Except for the interest and work of a second United States scientist, Grote Reber, for approximately ten years little attention was paid to Karl Jansky's discovery. Then, it was not primarily in the United States that major activity in the field of radio astronomy developed. Therefore, while there are many competent scientists in the United States doing outstanding work in this field, unfortunately this nation has been relatively slow in developing radio astronomy facilities comparable to those in other nations. Also, while without question the importance of Karl Jansky's work is recognized by many United States scientists, there is even greater appreciation of his work abroad than at home.

Early Radio Astronomy at Wheaton, Illinois*

GROTE REBER†

Although Karl Jansky discovered the existence of radio emissions from outer space as early as 1932, a decade passed before the scientific world began to take interest in it. During that barren period one man, and one man alone, compelled by a great love of science and research, carried forward Jansky's initial work. That same man now recounts for us in his own words the pioneering experiments he conducted during his lonely vigil of the heavens.—*The Editor.*

Summary—**A history is given of radio astronomy experiments conducted by the author from 1936 through 1947. A description of the parabolic reflector and equipment design is presented along with reasons for the choice of successive operating frequencies of 3300, 910, 160, and 480 mc. The results are reviewed in light of more recent knowledge. Published articles covering the scientific details will be found in the footnotes.**

INTRODUCTION

MY INTEREST in radio astronomy began after reading the original articles by Karl Jansky.[1,2] For some years previous I had been an ardent radio amateur and considerable of a DX addict, holding the call sign W9GFZ. After contacting over sixty countries and making WAC,[3] there did not appear to be any more worlds to conquer.

It is interesting to see how the mystifying peculiarities of short-wave communications of 1930 gradually have been resolved into an orderly whole. The solar activity minimum of the early thirties must have brought with it abnormally low-critical frequencies. Many a winter night was spent fishing for DX at 7 mc when nothing could be heard between midnight and dawn. It is now clear that the MUF over all of North America was well below 7 mc for several hours. An hour after sunset when the west coast stations disappeared 14 mc went dead. These years would have been a very fine time for low-frequency radio astronomy. The now appreciated long quiesence of the sun during the latter half of the seventeenth century[4] would have been even better!

One further recollection is that on these quiet nights it was always possible to make the receiver quieter by taking off the antenna. This receiver uses a regenerative detector and one rf stage. The detector and rf stage are tuned separately so that the latter may be gradually tuned across the former. When this was done with the antenna off, no appreciable change could be heard in the sound of rushing water. When the same thing was done with the antenna on, the rushing sound increased several times in loudness at the resonant frequency of the rf stage. Whether or not this difference was due to cosmic static or merely to some vaguery of the receiver is not readily resolved at present. Near the next solar activity minimum it might be interesting to try the old receiver out again with a similar antenna, which was an inverted "L" 40 feet high and 200 feet long. The above experiences were at 225 West Wesley Street, about 70 yards from 212 West Seminary Avenue where the rest of the observations were conducted. All this property now belongs to the Illinois Bell Telephone Company.

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* Original manuscript received by the IRE, November 5, 1957.

† Wailuku, Maui, Hawaii.

[1] K. G. Jansky, "Directional studies of atmospherics at high frequencies," PROC. IRE, vol. 20, pp. 1920–1932; December, 1932.

[2] K. G. Jansky, "Electrical disturbances apparently of extraterrestrial origin," PROC. IRE, vol. 21, pp. 1387–1398; October, 1933.

[3] Worked all continents.

[4] D. J. Schove, "The sunspot cycle 649 BC to AD 2000," *J. Geophys. Res.*, vol. 60, pp. 127–146; June, 1955.

ORGANIZED EXPERIMENTS

In my estimation it was obvious that K. G. 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 static. Two fundamental problems presented themselves. These were, are, and will continue to be: How does the cosmic static, at any given frequency, change in intensity with position in the sky; and how does cosmic static, at any given position in the sky, change in intensity with frequency? To solve these problems would require an antenna which could be tuned over a wide frequency range, provide a narrow acceptance pattern in mutually perpendicular planes, and be capable of pointing to all visible places in the sky.

About this time I had completed a modicum of academic learning. Two features stood out as pertinent. First, geometrical optics demonstrates that the angular resolving power of a device is proportional to its aperture in wavelengths. Consequently, for a given physical size aperture, the angular resolving power is proportional to frequency. Obviously a high frequency was indicated. Secondly, Planck's black body radiation law shows that for radio frequencies at any probable temperature, the intensity per unit frequency bandwidth of radiant energy is proportional to the square of the frequency. Again, a high frequency was indicated. Thus, on the face of the prevailing ignorance, a very high frequency should be used since much better resolution would be secured and very much more energy would be available for measurement. Some frequency in the decimeter region was indicated.

RADIO TELESCOPE

Consideration of the antenna problem showed that any type of wire network would be exceedingly complicated since several hundred minute dipoles would be needed. The only feasible antenna would be a parabolic reflector or mirror. By changing the simple focal device it would be possible to tune the mirror over a very wide frequency range. About this time Barrow[5] published some experiments on circular waveguides. The patterns of these apertures seemed just the thing for looking into a mirror. Thus I conceived the idea of using a single dipole inside a short length of waveguide at the focus of the mirror. It turned out to be a very satisfactory, simple arrangement providing good shielding against radiation other than from the desired direction. The focal point of the mirror was placed in the aperture plane of the waveguide.

If optical practice were to be followed, the mirror should be on an equatorial mounting. This would have been very complicated and exceedingly expensive. Even an alt-azimuth mounting would be prohibitive in cost and could not have been used profitably in the confined location available. Therefore, a meridian transit mount was decided upon. The mirror was to be as large as possible consistent with available funds. One inquiry was made for a purchased framework of steel. The American Bridge Company offered a design which consisted of a circular billboard 50 feet in diameter and 10 feet thick with a horizontal axis through the center mounted upon two vertical pillars 30 feet high. The billboard was to have a four leg parapet 35 feet high on one side with counterweights and locking mechanism on the other side. Since the mirror skin and supports plus turning motors were extras, I adjudged their offering price of 7000 dollars, erected, to be excessive! This was in 1936. Not many years later I wished I had been more of a speculator. In any case, I decided to design the mirror and do the job myself.

The mounting had been decided upon. Only one more problem remained, distortion of the surface by bending. This could be reduced greatly by using a deep framework. Various materials were considered. From an academic point of view, the best material for preventing bending is the one with the highest ratio of modulus of elasticity to density and not the highest ratio of strength to weight. Of the common materials, steel and aluminum are about equal. However, although much inferior, wood was decided upon because of cheapness and ease of working. Even with wood, the bending on a mirror 30 feet in diameter could be made negligible by using a deep framework. Most of the wooden members were 2 inches × 4 inches cross section and from 6 to 20 feet long. All joints were fastened by steel gusset plates of various widths and $\frac{1}{8}$ inch thick. The bolts were $\frac{1}{2}$ inch in diameter. All pieces were given two coats of paint before assembly and two coats afterwards. The framework was given added coats every couple of years. When disassembled in 1947, all pieces were found to be dry, solid, and as good as when put together. With reasonable care, it could have lasted indefinitely. The skin was 26-gauge galvanized iron in 45 pieces of pie; nine on the inside and 36 on the outside. These were supported on 72 radial wooden rafters cut to a parabolic curve. The sheet metal was not preformed but was allowed to drape snugly over the rafters and was fastened with a flat head brass wood screw at every lineal foot. The joints were overlapped about 2 inches and fastened with bolts every foot of lineal joint. All joints were spaced half way between rafters. The over-all diameter of skin was 31 feet 5 inches. Since the focal length was 20 feet, a relatively flat mirror was required. This, in conjunction with the multiple joint skin, allowed a good smooth surface to be secured. The major roughness was due to the bolt heads. The exact accuracy was unknown. However, the mirror platform was flat to plus or minus an eighth

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[5] W. L. Barrow, "Transmission of electromagnetic waves in hollow tubes of metal," PROC. IRE, vol. 24, pp. 1298–1328; October, 1936.

of an inch in all positions as found by measurement, so the skin had a commensurate parabolic accuracy. All the wooden pieces, including the lattice parapet, were cut, drilled, and painted by me personally. Part time assistance of two men was secured on the foundations, metal parts, and erecting the structure, with the exception of the skin which I personally put together piece by piece. The entire job was completed in four months; from June to September, 1937. The over-all weight was less than two tons. This mirror usually emitted snapping, popping, and banging sounds every morning and evening. The rising and setting sun caused unequal expansion in the skin and the various pieces would slip over one another until equilibrium was attained, no matter how tightly the joining bolts were pulled up. When parked in a vertical position, great volumes of water poured through the center hole during a rain storm. This caused rumors among the local inhabitants that the machine was for collecting water and for controlling the weather. The center hole, 2 feet in diameter, was included, just in case it would be desirable to use the mirror for centimeter waves with an elliptical secondary mirror at prime focus. A similar opening was built into the carriage, so that a very long focal length could be secured if the receiver were placed below the bottom of the carriage. This Gregorian scheme was never used. The lower parts of the machine provided an enticing structure for all the children of the neighborhood to climb upon. However, they were prevented from getting on top by the overhanging nature of the skin.

When working at the focal point, the mirror was tipped far south to an elevation of about 10°. The structure had a peculiar attraction for private flyers who would examine it from many directions and distances in their putt-putt airplanes. More than once, when one of these flyers would approach down the beam from the south, I had the sensation that a motorcycle was coming up out of the ground right through the center back of the mirror. Obviously, the mirror also had good acoustical properties.

This radio telescope was acquired by the National Bureau of Standards in 1947 and was erected on a turntable at their field station near Sterling, Va. About 1952, it was disassembled and the parts sent to Boulder, Colorado. Recently, the National Bureau of Standards has made the antenna available to the National Radio Astronomy Observatory on an indefinite loan basis for exhibition and demonstration purposes.

Electronic Apparatus and Tests at 9 CM

The shortest possible wavelength in the middle 1930's was on the order of 10 cm. An RCA type 103A end plate magnetron was acquired for general testing. This tube could be operated from 2500 to 5000 mc, depending upon the electrode voltages and magnetic field applied. The frequency limits really were due to the resonance of the internal anode structure which had a natural period of about 3300 mc. At optimum, nearly $\frac{1}{2}$ w could be put into a small lamp bulb. Audio modulation was applied in the end plate circuit.

Quite a variety of crystal detectors were experimented with. All could be made to work, more or less. However, a clear amber piece of zinc sulfide, known as sphalerite, was by far the best since it was sensitive all over, no matter where the cat whisker was placed. The rest of the receiver consisted of a four-stage audio amplifier using 6F5 triodes giving a gain of the order of 100 db. It was peculiarly free from microphonics and was very reliable. Using this equipment, a variety of experiments[6,7] were conducted on cavity resonators, etc. For close work, a 0–200 microammeter was used directly in the crystal circuit. The magnetron was tried as a detector in place of the crystal, but was found to be worthless because of very great shot noise voltage. Two other attempts were made to improve upon the crystal detector.

One was a special small diode entirely made of tungsten and pyrex. The spacing from anode to cathode was carefully adjusted to about 0.005 inch and the physical structure so arranged that the anode became part of a tunable line or cavity. Energy was fed into a cavity by a small dipole and hairpin loop. In spite of all efforts, this device was markedly poorer than the crystal. The significance of electron transit time was only beginning to be appreciated.

Next, an elaborate Barkhausen tube[8] was constructed on the theory that the virtual cathode beyond the grid could be made to come as close as desired to the anode and thus cut down on the electron transit time loss. The tunable system consisted of lecher wires three half-waves long. Sliding shorting-bars at each end provided outside adjustment. The tube seals were at the voltage nodes at third points and thus reduced capacity effects. A glass bellows allowed for unequal expansion between the glass envelope and the tungsten lecher bars. The anodes were small semicylinders at the voltage peak in the center of the system. The Barkhausen grid and the internal filament were placed in the exact center of the two anodes. Considerable effort was expended in getting this device, with all the minute parts, put together properly. Unfortunately, it was all for naught since the sensitivity was no better than the diode. Considerable shot-noise voltage, produced by stray electrons finding their way to the anodes, created a terrific racket and it was necessary to fall back on the crystal detector. This vacuum tube construction work was done by the glass experts at the University of Chicago.

During the spring and summer of 1938, a considerable number of observations were made at 3300 mc

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[6] Grote Reber, "Electric resonance chambers," *Communications*, vol. 18, pp. 5–25; December, 1938.

[7] Grote Reber, "Electromagnetic horns," *Communications*, vol. 19, pp. 13–15; February, 1939.

[8] H. E. Hollmann, "The retarding-field tube as a detector for any carrier frequency," Proc. IRE, vol. 22, pp. 630–656; May, 1934.

mostly during the day. The crystal detector in its cavity, a short length of waveguide horn, and the audio amplifier were mounted just behind the mirror focal point. The antenna was parallel to the celestial equator. Various parts of the Milky Way, Sun, Moon, Jupiter, Venus, Mars, and several of the bright stars, such as Sirius, Vega, Antares, etc., were all examined. The output of the audio amplifier was passed through a copper-oxide rectifier and displayed on a microammeter. Observations were made visually of the meter indication and were tabulated, sometimes at minute intervals, sometimes at longer intervals, such as an hour. Some small irregular fluctuations were encountered, but no repeatable results were secured which might be construed to be of celestial origin. All this was rather dampening to the enthusiasm. Admittedly, the sensitivity of the system was quite poor. However, the frequency was 160 times as great as Jansky used and the presumed black body radiation intensity should be 26,000 times as great. If anything could be deduced from these efforts, it seemed to be that the relation between celestial radiation intensity and frequency did not conform to Planck's law.

ELECTRONIC APPARATUS AND TESTS AT 33 CM

Consideration showed that it would be best to lower frequency a bit and build more conventional electronic apparatus using triode tubes with the aim of greatly increasing the sensitivity. A couple of years prior to this, RCA had brought out the type 955 acorn triode. These commercial tubes were of different internal construction and of considerably inferior performance to the experimental tubes described by Thompson and Rose.[9] The early 955's also were better than the later versions. These early type tubes had a smaller diameter cylinder and a hemispherical top, compared to the flat top of the later tubes. A pair of tubes were connected in a push-pull arrangement with the grid pins soldered together, since this circuit determined the highest operating frequency. The plate and cathode leads were tuned by lecher systems. The former determined the frequency and the latter the strength of oscillation. A pair of the early tubes could be made to oscillate up to nearly 1000 mc. In 1938, these early tubes were still abundant and several oscillators were made for testing receivers, etc. Only about fifty volts were required on the anodes.

About this time, RCA brought out the type 953 acorn diode with the anode lead coming out of the top. An adjustable cylindrical resonator was constructed which could be used with either the 953 or the above described tungsten diode. These diodes and crystals were all tested for sensitivity and were found to be about equal at 910 mc and some two orders of magnitude poorer than the regenerative detector. Also, it was now observed that the tungsten diode had a faint rattle sound associated with it which increased in strength as the filament temperature was increased. This rattle was not present in the 953 with its low-temperature cathode. Apparently, the rattle was due to minute bits of tungsten boiling off the white hot filament. This is typical of the kind of thing which may be overlooked when no comparative observations are possible.

A new cavity resonator with an iris was constructed, for use at the focal point of the mirror, out of a steel drum container for 100 pounds of white lead. The dimensions of this drum determined the operating frequency of 910 mc. A half-wave dipole was placed a quarter-wave length from the back of the cavity. A half-wave lecher wire went from the center of dipole through a hole in the rear of cavity and was coupled by a small loop to the filament tuner of the push-pull detector. Thus, the entire antenna system resonated in a three half-wave mode. The detector and audio amplifier were placed in a small drum attached to rear of cavity. The entire arrangement was supported in circular bands, so the drum could be turned on its axis to change the plane of polarization received, since it was thought that there might be some variation with the plane of polarization of the still to be found celestial energy.

During the autumn of 1938 and during the following winter, a variety of observations, both by day and by night and with various polarizations, were made at 910 mc. All the same objects were examined again without any positive results. In a measure, it was disappointing. However, since I am a rather stubborn Dutchman, this had the effect of whetting my appetite for more. Here was a circumstance where the frequency had dropped nearly two octaves and the sensitivity had improved by two orders of magnitude and still nothing resulted. Perhaps the actual relation between intensity of the celestial radiation and frequency was opposite from Planck's law.

All this old equipment is still in existence and it might be interesting to set it up again and measure just what absolute sensitivity was achieved, both at 3300 and at 910 mc.

ELECTRONIC APPARATUS AND TESTS AT 187 CM

By then, autumn 1938, it was perfectly clear that a further great increase in sensitivity was necessary and that attempting to operate at exceedingly high frequencies was wrong. The resolution would have to be whatever it came out, for better or for worse. Concurrent with these experiences, I had been following in the literature various articles on the input resistance of triodes by Ferris, wide-band amplifiers by Percival, and trying to understand a rather deep book about random fluctuations by Moullin. Also I had been gaining experience in the radio receiver industry. It was clear that a big jump in sensitivity could be made by changing from a crystal to a regenerative detector. Another big jump

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[9] B. J. Thompson, "Vacuum tubes of small dimensions for use at extremely high frequencies," PROC. IRE, vol. 21, pp. 1707–1721; December, 1933.

would be to a superheterodyne receiver. Also, a superhet with an rf stage was much better and two rf stages still better. The tunable feature of a superhet seemed of little value. What was important was the rf stages. Also, it seemed that a wide bandwidth should be used, which again ruled against a superhet. Finally, I decided upon a multistage tuned radio-frequency amplifier with as wide a bandwidth and as high a frequency as feasible.

RCA brought out the 954 acorn pentode in 1935; the first ones were exceedingly poor, having many internal shorts. However, by purchasing new tubes from the autumn 1938 production, instead of dealer stock, some respectable samples were secured. About this time a small bulletin[10] was issued by the National Bureau of Standards which described a multistage amplifier using 954 tubes with coaxial line resonators. It was tunable from about 100 to 300 mc and over-all gain data was included. This bulletin was of much assistance in determining a suitable design. The wide range tunable feature seemed of no particular value and tended to introduce feedback. Also, the gain dropped rapidly above 200 mc. A frequency somewhere near 150 mc appeared suitable since it already was clear that a low-internal random fluctuation voltage only could be secured if the first-stage gain was fairly high, such as eight or more.

The idea of a cavity resonator at the focus of a mirror still seemed good compared to an open dipole, and I decided to continue using a cavity. This relatively low frequency would require a large but light cavity, which should be cheap and with as little welding as possible. Inquiry disclosed that aluminum sheet 1/16 inch thick could be secured in pieces 6 feet wide and 12 feet long. One piece could be formed into a cylinder about 4 feet in diameter and 6 feet long. ALCOA fabricated this resonator, including various size irises for the aperture, at a very nominal price. In essence, the operating frequency of 162 mc was determined by the size of a drum which could easily be made from a standard size sheet of aluminum.

The NBS design was revised[11] to provide capacity tuning over a range of 150 to 170 mc and the whole assembly of copper water pipe and copper plate was brazed into one piece by the local blacksmith. After fitting the by-pass capacitors and connections, an over-all trial was made and the entire five stages worked immediately. Furthermore, the, by then, well-known thermal fluctuation voltage easily could be found when the first tuned circuit was tuned through resonance; this was very encouraging. No signal generator was available to measure the sensitivity, but obviously it was good. This amplifier was then attached to the back of the large aluminum drum. The antenna was quite similar to that used at 910 mc but with additional fine-tuning adjustments.

Before hoisting this cumbersome assembly atop the parapet of the mirror, some ground tests were made. These provided quite a shock, since all kinds of man-made electrical disturbances now could be heard which before were not known to exist. The main one was caused by automobile ignition sparking. However, this trouble mostly disappeared after 10:00 P.M.; this was reassuring. Thus on the first Saturday when help could be obtained, the whole assembly was placed atop the mirror and trials were started. This was in the early spring of 1939.

During the day, no worthwhile results could be secured because of the multitude of automobiles in continual operation. This disturbance leaked into the drum from the back around the edge of the mirror. Cars at the front side and in front of the mirror could hardly be detected. Thus, the shielding action of drum really was effective. The output of the receiver came down a coaxial microphone cable as a small dc voltage. About three-quarters of this voltage was bucked out by a battery and the remainder was fed into a dc amplifier. The display was a microammeter. About two hours were required for equipment warmup. After 10:00 P.M., disturbances quieted down and observations were made in earnest. Data were taken by manually recording the meter indication every minute. Continual aural monitoring was employed to delete those times when interference was present. This data was then plotted as meter reading vs time.

During the night, good smooth flat reproducible plots were secured, but nothing could be found which moved along in sidereal time. In early March, the plane of the galaxy to the south still crossed the meridian after sunrise. While the auto disturbances did not become really bad until about 10:00 A.M., the amplifier was subject to gain variations when the sun came up. This was found to be due to unequal thermal expansions which caused some of the resonators on the interstage couplers to become out of tune compared to the others. On cloudy mornings the trouble was absent and some plots were secured which seemed to show excess energy when the plane of the galaxy crossed the meridian. These occasions were few since the cloudy morning had to appear on a weekend when I was not at work in the city. By early April, the plane of the galaxy was crossing the meridian during hours of darkness and good reproducible plots were secured every night when observations were made. It was now apparent that cosmic static from the Milky Way had really been found and that it was of substantial strength, especially to the south. As the months went by, the more northerly parts of the galaxy became available. However, the cosmic static became weaker and dropped nearly to the limit of the system sensitivity at a declination of 20° north. These results confirmed Jansky in a general way.

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[10] F. W. J. Dunmore, "A unicontrol radio receiver for ultra-high frequencies," PROC. IRE, vol. 24, pp. 837–849; June, 1936; and *J. Res. NBS*, vol. 15, Res. Paper RP856; 1935.

[11] G. Reber W9GFZ and E. H. Conklin, "UHF receivers," *Radio*, no. 225, pp. 112–161; January, 1938; no. 235, pp. 17–177; January, 1939; no. 236, front cover; February, 1939.

During the summer of 1939, a variety of celestial objects were examined but nothing convincing could be found, except from the Milky Way. Particular effort was made to find the sun but it was lost under compound equipment difficulties. Only thickly clouded days were possible for observation since thermal effects were induced by scattered clouds. Also, it developed that the 953 diode had another internal trouble. The velocity potential of the diode was in series with the signal voltage. This velocity potential is dependent upon cathode temperature and effective spacing between anode and cathode. During quiet periods, the velocity potential was stable. However, when a strong auto ignition disturbance was imposed, there was a small internal rearrangement of active areas on the cathode. Thus, the diode velocity potential would be different after, compared to before, a strong burst of ignition sparking. Consequently, a shift in the dc zero level occurred irregularly up and down after each objectionable vehicle went by. Several 953's and 955's were tried but to no avail. A 200,000-ohm diode load resistor was used at the time. The solution seemed to be to move everything out to the country, which then was not feasible. These preliminary results[12,13] were published in 1940. The intensity was guessed at by noting the effect of resistance shunts across the first tuned circuit; no calibrated signal generator was available then. In any case, the observed intensity was far below that encountered by Jansky. Obviously, the source of cosmic static was some new and unknown phenomenon.

The above success further whetted my appetite on the basis of, "If a little is good, more is better." A survey of the sky was contemplated; this would mean collecting a lot of data. Obviously, an automatic recorder was a primary necessity. Thus, a General Radio dc amplifier and Esterline Angus 5-ma recorder were purchased early in 1940. Also, new power supplies with entire ac operation and automatic regulation were built to replace the old dc system with its manual voltage adjustments. The new steady power supply had a great effect on receiver stability and resulted in effective long-term sensitivity. A few all night vigils were made with this automatic apparatus to gain confidence in its operation and to gain experience in how interference manifested itself.

In addition, a decent signal generator was imperative, if any quantitative measures were to be secured. Since one could not be purchased, I built my own signal generator rather as a copy of a Hazeltine machine designed for the old low-frequency television band. My design uses a WE 316A tube, with a tuning range of 140 to 200 mc, a reference output level of 1 v across 10 ohms, and an inductive attenuator to 120 db. No detectable leakage could be found. The case is all brazed copper pipe and plate by the same blacksmith mentioned above and the cover is sealed water tight using lead foil gaskets.

Finally by 1941, things seemed to be in order for starting a survey of the sky. Preliminary results were published the following year[14] with an analysis of the theoretical conditions governing receiver sensitivity. Later studies merely have confirmed these early investigations. Even today, explorers of the Milky Way at wavelengths less than a few meters do not receive any net celestial energy, but in fact merely measure changes in the net rate at which their equipment dissipates energy into the sidereal universe via the antenna beam. Further efforts to detect the sun failed, as mentioned above.

Returning now to the theory, it is worth mentioning that a significant improvement in signal to ripple ratio of 3 db may be secured by using a push-pull full-wave rectifier instead of the common half-wave type which loses half of the random fluctuation peaks. This is not particularly important on wide bandwidths, but I have found it to be worthwhile at low frequencies, where only a few kilocycles of bandwidth may be secured due to crowded channels.

IMPROVED APPARATUS AND TESTS AT 187 CM

Before much data had been accumulated, a greatly improved receiver was designed on the basis of the above and other[15] equipment studies. The type 954 tube was still the best tube available in 1941. Improvement in sensitivity only seemed possible by increasing the bandwidth or lengthening the integration time. Since auto ignition disturbance was so severe, it was desirable that the integration time should remain short, in order that the auto disturbance might quickly clear when an offending car had passed. Thus I decided to widen the bandwidth to the maximum feasible. Wide-band couplers of the Y type were designed using coaxial elements. The load resistance turned out to be about 7000 ohms for an 8-mc bandwidth, with some impedance step down from plate to grid. Again the whole affair was brazed into one piece. Because of the circuit complexity, considerable time was required to align everything. It would have been nearly impossible without the signal generator. Finally, a five-stage receiver emerged having a gain of about 90 db over the frequency band of 156 to 164 mc, compared to only 0.16-mc bandwidth of the earlier design. To maintain bandwidth, the diode load resistor was reduced to 15,000 ohms. This had the effect of reducing and stabilizing the velocity potential. The wide bandwidth eliminated the detuning caused by the temperature effects and the resistor on each grid did

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[12] Grote Reber, "Cosmic static," Proc. IRE, vol. 28, pp. 68–71; February, 1940.

[13] Grote Reber, "Cosmic static," *Astrophys. J.*, vol. 91, pp. 621–632; June, 1940.

[14] Grote Reber, "Cosmic static," Proc. IRE, vol. 30, pp. 367–378; August, 1942.

[15] Grote Reber, "Filter networks for uhf amplifiers," *Electronic Indus.*, vol. 3, pp. 86–198; April, 1944.

wonders for holding the stage gain constant. This receiver is nearly impervious to mechanical and electrical shock. The traces became sharp and clear; sensitivity and stability were sufficient to read to 0.001 of total output voltage during a run of several hours. It was operated for several thousand hours, merely by replacing a 954 from time to time. The antenna system was broad-banded by removing the front iris, so that the drum had full aperture toward the mirror, and by replacing the wire dipole inside with two aluminum cones, also made by ALCOA, having a 15° angle of rotation.

Now that really worthwhile electronic equipment was at hand, a complete survey of the sky was undertaken early in 1943. Data also could be secured during the day, except that the traces were quite rough due to auto disturbances. For some reason, the sun was not tried until September. A relatively high-gain setting was used, corresponding to the weaker parts of the galaxy then under observation. On the very first try the quiet sun put the pen hard against the pin at full scale for half an hour near meridian transit. Two further day's tries were required before proper on scale readings were obtained. The observations continued daily up to the middle of 1944 before a complete coverage of the available Milky Way was secured. During these years, the sun was at low activity and the solar traces were all very much alike and uninteresting. The results[16] were published in 1944 and included a polar diagram of the antenna pattern taken on the strong source in Cassiopeia. At the time, it was not realized that at the center of these contour circles there was actually a minute object of very high surface brightness. If the solar data reported should change into units of temperature, then the sun could be represented by a disk one-half a degree in diameter at a temperature of slightly less than a million degrees. This had no meaning at the time.

The first man-made electronic interference appeared during this survey. It was caused by badly adjusted iff transceivers in aeroplanes. The squitter could be heard for many miles when the plane crossed the antenna acceptance pattern. The ignition systems in commercial planes were shielded sufficiently well so that no sparking could be detected. A few small private planes were heard, but these rarely operated at night.

Apparatus and Tests at 62½ CM

When it became apparent, toward the end of 1943, that the situation was fairly well in hand at 160 mc, I cast about to see what could be done at higher frequencies to improve the resolution. An increase of two to one would be the least acceptable and three to one would be more interesting and significant. Cosmic static, clearly now, had an inverse intensity vs frequency relation. Consequently, the effective sensitivity should be at least equal to, and preferably surpass, that achieved at 160 mc. The use of a rather anemic commercial signal generator covering a frequency range from 400 to 550 mc also became available. Therefore, I decided on a new operating frequency of 480 mc.

The only tube offering any hope as an rf amplifier, to which I had access, was the RCA orbital beam type A5588A. A four-stage amplifier providing a gain of over 100 db on a bandwidth of 10 mc was constructed in 1944. These tubes certainly would amplify but that is all that can be said for them. The secondary emitter had a life of only 50 hours or so and the internal fluctuation voltage was exceedingly high.

A re-examination of the antenna focal apparatus was made to improve its efficiency[17] and broad-band characteristics. The drum had desirable properties of shielding which should be retained, but it was cumbersome and tended to be rather sharply resonant. The concept of its operation was that the field radiated from a virtual image point in the aperture plane which was made coincident with the focal point of the mirror. The drum acted more or less like an ellipse which transformed this virtual image point back to the antenna. I decided it would be best to do away with this image transformation and place the tips of a cone antenna directly at the focal point of mirror. Since the field from a cone antenna is nominally radial, a hemispherical shield should be provided over the back half of cones with a radius of about one-half wavelength. Several models were built and tested.[18]

A couple of months observations were made during the spring of 1945 using the four-stage amplifier and the new focal point apparatus. The results were very poor since the Milky Way could not be detected, nor even the quiet sun. On one day only the sun was detected when it was radiating in a steady but enhanced manner. The significance of this was not realized at the time. Just how poor this equipment was, could easily be guessed by the fact that auto ignition disturbance rarely was detected. Since these electron multiplier tubes cost thirty dollars each and could be seen to rapidly die in a few hours, the cost of observation averaged several dollars an hour. In fact, the best part of the life of a new tube was used up in getting the set aligned. Thus, not only were the results practically nil, but operation was very uneconomical.

Improved Apparatus and New Tests at 62½ CM

Even before the four-stage amplifier was finished, it was clear that it would be rather ineffective. By using special dispensation, I secured some GE 446B lighthouse tubes in the summer of 1945. These had markedly

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[16] Grote Reber, "Cosmic static," *Astrophys. J.*, vol. 100, pp. 279–287; November, 1944.

[17] Grote Reber, "Reflector efficiency," *Electronic Indus.*, vol. 3, pp. 101–216; July, 1944.

[18] Grote Reber, "Antenna focal devices for parabolic mirrors," Proc. IRE, vol. 35, pp. 731–734; July, 1947.

less gain but were an immense improvement in life, stability, simplicity, and particularly low-internal fluctuation voltage. A new six-stage amplifier with a 6-mc bandwidth was built using these high grade triodes.

Observations commenced in the summer of 1946. Success was immediate on both the Milky Way and the sun. Also, automobile ignition sparking now was very objectionable during the day. The galactic radiation was markedly weaker than at 160 mc, as was expected. However, the quiet sun was much stronger. Again the gain was set much higher than need be, so that the quiet sun held the pen at full scale for a quarter-hour on the initial try. There seems to be no way of guessing these matters in advance, especially with such an unknown phenomenon. In fact, it seemed that perhaps the sun was a black body radiator but the temperature would have had to be nearer a million degrees than the optical value of six thousand degrees.

Most daytime observations were still unattended since I continued to work in the city. Examination of the solar records showed several cases where automobile ignition interference was abnormally strong and persistent during a half hour or so near solar transit. Why the cars should pick this time to be particularly objectionable seemed quite mysterious. In time, a similar circumstance occurred on a weekend when I was present. Listening observations and pointing the antenna beam away from and towards the sun quickly unravelled the situation. The sun was, in fact, emitting hiss-type transients which rose to great amplitude and fell again in a second or less. These occurred repeatedly and in an overlapping manner, so that for a couple of minutes at a time the pen would remain hard at full scale. Apparently there were many small independent sources of intense transient solar radio waves such as I had never encountered before.[19] The phenomenon became more frequent by the spring of 1947. Also the background intensity rose and fell with irregular periods of a week or more.[20] Obviously, circumstances in the sun were far different now than in 1943 and 1944. Also, as expected, much more detail was found in the structure of the Milky Way.[21] The Cygnus region was divided into two loops. One of these turned out to be the now well-known colliding galaxies source of minute dimensions, as was previously suspected.[22] The other is known as Cygnus-X and seems to be behind a dust cloud. One of the loops in Taurus later was identified as the Crab Nebula. A long slender source in Virgo now is suspected to be the resultant of local galactic clustering, that is, clustering of galaxies in the neighborhood of the Milky Way. These were the last set of observations completed at Wheaton, Ill.

Equipment for Use at 21 CM

During the autumn of 1945, I met H. C. van de Hulst. He explained his theoretical work on neutral hydrogen and asked for my estimate of the possibility of detecting it. Since I did not know anything about the matter, I could not guess. Neither could he guess whether or not the line would appear in emission or in absorption. At the time I had only the unsatisfactory experience with A5588A tubes at 480 mc. If the line were to be observed in absorption, the matter would be practically hopeless; if in emission, then there might be some possibility. In any case, before trying more microwave experiments, it seemed best to have the lighthouse tubes going at 480 mc. By the autumn of 1946, this had been accomplished.

Consideration was then possible for work at 1420 mc. First, there was no test equipment. To remedy this, I built another signal generator covering the range of 1200 to 1600 mc. The oscillator was modified from the transmitter section of an ABJ type iff equipment and it uses a 2C43 tube with an inductive attenuator. Experiment quickly showed that none of the GE lighthouse tubes would be satisfactory amplifiers at 1420 mc. About this time Sylvania brought out a better version known as the 5768 rocket tube which was similar to some European tubes. A prototype stage was tested and found satisfactory. The necessary movable selectivity was to be obtained by an echo box bought on the surplus market; it has a bandwidth of about 50 kc. It was intended to construct a multistage amplifier using the Sylvania tubes and insert the echo box in the chain. Provided that the amplifier was good enough to detect the continuum, it seemed likely that a fairly strong absorption line might be detected. If the line were to appear in emission, then so much the better. The entire setup was never completed because operations were closed at Wheaton, Ill., during the early summer of 1947. In view of present day knowledge, it seems likely that the experiment would have been successful.

Addenda

The above was written in Australia during August and September, 1957 from memory and without recourse to log books, etc., located in Wheaton and Hawaii. Thus, there may be some slight error in minor facts, for example, the date when certain tubes became available, etc.

Two errors are worth correcting. The data[13] purporting to show results from Andromeda Nebula were really chance drifts in the early equipment. Selected charts secured much later can be used to prove its existence. Equally good charts are available to deny it. The detectability of this object was on the edge of equipment capabilities as already explained.[21] If all the data had been combined statistically, as is common practice today, the Andromeda Nebula certainly would have appeared. This process is really one of greatly lengthening the integration time.

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[19] Grote Reber, "Solar radiation at 480 mc," *Nature*, vol. 158, p. 945; December, 1946.

[20] Grote Reber, "Solar intensity at 480 mc," Proc. IRE, vol. 36, p. 88; January, 1948.

[21] Grote Reber, "Cosmic static," Proc. IRE, vol. 36, pp. 1215–1218; October, 1948.

[22] G. Reber and J. L. Greenstein, "Radio frequency investigations of astronomical interest," *Observatory*, February, 1947.

Using fluctuation voltage it is possible[14] to deduce the size of the elementary charges causing this voltage. When the result was published, a value corresponding to three electrons was given. This was an error caused by an incorrect and much too low value of capacity. Afterwards, the mistake was found and the proper value of electron charge secured in agreement with other methods.

These old experiments at Wheaton were quite thrilling at the time. My present experiments[23] at the other end of the spectrum in Tasmania using cosmic static at kilometer wavelengths fully equal the old in the realm of the unexpected.

Much remains to be done.

[23] Grote Reber, "Between the atmospherics," *J. Geophys. Res.* (in press).

The Telescope Program for the National Radio Astronomy Observatory at Green Bank, West Virginia*

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Summary—**A brief account is given of the initiation of the feasibility study on the establishment and operation of the National Radio Astronomy Observatory at Green Bank, West Virginia. The principal research facilities will be the radio telescopes, and a series of such telescopes have been proposed. The desired performance characteristics are reviewed. A 140-foot steerable paraboloid on an equatorial mount has been designed. The steps leading to this design are described, as well as the general features of the designed and the expected operating performance. The National Radio Astronomy Observatory is being sponsored by the National Science Foundation.**

INTRODUCTION

IN January, 1954, a conference[1] on radio astronomy was held in Washington, D. C., jointly sponsored by the National Science Foundation, the California Institute of Technology, and the Department of Terrestrial Magnetism of the Carnegie Institution of Washington. Participants included both United States scientists and engineers, as well as numerous distinguished foreign visitors. The conference made clear to the US participants that the lead in radio astronomy had been taken by other countries, this despite such noteworthy contributions as Karl Jansky's initial discovery,[2] G. Reber's pioneering work,[3] the tremendous advances in our electronics techniques, particularly those related to radar and radio communications, and the first observation of the 1420-mc radiation of interstellar hydrogen by Ewen and Purcell.[4] The conference also indicated that US radio astronomy would fall behind further and further if steps were not taken to provide observing facilities comparable to those planned or being built in other countries.

The equipment requirements of radio astronomers are of three general classes: the antenna system; the receiver and data processing equipment; and the ancillary power supplies, time and frequency standards and similar items. In most instances, the antenna is, by far, the most costly part of the observing equipment. Because of the cost and other factors most US radio astronomers have been working with antennas that are smaller and less effective than those of foreign scientists, who, soon after World War II, gained support of their respective governments for the construction of large radio astronomy equipment. The smaller size, or gain of an antenna, can be compensated for in part through better electronics—a receiver with a better noise figure and extreme stability to permit integration of the very weak celestial signals over longer periods of time; but for angular resolution and the avoidance of confusion, which is important to astronomers, there is no substitute for aperture size. Hence, the conclusion from the January, 1954, conference was that larger and more effective antennas were needed in the United States. How to obtain them was another question. The suggestion was made that several institutions might join together

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[1] "Proceedings of conference on radio astronomy, January 4–6, 1954," *J. Geophys. Res*, vol. 59, p. 140; March, 1954. See also "Radio Astronomy Conference," *Science*, vol. 119, p. 588; April 30, 1954.

[2] K. Jansky, "Directional studies of atmospherics at high frequencies," PROC. IRE, vol. 20, pp. 1920–1932; December, 1932.
—, "Electrical disturbances apparently of extraterrestrial origin," PROC. IRE, vol. 21, pp. 1387–1398; October, 1933.

[3] G. Reber, "Cosmic static," PROC. IRE, vol. 28, pp. 68–70; February, 1940.
—, *Astrophys. J.*, vol. 91, pp. 621–632; June, 1940.

[4] H. I. Ewen and E. M. Purcell, *Nature*, vol. 168, p. 356; 1951.