signal band used. This is known as "Bandwidth decorrelation".

1.4 SCOPE OF THE PRESENT WORK

The present thesis describes the design, development and field tests of a digital multibeam forming receiver for a decametric array situated at Gauribidanur,India (Latitude=13° 36' N ;Longitude=77° 26' E). The decametric radio region contains a variety of astronomical sources. At these wavelengths they are much brighter than they are at lower wavelengths. The intensity of background radiation varies from around 40,000 K in the direction of the galactic centre to about 5,000-10,000 K in the direction of poles. Cas A is one of the strangest sources in the sky at this frequency with a flux of around 40,000 Jansky. (1 Jansky = 10^{-26} Watts/m^2/Hz). At these wavelengths, synchrotron radiation is the dominant type of radiation. There are not many radiotelescopes in the world which operate at these wavelengths. The main reasons for the relative neglect of the decameter wavelength region are

1. To obtain even reasonably modest resolutions of the order of 1°, one needs an aperture of large size. Thus its erection and maintenance are labour intensive.

2. Man made radio interference is very high at these wavelengths and render high sensitivity studies difficult.

3. Ionospheric variations makes antenna amplitude and phase calibrations very difficult.

Thus the main emphasis in the present receiver system design is to obtain long periods of interference free observation over as large a patch of sky as possible in a single observation schedule. Some of the important hardware innovations described in this thesis are:

1. A digital hybrid technique to generate quadrature samples of a band pass signal.

2. A simple scheme using one-bit correlators to obtain amplitude information of the signal which is lost during one-bit quantisation.

3. A simple scheme to correct for the true thresholds of the zero cross detectors used in one-bit correlators.

4. Usage of narrow band filters in the path of only one of the inputs of a cross correlator. Derivation of Signal to noise ratio (SNR) of such a scheme for one-bit DSB correlators.

5. One-bit filter design and discussion of its limited utility.

This thesis also describes continuum and line observations made using this receiver at Gauribidanur. Continuum observations and maps produced in this thesis clearly demonstrate the instrument's suitability for an all sky survey at 34.5 MHz.

The instrument can play a very prominent role in understanding galactic radio background and the contribution of discrete sources to it at these frequencies. Detection of low frequency recombination lines in the direction of Cas-A and attempts to detect the same in the direction of Crab,Cygnus and Galactic centre have been reported in this thesis. Spectral studies of various regions will indicate the percentage of thermal radiation in the galactic continuum and the attenuation of the radio background by HII regions.

This instrument can also be used in the study of the following interesting astronomical phenomena.

1. Sun: At low frequencies the Corona of the Sun is opaque. The radiation observed gives a direct measure of temperatures at different heights. The decametric radio range contains a multitude of burst phenomena with time scales ranging from milliseconds to minutes. A line receiver can be efficiently used to study the frequency structure of the bursts.

2. Interplanetary Scintillations are caused by the refraction of radio waves by the moving electron density irregularities due to solar wind. Statistical studies of the amplitude fluctuations of the radiation from distant sources can be used to infer the properties of irregularities, source size and sometimes source structure.

The low frequency observations can be a very useful tool to study the ionosphere.

3. Pulsars: The line receiver can be efficiently used to study high Dispersion measure pulsars. Existence of interpulses at low frequencies, detection of pulsars hitherto undiscovered due to sensitivity limitations and interstellar scintillation of pulsars can be studied.

4. Galactic Halos: Radio observations at these frequencies will reveal new facts about the Galactic halo which is an extensive spherical volume surrounding the galaxy probably laced by magnetic fields.

5. Cosmology: In the last few years counts of extragalactic sources as a function of their apparent strength have come very close to distinguishing between the many cosmological models of our universe.. Studies of weak extragalactic sources by this array may throw light on log N - Log S curves and lead to a better cosmological interpretation. Study of red shifted Hydrogen lines may throw light on the nature of the Universe.

6. Serendipitous Discoveries: There have been very few sky surveys in the declination ranges this telescope can cover. Important serendipitous discoveries may also be made when the receiver system is used for observations on a round the clock basis.