CHAPTER – II

RADIO INTERFEROMETERS - A SURVEY

2.1 Radiotelescopes - Historical Review

For thousands of years, man has watched the sun, the moon, the stars and the comets. By these visual observations man slowly learned the laws of movement of these celestial bodies. The invention of the optical telescope in the 15th century allowed these celestial bodies to be seen in much greater detail than before. In later years, as the knowledge of optics advanced, it became clear that the aperture of the telescope has to be very large compared to the wavelength of light in order to see the very fine structure of the objects being observed. Therefore, telescopes of larger and larger apertures were built in succeeding years. It has been known for quite some time that the sun and the stars emit EM radiations ranging from X-ray to Radio frequencies. However, attempts to receive these emissions from the sun by Sir Oliver Lodge [7], a well known radio pioneer, way back in 1894 were unsuccessful as radio techniques were still primitive. Karl G. Jansky is credited to be the pioneer in the first unambiguous detection of extraterrestrial radio emission [8]. Using a Bruce array which was directional and steerable in azimuth (Fig. 2.1), he recorded the data output of the radio receiver as the antenna was rotated. Apart from the static from local and distant thunderstorms, which was the object of this investigation, he also found a 'steady hiss' type of static of unknown origin. The time of the day of the maximum of this hiss was found to steadily advance daily by four minutes, suggesting that the source of this hiss was celestial. Important aspects of

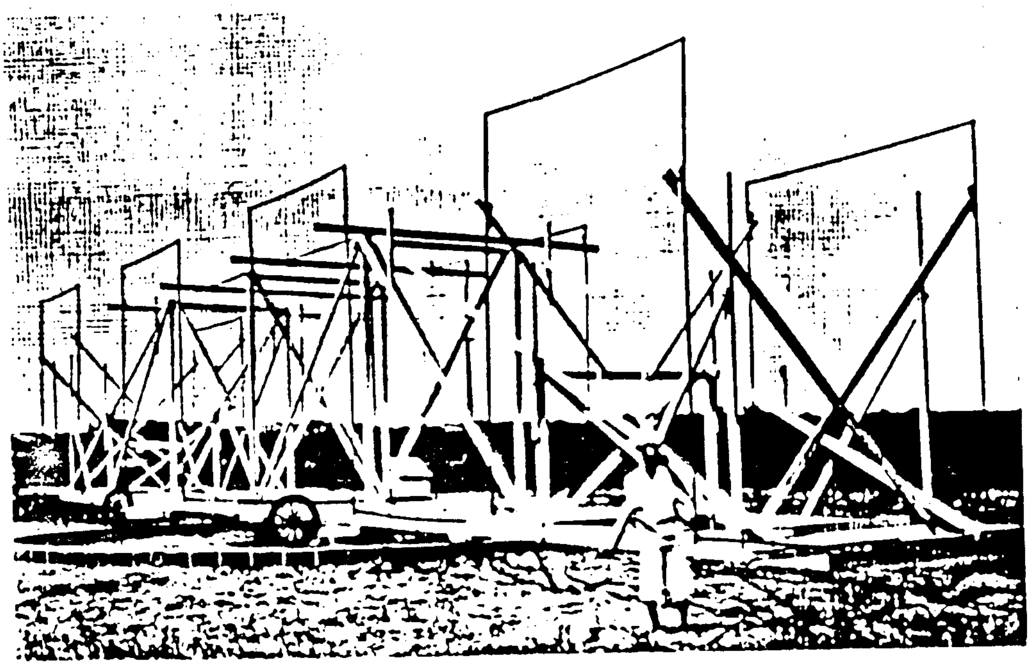

Figure 2.1 The BRUCE Array Used by Karl G. Jansky

this system are *summarised* in Table 2.1.

TABLE 2.1

KARL G. JANSKY's DETECTION SYSTEM FOR EXTRATERRESTRIAL RADIO SOURCES

Year Installed	Operating Frequency	Antenna	Steerability	Remarks
1929-30 [9,10]	20.53 MHz	Bruce array (29 m long)	Rotatable in azimuth	First observation of radio emission from extraterrestrial sources

The importance of these results took a while to be *recognised* but from then onwards radio astronomy rapidly became a major branch of astronomy. As radio waves are about a million times longer than light waves, and regions of space that are opaque to light waves because of interstellar dust are transparent to radio waves, radioastronomy found widespread acceptance leading to very rapid developments in later years. However, this *millionfold* longer wavelength makes it extremely difficult to see as much detail in the sky with radiotelescopes, as with their optical counterparts. Therefore it is nessary to have radio telescopes a million times longer to see equal amounts of detail as with an optical telescope. For example, *a* radiotelescope receiving emissions at $\lambda = 20$ cm, needs **an** aperture of about 1000 Km to give the same amount of resolution as would a large *optical* telescope. As radioastronomy progressed, the need for systems with better and better resolution started to mount. This lead to several innovations both in electronics and antenna engineering complementing each other. **A** direction of progress that needs special mention here, is the method devised to obtain higher and higher resolution in radio maps. This is now discussed.

2.2 Filled Aperture Radiotelescopes

The first radiotelescope designed for *astronomical* purposes **was** built by Grote Reber in **1937** *[11].* It **was** a single parabolic dish equivalent of the optical *reflecting* type telescope (Fig. 2.2). But it had many limitations. The resolving power being dependent on the ratio of wavelength to the diameter of the aperture, could be improved either by decreasing the wavelength or by building telescopes of larger aperture. The minimum wavelength of observation is usually restricted to a few mm by the absorption of shorter wavelengths in the Earth's atmosphere. *Also,in* general, radioastronomers are interested in the spectral characteristics of radiation from radio sources and hence wish to observe them at various wavelengths. There is also an upper limit to the size of a steerable paraboloid on account of the structural problems which limits the size of its aperture. Therefore single dish antennas *generally* suffer *from* limited resolving power. *In* order to overcome these inherent limitations, antennas with multiple support points from the ground were *designed,leading* to parabolic cylindrical reffector type antennas (Fig. **2.3).** But these antennas have steerability only in one axis, making it necessary to place them along the east-west or the north-south axes of the earth, so that the rotation of the earth could be made use of for steering in the non-steerable *direction.* For such *an* antenna the main disadvantage

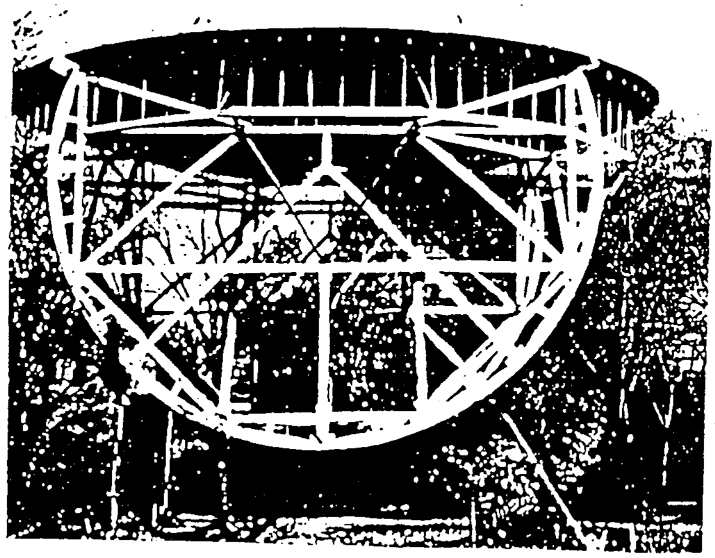

Figure 2.2 10m Parabolic Dish of First Radio Telescope

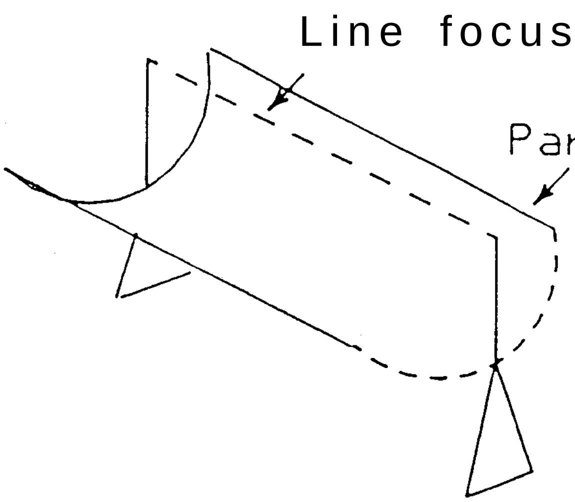

Figure 2.3 Parabolic Cylinder reflecting Telescope

is that the focus is now a line unlike a point as in the case of a paraboloid, which makes it very *difficult* for multiple frequency operation. Some of the well-known radiotelescope facilities using filled aperture antennas are summarised in Table 2.2

TABLE 2.2

RADIOTELESCOPES USING FILLED APERTURE ANTENNAS

Location/ Key Person	Period of Installation	Operating Frequency (in MHz)	Antenna size dia.(m) †	Resolution (min of arc)	Steerability	Remarks
Grote Reber	1936 [12]	160	10	11°	One axis	First radio astronomical telescope built
Mitaka Japan	1949 [13]	200	10	8°	Equatorial mount	Used for solar observation
Lebedev Inst. of Physics	1950 [14]	1420, 10,000	4	3°	Two axes	One of the early Russian telescopes
PT-22 U.S.S.R.	1953-54 [14]	37500	22	1.7 x 2.1	Two axes	First Russian high frequency telescope
J.D. Kraus	1956-62 [15]	20 - 3000	104 × 31 flat 110 x 21 curved	8° - 3	Tiltable flat, dec. only	Sky survey catalog at 1415 MHz (2 x 10^4 sources)

† Parabolic dish

contd...

Location/ Key Person	Period of Install- ation	Operating Frequency (in MHz)	Antenna size dia.(m) †	Resolut- ion (min of arc)	Steerability	Remarks
Jodrell Bank	1957 [16]	408	76	40 x 54	Alt-azimuth mount	World's first fully steerable radio telescope
Arecibo	1961 [17]	430	305 Spherical reflector	10	Tilting secondary ±20° zenith	World's biggest telescope
Parkes CSIRO	1961 [18]	136,400, 1420,3000	64	11	Two axes	First big telescope in southern hemisphere
Green Bank NRAO	1963 [19]	1400 - 4700 (tunable)	91	8	Declination only	Collapsed in '87 due to fatigue
Max Plank Bonn	1972 [20]	10,000	100	1.3	Two axes	World's largest fully tiltable telescope; 3200 tonnes of moving parts
Nobeyama Japan	1983 [21]	100,000- 150,000	45	14"	Two axes	Largestmm-wave instrument
MRT of IRAM at Spain	1986 [22]	75-115 140-170 216-236 GHz	30	11"	Two axes	Entire antenna is temperature controlled

† Parabolic dish

2.3 Unfilled aperture radiotelescopes

The limitations of filled aperture radio telescopes such as the paraboloids, and the parabolic cylinders, are overcome in another class of antennas which have unfilled apertures. Here, one can achieve an angular resolution of a large single filled aperture telescope while leaving out large portions of the aperture. The radio interferometer and the dilute aperture telescope are examples. But the interferometer is very special, in that it constitutes the basic building block for many unfilled-aperture telescopes.

2.3.1 Radio Interferometer : Two antennas separated by a distance of 'd' wave-lengths and having their outputs combined in a receiver constitute an interferometer (Fig.2.4). For radio waves from a direction θ, for which the path difference $p = d \sin\theta = n\lambda$, the voltages add at the input of the receiver; and for directions for which the path difference $p = (n+1/2)\lambda$ the voltages cancel each other as they are out of phase. The resulting interference between the two voltages from the antennas modulates the normal power pattern as the earth's rotation changes the angle θ. This interference pattern occurs only when the size of the source is comparable or smaller than the angular distance $1/d$ of the interferometer. As the distance between the two elements (antennas) of the intereferometer is increased, the interference patterns disappear when the angular distance $1/d$ becomes smaller than the size of the source. Hence, one can use this technique to determine the size of astronomical sources and this has attracted considerable attention. Some of the well known Radio Interferometers are listed in Table 2.3.

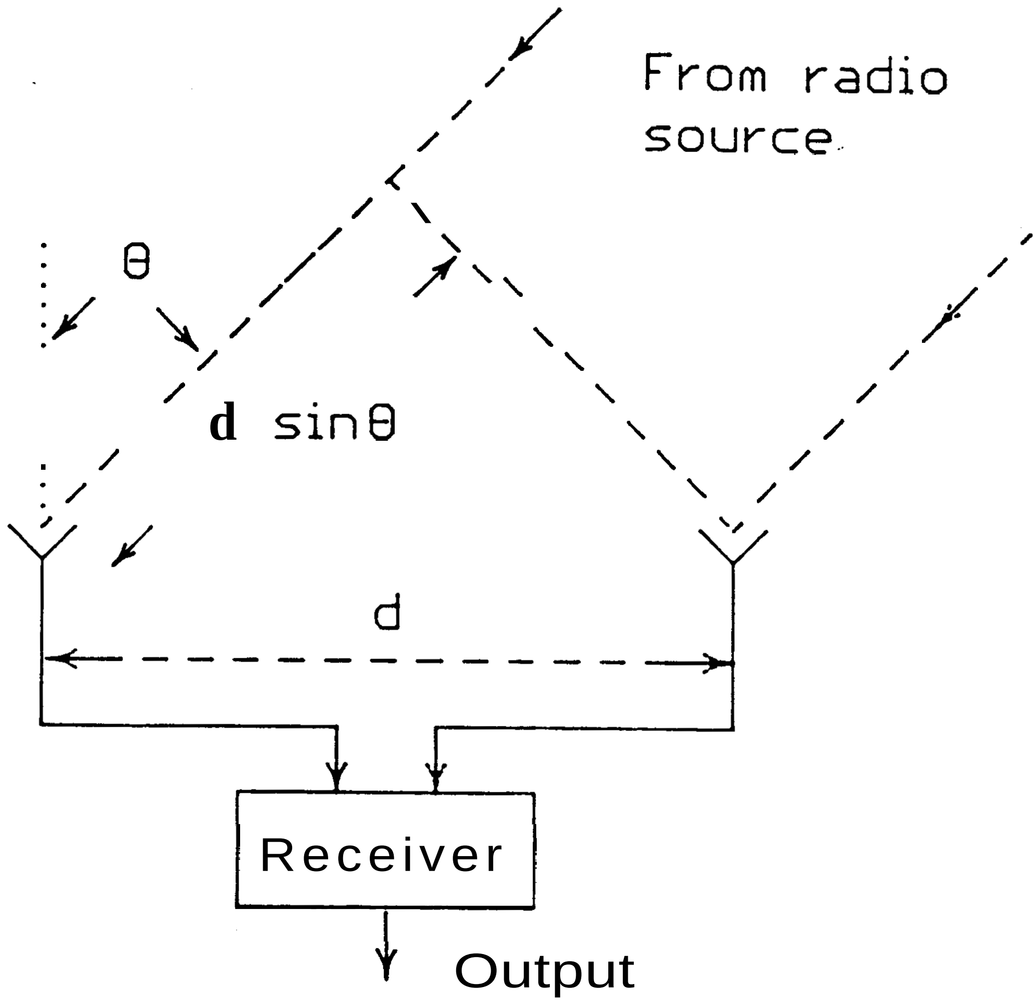

Figure 2.9 Simple Interferometer

TABLE 2.3

SOME WELL KNOWN RADIO INTERFEROMETERS - A SUMMARY

Location/ Key Person	Period of Install-ation	Operating F'requency (MHz)	Antenna size (m) Baseline (m)	Resolut-ion (min of arc)	Steerability	Remarks
Crimea Vitkevich	1954-55 [15]	51,85	2 of 30m † BL: 740	16	Transit instrument	Used in solar supercorona studies
Ohio J.D.Kraus	1955-57 [23]	27	3 Helices 7.3 x 3.3 BL: 30	12°	By rotating the extreme helices	Used in solar and planet observations
National Bureau of standards	1950's [24]	53,108 470	2 of 12m † BL: 475	43, 20, 4.6	One axes	Ionospheric scintillations study
Nancay Meudon	1956 [25]	169	32 of 5m † BL: 1550	3.8	Declination only	Precise position measurements
Fleurs	1960's [26]	1420	32 of 5.5m † 1 of 18m† BL: 400	1.5	32 - one axis 1 - two axis	Compound interferometer
Hat Creek	1971 [27]	19000 - 25500	3m, 6m † BL: 265	10"	Equatorial mount	Interstellar water vapour source position studies
Bordeaux	1973 [28]	35,000	2 of 2.5m † BL: 64	28"	Two axes	mm-wave solar studies

† Parabolic dish

2.3.2 <u>Dilute Aperture telescope</u>: An aperture shown in Fig. 2.5 can be imagined to be made up of smaller elements. Each of these will be collecting energy due to the radiation falling on it. At the receiver, the contribution from each element will produce interference patterns with each of the other $(N-1)$ elements. This will have a total of $N(N-1)/2$ interference patterns, which includes *all* the possible orientations and spacings. It is seen that in the square aperture of Fig *2.5b,* the *(N-1) interference* patterns of element X with all other elements and the (N-2) interference patterns of the element Y with ail other elements cover *all* the orientations and distances covered by the $N(N-1)/2$ patterns of Fig. *2.5a.* Therefore, these $(2N-3)$ patterns contain the same *information as* the $N(N-1)/2$ patterns. Hence there seems to be some redundancy in the information gathered in a filled aperture antenna. Thus, it is possible to design an aperture, which has *all* the essential spacings and orientations of the *axis,* for the necessary interference patterns, but which has a much reduced *total* area. This is the basis of the skeleton telescope commonly called the Dilute Aperture. Fig. 2.6 shows one such telescope, which is in the form of a 'T'. The vertical arm is made up of N elements and the horizontal arm is made up of $2N$ elements. This would lead to $2N^2$ different interferometer pairs and the patterns thus obtained *form* ail the spacings and orientations found in the $N(N-1)/2$ patterns obtainable from the aperture A of Fig.2.6. It is very clear *from* the figure that the 'T' occupies a much reduced area than the square aperture '**A**'. Some well known telescopes of this class are *summarised* in Table 2.4.

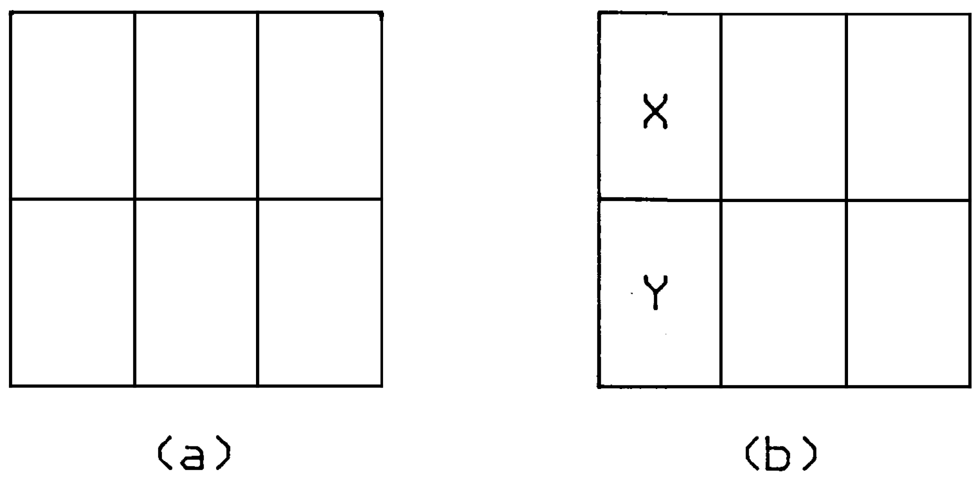

Figure 2.5 Square Aperture split into smaller elements

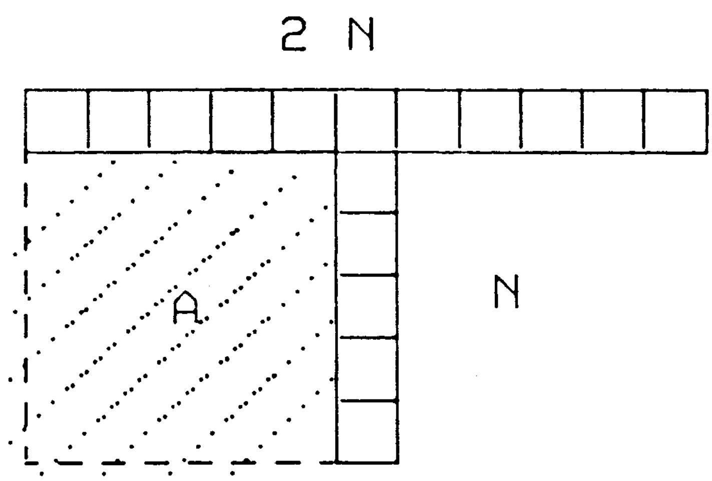

Figure 2.6 Skeleton Telescope

TABLE 2.4

SOME WELL KNOWN DILUTE APERTURE TELESCOPES

Location/ Key Person	Period of Install-ation	Operating Frequency (MHz)	Array size (m)	Resolut-ion (min of arc)	Steerability	Remarks
J.D. Kraus	1952-53 [29]	150-300 (tunable)	49 x 7 platform; 96 helices	1.2° x 8°	Tiltable in one axis	Used for 250 MHz sky survey
Fleurs B.Y.Mills	1954 [30]	85.5	457; Cross form; 1000 dipoles	49	Declination only	First high resolution array
Sydney C.A.Shain	1955-56 [31]	19.7	GW 1035, N-S 1100; Cross form	1.4°	In dec. by phase switching	Interstellar dust studies
Krest-MILSA U.S.S.R.	1956 [15]	200	40 x 1000 Cross form; Cylindrical parabolid	5	E-W dec. tion only; N-S fixed	Spiral arms and solar studies
Potts Hill Christiansen	1956-58 [32]	1420	64 of 5.8m † Cross type; BL: 380	3	One axis	Combination of multielement interferometer and Cross
Molonglo B.Y.Mills	1962-64 [33]	111.5, 408	12 x 1600; Cross form; Cylindrical parabolid	10, 2.8	Transit instrument; Declination only	Southern hemi-sphere's first low frequency high resolution telescope

† Parabolic dish

contd...

Location/ Key Person	Period of Install-ation	Operating Frequency (MHz)	Array size (m)	Resolut-ion (min of arc)	Steerability	Remarks
Tasmania G.Reber	[34]	2.1	1100 dipoles	≈ 8°	Phased array	World's lowest frequency telescope
CLRO Erickson	1972 [35]	15-130 (tunable)	E-W 3000 N-S 1800; 720 conical spirals	3 - 27	Electrically steerable	Was one of the best broad band, low frequency telescopes
GEETEE India Ch.V.Sastry	1978-82 [36]	34.5	E-W 1400 N-S 450 1000 dipoles	26 x 42	Tracking by phase switching	One of the few working low frequency arrays

2.3.3 Aperture synthesis : Radio astronomical sources *can* be broadly classified into two groups:

a) Time varying sources

b) Non time varying sources

To observe time-varying sources. all the information required will have to be recorded instantaneously, because at a later instant of time the parameters measured will be different. In the latter class of sources, as they do not change from day to day, one could obtain the information about the brightness distribution over the source from a two element interferometer pattern taken one at a time. Hence, it is not necessary to have all the interferometer pairs to *be* present simultaneously. On the other hand, one could move one element of 'A' along the A arm and one element of 'B' along the B arm, obtaining different interference patterns for the different interferometer pairs thus formed (Fig. 2.7). This is known as Aperture Synthesis, as an aperture is synthesised using just two elements and this technique was pioneered by Sir Martin Ryle [3]. There will be $2N^2$ separate patterns, which contain all the information that was present in the filled aperture telescope of Fig 2.5 or the dilute aperture telescope of Fig. 2.6. This would increase the observation time by a factor of $2N^2$, to make the same observations, with the same sensitivity for a point source, than in the previous cases. However there is one more facet, which makes aperture synthesis more attractive. Consider that the basic elements of all these telescopes are the same and have a collecting area of 'a' square wavelengths. Then the $2N^2$ observations made by the aperture synthesis telescope, will have information about the brightness distribution of a region of the sky to an extent of $1/a$ steradians. On the other hand, the filled aperture or the dilute aperture telescope would have a collecting area of 'N^2a' square wavelengths as the outputs from each of the basic elements are usually combined to form a single output. This would lead to a sky coverage of $1/N^2a$ steradians which is N^2 times smaller. Hence, to cover the same patch of the sky, the Aperture synthesis telescope would require twice the observation time as the filled aperture or the dilute aperture telescope. Table 2.5 gives a summary of some well known aperture synthesis radiotelescopes.

2.4 A Typical Radio Interferometer

The block schematic of a typical Radio Interferometer is shown in Fig 2.8.

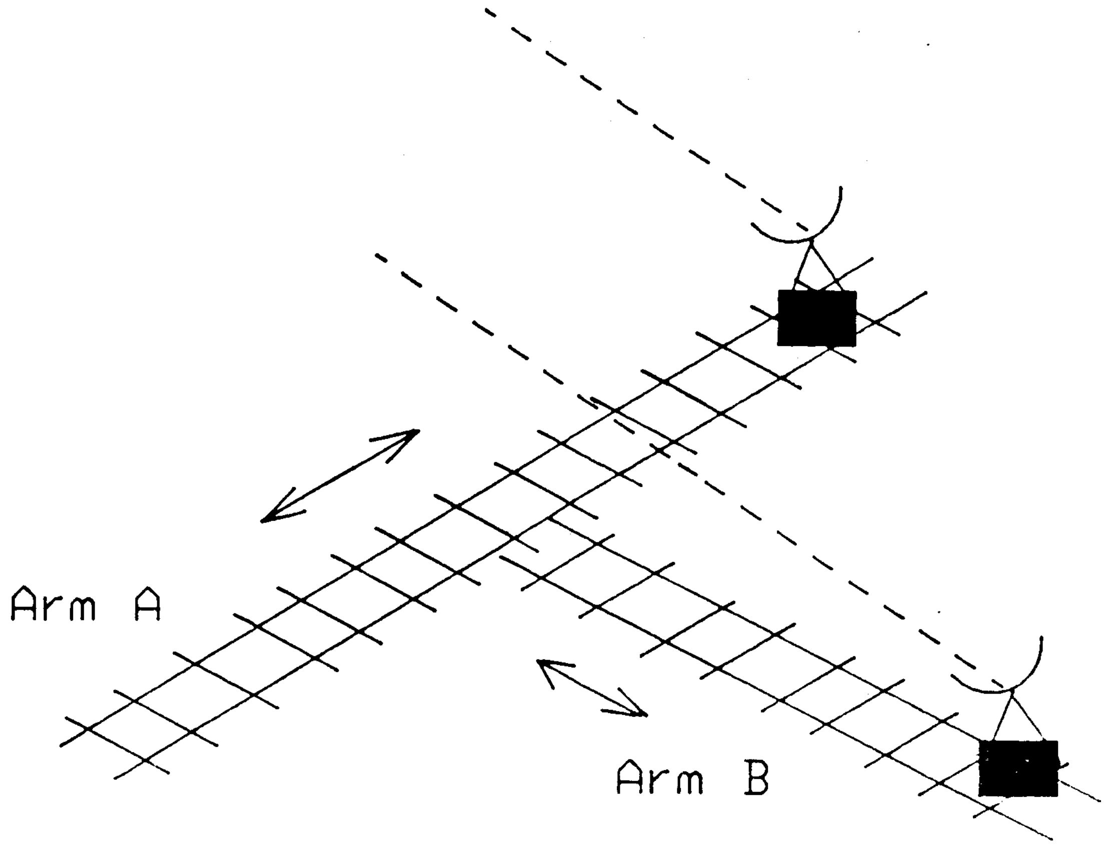

Figure 2.7 Tuo Element Aperture Synthesis - Principle

TABLE 2.5

SOME APERTURE SYNTHESIS RADIO TELESCOPES

Location/ Key Person	Period of Installation	Operating Frequency (in MHz)	Antenna size; Baseline(m)	Resolution (sec of arc)	Steerability	Remarks
Cambridge M.Ryle and Hewish	1960 [5]	178	442 x 20m Mobile N-S on BL: 300	60	E W arm one axis	First aperture synthesis telescope
Stanford Bracewell	1965-67 [37]	10690	5 of 18m † BL: 200	19	Equatorial mount, dec. only	10 hrs observation possible
Green Bank	1967-68 [38]	2695	3 of 26m † BL: 2700	8	Two axes	NRAO's first
Fleurs Christiansen	1966-68 [39]	1415	4 of 13.8m † 64 of 5.8m † BL: 800	40	Equatorial mount	12 - 16 hrs observation possible
Westerbork	1970 [40]	610,1415 4995	10 fixed + 2 mobile; 25m † BL: 1600	24	Two axes	Uses earth's rotation for synthesis
Cambridge M. Ryle	1972 [41]	2700 5000 15000	8 of 10m † BL: 4560	3.8 2 0.67	Two axes	First array to see details comparable to optical telescope
OSRT G. Swarup	1973 [42]	327	530 x 30m, 2 of 12.5m † one 5m †	48 × 5.5	One axis	India's first synthesis radio telescope

† Parabolic dish

contd...

Location/ Key Person	Period of Install- ation	Operating Frequency (in MHz)	Antenna size; Baseline(m)	Resolut- ion (sec of arc)	Steerability	Remarks
VLA New Mexico	197480 [43]	1.34-1.73 4.5- 5 14.4-15.4 22-24 GHz	27 of 25m † BL: 20 km form of Y	< 1	Two axes	World's largest synthesis array
Nobeyama Japan	1983-84 [44]	22,000 115,000	5 of 10m † BL: 560 E-W 520 N-S	4.1 × 0.8	Two axes	mm-wave studies

† Parabolic dish

The signal flow and the relevent building blocks in this intereferometer are summarised in Table 2.6.

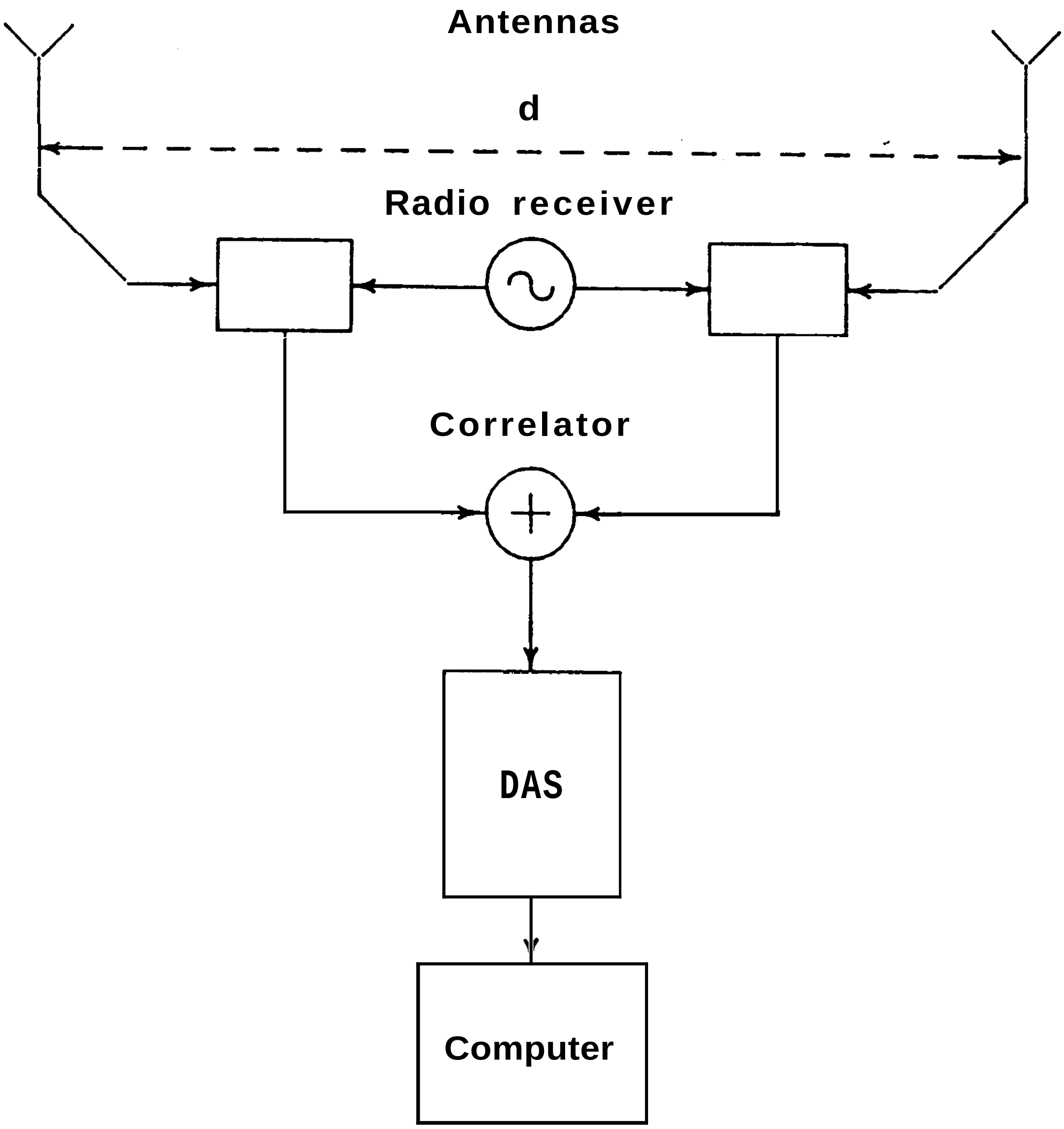

Figure 2.8 Typical Radio Interferometer

TABLE 2.6

SIGNAL FLOW IN A RADIO INTERFEROMETER

Building Blocks	Function	Remarks
Two Antennas separated by a distance 'd λ'	Reception of radio signals with time varying phase difference	Generally **fixed** Antennas; in some cases steerable in declination
Radio Receiver (with two arms)	- Signal amplification - RF to IF conversion	mostly Analog stages
Correlator	Multiplication of signals from the two arms	To produce interference **patterns;in** some cases using digital approach
Data Acquisition and recording	- Conversion to digital form, followed by data storage	Data generally stored in a secondary storage device
Computer	Analysis of observed data	Off-line machine; specification depending on location and need

The first input blocks of the radio interferometer being the antennas, receiving EM radiation from radio sources, they could follow any of the approaches discussed in the previous sections. Hence the antennas employed in interferometers range from simple dipoles to complicated fully tracking parabolic dishes operating at different *frequencies,* depending upon the need at each observatory. As the interferometer is the basic building block for all types of unfilled aperture telescopes, it is associated with the R F signal processing circuits that are generally found in any big telescope setup. The radio receiver used, generally employs double Superheterodyne technique for the conversion of R F to *IF signals* so **as** to obtain high image rejection. In the case of radio interferometers operating in the UHF band, it is often preferred to employ the first superheterodyning at the antenna site itself and the first IF is chosen to facilitate easy transmission of the signal *from* the remote antenna site to the central processing labarotary generally using a coaxial cable. The correlator that follows the receiver can employ a wide range of approaches, its complexity depending upon the factors such as frequency of operation, bandwidth of signals, and sampling periods. They could be broadly classified into analog or digital type based on their approach in the multiplication technique. Table **2.7** gives some important characteristics of the two approaches.

It is therefore evident that in cases where simplicity and the number of *cor*-relators required in the system are *small*, analog types are usually preferred. As seen from Table *2.6,* the data acquisition and storage system follows the *correla*tor stage. As this system is invariably of the digital type, it calls for the use of suitable analog to digital conversion **as** an interface between the *analog* correlator and the data acquisition system. While the data acquisition system facilitates the acquisition and storage of the *signal* in a suitable digital format, the final results of the interferometer set up are obtained with the use of the computer, which again is a fully digital system. The computer generally facilitates data analysis, manipulation etc. *as* required

TABLE 2.7

CORRELATION TECHNIQUE - BASIC APPROACHES

Correlation Techniques	Characteristics	Remarks
Analog	Continuous operation; Good S/N ratio; Large bandwith capacity	Simple circuitry; Sensitive to tempr. changes and component aging
Digital	Poorer S/N; Multibit quantization to improve S/N; Limited bandwith	Highly reliable; Insensitive to tempr. changes and component aging; Duplication to large no.s easy

in *the* system. It is seen that the data acquisition system is an *important* subsystem of the interferometer irrespective of the actual type of interferometer. This is now discussed in the next section.

2.5 A Typical Data Acquisition System

A detailed analysis of time *varying analog* signals is possible *only* if it is properly sampled, quantized to the required resolution and made available in a predetermined digital format. The general block schematic of any data acquisition system, which has *analog* voltages at its input and has storage facility in *digital* form at its output is given in Figure 2.9. *This* is now briefly described, with particular reference to its use in the radio interferometer.

2.5.1 Multiplexer : As simultaneous handling of more than one *signal* is required in the data acquisition system, it would *normally* warrant the need of similar signal processing hardware for each channel. However, a considerable reduction in complexity and cost would result if, the same signal processing hardware could be used for all the input channels on a time division basis. This process of time division multiplexing is possible only if, the time scale of processing by the hardware is very much less than the periodic sampling interval used. The multiplexer *(MUX)* block shown in Fig *2.9a* which is indeed an analog *MUX* achieves this. As seen in Figure 2.10 the basic building block of an *analog* MUX is a single pole *multithrow* switch with a control facility. It can be realised by employing several techniques. Table 2.5 *summarises* some of the commonly employed techniques for analog multiplexing. It is clear from this Table that, though there are different *ways* of *realising a MUX*, it is preferred to *use* the CMOS *IC* type because of its *compactness*, TTL compatible channel select control, good signal transfer efficiency, *and* realiability.

2.5.2 <u>Sample and Hold</u> : Any time varying *analog* signal that requires *conversion* to *digital* form should have the same amplitude during the conversion time to avoid any ambiguity. This is achieved by a Sample and Hold *(S/H)* circuit **as** shown in Fig. *2.9a*. This circuit block should also satisfy the requirements of the Sampling Theorem; *viz, atleast two* samples have to be acquired for every cycle of the input signal. However, in cases where the sampling rate is much higher than this, and if there is no appreciable change in the input signal in the conversion time of the *Analog* to Digital Converter (ADC), the Hold circuit may not be necessary. As seen from the circuit schematic of a

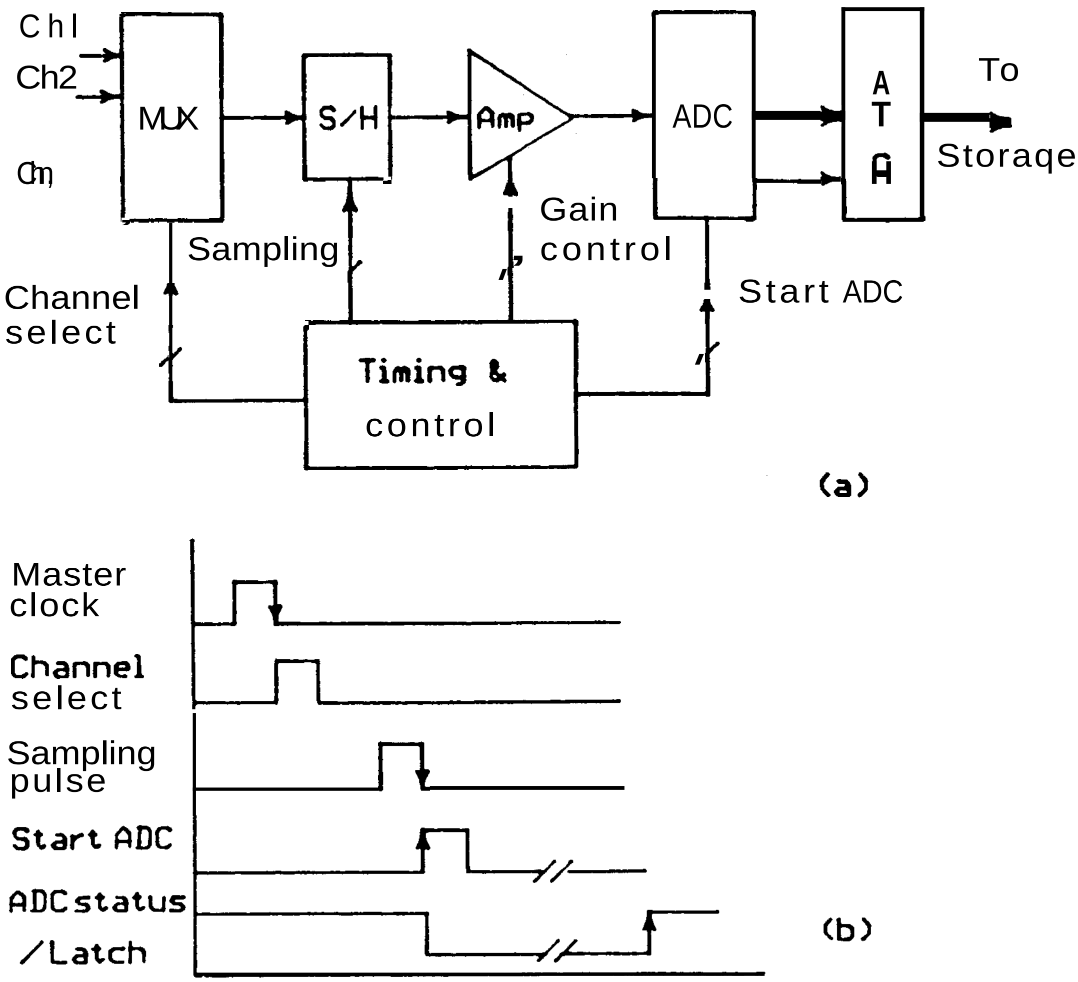

Figure 2.9 Typical Data Acquisition system (a), uith its Timing Diagram (b)

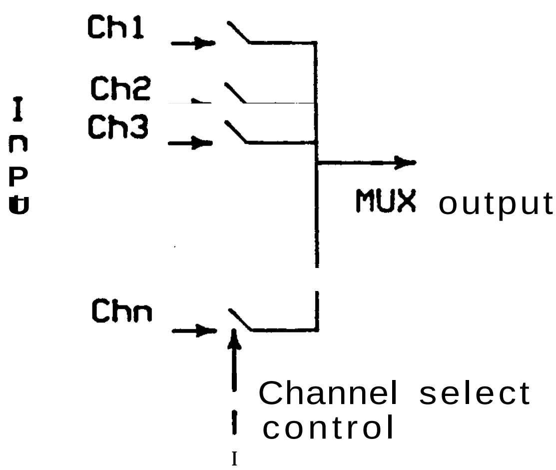

Figure 2.10 Analog Multiplexer - Schematic

TABLE 2.8

ANALOG MULTIPLEXING APPROACHES - A SUMMARY

MUX approach	R_{on} (in Rs)	R_{off} (in Rs)	Switching	Control requirement	Compact-ness	Remarks/ Application
Relays	< 5	∞	100's of ms	High current	Most bulky	High voltage switching
Bipolar transistor	~ 100	10^5	$< 1\mu$ s	5-10 V at $\sim$ mA	Discrete component	High speed; but limited by offset voltages
MOSFET	< 100	$10^5 -$ 10''	$\sim 10\mu$ s	$<$ 5 V low current	Available as IC	Static charge and polarity sensitive
CMOS	< 500	$10^6 - 10^9$	$\sim 1\mu$ s of mS	TTL compatible	Available as IC	Multi-channel input in single IC; cascading facility

S/H is shown in Figure 2.11, it is made up of a switch, *a* charge holding element (like *a* capacitor and a buffer). The desirable characteristics of these units respectively are:

a) Low ON and High ***OFF*** resistances

b) Low leakage current with high ***equivalent*** series resistance

c) High input impedance and insensitivity to aging and temperature changes

Though it is possible to build the S/H circuit using discrete components, they are available in *IC* form now a days, generally using MOS *IC* technology.

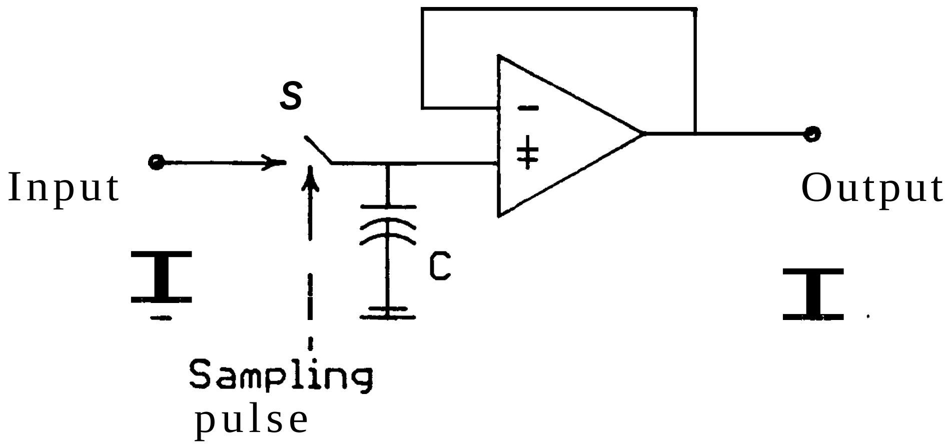

Figure 2.11 Sample & Hold Circuit - Schematic

It is preferred to use such an *IC* because of its compactness and reliability. In some cases, there is further simplification, as the S/H circuit may be built-in, as part of the input stage of the ADC.

2.5.3 Amplifier : As the resolution of an ADC is fully exploited when its input voltage range matches the dynamic range of the incoming signal, it is often necessary to introduce a gain-controlled amplifier in between the S/H circuit and the ADC. In this amplifier, it is necessary to ensure adequate bandwidth and gain stability, consistent with the input signal. Sometimes, this amplifier is of the programmable gain type to handle input signals of wide dynamic amplitude range. Some of the important electrical parameters that influence the choice of the amplifier type are given in Table 2.9. The availability of Operational Amplifiers (Op-Amp), with very high input impedance using *FET's* in its input stage and with very low output impedance, have largely influenced their use in such amplifiers. The requirement of *programmablity* in gain is also easily met, because *OpAmps* generally have very large open loop gains, and hence could be used in *a* negative feedback configuration, which can be controlled.

2.5.4 ADC : The number of quantizing levels *affect* the *Signal* to *Noise (S/N)* ratio of the analog signal being represented in the digital form. While larger number of quantizing levels increase the system complexity, a coarse quantization usually results in the degradation of S/N ratio. In addition, the A/D conversion approach has an important role to play in the final *S/N* of the digital output. There are many techniques for the AD conversion process nowadays, and several types of *ADC's* are available in *IC* form to facilitate

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TABLE 2.9

AMPLIFIER - DESIRABLE CHARACTERISTICS

Characteristics	Desirable values	Remarks
Input impedance	Very high	To counteract MUX on resistance
Output impedance	Low	To match S/H or ADC input
Bandwidth	DC - 100KHz	Adequate
Gain	Good stability; Dynamic programmability	Possible with Op-Amps
Tempr. and aging sensitivity	Low	Monolithic IC's better suited
Power supply sensitivity	Low	Good in Op-Amps
Common mode noise sensitivity	High	Op-Amps have very high CMRR

their use in data acquisition. Table 2.10 gives important characteristics of some popular ADC approaches. While Flash type *ADC's* are used in situations demanding very high sampling rates, as in the Clark *Lake* Radio

TABLE 2.10

POPULARADCAPPROACHES

ADC approach	Conversion time; T - clock (n - bit)	Feedback	Accuracy	Temp. & aging sensitivity	Cost	Remarks
Single slope	$(2^n - 1)\,T$ † Input dependent	No	Low	Highest	Low	Simple circuitry
Dual slope integration	T_c‡ + $(2^n - 1)T$ Input dependent	No	Highest	Least	Moderate	Good hum and noise rejection
Flash	T	No	Reference dependent	Moderate	Costliest	Very fast; limited quantization levels
Counter ramp	$(2^n - 1)\,T$ † Input dependent	Using D/A and counter	Fairly high	Low	Lowest	Simple circuitry
Continuous counter ramp	$<(2^n - 1)\,T$ Input dependent	Using D/A and counter	Fairly high	Low	Moderate	Uses up-down counter
Successive approximation	n T	Using D/A and SAR	Reference dependent	Low	Fairly expensive	Fast converters; require S/H

† **maximum**

‡ Canstant, dependent on charging time of integrating capacitor

Observatory *[45]*, the most commonly used **ADC,** is the successive approximation type, because of its availability in higher resolutions and a fairly good speed of conversion,at a comparatively lower cost. However, in *situations* demanding good noise immunity and high accuracies where speed is not the criterion the dual-slope integrating type is best suited. These factors are kept in view in the practical implementation of the system.

2.5.5 Latch : The **ADC** data output is normally available in serial and/or in parallel form. In transfers involving slow data rates, the serial data string is *usually* employed; but, in situations that warrant fast data transfers, it is preferred to obtain the data output in parallel form. In such cases, the **ADC** output is transferred on to a suitable latch *as* shown in the block schematic of Fig. *2.9a.* This latch aids in presenting all the bits of the *digital* data simultaneously to the following stage irrespective of the output circuit of the **ADC.** Latches are also standard *IC's* available nowadays using different technologies. Based on the data rate of the **ADC** output, an appropriate latch has to be chosen for use in these systems.

2.5.6 Storage : The **ADC** data output is now a measure of the input *signal* and it needs to be processed further. For this purpose, it is desirable to store this data in a suitable manner. There are different approaches to data storage *viz.*, primary and secondary. In each of these cases, a number of storage techniques are available now a days. Tables 2.11(a) and (b) *summarise* some of the *commonly* employed storage techniques in both these categories. It is seen *from* these Tables that, while most of the secondary storage techniques employ magnetic media as the means for storage, the primary storage *tech-*

TABLE **2.11(a)**

SECONDARY STORAGE FACILITIES

Memory type	Storage capacity (10^6 bits)	Access time (typical)	Replacable or fixed (R/F)	Read write (R-W)	Remarks
Magnetic media					
a) Audio cassette	< 1	~ s	R	R-W	Not very reliable
b) Magnetic tape	160	~ s	R	R-W	Most commonly used
c) Hard disk	160	50 ms	F	R-W	Mosty used in mini and mainframe computers
d) Floppy disk	50 (max)	200 ms	R	R-W	Most popular in PCs
e) Winchester disk	1200	20 ms	F	R-W	Most popular in PCs
f) Cartridge tape	320	~ s	R	R-W	Used for data backup
g) Video cassette	16000	~ s	R	R-W	Interfacing and data retrieval difficult
Optical media a) Digital disk	1600	< 1 s	R	R	Most suited for archival storage as writing into not possible

niques are *IC* based. This IC technology offers not only high speed operation and compactness but it is also directly logic compatible and does not require any complicated interfacing mechanism between the *digital* data and the storage device. Hence it is *usually* preferred to use MOS memories as an immediate means of storage for the data acquired and to transfer it later

TABLE 2.11(b)

PRIMARY STORAGE FACILITIES

Memory type	Storage capacity (10^3 bits)	Access time (typical)	Read or Write (R-W)	Power consumption	Remarks
Non-volatile					
a) Ferrite core	< 64	~ 500 ms	R-W	High	Obsolete
b) EPROM	512	~ 100 ns	R	Low	Most commonly used program memory
b) E^2PROM	64	~ 200 ns	R-W	Low	Critical data storage
Volatile					
a) Bi-polar transistor	< 10	~ 50 ns	R-W	High	High speed applications
b) NMOS FETs	~ 16	~ 300 ms	R-W	Moderate	Phased out
c) ECL	< 2	< 10 ns	R-W	Highest	Very fast applications
d) CMOS static	512	~ 70 ns	R-W	Lowest	Common in μ P systems
e) DRAMs	16 x 10^3	~ 70 ns	R-W	Low	Used in PCs, Minis and Mainframes

to a suitable secondary storage device such as a Magnetic tape for further manipulation and analysis by the computer.

2.5.7 Timing and Control block : All the blocks discussed so far, have to be controlled and their operations suitably *synchronised.* This is usually carried out by the timing and control block shown in Fig. *2.9a.* The main function of this block, apart from providing the master clock to the ADC, is to generate the timing and control sequence shown in Fig. *2.9b.* The timing diagram shown in Fig. *2.9b* summarises the operation of this block, treating the sampling pulse as the master periodic signal for all events such as:

a) Channel select in the MUX

b) Sampling in the *S/H* circuit

c) Gain control of the amplifier

d) Start of conversion in the ADC

e) Latch the ADC output at end of conversion

f) Initiate a transfer to the storage unit from the latch

Many approaches are possible for this function viz., a dedicated hardware, a microcontroller, or a computer. The choice of one or the other of these depends upon their need and the complexity of multiplexing, sampling and synchronising required.

2.6 Computers in Radio Interferometers

Since the dawn of the electronic computer era in the 1940's, there has always been a steady increase in the performance of the computers and a decline in their cost. As the cost of computer logic and memories have continued to decrease year by year, many computer manufacturers and individuals have begun to develop and manufacture computers that would fall within the reach of individuals. The advent of microprocessors which was a spin-off from microcontrollers, which were made for industrial control, has led to this big leap forward, in providing computers in the under $ 1000 price range. It was the success of groups like Radio shack and Apple computers in 1976-77, when they first introduced low cost *PCs*, that made giants like IBM venture into this field. From then onwards *PCs* have taken a big leap forward. Unlike the machines made by Radio shack and Apple, which mainly catered to hobbyists, the *IBM* range of *PCs* introduced in the early *80's* were targeted towards scientific and engineering applications. The user friendliness of these *PCs* along with the simultaneous availability of third party software has seen their widespread acceptance. *This* has led to the making of clones which *perform equally* well, but are of much lower cost. Due to this intense competition, many *PCs* of the present time are comparable to mini computers in their performance but available *at* a fraction of their cost. The development of *PCs* has gone through several generations **as** indicated in Table 2.12, clearly illustrating the present capabilities and usefulness of *PC-ATs*. Also, the possible general purpose scientific and engineering applications of *PCs* in different classes are presented in Table 2.13. Hence the advent of *PCs* and their subsequent availability in large numbers with a fairly good standardization and at low cost, has led to their wide use in the field of instrumentation. Table 2.14 *summarises* the trend set in the use of *PCs* over the last decade *[46]*. This has opened up many applications in the frontier areas of instrumentation as it can not only store data but aiso *analyse* it *on/off* line.

As seen from Table 2.6, the computer is one of the main building blocks in any radio interferometer setup. As the interferometer *could* be used to compute the diameter of the radio source, or study the disturbances in the

TABLE 2.12

IBM PCs FAMILY COMPARISONS

Characteristics	PC	PC-XT	PC-AT	PC - AT Plus
Processor	8088	8088/v20	80286	80386
Data bus (in bits)	8	8	8 and 16	32
Memory	256 kb	640 kb	1 Mb	1 Mb
Floppy disk	180/360 kb	360	360/1.2 Mb	360/1.2 Mb
Winchester (in Mb)	nil	10/20	20	up to 150
Graphics	Monochrome	Colour	Extended	extended/ vectored
Cost (1000's Rs)	10	25	60	above 100

ionosphere over *several* hours or days etc., this involves manipulation of *a* large database. Hence the major role of computers has been in the manipulation and analysis of the data collected from the various observations. However, in later years, *as* the cost of computers began to drop, and as they were easily available, they were also used for data acquisition systems in association with radio *interferometers*. While acquisition and storage of

TABLE 2.13

POSSIBLE FUNCTIONS IN PCs FOR

SCIENTIFIC AND ENGINEERING APPLICATIONS

Catagorey	Possible functions
PC	Acquisition possible but secondary storage limited
PC-XT	On-line acquisition and **storage;but** off-line analysis
PC-AT	On-line acquisition, storage and analysis

TABLE 2.14

END USE OF PCs - A **SUMMARY**

Category used	1981-82 %	'83-84 %	'85-86 %	'87-88 %	'89-90 %
Hobby	40	30	20	11	4.5
Science/ Engineering	50	40	35	32	30
Office automation	**10**	**20**	**25**	30	33.5
Instrumentation	-	**10**	**20**	27	32

data are done in real time, its analysis is often carried out off-line by a computer. The observatory at Clarke Lake *[45]* had a digital computer (Interdata 7/32) for its data acquisition from the 1024 channel *correlator* system and storage on a Magnetic Tape Unit (MTU). This data was analysed off-line by using a separate computer (Interdata 3230). The radio telescope at Gauribidanur has a dedicated data acquisition system and a VAX 11/30 for its data analysis off-line *[47]*. And nowadays there is a wide variety of main-frame and mini-computers in use *all* over the world, in radio astronomy applications. As there is very little standardization in their data structures, the data acquired at one location cannot be easily analysed at another location. This incompatibility in the form of data recording has posed a limitation on free exchange of unprocessed data from one observatory to another. This has greatly reduced the flexibility that is so much needed in this important field.

2.7 PC-based Interferometer - A Need

As seen form the previous section, the observatories with radio interferometers suffer from:

a) Lack of standardisation in their data structures

b) Incompatibility of secondary storage media

c) Use of different programmes for the same type of analysis (as different computers operate with *different OS)*

d) Possible use of of two computers viz., one each for data acquisition and analysis

Considering these limitations, and keeping in view the recent developments in the use of *PCs* in instrumentation, it was decided to investigate this problem in depth. The result of this, is the design and development of a PC based data acquisition system for the radio interferometer project at *Gauribidanur* being built by the *Raman* Research *Institute,* which is a prototype unit for the final radio telescope to be built on the island of *Mauritius.* Such a radio interferometer would, not only solve the problem of data transportability but also incorporate the real time data acquisition system in it. Thus, on-line data acquisition and storage and off-line data analysis can both be facilitated using the same PC. Thus the use of *PCs* in radio interferometers is *an* elegant and attractive *approach* in improving the performance and reliability of the system. This is the subject matter of the thesis.