NASA SP-4218

TO SEE THE UNSEEN

A History of Planetary Radar Astronomy

by Andrew J. Butrica

The NASA History Series

National Aeronautics and Space Administration
NASA History Office
Washington, D.C. 1996

Library of Congress Cataloguing-in-Publication Data

To See the Unseen: A History of Planetary Radar Astronomy / Andrew J. Butrica
p. cm.—(The NASA history series) (NASA SP: 4218)

Includes bibliographical references and indexes.
1. Planetology—United States. 2. Planets—Exploration. 3. Radar in Astronomy. I. Title. II. Series. III. Series: NASA SP: 4218.
QB602.9.B87 1996 95-55890
523.2'028-dc20 CIP

For sale by the U.S. Government Printing Office
Superintendent of Documents, Mail Stop: SSOP, Washington, DC 20402-9328
ISBN 0-16-048578-9

signalling the emergence of Big Science Ultimately, from out of the concentration of personnel, expertise, materiel, and financial resources at the successor of the Radiation Laboratory, Lincoln Laboratory, arose the first attempts to detect the planet Venus with radar The Radiation Laboratory Big Science venture, however, did not contribute immediately to the rise of radar astronomy

The radar and digital technology used in those attempts on Venus was not available at the end of World War II, when the first lunar and meteor radar experiments were conducted Moreover, the microwave radars issued from Radiation Laboratory research were far too weak for planetary or lunar work and operated at frequencies too high to be useful in meteor studies Outside the Radiation Laboratory, though, U.S Army Signal Corps and Navy researchers had created radars, like the SCR-270, that were more powerful and operated at lower frequencies, in research and development programs that were less concentrated and conducted on a smaller scale than the Radiation Laboratory effort

Wartime production created an incredible excess of such radar equipment The end of fighting turned it into war surplus to be auctioned off, given away, or buried as waste. World War II also begot a large pool of scientists and engineers with radar expertise who sought peacetime scientific and technical careers at war's end That pool of expertise, when combined with the cornucopia of high-power, low-frequency radar equipment and a pinch of curiosity, gave rise to radar astronomy

A catalyst crucial to that rise was ionospheric research In the decade and a half following World War II, ionospheric research underwent the kind of swift growth that is typical of Big Science The ionospheric journal literature doubled every 2 9 years from [illegible] to 1938, before stagnating during the war, but between 1947 and 1960, the literature doubled every 5 8 years, a rate several times faster than the growth rate of scientific literature as a whole[17] Interest in ionospheric phenomena, as expressed in the rapidly growing research literature, motivated many of the first radar astronomy experiments undertaken on targets beyond the Earth's atmosphere

Project Diana

Typical was the first successful radar experiment aimed at the Moon That experiment was performed with Signal Corps equipment at the Corps' Evans Signal Laboratory, near Belmar, New Jersey, under the direction of John H DeWitt, Jr., Laboratory Director DeWitt was born in Nashville and attended Vanderbilt University Engineering School for two years Vanderbilt did not offer a program in electrical engineering, so DeWitt dropped out in order to satisfy his interest in broadcasting and amateur radio. In 1929, after building Nashville's first broadcasting station, DeWitt joined the Bell Telephone Laboratories technical staff in New York City, where he designed radio broadcasting transmitters He returned to Nashville in 1932 to become Chief Engineer of radio station WSM Intrigued by Karl Jansky's discovery of "cosmic noise," DeWitt built a radio telescope and searched for radio signals from the Milky Way

In 1940, DeWitt attempted to bounce radio signals off the Moon in order to study the Earth's atmosphere He wrote in his notebook "It occurred to me that it might be possible to reflect ultrashort waves from the moon If this could be done it would open up wide possibilities for the study of the upper atmosphere So far as I know no one has ever

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[17] Gillmor, "Geospace and its Uses The Restructuring of Ionospheric Physics Following World War II," in DeMaria, Grilli, and Sebastiani, pp 75–84, especially pp 78–79

[18] DeWitt notebook, 21 May 1940, and DeWitt biographical sketch, HL Diana 46 (04), HAUSACEC There is a rich literature on Jansky's discovery A good place to start is Woodruff T Sullivan III, "Karl Jansky and the Discovery of Extraterrestrial Radio Waves," in Sullivan, ed , *The Early Years of Radio Astronomy Reflections Fifty Years after Jansky's Discovery* (New York Cambridge University Press, 1984), pp 3–42

sent waves off the earth and measured their return through the entire atmosphere of the earth."[18]

On the night of 20 May 1940, using the receiver and 80-watt transmitter configured for radio station WSM, DeWitt tried to reflect 138-MHz (2-meter) radio waves off the Moon, but he failed because of insufficient receiver sensitivity. After joining the staff of Bell Telephone Laboratories in Whippany, New Jersey, in 1942, where he worked exclusively on the design of a radar antenna for the Navy, DeWitt was commissioned in the Signal Corps and was assigned to serve as Executive Officer, later as Director, of Evans Signal Laboratory.

On 10 August 1945, the day after the United States unleashed a second atomic bomb on Japan, military hostilities between the two countries ceased. DeWitt was not demobilized immediately, and he began to plan his pet project, the reflection of radio waves off the Moon. He dubbed the scheme Project Diana after the Roman mythological goddess of the Moon, partly because "the Greek [sic] mythology books said that she had never been cracked."

In September 1945, DeWitt assembled his team: Dr. Harold D. Webb, Herbert P. Kauffman, E. King Stodola, and Jack Mofenson. Dr. Walter S. McAfee, in the Laboratory's Theoretical Studies Group, calculated the reflectivity coefficient of the Moon. Members of the Antenna and Mechanical Design Group, Research Section, and other Laboratory groups contributed too.

No attempt was made to design major components specifically for the experiment. The selection of the receiver, transmitter, and antenna was made from equipment already on hand, including a special crystal-controlled receiver and transmitter designed for the Signal Corps by radio pioneer Edwin H. Armstrong. Crystal control provided frequency stability, and the apparatus provided the power and bandwidth needed. The relative velocities of the Earth and the Moon caused the return signal to differ from the transmitted signal by as much as 300 Hz, a phenomenon known as Doppler shift. The narrow-band receiver permitted tuning to the exact radio frequency of the returning echo. As DeWitt later recalled: "We realized that the moon echoes would be very weak so we had to use a very narrow receiver bandwidth to reduce thermal noise to tolerable levels.. .We had to tune the receiver each time for a slightly different frequency from that sent out because of the Doppler shift due to the earth's rotation and the radial velocity of the moon at the time."[19]

The echoes were received both visually, on a nine-inch cathode-ray tube, and acoustically, as a 180-Hz beep. The aerial was a pair of "bedspring" antennas from an SCR-271 stationary radar positioned side by side to form a 32-dipole array antenna and mounted on a 30-meter (100-ft) tower. The antenna had only azimuth control; it had not been practical to secure a better mechanism. Hence, experiments were limited to the rising and setting of the Moon.

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[19] DeWitt to Trevor Clark, 18 December 1977, HL Diana 46 (04), "Background Information on DeWitt Observatory" and "U.S. Army Electronics Research and Development Laboratory, Fort Monmouth, New Jersey," March 1963, HL Diana 46 (26), HAUSACEC. For published full descriptions of the equipment and experiments, see DeWitt and E. King Stodola, "Detection of Radio Signals Reflected from the Moon," *Proceedings of the Institute of Radio Engineers* 37 (1949): 229–242; Jack Molenson, "Radar Echoes from the Moon," *Electronics* 19 (1946): 92–98; and Herbert Kauffman, "A DX Record: To the Moon and Bark," *QST* 30 (1946): 65–68.

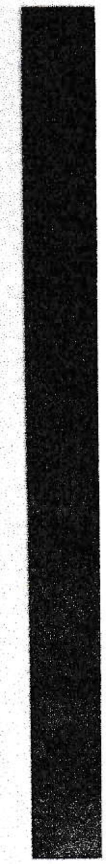

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Figure 1

The "bedspring" mast antenna, U.S. Army Signal Corps, Ft. Monmouth, New Jersey, used by Lt. Col. John H. DeWitt, Jr., to bounce radar echoes off the Moon on 10 January 1946. Two antennas from SCR-271 stationary radars were positioned side by side to form a 32-dipole array aerial and were mounted on a 100-ft (30-meter) tower. (Courtesy of the U.S. Army Communications-Electronics Museum, Ft. Monmouth, New Jersey.)

The Signal Corps tried several times, but without success. "The equipment was very haywire," recalled DeWitt. Finally, at moonrise, 11:48 A.M., on 10 January 1946, they aimed the antenna at the horizon and began transmitting. Ironically, DeWitt was not present. "I was over in Belmar having lunch and picking up some items like cigarettes at the drug store (stopped smoking 1952 thank God)."[20] The first signals were detected at 11:58 A.M., and the experiment was concluded at 12:09 P.M., when the Moon moved out of the radar's range. The radio waves had taken about 2.5 seconds to travel from New Jersey to the Moon and back, a distance of over 800,000 km. The experiment was repeated daily over the next three days and on eight more days later that month.

The War Department withheld announcement of the success until the night of 24 January 1946. By then, a press release explained, "the Signal Corps was certain beyond doubt that the experiment was successful and that the results achieved were pain-stakingly [sic] verified."[21]

As DeWitt recounted years later: "We had trouble with General Van Deusen our head of R&D in Washington. When my C.O. Col. Victor Conrad told him about it over the telephone the General did not want the story released until it was confirmed by outsiders for fear it would embarrass the Sig[nal]. C[orps]." Two outsiders from the Radiation Laboratory, George E. Valley, Jr. and Donald G. Fink, arrived and, with Gen. Van Deusen, observed a moonrise test of the system carried out under the direction of King Stodola. Nothing happened. DeWitt explained: "You can imagine that at this point I was dying. Shortly, a big truck passed by on the road next to the equipment and immediately the echoes popped up. I will always believe that one of the crystals was not oscillating until it was shaken up or there was a loose connection which fixed itself. Everyone cheered except the General who tried to look pleased."[22]

Although he had had other motives for undertaking Project Diana, DeWitt had received a directive from the Chief Signal Officer, the head of the Signal Corps, to develop radars capable of detecting missiles coming from the Soviet Union. No missiles were available for tests, so the Moon experiment stood in their place. Several years later, the Signal Corps erected a new 50-ft (15-meter) Diana antenna and 108-MHz transmitter for ionospheric research. It carried out further lunar echo studies and participated in the tracking of Apollo launches.[23]

The news also hit the popular press. The implications of the Signal Corps experiment were grasped by the War Department, although *Newsweek* cynically cast doubt on the War Department's predictions by calling them worthy of Jules Verne. Among those War Department predictions were the accurate topographical mapping of the Moon and planets, measurement and analysis of the ionosphere, and radio control from Earth of "space ships" and "jet or rocket-controlled missiles, circling the Earth above the stratosphere." *Time* reported that Diana might provide a test of Albert Einstein's Theory of Relativity. In contrast to the typically up-beat mood of *Life*, both news magazines were skeptical, and

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[20] DeWitt replies to Clark questions, HL Diana 46 (04), HAUSACEC.

[21] HL Radar 46 (07), HAUSACEC, Harold D. Webb, "Project Diana: Army Radar Contacts the Moon," *Sky and Telescope* 5 (1946): 3–6.

[22] DeWitt to Clark, 18 December 1977, HL Diana 46 (04), HAUSACEC, Guerlac, *Radar in World War II*, 1: 380 and 382, 2: 702.

[23] DeWitt, telephone conversation, 14 June 1993, Materials in folders HL Diana 46 (25), HL Diana 46 (28), and HL Diana 46 (33), *USASEL Research & Development Summary* vol. 5, no. 3 (10 February 1958): 58, in "Signal Corps Engineering Laboratory Journal/R&D Summary," and *Monmouth Message*, 7 November 1963, n.p., in "Biographical Files," "Daniels, Fred Bryan," HAUSACEC, Daniels, "Radar Determination of the Scattering Properties of the Moon," *Nature* 187 (1960): 399, and idem, "A Theory of Radar Reflection from the Moon and Planets," *Journal of Geophysical Research* 66 (1961): 1781–1788.

rightly so, yet all of the predictions made by the War Department, including the relativity test, have come true in the manner of a Jules Verne novel [24]

Zoltán Bay

Less than a month after DeWitt's initial experiment, a radar in Hungary replicated his results The Hungarian apparatus differed from that of DeWitt in one key respect, it utilized a procedure, called integration, that was essential to the first attempt to bounce radar waves off Venus and that later became a standard planetary radar technique The procedure's inventor was Hungarian physicist Zoltán Bay

Bay graduated with highest honors from Budapest University with a Ph D. in physics in 1926 Like many Hungarian physicists before him, Bay spent several years in Berlin on scholarships, doing research at both the prestigious Physikalisch-Technische-Reichanstalt and the Physikalisch-Chemisches-Institut of the University of Berlin The results of his research tour of Berlin earned Bay the Chair of Theoretical Physics at the University of Szeged (Hungary), where he taught and conducted research on high intensity gas discharges

Bay left the University of Szeged when the United Incandescent Lamps and Electric Company (Tungsram) invited him to head its industrial research laboratory in Budapest Tungsram was the third largest manufacturer of incandescent lamps, radio tubes, and radio receivers in Europe and supplied a fifth of all radio tubes. As laboratory head, Zoltán Bay oversaw the improvement of high-intensity gas discharge lamps, fluorescent lamps, radio tubes, radio receiver circuitry, and decimeter radio wave techniques [25]

Although Hungary sought to stay out of the war through diplomatic maneuvering, the threat of a German invasion remained real. In the fall of 1942, the Hungarian Minister of Defense asked Bay to organize an early-warning system He achieved that goal, though the Germans occupied Hungary anyway In March 1944, Bay recommended using the radar for scientific experimentation, including the detection of radar waves bounced off the Moon. The scientific interest in the experiment arose from the opportunity to test the theoretical notion that short wavelength radio waves could pass through the ionosphere without considerable absorption or reflection Bay's calculations, however, showed that the equipment would be incapable of detecting the signals, since they would be significantly below the receiver's noise level

The critical difference between the American and Hungarian apparatus was frequency stability, which DeWitt achieved through crystal control in both the transmitter and receiver Without frequency stability, Bay had to find a means of accommodating the frequency drifts of the transmitter and receiver and the resulting inferior signal-to-noise ratio He chose to boost the signal-to-noise ratio His solution was both ingenious and far-reaching in its impact

Bay devised a process he called cumulation, which is known today as integration His integrating device consisted of ten coulometers, in which electric currents broke down a watery solution and released hydrogen gas. The amount of gas released was directly proportional to the quantity of electric current. The coulometers were connected to the output of the radar receiver through a rotating switch The radar echoes were expected

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[24] "Diana," *Time* Vol 47, no 5 (4 February 1946)· 84, "Radar Bounces Echo off the Moon to Throw Light on Lunar Riddle," *Newsweek* vol 27, no 5 (4 February 1946) 76–77, "Man Reaches Moon with Radar," *Life* vol 20, no 5 (4 February 1946) 30

[25] Zoltán Bay, *Life is Stronger*, trans Margaret Blakey Hajdu (Budapest Püski Publisher, 1991), pp 5 and 17–18, Francis S Wagner, *Zoltán Bay, Atomic Physicist A Pioneer of Space Research* (Budapest Akadémiai Kiadó, 1985), pp 23–27, 29, 31–32, Wagner, *Fifty Years in the Laboratory A Survey of the Research Activities of Physicist Zoltán Bay* (Center Square, PA Alpha Publications, 1977), p 1

13 • The New Astronomers

"At the beginning of the meeting on that Friday afternoon we were strangers to the astronomers, aliens infiltrating a privileged assembly. As we showed our slides, the mood changed. The fellows of the society began to grasp that this was a new astronomical technique, and by the end of the meeting we were part of the astronomical community."

Sir Bernard Lovell

CONTACT WITH MOON
ACHIEVED BY RADAR
IN TEST BY THE ARMY

Signal Sent From Laboratory
in Jersey is Reflected Back
2.4 Seconds Later

VAST POSSIBILITIES SEEN

Mapping of Planets, Defense
Against Bombs in Cosmic
Space are Suggested

As Ed Purcell pried loose the secrets of the atomic nucleus, other radar men turned their attention to the limitless cosmos. The news of the moon's detection by radar jumped off *The New York Times* front page on January 25, 1946, firing imaginations around the world to a far greater degree than the hard-to-envision magnetic resonance experiment. Here was something people could understand, and a stark black-and-white photograph accompanying the article made the event even more real. A long, squiggly line like that on a modern electrocardiogram display zigzagged across the picture from right to left, hovering over a distance scale that ran out to 300,000 miles to make it easy to gauge how far the radar pulse had traveled to find its quarry. Readers saw the sharp spike of the transmitted signal settle down to a meaningless quiver as it spread across space. Then, just at the 240,000-mile mark, came the unmistakable blip of Earth's satellite.

The image fairly embodied the promise of the golden age of science and technology that arose from World War II. It demonstrated conclusively that radio waves suitable for carrying long-range communications could penetrate the Earth's atmosphere and return—detectable. More than that, for the first time researchers had pushed past the protective envelope of the Earth's ionosphere and interacted with the solar system, not just stargazing, but actively probing. As *Time* later extolled dramatically: "Man had finally reached beyond his own planet."

It was somewhat ironic that for all the attention paid to university scientists rushing back to academe after the war, the moon detection was an Army coup. The landmark radar experiment had been carried out at the Evans Signal Laboratory at Belmar, New Jersey, fifteen days before the *Times* article appeared. Outside experts, among them George Valley, fresh from the Rad Lab's closing, had checked the work upside down and sideways. Then, beginning with the annual meeting of the Institute of Radio Engineers in New York on January 24, the Signal Corps had trotted out a bevy of officers and technicians to bask in the limelight—everyone from Chief Signal Officer Harry C. Ingles to a onetime New York diamond dealer named Jacob Mofsenson, who played a supporting role in the experiment.

The star of the show was an unassuming Tennessean with a longtime fascination for the moon. In 1922, as a sixteen-year-old ham radio operator, John H. DeWitt Jr. had built Nashville's first broadcasting station, a fifteen-watt outpost with the call letters WDAA. For nearly two decades he had worked in radio while cultivating a love of astronomy. In May 1940, DeWitt had attempted to detect radio signals reflected off the lunar surface by a self-made eighty-watt transmitter. The experiment failed because of power losses and lack of receiver sensitivity. Before he could try again, the war had intervened. DeWitt joined the Army, first as a civilian consultant, then as a uniformed Signal Corps major. By the end of the war, he was a lieutenant colonel and running the Evans Lab.

The Army had given DeWitt a second excuse to find the moon. Immediately after V-J Day, worried that the Soviets had captured enough German rocketry expertise to build ballistic missiles capable of reaching the United States, the Pentagon directed the Evans group to study how such invaders could be detected and tracked. At that point, for all radar's effectiveness against German and Japanese aircraft, scientists were not convinced that radio waves could penetrate the ionosphere, bounce off a target, and be detected back on Earth. DeWitt seized the opportunity to settle the matter. With no space-going rockets in existence to test his radar systems, he recalled, "I thought, well, if we could hit the moon with radar, we could probably detect the rockets." Lieutenant Colonel DeWitt dubbed the unofficial study Project Diana, after the virgin Roman goddess of the moon and hunting.

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As the Evans director, DeWitt supervised seventy officers and 1100 civilians. At war's end, most had little to do. He selected diminutive, bespectacled E. King Stodola as chief scientist of a five-man team and got down to business. The main piece of equipment was an SCR-271 early warning radar operating on a wavelength of 2.6 meters. The set had been modified by Major Edwin H. Armstrong, an Army consultant during the war famous for pioneering frequency modulation, the FM type of transmission common in modern radios. The enemy capitulation had ended the major's Army work, but not before he had cobbled together jump wires and temporary connections to turn the once ordinary radar set into a powerful transmitter and sensitive receiver. DeWitt's group further modified the receiver by employing a tunable crystal that could pick up an elusive return signal whose frequency would be Doppler-shifted by the relative motions of the Earth and moon. Two conventional antennas were married into a forty-foot-square bedspring affair and mounted on a tower overlooking the ocean. The high-gain antenna could be steered in azimuth only, not elevation, and so could be used only for half-hour periods at moonrise and moonset, when its target rode near the horizon.

On January 10, 1946, everything finally came together. Several minutes after the moon rose at 11:48 in the morning, the first radar pulses were beamed skyward. Rather than the microsecond bursts used in wartime tracking, the set belched out a quarter-second-long signal with a great clatter of the mechanical transmit-receive switch. To allow time for the moon's return echo to arrive, the transmitter waited in silence for 4.75 seconds before sending out another pulse.

DeWitt had driven into the nearby town of Belmar for lunch and cigarettes, and missed the big event. Harold Webb and Herbert Kauffman were hunched inside the large control shack when the first faint lunar echo arrived just before noon. Besides viewing the signal on a cathode ray screen, the men listened over loudspeakers to the response — a half-second-long hum like the buzz of an untuned radio set. Although they couldn't be absolutely certain it was the moon answering their call, Webb and Kauffman grew excited. The historic signal had arrived about 2.4 seconds after a pulse had gone out, and at the speed of light that would be just about the right amount of time for a radio wave to journey 240,000 miles or so into space and back. Besides, it had to be the moon they detected, DeWitt later stated, "because there was nothing else there but the moon."

The *Times* played the story on the front page again on January 26, and followed DeWitt's exploits for several more days. High-frequency radio waves waltzing back and forth through the ionosphere heralded a revolution in long-distance communications. One popular idea in the days before satellites was that the moon might reflect signals from point to point around the world. The War Department talked, too, about radio control of missiles orbiting Earth above the stratosphere and of spaceships sallying forth to unknown adventures. Major General Harold McClelland, the Air Forces' air communications officer, felt emboldened to suggest that a radar code might be developed to enable interactions with other species millions of miles across space. "If intelligent human life exists beyond the earth such signals could be answered," he theorized. "We might even find that other planets had developed techniques superior to our own." Harry Edward Burton, the distinguished sixty-nine-year-old principal astronomer of the Naval Observatory, went so far as to postulate that probing the lunar surface by radar might reveal hidden moisture — a hint that life could be present.

Such comments provoked a warning from Sir Robert Watson-Watt, who had arrived in New York the night of the announcement and was never one to shy away from publicity. While congratulating DeWitt on his achievement, the British radar pioneer admonished that the technology's primary mission was to aid life on Earth by allowing for safer travel on land, sea, and through the air.

The hullabaloo soon died down. For all its remarkability as an engineering feat, the DeWitt experiment held next to nothing of scientific interest. Nor did the stunning work of Zoltán Bay, an enterprising Hungarian wartime radar researcher who detected the moon with a crude fifty-centimeter set within two weeks of DeWitt's announcement: lacking a sensitive receiver, Bay arranged an ingenious assembly of water voltmeters that indicated the moon's reflected signal through a slowly built-up excess of hydrogen.

Still, the pundits were on the right track in predicting that the moon detection foretold a vast bounty about to descend upon astronomy. The visible portion of the electromagnetic spectrum, far and away mankind's main observation post since the days of the ancient Chinese astronomers, spans only the single octave between .4 micron and .8 micron in wavelength. The radio band, by contrast, covers some ten octaves, from ten meters to 1 centimeter. Breaking into this vast, essentially untapped region was just the sort of swords-to-plowshares trick radar could perform, whether it be to actively send out pulses and study the returns, or simply listen passively and chart the radio noise streaming in from space: radio astronomy as opposed to radar astronomy.

Even as DeWitt began his work in the summer of 1945, and while Ed Purcell still puzzled over the water vapor problem, a tiny contingent of scientists seized the potential radar offered for astronomy. American sets like the SCR-271, British early warning systems, and especially German

Würzburgs — were all salvaged and transported to academic centers to provide the foundation for a promising field of study. Somewhat surprisingly, established optical astronomers did not embrace the emerging branch of their science. Like John DeWitt Jr. and Zoltán Bay, who had blazed the trails, the new astronomers were radar men.

The scientist who most cleverly seized the opportunity to use military radar equipment for astronomy was J. S. Hey, a physicist recruited during the war to study jamming and counterjamming for the British Army. Hey, a civilian, trained a network of anti-aircraft artillery radar operators to note the characteristics of enemy jamming and report the details. In the last days of February 1942, a week after German jamming of British coastal radars had aided the escape of the *Scharnhorst* and *Gneisenau* from Brest, Hey's listening posts operated at a heightened state of alert. Suddenly, he began receiving reports of an intense daytime enemy jamming campaign that completely obliterated anti-aircraft radar signals between four and eight meters in wavelength. When no air raids materialized, Hey studied the jamming patterns and noticed that the directions of the most intense disruptions seemed to follow the sun. After telephoning the Royal Greenwich Observatory and learning of a recent large sunspot group in the sun's central meridian, he concluded the solar outburst had accounted for the jamming.

If Hey was correct, it meant that sunspot activity and other astronomical phenomena such as meteors and even cosmic rays could be studied by radio. Many notable experts questioned his conclusions about the sunspot interference, reasoning that, if real, the phenomenon would have shown up before. Still, the physicist kept at it. In the spring of 1945, just before the war ended, he used modified radar from two unneeded V-2 tracking sites, along with a third experimental set, to watch the stream of radio emissions from meteors crashing into the ionosphere.

Hey's classified reports went the rounds of the radar establishments. A few investigators had made pioneering radio wave studies before the war — most notably Karl Jansky of Bell Labs and the electronics engineer and amateur astronomer Grote Reber, who built a parabolic dish in his backyard in Wheaton, Illinois, and used it to develop the first radio maps of the sky by cataloguing emissions at about two meters in wavelength. But the British scientist's work sparked a new race to investigate the heavens through radio technology, one made feasible by the dramatic advances in precision and sensitivity brought about by wartime radar, as well as by the well-stocked pool of young people trained in radio science and engineering still out to make their professional marks.

The gun went off as soon as the war ended. Hey quickly produced his own *detailed* radio map of the cosmos, following Reber's footsteps on a longer wavelength. At Cambridge University, J. A. Ratcliffe returned from the Telecommunications Research Establishment, where he had worked on airborne radar, to lead the school's radio and ionospheric research. He brought with him TRE colleague Martin Ryle, a brilliant, if highly strung researcher who in a fit had once hurled an inkpot at countermeasures guru Robert Cockburn's head. As a young physicist before the war, Ryle couldn't have asked for anything better than joining Ratcliffe's ionospheric group. By late 1945, however, that shopworn idea seemed so boring that he cast about for something fresh and exciting. Ratcliffe, who had access to Hey's reports, suggested investigating the still-controversial association of intense solar radio noise with sunspot activity—as well as determining whether the sun emitted radio noise in the meter wave band even in the absence of such disturbances. With the sunspot cycle only a few years from its maximum, he advised, the field seemed ripe for major discoveries.

Ryle liked the idea. Money was tight, so he commandeered surplus wartime radio and radar equipment and enlisted the aid of a few other TRE grads, among them Graham Smith and Tony Hewish. Bettering Hey's resolution dictated building an aerial system with the infeasible diameter of five hundred feet. To get around that logjam, Ryle hit upon the idea of a radio interferometer, much like, as he later learned, an optical device erected in the early 1900s on California's Mount Wilson by A. A. Michelson and Francis Pease. By cabling two small aerials to a shared receiver, he could achieve the resolving power of a gigantic antenna with a diameter as great as the distance separating the two small arrays. With his interferometer, Ryle was able to narrow in on the solar region from which radio emissions arose and determine that it corresponded closely to the area of sunspot activity.

Almost simultaneously, a pale and exhausted Bernard Lovell left TRE's centimeter radar program and returned to cosmic ray research at Manchester University. Although the city had been bombed, the school's grime-covered Victorian structures stood unscarred by war. It was a trying time. The university salary ran at half Lovell's TRE wages. Bread, clothing, and gasoline were rationed, and much else in short supply. Still, the excitement of getting back to science soon energized the thirty-two-year-old physicist. Lovell and prewar boss Patrick Blackett, back at Manchester after wrapping up his operational research duties, had once written a paper theorizing that radio echoes might be spotted from the columns of ionized molecules produced in the atmosphere by cosmic ray showers. Such showers had been keenly studied by scientists investigating fundamental physical events since the 1930s, and the men were interested in adding the radio dimension to

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the body of work. Blackett reminded his co-author of the paper and told Lovell to get to it. The task, which required a high-gain antenna, sensitive receiver, and powerful longwave transmitter, appealed to Lovell. "I began to feel at home again," he writes. "This was exactly the gear I had been dealing with for six years — except the wavelength." He contacted Hey, a Manchester alumnus, and expressed the hope of using some gunlaying radars on 4.2 meters. One day that September, less than two months after the war ended, an Army convoy arrived in the quadrangle outside the school's physics department, dropping off three trailers stocked with the necessary equipment, including a diesel generator.

Lovell coaxed the radar to life, only to find that the screeching electrical noise from trams running near the university grounds obliterated any signals. He rooted around for a better site, finally discovering the Jodrell Bank Experimental Grounds twenty-five miles south of the city, where the university's botanical department operated an experimental horticultural plot. The botanist who ran the site was an amateur radio enthusiast and quickly accepted Lovell's proposal to park the trailers at Jodrell Bank. The eager physicist set up shop in a muddy field, near some ramshackle wooden huts and a manure heap.

As Bernard Lovell at Manchester and Martin Ryle at Cambridge began exploring the promise that radar and radio offered to astronomy, they kicked off a keen competition — mainly scholarly, but occasionally personal — that would last for years. Ryle's interferometer continued to listen for solar radio emissions. By spring 1946, though, Lovell had switched his main focus from unfruitful cosmic ray work to tracking the ionized trails left by meteors. The revitalized scientist sped between campus and Jodrell Bank in an open Triumph sports car, quickly supplementing his equipment stocks with more than a million pounds' worth of surplus military transmitters and receivers due to be warehoused or dumped down abandoned mine shafts. His setup recorded the first meteors charted in daylight, and the muddy outpost began to amass a definitive body of evidence on the numbers and habits of the fiery heavenly visitors. He plowed on in relative obscurity for months. But everything changed that December, when Lovell and two colleagues, C. J. Banwell and John A. Clegg, summarized some of this early work before the Royal Astronomical Society. "By the end of the meeting," Lovell later wrote, "we were part of the astronomical community."

Curiously, no one emerged in America to join in the hunt. As in Britain, the mainstream astronomical establishment wasn't interested in radar and radio technology, and none of the World War II radar veterans were willing or able to take up the gauntlet in the face of that intransigence and the rich attraction of nuclear physics.

Other centers for the new astronomy were starting to crop up, however. One was in The Netherlands, where the theorist Jan Oort, director of the Leiden Observatory, and researcher H. C. van de Hulst began musing about radio astronomy. But the main challenger to the British did not come from any of the science-rich European nations, as might be expected. Instead, it arose from Down Under in Australia, where no Ph.D. had yet been awarded in any academic field, and wouldn't be until 1948. The upstart Aussies made their mark almost by hook and by crook, rounding up comrades who had studied abroad, luring Britishers being discharged from the service, and through raw native talent. When combined with the Cambridge and Manchester groups, their efforts were about to expose the world to an unsuspected universe laced with radio stars, hidden galaxies, and other phantasmal bodies. At the center of the scientific upheaval, beginning a third career on a third continent, was Lovell's old boss from the early days of British radar, Taffy Bowen.

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Somewhat to his surprise, the Welshman was getting to like Australia. He had closed out his days in America despondent over the lack of challenges remaining for him at the Rad Lab. And when he arrived in Sydney on the first day of 1944, after stops in exotic venues like Hawaii, Canton Island, and Nouméa, the airborne-radar pioneer hadn't expected things to be much better in the Southern Hemisphere. He planned on staying only for the duration: help the Aussies get started on the microwave front, then hurry back to real life in Britain. But the rewarding job and pleasant sea-oriented life he found had quickly begun to work their magic.

A few months after Bowen's arrival, Vesta had come over. The couple's first son, Edward, had been born the previous November back in Boston. As soon as Vesta deemed the infant able to travel, she had given up the apartment on Brattle Circle, disposed of their furniture, and taken a train to San Francisco accompanied by a representative of the Australian embassy in Washington. An unescorted Swedish freighter had ferried mother and son to Brisbane, where Taffy waited. Vesta was thrilled when he arranged for a flying boat to wing the reunited family on to Sydney.

The couple settled in a two-bedroom flat in the prestigious Double Bay suburb on the coast a few miles southeast of downtown Sydney. The fear of Japanese mini-submarines sneaking into the calm harbor and lobbing a few shells had left many spacious houses for rent, but Bowen preferred the security of an apartment building. When a second son, David, arrived at the end of 1945, the couple had felt cramped and eventually rented a house in nearby Bellevue Hill. As his sprouting family grew up — there would be one more boy, John, born in 1947—Bowen cultivated a love of sailing and boat building, hobbies he would share with his sons late into life. Nearly every weekend when the boys were little, the family would go out: David and John sailed together, with their father following in a rowboat.

Australian radar development took place in the government-run Radiophysics Laboratory, which shared a castle-like redbrick edifice on the eastern edge of the University of Sydney with the National Standards Laboratory: radar workers entered around the back of the three-story structure, down a slight incline and a floor below the building's main entrance. The Radiophysics Laboratory had been formed in late 1939 as a secret arm of the Australian Council for Scientific and Industrial Research, after a leading physicist, D. F. Martyn, had been called to England for a radar briefing and returned with a lead-lined trunk—eerily reminiscent of the Tizard Mission's black box—crammed with a few valves and two thousand–odd reports and blueprints. The first job had been to develop an Army shore defense radar. But the lab, stocked with Australia's top engineering talent, had quickly moved on to bigger things. Hallways and labs teemed with electronics, and an unmistakable spirit of camaraderie crackled in the air. With the payroll held steady at about two hundred, it was a mini–Rad Lab, bottled up and preserved in its formative years. When work ended at 4:50 each evening, staff members dashed kitty-corner across City Road to the Lalla Rookh hotel and pub, downing beers to beat the 6 P.M. closing before heading home in cars and commuter trains.

Unlike its American counterpart, Radiophysics did not close after the war. Unlike the Telecommunications Research Establishment in Britain, it did not continue with military radar development, which was shifted to other agencies. Instead, the lab was transformed into a research and development center for the civilian technologies Australia hoped would carry it into the modern age.

Bowen inherited it all. Promoted to be the division's acting director in 1944, and later given the directorship outright, as the war ended he found himself in charge of a powerful group. Of the two hundred staffers, about 70 percent remained on board, including the bulk of the sixty-six-person scientific core. As a nation, Australia was still a technological neophyte. But those staying on formed the cream of its radio science and engineering crop. Several had earned doctorates in Britain or studied in top overseas laboratories. Others had received a special joint engineering and physics master's degree from the University of Sydney that seemed to tailor recipients for R&D. Instead of hurrying back to Britain, Bowen found himself turning down job offers in his native land to stay at the helm of this talented bunch.

Radar was the clay with which Bowen and the Radiophysics staff sought to mold Australia's scientific future. A world of equipment was left over from the war: klystrons, magnetrons, pulse counting circuits, "the whole paraphernalia of a new electronic era," Bowen writes. Large stocks of radar and communications gear were stored in Sydney. More equipment arrived on the U.S. Pacific Fleet, which assembled in the port before returning home. Ordered to destroy the surplus, the Navy began dumping tons of electronics a few miles outside the harbor. Aided by friends in both the American and Australian governments, Bowen scrambled to preserve the rest. "After a few frantic weeks loading our own trucks on the dockside, we ended up with a cornucopia of invaluable equipment, often brand new and in the original crates," he relates. "I seem to remember two huge warehouses full of these good things near Botany Bay, which we were to draw on for many years to come."

So equipped, Bowen drew up plans for research programs in vacuum tube technology, radio propagation, radar navigation, electronic surveying, meteorology—and astronomy, though not one staff member had even taken a college course in the subject. As he organized the efforts, he was influenced by the postwar goings-on in Britain. Watson-Watt, who had set up a London-based research consulting firm with Robert Hanbury Brown as one of his partners, appeared to be everywhere, reveling in his role as the perceived inventor of radar. It seemed to Bowen that the Scotsman took credit for everything, including his own field of airborne radar, and it rankled. In running the Radiophysics Lab, the Welshman vowed, "I was going to be quite certain of one thing . . . I was not going to jump in and claim credit when somebody else did the work."

Over the next few years, under his leadership, the lab made steady gains on several fronts. Radiophysics developed a method for precise distance measuring that helped pilots navigate between airports. Bowen himself sought methods of cloud seeding that could bring relief to his adopted land's vast arid regions, thereby cultivating what turned out to be a lifelong interest in rain and cloud physics. It was the astronomy effort, though, that put Australia on the world's scientific map.

Bowen had left this end of things almost entirely to his best researcher, a gangly native Australian named Joseph Lade Pawsey. Coming out of the war, Pawsey ranked as one of the world's experts in antenna development. In the early 1930s he had earned a doctorate from Cambridge University, where he had studied radio wave propagation at the Cavendish under J. A. Ratcliffe. Afterwards, he had worked at Electrical and Musical Industries on antenna systems for early television, only returning to Australia at the outbreak of war. A brilliant researcher, Pawsey possessed a knack for homing in on the right questions and recognized immediately the vast possibilities radar offered for astronomical studies.

In particular, Pawsey was fascinated by the idea of using antennas to pick up the thermal noise that revealed the temperature of distant objects and set out soon after the war to determine the sun's temperature through its thermal radiation. He designed an experiment at the standard radar frequency of 200 megahertz, or 1.5 meters in wavelength, co-opting for his eyes a series of existing Air Force radar antennas lining the Australian coast around Sydney harbor. By late October 1945, after coaxing military personnel into making some observations for him, he had enough data to announce that solar temperatures reached a million degrees kelvin. That was almost improbably higher than optical spectrum values of 6000 kelvin, and only later did researchers develop a full theory explaining the temperature gradient from optical wavelengths to 1.5 meters as largely due to partially ionized atoms of solar radiation that cause the very thin outer layer of the sun's atmosphere to heat to enormous temperatures visible only at longer wavelengths. At the same time Pawsey loosely verified J. S. Hey's wartime work and concluded that the intensity of the sun's radio emissions seemed to vary with sunspot activity.

Encouraged by Australia's initial foray into radio astronomy, published as a letter to *Nature*, Bowen and Pawsey decided to ramp up solar noise studies. In February 1946, during what was then the century's largest sunspot eruption, Pawsey set out to locate more precisely the origin of the intense solar radio bursts and determine once and for all whether the noise came from sunspots. Joining him were receiver expert Lindsay McCready and Ruby Payne-Scott, a talented researcher who for nearly two years had escaped a rule barring married women from serving on the Radiophysics staff by keeping her own marriage a secret.

The experiment would put Australian radio astronomy on a par with the group in Cambridge, where Martin Ryle was deploying his radio interferometer to resolve the same question. Like the Britisher, Pawsey saw that pinpointing the source of the radio emissions with significant accuracy depended on achieving a much greater angular resolution than possible with a single aerial. His elegantly simple solution took advantage of the military radars positioned on high cliffs overlooking the Pacific. On calm days, the sea itself could act as another antenna by reflecting the sun's emissions back to the cliffside outposts. The signals picked up from the rising sun would therefore show a fringe pattern resulting from the interference of the reflected and direct rays, making it possible for Pawsey to later get a good fix on the point of origin. In classical optics, the effect was known as Lloyd's mirror: instead of being stuck with the antenna's six-degree beamwidth, Pawsey could in theory locate celestial objects to around ten arc minutes, about a third the size of the visible sun.

He took measurements for weeks. Processing the results took still more time and consideration. The seminal paper submitted to the *Proceedings of the Royal Society* in July 1946 accounted for the Earth's curvature, reflections from chopping seas, tides, and refraction. But the conclusion was sound: intense solar radio emissions, Pawsey asserted, followed the sunspot group as the sun climbed over the Pacific.

Bowen summarized Pawsey's work in a talk at the Cavendish Lab at Cambridge University about two months later, telling an assembly of thirty to forty scientists the details of Pawsey's discoveries, which still awaited publication. Martin Ryle sat in the audience. Although the Australians had beaten him to the draw proving that the increased radio signals originated near sunspots, Ryle's two-aerial interferometer suffered less severe refraction effects than the sea-cliff interferometer, and he recently had been able to pin down the source of the emissions more precisely. As Bowen finished, Ryle rose and took issue with several points, including Pawsey's repeated claim of a million-degree corona. Bowen boiled. It was a minor thing, a scientific spat. But from that point on, he suspected the Cambridge man of striving to undermine the reputation of Radiophysics—and the tension between the two groups grew as time went on.

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Dover Heights is one of a series of rocky outcroppings that tower above the Pacific north and south of the entrance to Sydney harbor. Poised a few miles below the scenic gateway, halfway between South Head and the famous sandy stretches of Bondi Beach, it rises some 250 feet above the ocean's rounded expanse to offer a commanding view of the sea. During World War II the Royal Australian Air Force built a radar station on the cliff edge to provide warning of anticipated Japanese attacks.

After the fighting Dover Heights became a favorite spot for Joe Pawsey's sun watchers. Working from a three-room blockhouse on the sloped cliff edge that served as office, equipment room, and bivouac, researchers conducted a variety of sea-cliff interferometer studies. Sometimes swollen waves crashing into the cliff face kicked a cold mist of salty spray onto the bluff. In those days, long before a pipeline carried sewage farther out to sea, the city's effluence was dumped just to the south. Clusters of seagulls hung around picking orts, and when the winds blew wrong the stench permeated the radar station. All the same, Dover Heights was good duty, away from the lab and Pawsey's supervision, a spot where a daring soul could sneak time for a

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bootleg experiment. Settling in at Dover Heights in March 1947, that was the way John Bolton seemed to view it, anyway.

The highly talented Bolton was another one of Taffy Bowen's up-and-coming stars. A native Yorkshireman who had studied physics as a Cambridge University undergraduate, he had served during the war as a Royal Navy radar officer on the carrier HMS *Unicorn*. Demobilized in Sydney, he had hooked up with Radiophysics as its second postwar recruit the previous September. Bolton was a small man with close-cropped hair that made his large ears stand out, and he could chill people with an intense, piercing stare. He loved precision hand labor and was happiest holding a drill or welding torch. And he vastly preferred to work away from the madding crowd.

The autumn assignment was Bolton's second tour of duty at Dover Heights. As his initial Radiophysics task the previous November, the former radar officer had been sent out to the cliff site to study solar noise. But on a surprise visit, Pawsey had caught him aiming the aerials at the stars, trying to detect radio emissions from objects listed in *Norton's Star Atlas*. Bolton and technical assistant Bruce Slee were reassigned to projects back at the Sydney lab.

It had taken several months, but Pawsey had finally decided to grant his insubordinate subordinate a reprieve. Bolton returned to Dover Heights with Gordon Stanley, an electrical engineer from New Zealand who had joined the lab three years earlier after an Army stint. Obediently, the men spent several months enmeshed in solar observations. But when the sun lapsed into inactivity in June 1947, they turned to the stargazing that had landed Bolton in hot water a few months earlier.

Bolton was particularly intrigued by an observation J. S. Hey had made soon after the war. While producing his meter-wave radio map of the sky, Hey had accidentally discovered an oddity in the direction of the constellation Cygnus, a rapid fluctuation in the signal intensity that he concluded must be a discrete source like a star. Bolton and Stanley set out to measure the Cygnus source on two frequencies, 100 and 200 megahertz. On the first night, a cable snapped on the array for the longer wavelength. When the men attempted repairs their only soldering iron broke, so they dumped the aerial over the cliff and continued the search with their remaining eyes, a pair of Yagi antennas attached to a converted radar receiver.

Almost immediately the relatively smooth straight line being drawn on the blockhouse recorder changed into a regular sinusoidal pattern, indicating that direct rays from some distant source were being interfered with by those reflected off the sea—and telling the men something was out there.

For several months, they studied the phenomenon, adding observations from other cliff sites. Cygnus never rose more than fifteen degrees over the northern Sydney horizon, so it was hard to be precise. Nevertheless, the bumpy measures of fringe maxima and minima indicated that whatever was causing the signal had a dimension of something less than eight minutes of arc. That indeed made it small and discrete by galactic standards, like the star Hey had hinted might exist. Bolton called it a point source.

Nothing of the sort had ever been positively identified. Even more intriguing, the radio emissions the Australian pair recorded were of an intensity comparable to that streaming in from the sun. Coming from stellar distances, that was jolting. But Bolton and Stanley got a far greater shock when they moved to identify the star or nebula responsible for such activity. Their calculations put the mystery radio emitter in Cygnus—at 19 hours, 58 minutes, 47 seconds, plus or minus 10 seconds, +41 degrees, 47 minutes, plus or minus 7 minutes. It was not exact, but far better than Hey's five degrees of uncertainty. However, when they consulted star catalogues, the region came up virtually empty. No bright stars. No nebula. Just a bland, nondescript area of the Milky Way. The mystery deepened when they attempted to pin down its distance. From the lack of any position change in the source as the Earth orbited further away, they calculated it had to lie at least ten times the distance to Pluto. As an upper limit, the men figured that a star with a total power output similar to the sun's, but with all its energy channeled into the radio spectrum, could be as far away as three thousand light-years. But how such an object could exist was beyond them.

Once known to the general astronomical community, the findings engendered a host of questions. Did other such sources exist? If so, how many? Could the cosmic static that pervaded the universe arise from these unknown objects rather than expanding clouds of ionized gas as commonly believed? At least one eminent optical astronomer, Rudolph Minkowski in America, grew intrigued. Just as Bolton and Stanley were wrapping up their reports, for publication in *Nature* and the premier issue of the *Australian Journal of Scientific Research*, they heard from Pawsey, who was visiting Mount Wilson Observatory near Pasadena. He told them Minkowski had suggested searching for radio noise among a handful of galactic curiosities: the Crab Nebula, the white dwarf near Sirius, or perhaps the strange nebula in Orion.

Others might have taken up the distinguished Minkowski's suggestion without a thought. Returning to the hunt that November, however, Bolton and Stanley, joined by Bruce Slee, chose to launch an empirical survey of the entire sky, instead of focusing exclusively on the optical astronomer's list. The New Zealander first laboriously stabilized the receiver's power supplies to cut noise fluctuations and increase its sensitivity to faint signals. Within a few days of being put into service, the improved apparatus picked up a second strong radio source, in Taurus. By the following February, the team had painstakingly plotted half the southern sky, accumulating evidence for five additional objects. As more contacts appeared, Bolton devised the nomenclature that became for a time the standard means for identifying radio sources: the strongest emitter in a constellation was called A, the next strongest B, and so on.

Cygnus A, the original curiosity, thus turned out not to be so unique. Moreover, none of the newly charted radio emitters could be squarely lined up with known stellar objects. Convinced they were hot on the trail of something big, Bolton dashed off a short note to *Nature* announcing a novel class of astronomical oddities.

Immediately, the men moved to draw a tighter bead on the origins of their puzzling radio emissions. From Australia's east coast, Bolton, Stanley, and Slee were only able to follow rising stars. They proposed setting up additional aerials on the western rim of New Zealand so sources could be tracked coming and going. Caught up in their excitement, Taffy Bowen okayed the funding and arranged for logistics support from the New Zealand government.

At the end of May, the researchers shipped an old Army gunlaying radar trailer packed with 100 megahertz Yagi aerials, receivers, recorders, and other equipment from Sydney to Auckland. Slee stayed in Australia to man Dover Heights, while Bolton and Stanley went over to set up their installation at Pakiri Hill, a farm roughly forty miles northwest of the capital that was situated on a bluff nearly a thousand feet above the sea. From three times the elevation of Dover Heights, the site gave significantly better angular resolution on sea-cliff interferometry measurements. After two months of observations the men carted the equipment over to Phia, a surfing haven halfway between Pakiri Hill and Auckland. Finally, following three more weeks of near-nightly studies, they returned to Australia for the long process of reducing the data.

Astronomy had reached a turning point. When the data were reduced back in Sydney, good fixes came through on four sources—Taurus A, Centaurus A, Virgo A, and the original puzzler, Cygnus A. More important, all but the Cygnus source were associated with optical objects, the first time such a link had been established.

For starters, Taurus A emanated from the Crab Nebula, the expanding gaseous remnant of the supernova explosion observed by the Chinese in 1054. Since the radio emissions pouring forth from this galactic landmark would be of intense interest to optical astronomers like Minkowski and Jan

Oort, who strove to understand all processes surrounding the Crab, in this discovery alone Bolton, Stanley, Slee, and their ilk seemed justified in claiming membership in the inner circle of astronomy. Even more exciting, while the origin of Cygnus A remained elusive, the Virgo and Centaurus sources seemed to line up with the external galaxies M87 and NGC 5128. The former was a bright elliptical entity a staggering five million light-years distant. NGC 5128 ranked as one of the most curious nebulosities known, a hazy sheet of stardust so elusive in its properties astronomers couldn't even be certain it did not actually reside in the Milky Way.

The idea that radio astronomy, initially concerned mainly with the sun, could look far beyond the galaxy and root out the physical processes of some of the most distant and peculiar objects in the universe proved daunting. Before submitting a paper, Bolton summarized the findings in letters to a handful of leading astronomers, among them Minkowski, Oort, and Bengt Strømgren in Denmark.

The initial feedback shook their confidence even further. While the Crab Nebula data was viewed with great interest, no one believed radio noise could be picked up from external galaxies: the sheer power implied was mind-boggling. Bolton was cowed. Especially when it came to claiming they had recorded extragalactic signals, the three men hedged enormously in their final paper, afraid, as Bolton later said, of being denied publication because it was too unbelievable. But they believed it.

As it was, the relatively firm identification of the Crab Nebula as the source for one set of strong radio emissions solidified the Radiophysics Lab's position at the forefront of radio astronomy, and the early successes of the Pawsey and Bolton efforts begat more success. Astronomical studies flourished, dominating the Radiophysics agenda at the expense of virtually everything else: only Taffy Bowen's pet project of rainmaking and cloud physics also continued to receive funding at a strong level.

Most of the radio astronomers were young men working in small teams and doing all the dirty repair jobs themselves. "Each morning people set off in open trucks to the field stations where their equipment, mainly salvaged and modified from radar installations, had been installed in ex-army and navy huts," recalled W. N. "Chris" Christiansen, one of the group. Paul Wild, another recruit, also considered the early days of Australian radio astronomy a special time. He writes glowingly: "With the flow of new discoveries from a brand new science a special atmosphere developed—perhaps, though on a humbler scale, something like that at the Cavendish in Rutherford's time."

By the time of Bolton's announcement, Martin Ryle's pathbreaking interferometer was paying its own dividends. Besides taking advantage of his

Northern Hemisphere position to improve on the Cygnus fix, he picked up another, even stronger radio signal in the constellation Cassiopeia, and by 1950 had produced a catalogue of fifty distinct radio sources, to go along with twenty-two identified by then in Bolton's group. Still, only one of the mysterious fountains of radio waves had been firmly—though even then not conclusively—linked with an optical object: the Crab Nebula. In contrast to what Bolton, Stanley, and Slee believed, but were afraid to publish, Ryle proposed that nothing outside the Milky Way galaxy could emit such intense waves, deducing instead that the signals stemmed from a class of undiscovered dark stars. Thrilled at the prospect, the popular press gave the idea great coverage. The supposed stellar bodies became known as radio stars.

The almost palpable existence of a hidden galactic neighbor set off a heavenly fox hunt. Bernard Lovell's group at Manchester jumped into the fray, led by Robert Hanbury Brown. The radar veteran had left Watson-Watt's consulting business after the Scotsman met a Canadian woman and, still married, decided to uproot the firm's main operations to Ontario; Sir Robert would later divorce Margaret and marry Jean Drew Smith. Brown had refused to move overseas and instead accepted a research fellowship at Jodrell Bank, where Lovell had built a gigantic 218-foot-wide parabolic reflector to further his radar studies. By the time Brown arrived, however, Lovell had decided to turn the massive aerial into a radio astronomy telescope that could scan the heavens for cosmic noise. The newcomer's first major task lay in building a more sensitive receiver, improving the aerial feed, and reorienting the massive paraboloid and its spidery array of guy wires toward the zenith. When he finished nearly a year later, Jodrell Bank boasted the world's largest radio astronomy dish.

Brown and research student Cyril Hazard immediately launched a time-consuming, detailed survey of everything in the telescope's field of view. Beginning in August 1950, hoping to determine whether other galaxies also hosted radio sources, they trained the scope toward M31, the spiral nebula in Andromeda, an extragalactic cousin to the Milky Way two million light-years off. After an exhausting ninety-night survey, the pair produced contour maps that proved M31 did emit radio waves of much the same intensity as those coming from inside the Milky Way. With the information, Brown was able to say what Bolton dared not: radio astronomy could see far beyond the local galaxy.

There was one catch. The Andromeda signals were faint and hard to pick up, even for the huge 218-foot telescope. Therefore Brown and Hazard concluded that Ryle must have been right in arguing that the far stronger sources discovered by less sensitive arrays in Cambridge and Australia emanated from radio stars hiding somewhere in the Milky Way. There arose around the issue a furious debate — widening the Radiophysics feud with Ryle — that would not be settled for many more years, when the long-elusive Cygnus source was dramatically identified as two distant galaxies in collision. On the heels of that finding, more precise studies from Australia and Britain established that what were once thought of as radio stars were really radio nebulae. So while the astronomical world lost the radio stars that had kindled so many imaginations, it gained a window on supernovas and what looked to be colliding galaxies, some of the great catastrophes of the universe.

Late in 1950, even without this critical piece of the puzzle, radio astronomy was making its presence felt. Receptive optical astronomers like Minkowski took serious note of the upstarts and treated them as equals. For the diehards who continued to look with disdain on the emerging discipline, an event was about to take place that would shatter their complacency and elevate the field into an even more important tool for probing the cosmos than its optical counterpart.

Wartime radar had bequeathed the people and equipment that formed the foundations of radio astronomy. The coming breakthrough was a second great gift.

Detection of Radio Signals Reflected from the Moon*

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Summary—This paper describes the experiments at Evans Signal Laboratory which resulted in the obtaining of radio reflections from the moon, and reviews the considerations involved in such transmissions. The character of the moon as a radar target is considered in some detail, followed by development of formulas and curves which show the attenuation between transmitting and receiving antennas in a moon radar system. An experimental radar equipment capable of producing reflections from the moon is briefly described, and results obtained with it are given. Some of the considerations with respect to communication circuits involving the moon are presented. The effects of reflection at the moon on pulse shape and pulse intensity for various transmitted pulse widths are dealt with quantitatively in the Appendix.

I. INTRODUCTION

THE POSSIBILITY of radio signals being reflected from the moon to the earth has been frequently speculated upon by workers in the radio field. Various uses for such reflections exist, particularly in respect to measurement of the refracting and attenuating properties of the earth's atmosphere. Other conceivable uses include communication between points on the earth using the moon as a relaying reflector, and the performance of astronomical measurements.

Late in 1945, a program to determine whether such reflections could be obtained and the uses which might be made of them was undertaken by the U. S. Army Signal Corps at Evans Signal Laboratory, Belmar, N. J. The work has been continued since then, and, although for various reasons progress on it has been slow, this paper has been prepared to indicate the nature of the work and results so far obtained.

II. THE MOON AS A RADAR TARGET

The moon is approximately spherical in shape, is some 2,160 miles in diameter, and moves in an orbit around the earth at a distance which varies from 221,463 miles to 252,710 miles over a period of about one month.

In considering the type of signals to be used for reflections, the manner in which the reflection occurs must be considered. If it were assumed that the moon were a perfectly smooth sphere, the reflection would be expected to occur from a single small area at the nearest surface, as would be the case with light and a mirror-surfaced sphere. However, astronomical examination of the moon reveals that, in its grosser aspects at least, its terrain consists of plains and mountains of the same magnitude as those on the earth. Further, because of the lack of water and air on the moon to produce weathering, it is probable that the details of the surface are even rougher than the earth. Thus, it is assumed that the type of reflection to be obtained from the moon will resemble the reflections obtained on earth from large land masses, or, to use radar terminology, ground clutter. An example of such a reflection obtained experimentally on earth is shown in Fig. 1. The echoes shown were plotted from observations made with a 25-microsecond 106-Mc pulse transmitted into a mountainous region near Ellenville, N. Y. It will be seen that the intensity of reflection at various ranges varies in a quite random fashion, subject to a general dropping as the range increases. In this case, at 30 miles range and taking the antenna beam width as 12° and for the pulse width of 25 microseconds, or 2.7 miles, the echo at 30 miles range is the averaging of all echoes over an area of about 17 square miles. A pulse of the same width directed at the moon, using equation (35) in the Appendix, may act upon as much as 5,800 square miles. Thus, in the case of the moon, the return echo for a major portion of the time is an averaging of echoes over a very large area and could be expected to exhibit a high degree of constancy per unit projected area.

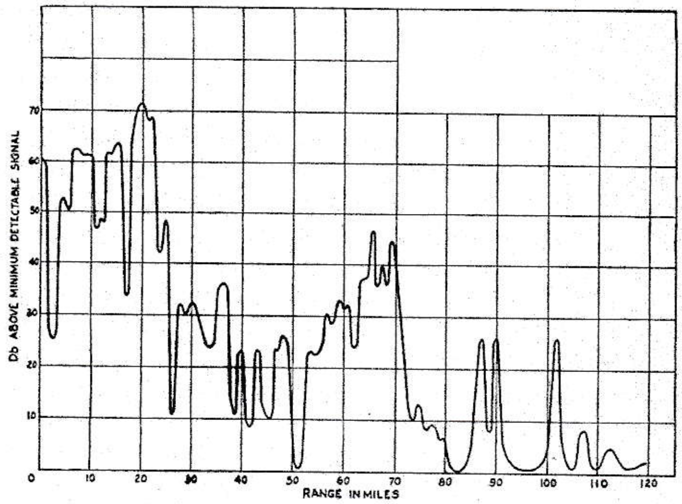

Fig. 1—Reflection obtained from a mountainous region on earth with a 25-microsecond, 106-Mc pulse.

Thus the most reasonable assumption seems to be that, on the whole, the moon behaves for radio waves much as it behaves for light; that is, when illuminated from the direction of the earth, it presents a disk equal in area to the projected area of the sphere, the disk being illuminated in a generally uniform manner with any bright or dark spots distributed over the disk in a random manner. On the basis of this, it is evident that appreciable power contributions to the returning signal are received from areas on the moon which are at various ranges from the earth. Therefore, if a pulse system is used, to obtain maximum reflection the pulses should be long in time compared to the time required for a radio wave to travel in space the distance from the nearest

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* Decimal classification: R537.4. Original manuscript received by the Institute, March 11, 1948.

† Radio Station WSM, Inc., Nashville, Tenn.

‡ Reeves Instrument Corporation, New York, N. Y.

point on the moon to the center and back again, if one is to be certain of the entire half surface of the moon contributing to the reflection. Since this distance is two times 2,160/2 miles and the velocity of propagation is about 186,000 miles per second, this time interval is $2{,}160/186{,}000 = 0.0116$ second.

Thus, provided the pulse used for tests is appreciably greater than 0.0116 second, the moon is assumed to act as an isotropic reflector which has an area equal to the projected area of the sphere. Thus, for a wide pulse, the reflecting area of the moon is $\pi r^2 = \pi(2{,}160/2)^2 = 3.66\times 10^6$ square miles, or 9.48×10^{12} square meters.

However, since the moon's surface is not a perfect conductor, this area must be multiplied by a reflection coefficient to account for the fact that all of the energy impinging is not reflected. With a target of this type, which assumes that the projected disk of the moon acts as a uniform reflector, the reflection coefficient for normal incidence would seem to be appropriate. A value of 17 per cent is given for the reflection coefficient of earth by Stratton.[1]

In the above discussion no attention has been given to the effect of depolarization of the wave by the reflection at the moon. This will probably cause some further reduction in effective reflection coefficient of the moon, but such further reduction is assumed to be not significantly large.

In the Appendix, the quantitative implications of this concept are considered, and it is shown that any pulse signal impinging on the moon is broadened by 0.0116 second. For pulses less than 0.0116 second duration, the maximum area effective in creating a reflection depends upon the pulse width, according to a curve given in Fig. 18 of the Appendix, so that, for a 1-microsecond pulse, the maximum effective area is only 0.00017 of the full disk area, representing a decrease in available peak signal of 37.7 db.

The previous discussion is primarily concerned with the case in which the antenna beam illuminates the entire disk of the moon in a uniform manner. If the beam is narrow enough to illuminate only a portion of the moon, the same type of considerations also apply, but spreading of pulses because of the bulk of the moon is reduced.

III. ATTENUATION IN THE EARTH-MOON-EARTH PATH

The ratio of the signal power available at the receiver terminals to that available from the transmitter is a factor which must be known to determine the type of equipment capable of performing the experiment. This ratio may be determined in the following manner:[2,3]

At a range R from the transmitting antenna the power flow S_0 per unit area is

$$S_0 = \frac{P_tG_t}{4\pi R^2} \tag{1}$$

where

P_t = transmitter power
G_t = transmitter antenna gain over isotropic radiator
R = range.

This power impinges on the equivalent isotropic echoing area of the target A_E, is attenuated by the reflection coefficient m of the target,[4] is then re-radiated and is subject to the same spherical dispersion, so that the power flow at the receiving point S_R is given by

$$S_R = \frac{S_0A_Em}{4\pi R^2} = \frac{P_tG_tA_Em}{16\pi^2R^4}. \tag{2}$$

This power flow impinges on the receiving antenna of area A_R to give an available received power of

$$P_R = S_RA_R = \frac{P_tG_tA_EA_Rm}{16\pi^2R^4}. \tag{3}$$

The relation of gain to effective antenna area is given by

$$A_R = \frac{G_R\lambda^2}{4\pi}\text{ (square meters)} \tag{4a}$$

where λ is the wavelength in meters, or, since $\lambda = 300/F$, where F is the radio frequency in megacycles, and

$$A_R = \frac{7160G_R}{F^2}\text{ (square meters).} \tag{4b}$$

Substituting (4a) or (4b) in (3) and noting that $G_t = G_R = G$ for radar-type operations, and that because of the units of (4a) and (4b) all distances must be in meters,

$$\frac{P_R}{P_t} = \frac{G^2A_E\lambda^2m}{1984R^4} \tag{5a}$$

or

$$\frac{P_R}{R_t} = \frac{45.4G^2A_Em}{F^2R^4}. \tag{5b}$$

It is also of interest to have the formulas in terms of the receiving and transmitting antenna area A_R. These can be obtained by combining (3) and (4a) or (4b), again taking $G_R = G_t$ to give

$$\frac{P_R}{P_t} = \frac{A_R^2A_Em}{4\pi\lambda^2R^4} \tag{6a}$$

or

$$\frac{P_R}{P_t} = \frac{A_R^2A_EF^2m}{1.13\times 10^6R^4}. \tag{6b}$$

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[1] J. A. Stratton, "Electro-Magnetic Theory," McGraw-Hill Book Co., New York, N. Y., First Edition, p. 510; 1941.

[2] K. A. Norton and A. C. Omberg, "Maximum range of a radar set," report ORG-P-9-1 issued by the Chief Signal Officer, War Department, Washington, D. C. February, 1943; and PROC. I.R.E., vol. 35, pp. 4–24; January, 1947.

[3] The treatment is given sketchily here, as it follows generally the method of the reference.

[4] The effect of area of the target and its reflection coefficient m are kept separate in this treatment to avoid later confusion.

The formulas (5) and (6) are based on the tacit assumption that the beam width of the antenna is sufficiently large that the moon is illuminated over its entire surface by the transmitted beam. If the beam width is so narrow that the entire beam falls on the moon, then the moon can be considered as an isotropic source radiating the transmitter power reduced by the reflection coefficient m, and the power received back at the earth is simply

$$P_R = \frac{P_t A_R m}{4\pi R^2}, \tag{7a}$$

whence

$$\frac{P_R}{P_t} = \frac{A_R m}{4\pi R^2}, \tag{7b}$$

and substituting the values of (4a) and (4b) in (7b) gives

$$\frac{P_R}{P_t} = \frac{G_R \lambda^2 m}{16\pi^2 R^2} \tag{8a}$$

or

$$\frac{P_R}{P_t} = \frac{570 G_R m}{F^2 R^2}. \tag{8b}$$

Equations (5) and (6) hold for relatively wide beam widths, while (7) and (8) hold for very narrow beam widths. Since antennas do not have sharply defined beams of uniform density, the transition from the region where (5) and (6) are valid to the region where (7) and (8) are valid is not a sudden one, and neither one is precise in the region of transition. However, the region in which the transition occurs can be determined by assuming that the values of P_R/P_T obtained from each equation are equal and calculating the relations which must exist for their equality. Equating (6a) and (7b) gives

$$\frac{A_R^2 A_E m}{4\pi\lambda^2 R^4} = \frac{A_R m}{4\pi R^2},$$

and writing the area of the moon's disk at πr^2 where r is the radius of the moon, and the area of the antenna A_E as $\pi D'^2/4$ where D' is the diameter of the antenna aperture in meters, gives

$$\frac{r}{R} = \frac{\lambda}{D'} \cdot \frac{2}{\pi}. \tag{9}$$

Now, if α = the angle subtended by the moon, and since α is a very small angle, $\alpha/2 = r/R$, substituting in (9) and solving for α gives

$$\alpha = 1.28 \frac{\lambda}{D'} \tag{10}$$

where α is expressed in radians.

From the earth, the moon subtends an angle of almost exactly 1/2° or 0.0087 radians, the precise amount depending upon the exact position of the moon in its orbit. At its most distant point (apogee), this angle is 2,160/252,710 = 0.00855 radian. If such value be placed in (10), then $\lambda/D' = 0.00855/1.28$ gives the value of λ/D' at which the transition of validity from (5) and (6) to (7) and (8) occurs. Converting to a more useful form, the substitution of $\lambda = 300/F$ where F is the frequency in megacycles, and $D' = D/3.28$ where D is in feet (D' in meters), is made. Using these, it may then be said that (7) and (8) should be used for

$$FD > 1.46 \times 10^5, \quad \text{or} \quad F > \frac{146 \times 10^3}{D} \tag{11}$$

where F is in megacycles and D is in feet.

In the case of a square-aperture antenna, the same general considerations approximately apply, if D is taken as the length of one side.

In order to determine the actual attenuation involved, it is necessary to insert in (6b) the values for R and A_E. R will be taken as the maximum range, 252,710 miles or 4.07×10^8 meters. The area has previously been given as 9.48×10^{12} square meters, and the reflection coefficient m as 0.17. The area in square meters of a round-aperture antenna is $\pi D^2/4 \times 10.75$ where D is in feet. Substituting these values in (6b) gives

$$\frac{P_R}{P_t} = 2.77 \times 10^{-31} D^4 F^2 \tag{12}$$

where D is the effective antenna diameter in feet and F is in megacycles. Performing a similar substitution in (7b), one obtains

$$\frac{P_R}{P_t} = 5.97 \times 10^{-21} D^2 \tag{13}$$

where D is the effective antenna diameter in feet.

In practical antennas it is usually not possible to obtain the gain given by (4) because the aperture is usually not uniformly illuminated, either because of practical difficulties or to reduce side lobes in the pattern. The effective diameter of a round-aperture antenna should be taken as about 85 per cent of its physical diameter in applying (11), (12), and (13), so that, for practical antennas, (12), (11), and (13), respectively, become

$$\frac{P_R}{P_t} = 1.448 \times 10^{-31} D^4 F^2. \tag{14}$$

The above is true for low frequencies. If

$$F > \frac{172 \times 10^3}{D}, \tag{15}$$

then

$$\frac{P_R}{P_t} = 4.31 \times 10^{-21} D^2 \tag{16}$$

where, in each case, D is the actual antenna-aperture diameter in feet and F is the radio frequency in megacycles.

The results of these equations are shown in Fig. 2. The solid curves give the attenuation for various sizes of antenna apertures, as indicated. The dashed line indicates the transition between a beam wider than the moon and one narrower. As indicated previously, this transition does not occur abruptly as in these idealized curves, but the curves do give a basis for close estimation of the system requirement.

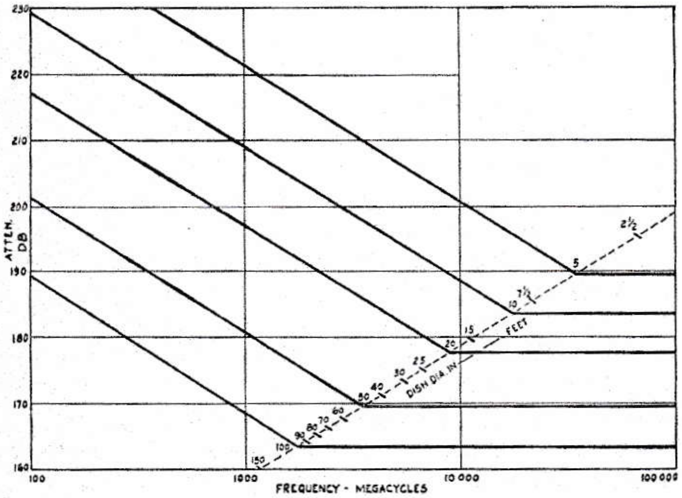

Fig. 2—Attenuation of the earth-moon-earth radar path for various frequencies and antenna apertures.

In all of the above, no effects of attenuation due to losses in the atmosphere or space, nor to the effect of refraction in the atmosphere, have been considered. However, at frequencies in the range from 100 to perhaps a few thousand megacycles, it is probable that for a considerable portion of the time these effects will not materially affect the attenuation figures given in the curve, since shorter-range radar operation in this frequency range gives results which are consistent with the assumption of negligible losses in the atmosphere and, with some exceptions, no refraction effects.

At frequencies much below 100 Mc, ionospheric refraction or reflection effects become much more pronounced, and it is probable that signals could not be sent to the moon and back at these lower frequencies.

It should also be noted that, in the above discussion, no attention has been given to ground reflections. If the antenna beam width is wide enough and the angle at which the antenna is aimed is low enough so that the ground is heavily illuminated by the beam, the ground-reflected wave will, at certain elevation angles, reinforce the direct wave, so that, under ideal conditions, the antenna gain will be increased by 6 db, and the over-all attenuation of Fig. 2 may be reduced under these conditions by as much as 12 db.

EQUIPMENT REQUIREMENTS

The attenuations shown in Fig. 2 for ordinarily used antenna sizes are considerably in excess of the spread between transmitter power and minimum detectable signal for the receiver in a usual radar system. Further, as shown in the Appendix, to obtain attenuation even as small as shown in Fig. 2, a pulse width in excess of 12,000 microseconds is necessary, so that consideration of ordinary radar systems is ruled out on this ground, in addition to the long travel time to the moon and back which makes desirable the use of a low pulse-repetition rate.

Fig. 3 gives a basis on which the performance of a radar system may be approximately estimated. The input noise power with which a signal must compete is given by $P_{\text{noise}} = KTB$ where K = Boltzmann's constant $= 1.37 \times 10^{-23}$ joules/degree, T is the effective input (antenna) resistance temperature in °K, and B is the bandwidth in cps. This figure must in increased by the noise factor of the receiver.[2,5-7]

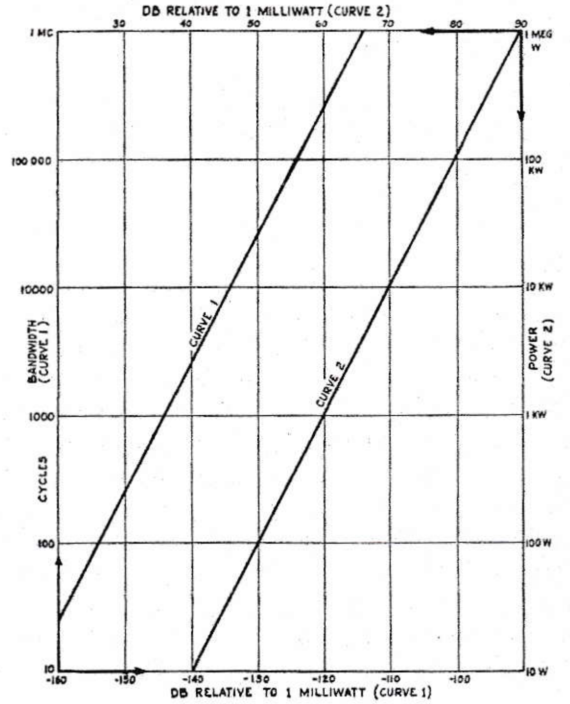

Fig. 3—Johnson noise and transmitter power levels in decibels with respect to 1 milliwatt.

If the pulse width of a radar transmitter is approximately (by a factor of from 1/2 to 2) equal in seconds to the reciprocal of receiver intermediate-frequency-amplifier bandwidth in cps, the minimum detectable signal will be of the order of the effective input noise (that is, KTB increased by the noise factor). It can be assumed that the effective antenna resistance is at a temperature of 300°K and, even if this assumption is not precise, when the noise factor referred to this temperature is not too close to 1, the error introduced by a lower effective antenna temperature will not be serious. The minimum detectable signal is also affected by pulse-repetition rate and other factors, but the above consideration gives a useful initial approximation.

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[5] The references given are relevant to this and later discussion.

[6] A. V. Haeff, "Minimum detectable radar signal and its dependence upon the parameters of radar systems," Proc. I.R.E., vol. 34, pp. 857–861; November, 1946.

[7] H. T. Friis, "Noise figures of radio receivers," Proc. I.R.E., vol. 32, pp. 419–422; July, 1944.

In Fig. 3, curve 1 gives decibels relative to 1 milliwatt corresponding to Johnson noise (*KTB*) for various bandwidths at a temperature of 300°K, while curve 2 gives decibels relative to 1 milliwatt for various transmitter powers. As an example of the use of these curves, a typical 3,000-Mc radar set might have a receiver noise figure of 12 db, a receiver bandwidth of 1 Mc, a pulse width which is the reciprocal of this, 1 microsecond, and a transmitter peak power of 100 kw. The spread between transmitter and receiver would in this case be determined by:

(1) Receiver minimum signal is -114 db from the point on curve 1 for 1 Mc, increased by the noise factor of 12 db, or -102 db.

(2) Transmitter power from the point on curve 2 corresponding to 100 kw is $+80$ db.

The spread in this case is 182 db. In Fig. 2 it will be seen that, even with a 20-foot dish and assuming that full reflection could be obtained with the 1-microsecond pulse, the attenuation in the earth-moon-earth path would be 185 db. Actually, the use of the short (1-microsecond) pulse would make the attenuation 37.7 db greater, as discussed in the Appendix. Thus, on the basis of the assumptions used here, such a system falls about 40 db short of being capable of producing reflections from the moon.

All of this suggests that the type of radar system needed is one with a very wide pulse and correspondingly narrow receiver bandwidth. As previously pointed out, a pulse width substantially greater than 0.012 second is desirable, and, if a pulse width of 0.05 second be considered, using the criterion that the bandwidth should be the reciprocal of the pulse width, a bandwidth of about 20 cps is indicated.

To use such a narrow bandwidth requires a degree of frequency stability far beyond usual radar requirements, and so, in undertaking the moon-reflection experiment, the use of a rather elaborate crystal control was contemplated. The narrow bandwidth in the receiver makes it necessary to consider doppler shift between the frequencies of received and transmitted signal due to the relative velocity between the moon and the equipment on the earth. The relative velocity between a point on earth and the moon depends upon two components, one due to the rotation of the earth about its axis, and the second due to the motion of the moon in its orbit about the center of the earth. At the latitude of Evans Signal Laboratory, 40° 10′ North, the velocity component due to earth's rotation depends upon the angle at which the moon is viewed, and may be as much as 795 miles per hour at moonrise or moonset. Added algebraically to this is the velocity relative to the center of the earth of the moon in its orbit. This varies between plus 185 miles per hour and minus 185 miles per hour, so that the relative velocity may reach 795 plus 185 equals 980 miles per hour or 0.273 mile per second at this latitude. Since the velocity of light is 186,000 miles per second, and since the velocity with which the path length changes is twice the figure given above because of the two-way path, the frequency may be shifted by as much as a maximum amount ΔF which is related to the operating frequency by

$$\Delta F = F \times \frac{0.273 \times 2}{186{,}000} = 2.96F \times 10^{-6}. \tag{17}$$

It was found that the Signal Corps was in possession of some experimental transmitting and receiving equipment, obtained from E. H. Armstrong, which was designed for 111.5-Mc operation, and which could be modified to approximate the requirements above. The system finally used overcame the frequency-stability problem by using a single crystal for obtaining the frequency control of the transmitter and all of the local-oscillator injections in the receiver except the final one. A multiplicity of mixers based on this single crystal is used to heterodyne the signal down to 1.55 Mc, where an independent adjustable-frequency crystal provides the final local-oscillator injection to heterodyne the signal down to the final intermediate frequency of 180 cps with a bandwidth of about 50 cps. Thus, the problem of frequency stability becomes one of maintaining a stability of about ±20 cps at 1,500 kc, which does not require unusual techniques. Variation of the frequency of this crystal allows tuning of the receiver to the precise frequency required. The frequency to which the receiver is tuned, or, more precisely, the frequency by which its tuning must differ from the transmitter, depends upon the magnitude of the doppler effect, which must be calculated for the particular circumstances under which the operation is conducted. At the 40° 10′ North latitude, considered here, the maximum shift for a 111.5-Mc signal, using (17), will be $\Delta F = 111.5 \times 10^6 \times 2.96 \times 10^{-6} = 327$ cps, which, although small, is an appreciable shift when bandwidths of 50 cps are being considered. A simplified block diagram of the equipment is shown in Fig. 4. The apparatus has been described in detail elsewhere.[8]

The transmitter used initially had a peak power of about 3 kw. The noise factor of the receiver was 5 db and its bandwidth about 50 cps. However, because the amplifiers preceding the 180-cps narrow-bandwidth amplifier had a bandwidth wide compared to the 180-cps intermediate frequency, the receiver had an image response equal to the main response and separated from it by 360 cps. This image in effect doubles the bandwidth of the receiver, so that the incoming signal must compete with the noise in 100 cps of bandwidth rather than 50. Referring to Fig. 3, the equivalent receiver noise level is -154 db for 100 cps plus 5 db for noise factor, or -149 db. The transmitter level is plus 65 db for 3 kw, so that the total spread is 149 plus 65, or 214 db.

Reference to Fig. 2 shows, at 111.5 Mc and with an

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[8] Jack Mofenson, "Radar echoes from the moon," *Electronics*, vol. 19, pp. 92–98; April, 1946.

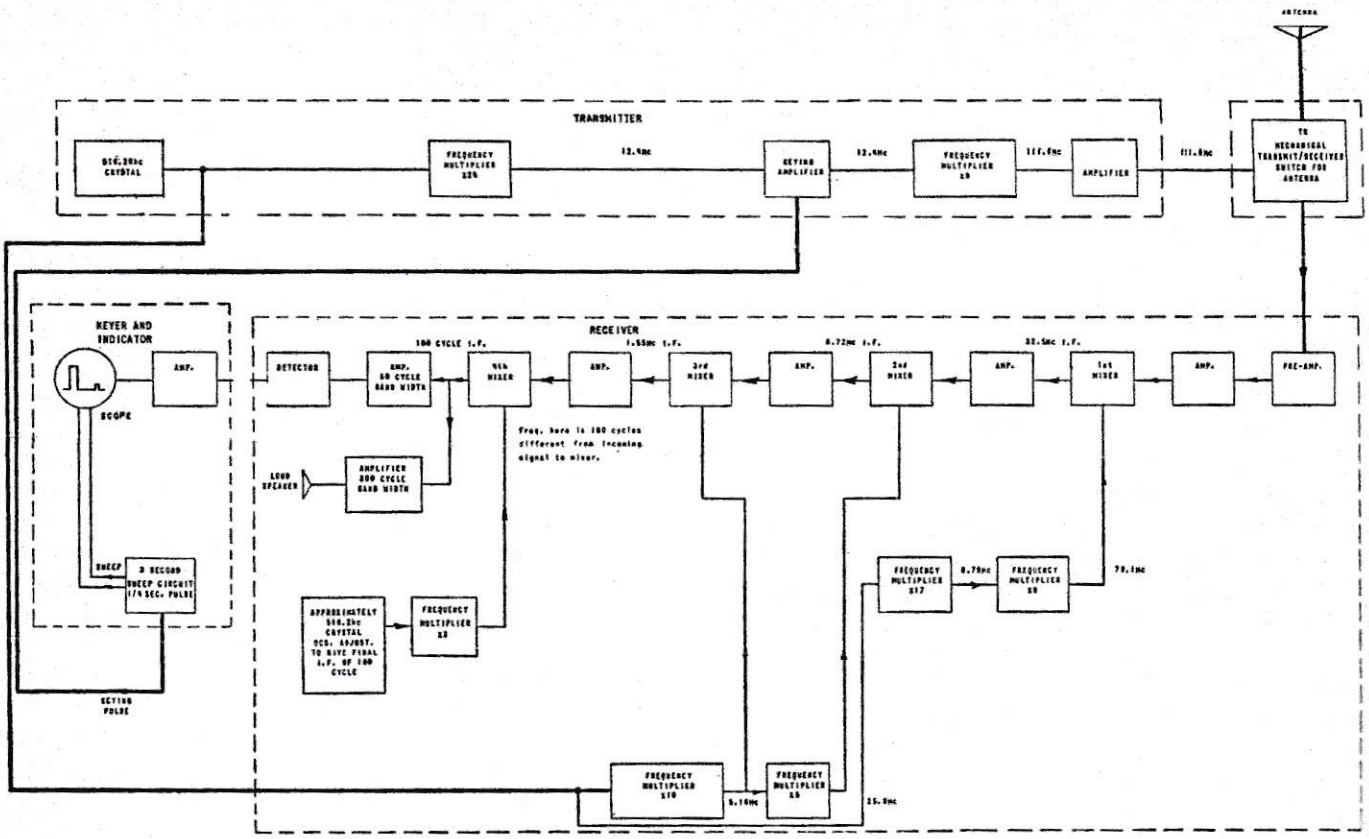

Fig. 4—Simplified block diagram of the 111.5-Mc moon radar system.

antenna diameter of 50 feet, an attenuation of slightly under 200 db. For 111.5-Mc operation, an antenna having gain equivalent to that of a 50-foot circular antenna is not too difficult to construct. (Large antennas for higher frequencies become difficult because of the accuracy of construction required.) It was decided that two antennas of the type used on the Army SCR-270-271 radar series could be assembled together to provide an array of dipoles about 40 feet square to give a gain (with the current distribution used) of about 250 over that of an isotropic radiator. Substituting this value in (5b) for $F=111.5$ Mc and the other values as used in deriving (12), it is found that $P_r/P_t = 1.34\times10^{-21}$, corresponding to 198.7 db attenuation. Thus the equipment previously described, with its 214-db capability, should be capable of showing a reflection from the moon, even with allowance for moderate transmission-line losses not considered previously, some atmospheric attenuation, and a loss due to depolarization by the reflection at the moon.

The antenna described above was mounted on a reinforced standard mount for the SCR-271 radar system, which is capable of rotating the antenna in azimuth only. Because of this search limitation, observations were restricted to a relatively short time near moonset and moonrise. (The antenna beam width is about 12 degrees.) The fact that the beam necessarily is directed horizontally implies that substantial ground reflections occur which break the antenna beam into a lobed structure, with the round-trip attenuation in the center of these lobes being, under ideal conditions, as much as 12 db less than if no ground reflections were present. The extent to which this 12 db is realized depends upon ground conditions at the "bounce point," and in this case an arbitrary estimate is made of an 8-db gain from this source. Using the previous figures, which show an approximate 15-db margin, and adding the above 8 db gives a 23-db excess performance, neglecting transmission line, polarization, and propagation losses.

The power output of the transmitter was later increased to about 15 kw by use of an SCR-270-271 trans-

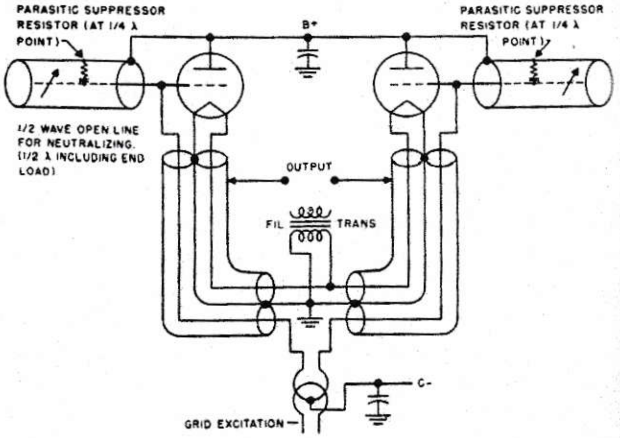

Fig. 5—Schematic diagram of the triode radar transmitter converted to a neutralized 15-kw amplifier.

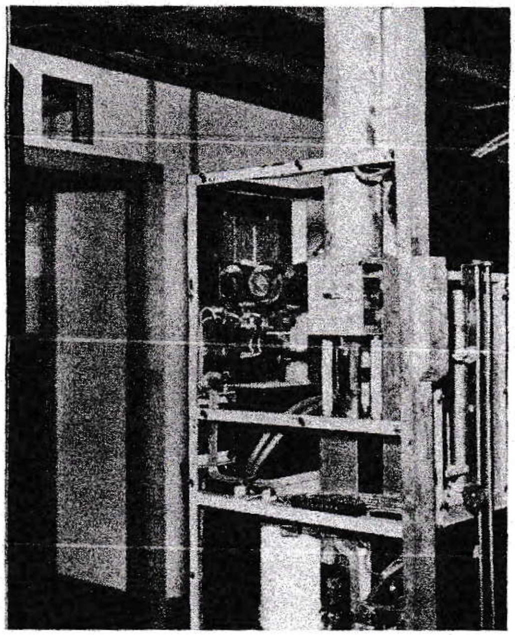

Fig. 6—Photograph of the radar transmitter converted to an amplifier. The $\frac{1}{2}$-wavelength open lines for neutralizing are visible projecting out the top.

mitter modified to operate as a neutralized triode amplifier. The neutralizing was accomplished by open 1/2-wavelength lines connected between the plate and grid of the WL 530 tubes originally used as oscillators, and the grid excitation is supplied "bazooka" fashion by lengths of coaxial line attached to the cathode output lines. A schematic diagram of the rather unusual arrangement is shown in Fig. 5. Fig. 6 is a photograph of this amplifier, and Figs. 7 and 8 show other apparatus used in the experiments, and an aerial view of the station.

MEASUREMENT OF SYSTEM PERFORMANCE

Measurements of the performance of such a system are necessary in order to evaluate the results obtained.

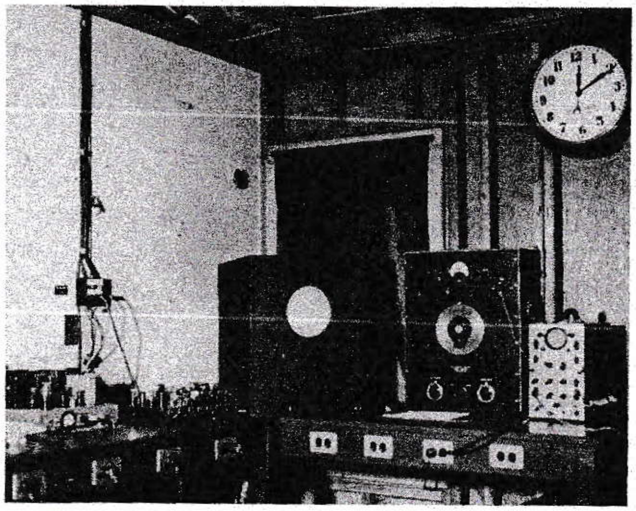

Fig. 7—Keying oscillator and sweep circuits, viewing oscilloscope, audio oscillator and oscilloscope for tuning the receiver to proper doppler shift, and miscellaneous controls.

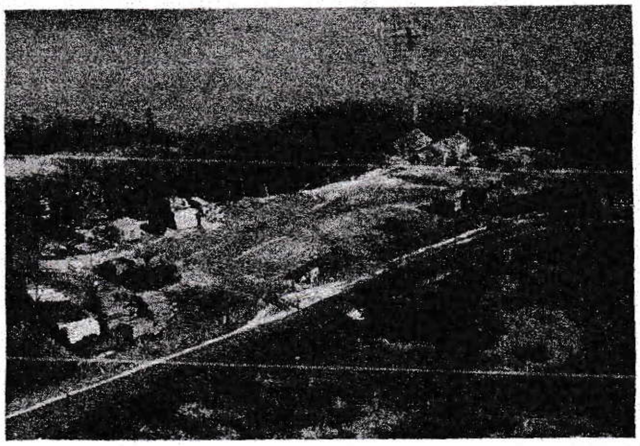

Fig. 8—Aerial view of the moon-radar installation looking in the general direction of moonrise.

Some of the measurements and adjustments are performed in a somewhat unusual way and will be described here.

The receiver has a pass band of about 50 cps at 111.5 Mc. It was found that ordinary signal generators are not capable of maintaining such stability even for a fraction of a second. A signal generator was converted to crystal-control operation with a vernier frequency control in the form of a variable capacitor across the crystal. With this it was found possible to maintain the frequency for very short intervals, but the problem of leakage due to inadequate shielding and filtering remained. This problem can be appreciated by considering the fact that, as indicated previously, the equivalent receiver input noise level is -149 db with respect to 1 milliwatt, or 1.25×10^{-18} watt, which in terms of voltage across a 50-ohm transmission line is 0.008 microvolts. In view of these difficulties, use of the signal generator was abandoned in favor of noise-factor measurement by a diode noise generator. The use of such a diode will be briefly described, since its use for this purpose has not been widely publicized.

In a diode operated so that the plate current is adjusted by the filament temperature with plate voltage fixed and high enough so that increasing plate voltage causes no increase in plate current (that is to say, a temperature-limited diode), a noise current is present in the plate circuit whose value is given by

$$I_{\text{noise}}^2 = 2eI_dB \tag{18}$$

where

e = the charge on an electron, 1.59×10^{-19} coulombs
I_d = the diode plate current in amperes
B = the bandwidth in cps
I_{noise} = the rms noise current.

If this current is made to flow in a resistor of R ohms, the voltage developed across the resistor is

$$E_{\text{noise}} = R\sqrt{2eI_dB}. \tag{19}$$

Thus the resistor may now be considered as a constant-voltage noise source E in series with a resistor R, from which the available power[4] is

$$P_{\text{noise}} = \frac{E_{\text{noise}}^2}{4R} = \frac{eI_dBR}{2}. \qquad (20)$$

The noise available at the receiver output in the absence of any added diode noise is

$$P_{0_1} = NKTBG \qquad (21)$$

where

G = the available power gain of the receiver
N = the noise factor of the receiver (N here is a power ratio. It may be converted to decibels if desired) .
P_{0_1} = the receiver noise power with the diode noise source connected but no diode plate current; that is, no noise contribution from the diode.

If the diode noise is now added to the receiver input and increased until the receiver noise output is doubled, that is, increased to $2P_{0_1}$, then the contribution due to the added diode noise P_{noise} is P_{0_1}. For this condition, the added noise-output contribution of the diode is

$$P_{0_2} = P_{0_1} = \frac{eI_dBR}{2} G \qquad (22)$$

where P_{0_2} is the added output noise power due to th diode plate current. Equating (21) and (22),

$$N = \frac{e}{2KT} I_dR \qquad (23)$$

and substituting the previously given value of $e = 1.59 \times 10^{-19}$, $K = 1.37 \times 10^{-23}$, and $T = 300$, gives

$$N = 19.4 I_dR. \qquad (24)$$

Fig. 9 shows a schematic diagram of the diode no source for use on the 250-ohm line feeding the anten system. The one-fourth-wave tubing supports for t diode assembly serve as isolating elements to feed fil-ment and plate voltages to a special tungsten-filame diode. The whole assembly is placed on the transmiss

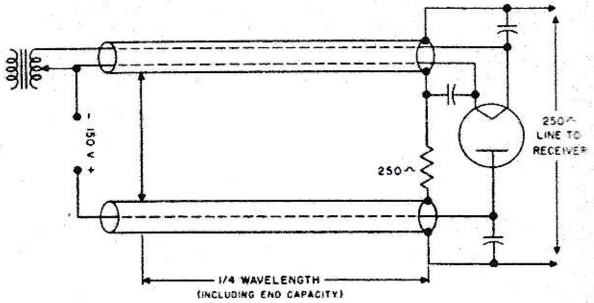

Fig. 9—Schematic diagram of diode noise generator for noise-factor tests.

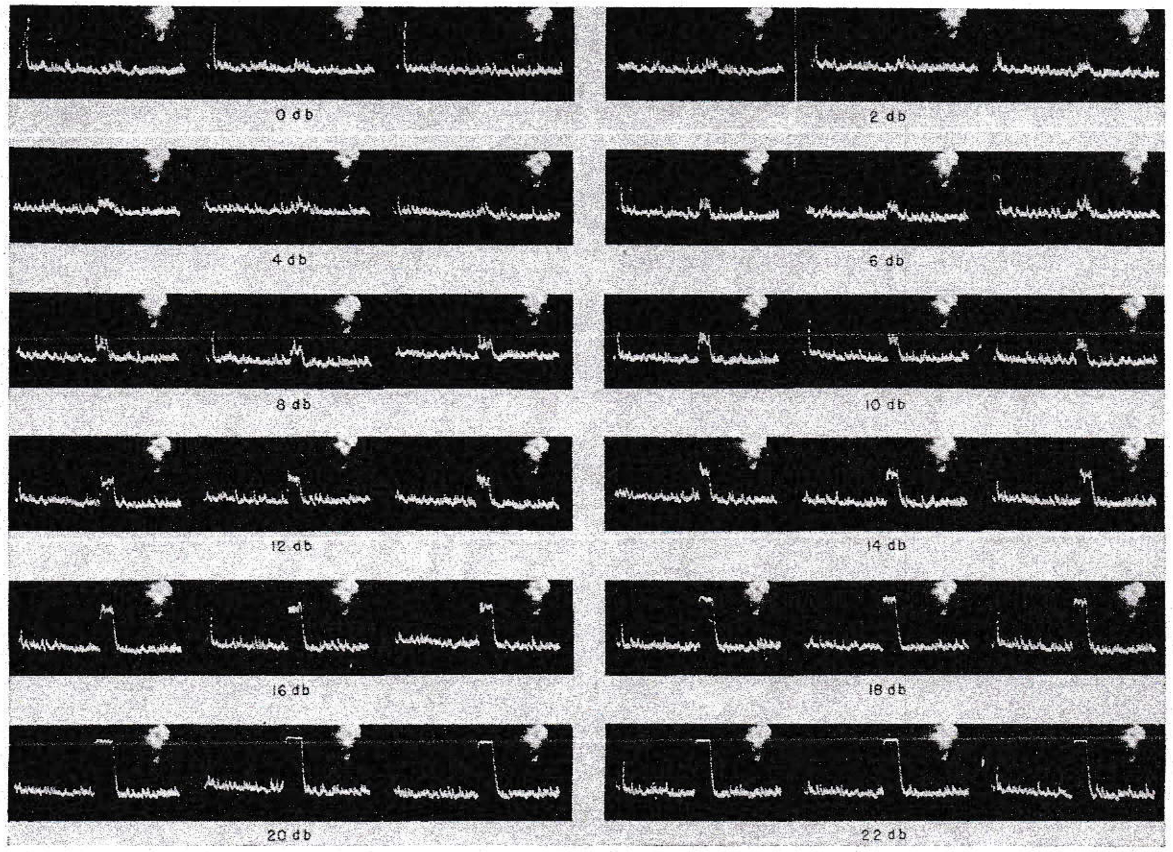

Fig. 10—Test calibrating signals in the moon-radar receiver. Levels given are db with respect to receiver equivalent-input-noise le

line, and a short circuit placed on the line to the antenna at a distance of one-fourth-wavelength from the diode, so that the 250-ohm diode load replaces the antenna impedance. The diode current is then raised until the receiver noise power output, as indicated by a thermocouple connected *before* the final detector, is twice the output for no diode current. Substituting $R = 250$ in (24), the noise factor is

$$N = 4.85 I_{ma} \tag{25}$$

where I_{ma} is the diode plate current in milliamperes.

The effect of a pulsed signal of any given intensity may be simulated by injecting a signal at one of the intermediate frequencies, and by means of a thermocouple at the receiver output, referring the level to the receiver input. This injection can be most conveniently done at the 180-cps intermediate frequency. A series of test signals of this kind is shown in the oscilloscope photographs of Fig. 10. These photographs show the test pulses on the 4-second sweep of the oscillosope, and the decibel levels shown are with respect to the noise output of the receiver. Referred to the receiver input, if the noise factor is 3.2, that is, 5 db, then the 0-db signal in the photo corresponds to an input signal of −149 db with respect to 1 milliwatt, the 2-db signal to −147 db, etc. These photographs facilitate estimation of the intensity of returns from the moon.

The receiver frequency can be easily adjusted by connecting the vertical deflection plates of an oscilloscope to the receiver output and a standard audio oscillator to the horizontal deflection plates. (See Fig. 7.) The small leakage from the transmitter produces a frequency in the output circuit which is the difference between the transmitter and receiver frequencies, ± the 180-cps final intermediate frequency. Thus, for example, if it is desired to receive on a frequency 200 cps higher than the transmitter frequency, the audio oscillator is set to 180 plus 200 or 380 cps, and the final receiver crystal oscillator is adjusted until a stationary circular pattern is obtained on the oscilloscope (care must, of course, be taken that the upper or lower heterodyne as required be chosen).

The transmitter output power is measured by a crystal detector used with a directional coupler.[9] This detector operates in conjunction with a calibrated amplifier and oscilloscope arrangement to give an oscilloscope deflection which is a measure of the transmitter power on each pulse. The directional coupler used is also capable of measuring power reflected back down the transmission line from the antenna, and so may also be used to determine the SWR of the transmission line.

Directional couplers for open lines and at this relatively low frequency are rather unusual, and the one used here will be briefly described. A photograph of the coupler is shown in Fig. 11. It consists of two one-fourth-wave shorted sections A and B which are tapped onto the main open 250-ohm transmission line at two points C and D which are separated by one-fourth wavelength. On each of these a 50-ohm unbalanced line is tapped at a point (E and F) near the shorted end, so that approximately 1/30 of the voltages on the 250-ohm line at points C and D are applied to the respective 50-ohm lines. The 50-ohm lines are provided with "bazooka" one-fourth-wave skirts (G and H) to provide a balanced to unbalanced connection. The 20-db 50-ohm pads (J and K) are provided to furnish additional attenuation and assure proper termination of the 50-ohm lines. L and M are the two output points which are connected by the auxiliary one-fourth-wave line P (which is shorter physically than the open line one-fourth-wave section CD because of the dielectric material used in the 50-ohm line). It will be seen that energy extracted from the line at C travels to point L through a path of the same length as the energy extracted at point D which travels to point M.

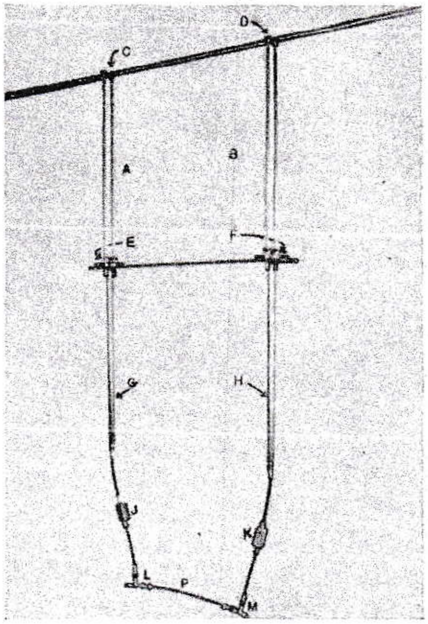

Fig. 11—Photograph of the directional coupler used for power measurement on the moon-radar system open transmission line.

Now, considering the functioning of the coupler, it will be seen that, of the energy traveling along the main transmission line, say in the direction C to D, small and (very nearly) equal fractions are extracted by lines A and B. These two fractions of the energy reach point M by equal path lengths and so are in phase at this point, and reach point L by path lengths which differ by one-half wavelength and so cancel (except for a small residue which exists because the energy available at D is less than that at C by the amount which has been extracted at C). Similar reasoning for the energy traveling along the main line in the direction from D to C will reveal that the extracted fractions add at L and cancel

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[9] W. W. Mumford, "Directional couplers," PROC. I.R.E., vol. 35, pp. 160–165; February, 1948.

at *M*. Thus, very closely, a measurement at *M* is a measure of the power being transmitted along the main line in the direction *CD*, and a measurement at *L* is a measure of the power being transmitted along the main line in the opposite direction. From these measurements the net power and the SWR may be determined.

REFLECTIONS OBTAINED FROM THE MOON

With the apparatus in somewhat cruder state than described above, echoes from the moon were first obtained at moonrise on January 10, 1946. Oscilloscope deflections and an audible tone pulse in the loudspeaker connected across the 180-cps if amplifier were easily perceptible. One of the earliest photographs, that of an echo at moonrise on January 22, 1946, is shown in Fig. 12. In this photograph the sweep is that of a conventional type-A radar oscilloscope; that is, the sweep starts at the left of the screen with the transmitter pulse (not visible except for a disturbance due to the mechanical transmit/receive switch) and progresses uniformly across the screen. At about $2\frac{1}{2}$ seconds a vertical deflection occurs due to the reception of the pulse returned from the moon. The total sweep in this case is slightly in excess of 3 seconds.

Unfortunately, the project has been beset by numerous apparatus difficulties and the fact that, because of other work, it has been difficult to concentrate effort on it. As a result, the data which can now be reported are still fragmentary, but some useful qualitative conclusions can be drawn.

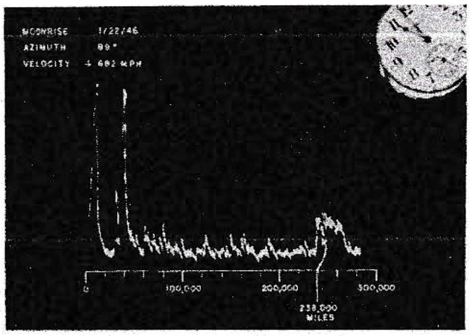

Fig. 12—Oscilloscope traces of moon radar echo observed during rising of the moon, January 22, 1946.

As previously indicated, observations have so far been limited to moonset and moonrise because of the limitations of the antenna structure. In general, results have been poorer at moonset than at moonrise, presumably

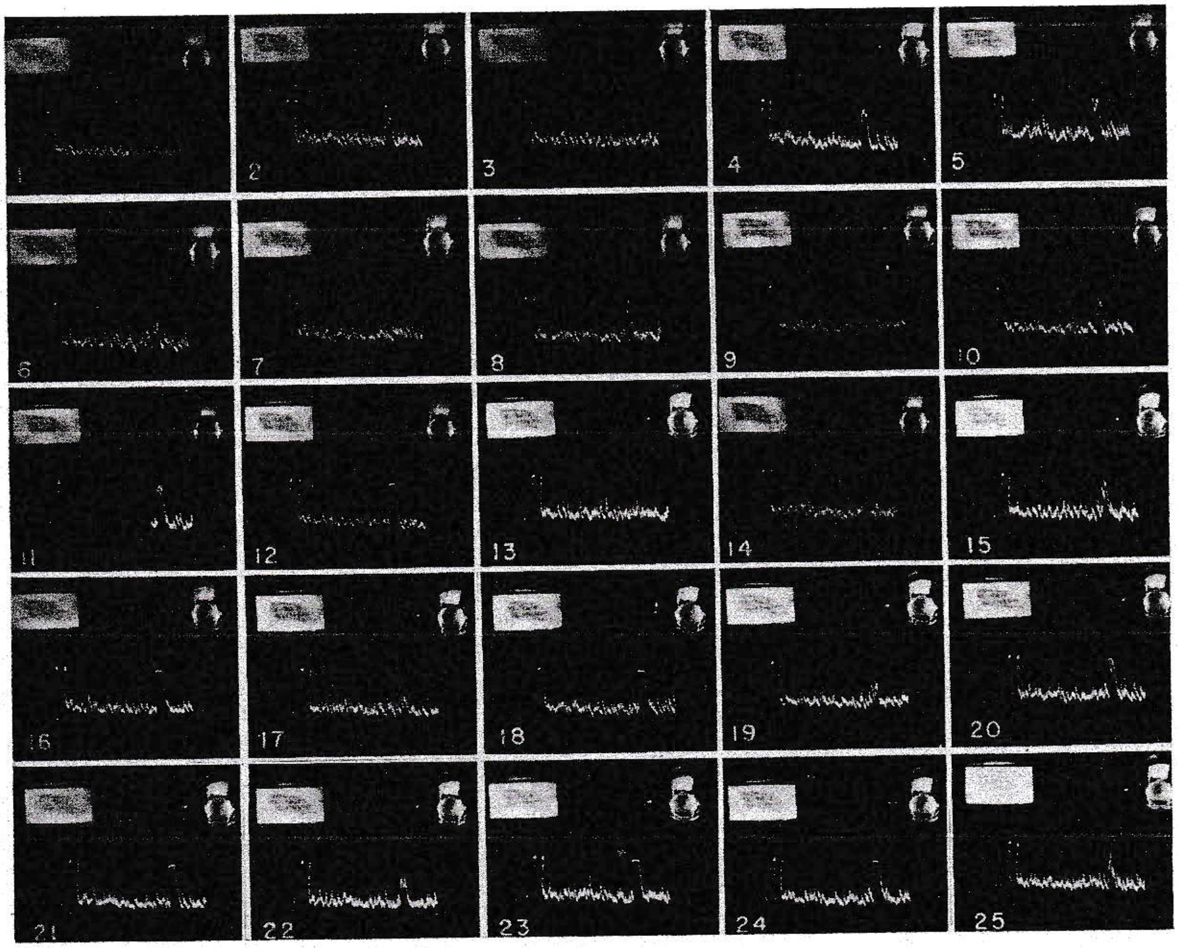

Fig. 13—Twenty-five successive moon echoes. The time interval between photographs is approximately 4 seconds.

because the antenna looks over land at moonset, under which condition the effect of ground reflection is probably less effective than when, as at moonrise, the antenna looks over the sea. So far, no significant correlation has been observed between echo effects and the time of day at which observations must be made, weather conditions, and the azimuth position of the moon. Undoubtedly, however, there are relations involving at least some of these factors, and it is hoped that eventually some precise information of this kind may be obtained. For example, it has been noted that the relation between the time on a particular day at which the first echoes were received differs from the time of optical moonrise by an amount which varies by several minutes from day to day. Frequently echoes are received before optical moonrise. This is undoubtedly due in part to changes in atmospheric refraction and attenuation from day to day, and in part to changes in the radiation pattern in different directions. Frequently, even with the equipment to all appearances in satisfactory working order, no echoes are observed.

One of the most striking effects noted has been a large, rapid variation in the signal strength observed. These changes occur much too rapidly to be accounted for by the coarse lobe structure of the antenna. In Fig. 13 is a sequence of 25 successive sweeps with the echoes in successive pictures separated by about 4 seconds. It will be seen by comparison between the test signals of Fig. 10 and the actual echo signals of Fig. 13 that, in the fourth line of echo signals, pictures 16 to 20, the decibel levels are about as follows:

Picture No. (Fig. 13)	*Decibel Level*
16	20
17	2
18	20
19	6
20	14

These are separated in time by only about 4 seconds, which corresponds to a change in elevation of the moon of about 0.016 degree, which is a very small amount in terms of the beam width, or even the width of the lobes into which the beam is broken by the ground reflections. This rapid variation in signal level conceivably could be due to rapid bending or absorption of the path through the atmosphere, and this seems reasonable and probable in view of the fact that on numerous occasions, when the equipment appeared to be working in a completely satisfactory manner, no echoes were obtained. Another possibility is that libration of the moon (rotation of the moon with respect to the point on earth from which it is viewed), might account for such variations. At moonrise or moonset this rotation reaches a maximum rate of 3 degrees per day. This corresponds to a (differential) velocity at the outer edge of the moon of about 1 meter per second. That is, in 4 seconds, one edge of the moon moves 4 meters closer to and the other edge 4 meters away from the observer. If large contributions to the particular reflection happen to come from large areas near the edge of the moon, this movement might easily cause large variations in signal strength. This view, however, is not consistent with the concept of random roughness of the moon, and is one of the questions which it is hoped future work will answer. An effort was made particularly to observe variations in signal strength on a day when it was calculated that the rate of libration in both latitude and longitude would be at a minimum, but no conclusive result was obtained.

It should be noted that the photographs of Fig. 13 were obtained with a transmitter peak power output of about 15 kw. According to the calculations given previously, this corresponds to a calculated excess system performance of about 30 db. Neglecting transmission-line losses, depolarization, and atmospheric attenuation, the signals received should have a peak power of 30 db above rms receiver noise. From comparison of Figs. 10 and 13 it is seen that moon echoes in excess of 20 db above receiver noise were obtained.

The effects of extraneous noise, both local and cosmic, have been very bothersome, and the effects are difficult to separate. Interference from ignition systems of passing automobiles, neon signs, harmonics, or other interference from other radio operations, and interference from other laboratory operations are among the local sources which have been identified, together with many unidentified disturbances. A 111.5-Mc narrow-band amplifier (about 100 kc wide using cavity resonant circuits) is included in the rf amplifier system to reject strong near-by signals which might cause cross-modulation difficulties in later stages, but does not aid in eliminating the interference from disturbances within the finally used pass band.

Noise from the sun has been observed in the form of a considerable increase in output noise level, superimposed on which are large bursts of noise of shorter duration. A comparison device in which the antenna connection of the receiver is periodically switched between the antenna and a resistor, with the output of the receiver being synchronously switched from one side to the other of a balance device, has been used as an extremely sensitive means to measure such noise. The resistor is so arranged that the known noise current from a temperature-limited diode may be passed through it to permit calibration of the system.

The noise from the sun has been observed as the sun rises and sets, and the maxima and minima of the antenna lobe structure are discernible as the sun passes through the beam. Observation of the echoes from the moon is usually impossible when the sun is in the same direction as the moon at the time observations must be made. It is outside the scope of this paper to discuss this noise question in more detail, but it is mentioned as one of the difficulties encountered.

From the time when the first moon-radar experiments were performed there appears to have been a progressive increase in the external noise level to an extent that it is frequently difficult or impossible to discern radar echoes from the moon because of the high noise level. Whether the increase has been local or cosmic is difficult to determine, because of the wide antenna beam width and the fact that the present antenna cannot be raised in elevation.

USE OF THE MOON IN COMMUNICATION CIRCUITS

One of the reasons for initiating the moon-radar study was the possibility that the moon might be used to reflect communication signals from one point on earth to another. It is outside the scope of this paper to consider this matter in extended detail, but it will be briefly discussed in the light of the moon radar experiments.

Analytical consideration of the question indicates that communication in this manner is subject to limitations and difficulties which rather discourage its consideration except in extreme situations. Some of these considerations are:

(a) Unless a very narrow-beam-width transmitting antenna is used, the probable multiplicity of reflections from the moon would make necessary complicated apparatus to obtain a wide-bandwidth communication channel.

(b) Unless narrow-beam-width antennas are used, the power requirements are very large.

(c) If narrow-beam antennas are used, the construction of them is difficult, and a tracking problem arises.

(d) A moon-communication circuit is only usable at such times as the moon is simultaneously visible from both receiving and transmitting points.

(e) The long transmission travel time would be objectionable in some cases.

The experiments reported above indicate that some of these considerations are very important, and that there are additional considerations that should also be mentioned.

(f) Examination of Fig. 13 indicates that the attenuation of the earth-moon-earth path is subject to rapid and large variations.

(g) If the attenuation variation mentioned in (f) is due to rapid bending of the path, the problem of using narrow-beam antennas becomes even more difficult.

(h) During periods when the sun and moon both fall in the beam width of the receiving antenna, the noise contribution of the sun will be very high. At other times there may be some contribution of noise from the sun by reflection from the moon, but this will probably be negligible. (It was not identifiable in the moon-radar experiments.)

Thus, while the moon-radar experiments are in themselves a demonstration of the fact that a communication link using the moon as a passive reflector is definitely possible, such a system is subject to difficulties and limitations which make its extensive and general use unlikely, as viewed at present.

In connection with the subject of communication circuits involving the moon, it is interesting to consider the possibility of a one-way radio circuit to the moon. Equation (1) gives the power flow per unit area at the moon at a range R. If a receiving antenna of area A_R' were placed on the moon, it would intercept a power P_R' given by

$$P_R' = S_0 A_R'. \tag{26}$$

If G_R' is the gain of this receiving antenna, the relation of G_R' and A_R' is given in (4b). Combining (1), (4b), and (26) gives the gain from the transmitter antenna terminals on earth to the receiver antenna terminals on the moon as

$$\frac{P_R'}{P_t} = \frac{571 G_t G_R'}{R^2 F^2}. \tag{27}$$

It should be remembered that the antenna gains are with respect to an isotropic antenna, R is in meters, and F is in megacyles.

To evaluate the above figures, consider a nondirectional transmitting antenna (gain of 1) and a simple receiving antenna with a gain of 10, at a frequency of 100 Mc. For this case and the range of 4.07×10^8 meters, $P_R/P_T = 3.45 \times 10^{-17}$, or an attenuation of 164.6 db.

Now consider a standard FM broadcast station of 50 kw operating on 100 Mc and an FM receiver operating with a bandwidth of 200 kc. From curve 1 of Fig. 3 the thermal input noise to such a receiver is -121 db with reference to 1 milliwatt and, allowing a receiver noise factor of 5 db, the equivalent input noise is $-121+5 = -116$ db. If it be assumed that a signal 10 db greater than this might give usable FM reception, a -106-db signal would be sufficient for operation of the receiver. The 50-kw transmitter output corresponds, from curve 2 of Fig. 3, to $+77$ db with respect to 1 milliwatt, so the spread between transmitter and receiver is 183 db against the path attenuation of 164.6 db. Thus it is evident that, even without an extraordinary antenna system, an FM broadcast station on earth could be readily received on the moon. In fact, this calculation shows that even a 1-kw FM station could probably be detected. If antennas similar to those used in the moon-radar experiment were used at each end of the circuit, the 164.6-db path attenuation would be reduced to about 127 db. If the path length were then increased to 50,000,000 miles, the attenuation would only be increased by 46 to 173 db, a figure still within the 183-db spread of the 50-kw 200-kc bandwidth FM system. Thus, using only presently developed radio equipment, Mars and Venus also are at times within reach of a 50-kw FM station on the earth, and vice versa.

These speculations, of course, omit consideration of the fading and attenuation observed in the radar experiments and which might make reception difficult. However, in the one-way path considered here, this should be less serious than in the two-way radar path, and if it ever becomes practical to place a nonpassive relay station on the moon, possibly with means for regenerating the signal shapes, earth-point to earth-point-communication via the moon might look much less discouraging.

General Conclusions

The work so far has indicated that, under some conditions, a radio signal can be transmitted from the earth to the moon, be reflected, and again be detected on the earth, and that the character of this path changes materially from time to time, both rapidly and on a long-time basis. The most important observations concern the interesting questions which are raised and which it is hoped future research and experiment will answer.

More detailed information concerning the precise nature of the reflection at the moon should be obtained by use of a pulse narrower than the 0.0116 second required for travel across the moon and back. Fig. 18 shows that with a pulse of 1,000 microseconds the peak return would only be down about 8 db, and the increased bandwidth required for a 0.001-second pulse over the 50-cps bandwidth used in the experiments reported here would increase the receiver noise contribution by 13 db, representing a degradation in system performance of 21 db. Fig. 13 shows just about this excess in system performance for the present equipment arrangement. Thus, with some increase in transmitter power and a compromise pulse width of perhaps 2,000 microseconds, under the best conditions it should be possible to get some indication of return pulse shape with equipment generally similar to that described in this paper, except with wider intermediate-frequency and video bandwidth in the receiver.

It would be desirable to obtain observations of moon echoes over extended periods, not only with a horizontally directed antenna as described, but also with an antenna capable of movement in all directions. The work should also be extended to other frequencies.

Fig. 13 shows the need for an arrangement for transmitting pulses in more rapid sequence so that the effects which occur during the 4-second intervals between the pulses in Fig. 13 can be observed. The effects of noise from the sun and other cosmic sources, and its effect on these operations, should be further investigated.

It is hoped that the plans which have been made for investigating these and other questions can be carried to completion and the results published in a later paper.

Acknowledgments

The authors particularly acknowledge the help of H. D. Webb and J. Mofenson for their extended work in the conduct of this experiment and in the review of this paper, and the contribution of Walter McAfee in discussions of echoing-area problems and review of this paper. Some of the other individuals who made substantial contributions to the work were J. Ruze, O. C. Woodyard, A. Kampinsky, J. Corwin, C. G. McMullen, W. S. Pike, F. Blackwell, H. Kaufman, R. Guthrie, H. Lisman, J. Snyder, G. Cantor, and A. Davis.

APPENDIX

Effect of Reflection from Moon on Shapes and Amplitude of Radio-Frequency Pulses

The shapes and intensity of echo pulses from the moon can be derived on the basis of the assumption that the moon looks, for radio waves in the frequency range considered, like a uniformly illuminated disk. Consider first the situation for a pulse of duration ΔT, which is small conpared to the time required for a wave to travel twice the distance equal to the radius of the moon (that is, the time for a round trip over a path length equal to the radius of the moon). If ΔT is the pulse length, the range interval in miles over which the reflection is obtained is $\Delta X = \Delta T/2 \times 186{,}000$.

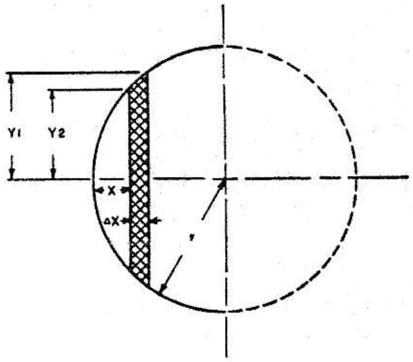

Fig. 14—Short radar pulse passing across the moon.

Referring to Fig. 14, the projected area active in producing a reflection for a pulse of width ΔX is the difference in the circles having radius of y_1 and y_2. That is,

$$\Delta A = \pi Y_1^2 - \pi Y_2^2. \tag{28}$$

By the geometry of Fig. 14,

$$Y_1^2 = r^2 - (r - X - \Delta X)^2 \tag{29}$$

and

$$Y_2^2 = r^2 - (r - X)^2. \tag{30}$$

Combining (28), (29), and (30)

$$\Delta A = 2\pi \Delta X \left(r - X - \frac{\Delta X}{2} \right) \tag{31}$$

and, for the condition stated, that ΔX is small compared to $r - X$ except for the very end of travel, where $r \approx X$, the $\Delta X/2$ may be ignored, leaving

$$\Delta A \approx 2\pi \Delta X (r - X). \tag{32a}$$

In Fig. 15 this is plotted and shows the shape (in terms of *power*) of the returned pulse (observed from a great distance) as the radiated pulse (measured from its trailing edge) passes over the moon. The manner of rise to the peak value $2\pi r \Delta X$ has not yet been considered, but obviously it rises to this value in the time ΔT in some such fashion as shown in the dotted portion of Fig. 15.

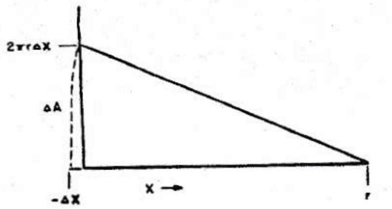

Fig. 15—Shape of return pulse from the moon for very short transmitted pulse. (Curve is on a power basis.)

The manner of rise will be considered in more detail in the analysis of the effect on a pulse wide compared to the moon.

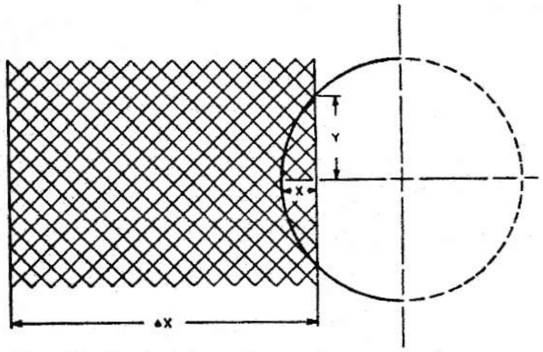

Fig. 16—Long radar pulse passing across the moon.

Consider a pulse such that ΔX is larger than r (see Fig. 16). Now, as the leading edge of pulse starts across the moon, the power returned varies in proportion to the area illuminated—that is, the area illuminated when the leading edge is at point X is

$$A_X = \pi(2rX - X^2). \tag{33}$$

This will continue until X reaches the value r when the pulse levels off to its peak value, corresponding to $A = \pi r^2$, at which level it continues until the trailing edge of the pulse reaches the edge of the moon at which time the power level starts to decrease. The power returned at the time the trailing edge is at position X' measured in the same co-ordinate as X is proportional to the total disk area less the portion left unilluminated, or, now using (33) for the unilluminated area

$$A_{X'} = \pi(r^2 - 2rX + X^2). \tag{34}$$

A plot of the effective area in terms of time which is the power shape of the returned pulse is given in Fig. 17, based on (33) and (34) and the above considerations. In this figure, distances have been converted to a time basis to show the extent of pulse broadening.

For values of pulse width $\Delta T'$ intermediate between ΔT very short and ΔT larger than 0.0116 second, the pulse will rise along the initial rise curve of Fig. 17 to a value given by analogy to (33) as

$$A_{\max}' = \pi(2r\Delta X - \Delta X^2) \tag{35}$$

and then drop linearly for a period of (0.0116 second $-\Delta T$) as shown in Fig. 15. At this point the leading edge of the pulse has reached the center of the moon, and the trailing edge is at $r - \Delta X$ so that the power contributing area has reached an intermediate value given by substituting $r - \Delta X$ for X in (34) or,

$$A_{\text{int}}' = \pi(\Delta X)^2 \tag{36}$$

after which the value then drops to zero as along the main decay curve of Fig. 17. This action has been dotted in on Fig. 17.

Fig. 18 facilitates estimation of the maximum value of area effective for a particular value of pulse width in terms of the area which would be effective if the pulse were wide enough to utilize the full moon. The rising portion of the curve of Fig. 4 has been replotted in Fig. 18 to show area (or echo power) in terms of db relative to power from full area and microseconds transmitted pulse length.

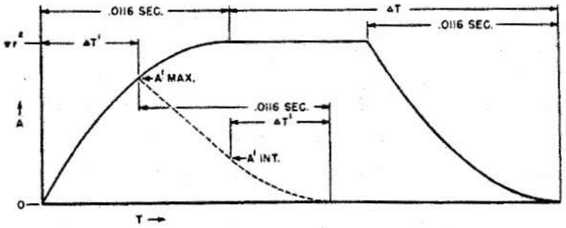

Fig. 17—Shape of return pulse from the moon for very long or fairly long (dotted curve) transmitted pulse. (Curves are on a power basis.)

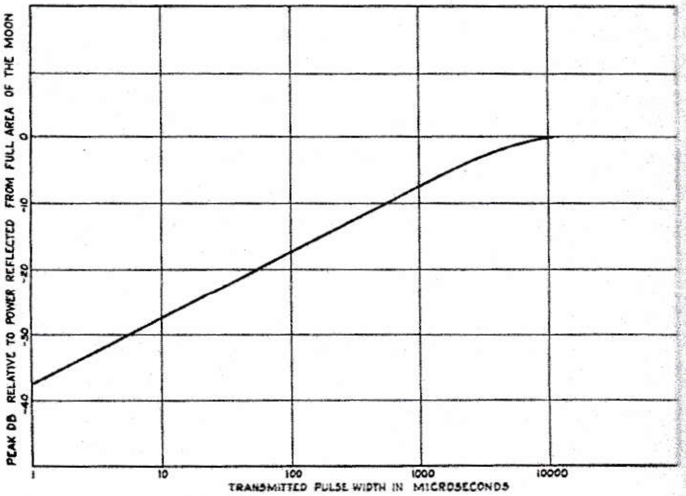

Fig. 18—Peak power reflected from moon as a function of pulse width, in terms of peak power reflected for a very long pulse.

Thus, for example, the peak power level of echo from a 1-microsecond transmitted pulse of a given peak power would be expected to be about 38 db below that of the echo from a 0.05-second transmitted pulse of the same peak power.

In all of the above, the effect of the back side of the moon is ignored, since, at the "line-of-sight" frequencies considered here, it is in a "shadow" region.

drainage, heating and air conditioning, electric equipment, and acoustics.

ELECTROLYTIC CAPACITOR. By A. M. Georgiev. Murray Hill Books, Inc., New York, N. Y. 191 pages, $3. Describes the construction, manufacture, function, and testing of dry and wet electrolytic capacitors, explains the operating characteristics of the various types, and indicates their useful applications and limitations.

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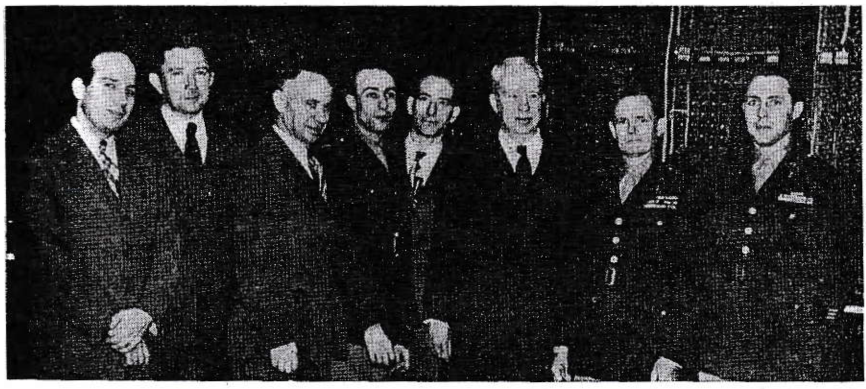
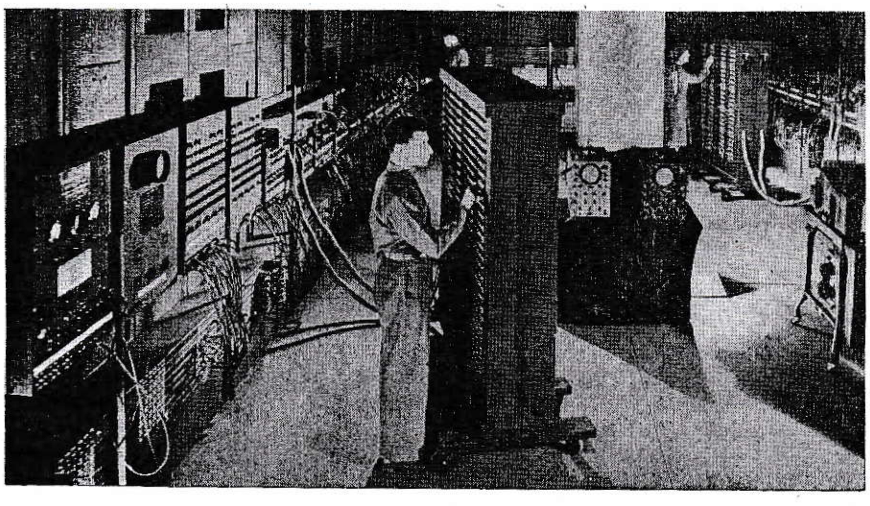
New Electronic Calculator



Officials who were responsible for the development of the "electronic numerical integrator and computor" designed and constructed by the Moore School of Electrical Engineering, University of Pennsylvania, Philadelphia, for the United States Army Ordnance Department are shown at its dedication. Containing nearly 18,000 vacuum tubes in its mechanism, the new calculator occupies a room 30 by 50 feet and weighs 30 tons. It is said to be the first all-electronic general purpose calculator and to compute 1,000 times faster than any similar machine previously built. Originally developed for the computation of firing and bombing tables for vital ordnance equipment, the device can find many peacetime applications in such fields as nuclear physics, aerodynamics, and scientific weather predictions. Left to right are J. P. Eckert, Jr., Moore School; Professor J. G. Brainerd (M '39) Moore School, and chairman of the AIEE committee on basic sciences; Sam Feltman, chief engineer for ballistics, United States Army Ordnance Department; Captain H. H. Goldstine, liaison officer; Doctor J. W. Mauchly, Moore School; Doctor Harold Pender (F '14) dean, Moore School; General G. M. Barnes, chief of the United States Army Ordnance Research and Development Service; and Colonel P. N. Gillon, chief of the research branch, United States Army Ordnance Research and Development Service



Message to Moon Proves Atmosphere Penetration

The principal significance of the radar-to-the-moon tests recently conducted by the United States Army Signal Corps, according to Major General Harry C. Ingles, Chief Signal Officer of the Army, is that they demonstrated for the first time that radio waves in the very high frequency band will penetrate completely the ionosphere, the celestial void, and whatever form of atmosphere that may surround the moon. Although the waves had to travel 238,000 miles to the moon the penetration was accomplished without distortion or refraction.

The radar set employed in the tests at the Evans Signal Laboratory, Belmar, N. J., was designed primarily for long-range detection of hostile aircraft but for transmission over so great a distance it was necessary to modify the oscillators and to add a second complete antenna unit. The set was operated on its standard frequency of 111 megacycles, a wave length of 300 centimeters, which lies in the very high frequency range.

REA Adds Electro-Agricultural Section. A new section of the Rural Electrification Administration's Technical Standards Division has been established to organize, promote, and co-ordinate programs in the development of new electro-agricultural equipment and the improvement of existing devices of benefit to the farmer according to an announcement made by Claude R. Wickard, administrator. The electro-agriculture section, as it will be known, will be concerned with the development of new electric equipment designed to meet farm needs and will work with colleges and other groups carrying on research programs. The information will be made available to manufacturers for commercial development and quantity production at lower costs. REA borrowers will be given information concerning new developments in electric equipment which will improve living conditions and increase farm profits.

INDUSTRY • • • • •

Gwilym A. Price Westinghouse President

Gwilym A. Price, vice-president and member of the board of directors, has been elected president of the Westinghouse Electric Corporation, East Pittsburgh, Pa., to succeed George H. Bucher, who has resigned. Under a recent amendment of the corporation's bylaws, Mr. Price as president will be chief executive officer.

Mr. Price at the age of 50 is one of the United States' youngest directors of a large corporation. He was born in Canonsburg, Pa., in 1895 and is a graduate of the University of Pittsburgh Law School (1917). Prior to his election as an officer of the Westinghouse corporation in 1943, Mr. Price had been president of the Peoples-Pittsburgh Trust Company of Pittsburgh, Pa., an organization with which he had been associated since 1923.

Mr. Bucher will continue with the company as vice-chairman of the board of directors and as chairman of the Westinghouse Electric International Company.

Lighting Survey. A minimum of four million new luminaires or lighting fixtures for approximately 50,000 miles of automotive throughfare and 250,000 miles of residential streets at an estimated installed cost of 500 million dollars will be needed for new and replacement traffic safety lighting in the United States during the next ten years according to a recently completed survey of the country's lighting conditions made by Doctor A. F. Dickerson, manager of the lighting division, General Electric Company, Schenectady, N. Y. The survey emphasized the fact that improper illumination can be credited as the chief cause of increasing automobile accidents which claimed, during the period from December 7, 1941, to June 1, 1945, three casualties for every American war casualty.

Wire Stripping Method. After a year of production and demonstration, a method for removing insulation from fine electrical wires, developed by the Fairchild Camera and Instrument Corporation, Jamaica, N. Y., is said to have exceeded original expectations. Initially intended for application to wires covered with certain synthetics, it has enabled electrical manufacturers to strip all modern types of synthetic covered wires with no change in wire size or physical properties. In this method the ends of fine wire to be stripped first are dipped quickly in one chemical solution, then immediately in a final solution which acts as an accelerator, and then gently stroked to remove the insulation. The process is patented by the corporation which is licensing electrical manufacturers to use it.

Gas Turbine Progress. Successful operation at a gas temperature of 1,350 degrees Fahrenheit has been accomplished in tests on a gas turbine plant installed in the United States Naval Engineering Experiment Station, Annapolis, Md., it was announced recently. The 3,500-horsepower unit was designed by the Allis-Chalmers Manufacturing Company, Milwaukee, Wis., for eventual operation with hot gas at a temperature of 1,500 degrees Fahrenheit. It embodies cooling methods which permit the multistage turbines to operate safely at high inlet temperature by avoiding the undue weakening effect of the high temperature on the materials used for the rotating parts.

New Generating Station. Construction of a new generating station on the Arthur Kill at Sewaren, Woodbridge, N. J., is planned by the Public Service Electric and Gas Company for the autumn of 1946. The initial step in the project includes the installation of two 100,000-kw high-pressure high-efficiency generating units, with the necessary auxiliary apparatus, buildings, docks, electrical switching and transformer equipment, and connecting transmission lines, estimated to cost 23 million dollars.

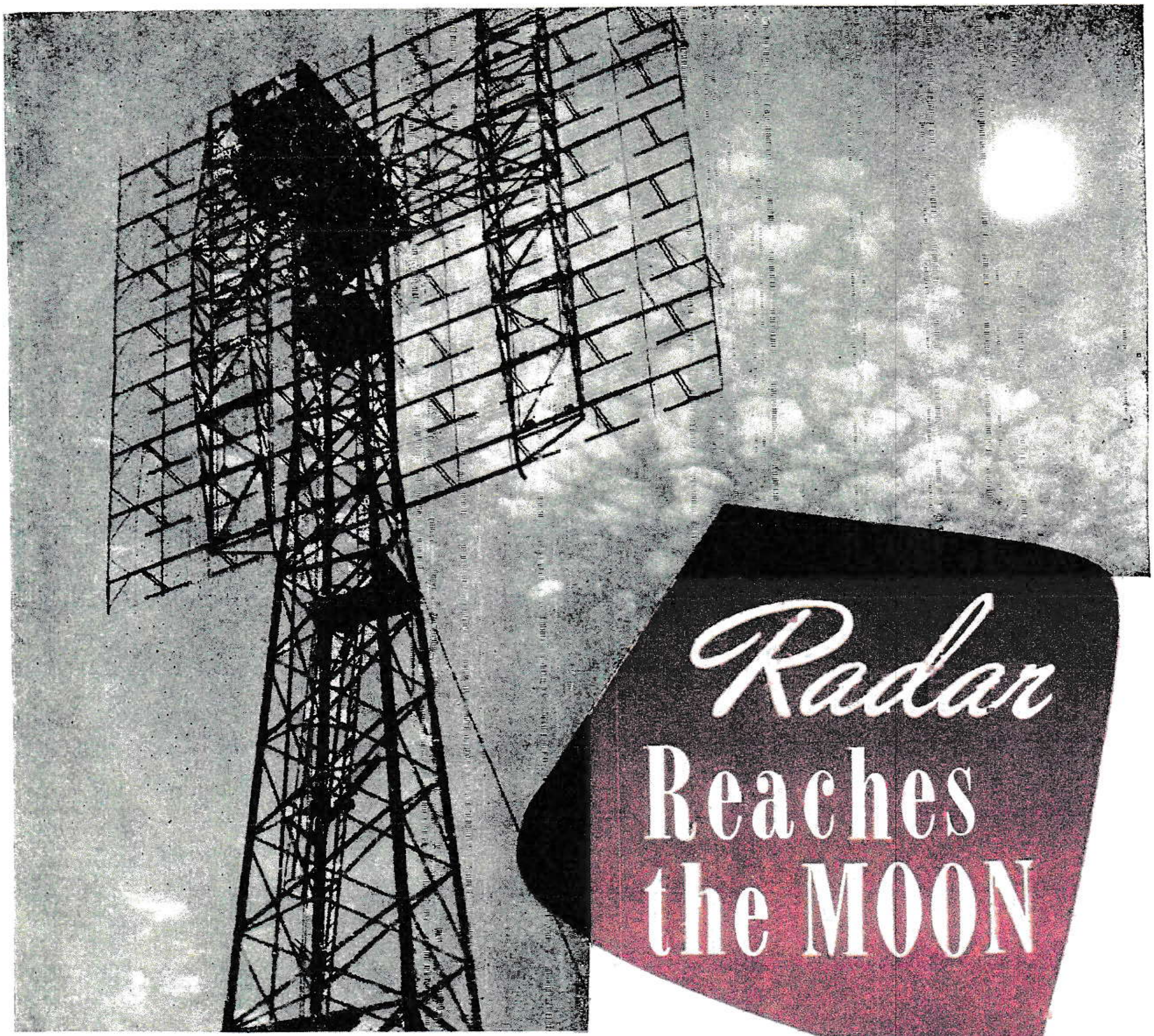
Elastic Plastic. A new elastic plastic, "Marvinol" resin, has been developed by The Glenn L. Martin Company, Baltimore, Md., according to a recent announcement. The raw material will be manufactured by a new plant to be operated by the plastics and chemicals divisions of the company and will be sold only to converters and fabricators. Mixed with other substances, these polyvinyl resins can be used for a large variety of commercial products including multicolored wire insulation, woven fabrics, and industrial gloves.

"Electrical Living." Jobs for 600,000 persons and an annual business of more than four billion dollars for the next five years were forecast by B. W. Clark, vice-president in charge of sales of Westinghouse Electric Corporation, as a result of expanded application of electricity in homes. Speaking at a preview of new home products, Mr. Clark emphasized the need for adequate wiring in homes, and estimated that $150,000,000 per year for several years should be expended in rewiring existing homes. A color cartoon film produced by Walt Disney Studios has been made available to help inform the public of this need.

Newcomer in F-M Field. According to a recent announcement of the Federal Telephone and Radio Corporation, Newark, N. J., the company currently is building frequency modulated broadcast transmitting equipment for 170 installations, its initial venture into that field. The equipment will incorporate a new type of modulator-oscillator unit which is claimed to make possible a very low noise reception level.

Movie Presents Transportation Problem. An all-color sound motion picture, "Lifestream of the City," produced to illustrate the advantages of a well-planned efficient public transit system, has been made available by the General Electric Company, Schenectady, N. Y., to civic and business organizations, schools, colleges, and transit and power companies. The film attempts to prove that modern public transit vehicles, by using existing street space more efficiently, will solve the traffic congestion problem caused by the increasing use of private automobiles. Information about the film, which can be used on sound-equipped 16-millimeter projectors only, may be obtained from the company's visual instruction section, Schenectady, N. Y., or by inquiry at any local office.

"Standardized" Steam Turbines. In accordance with "Preferred Standards for Large 3,600-Rpm Three-Phase 60-Cycle Condensing Steam Turbine Generators" prepared by the joint committee on steam turbine generators of the AIEE and the American Society of Mechanical Engineers (*EE, May '45, p 180*), the first "standardized" steam turbine built for electric power generation is in production at the South Philadelphia, Pa., plant of the Westinghouse Electric Corporation, L. E. Osborne, vice-president, announced recently. The unit, a 30,000-kw machine, initiates a program of standardization which, it is expected, not only will speed up production but will facilitate repairs and servicing.



Special radar antenna array of 64 dipoles used for the transmission of pulses and the reception of radar echoes from the moon.

Radar Reaches the MOON

By
TOM GOOTÉE

A new era of scientific exploration begins with development of the first lunar radar.

PULSES of r.f. energy shoot heavenward from the massive radar set—up and out into the darkness of unknown space. It might be like other nights during the five long years of war—when other radar sets swept other skies in search of enemy planes. But this is different.

This is *lunar* radar.

The radar antenna—one of the largest ever constructed—points toward no military target. Its dipoles concentrate the r.f. pulses toward a great ball of whiteness, the moon, just rising above the New Jersey horizon.

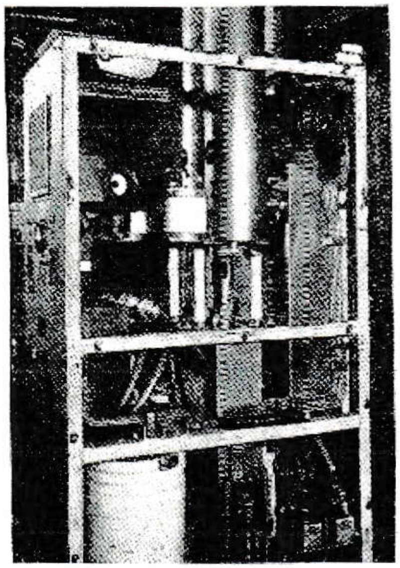
In a tiny shack near the base of the antenna tower, components of the radar set generate the sharp pulses of r.f. energy. The pace is slow, compared to military radar sets. The transmitter functions only once every five seconds. Like the heavy, labored pulsing of a giant heartbeat.

Then, concentrated into a narrow beam by the antenna array, these pulses speed toward the moon at the fantastic speed of light—more than 186,000 miles *per second*—through the ionosphere and on into the unknown void surrounding the earth's atmosphere. The pulses probe where man has never been before, where man has never even dared explore before—with radio waves.

But the men who guide these pulses across distant space have never left their prosaic, tiny shack near Belmar, New Jersey. They wait quietly for results of their inter-planetary effort, they wait for echoes of the radar pulses to return to earth.

Seconds seem like eternities, as the base line crawls across the face of a single 9-inch oscilloscope. Even the scope is geared to cosmic thinking: its calibrated scale is not in miles, but in *hundreds of thousands of miles!*

Suddenly, through the "grass" of noise a wide pip appears along the base line of the scope. And simultaneously, a 180-cycle tone is heard from a speaker on the receiver console. Both last for almost half a sec-



Output stage of the radar transmitter. Two WL-530 tubes (inside large copper shields) supply 50 kilowatts of pulsed power to the antenna. Blowers and filter equipment are in the lower compartment.

ond, then fade out. The time base finishes its sweep, there is a microseconds pause, and the entire procedure is repeated.

An echo pip lasts for almost half a second, and for every radar pulse transmitted: a received pip—appearing at the same place along the base line, indicating a reflecting surface about 238,000 miles distant! An almost stationary image appears on the base line that represents—the moon!

Radar echoes from the moon!

No scientific dream this, no wild tale of phantasy.

Almost every night and day for the past few months, radar engineers and scientists at the Evans Signal Corps Engineering Laboratory in New Jersey have repeated this astounding feat. And the results have been proven beyond a doubt, by leading scientists.

Radar echoes from the moon!

This is the outstanding scientific achievement since the revelation of the atomic bomb. Radar, itself, was a miracle of science—bent to the defensive and offensive requirements of modern warfare: to detect and locate air and surface vessels.

But this *extension* of the use of radar—to measure vast distances that heretofore could only be computed in theory—becomes a singular and major step forward in the field of science.

Planned Strategy

Contact with the moon was no mere accident.

Within a few hours after V-J Day, work was begun on the equipment—under the personal direction of Lt. Col. John H. DeWitt and his four chief associates. Some degree of secrecy was deemed necessary—at least until results were obtained, and proven certain and definite.

The new project was referred to only as the "Diana Project." And the men went to work designing, building, rebuilding, and adapting suitable radar equipment to do the job.

All preparations were completed for a test on January 10th.

On that day the moon rose at 11:48 a.m. At about that time the first radar pulses were transmitted, and the first echoes appeared on the oscilloscope—indicating success.

Accurate timing of *each* pulse and its reflected echo indicated that it took 2.5 seconds for the echo to return.

Since radio waves travel at a fixed rate of speed—about 186,000 miles *per second*—it wasn't difficult to compute the distance from the radar set to the reflecting surface: about 238,000 miles. Col. DeWitt and his radar engineers were convinced they had contacted the moon, because there was nothing else in space at that distance from the earth.

But additional tests were made on following days and nights—each time the moon rose and set.

Said Col. DeWitt, "We knew our months of thinking, planning, calculations, and design were on the right track, but to make doubly positive and sure, as our Army Laboratories must be, we aimed our radar beam at the rising and setting satellite time and time again, so that we knew without question of a doubt that our pulses were striking the moon and echoes were rebounding back to earth."

Finally, a group of distinguished but unidentified scientists visited Belmar and verified all of the findings and conclusions of Col. DeWitt and his group.

Only then, weeks after the initial contact with the moon, did the War Department announce details of the Diana Project. The first earth-to-moon, inter-planetary circuit had been definitely established. All records of long-distance radio transmission had been broken.

And repercussions from the announcement were heard around the world—speculating on both the wartime and peacetime applications of the new long-range radar equipment.

For there are many possible, future applications of such radar equipment—some almost beyond the immediate comprehension of mankind.

A new and far more accurate study of the solar system will be entirely feasible, as soon as adequate and more powerful equipment can be built.

One war possibility is radar-beam control of long-range rockets and jet-propelled missiles. Man has gained *control* of outer space.

But the primary significance of the Signal Corps' achievement is that this is the first time scientists have known with certainty that a very high frequency radio wave sent out from the earth *can actually penetrate the electrically charged ionosphere* which encircles the earth and stratosphere.

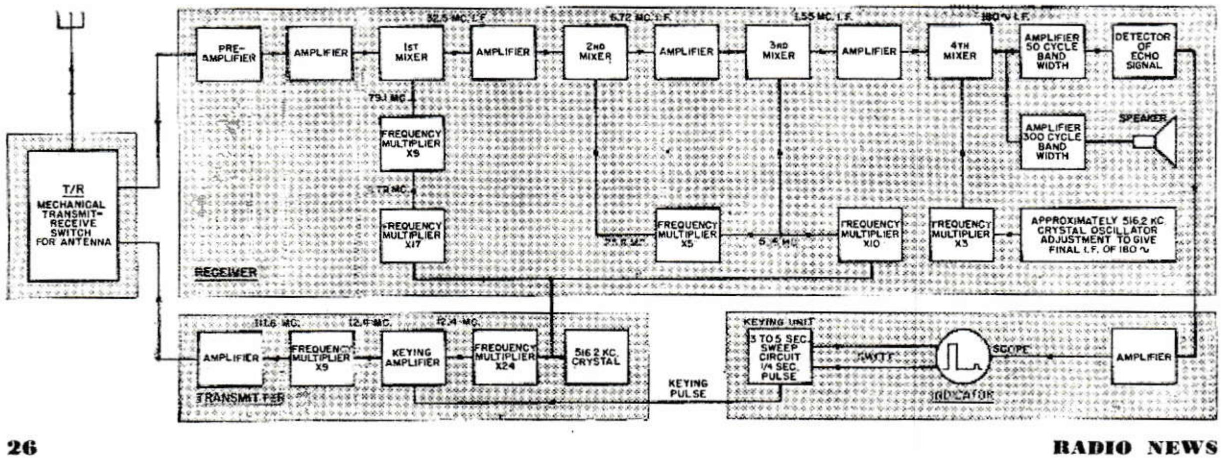
And this proves to be a curious parallel with history.

Link with the Past

More than two decades before contact with the moon was recorded in New Jersey, radio waves were first used for a very similar purpose: to determine the distance to the reflecting surface of the ionosphere.

In 1924, a particular portion of the upper atmosphere, called the Heaviside layer, was believed responsible for the transmission (by reflection) of low-frequency radio signals around the earth. In that year, experiments

Block diagram of the radar set that was used in the original detection of the moon echoes.



were begun in England by Dr. Edward Appleton and M. A. F. Barnett. Using frequency-modulated transmissions of a large broadcasting station, they were able to prove that the received signal varied in intensity with frequency—because it consisted of a direct wave and a reflected component. And a measure of signal intensity caused by a known change in wavelength resulted in a measure of the height of the reflecting layer.

In the same year in the United States, Dr. Gregory Breit and Dr. Merle A. Tuve, of the Carnegie Institute of Washington, used *pulses* of continuous waves for measuring the distance to the reflecting surface of the ionosphere. Their technique consisted of sending skyward a train of very short pulses—a small fraction of a second in length—and measuring the time it took the reflected pulse to return to earth. Fairly low-frequency radio waves were employed. And, after completion of the experiments, pulse ranging soon became the accepted method of ionospheric investigation.

The advent of short-wave radio transmission and the success of these early experiments led scientists in many countries to speculate on the possibility of using such energy to detect the presence of man-made reflectors, such as ships and airplanes. When powerful sources of high-frequency energy, highly sensitive receivers, and refinements in radio technique became available, these possibilities of detection were converted into working devices. Then, with the coming of war, pulse ranging—or radar—was developed under great impetus. And the story of radar's part in winning the war is now well known.

But even before the war, there were a few radio engineers and scientists who saw in the pulse ranging method a means for measuring phenomenal distances: to the moon, other planets, even, perhaps some day, the sun.

One of these men was John H. DeWitt—then chief engineer of station WSM in Nashville. He was also a "ham", and an amateur astronomer. Using his then meager knowledge of pulse ranging, in 1940 he built his own equipment and attempted to contact the moon. His efforts were wholly unsuccessful, but he was undaunted. He looked forward to the day when he might experiment on a really grandiose scale. A year later the country was plunged into war, and DeWitt entered the Armed Forces.

It was not until after the defeat of Japan that his thoughts returned to contacting the moon. Then a Lieutenant Colonel in the Army Signal Corps, he had participated directly in much of the radar development activity of the Army—particularly as Director of the Evans Signal Laboratory near Belmar, New Jersey, with its wartime personnel of over 6000.

Seizing the opportunity, Col. DeWitt immediately started work on equipment suitable for measuring great distances. Four key civilian radar engineers joined his group: E. K. Stodola, Dr. Harold Webb, Herbert Kauffman, and Jacob Mofenson. They had all worked at Evans during the war developing military radar equipment.

First problem facing the group of men was a new philosophy of thought.

They no longer could think of radar ranges in terms of a few hundred miles. The distance to the moon is about 238,567 miles. But this figure varies from day to day, as the moon revolves and moves in an elliptical orbit around the earth. And both the earth and the moon move around the sun.

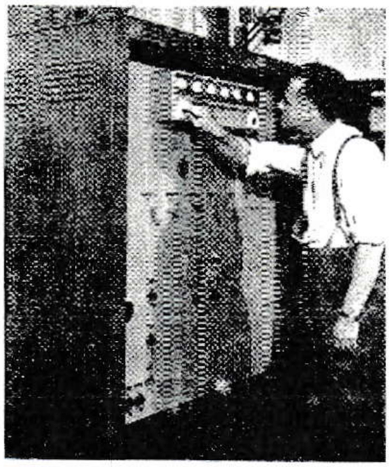
A staff of mathematicians and physicists spent weeks computing the trend in relationship between the earth and moon, before assembly of the equipment began. It was necessary to determine accurately the speed of the moon relative to the movement of the earth. And this speed varies—with respect to the earth's rotation—from 750 miles faster to 750 miles slower, at Belmar, New Jersey.

Variations in speed and positions of the earth and its satellite must be taken into consideration *each time* the moon is contacted. Because the net effect of two variables of movement causes a Doppler effect—a shift in the frequency of radio waves. Often this shift is greater than the receiver bandwidth. Thus the relative speeds of earth and moon must be calculated each day with the radar receiver tuned and adjusted to take advantage of the Doppler effect.

Only in this way can a positive check be made on the direct range measurements of the oscilloscope. These calculations are the most reliable verification that the moon is actually being contacted.

General Characteristics

Equipment used on the Diana Project comprised extensive adaptations to the standard wartime long-range radar known as the type SCR-271—originally designed in 1937 and used widely during the war.



Herbert Kauffman, radio engineer who worked on the "Diana" project, adjusts one of the many stages of frequency multiplication.

Principal components are; transmitter, receiver, antenna system, and indicator. The timer or keyer is part of the indicator unit.

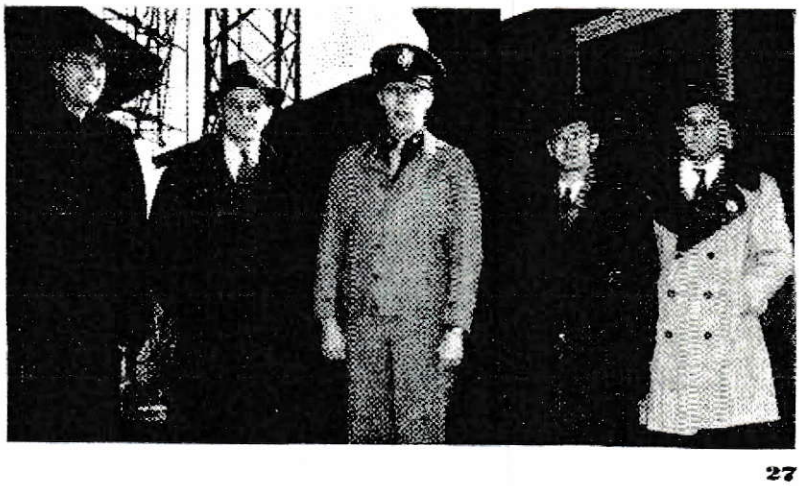
The radar transmitter sends out bursts of radio energy, known as pulses. During intervals between pulses the transmitter is turned off, but the radar receiver functions—and picks up any echo reflections which may be received from distant objects or surfaces. These echoes are amplified and then displayed on the time base of a calibrated oscilloscope. The elapsed time between the transmission of a pulse and the reception of its echo is a measure of the distance from the radar set to the reflecting surface—because radio energy travels through space at the speed of light: about 186,000 miles per second.

Because of the distance and nature of the target, this radar set had to have a number of special features.

A very slow pulse rate was necessary—since the radio signal must travel a round trip distance of more than 477,714 miles. Time must be allowed for an echo to be received, be-

(*Continued on page 84*)

The five Signal Corps scientists responsible for contacting the moon by radar. (Left to right) Jacob Mofenson, Dr. Harold Webb, Lt. Col. J. H. DeWitt, E. King Stodola, and Herbert Kauffman.



furnished upon request to *Hanlan Company*, 1419 West Jefferson Blvd., Los Angeles 7, California.

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Radar Reaches the Moon

(*Continued from page 27*)

fore another pulse is transmitted to the moon.

And each radar pulse must be of appreciable duration—from ¼ to ½ second—to insure a strong signal at the receiver after reflection by the moon.

A three-kilowatt radar transmitter was available for the experiments, and this was modified to supply an output of fifty kilowatts. Through the use of a high-gain antenna, effective radiation was raised to about 10 megawatts, or 10 million watts.

Strength of the received echo reflection has been estimated to be only a few tenths of a watt. Thus the most difficult step in contacting the moon was not so much in the transmission, but in the design and construction of an extremely sensitive receiver.

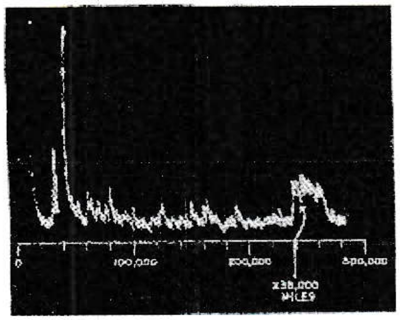
This receiver—using 34 tubes, and four different intermediate frequencies—has a sensitivity of about 0.01 microvolts.

A good idea of the over-all equivalent sensitivity is that the radar set could pick up an airplane at a distance of more than 1900 miles—assuming, of course, that the target was within the set's line of sight.

The complete radar set incorporates a number of new design techniques, thus a detailed analysis of the Diana Project is worthy of further study.

Details of Components

The radar transmitter consists of a series of frequency multiplying stages which raise the frequency of a 516.20 kc. crystal to 111.6 megacycles (the carrier frequency). A pair of type WL-530 tubes are used in the output. These are driven by a pair of type 450-TH tubes (triplers) which, in turn, are driven by a pair of type 257-B tubes (doublers) which, in turn, are driven by an 807 which, in turn, is driven by tubes in the radar receiver.



Photographic record of reception of radar signals reflected by moon on night of Jan. 22, 1946. Heavy pulse at 0 represents initial transmission of energy toward the moon. Jagged lines indicate general noise reception. Distinct echo at about 238,000 miles represents reception of radar echo 2.4 seconds later, after echo had actually traveled a round trip distance of over 477,000 miles between earth and moon. Actual mean distance from earth to moon is 238,857 miles.

The same crystal controls both the transmitter frequency and the heterodyne voltage for the receiver.

A pulse of variable width is supplied the transmitter by the electronic keyer or timer—a physical part of the indicator unit. A pulse duration of from ¼ to ½ second can be used.

Pulse recurrence frequency is also variable. The electronic keyer or timer can supply a pulse once every three to five seconds. This is equiva-

BEAM CENTERING CONTROL FOR 5" OSCILLOSCOPE

RADIO NEWS has received innumerable letters from its subscribers commenting favorably on the article entitled "5" Oscilloscope Design" appearing in the August, 1945 issue of RADIO NEWS. Interest indicated that many of those who constructed the unit would like to add beam centering controls to their new instruments.

In view of this demand, we are presenting the schematic diagram for the addition of such controls. The circuit is exceptionally simple and consists of five components, namely three resistors and two potentiometers.

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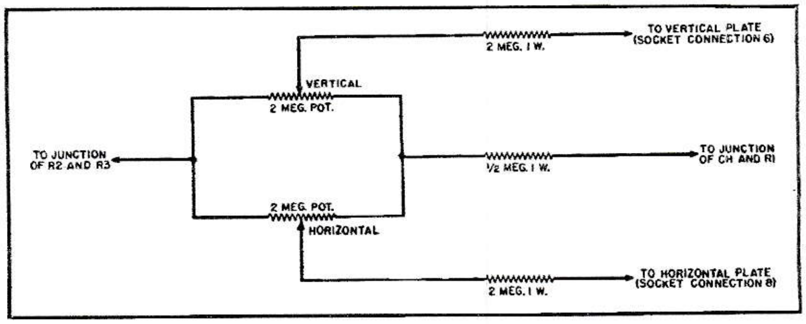
Schematic diagram for beam centering control to be used in conjunction with the 5" oscilloscope design appearing in the August, 1945 issue of Radio News.



lent to p.r.f. of ⅓ to ⅕ cycles per sec.

The peak output of the radar transmitter during pulses is fifty kilowatts.

The transmitter feeds through a mechanical, low-loss *T/R* switch to the antenna system. The *T/R* switch consists of specially constructed relays to obtain positive low-loss action on the long and relatively low peak power pulse used.

The antenna consists of a broadside array of 64 half-wave dipoles. The array is movable and mounted 100 feet above ground.

The antenna system has a forward power gain of about 200. It has a beam width of 15 degrees at half power points—in both the vertical and horizontal planes.

Received echoes are applied to the radar receiver—the real secret of the set's ability to pick up reflections from such distant targets. The receiver is a 4-mixer superheterodyne, with all but one of the mixer injection frequencies directly controlled by the transmitter crystal—to provide locking with the transmitter frequency. Fourth mixer is provided with an adjustable frequency crystal; this sets exactly the final intermediate frequency and depends upon the actual radio frequency being received. The received frequency of the radar signal differs from the transmitted frequency by an amount depending upon the Doppler effect which, in turn, is caused by the moon's relative velocity.

Operating noise factor of the receiver is about 8 db. The receiver bandwidth is about 50 cycles.

A loudspeaker is coupled to the output of the last i.f. amplifier to provide audible indications of echoes.

A long-persistence oscilloscope is used to display the echo output from the detector. The scope uses a type "A" time base with a three to five second sweep, depending upon the desired pulse recurrence frequency. Direct coupling is used for both sweep and deflection circuits.


Servicing and aligning intricate circuits of the sensitive radar receiver. Col. DeWitt discusses procedure with Herbert Kauffman and Dr. Harold Webb.

New Equipment

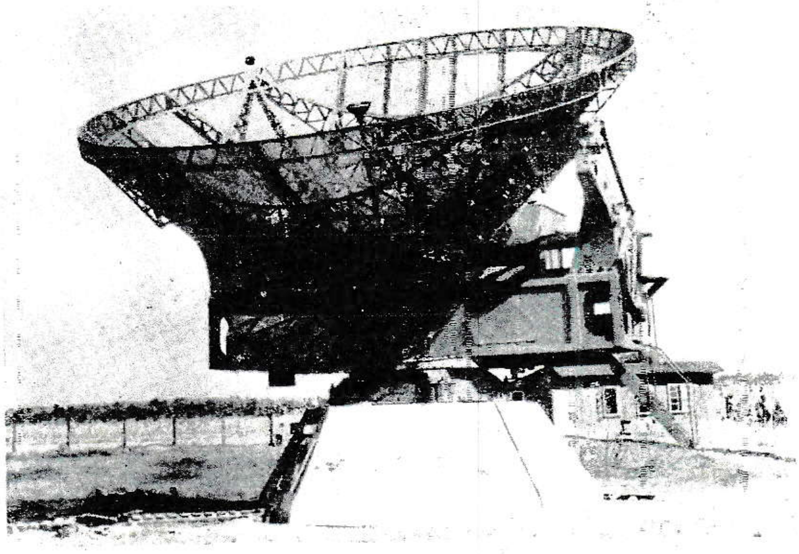
Work has already begun on the design of new and more compact permanent equipment to replace the composite gear used on the first experiments.

The multi-dipole antenna array will probably be replaced by a parabolic reflector—forty or fifty feet in diameter—capable of movement in three dimensions. The base will be comparable in design to bases used for large telescopes at astronomical observatories.

It is also fairly certain that the operating frequency will be considerably increased, when the present radar transmitter is replaced with a more powerful one—possibly using magnetrons.

Other improvements will be incorporated in other components in an at-

One of the German radars successfully jammed by the Allies. Used for ground control of fighters and, later on in the war, for direction of anti-aircraft fire.



tempt to increase both the output power and the sensitivity of the lunar radar.

The Signal Corps intends to continue experiments in this fascinating new realm of exploration and discovery. The War Department has already embarked upon a long-range research program to develop more reliable and informative techniques for radar study of the moon and the ionosphere.

Study of the effect of radio waves in traveling through the atmosphere is of utmost importance. This includes bending and refraction of radio waves, and more complete data concerning the Doppler effect on radio signals passing beyond the earth's atmosphere.

Another valuable application of lunar radar will be the provision of new meteorological and astronomical information. Cosmic dust in space can be detected and located. And not only may it be possible to construct topographical maps of distant planets with the aid of radar data, but scientists may be able to determine the composition and atmospheric characteristics of other celestial bodies by means of long-range radar.

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Pulse Modulation

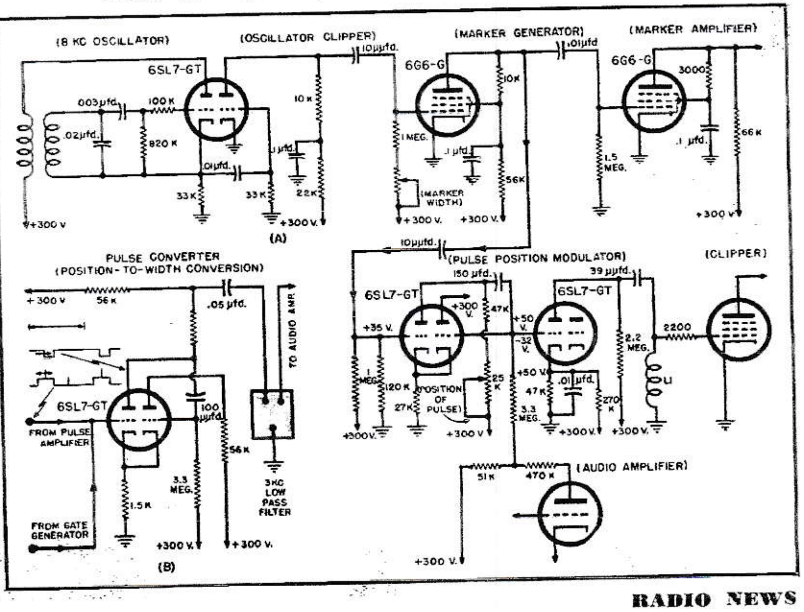
(*Continued from page* 44)

of marker pulses—makes use of two tubes, known as the "cyclodos" and the "cyclophone," developed specifically for this purpose. The essential features of these tubes are shown schematically in Fig. 10. Both tubes make use of an electron beam which, by means of an ordinary circular sweep circuit, is made to strike the aperture plate in a circular path. (For ordinary telephone communication, 8000 revolutions per second is a suitable frequency of rotation for the electron beam.) The aperture plate contains radial slits, so that during the time the beam is passing each slit the electrons go through and strike the collector segments, while at all other times they are intercepted by the aperture plate. Thus, once in each complete rotation of the electron beam a short pulse of current is passed to each collector segment. The tubes shown in the diagram, having aperture plates with four slits, would be suitable for a multiplex system having three channels, one slit serving for the marker pulse and the others for the three time-modulated signals.

In the modulating tube (the cyclodos) the slits are placed at an angle to the radius of the circular plate, as shown in Fig. 10A. It can be seen from the diagram that because the slits are tilted at an angle, the time when the beam crosses the open slit changes either forward or backward as the radius of rotation of the beam changes. Thus, audio-frequency amplitude variations may be converted into pulse-time variations by varying the instantaneous voltage on the deflecting plates and thereby changing the radius of rotation of the electron beam. The dotted circle in Fig. 10A represents the circular pattern obtained when all three channels are unmodulated. The solid path represents modulation in all three channels — instantaneous peak positive modulation in channels 1 and 3, negative modulation in channel 2. (The marker pulse, of course, is always unmodulated.)

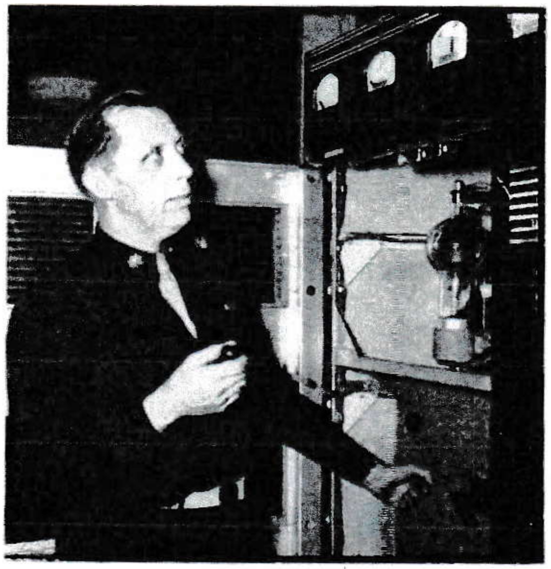
In the demodulator tube (the cyclophone) shown in Fig. 10B, the slits are placed along the radius of the circular aperture plate instead of being tilted. To convert the time-modulated pulses into amplitude variations, the electron

Fig. 8. (A) Schematic diagram of pulse-time transmitter modulating circuit. (B) Diagram of pulse-time receiver demodulating circuit.



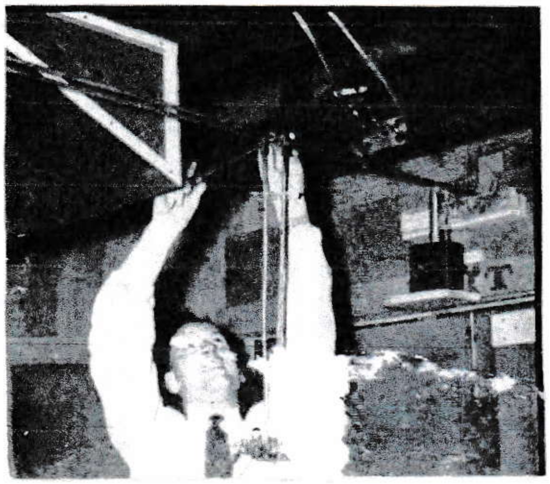
RADAR ECHOES

Dr. Harold D. Webb (right) adjusts the auxiliary tuning crystal in the lunar receiver while E. K. Stodola looks on. Behind Stodola is the nine-inch type-A indicator which records the echoes



Lt. Colonel John H. DeWitt, Jr., in charge of the project, at the power supply controls of the transmitter, a modified version of the SCR-271 early-warning radar used at Pearl Harbor. DeWitt is former chief engineer of WSM

The author, Jack Mofenson, adjusts the position of the waveform-monitoring stub. Over this transmission line traveled the 3-kw transmitted pulse and the millionth of a billionth of a watt echo



THE RECENT EXPERIMENTS performed by the Signal Corps Engineering Laboratories in receiving radar echoes from the moon have aroused much comment from engineers, astronomers and others engaged in technical pursuits. Although the scientific aspects of sending radio-frequency signals through the ionosphere are certainly of importance, the work done on the project is better classified as an engineering achievement. As yet, no long-term systematic observations have been made. This article is confined, therefore, to a discussion of the technical characteristics and general description of the equipment employed.

Briefly, the experiment consisted of transmitting quarter-second pulses of radio-frequency energy at 111.5 mc every four seconds in the direction of the moon, and detecting echo signals approximately 2.5 seconds after transmission. Display of the detected signals was audible as well as visible. Technically, the experiment utilized well-established radar techniques, but with radically different constants throughout the system. Considerations of pulse width, receiver bandwidth, transmitter power and the precise frequency of the returned signal due to Doppler effect, were such that careful attention had to be given to the design of the overall equipment.

After preliminary calculations were made concerning transmitter power, the reflectivity coefficient of the target, and receiver noise figure, it was apparent that receiving radar echoes from the moon was technically possible. Under the direction of Lt. Col. John H. DeWitt, a project called "project Diana" was set up in September 1945 to develop a radar system capable of transmitting r-f pulses to the moon, and detecting echoes more than 2 seconds later. Prior to entering the Signal Corps, Colonel DeWitt, who at that time was chief engineer of Radio Station WSM in Nashville, Tenn., designed and constructed transmitting and receiving equipment for the purpose of receiving echoes from the moon. This equipment employed substantially similar transmitter power and frequency to that used by the Signal Corps, but the attempt was a failure due to insufficient sensitivity in the receiver. Colonel DeWitt's appreciation of the problem and personal supervision were the driving forces that made the present experiment successful. Assisting Lt, Colonel DeWitt were: E. K. Stodola, Dr. Harold D. Webb, Herbert P. Kauffman and the writer, all of Evans Signal Laboratory. Credit is also due the members of the Antenna and Mechanical Design Group, Research Section, Theoretical Studies Group and others.

The practical implications of radar contact with the moon are numerous. During the war the Germans used the V2 Rocket which climbed some 70 miles above the earth, and the future holds the unhappy prospect of missiles going far higher than this. The matter of transmission of radio signals to great distances above the earth for detection and control of such weapons becomes a problem of military importance. Further, the use of a reflector far beyond the earth for radio waves makes possible direct measurement of the ability of radio waves to penetrate the ionosphere. A more complete investigation in this direction is indicated. The possibility of using the moon as the reflector for a part-time long-distance point-to-point

electronics
WAR REPORT

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FROM THE MOON

Detailed description of the techniques underlying the first recorded radio transmission through outer space. Calculations show that the maximum range of Signal Corps radar on lunar target exceeds one million miles

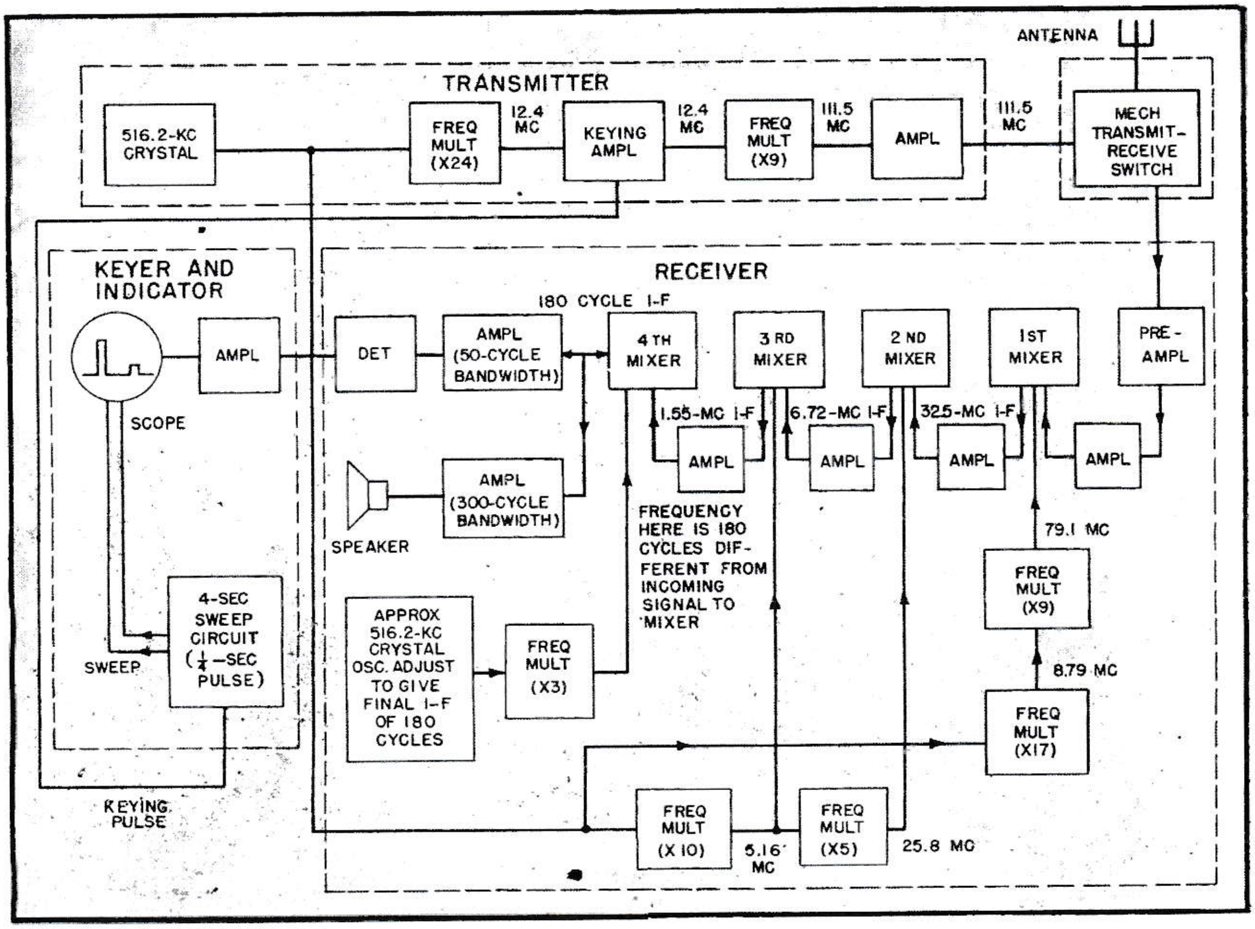


FIG. 1—Block diagram showing the essential elements of the system. Transmitter and receiver are controlled by the same crystal, permitting stable tuning of the narrow-band receiver relative to transmitter frequency

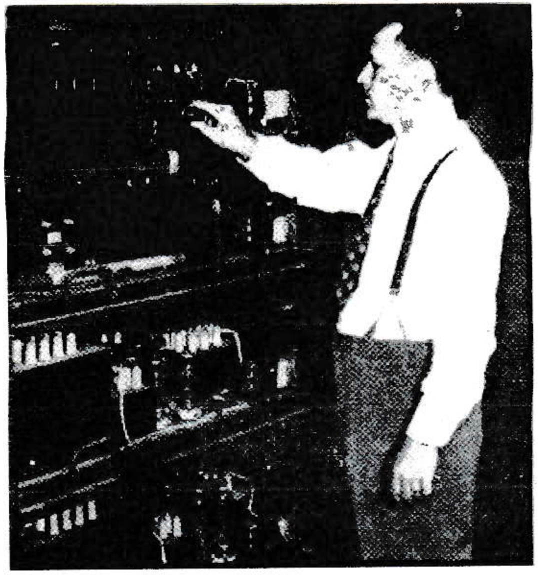
communication system is also being considered, as well as using the moon as a target to measure field-strength patterns.

Determination of Requirements

Several of the constants which determine the maximum distance at which a radar set can detect targets are peak transmitter power, radio-frequency of the transmitted signal, duration of the signal, receiver noise figure, and target echoing area. These constants, among others, are concisely summarized in what has been called the free-space radar equation.

$$r = \sqrt[4]{\frac{P_t A_o G_o \sigma}{P_r (4\pi)^2}} \qquad (1)$$

This equation has already been derived in ELECTRONICS[1]. In this equation, r is the radar range at which a signal may be detected, P_t is the transmitter power during the pulse,



Herbert Kaufman adjusts the bias on the high-level multiplying stages of the transmitter. Kaufman and the four others shown were the personnel of "project Diana"

G_t the transmitting antenna power gain, A_r the absorption area of the receiving antenna, σ the effective echoing area of the target, and P_r the power of a barely discernible signal, on the same basis as P_t. The power gain due to ground reflections (not considered in the free-space equation) at maximum effectiveness increases the range of the system by a factor of 2. This is equivalent to a power gain of 12 db.

In the case of a target as large as the moon (2160 miles diameter), calculations showed that in order to receive an echo from the whole hemisphere of the moon at once a pulse width greater than 0.02 seconds was required. This set a lower limit on the transmitter pulse width which corresponds to an optimum bandwidth of 50 cps for the receiver. These requirements eliminate, for the present, the use of the microwave frequencies, because of considerations of pulse length.

Propagation studies indicated that electromagnetic waves at a frequency of 110 mc were capable of penetrating the ionosphere, and because of availability of equipment, a radar set operating at 111.5 mc was chosen for the experiment. The peak power available in this transmitter was equivalent to 3000 watts for P_t using a 0.25-second pulse. The transmitter had the added advantage of being crystal controlled, deriving its final radio frequency after a series of frequency multiplications from a 516.2-kc crystal oscillator. The receiver associated with the transmitter was of the multi-mixer type (quadruple superheterodyne) capable of beating down radio-frequency signals to a final intermediate frequency of 180 cycles per second. Such an arrangement permitted use of an extremely narrow pass band, 57 cps, thus making the receiver highly selective and limiting the noise to a very low value. The extremely narrow-band receiver was an advantage, also, because it permitted tuning the receiver to the exact radio frequency of the returned echo. The importance of this can best be realized by considering the fact that due to the relative velocities of the earth and the moon, the returned signal may differ from the transmitted signal by as much as 300 cycles, due to the Doppler frequency shift. In using a highly selective receiver whose final mixer is tuned to receive the precalculated frequency of an echo return from the moon, the receiver rejects any signal returned at any other frequency.

To reduce the noise contribution of the receiver, a high-gain, low-noise-figure pre-amplifier was connected between the antenna and the receiver proper. The minimum perceptible received power was P_r readily calculated from the formula for noise figure.

$$\overline{NF} = \frac{E^2/4R}{KTB} \qquad (2)$$

In this formula $E^2/4R$ is the maximum available signal power at the receiver input terminals in watts, where E is the signal voltage at the antenna terminals, and R is the effective impedance in ohms. KTB is the maximum available noise power at the receiver input, where K is Boltzman's constant, 1.37×10^{-23} joules per degree Kelvin, T is the temperature in degrees Kelvin, chosen at 300 degrees, and B is the noise bandwidth of the receiver in cycles per second. For this receiver B is 57.. For a one-to-one ratio Eq. 3 gives signal-power to noise-power of

$$P_r = \frac{E^2}{4R} = \overline{NF}\,KTB \qquad (3)$$

1.48×10^{-18} watts, taking the effective noise figure of the receiver as 7 db.

The best antenna available at this frequency was a 32-dipole array utilized by the SCR-271 early-warning radar. Two of these arrays were secured side by side and mounted on a 100-foot tower. Calculations show that the array had a power gain of 152 times that of a single halfwave dipole antenna. Since the effective gain of a single dipole is 1.64 times that of an isotropic radiator, the value of G_t is given as 1.64×152 or 250.

The absorption area A_r of the re-

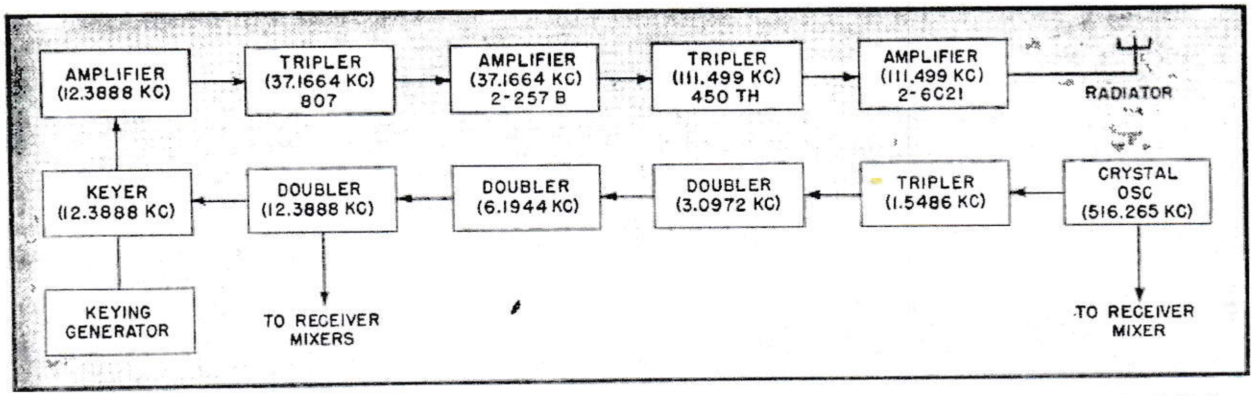


FIG. 2—Block diagram of the transmitter proper. This arrangement is a part of equipment designed for another purpose by E. H. Armstrong, adapted by the Signal Corps for the lunar studies

ceiving antenna is calculated from

$$A_e = \frac{G_o \lambda^2}{4\pi} \quad (4)$$

Substituting the value of G_o previously given, $A_e = 522.1 \times 10^{-7}$ square miles.

The remaining constant to be determined before solving Eq. 1 is σ the effective echoing area of the target. Calculations of the reflectivity coefficient made by Walter McAfee of the Theoretical Studies Group, assuming zero conductivity and a dielectric constant of six for the moon, resulted in the figure 0.1766. The effective echoing area is this figure multiplied by the projected area of the moon, $\pi d^2/4$ where d is the lunar diameter. This gave an effective echoing area of $0.1766\ (2160)^2\ (3.1416)/4$ or 647,000 square miles.

Substitution of these values in the free-space radar equation gave a maximum range of 573,500 miles and indicated that the effective range of the equipment chosen was more than twice that needed to receive echoes from the moon. By adding the power gain due to ground reflection, a further excess of power of 12 db or a range of 1,140,000 miles was indicated, which meant that according to calculations, the received signal should be about 20 db above thermal noise. This calculation of the signal strength of the returned echo checked closely with observations, and indicated that no appreciable attenuation occurs in free space.

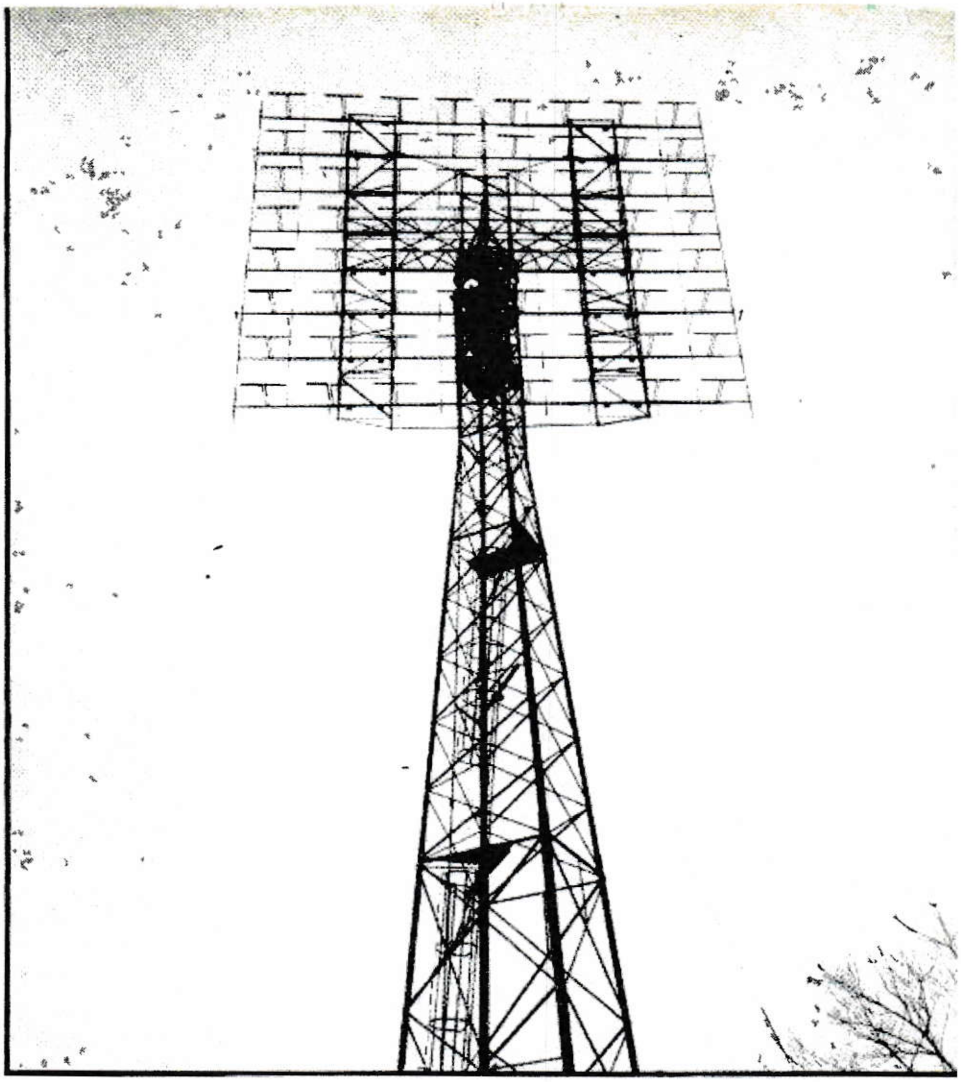


FIG. 3—The radiator consists of two standard SCR-271 "mattresses" mounted side by side, 64 dipoles in all. This 40-foot-square array is supported on a 100-foot tower, can look at the moon only at moonrise and moonset

Transmitter

Once the determination of constants was completed, the choice of available radar sets was made. Since no attempt was made to design major components specifically for this experiment, the selection of receiver and transmitter was made from equipment on hand. A crystal-controlled radar transmitter and receiver designed by Major E. H. Armstrong for another purpose were selected since they met the requirements of power and bandwidth. A block diagram of the complete transmitting, receiving and indicating system is shown in Fig. 1.

The transmitter is crystal controlled, deriving its final radio frequency of 111.5 mc after a series of frequency multiplications from a fundamental crystal oscillator frequency of 516.2 kc. Keying is accomplished by causing a low-level multiplier stage to conduct by driving its cathode negative for the duration of the transmitted pulse. In the initial setup, keying was performed mechanically by a relay, but this has since been replaced by an electronic keyer with the pulse width controllable between 0.02 to 0.2 seconds. A block diagram of the transmitter is shown in Fig. 2.

From the diagram it is apparent that the transmitter is of a conventional type. The output is fed over a 250-ohm open-wire transmission line to the antenna array. The antenna contains 64 dipoles horizontally polarized. The effective power gain of the array is 250, or 24 db.

The antenna, shown in Fig. 3, is mounted on a steel tower 100 feet high and is controllable in azimuth only. No provision has been made to incline the antenna in elevation. Because of this restriction, the times of observation using the present equipment were necessarily limited to moonrise and moonset. That this condition of observation is the worst possible (due to the long path through the atmosphere and the consequent possibility of trapped radiation) has been recognized. But it was impractical to procure an array of the equatorial type. Aside from propagation deficiencies, a far more serious limitation was the fact that observations were limited to two short periods daily.

The beam width of the array is approximately 15 deg at the half-power points, with the first three lobes spaced approximately 3 deg in elevation. Since the diameter of the moon subtends roughly one half degree of arc, most of the power transmitted does not illuminate the target, which constitutes a serious waste of power. The rate of rise of the moon along its ecliptic is 1 degree of arc every

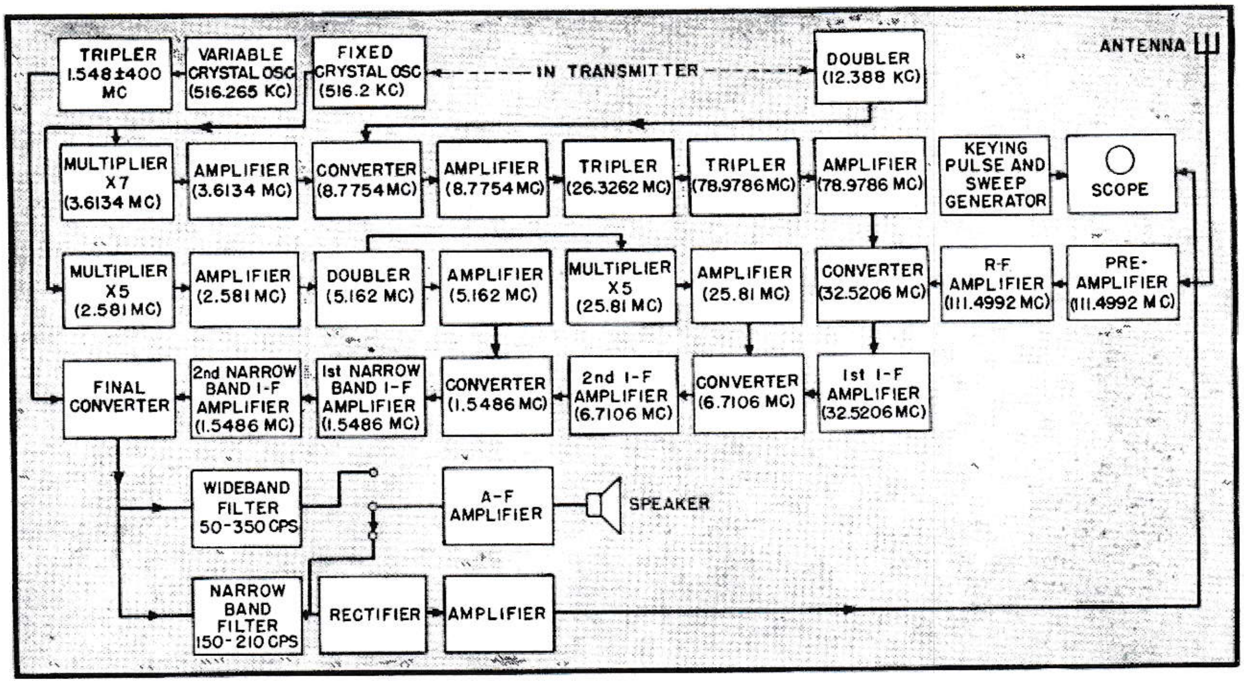


FIG. 4—Block diagram of receiver, a quadruple superheterodyne. Four mixers, controlled from transmitter crystal, keep receiver in tune, beat signal down to 180-cps i-f frequency. Visual as well as aural indications are provided

4 minutes, which allowed roughly 40 minutes of observation as the moon intercepted the first three lobes of the antenna. Bending effects due to long transmission path through the ionosphere undoubtedly exist, but no precise measurement of this effect has yet been made.

Receiving System

The receiving system is sufficiently different from conventional design to warrant a more complete description. A block diagram is shown in Fig. 4. The entire receiver is frequency controlled, and contains four mixer stages which heterodyne the radio-frequency signal to a final intermediate frequency of 180 cps. Since the first three injection frequency voltages as well as the final radio frequency are derived from multiples of a common crystal oscillator, a high degree of frequency stability is achieved in the system. This high degree of stability is essential to permit tuning the highly selective receiver to the frequency of the echo signal. This tuning is accomplished in the final heterodyne stage.

In tuning it is necessary to take account of the change in frequency of the returned signal which results from variations in the relative velocity of the moon with respect to the earth. The frequency of the returning echo may differ from the transmitted frequency by as much as 300 cycles per second, since the relative velocities of the earth and moon vary from about +900 mph at moonrise to −900 mph at moonset. At the frequency of the transmitter, a relative velocity of 3 miles per hour between antenna and target causes a shift of approximately 1 cycle per second in the received signal. This frequency shift, due to relative velocities of the transmitting antenna and target, is present in all radar echoes from moving targets, but is undetected in conventional receivers because the bandwidth of the normal receiver is many times greater than the frequency shift. In the Diana receiver, a bandwidth of 57 cps is achieved in the final i-f stages. It is therefore necessary to predetermine the Doppler frequency shift for the particular observation being made, and to select the proper crystal for the final heterodyne mixer. To achieve the high degree of accuracy required in the final mixer, provision is made to modify the frequency of the crystal-controlled oscillator by means of a screwdriver control which varies the air gap above the crystal. Final adjustment of the oscillator is made by beating the crystal oscillator output against a secondary frequency standard source, and observing the output on a monitoring oscilloscope.

The output of the final heterodyne mixer is fed into two channels, one audio, the other video. The audio channel is simply a power amplifier stage with the output connected to a loud speaker. The video output channel is fed into a second detector to recover the envelope of the 180 cps intermediate-frequency signal, and then is amplified by a high-gain video amplifier and connected directly to the vertical deflecting plates of a nine-inch cathode-ray tube. The horizontal deflection is a linear 4-second type-A sweep. The visible output is the characteristic low-frequency noise pattern representing a 57-cycle bandwidth centered at 180 cycles. A sudden upward departure from the base line occurs when an echo signal is received from the moon. This is shown clearly in Fig. 5. The audible signal is random noise of 57-cycle bandwidth, superimposed on a fixed-frequency note, at the intermediate frequency of 180 cycles, when the echo is received.

As stated previously, tuning of the receiver is accomplished in the final mixer. The injection signal frequency must be calculated for each observation to take into account the

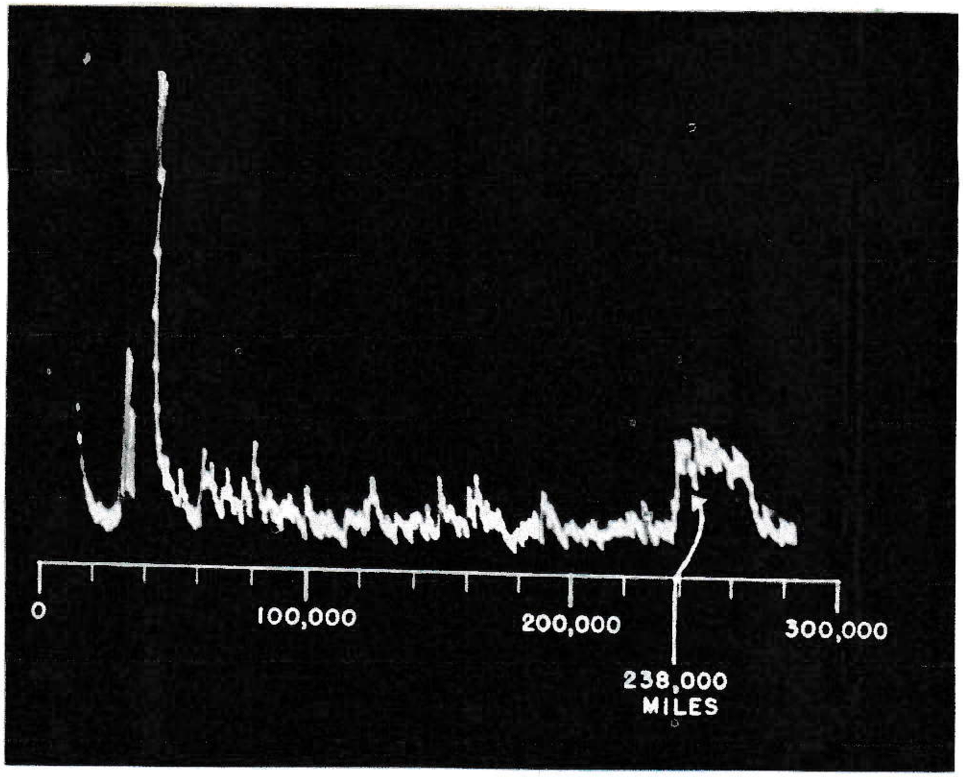


FIG. 5—Most widely published cathode-ray trace in history, this type-A presentation shows amplitude of moon echo about three times peak noise. Taken at moonrise, January 22, 1946. The relative velocity of moon and earth was 682 miles per hour, requiring a 227-cps shift in tuning to allow for Doppler effect. Signal-to-noise ratios as high as 20 db have been recorded

relative velocity of target and antenna due to both the rotational velocity of the earth and the orbital velocity of the moon. These data, together with azimuth angle and time, are calculated daily from information given by the Nautical Almanac and Ephemeris. The detection of the frequency due to Doppler shift is made with a high degree of accuracy by the selective receiver. This in itself is corroboration that the echo signal is from the moon. Also, the echo interval of 2.4 seconds admits of no other explanation.

The pre-amplifier of the receiver consists of a three-stage tuned r-f amplifier employing two grounded-grid stages (6J4) followed by a 6SH7 tuned amplifier at the transmitter frequency. The overall gain of the pre-amplifier alone is 30 db with an overall noise figure of 3.5 db and a bandwidth of 1 mc. The electrical design of the first two stages was suggested by a development of Dr. F. B. Llewellyn. A simplified schematic of the first two stages is shown in Fig. 6. The use of concentric tubing inductances for the tuned circuits provides automatic r-f filtering on the direct-current and filament leads. The pre-amplifier was designed originally as an improvement kit for the SCR-271 radar, and like the transmitter and receiver, was chosen for the Diana experiment because it satisfied one of the requirements, that of a very low noise figure receiver. A tuned impedance-matching transformer is used between the receiver and transmission line to convert the 250-ohm balanced input to the 50-ohm unbalanced input of the pre-amplifier.

The transmit-receive switching system (t/r box) employed in the original experiment was a set of two

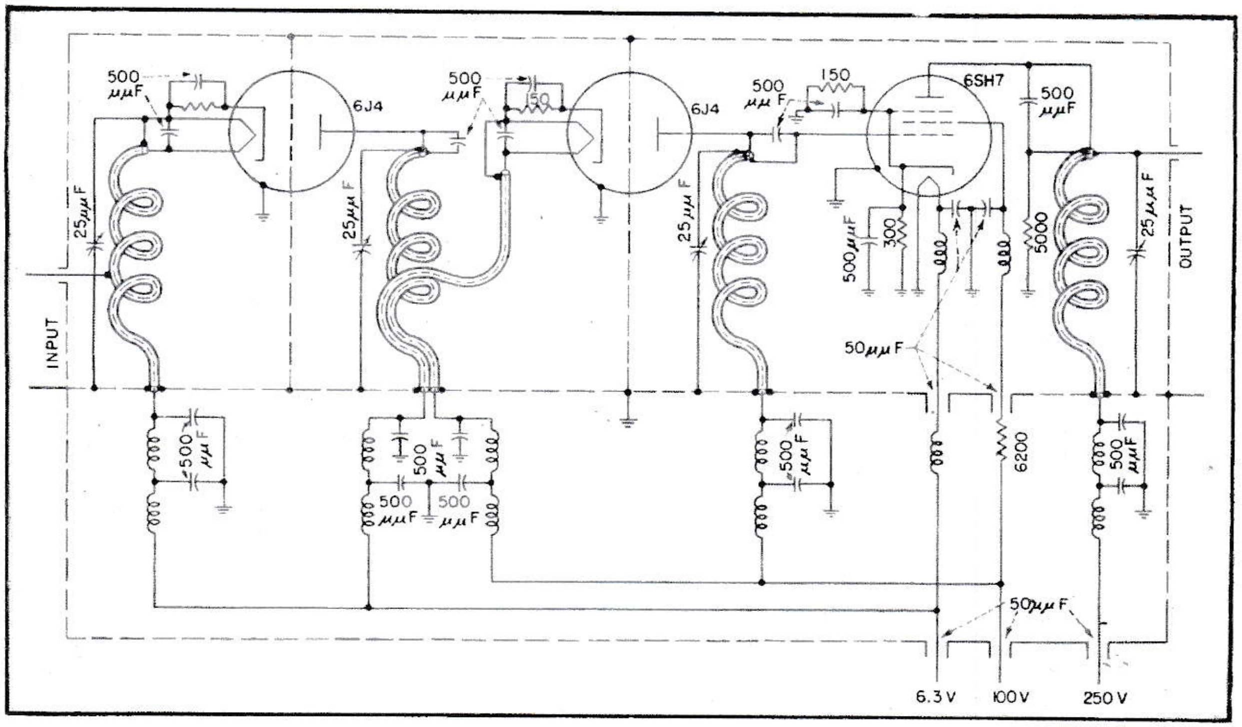


FIG. 6—Secret of success was low-noise pre-amplifier, a grounded-grid circuit based on a design by F. B. Llewellyn. Coaxial leads inside coils exclude r-f from d-c circuits

mechanically-operated shorting bars on the transmission line, operating from a multivibrator-controlled relay during the transmitted pulse interval of 0.25 sec. One of the shorting bars serves to short out the receiver input during transmission, and the other shorts out the transmitter during reception.

Keyer and Indicator

The visual indicator used is a nine-inch electrostatic cathode-ray tube, 9EP7, with a long-persistence screen. The electron beam is caused to scan the width of the tube, synchronously with the transmitted pulse, in 4 seconds, forming a linear time base. The persistence of the tube is long enough to retain the pattern for at least two sweeps. The circuit employed to generate this sweep is a direct-coupled transitron sawtooth oscillator, described below. A pulse equivalent in time to the keying pulse is also generated by this circuit and is applied to the cathode of a low-level multiplier stage of the transmitter, causing it to conduct for the pulse duration and to drive the subsequent multipliers.

The time-base generator consists essentially of a high-gain pentode amplifier with capacitance coupling between plate and grid. The schematic is shown in Fig. 7. The capacitance coupled path includes a cathode follower stage, the left hand section of V_2. For the duration of the conduction cycle, the anode voltage of the pentode V_1 drops and capacitor C_1 begins to discharge through the tube. As the voltage on the plate drops the current flow in C_1 drives the grid negative, tending to cut off the plate current. A condition of dynamic equilibrium then exists with the plate voltage dropping at a linear rate determined by R_1 and C_1 and the grid being maintained at a constant voltage, since each decrement in plate voltage causes a corresponding drop on the grid which keeps the grid signal and hence the output of the tube substantially constant. The time constant of R_1 C_1 is chosen to cause C_1 to become fully discharged during the cycle.

When the plate voltage drops to the point where electrons from the cathode can no longer flow to it, an increase in screen current occurs which rapidly decreases the screen voltage and correspondingly decreases the suppressor voltage. This action, which is cumulative, has the effect of suddenly cutting off the anode current. This causes the cathode current to be retarded by the suppressor grid and made to flow to the screen. A negative pulse appears at the screen, and C_1 begins to charge through the cathode follower until a point is reached where the plate begins to draw current and the oscillator is recycled. The screen returns to its original voltage, and the plate voltage begins to fall. By suitable choice of R_1 and C_1 a range of from about 0.1 to 3 cps is obtained.

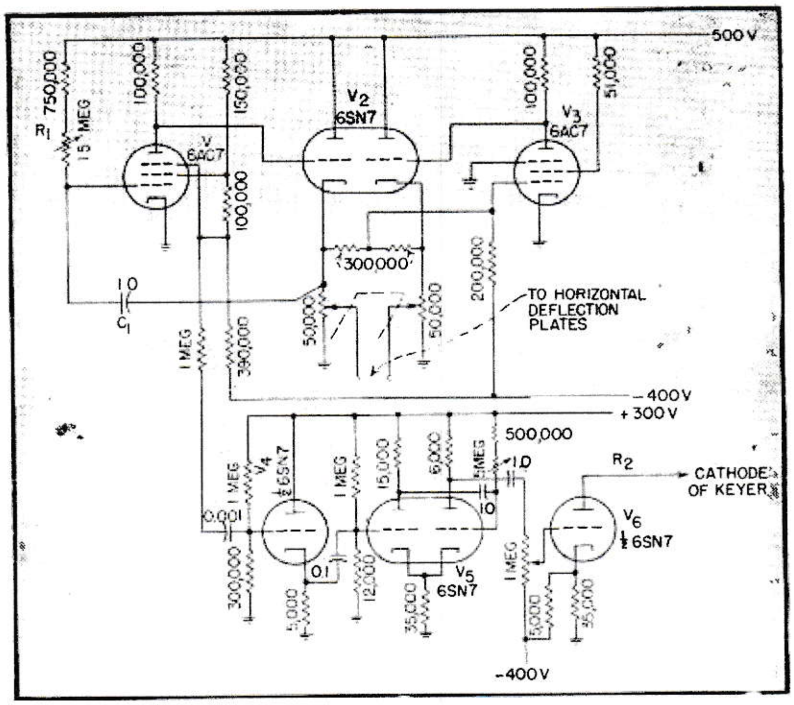


FIG. 7—Linear deflection circuit of type-A indicator, which sweeps spot across screen in up to ten seconds. Basic circuit is transitron oscillator. Sweep and keyer are controlled by the cathode-coupled flip-flop circuit at bottom of diagram

Keying-voltage signals are derived from the differentiated output of the negative pulse appearing on the screen of the oscillator. This is used to trigger a multivibrator whose time constant is controllable by a variable 5 meg resistor, varying the output pulse width from 0.02 to 0.25 seconds.

The addition of the cathode follower stage V_2 was made to shorten the charge time of C_1 by causing it to charge through the grid cathode space of the cathode follower. This reduces the return trace time. Tube V_3 serves as a degenerative phase-inverting amplifier to secure push-pull sweep voltage.

The keyer multivibrator is a conventional cathode-coupled flip-flop circuit with the initiating trigger applied as a positive pulse on the grid of the normally non-conducting section. A positive pulse varying in width from 0.02 to 0.25 seconds is obtained at the plate of the other section. This signal is applied to a normally cut off pentode whose load impedance is the cathode of the 12.388 mc amplifier stage in the transmitter. For the duration of this applied signal, the plate of the amplifier is driven negative, taking the cathode of the keying tube down with it, thus causing it to conduct.

The first echoes from the moon were received at moonrise on January 10, 1946. The indication was of the audible type in the form of a 180-cycle beat note occurring 2.5 seconds after transmission.

Although numerous observations have been made, both at moonrise and moonset, echo returns do not occur after every transmission. Further measurements are needed before precise scientific conclusions can be drawn.

REFERENCE

(1) The Radar Equation, ELECTRONICS, p. 92, April 1945.