John Kraus, W8JK – Antenna Inventor, Radio Astronomer and Electromagnetics Master

by Brian Austin, G0GSF

Any electrical engineering student and, indeed, most academics in the field who taught the subject of electromagnetics will have come across the name of John Kraus. And so will some radio amateurs and most radio astronomers, though many, in one camp or another, might not have thought that they were encountering the same man. Kraus was an engineer, educator and scientist – all rolled into one – and, as a result of his many achievements and remarkable books, his name is well known. Or at least it should be.

Amateur Radio Operator

John Kraus was born in 1910 in Ann Arbor, Michigan. He obtained his physics degree at the University of Michigan and then, after completing his research dissertation, he was awarded his PhD in 1933. By then he was already immersed in amateur radio having obtained his first temporary call sign in 1926 and a couple of years later, after passing both the Morse code test and an examination, he was allocated the call sign W8JK: his initials following the prefix indicating a US amateur resident in the state of Michigan.

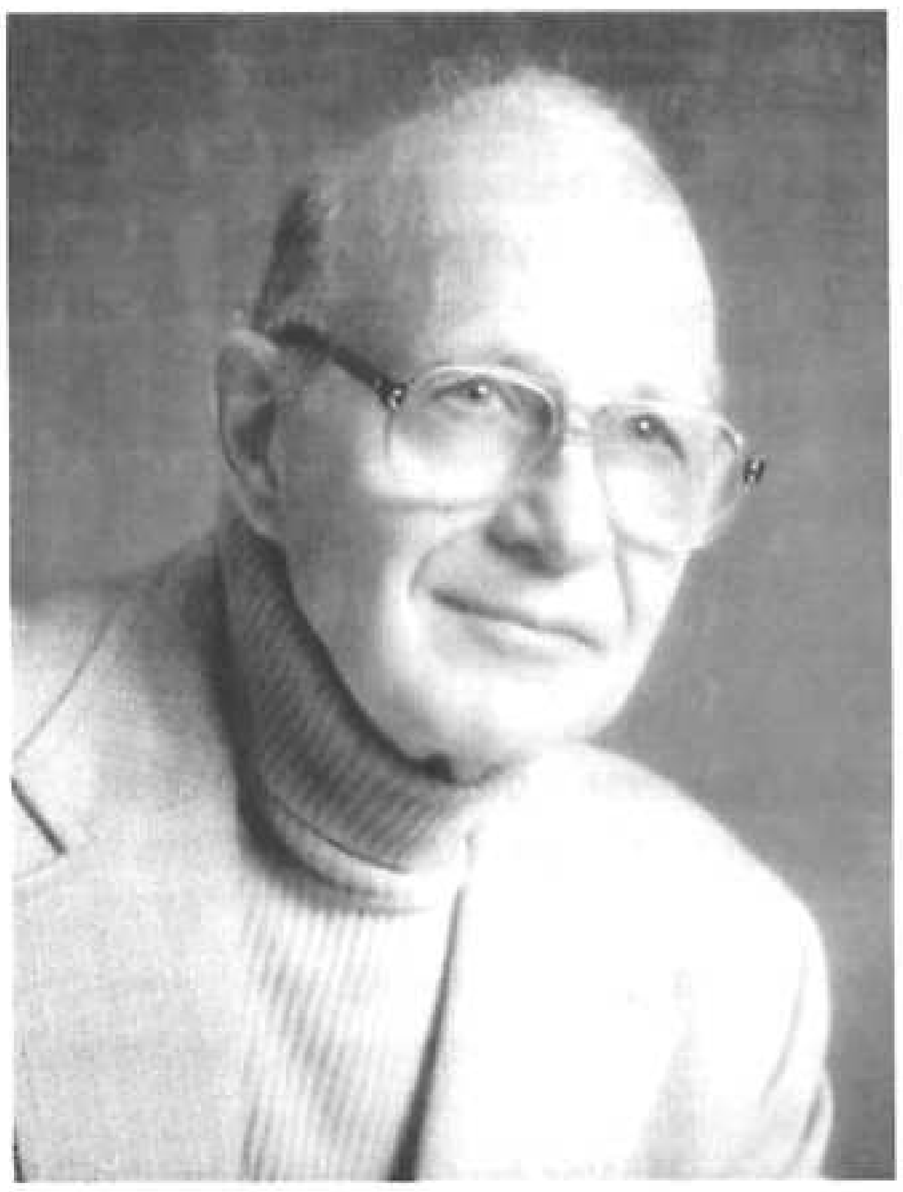
In those days the hobby of amateur radio made its many enthusiasts around the world feel like pioneers. And, indeed, in many respects they were. Wireless broadcasting had only been in existence a few years and was considered by many to be a great novelty, if not a complete mystery. The BBC transmitted its first news programme in 1922 while it would be another four years before the National Broadcasting Company began transmitting in the US, though private enterprise in the form of AT&T (American Telephone and Telegraph Company), the Westinghouse Company, some newspapers and even advertising organizations had already started their own wireless services by then. And the technology of wireless (or radio as it was always called in the States) was advancing rapidly too.

The concept, if not the implementation, of heterodyning or mixing two frequencies together to produce others was first proposed as early as 1905 by Reginald A. Fessenden in Canada. It became feasible only once thermionic valves had been developed some years later when it saw the light of day in the superhet receiver due to the genius of Edwin H. Armstrong in 1918. Transmitters using valves appeared about that time too, while the all-important antenna had evolved rapidly from Marconi's multi-wire structures of 1901 to the remarkable 'short-wave directional wireless telegraphy' devices developed by C.S. Franklin, one of Marconi's most inventive engineers, in the early 1920s.

John Kraus soon became aware of all this since he was an avid reader of *R/9* and then its successor, *RADIO*, which were the leading American amateur radio magazines of their day. As his career as a physicist with a particular interest in radio progressed, he started to follow developments as they were reported in the *Proceedings of the Institute of Radio Engineers*, or *Proc IRE* as it was known to all radio engineers. Over the years Kraus himself became a prolific author, publishing articles and papers in all those journals and others, but his greatest contributions were to appear in his books.

Radio Physicist

In September 1933 Kraus published a paper in the *Proc IRE* in which he described some of the results he'd obtained during his PhD research. This had involved making numerous measurements of the propagation of radio signals at around 60MHz from a transmitter he had designed that was located on the roof of the University's physics building. In the very next issue a paper appeared, written by a radio engineer from the Bell Telephone Laboratories, entitled *Electrical Disturbances Apparently of Extraterrestrial Origin*. Its author was Karl Jansky. In 1932, Jansky had published his first paper on this subject, also in the *Proc IRE*, but neither paper had attracted much attention, especially from the astronomical community, very few of whom read radio engineering journals – and why should they? But Kraus was intrigued and two years later he made a special effort to attend a lecture by Jansky. Again it attracted very little attention with a mere two dozen people in the audience, five of whom were taken along by Kraus himself! Years later John Kraus became a radio astronomer, pioneering a completely new field of science that was opened up by Karl Jansky with his two, apparently invisible, publications.



Dr John Kraus, W8JK (1910 – 2004)

But before we come to that we need to consider Kraus's own career that was only just beginning.

After completing his doctorate he stayed on at the university where he became part of the team designing and building a cyclotron, a powerful particle accelerator to be used for research in high-energy physics. This was the second such machine to be built in the USA, the first being at Berkeley in California. Kraus gained considerable experience of large-scale projects while engaged in that construction programme, and years later, when he was in Ohio, it would certainly pay off. Of particular interest to him was the radio frequency power source required to drive the deuteron beam around its circular path.

By mid 1936 the University of Michigan cyclotron was working and a series of experiments began under the direction of men whose names would become famous in the world of nuclear physics. But by then John Kraus had moved on; his interest in radio frequency phenomena began to lead him in other directions. And, perhaps serendipitously, it was his great interest in amateur radio that was the spur.

Antennas, Wires And Waves

Working DX became almost a daily activity at W8JK and this was made possible by the effective antennas employed there. Initially, all were made of wire arranged in various configurations to try to produce the sharpest beam in a given direction. The Bruce array (**Figure 1**) was the first of these. It was essentially a rectangular zig-zag arrangement of a continuous length of wire. Its length, and the dimensions of the vertical and horizontal sections, were carefully chosen to produce an array of vertically polarised radiating sections connected together by horizontal elements that did not radiate at all. The key to this behaviour was the distribution of the current waveform along the array. This is shown by the direction of the arrows in the diagram: all vertical elements have their current in the same direction thus they radiate in-phase. By contrast, the currents in any horizontal section are out-of-phase with each other and so their fields cancel.

Those horizontal wires merely connect one vertical radiator to another while not radiating themselves. The longer the array the greater its gain and, by the simple expedient of placing another similar array about an eighth of a wavelength behind it to act as a reflector, the antenna became a unidirectional radiator and its gain was doubled. Power could be fed to the radiating elements in a number of ways while the reflector was not fed itself but simply coupled parasitically to the driven element.

Of especial interest in the context of John Kraus's subsequent career is the fact that Karl Jansky had used a rotatable form of the Bruce array (with a similar reflecting element behind it) when he discovered the radiation from the Milky Way. The antenna had been designed by Jansky's colleague, Edmund Bruce of Bell Labs, in 1927.

As mentioned above, Kraus was an enthusiastic member of the IRE and its monthly journal provided him with much inspirational reading. The issue of January 1937 contained an article by George H. Brown of the RCA Research Laboratory entitled *Directional Antennas*. It contained a detailed analysis of the underlying electromagnetics of directional radiators as well as the results of extensive measurements of those characteristics. What particularly caught Kraus's eye was a graph, deep within this long paper. It showed the gain that would result when two half-wave elements, fed with out-of-phase currents, were much more closely spaced than was usual at the time. Brown's graph showed that when just an eighth of a wavelength apart the two parallel elements produced significant (bi-directional) gain in what was called the 'end fire' direction in the plane of the elements. In fact the gain actually increased as the spacing was made even closer, while increasing the number of element pairs added yet more gain.

Within a week of reading Brown's paper, Kraus had built and erected in the field behind the house such a closed-spaced array consisting of four half-wave dipoles cut to resonate in the '20 metre' (14MHz) amateur band. He described its performance as being "phenomenally effective". The graph in **Figure 2** shows the variation of gain, relative to that of a half-wave dipole, as the spacing between the two out-of-phase elements is changed. On closer examination of those curves it will be seen that the increased gain with decreasing element spacing comes at the cost of radiation efficiency. Any resistance within the elements, for example, caused by their thickness and the material of which they're constructed, will cause power loss and this loss increases as the square of the current flowing within each element.

As might be expected, the closer the elements are to one another the closer the coupling between them, hence the greater the currents that flow. For any given amount of loss resistance,

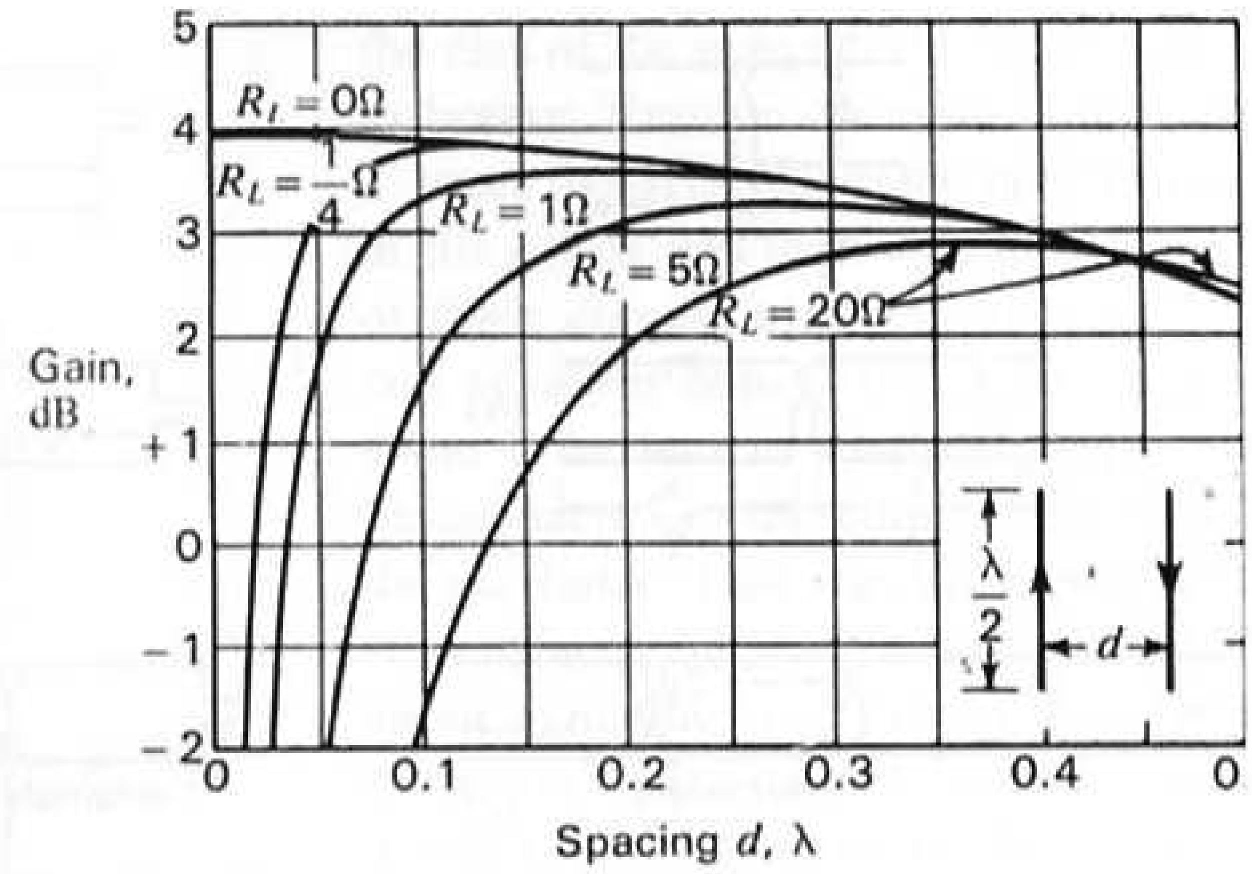


Fig. 2. Variation of gain with element spacing in close-spaced arrays

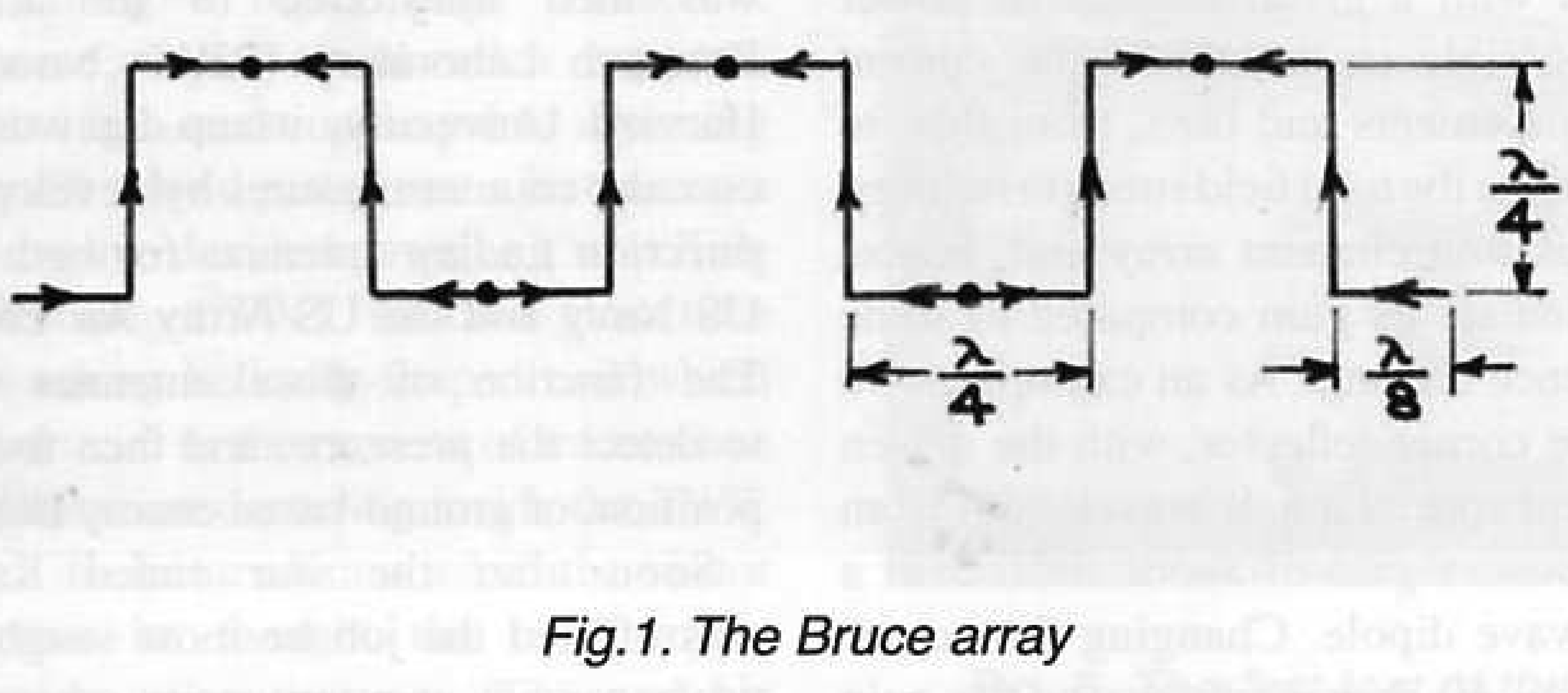


Fig.1. The Bruce array

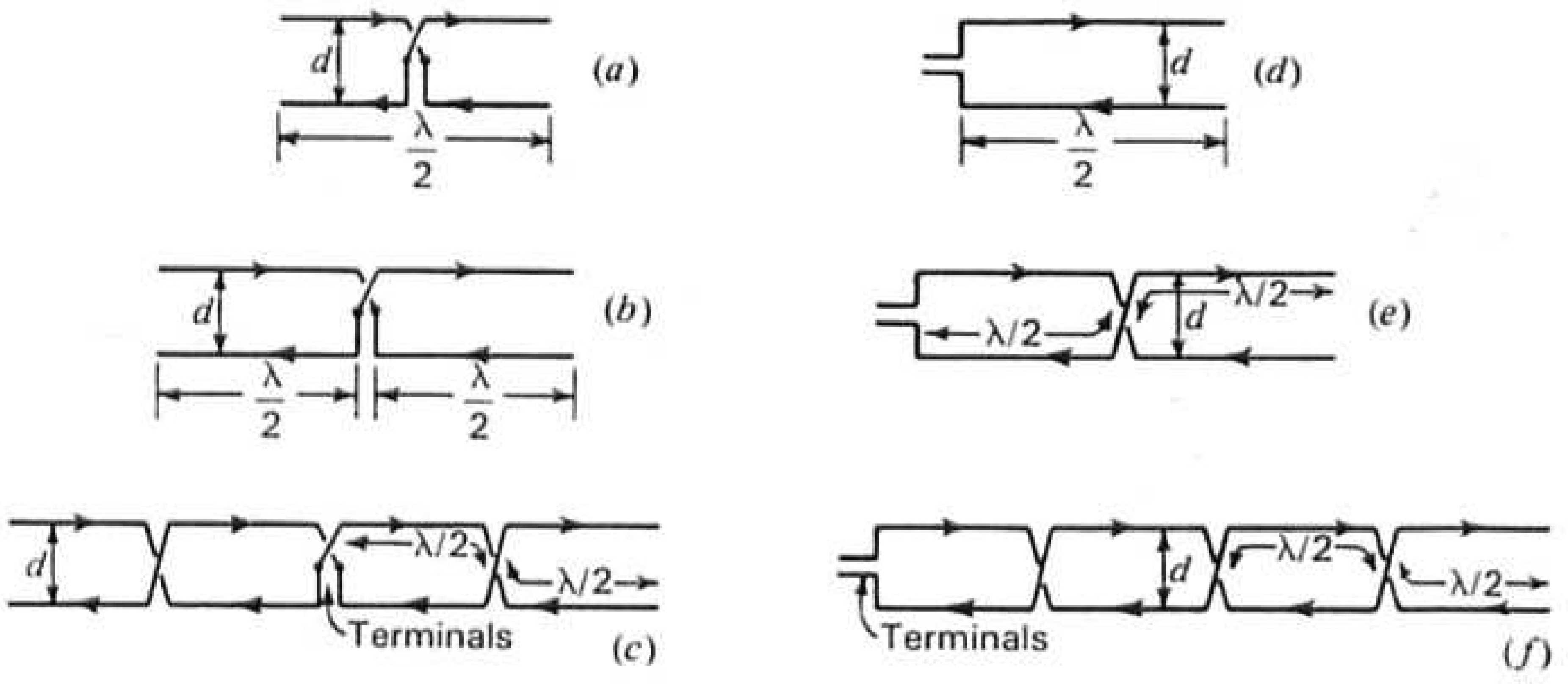


Fig. 3. Centre-fed and end-fed W8JK arrays

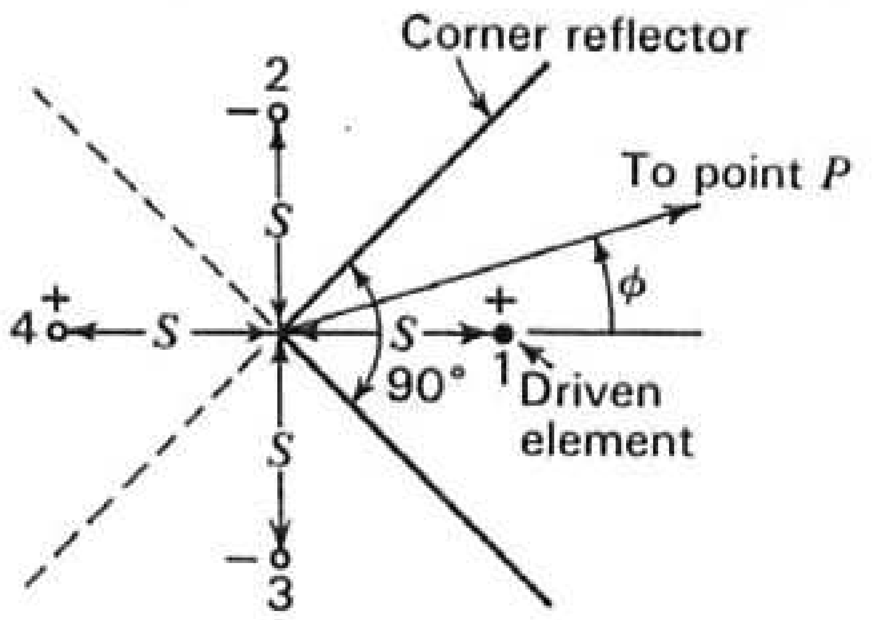


Fig. 4. The corner reflector and its images

the gain reaches its maximum at a particular spacing and then falls sharply as the spacing is decreased further. So, increased directivity comes at the price of decreased efficiency and, taken together, that combination implies a loss of gain if the spacing is made too small.

An amusing aside to Kraus's reading of George Brown's paper appeared in Brown's autobiography, published after he'd retired from RCA. In it he relates how, in 1932, he'd submitted a shorter paper on the subject of directional antennas to the IRE only to have it rejected by a referee on the grounds that the close-spacing effect he'd described was erroneous. When in 1937 he wrote his much more detailed paper, covering a wider field of directional antennas, he 'buried' the bit about these closely spaced antennas in the middle of the text in the hope that a sceptical referee would miss it. He did and the paper was duly published and to considerable acclaim too!

Not surprisingly, the amateur community around the world soon got to hear about John Kraus's antenna which they dubbed the "W8JK". (**Figure 3**) They'd either heard the powerful signal emanating from his station or they'd read about the antenna in the pages of *RADIO* because Kraus was, by then, both a regular author and frequent correspondent to its letters pages. The W8JK took the world of amateur radio by storm and it even made its way to the world of commercial broadcasting when certain shortwave stations adopted it too.

The Corner Reflector

In 1938 it occurred to Kraus, when he was analysing antennas near reflecting surfaces, that the reflector could be bent into a square corner with interesting results. Effectively what he was doing with pencil and paper was using what's called the method of images where one replaces the reflector by an image of the antenna at a distance behind the reflector equal to the distance the actual antenna is in front of it. That technique is well known in the field of optics. For a square (or 90 degree) corner there would, in effect, be three images of the antenna: one directly behind the apex of the corner and two others behind each of the angled reflector sides. Hence, on removing the reflector and considering just the antenna and its three images, we have a four-element array with all elements carrying the same magnitude of current. But their phases are not the same. The actual antenna and its image behind the apex are in-phase whereas the other two elements have currents that are 180 degrees out of phase. This comes about because one has to satisfy what are called the boundary conditions at the surfaces of the conducting reflector. (**Figure 4**)

All this leads to some interesting mathematics involving the self-impedance of the antenna plus the mutual impedances between itself and all the images and, in the practical case, a loss resistance term must be included as well. After assuming that the array is fed with a given amount of power it's possible to determine the current in the elements and then, from that, to determine the total field strength radiated by this four-element array and, hence, to calculate its gain compared to some reference antenna. As an example, a 90 degree corner reflector, with the driven element spaced a half-wavelength from it, produces gain of about 10dB over a half-wave dipole. Changing the corner angle to 60 degrees increases the gain still further but at the cost of having to increase the side lengths of the reflector.

Figure 5 shows Kraus standing alongside the first corner reflector which he built and tested in 1938. It operated at a frequency of about 60MHz. Notice that the reflector is not solid but is made up of a number of closely-spaced vertical wires. To approximate a solid sheet his experiments indicated that the spacing between wires must be no more than an eighth of a wavelength. These days we would suggest that it should not exceed a tenth of a wavelength. This simple antenna, invented by John Kraus, has been manufactured by the millions – many for UHF television use – and they, along with Yagi-Uda arrays, are to be seen on the rooftops of the world.

Wartime Work

During WWII Kraus worked as a civilian scientist in the government service. He spent three years at the Naval Ordnance Laboratory (NOL) where he was engaged in counteracting the natural magnetism inherent in all large iron and steel objects, by the process known as degaussing. This involved winding large coils of insulated wire around the hulls of the vessels and driving current through them in a direction to counteract the naturally-induced magnetic field. The intention was to reduce their susceptibility to magnetic mines. He was then transferred to the Radio Research Laboratory (RRL), based at Harvard University, where he worked on radar countermeasures by developing direction finding antennas for both the US Navy and the US Army Air Force. The function of those antennas was to detect the presence, and then fix the position, of ground-based enemy radars.

Soon after the war ended Kraus was offered the job he most sought: a professorship at a university where he

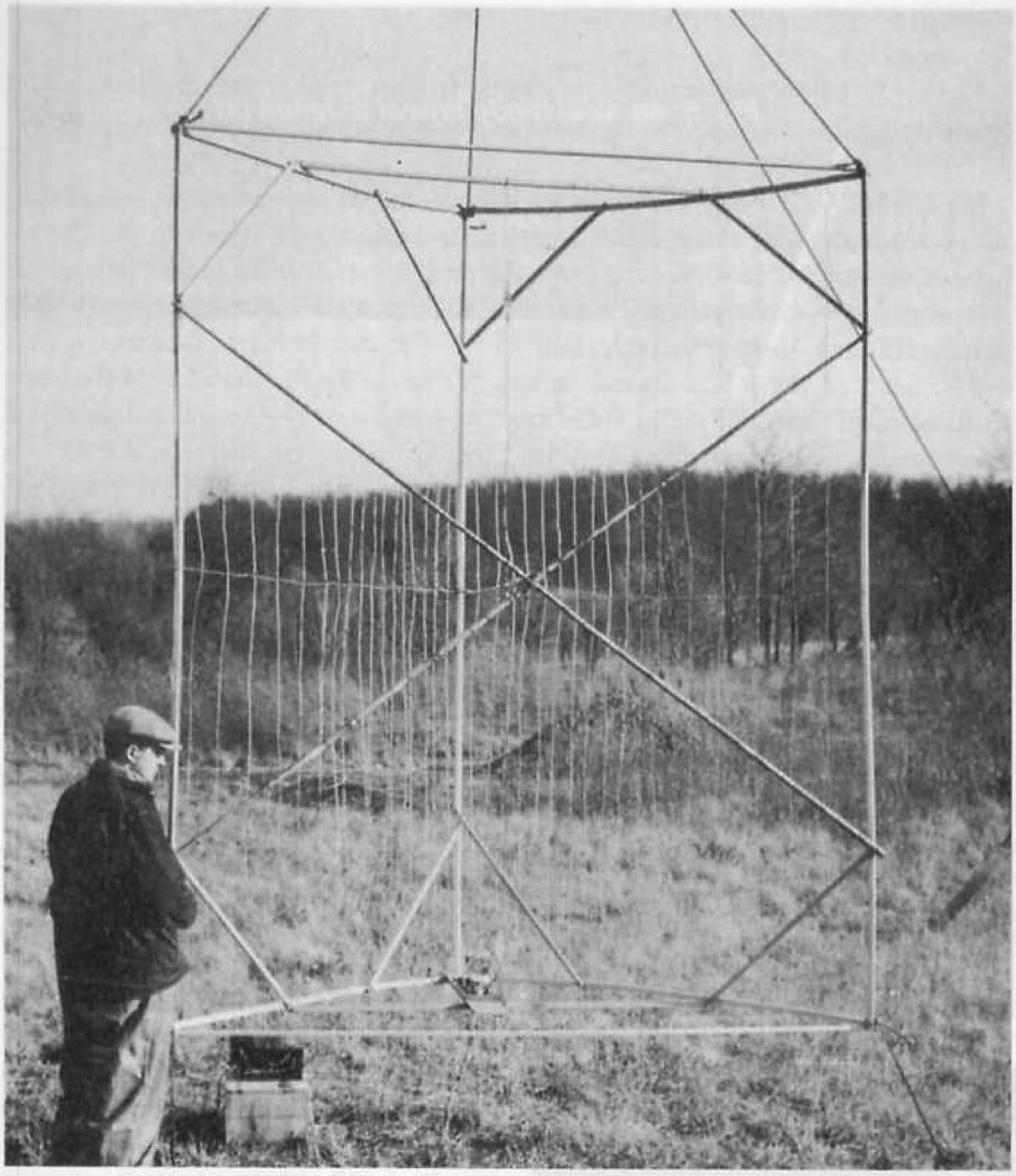


Fig. 5. Kraus with his first corner reflector antenna

could both teach and do research in his chosen field of antennas. The Ohio State University (OSU) employed him and it was there that Kraus spent the rest of his working life. It was at Ohio State that he made perhaps his most important contribution to the antenna art when he developed the helical antenna.

Corkscrews And Spirals

More accurately known as the axial-mode helical antenna to distinguish it from the much smaller normal-mode helical, Kraus's helix began life resembling a rather large corkscrew. It came about, as so often happens, following a question he put to a visiting scientist who'd just given a lecture on a microwave device known as a travelling wave tube or TWT. Inside a glass tube was a long helically-shaped coil which was crucial to the process of microwave amplification occurring inside the TWT. After the lecture Kraus asked the visitor whether he thought the helix might function as an antenna. "No" was his unequivocal reply: "I've tried and it doesn't work". The answer didn't satisfy Kraus and he resolved to try himself.

Since laboratory space was very cramped in the Department of Electrical Engineering at OSU, and because he wished to experiment in private lest word of a failed experiment should reach the ears of the man who'd told him not to bother, Kraus took home with him a small 2.5GHz oscillator that he had in his office. He then wound a length of thick copper wire into an arbitrary coil of seven turns a few cm long and some 3 to 4cm in diameter. One end he connected to the output terminal of the oscillator. That was his transmitter. As a receiver he made a dipole antenna about 5cm long and cut in a bow-tie shape to give it a wider bandwidth. This dipole probe was fixed to the end of a wooden dowel. Across the centre of the dipole he soldered a crystal diode of the type used in microwave radar receivers during the war. And across the diode he connected a pair of headphones. That was his receiver. (**Figure 6**)

To Kraus's great surprise, when he switched on the oscillator and moved his sensing antenna around the helix, he discovered that it produced a powerful beam of energy off its open end while, at the same time, radiating very little to the sides. In addition, this strong signal seemed to be concentrated in a narrow beam firing along the axis of the helix. By rotating the dipole probe he found that the energy seemed quite independent of the position of the dipole, whether pointing vertically, horizontally or in any other direction. That immediately suggested the radiation was circularly polarised. All this was an astounding discovery made in the basement of the Kraus home, surrounded by the week's washing drying on lines all around him.

Maths And Measurement

Back in his office over the following many months, much mathematical analysis and many careful measurements

Fig. 6. The first test of the axial-mode helical antenna's behaviour

were carried out. It soon transpired that the dimensions Kraus had chosen for his corkscrew antenna were just about optimum. But even more importantly, he found that they were surprisingly non-critical. The radiation pattern and the antenna's input impedance remained almost constant over a significant bandwidth. It further transpired that to produce a sharp beam along the axis of the helix required it to have a circumference of about a wavelength, while the more turns on the coil the greater the gain in signal strength. However, too many turns led to a narrowing of the antenna's bandwidth, so there was scope for optimisation. Given its simplicity this was undoubtedly a truly remarkable device.

Between 1947 and 1949 Kraus, in collaboration with his research students, published seven papers in the *Proc IRE* and in other journals describing the antenna, its underlying theory, its characteristics and performance. They soon reached a wide readership and soon others around the world found a multitude of applications for this novel antenna. When the space age dawned some ten years later, the axial-mode helix was used extensively. **Figure 7** shows the Fleetsatcom geostationary satellite with its two helical antennas pointing earthwards. It, and others like it, soon became the mainstay of the US military's worldwide communications. In 1978, with the launch of the constellation of 18 Navstar GPS satellites, that soon transformed global navigation forever, each satellite had an array of ten helical antennas.

As directional antennas go Kraus's axial-mode helix is probably as well-travelled as any antenna ever invented. It soon became the workhorse for space communications and was used as a key communications antenna on the Moon (**Figure 8**) during the Apollo missions, and also on space probes sent to Mars. And in just a short while it would dominate the horizon at the OHU when Kraus turned his helicals skywards in his first venture into radio astronomy.

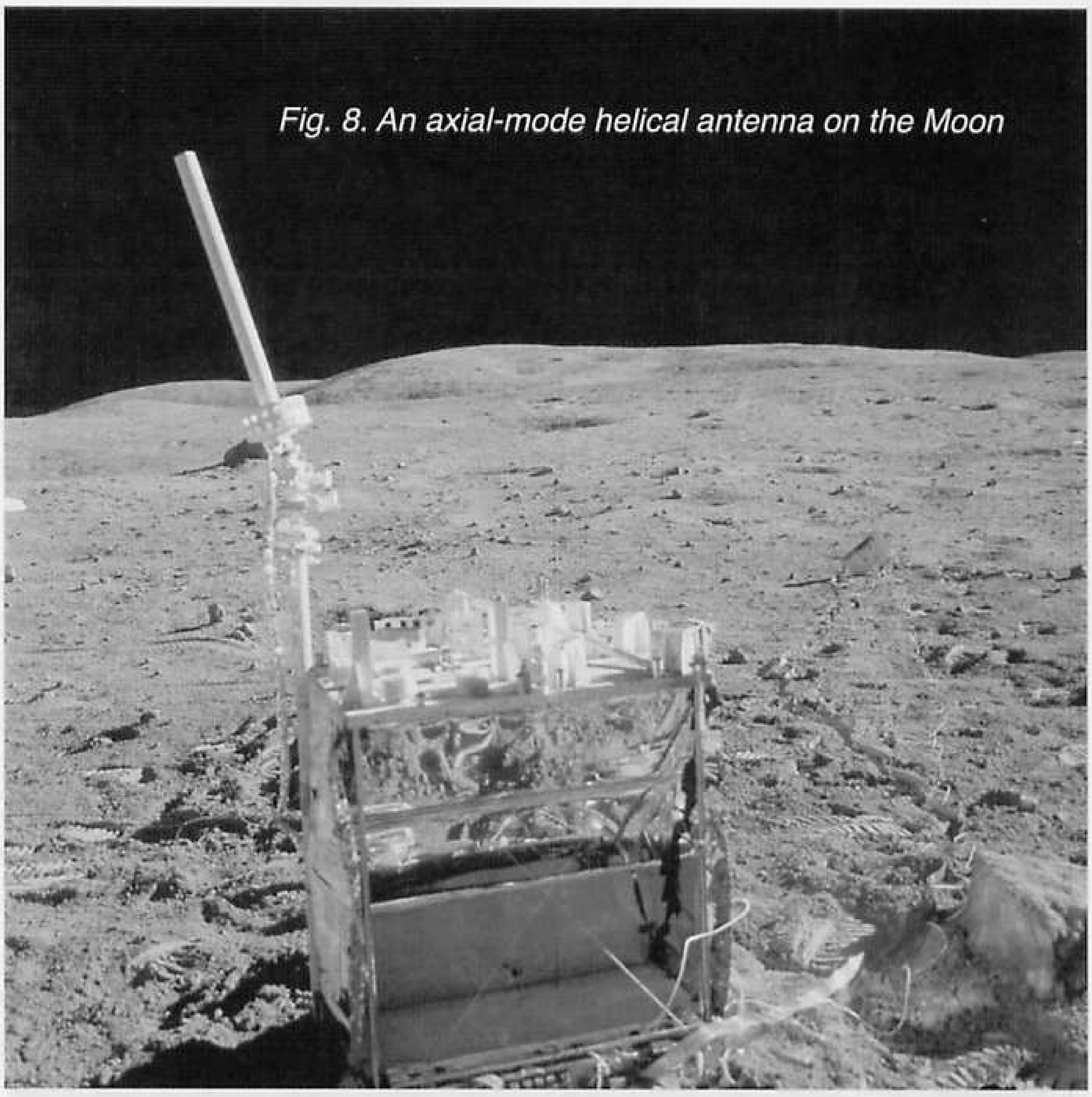


Fig. 8. An axial-mode helical antenna on the Moon

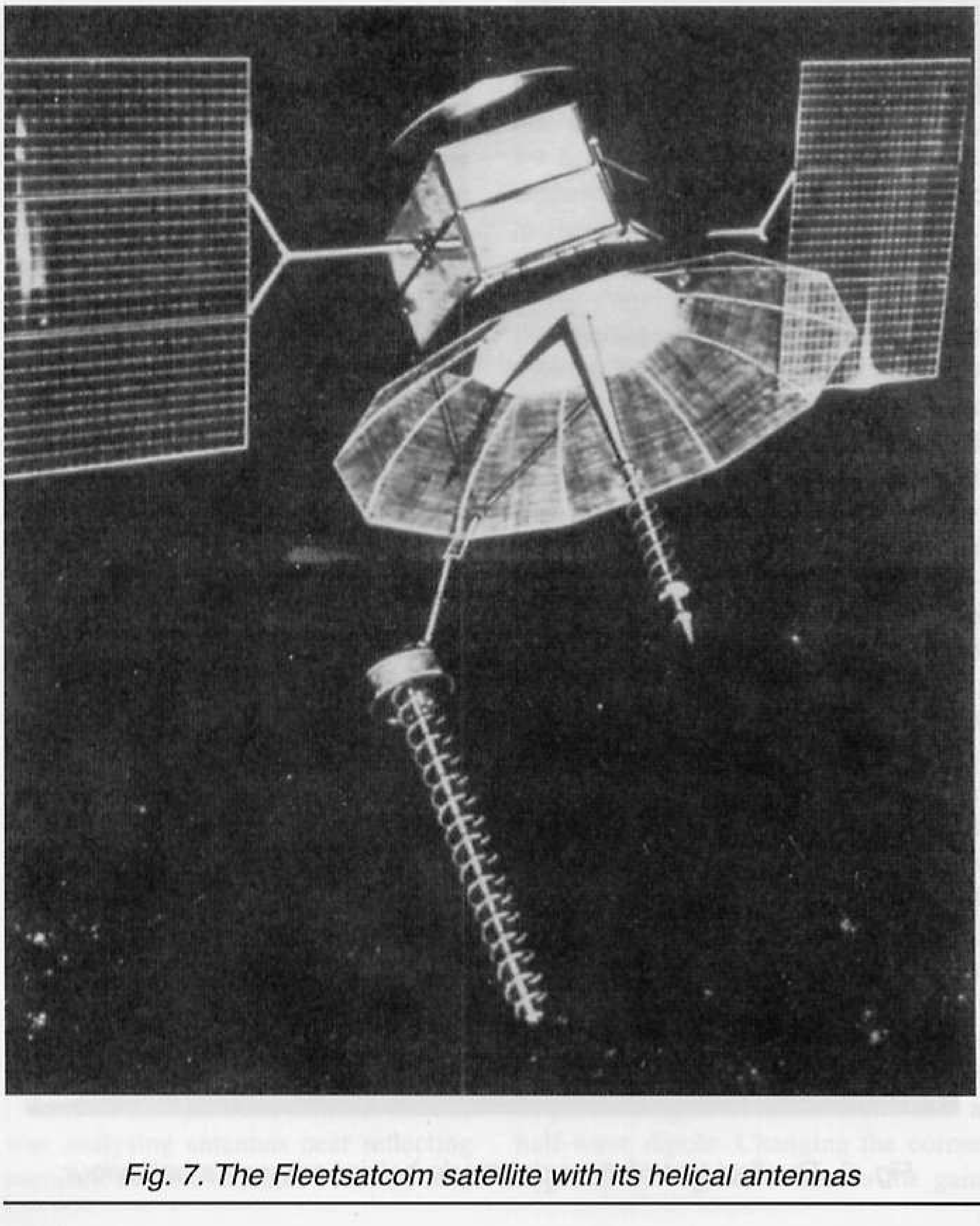


Fig. 7. The Fleetsatcom satellite with its helical antennas

Scanning The Heavens

During the war Kraus had got to know Grote Reber, the American radio engineer who, in 1937 in his own time and in his own backyard, had built a remarkable 9m diameter parabolic antenna for the express purpose of carrying on where Karl Jansky left off some years before. Jansky's brief but highly significant interlude as a radio astronomer came to a sudden end when his employer, the Bell Telephone Laboratories, assigned him to other duties after he'd completed the task of identifying the source (lightning, as it turned out) of radio 'static' that interfered with the company's trans-Atlantic radio telephone service. The fact that, while doing so, he'd actually discovered a completely new area of scientific research was apparently lost on the managers concerned.

With his homemade apparatus Reber undertook a systematic survey of radio sources in the sky and in 1944 he produced a map of the sky showing their positions. It was the first sky survey ever undertaken at radio frequencies. Reber's account of this work to Kraus undoubtedly sowed a seed which would start to bear significant fruit some seven years later.

In 1951 Kraus started working on the construction of an array of six helical antennas of 11 turns each and about 2m long, with a diameter of 30cm. They were mounted on a steel frame with a coarse wire mesh screen behind them that acted as the tiltable ground plane of the array. By October the next year the array had expanded to 48 antennas and over the next twelve months it had doubled to become the largest array of helical antennas yet constructed anywhere with 96 elements pointing skyward (**Figure 9**). This structure, only the third antenna operated by a university in the USA to be dedicated to radio astronomy, was located on a piece of land belonging to the university's college of agriculture. A local newspaper reporter, on seeing this strange configuration for the first time and hearing of its intended purpose, dubbed it the 'Big Ear'. Kraus liked that and forever after it was the name given to the OHU radio astronomy antennas.

The array of helicals operated at a wavelength of 1.2m (250MHz) and produced a fan-shaped beam one degree wide in the horizontal plane and eight degrees wide in the vertical plane. In astronomical parlance these would be referred to as right ascension and declination. From an engineering point of view we would see those figures as representing an antenna with gain somewhat more than 30dB.

Work started almost immediately on a survey of all detectable radio sources in the heavens. Clearly, since the antenna could only be tilted along one axis, it relied on the rotation of the earth to provide complete coverage of the visible sky over a period of time. This type of instrument is therefore known as a transit radio telescope.

By the end of 1954 the OSU helical array had detected and accurately mapped over one hundred radio sources. At that stage only two other radio telescopes had yielded even comparable results: Martin Ryle at Cambridge had recorded 50 and Bernard Mills in Australia had notched up 77. So this was a remarkable achievement for Kraus and his small team, but he wasn't complacent. He wanted to explore yet further into the depths of space, but that would require an even larger telescope to do so. Physical space was limited where the helical array resided and increasing levels of electrical interference from passing motor vehicles and from nearby radio and television stations caused him to look further afield.

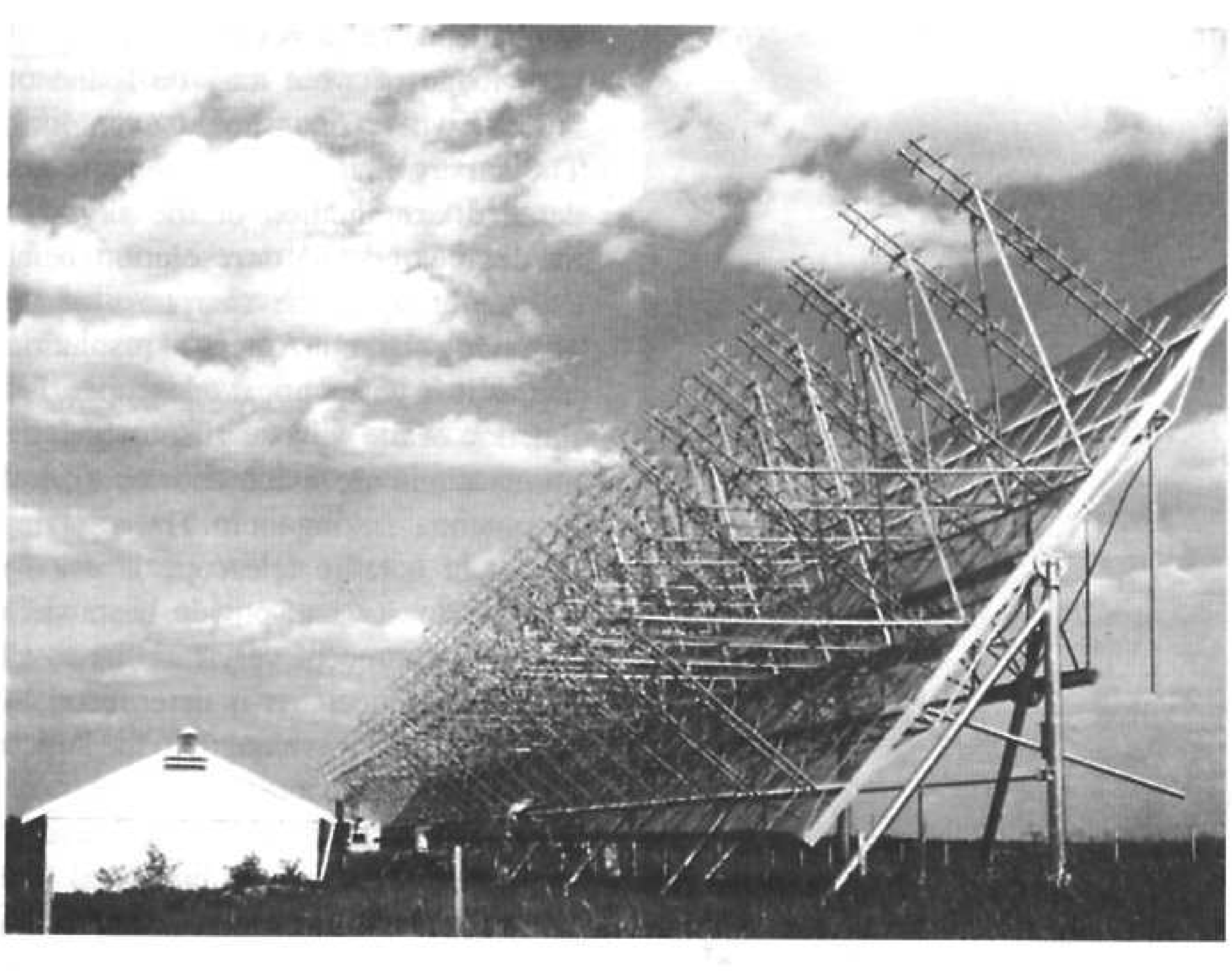


Fig. 9. The OHU array of 96 helical antennas pointing skyward

Big Ear Two

About a 30-minute drive from the university was a large tract of farming land belonging to the Ohio Wesleyan University, one of the OSU's academic neighbours. Negotiations between them resulted in an agreement that allowed Kraus access to '20 acres more or less' with an area around it restricted to other use so as to afford some degree of protection against interference to the radio telescope. The instrument itself had not yet appeared on paper but John Kraus had some ideas clearly in mind.

The outcome of his thinking was a completely new approach to the design of a radio telescope. Instead of going for a huge parabolic dish such as that Bernard Lovell was busy constructing at Jodrell Bank, or an array of dishes or dipoles, some of which could be moved along a railway track, as were being used by Martin Ryle in Cambridge, Kraus chose to use two reflectors, one flat and tiltable, the other a fixed-standing parabolic surface, with a feed system positioned between them at ground level on a conducting metal surface. Placing the feed there removed the need for a large and possibly disadvantageous support structure as was needed with the dishes. In time this antenna became known as a Kraus-type reflector but to Kraus and his colleagues at OHU it was always the 'Big Ear'. Subsequently it was copied by both the French and the Russians who built considerably larger versions for their own radio-astronomical investigations. A diagram showing how this interesting new form of radio telescope actually functioned is shown in **Figure 10**.

Radio frequency energy, emitted by a variety of objects and regions of space, strikes the earth all the time. By the simple laws of optics radio waves incident upon the flat reflector, tilted at

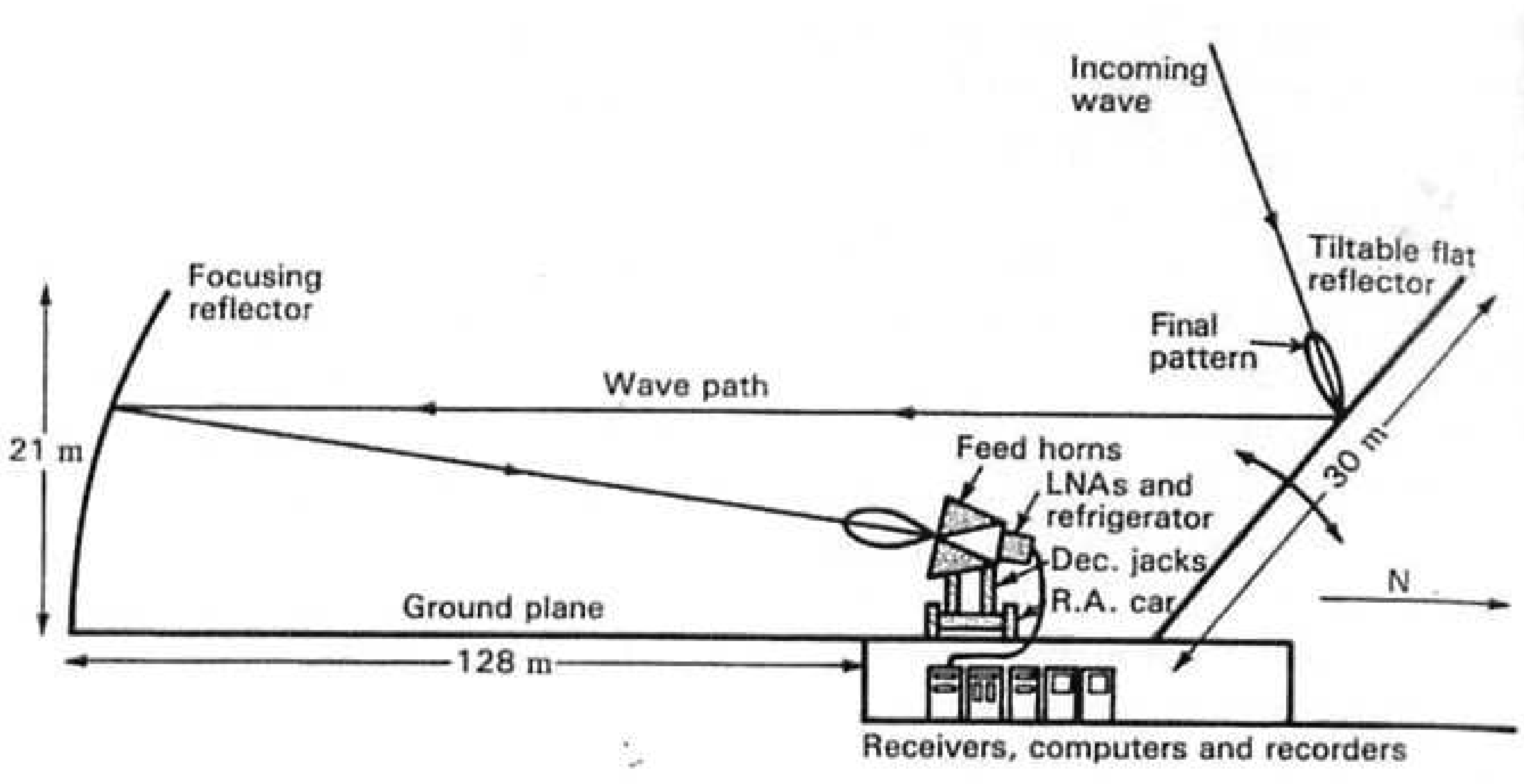


Fig. 10. Diagram showing the 'Big Ear' antenna at the OHU

some angle, will be transferred across the large metal ground plane to the curved reflector. There they are reflected again, but this time they are focused onto a pair of feed horns which are mounted on the ground plane surface. From there, after suitable low-noise amplification, the signals are passed to the radio receivers, recorders and computers that are located in an underground laboratory directly beneath the feed horns. (**Figure 11**) By changing the tilt-angle of the flat reflector an arc of the sky can be explored while the rotation of the earth causes the telescope to cover a swathe of sky determined by the particular tilt angle in use at the time. In this way, the transit telescope was able to map the heavens above Ohio slice by slice.

Construction commenced in 1956. All the engineering work was undertaken by post-graduate university students who were working under John Kraus's supervision towards higher degrees in radio astronomy. As a consequence, progress on the building of the telescope was slow and at times sporadic: lectures, examinations, research and the preparation of dissertations all took precedence. Eventually, after 10 years of, at times, back-breaking labour the 'Big Ear' was completed. Its size was impressive. The standing parabolic reflector was 110m in length and 21m high, the tiltable flat reflector was 104m long and 31m high. They were joined by the flat, 128m conducting ground plane on which were positioned the two feed horns. In all, the telescope occupied an area of three (American) football fields. **Figure 12** shows the 'Big Ear' surrounded by farmland with dense woodland behind each of the reflectors.

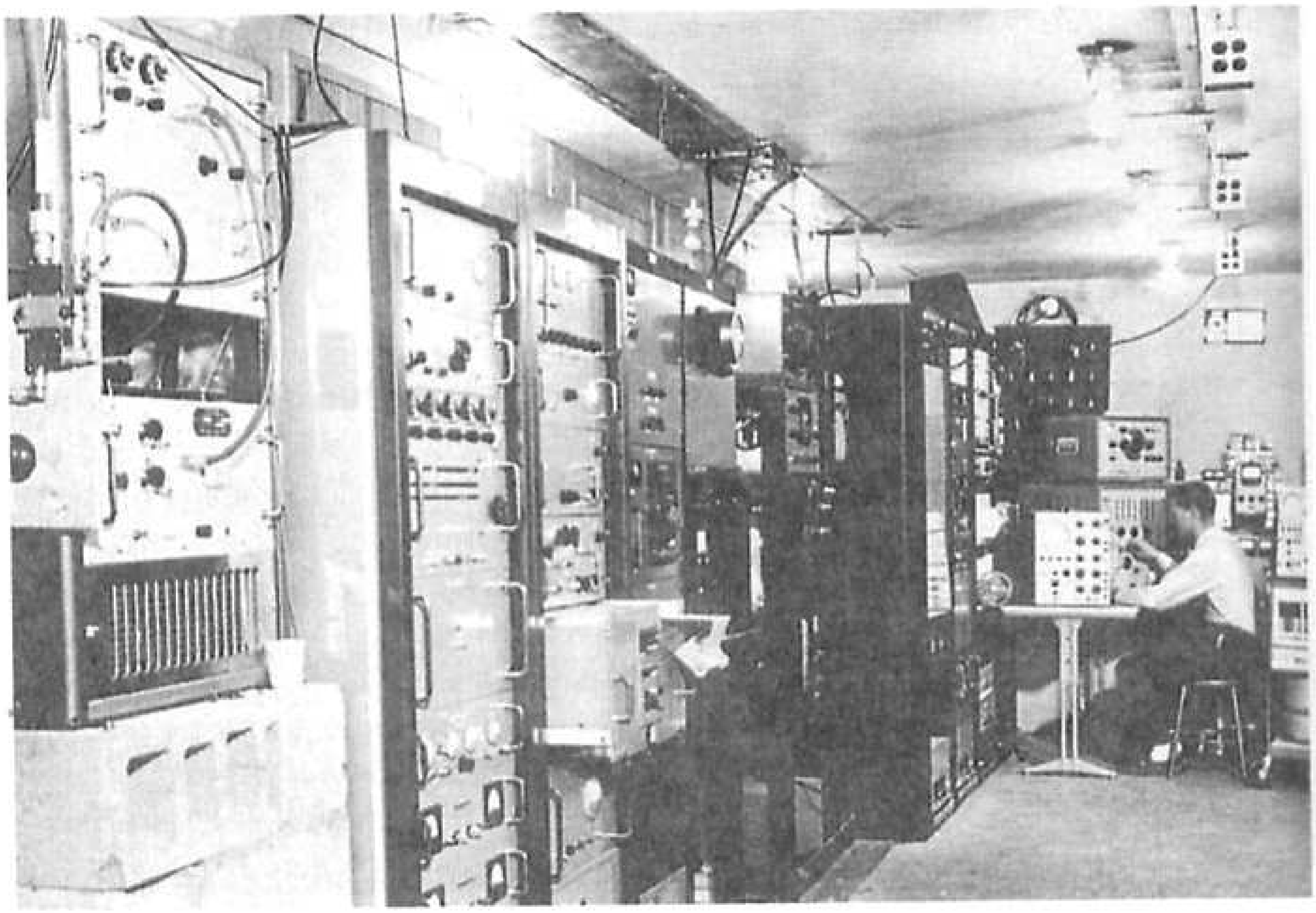


Fig. 11. Receiver and computer laboratory beneath the Big Ear antenna

Mapping The Sky

A good antenna is vital if a radio telescope is to be able to explore the cosmos for signals (noise is perhaps a better term!) emanating from some of the strangest objects science has ever contemplated. However, it matters not how good the antenna is unless the receiver to which it is connected is equally good. The receiver specification of most importance in this application is a very low noise figure and since Kraus intended to use 'Big Ear' to explore the spectrum at a wavelength around 21cm (or about 1400MHz), the spectral line of interstellar hydrogen, the most abundant element in the universe, it would require a parametric amplifier to achieve it. Fortunately, Bell Labs in New Jersey had considerable expertise in the design of such amplifiers because they were used extensively in the satellite-based communication systems then under development.

In 1963 Kraus's 'Big Ear', with the Bell Labs liquid nitrogen-cooled 'paramp' at its front-end, commenced its search for signals from outer-space. It is perhaps ironic that some thirty years before those same Labs had peremptorily terminated Karl Jansky's pioneering research into extraterrestrial radio phenomena.

The OSU radio telescope immediately began its primary radio survey. As implied, such a survey assumes no prior knowledge of what may be found or, indeed, where one should even look. The survey involved a systematic and detailed examination of the sky with the degree of detail, or resolution, being dependent upon the sharpness of the observing beam. Antenna resolution, just as it is with optical telescopes, is a function of the wavelength at which the observations are made and the size of the antenna making them. The resolving power of a radio telescope is usually equated to its half-power beamwidth which is a concept very familiar to all antenna engineers. It is determined by the ratio of the wavelength to the largest dimension of the antenna.

In May 1970, the IVth instalment of the *Ohio Sky Survey* was published. The 'Big Ear' had identified over 8,000 radio sources, more than the number of all other surveys conducted by other radio telescopes around the world combined.

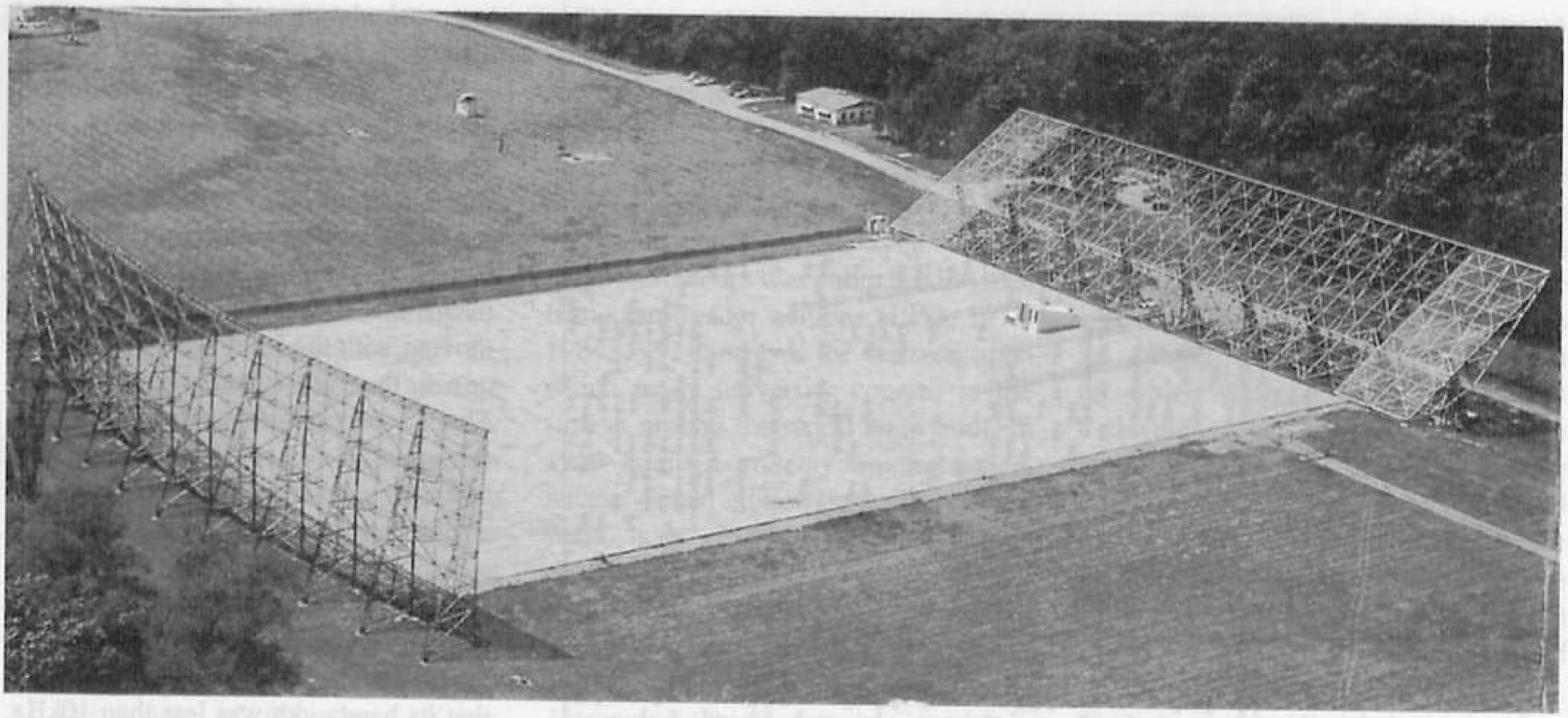


Fig. 12. 'Big Ear' photographed from the air

One of the most remarkable observations made was of the Andromeda galaxy, known to astronomers as M31, which is the nearest of the extragalactic radio sources with a size similar to our own galaxy. It was first observed in 1951 at Jodrell Bank using the original wire mesh transit telescope that preceded the famous 76m dish that dominates the Cheshire countryside today. The numbers associated with such galactic phenomena are almost beyond comprehension. At a distance of around two-million light-years from the earth (a mere stone's throw in astronomical terms!), M31 has a radio-frequency output of about 1,032 watts. Remarkably this is not considered to be a particularly powerful radio source; Cygnus A, at a distance of around 600-million light years, has a radio output of about 1,038 watts! **Figure 13** shows, as a series of contour lines, the radio emission from M31 compared with its optical appearance as indicated by the bright white area in the middle. The extent of the radio emitting region is far greater than the optical galaxy and is suggestive of an explosion millions of years ago which ejected clouds of electrically charged particles, known as plasma, which actually emits the radio waves.

In 1970 the OHU telescope discovered what was recognised at that time as being the most distant and most powerful cosmic object yet observed. They designated it OH471. It turned out to be a quasar, or quasi-stellar radio source, which had a measured redshift of 3.4, meaning that it was moving away from the earth at a velocity of 90 percent of the speed of light. OH471 was the first object to be discovered with a redshift exceeding three but it was not long before OQ172, with a redshift of 3.53 was found. It is astonishing to note that galaxies with redshifts as high as 12 have been reported in the most recent scientific literature.

Are We Alone?

Possibly the most astounding use to which a radio telescope could be

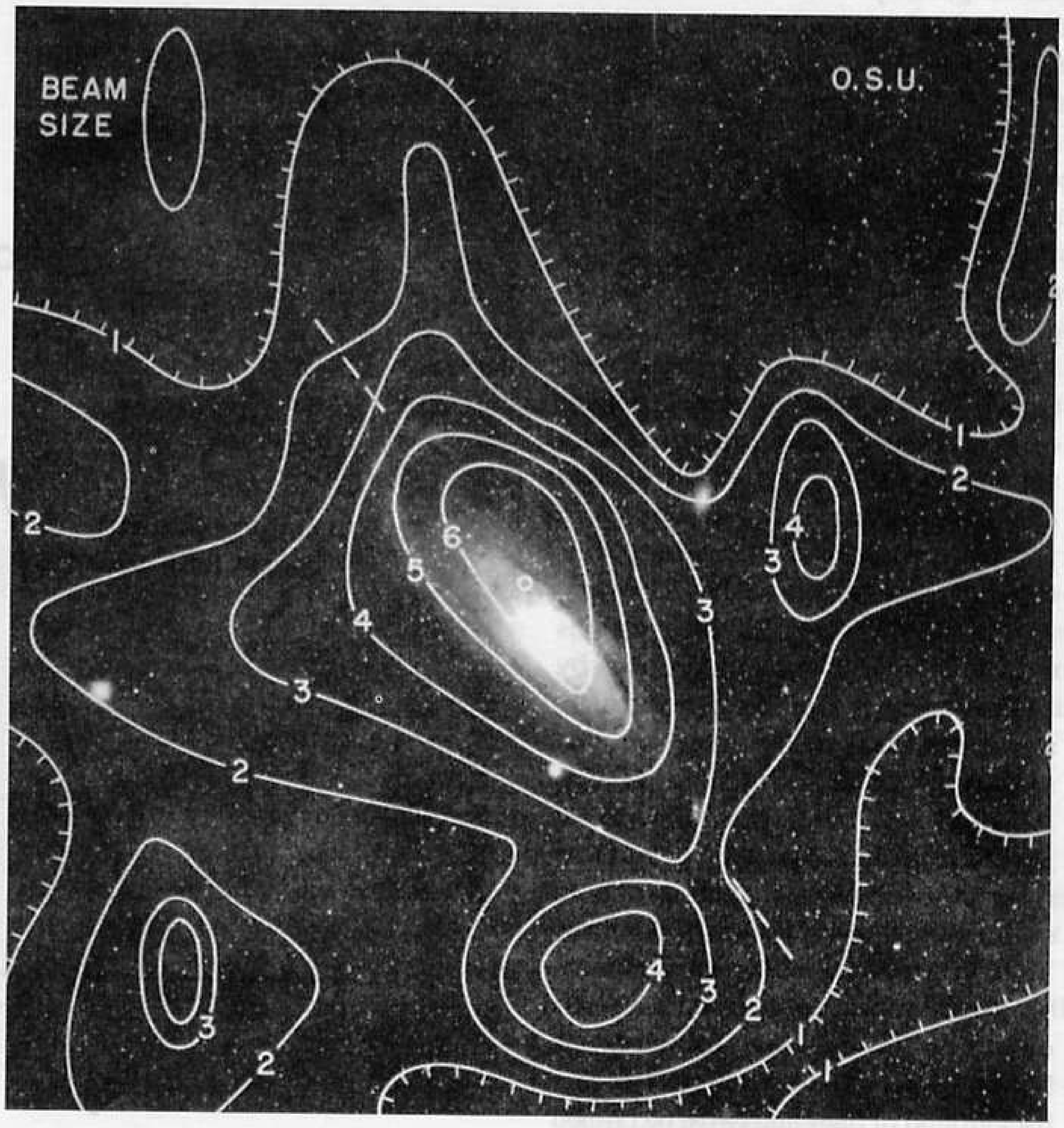


Fig. 13. The Andromeda galaxy M31 showing its radio and optical components

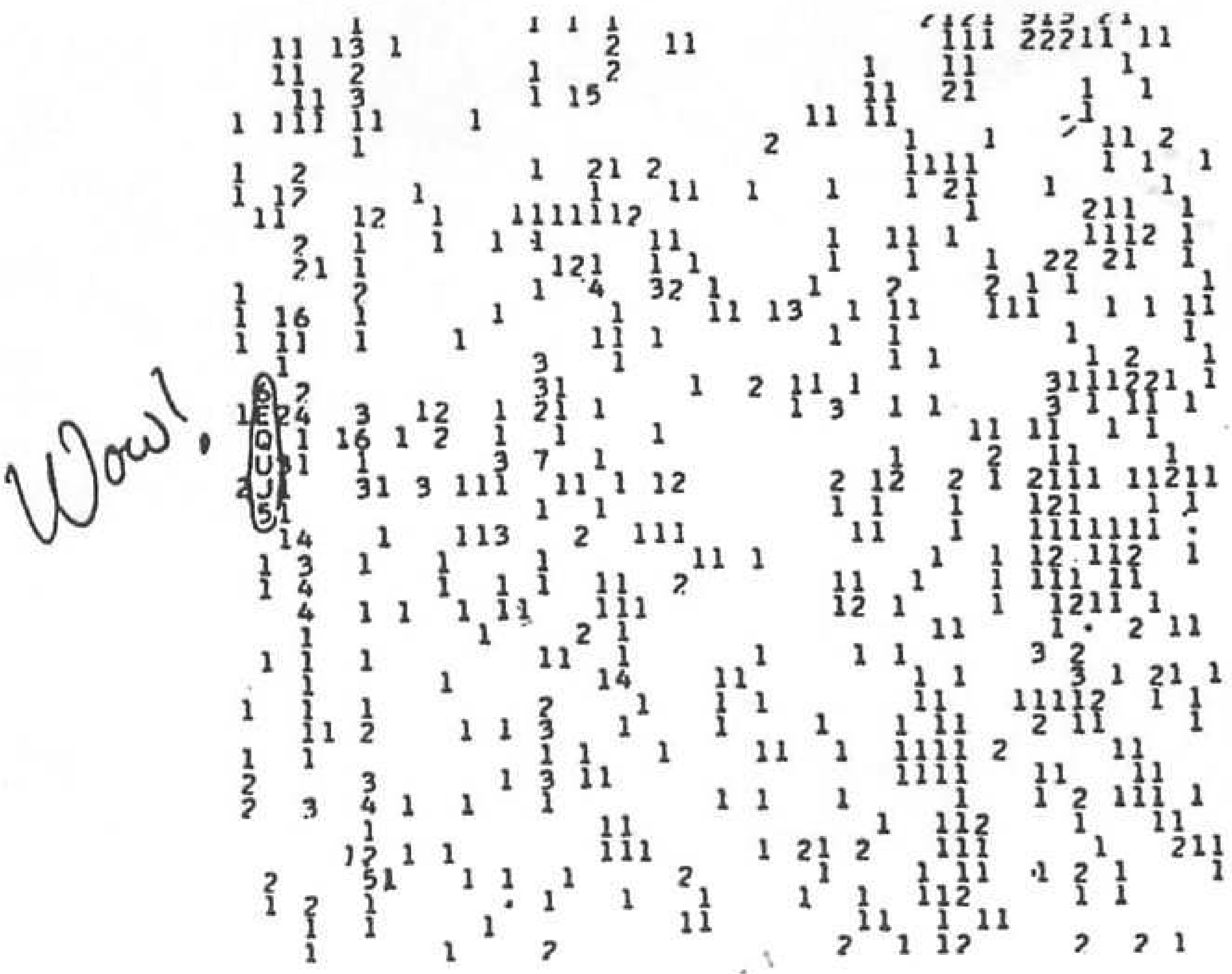


Fig. 14. The "Wow!" computer print-out. Each column represents one of 50 receiving channels 10kHz wide

put is the quest to discover whether other forms of intelligent life exist somewhere else in the Universe. That search goes by the name of SETI, the Search for Extraterrestrial Intelligence. John Kraus began using the Big Ear telescope for that purpose in December 1973. It ran continuously from then on until the demise of the 'Big Ear'. But more of that later.

On 15th August 1977, the computer print-out from the 'Big Ear' receiver produced a remarkable record. (**Figure 14**) From lists of digits seldom exceeding two (the value indicating the strength of the recorded signal compared with the background noise), which implied that the antenna was pointing to a particularly quiet part of the Milky Way, there suddenly appeared the following sequence: 6EQUJ5. Signal strengths exceeding nine were represented by letters so that A was 10, B became 11 and so on. Numerically, therefore, that sequence was as follows: 6, 14, 26, 30, 19, 5 with the largest value being 30 times greater than the background noise. Another way of putting it is to say the signal-to-noise ratio (SNR) was 30. When the astronomer Jerry Ehman, whose task it was to examine the print-out, came across this extraordinary burst of energy that had popped out of a background of ones and twos, he circled it with his red pen and wrote "Wow!" in the margin. Scientists, though supposedly unemotional creatures, do have their moments!

He immediately informed John Kraus who hastened to see the print-out for himself. Satisfied that there was no apparent malfunction evident in the equipment, Kraus immediately initiated a detailed investigation and numerous tests, calculations and, of course, much discussion followed.

When those numbers are plotted graphically (**Figure 15**) against time, which is a measure of the rate of rotation of the earth and hence of the antenna, they replicated almost exactly the radiation pattern of the 'Big Ear' antenna. This means that the source of the signal was moving with the stars; nothing either on or near the earth would behave like that. That 72 second burst of energy occurred only once. It was not there the day after, nor on any subsequent day when, as one might imagine, the scrutiny within the control room was at its most intense. And it has never been seen again. In addition, it existed in only one channel of the 50 channel receiver which indicated that its bandwidth was less than 10kHz. This is particularly curious since most natural celestial radio sources have very wide bandwidths. The investigation then switched to likely sources of interference which may have entered the receiver and corrupted the computer print-out.

The fact that the signal occurred at a frequency of 1420.4556MHz, which is within the internationally agreed and protected band of frequencies allocated to radio astronomy, ruled out interference from normal radio communications, radar and any other conventional electromagnetic transmissions, whether earth-based

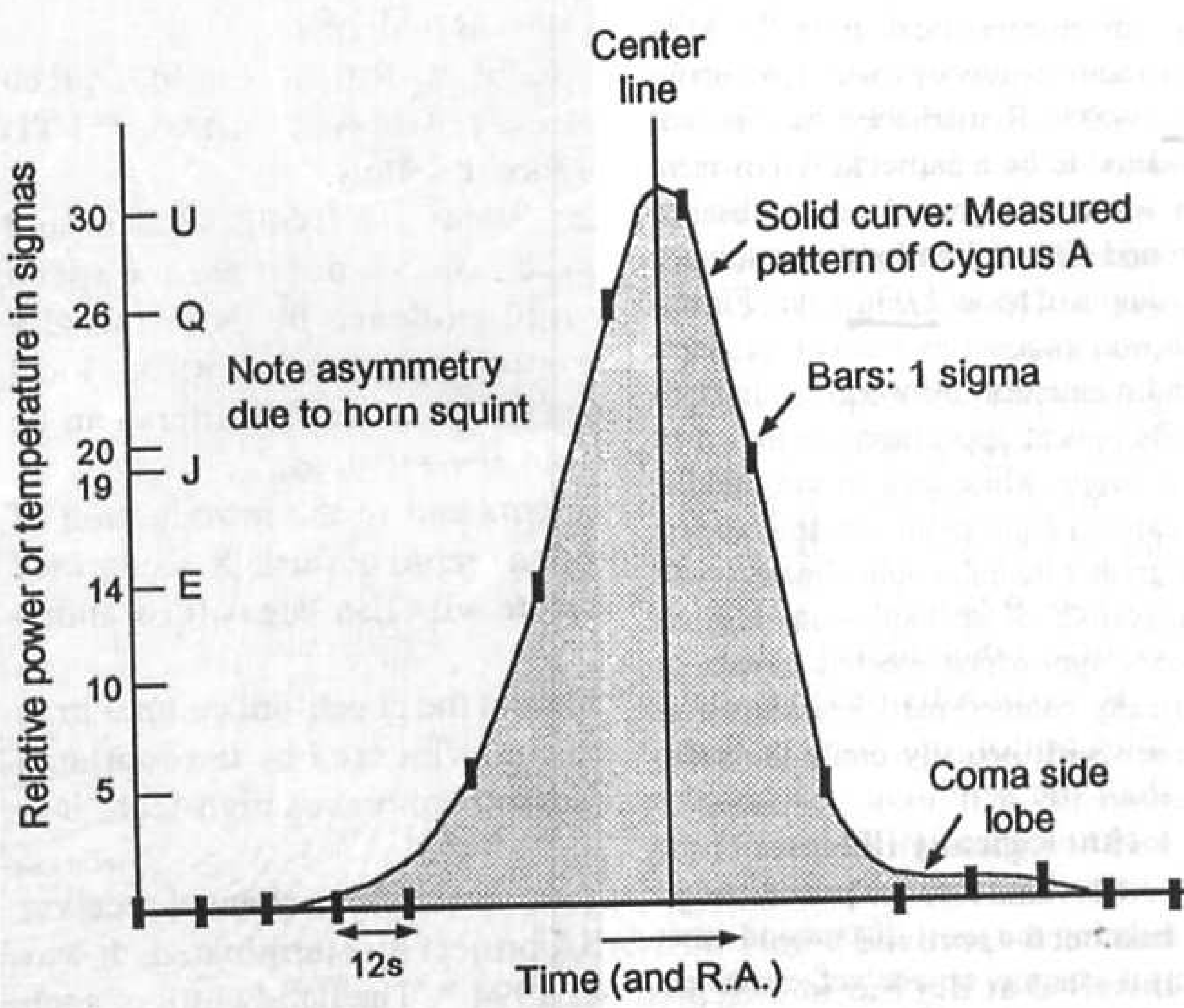


Fig. 15. Graph comparing the "Wow!" signal strengths with the 'Big Ear' antenna pattern

or from orbiting satellites and space probes. Of course, there was always the possibility that a spurious signal (harmonics, intermodulation products and so on), produced unintentionally by some piece of malfunctioning electronic equipment, might have been responsible, but careful consideration of all factors ruled that out as well.

Of considerable importance was the direction in which the 'Big Ear' antenna was pointing at the time. Its very narrow and accurately oriented beam provided a high degree of spatial filtering and fixing the beam's position would pinpoint the source. The computer print-out listed the galactic coordinates coinciding with each sample of displayed data. It was therefore easy to determine the location of the source of the signal. Kraus described it poetically as lying on "the eastern slopes of the galactic ridge not far from the centre of the galaxy". That put it in the constellation of Sagittarius.

And that's as close as we get to it. To this day the "Wow!" signal remains a mystery. Was it caused by some extraterrestrial intelligence and, if so, what? Or was it just some artefact of the equipment, or from elsewhere, with man maybe playing some part? No one knows.

Kraus The Author

In a career that lasted nearly fifty years, John Kraus the scientist and engineer also displayed another side to his make-up: a facility with words. But he didn't write fiction. Kraus's forte was to write, with wonderful clarity, about the subject he loved and in which he made some very significant contributions. In the broadest terms he wrote about electromagnetics: the physical processes by which energy and information are conveyed across the emptiness of space, via the ionised regions of the earth (and other planets), through solid, liquid and gaseous media of all types and, also, along cables, pipes and wires (and even through the plastic tubes of fibre optics) for the benefit of mankind. In all he wrote seven books, some of which ran to multiple editions and numerous printings. Many of his books were translated into other languages including Japanese, Chinese, Korean, Russian, Greek, Spanish, Portuguese and others.

His first book, published in 1949, was *Elements of Electromagnetics*. It started life as lithographed pages based on his lecture notes at OSU. This was followed, within a year, by *Antennas*, which went into four editions with the latest appearing as recently as 2010. *Antennas* is still regarded by many practitioners of the art as their bible. Next came the first edition of what became almost the standard text on the subject when *Electromagnetics* was published in 1953. It too ran to four editions (1953, 1973, 1984, 1992) and was the bedrock upon which many university courses in the subject around the world were built. In 1966 *Radio Astronomy* was published, with a second edition appearing twenty years later. There can't be a radio observatory anywhere on the planet that doesn't possess at least one copy. Shortly after it was published, Kraus happened to be on a visit to the US National Radio Astronomy Observatory in Greenbank, West Virginia where he discovered that its library contained 17 copies. All were out on loan!

In 1976, John Kraus wrote a personal account of his life and work but it was by no means a turgid autobiography. Called *Big Ear* it tells the story of how he came to radio and through it, following wartime service as a civilian scientist and electromagnetics specialist, his career as an engineering academic took off. The book is a fascinating read for anyone with an interest in the applied sciences and especially those related to radio frequency phenomena. It ranks alongside Sir Bernard Lovell's autobiographical blockbuster, *Astronomer By Chance*, as a story of the triumphs (and travails) of two of the pioneers of the newest branch of the 'Queen of the Sciences'. Following this, in 1980, came Kraus's only book written under the banner of 'popular science'. It was called *Our Cosmic Universe*. The foreword was written by Arno Penzias, the Nobel Prize-winning physicist who shared the 1978 prize for the discovery of the cosmic microwave background radiation that underpinned the Big Bang theory of cosmology. He summed the book up admirably as a "kaleidoscopic panorama of the universe ... with an enjoyable series of human-interest glimpses showing how flashes of insight, gained through the creation and use of new instruments, have enlarged mankind's perception of the electromagnetic spectrum".

The Day Of Infamy

In 1995, and now well into his retirement, Kraus updated his personal story in *Big Ear Two*. It took the history of the Ohio radio telescope from its earliest beginnings to the stage when it was one of the most successful instruments in use for observing the heavens. But it also relates how, in December 1982, a bombshell fell when Kraus was informed, without any prior consultation, that the 'Big Ear' was to be demolished. Apparently the land on which it stood had been sold to a developer and the joint agreement between OSU and its neighbouring academic institution, which owned the land, had been terminated. As far as those who took the decision were concerned, the major sky survey on which the telescope had been engaged for many years was now complete and, to them, that implied it had served its purpose!

As one might expect, Kraus fought with every piece of armament he could muster while the international astronomy community rallied to his assistance and correspondence flew thick and fast between all the parties concerned. With that support, but lacking any financial backing from the US government which had made the decision to withdraw funding for radio astronomy research by the US universities and place it, instead, with the national observatories, Kraus only managed to negotiate a stay of execution. In 1998 'Big Ear' was destroyed and the land on which it had stood for over 40 years, and where it had made numerous significant contributions to our understanding of the Universe, was turned into a golf course. It was, as he wrote in 2004 the year he died, a 'Day of Infamy'.

Acknowledgement

The source of most of the photographs and diagrams used here was Cygnus-Quasar Books, the late John Kraus's publishing company. Due acknowledgement is made to them.

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