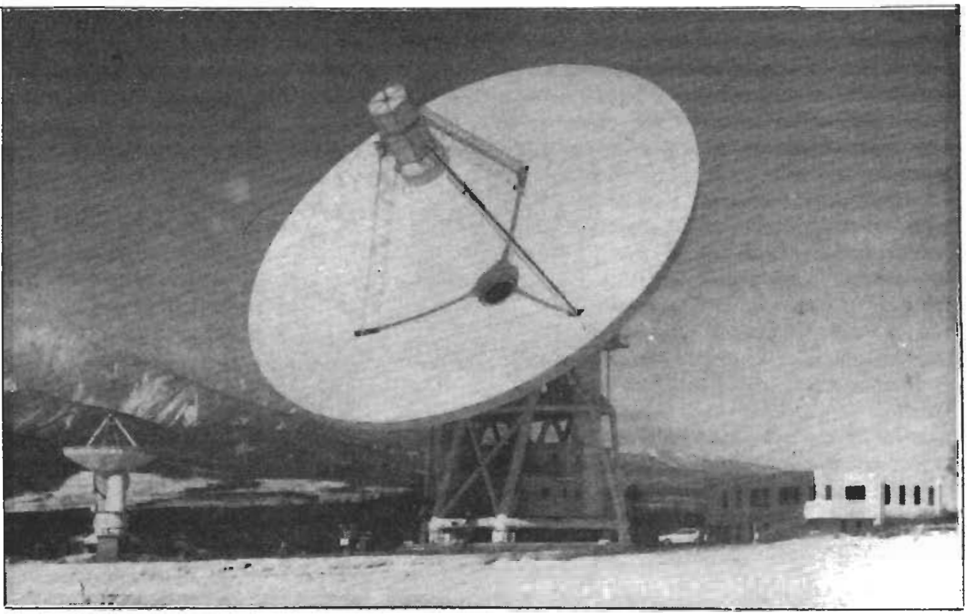
Radio Astronomy

Part 1

The use of radio telescopes really started after WWII but is now the dominant method of studying the cosmos. Roger Allan looks at the history and recent developments.



Radio telescopes have now largely taken over from optical types in the search for new information on the cosmos. The resolution now available using special techniques has improved enormously in recent years.

THERE ARE ESSENTIALLY four ways in which the physical heavens may be studied: optically, physically, by radio analysis, or by a combination of the first three.

Optical examinations and surveys suffer from the handicap of the earth's atmosphere — a constantly moving, optically confusing medium that interferes with light rays. What we can learn from ground based optics is limited, and while the amount of knowledge learned by such telescopes is tremendous, it is also finite — and the end of its usefulness as an instrument of examination is quietly creeping up on astronomers and astrophysicists. Combining an optical telescope with some sort of space platform, such as is to be launched by the shuttle, eliminates atmospheric interference, but there is a limit to the resolution of the telescope itself.

Physical visitation is obviously the ideal, but it is very expensive, prone to error and, while frequently awe inspiring in its data collection (such as the recent fly past of Saturn and the spectacle of its rings), it is limited to nearby planets.

The best of the lot, particularly for deep space studies, as to the composition of the cosmos, its age, and the big cosmological questions, such as how was the universe created, is by radio analysis — sometime called radio astronomy, and sometimes radio astrophysics.

Early Theories

The basis of radio astronomy is found in the work of Maxwell, who in the 1870's suggested that planets and the stars should not only emit waves of radiation in the form of light, but other forms of radiation both higher and lower on the spectrum. In the 1880's Hertz, having demonstrated the existence of radio waves, attempted to find radio wave emission from the sun. He failed. Simultaneously, Thomas Alva Edison was also attempting to detect radio waves from the sun. In 1894 the search for solar radio emission was continued by Sir Oliver Lodge, Professor of Physics at Liverpool University in England. Of his attempt, he wrote that, *"I hope to try for long wave radiation from the Sun, filtering out the ordinary well known waves by a blackboard, or other sufficiently opaque substance."* He, too, failed, later writing, *"There were evidently too many terrestrial sources of disturbance in a city like Liverpool to make the experiment feasible. I don't know that it might not possibly be successful in some isolated country place, but clearly the arrangement must be highly sensitive in order to succeed."*

The uncertainty of knowledge at the time concerning the ionosphere is demonstrated by the work of Nordman, a Frenchman, in 1900. He used an aerial 197m long and set his apparatus up on a glacier at an altitude of 3100m, *"to eliminate as much as possible the absorbing action of the atmosphere".* He, too, failed, but we now know that high altitude was not essential, but that the very long wavelengths he was attempting to find would be absorbed by the ionosphere.

With 20/20 hindsight, a lull in appropriate research then became apparent. Apparently, researchers felt that there was just no way that the effect of the ionosphere on the transmission characteristics of radio waves could be punctured. However, radio research continued and expanded for commercial purposes until by the 1920's there was a great deal of experimentation being conducted at several universities and at a number of private companies such as the Bell Telephone Laboratories and the Marconi Telegraph Company.

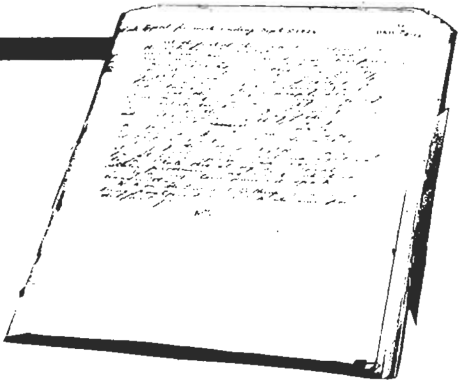
Radio performance depends not only on the sensitivity of the equipment, but also on the conditions governing the propagation of radio waves through the atmosphere, and on the level of back-ground noise which can be heard in headphones at the receiver. In the 1920's, the limitations imposed by propagational effects and received noise were only partially understood. It was realized that external radio noise could originate from lightning flashes in thunderstorms and the numerous minor discharges of electricity generated in storm clouds, hence the terms *'static'* and *'atmospherics'*. It was an investigation in the US of this atmospheric noise at shorter wavelengths, around 15m, that led to the discovery on which radio astronomy may be considered to be based.

Karl Jansky

In 1930 Karl Guthe Jansky, a young physicist on the technical staff of Bell Telephone Laboratories was assigned the task of studying the direction of arrival of atmospheric static at wavelengths of about 15m, which were then being used for ship-to-shore and transatlantic communication. For this purpose, Jansky planned the construction of a rotatable aerial array 30m long and 4m high, providing directional receptions of about 30 degrees width in azimuth. The frame was mounted on four wheels taken from a Model T Ford to allow rotation about a central pivot. With the aid of a motor and chain drive, a revolution was completed every twenty minutes, earning it the nickname "the merry-go-round."

In a 1932 paper, Jansky distinguished three distinct types of static: the intermittent crashes from local thunderstorms, a steadier weaker static due to the combined effect of many distant storms and lastly a steady weak hiss of unknown origin producing a sound in headphones similar to the noise generated within the radio receiver by random thermal agitation by electrons in the components. Initially, he thought this latter hiss to be manmade, but then realized that the apparent direction of arrival moved round the sky each day, but was *not* originating from the sun. By following his initial investigation with a year's worth of data recording, Jansky finally determined the significance of his discovery, published in 1933 under the title *"Electrical disturbances apparently of extraterrestrial origin."* He determined the direction of the main source as the centre of the galaxy (in the constellation Sagittarius).

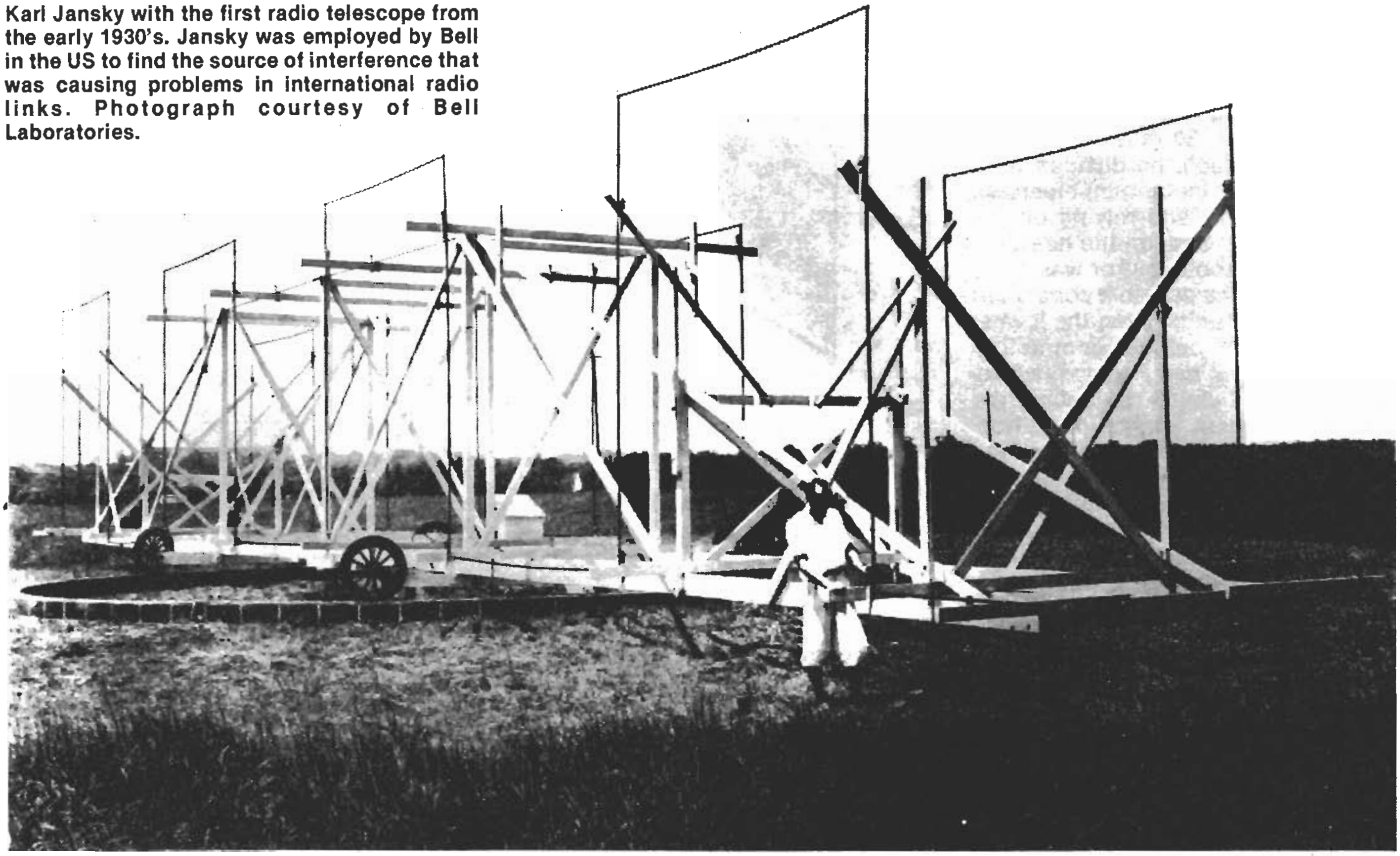
Continuing his work in 1935, Jansky published a paper in which he attempted to resolve the problem. *"It leads one to speculate,"* he wrote, *"as to whether or not the radiations might be caused by some sort of thermal agitation of charged particles. Such particles are found not only in the stars but also in the very considerable amount of interstellar matter that is distributed throughout the Milky Way, which matter, according to Eddington, has an effective temperature of 15,000°C."*



The famous entry in Jansky's logbook when he established that the source of his signals was the centre of our own galaxy. Photograph courtesy of Bell.

His discovery attracted some publicity, and on 5 May 1935 the *New York Times* carried a front page full column report entitled, "New Radio Waves traced to Centre of Milky Way." The discovery was also featured on an American radio programme and the galactic noise received by Jansky's aerial array was broadcast, the commentator announcing, *"I want you to hear for yourself this radio hiss from the depths of the universe."* The listeners' reaction to the ten seconds of hiss is unrecorded, but one reporter said that it sounded *"like steam escaping from a radiator."*

As he had fulfilled his practical



Karl Jansky with the first radio telescope from the early 1930's. Jansky was employed by Bell in the US to find the source of interference that was causing problems in international radio links. Photograph courtesy of Bell Laboratories.

objective, Bell Laboratories refused to fund any more research into the subject, stating that the 100 ft disk Jansky proposed was an "unjustified expense." He never again worked on radio astronomy, and died at the age of 44, in 1950.

Grote Reber

Radio astronomy would have effectively halted for the better part of a decade if it hadn't been for the initiative of a lone pioneer, Grote Reber. Reber was a young graduate radio engineer from Wheaton, Illinois, who decided to pursue the research as a hobby at his own expense in his spare time. *"In my estimation,"* he wrote, *"it was obvious that Jansky had made a fundamental and very important discovery. Furthermore, he had exploited it to the limit of his equipment facilities. If greater progress were to be made it would be necessary to construct new and different equipment especially designed to measure the cosmic state."* In the face of prevailing ignorance, he decided to construct a large parabolic reflector with the intention of observing intially at a very short wavelength, about 10cm. He realized that a parabolic reflector would have the advantage of providing a narrow, symmetrical beam and would also enable the wavelength to be altered simply by changing the receptor at the focus.

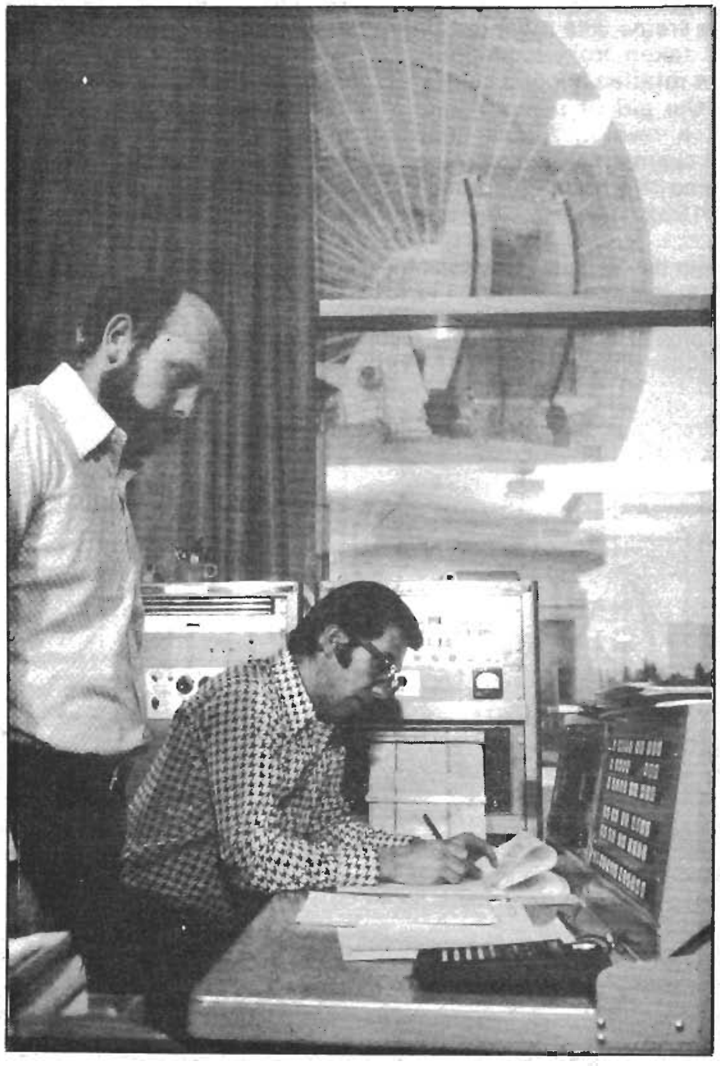
Reber would have preferred a full steerable mounting but this was far too expensive (he was paying for it out of his own pocket and erecting it in his backyard, 30 miles outside of Chicago.) As such, he decided on a meridian transit instrument steerable in elevation only and relying on the Earth's rotation to scan the heavens. The metal parabolic mirror was to be made as large as possible consistent with available funds. Even the lowest estimates from outside contractors were prohibitive, and Reber was forced to build it himself. Balancing the cost of materials against the structural demands, Reber finalised the parameters of his design and decided on a sheet metal surface of 32 feet diameter, to be mounted on a wooden supporting structure for the sake of cheapness and ease of construction.

The reflector surface consisted of 45 pieces of 26 gauge galvanized iron sheet screwed on 72 radial wooden rafters cut to parabolic shape. Reber cut, drilled and painted all the parts and personally put together the radio telescope piece by piece, completing the job in four months from June to September 1937. The building of the telescope cost $1300.

Grote Reber photographed last year when he was interviewed by our sister magazine ETI-Australia. Mr. Reber now lives in Tasmania where he has taken up solar energy as his interest.

Initially, he used a crystal detector followed by an audio triode amplifier. His initial attempt, at wavelengths of 9cm, produced no response. Changing to 33cm for which an acorn triode proved the most likely detector, Reber again failed. During the autumn of 1938 and during the winter a variety of observations, both by day and night, were made with both polarizations. All the objects were examined again without any positive results. Moving down in wavelength to 1.87cm, Reber was at last successful in detecting radio emission from the Milky Way.

In his first paper, in 1940 entitled *"Cosmic Static,"* Reber determined the radiation intensity at 1.87 cm and confirmed the source as laying predominantly along the Milky Way. He then made an important step in theoretical interpretation by evaluating the intensity of radio emission from free electrons during encounters with positive ions of ionised hydrogen in intersteller space. In 1944, a further article marked the pinnacle of Reber's achievement — he produced the first radio maps of the Milky Way. The beamwidth of his



View of the Algonquin telescope in northern Ontario taken from the control room. Photograph courtesy NRC Canada.

radio telescope, about 12 degrees at a wavelength of 2m, enabled him to draw a contour map of the distribution of radio noise which showed its relation to the Galaxy, the structure of the main peak at the galactic centre in Sagittarius, and the subsidiary peaks in Cygnus and Cassiopeia. Attempts to detect individual objects, like planets, stars and nebulae failed, but his paper did report radio emissions from the sun.

The Fighting Forties

With the advent of war, radio astronomy fell again on fallow ground, with those whose knowledge and expertise which could be applied to such an endeavour devoting their time to national service, particularly the study of radar and radio communications on a practical level. None the less, the foundations of contemporary radio astronomy were still being layed in an indirect and unexpected way.

During 1941, the enemy made increasing endeavours to jam radar operations. The British War Office became anxious lest their radar devices, particularly vulnerable to airborne jamming, might be rendered useless. On 12 February, 1942, the passage of the German warships *Scharnhorst* and *Gneisenau* through the English Channel, in which they slipped by almost unnoticed until it was too late to muster any effective attack on them, to the accompaniment of radar jamming from the French coast, resulted in a drastic reappraisal and upgrading of the "jamming menance." The study of jamming was not a particularly interesting one for scientists, but it had to be done and a group was rapidly assembled. On 27 and 28 February, 1942, a remarkable series of reports from sites in many parts of Britain described the daytime occurence of severe noise jamming experienced by anti-aircraft radar working at wavelengths between 4 and 8 metres. This 'jamming' was of such intensity as to render radar operation impossible. Fortunately, no air raids were in progress, but alarm was widespread at the incidence of this new form of 'jamming". The Army Operation Research Group, newly formulated in response to the *Scharnhorst* fiasco a mere 15 days earlier and now stationed in Dover, were able to determine that the "jamming" was in fact due to radio radiation from the sun, a realization and discovery which had eluded Hertz so long before.

For the remainder of the war, study of celestial radiation, radar, jamming and anti-jamming techniques went hand in hand, and a good deal of foundation research was done on the subject during this period, virtually all of it under an official classification of "Secret". By the conclusion of hostilities, there were a large number of scientists and technicians who had learned the fundamentals of radio astronomy, some of the techniques involved, and what sort of things they could start looking for.

The Breakthrough

It was after the end of the war that radio astronomy really got going in a big way. So much was accomplished so relatively quickly that it is impossible to cover it all. However here is some of the physics involved. There are essentially three types of radio emissions:

Free-free emission: Radio emission, like light, is produced when a charged particle, generally an electron, is made to accelerate. One class of astronomical radio sources consists of clouds of hot ionized gas, that is, a gas whose atoms and molecules have absorbed enough energy to lose their electrons and become positively charged ions. Such a cloud emits radio waves by the process known as *free-free emission.* In this process, the free electrons are attracted toward positively charged ions as they pass each other — the acceleration producing a pulse of radiation. The sum of such pulses originating in a large number of such encounters between electrons and positive ions gives a continuous spectrum in which the power (energy per unit of time) radiated per unit frequency interval is constant with frequency. Radio sources that emit by the free-free process include the outer regions of the sun and the ionized hydrogen regions of interstellar space.

A similar process is that known as blackbody radiation, in which the emitting region is so compact or deep that the only emission that can escape comes from the near side. In this case, the power radiated increases as the square of the frequency. Measurements of the emitted radio power give a direct estimate of the temperature of the source. The planets belong to this class of source.

Synchrotron radiation: This is the most important process, in which electrons moving at speeds very close to that of light (relativistic speed), spiral around magnetic fields

Large Radio Telescopes and Synthesis Arrays

Institution	Location	Size of Reflector,m
Fully steerable parabaloids		
Max Planck Institute of Radio Astronomy	Effelsberg, West Germany	100
Nuffield Radio Astronomy Laboratory	Jodrell Bank, England	76
CSIRO	Parkes, NSW Australia	64
Jet Propulsion Laboratory	Goldstone, California	64
Algonquin Radio Observatory	Lake Traverse, Ontario	46
National Radio Astronomy Observatory	Green Bank, West Virginia	43
California Institute of Technology	Big Pine, California	40
Haystack Observatory	Westford, Massachusetts	37
Crimean Astrophysical Observatory	USSR	22
Limited tracking transit telescopes		
Special Astrophysical Observatory	Zelenchukskaya, USSR	10 × 1885
Tata Institute	Ootacamund, India	30 × 529
National Astronomy and Ionosphere Center	Arecibo, Puerto Rico	305
Observatory of Paris	Nancay, France	40 × 200
National Radio Astronomy Observatory	Green Bank, West Virginia	91
Radio Telescopes for millimetre wavelengths		
Onsala Observatory	Gothenburg, Sweden	20
University of Massachusetts	Amherst, Massachusetts	14
National Radio Astronomy Observatory	Kitt Peak, Arizona	11
California Institute of Technology	Big Pine, California	10
University of Texas	Fort Davis, Texas	5
Synthesis Arrays		
National Radio Astronomy Observatory (Very large array, VLA)	Socorro, New Mexico	Resolution 0".1
Mullard Radio Astronomy Observatory (5km array)	Cambridge, England	Resolution 0".5
Westerbork Radio Observatory (WSRT)	Westerbork, Holland	Resolution 1"

emitting radiation that is polarized — that is, which vibrates more strongly in a direction perpendicular to the magnetic field. This radiation was first found in the beams from synchrotron particle accelerators. The electrons may be a part of the energetic cosmic ray background flux in the Milky Way, or may be produced in some violent event in the radio source itself. The precise shape of the continuous spectrum of synchrotron radiation depends, among other things, on the energy spectrum of the electrons.

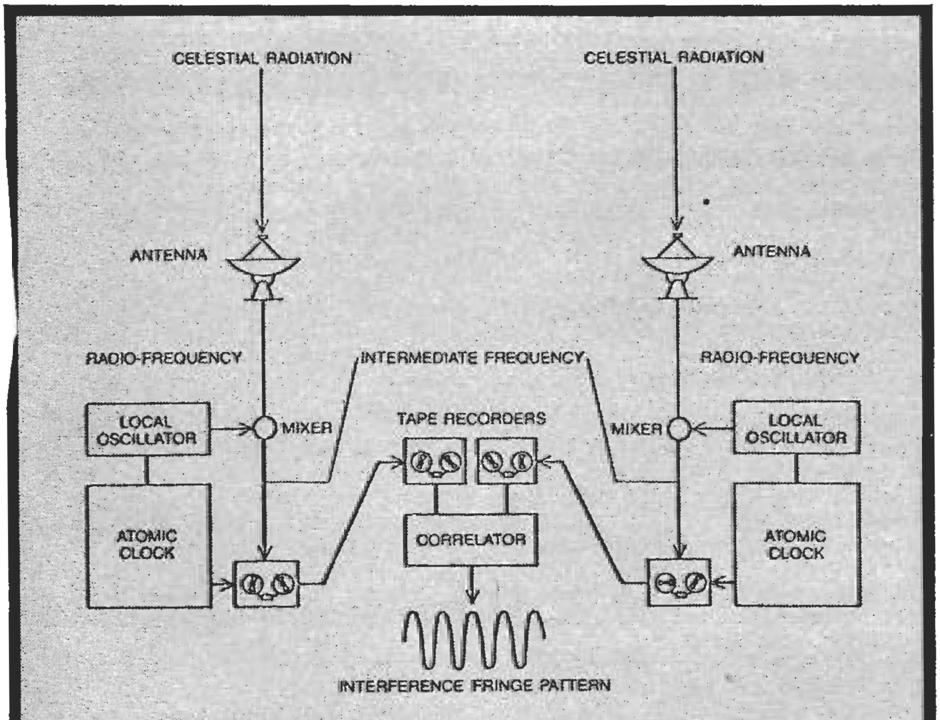
Emission from neutral hydrogen: Line radiations (that is, radiation strongly concentrated toward a particular wavelength) at the 21.1 centimetre wavelength was first detected from clouds of neutral atomic hydrogen in the Milky Way in 1951. This radiation provides a very useful tool for studying the motion of many components of the Milky Way and of external galaxies. Motion in the line of sight toward or away from the observer is calculated from measurements of the Doppler shift. Many interstellar spectral lines have now been detected from atoms and molecules that radiate in the radio range. Of these lines, the 21.1cm line of neutral hydrogen, which appears in many parts of interstellar space, is very important because hydrogen is widely distributed in the universe as the building material of stars.

VLBI's

The state-of-the-art for radio wave collection involves the use of the *Very-Long-Baseline Interferometer* (VLBI). Essentially, the remarkable images produced by VLBI are governed by the same laws of physics that apply to light gathering telescopes. In order to improve the resolving power of an imaging system the aperture over which radiation is collected must be increased in relation to the wavelength of the radiation. Resolving power, or resolution, is the minimum angular separation, measured in minutes or seconds of arc, that can be detected by an observing instrument. For a telescope, the resolution is given approximately by the ratio *wavelength/D,* where D is the aperture of the telescope. In order to record fine details, D should be as large as possible for the particular wavelength being studied. The resolving power of large optical telescopes under good viewing conditions is about one arc-second, roughly the angle subtended by a small coin at a distance of four kilometers.

If equivalent resolution were to be achieved by a radio telescope operating at a wavelength of one meter, the diameter of the collecting surface would have to be some 150 miles. The largest optical telescope, at Palomar Mountain, has a theoretical resolution of 0.023 arc-second, while radio telescopes now have a resolution of 0.0001 arc-second. This is accomplished by making D very large by what is called "aperture synthesis", a technique by which the radio waves, collected by two (or more) instruments hundreds or thousands of kilometers apart, are recorded simultaneously and subsequently added together. This has to be handled very cautiously. If the phase relations of the radio waves arriving at the telescopes preserve their synthesis the waves are said to be coherent. The intensity of the radiation will be high or low depending on whether the arriving radio waves are in phase or out of phase at the two telescopes. Such a combination of telescopes is called an interferometer. As the earth moves, the difficulty in keeping the waves in phase becomes a major problem, resulting in the signal intensity at the output of the interferometer passing rapidly through a succession of highs and lows as the radio waves from the celestial object are successively in phase and out of phase. These intensity maximums and minimums are called *interference fringes.*

The amplitudes and phases of the fringes, sampled for a large number of separations of the two telescopes are called the *visibility function.* When this function is subjected to the mathematical operation known as a Fourier transformation (which converts a curve of *amplitude v. time* to curve of *amplitude v. angle)* one obtains a direct image. It is possible to obtain the fringe pattern for all separations of two telescopes out to a given separation D and hence to obtain the same image that one would get from a single giant telescope of diameter D. When the rotation of the earth is exploited to increase the number of separations, the resulting operation is called *earth-rotation aperture synthesis.* This process was developed in the early 1950's at Cambridge University, and has been used a number of times, particularly at the Very Large Array in Socorro, New Mexico, which utilizes 27 movable radio telescopes spread out in a Y shaped configuration. ETI



Highly accurate atomic clocks make it unnecessary for two or more telescopes in a VLBI array to be linked physically. At each telescope site the RF signal from the celestial source is recorded on videotape at a rate of four million samples a second, together with periodic time signals from a local atomic clock. The tapes are later played back at a central processor in order to extract the pattern of interference fringes. The tapes must be synchronized to a fraction of a second.

To be continued next month