Telephone: B 0388
Box No. 1610, G.P.O.

The Australia Hotel
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Dear Dr. Southworth:

Thank you for your note of the 26th and enclosure. That is quite satisfactory as I worked full time in the radio industry during those years.

Yesterday I arrived back here from a year in ~~Australia~~ Tasmania where I made some lower frequency observations at 2130, 1435, 900 & 520 kc. It is now certain that these celestial radiations exist with considerable strength at kilometer waves.

Some time in January I expect to be on the east coast and hope to stop for an afternoon visit with you.

Best regards,

Grote Reber

1212 W. Seminary Ave.
Wheaton, Illinois.

Early History of Radio Astronomy

Property of
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REBER

GEORGE C. SOUTHWORTH

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Early History of Radio Astronomy

GEORGE C. SOUTHWORTH

Dr. Southworth, a research engineer at Bell Telephone Laboratories from 1934 until his retirement last year, has studied wave propagation, directional antennas, waveguide transmission and associated microwave techniques, radio astronomy, and earth currents as related to various solar and terrestrial phenomena. He received his training at Grove City College, Columbia University, and Yale University. In 1917–18 he was a physicist with the National Bureau of Standards. From 1918–23 he was instructor and assistant professor at Yale University, and from 1923 to 1934 he was a radio engineer with the American Telephone and Telegraph Company

IT is often asked: What are the important steps that lead to a discovery? Are discoveries invariably predicted by prior theory or experiment or are they more often purely accidental or at best based on a good hunch? Examples of at least two of these three possibilities appear in the relatively new subject, radio astronomy. In one of the cases in question, discovery was indeed accidental, but it is to the everlasting credit of the discoverer that he was sufficiently keen and alert to note the new phenomenon even though it was often masked by other far more obvious effects. Not being content with mere discovery, he then invoked lines of reasoning for which he had no special training to trace his objective to its lair, which turned out to be many many light years away. A less curious radio engineer might well have reported his discovery as a factual but sterile summary entitled, "A new kind of static too small to be of importance to radio communications." Not only is it desirable to record the important steps that led to this discovery, but also such a record represents a very interesting detective story that is quite comparable with the *Adventures of Sherlock Holmes*.

By way of review, it should be noted that present-day radio astronomy includes at least two major domains of exploration. One is our own sun and the other is the general region of the Milky Way. Studies in radio astronomy range in wavelength from perhaps 1 centimeter to about 30,000 centimeters. As Bart Bok of Harvard University has pointed out, this is roughly 12 octaves. Previously, the wavelength range available to the astronomer extended from about 3000 to perhaps 30,000 A, or roughly 4 octaves. Between the two ranges lies a vast region of about 12 octaves. Thus the newer radio techniques have not only given the astronomer a much wider range of wavelengths, but, since they come at a very different place in the spectrum, they have also provided him with an entirely different line of approach. As might be expected, this new approach is now leading to some very interesting results. Results of recent research have been described in a number of places and they need not be repeated here (*1*). Instead, I wish to describe some of the early steps that marked the beginnings of this new field of study.

It might be reasonable to expect that the first work in radio astronomy would have been done on the sun since it is the most obvious of our heavenly bodies. But, interestingly enough, this was not the case. Instead, the first work was done on an object that at the time must have seemed far less likely—namely, the Milky Way. Not only was this source much more removed in space, but it may well have seemed, at the time, to be a very unpromising direction in which to look for radio waves.

Waves from the Milky Way were first noted by one of my close friends, the late Karl Jansky of Bell Telephone Laboratories. This was possibly as early as November 1930, but it required 10 more months before the identity of the waves was first suspected and still another 11 months before their source could be located in space even approximately. In the case of radio waves from the sun, the discovery occurred much later and there are numerous people, any one of whom could very well have made the first observation. In view of this situation, I have made no attempt to name the discoverer but instead have described one of the more comprehensive sets of observations that were made during the year of discovery, 1942. In both cases referred to, I was either present or I was, figuratively speaking, standing nearby as the discovery was made. Based partly on memory but more particularly on notebook entries, I have in the paragraphs that follow merely played the role of reporter of what I saw and heard.

Extraterrestrial Radiation

As a suitable backdrop for the work of Karl Jansky, it may be well to review the status of radio technology at the time he entered the field. Frequencies in the region 2 to 20 megacycles per second, which were referred to at the time simply as "short waves," were just coming into general use. The vagaries of this new part of the radio spectrum seemed very disconcerting, particularly to those who had previously worked with the older and more orderly long waves. Earlier, the relatively simple Austin-Cohen formula had accounted for most of the known facts of radio transmission, but with the advent of the newer short waves, many new dimensions and many unknowns were brought into the picture. The latter related not only to signal level but also to the level of noise.

In the Bell System, work was in progress at two special laboratories that had been set up at Deal and Cliffwood, New Jersey. At the Cliffwood laboratory in particular, studies proceeded under the direction of H. T. Friis and C. R. Englund, whose interests included not only radio propagation but such related subjects as receivers and antennas. From the first, Friis and Englund stressed the importance of careful experimental work with accurate measurements of both signal level and noise. These quantities were particularly important to them, for the ratio of signal to noise materially affected the design of both the receivers and transmitters that were then under development.

At the longer wavelengths, it had already been found that static was usually the limiting noise (2). Accordingly, in the earlier years, it was expected that static might likewise be important in short waves. It turned out, however, that this was only occasionally true. Very often other noises such as, for example, those arising in the radio receiver itself became the limiting factor. Very important questions arose: How intense is the prevailing static? From what directions does it arrive? How frequently does it appear above the noise inherent in the receiver? It was therefore a thoroughly practical point of view that prompted Karl Jansky's supervisors to give him as his first assignment the study and measurement of static.

Long-wave static measurements. At low frequencies (long waves), static level was already a fairly common measurement. Of the several methods of measurement, in considerable favor was the one that had been developed by Jansky's supervisor, Friis. It made use of (i) a double-detection receiver of specified bandwidth together with (ii) a calibrated attenuator located in the intermediate-frequency part of the receiver and (iii) an integrating power-measuring device in the output. The attenuation necessary to adjust the output of the set to a common arbitrary datum level thus became a measure of the relative noise level. This arbitrary datum level was compared from time to time with a single-frequency power source of known level. The necessary attenuation was introduced and recorded by a suitably modified bridge balancing device that was then used extensively in pyrometric work. A slowly rotating coil antenna provided the necessary information about the direction of arrival.

Short-wave static measurements. Part of Jansky's first assignment was the operation and maintenance of the long-wave recorder just described, as well as the analysis of its results. This alone was a sizable job. In addition, he was assigned the more difficult task of adapting this method to the new short-wave range. Although there were great difficulties in adapting this method to the higher frequencies, the higher frequencies brought certain compensating advantages. In particular, sharper directional antennas became available. For Jansky's static measurements, it was proposed that a Bruce array similar to the kind then in use on overseas short-wave radiotelephone facilities be mounted on a motor-driven rotating platform. With this arrangement, the azimuthal direction of arrival of static could be determined with considerable accuracy. The directional feature was regarded as important, for it seemed desirable to know whether short-wave static arrived from the same general direction as that received on long waves. In addition to the antenna, there were certain other building blocks of the new recorder that had already been designed and built. However, most of the existing equipment was already in use. Therefore it fell to Jansky, a new recruit from the University of Wisconsin who was only 22 years of age, to build these components anew and, furthermore, to make them work as an integrated whole. In addition, there were certain gaps in the over-all system, each of which called for a separate development project. These development projects, together with the analysis of long-wave static data, occupied Jansky almost continuously for the 3 years between 1928 and 1931. No doubt the time seemed even longer, for doubtless he was anxious to get at his task of measuring short-wave static. Little did he realize that a much greater adventure lay in store for him.

Certain feaures of Jansky's short-wave method are shown in the accompanying illustrations. Figure 1 shows a schematic diagram of his circuit arrangement. The top part is a block diagram of the equipment; the bottom part is the circuit of the output integrating arrangement that was called the "rectifier and time-constant circuit." Figure 2 is a photograph of the rotating antenna. The array was turned at the rate of 3 revolutions per hour. Figure 3 shows a representative directional antenna pattern as measured in the horizontal plane. The corresponding vertical-plane characteristic was relatively dull. Thus the beam had roughly the shape of a fan. The final static recording equipment is shown in Fig. 4. On the rack at the left is the long-wave receiver with its recorder at the left center. On the rack at the right is the short-wave receiver. Its recorder is in the right center.

It is of passing interest that Jansky found the static that was expected but it was generally low except when nearby thunderstorms were in evidence. In the winter time in particular, conditions were very favorable for the detection of any unusual noises that might be present; this was the time of year when he first noted extraterrestrial noise. In Fig. 5 there is shown a typical record of extraterrestrial noise as taken on a representative autumn afternoon and evening. Note that as the antenna rotated through the 20-minute cycle, peaks appeared in the low-level noise then pre-

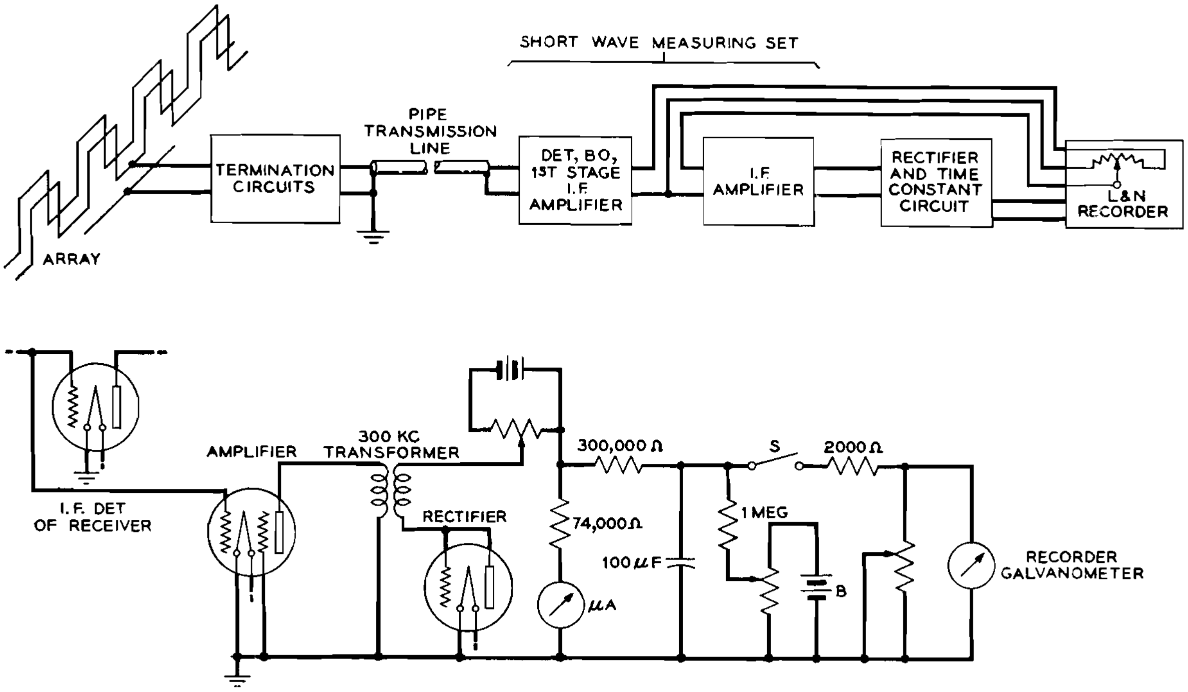


Fig. 1. Circuits used by Karl Jansky at the time of his discovery of radio waves from the Milky Way. (Top) Block diagram of the short-wave static recording system; (bottom) rectifier and time-constant circuit.

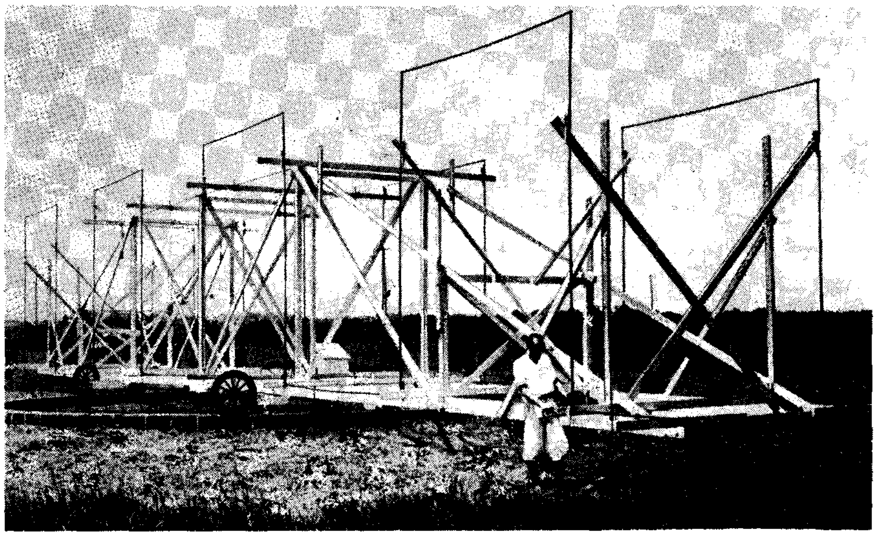


Fig. 2. Karl Jansky and his rotating antenna. Although this antenna was well adapted to the frequencies that were then in use, this type of antenna was far less directive than those that are now used in radio astronomy.

vailing. These peaks continued through the entire 24-hour day. Jansky was, of course, able to identify these peaks not only with time of day but with direction of the compass as well.

As a first step in analyzing his data, Jansky transferred directions of arrival and times of day from his daily records. Monthly means of these data were plotted as a new diagram. Curve *1* of Fig. 6 is a representative example. Note that in the early morning noise came in a general way from the east; at noon it came from the south and at night it came from the west. Thus, the noise at this stage appeared to be coming from the sun. No doubt at this point it all seemed rather simple, and additional data could be expected to bring a more complete verification.

As often happens, the simplicity that presented itself was short-lived, for, when the next month's data became available, they differed materially from those of the previous month, as is evident from Curve *2*. The discrepancy was even more evident when the third month's data (curve *3*) became available. This discrepancy continued with passing months. There is evidence that Jansky expected, at this second stage, that there was super-imposed on the diurnal variation some kind of a seasonal cycle such that the autumn data would appear somewhat like that noted for the vernal equinox. At this point, he was obviously thinking in terms of terrestrial effects. Again he was to meet with surprise, for, as shown in Fig. 7, the discrepancy continued indefinitely. It is easy to see now that this was merely the result of the difference between solar and sidereal time, but to a young electrical engineer viewing a new phenomenon for the first time, this was by no means obvious.

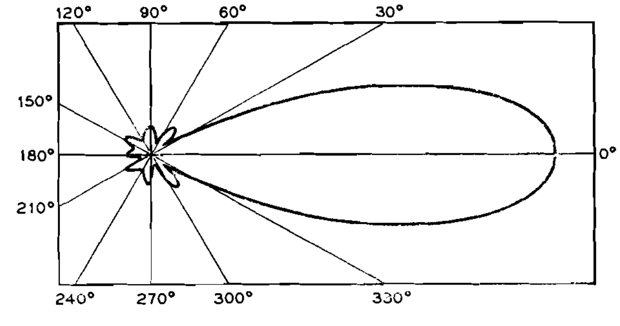


Fig. 3. Horizontal-plane characteristics of the antenna used by Jansky, at a wavelength of 14.6 meters. The vertical-plane characteristic was relatively dull.

Steps toward Discovery

By reviewing Jansky's notebooks and work reports, and from other sources of information, we may piece together the more important steps that led him to his very important discovery. First we find that he reported for work at Bell Telephone Laboratories in New York on 20 July 1928. A month later he was at the Cliffwood laboratory working on a static receiver. This was no doubt the long-wave recorder that has already been referred to. It operated at a frequency of 44.12 kilocycles per second. In September 1928 he recorded in his notebook that he had been working on the calibration of a long-wave static receiver but that he would shortly start work on a similar short-wave receiver. Work on the long-wave recorder apparently continued through the autumn and early winter months.

In March 1929 he records in his notebook that he is studying antenna arrays and is designing an array for short-wave use that can be mounted on a turntable. In addition, he tells of discussions with his supervisor, H. T. Friis, about a short-wave receiver that is to be built soon. This, no doubt, marks the beginning of the particular work that led ultimately to the discovery of extraterrestrial noise. It will be noted that this was 2 years in advance of the discovery itself.

Throughout the summer of 1929 there are records of work on the short-wave receiver and troubles with it. There were, for example, singing amplifiers and stages of the amplifier in which the response was nonlinear. These were traced to feedback difficulties that were corrected only after the several circuits were enclosed in separate metal compartments with lead wires and even batteries appropriately shielded. Also during the summer, plans were being drawn for the antenna array. For this period, the date 24 August 1929 is especially significant, for the record states: "Mr. Sykes will start work on the merry-go-round next Monday."

Entries relating to the short-wave recording system were rather infrequent during the autumn. However, it is evident that the array and mounting were nearly complete by 10 December 1929. It is reasonable to assume that a considerable portion of this period was spent on the long-wave recorder and the analysis of its data. About this time another deterrent appeared. It was announced that the entire Cliffwood laboratory, of which Jansky was a part, was to be moved to a point near Holmdel, a distance of perhaps 5 miles. This meant that Jansky's antenna setup, including the array complete with cement foundation and track, would have to be reassembled at the new location. No doubt Jansky received the usual pious promises that there would be a minimum of delay, but, as many people know, moving schedules and facts never seem to match. Records show that the move was made in the early part of 1930 but that the array was not restored to good running order until late fall. This represented a delay of nearly a year.

A work report for November 1930 indicates that the array was by then completed and that as of that date static seemed to come from 13 degrees south of west. Jansky remarked that there was no disturbance evident on the weather map. Therefore we wonder whether this may not have been extraterrestrial noise. It was certainly not so recognized. The winter months of 1930–31 were apparently spent on other matters, but an entry dated 28 February 1931 says: "Static on short waves was not recorded this week but was observed several times by ear. The most common direction of arrival was slightly north of east." Unless there was an error in recording directions, this could hardly have been extraterrestrial noise, for during the usual working hours of February the most likely direction would be southwest. An error of 180 degrees might easily have been made, however, and after all it is possible that Jansky was observing the radiation for which he is now so well known. In March 1931, he reported heavy short-wave static coming from the south but sometimes from south southeast and even east. Since March is a month of low thunderstorm activity, we suspect that he was again observing extraterrestrial noise.

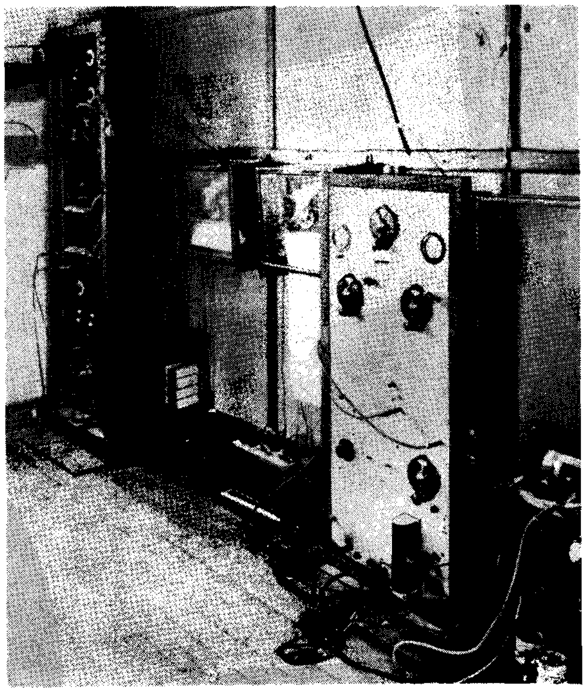


Fig. 4. Jansky's receiving apparatus. The long-wave apparatus is on the left, the short-wave apparatus on the right.

Much of the summer of 1931 was evidently spent on a receiver for ultrashort-wave static that he had apparently been asked to build. Again Jansky was encountering a familiar deterrent. He was being asked to start a new job before the old job was finished. This difficulty notwithstanding, we find in his August 1931 report that he is back on his old job. In this same report, he makes a very significant statement as follows: "The 14.5-meter static recording system has been overhauled; it was put in operation about the middle of the month and has run almost continuously since. Static has been received from nearly every point of the compass at some time or other while the system has been operating; however, most of the

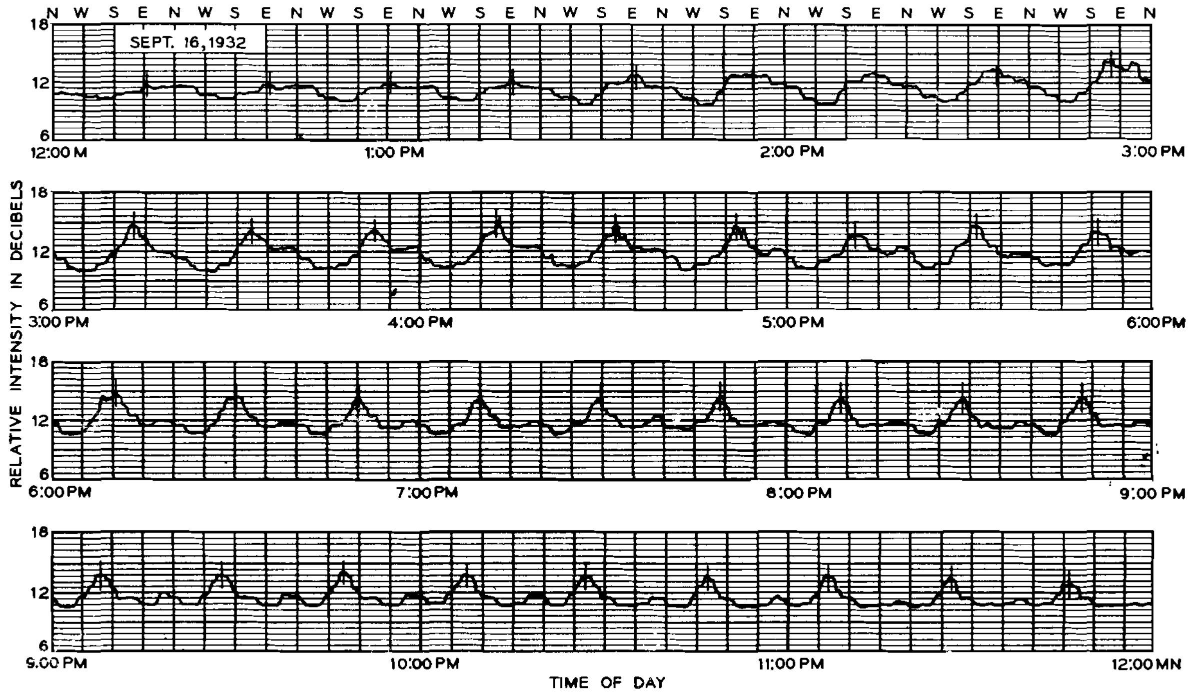


Fig. 5. Typical autumn record of waves of extraterrestrial origin. As the antenna was rotated through its 20-minute cycle, peaks appeared in the low-level noise that was then prevailing.

static has come from directions varying between southwest and southeast. . . . Static was strongest, during the month, just before, during, or just after an electrical storm; however, nearly every night that the receiver was run, static was received from a source that apparently always follows the same path. Early in the evening, about 6 P.M., this static (it has always been quite weak) comes from the southeast; by about 8 P.M. it has slowly moved to the south; by midnight it comes from the southwest; and by 3 A.M. it comes from the west. The reason for this phenomenon is not yet known, but it is believed that a study of the changes in the range of the receiver in different directions and for different hours of the day, together with a study of the known thunderstorm areas of the world, will reveal the cause." It is quite evident that at this stage Jansky was recording extraterrestrial noise, but as yet he was still trying to identify it with sources of terrestrial origin.

In the September 1931 work report, it is stated: "The 14.5-meter recorder and rotating array have been run constantly day and night during the month. As during last month, the strongest static came during the period of thunderstorm activity. It reached a peak of 3.68 μv/m at 4 P.M. September 14. The usual 'night-time' static has been recorded nearly every night during the month; however, instead of continuing on through the night till 4 or 5 A.M., it now disappears about midnight. Occasionally it will reappear again for a short time about 4 A.M. A new static source is now developing late in the morning, beginning about 8 A.M. and continuing till noon. Weak static has been heard several days lately coming from almost due south."

In the October work report, it is stated: "The usual night-time static was recorded during the early part of the month, but near the middle of the month it dropped to an intensity below that of the first circuit noise and could be recorded no longer."

In the November report, Jansky says: "The usual night-time static is still being observed."

By January 1932, things were becoming very interesting indeed. It is recorded: "The short-wave rotating array and static recorder have been run almost continuously during the month, and some very interesting results were obtained. Thunderstorm static was almost completely absent, but there was and still is present a very steady continuous interference; the term *static* does not quite fit it. It changes direction continuously throughout the day, going completely around the compass in 24 hours. During the month of December, this varying direction of arrival followed the sun almost exactly, making it appear that perhaps the sun causes this interference or at least has something to do with it."

In February 1932 he records: "The short-wave rotating array and static recorder were run about 2 weeks last month during which time records were made of the steady hiss-type of static. The direction of arrival is no longer following the direction of the sun as it did in December and the first part of January, but precedes it now in time by as much as an hour."

In this same report, Jansky informs us that he is preparing for the forthcoming April meeting of the International Scientific Radio Union (URSI) a paper entitled "Directional studies of static on short waves" (*3*). This was the paper that first reported extraterrestrial noise, but because data for only the first 3 months of the year were included, the source of this noise was not yet established. In this paper, the day-by-day shift was reported, but it was tentatively attributed to some kind of seasonal effect. Jansky states quite correctly that more data are needed.

Apparently Jansky watched with interest the continued shift of the diurnal characteristic from month to month during the early summer and through the summer solstice, for it was this that would mark the seasonal effect expected. In his August report, he stated: "The short-wave rotating array and recording system were operated over every week end during the month, and many good records of hiss-type and thunderstorm static were obtained. As yet, these records have not been replotted, but the indications are that the curve for the hiss-type static (direction of arrival plotted against time of day) is not going to shift in accordance with the position of the sun as was expected. Instead of returning with the sun to the same position it had last spring, it is continuing to

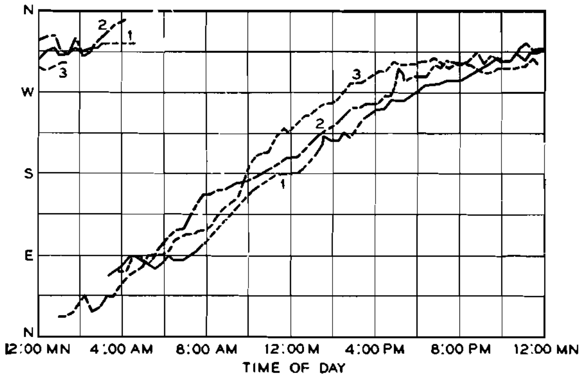


Fig. 6. Direction of arrival versus time of day of waves of extraterrestrial origin. Wavelength 14.6 meters. The three curves were obtained in successive months.

shift in the same direction that it has shifted throughout the summer."

It is to be noted at this point that Jansky was quick to note that the trend he was observing followed no simple seasonal cycle, but apparently it had not yet occurred to him that the source was of extraterrestrial origin. These facts notwithstanding, July and August 1932 probably marked a turning point leading to the ultimate discovery of the source.

The work reports for September through November contain no significant data, but interviews with Jansky's associates of that time indicate that much was going on in his mind. He discussed his results with many people, including me. It is to be noted, however, that I was at that time in another company of the Bell system and therefore was not closely associated with Jansky. Others who were more intimately associated with him were Friis, his supervisor; Bruce, who was then working on short-wave antennas; and Beck and Crawford,

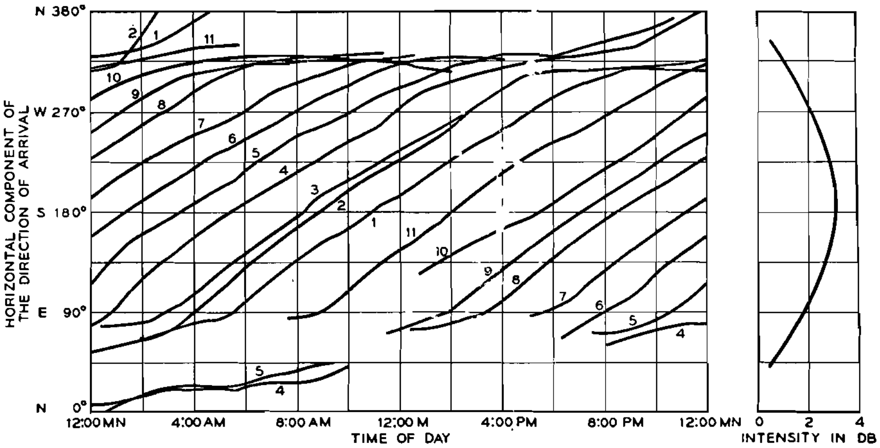


Fig. 7. Representative data concerning extraterrestrial noise for the year 1932, showing direction of arrival of waves. *1*, 21 Jan.; *2*, 24 Feb.; *3*, 4 Mar.; *4*, 9 Apr.; *5*, 8 May; *6*, 11 June; *7*, 15 July; *8*, 21 Aug.; *9*, 17 Sept.; *10*, 8 Oct.; *11*, 4 Dec. The curve at the right shows the noise intensity in decibels above the set noise.

who were working on receivers. One of his associates who was able to help perhaps most was A. M. Skellett, who is now director of color television of Tung-Sol Electric, Inc. Skellett had recently completed his graduate work in astronomy at Princeton University and of course was altogether familiar with the subject of celestial mechanics. It is Skellett's recollection, now attenuated by nearly 25 years of time, that he suspected then that Jansky's phenomenon was following sidereal time and that he accordingly directed Jansky to textbooks giving standard methods of calculation.

We have thus far found no record of the exact time when these calculations were made, but it was almost certainly sometime between August 1932 and December 1932, for in the latter monthly review, Jansky states that at Southworth's suggestion he had replotted several of the old records and one group of the new records. He says: "The curves obtained show conclusively that the noise I have termed 'hiss-type static' comes from a direction that always lies in a plane that is fixed in space." I do not remember the incident to which he refers, but the suggestion was obviously merely one that he reach back into the previous year for fragmentary data to complete the annual cycle. Later, as more reliable information became available these temporary data were replaced.

With the completion of the December 1932 records, Jansky had at hand data covering the entire calendar year of 1932. These form the basis for Fig. 7. At this point Jansky prepared the well-known paper describing his results (*4*). Other papers describing other aspects of his findings followed (*5*). Somewhat later, he was assigned to other duties and his work in radio astronomy came to an end. His interest nevertheless continued.

It is of interest that, following Jansky's pioneering work, the study of extraterrestrial noise passed to Grote Reber, another lone worker in the field. Working in his own back yard observatory in Wheaton, Illinois, under the severe handicap of carrying on at the same time full time employment, Reber was able to extend Jansky's results very materially. In particular, he operated at higher frequencies and introduced into radio astronomy the idea of the paraboloidal antenna, thereby obtaining sharp directivity in mutually perpendicular planes. As many readers know, his work is still in progress in Hawaii and Tasmania under far more favorable conditions. Its importance, through the years, speaks very eloquently for itself. Not only has he made important contributions, but he has also more-or-less singlehandedly maintained for years a continuity of data that, together with Jansky's work, gives us nearly a quarter-century of nearly continuous radio astronomy. Indeed, when it is written, Chapter 2 of the history of radio astronomy, which includes Reber's part, promises to be quite as interesting as Chapter 1.

Radio Waves from the Sun

It will be noted that Jansky's discovery was one in which an experiment set up for another purpose led to the discovery of a phenomenon that at the time was altogether unknown and even unsuspected. In contrast, radiation from the sun was a phenomenon that had long been expected. Both the principles of radiation from incandescent bodies and resistance noise, perhaps two aspects of the same phenomenon, had pointed to sources of energy of this kind. True enough, there was doubt in some minds that the laws of radiation that were formulated for the visible region of our frequency spectrum could be expected to hold in the centimeter region. In addition, similar doubts may have surrounded the consideration of an incandescent source like the sun, 93 million miles away, as the equivalent of a circuit element in a transmission system. Yet there was a plausibility in either of these lines of reasoning that was inviting.

The idea that the sun might be a possible source of radio waves certainly existed at the time of Oliver Lodge's early work with wireless. We find in a record of a lecture that he gave before the Royal Institution of Great Britain in 1894 that he expressed the hope to "try for long-wave radiation from the sun." Later, he reported that the experi-

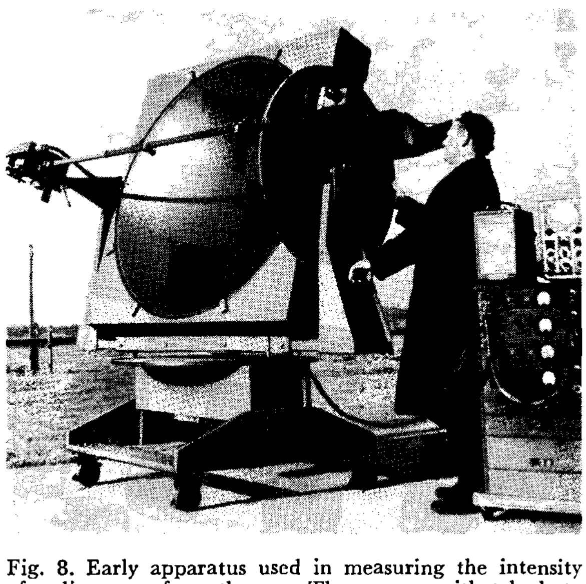


Fig. 8. Early apparatus used in measuring the intensity of radio waves from the sun. The camera with telephoto lens shown mounted on the side was not actually in use when these experiments were made.

ment had been tried and that no such radiation had been found (*6*). Bearing in mind that there was then no amplifier and that the relatively crude nickel-filings coherer was still the accepted receiver, it would appear that at best this hope was a bit optimistic.

It seems very probable that, in the 60 years that have followed, many people must have thought of looking for radio waves in the sun; they may indeed have done so. The outlook for many years was not, however, attractive. For calculations based on black-body theory indicated that, even at the highest radio frequencies and with antennas of the highest directivity then available, the intensity would probably be far below the noise level prevailing in the local radio receiver. This discouraging outlook notwithstanding, radio waves from the sun must have remained an interesting possibility.

Nearly 25 years ago at Bell Laboratories, I became interested in the subject of waveguides and in this connection evolved new cavity techniques that subsequently became very useful in microwave radio work. This work had an important bearing on the solar problem, for it provided important building blocks for translating our existing double-detection receiver methods, which were then poised at a frequency of 100 megacycles per second, on up the frequency scale. This more advanced double-detection receiver work had been under development since 1938 or before.

After we had groomed a receiver of this kind to the point that it had relatively low first-detector noise, it was natural that we should point the antenna at the sun. This was first done at my request by one of my associates, A. P. King, on 29 June 1942. We found, as expected, that the solar noise represented a small increase in the total noise output. This experiment was performed first at a frequency of roughly 9400 megacycles per second (wavelength, 3.2 centimeters), but a week or two later it was repeated at 3060 megacycles per second (wavelength, 9.8 centimeters). Because the war was on, it was difficult to find time to work on solar observations. It was possible, however, to make many measurements between June and October. For the most part they were spread at closely spaced intervals over the entire daylight period. The days were distributed more or less randomly as weather conditions and the pressure of other work permitted. Substantially the same power was received at sunrise and sunset as at noon. For this reason, it was concluded that the earth's atmosphere had no appreciable attenuating effect. When the results obtained in October were compared with those of June, we found no very obvious seasonal effect.

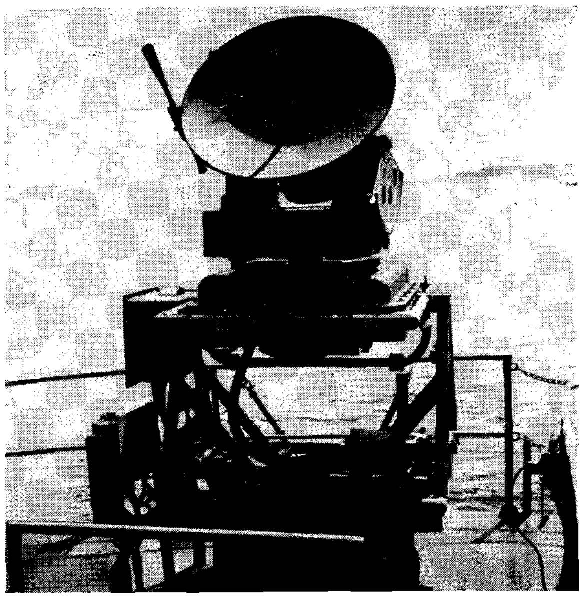


Fig. 9. Experimental radio sextant of current design built by the Collins Radio Company. [Courtesy Collins Radio Company]

Because Jansky's interesting results were still fresh in mind, some time was spent looking at the Milky Way, particularly in the direction of Sagittarius, the region that Jansky had previously reported as the probable source of extraterrestrial noise. Nothing was found. Although our study of the Milky Way was not as complete as we should have liked, we did make observations over one complete 24-hour cycle, at times using a standard star map as our guide.

During the year that followed, development work continued toward higher and higher frequencies until by June 1943 there was available a beating oscillator and first detector for frequencies of about 24,000 megacycles per second (wavelength, 1.25 centimeters). This is near the present upper frequency range of radio astronomy. The measurements during this second summer were confined mainly to 9400 megacycles per second and to the newer frequency of 24,000 megacycles per second. At the lower frequency most clouds were sensibly transparent, but at the higher frequency there was substantial absorption. Indeed, there was conclusive evidence that at the higher frequency the atmosphere, even on a clear day, was absorptive.

During the years when this work was in progress, two or more technical reports describing our work were prepared. These were circulated through the established wartime channels to all those who were authorized to see such material. A few copies went to agencies less intimately related to the wartime radar effort—for example, to the Harvard College

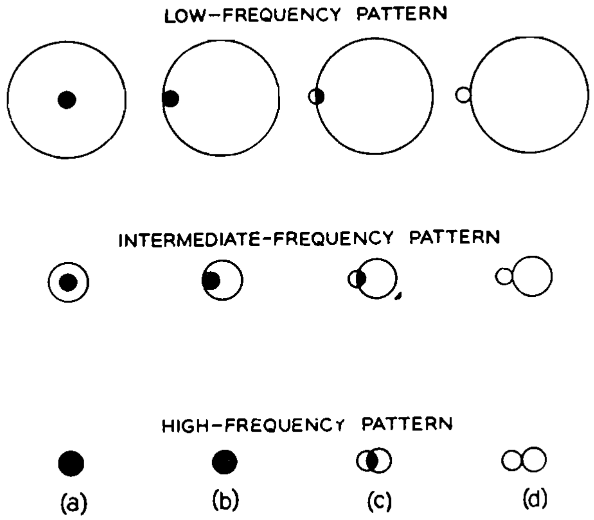


Fig. 10. Series of diagrams comparing the apparent diameter of the sun (solid black portions) with the directive pattern of the antenna for various frequencies. (Top) Low-frequency pattern (3000 megacycles per second); (middle) intermediate-frequency pattern (9400 megacycles per second); (bottom) high-frequency pattern (24,000 megacycles per second).

Observatory. Many copies went to the British War Office for circulation, not only to their own people in England, but to their colonial possessions as well. Later the British War Office requested additional copies. In addition, many of the current visitors to our Holmdel laboratory saw the work while it was in progress. Included were several who have subsequently become very active in this field —for example, A. G. Bowen and J. W. Pawsey of the now famous Radiophysics Laboratory of Sydney, Australia.

As soon as it seemed reasonable to do so, an effort was made to obtain the necessary military releases for publication in an accredited journal, but many difficulties were encountered. These were possibly prompted by the fear that the paper might supply the enemy with useful information about the frequencies and techniques used in Allied radar. After repeated attempts to obtain clearance, which extended over a period of a year or more, we omitted references both to particular frequencies and to details of our apparatus. This time we succeeded in getting the releases. The deletion of pertinent facts naturally detracted materially from the value of the article, but it seemed to be an acceptable compromise. Publication followed in April 1945 (*7*). The results, when they were modified to take into account an inadvertant error, gave about 20,000°K as the effective temperature of the sun.

Figure 8 shows the physical arrangement that was used in these experiments. The antenna system consisted of a 5-foot-diameter paraboloid together with a waveguide pickup that was located at the principal focus. The waveguide led to a box on the side that contained the first [illegible]or and beating oscillator. The intermediate-frequency power so obtained (at 60 megacycles per second), was connected to a nearby amplifier and second detector. The possibility of using this device as a sextant in cloudy weather was not overlooked (*8*). It is understood that the U.S. Navy has recently had under test an experimental sextant of this kind (*9*). One of the current models built by the Collins Radio Company is shown in Fig. 9.

There is shown in Fig. 10 a series of diagrams that give, approximately to scale, the apparent diameter of the sun as measured by optical means. Outside is drawn a circle corresponding roughly to the locally measured pattern of the paraboloidal reflector used as the antenna. Note that for the lowest frequency (3000 megacycles per second) this is about three times the diameter of the sun; for the middle frequency (9400 megacycles per second), it is roughly twice the diameter of the

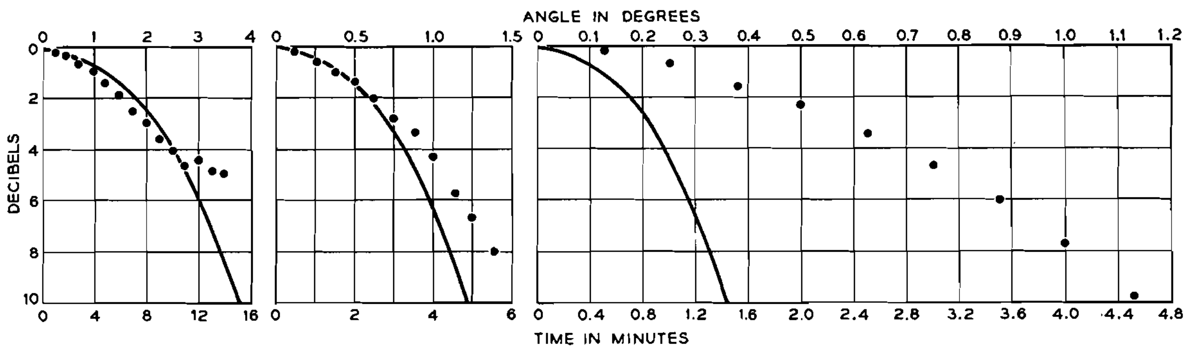
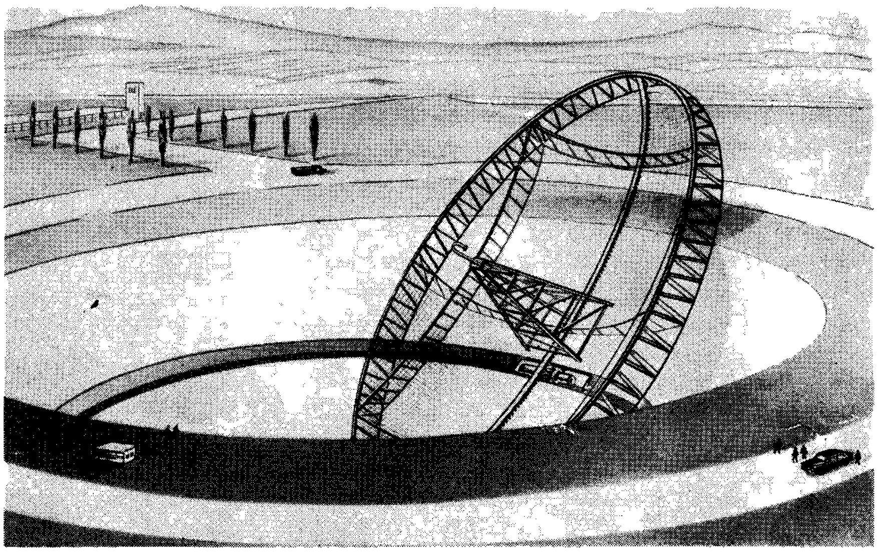


Fig. 11. Apparent diameter of sun measured by radio methods compared with locally measured pattern of the antenna for various frequencies. (Left) low frequency (3000 megacycles per second); (middle) intermediate frequency (9400 megacycles per second); (right) high frequency (24,000 megacycles per second).

Fig. 12. One favored design of a radio astronomer's telescope. The reflector moves on tracks inside a hemispherical hole in the ground. A very large excavation is required, but some of the structural and windage difficulties are overcome. [Courtesy Division of Radio Physics, Commonwealth Scientific and Industrial Organization of Australia]



sun; and for the highest frequency (24,000 megacycles per second), it is approximately the same diameter as the sun. It might be expected that in the first case the sun's disk, being small compared with the diameter of the directive pattern, would behave much like a point source. Hence, the locally measured pattern and the solar pattern might be expected to be approximately the same. In contrast, we might expect for the last case that, since the two diameters are roughly the same, the solar pattern would be somewhat larger than the locally measured pattern, but perhaps larger by only a factor of two. The facts are otherwise.

One of the routine measurements consisted of directing the antenna toward a point immediately ahead of the sun. Then, with the antenna fixed, a number of evenly spaced measurements of received noise power were made as the sun traversed the aperture of the antenna. Representative data are shown in Fig. 11. Note that for the lowest frequency (3000 megacycles per second), the solar pattern has approximately the same angular width as the locally measured pattern, as was expected. For the middle frequency (9400 megacycles per second), the solar pattern is perceptibly larger than the locally measured pattern. Finally, for the highest frequency (24,000 megacycles per second), the solar pattern is considerably larger than the locally measured pattern. Indeed, it is much larger than the factor of two that was expected. This seemed to say that the apparent diameter of the sun increased with frequency (*10*).

It may be of interest that at the time of publication we were very much interested in radio astronomy and had under consideration not only larger antennas but also suitable equatorial mountings. Although we had gained a great deal of definition through the use of very short waves, we were only approaching the point where particular portions of the sun's disk could be explored. In November 1944 I discussed the matter of mountings with authorities on the subject such as Harlow Shapley of the Harvard College Observatory and Charles Elmer of the Perkin-Elmer Corporation. Covetous eyes were even turned toward Palomar! It was, however, already evident that ultimately a structure would be needed that in size would far overshadow anything so far built, even Palomar. Very soon, this work came to an end, for I was assigned to another task that was possibly more important but certainly far less interesting. By the time I returned to my original interest, similar work was in progress at a number of other places and it seemed inadvisable to break afresh into a field that was already in capable hands.

It is interesting that from the very humble beginnings outlined here there should have evolved in a relatively short time a very spectacular new field of science. Even one who is moderately familiar with the steps that have so far been taken finds it hard to believe that so much could be accomplished in so short a time. No longer is the modern radio astronomer content with a paraboloidal reflector having an aperture of a mere 5 feet; he has passed rather rapidly to diameters of 10, 50, and 250 feet, and now we are told that he is looking hopefully toward much larger apertures. There is shown in Fig. 12 in very preliminary form one of several possible designs for a giant radio telescope. This one, considered specifically in connection with a diameter of 250 feet, has been proposed by the Division of Radiophysics of the Commonwealth Scientific and Industrial Research Organization of Australia.

It is interesting too that no longer need the modern radio astronomer speak with caution, as did Jansky, of a *possible* source of noise outside our solar system. Instead he now speaks with considerable certainty not only of active regions in space but of rather well-defined radio stars. Some are quite dark as viewed by the human eye. Indeed, following Reber's very creditable start at mapping the radio heavens, the astronomer is now filling in a substantial amount of detail. With his new tools he is apparently having quite as much of a field day as did Galileo more than three centuries ago when, with his newly invented telescope, he discovered, in rather rapid succession, the moons of Jupiter, the rings of Saturn, and the dark spots of the sun's disk as well as certain mountainous features of the moon.

References and Notes

1. B. J. Bok, *Sci. Monthly* **80**, 333 (1955).
2. As most people know, static gives rise to the "snapping and cracking" sound sometimes heard from a radio receiver. When Jansky entered the scene, ideas about static were not yet altogether clear. The idea was already taking form, however, that most static originated in electric discharges between adjacent clouds or possibly between clouds and ground. This view was easy to accept, for one of the earlier forms of wireless transmitters had used, as its source of power, electric discharges between an elevated antenna and ground. The studies of static then in progress included the measurement of not only the intensity of static but its direction of arrival as well. Attempts were made to correlate these two data with known areas of thunderstorm activity. One apparent source of static was in the general region of the Caribbean Sea. It was also found early in the history of radio that the ignition systems of automobiles and nearby power lines were in effect miniature transmitters and that they too constituted a source of noise. These noises were sometimes confused with static. Later, as communications research developed, it was shown that in any communications path—for example, in a wire transmission line or possibly in the earlier circuits of a sensitive radio receiver—there was present a very subtle source of noise that was much like static in superficial appearance. Although this noise was often extremely low compared with static, it might under certain circumstances be very important. This kind of noise depended on both the temperature of the element in which it originated and the width of the band of frequencies over which it was observed. It was sometimes known as "first-circuit noise." The theory underlying first-circuit noise seemed to say that the elemental source need not be merely a transmission line or a circuit element. Indeed, it could be a hot body somewhere along the radio path such as, for example, a glowing furnace or perhaps the sun. This new theory showed a striking resemblance to an older theory, sometimes referred to as "black-body theory." The latter had for decades been invoked to explain why an incandescent body gave off not only visible light, but also radiations much longer and also much shorter than those that can be detected by the human eye. Indeed, this theory seemed to say that an incandescent body could give out microscopic amounts of energy at wave lengths even as long as those used in radio. It is interesting that among these various possibilities there was at that time no very good reason to believe that any considerable amount of noise could arise in the Milky Way. It was in this welter of rather confused ideas about static, man-made noise, and thermal noise that Jansky was working as he isolated a fourth type of noise and thereby set off a chain reaction of speculations and investigations in the neighboring field of astronomy.
3. K. G. Jansky, "Directional studies of static on short waves," *Proc. Inst. Radio Engrs.* **20**, 1920 (1932).
4. ———, "Electrical disturbances apparently of extraterrestrial origin," *ibid.* **21**, 1387 (1933).
5. ———, "Radio waves from outside our solar system," *Nature* **132**, 66 (1933); "Note on source of interstellar interference," *Proc. Inst. Radio Engrs.* **23**, 1158 (1935). In addition, there were 20 or more semipopular articles on extraterrestrial noise. The technical articles appeared in abstract form in many other periodicals.
6. O. Lodge, *Signalling across Space without Wires* (Electrician, London, ed. 4).
7. G. C. Southworth, *J. Franklin Inst.* **239**, 285 (1945).
8. ———, U.S. Patent 2458654, filed 27 Dec. 1943.
9. D. O. McCoy, Rept. No. CTR-133, presented at the annual convention of the Institute of Radio Engineers in New York, 21–24 Mar. 1955.
10. Measurements made by subsequent observers seem to indicate that the opposite is the case.