- Chapter One -

A Meteoric Start

[1] During the 1940s, investigators in the United States and Hungary bounced radar waves off the Moon for the first time, while others made the first systematic radar studies of meteors. These experiments constituted the initial exploration of the solar system with radar. In order to understand the beginnings of radar astronomy, we first must examine the origins of radar in radio, the decisive role of ionospheric research, and the rapid development of radar technology triggered by World War II.

As early as 20 June 1922, in an address to a joint meeting of the Institute of Electrical Engineers and the Institute of Radio Engineers in New York, the radio pioneer Guglielmo Marconi suggested using radio waves to detect ships:[1]

As was first shown by Hertz, electric waves can be completely reflected by conducting bodies. In some of my tests I have noticed the effects of reflection and deflection of these waves by metallic objects miles away.

It seems to me that it should be possible to design apparatus by means of which a ship could radiate or project a divergent beam of these rays in any desired direction, which rays, if coming across a metallic object, such as another steamer or ship, would be reflected back to a receiver screened from the local transmitter on the sending ship, and thereby immediately reveal the presence and bearing of the other ship in fog or thick weather.

One further advantage of such an arrangement would be that it would be able to give warning of the presence and bearing of ships, even should these ships be unprovided with any kind of radio.

By the time Germany invaded Poland in September 1939 and World War II was underway, radio detection, location, and ranging technologies and techniques were available in Japan, France, Italy, Germany, England, Hungary, Russia, Holland, Canada, and the United States. Radar was not so much an invention, springing from the laboratory bench to the factory floor, but an ongoing adaptation and refinement of radio technology. The apparent emergence of radar in Japan, Europe, and North America more or less at the same time was less a case of simultaneous invention than a consequence of the global nature of radio research.[2]

Although radar is identified overwhelmingly with World War II, historian Sean S. Swords has argued that the rise of high-performance and long-range aircraft in the late 1930s would have promoted the design of advanced radio navigational aids, including radar, even without a war.[3] More decisively, however, ionospheric research propelled radar development in the 1920s and 1930s. As historian Henry Guerlac has pointed out, "Radar was developed by men who were familiar with the ionospheric work. It was a relatively straightforward adaptation for military purposes of a widely-known scientific technique, [2] which explains why this adaptation--the development of radar--took place simultaneously in several different countries."[4]

The prominence of ionospheric research in the history of radar and later of radar astronomy cannot be ignored. Out of ionospheric research came the essential technology for the beginnings of military radar in Britain, as well as its first radar researchers and research institutions. After the war, as we shall see, ionospheric research also drove the emergence of radar astronomy.

Chain Home

Despite its scientific origins, radar made its mark and was baptized during World War II as an integral and necessary instrument of offensive and defensive warfare. Located on land, at sea, and in the air, radars detected enemy targets and determined their position and range for artillery and aircraft in direct enemy encounters on the battlefield. Other radars identified aircraft to ground bases as friend or foe, while others provided navigational assistance and coastal defense. World War II was the first electronic war, and radar was its prime agent.[5]

In 1940, nowhere did radar research achieve the same advanced state as in Britain. The British lead initially resulted from a decision to design and build a radar system for coastal defense, while subsequent research led to the invention of the cavity magnetron, which placed Britain in the forefront of microwave radar. The impetus to achieve that lead in radar came from a realization that the island nation was no longer safe from enemy invasion.

For centuries, Britain's insularity and navy protected it from invasion. The advent of long-range airplanes that routinely outperformed their wooden predecessors spelled the end of that protection. Existing aircraft warning methods were ineffectual. That Britain was virtually defenseless against an air assault became clear during the summer air exercises of 1934. In simulated night attacks on London and Coventry, both the Air Ministry and the Houses of Parliament were successfully "destroyed," while few "enemy" bombers were intercepted.[6]

International politics also had reached a critical point. The Geneva Disarmament Conference had collapsed, and Germany was rearming in defiance of the Treaty of Versailles. Under attack from Winston Churchill and the Tory opposition, the British government abandoned its disarmament policy and initiated a five-year expansion of the Royal Air Force. Simultaneously, the Air Ministry Director of Scientific Research, Henry Egerton Wimperis, created a committee to study air defense methods. Just before the Committee for the Scientific Survey of Air Defence first met on 28 January 1935, Wimperis contacted fellow Radio Research Board member Robert (later Sir) Watson-Watt. Watson-Watt, who oversaw the Radio Research Station at Slough, was a scientist with twenty years of experience as a government researcher. Ionospheric research had been a principal component of Radio Research Station studies, and Watson-Watt fostered the development there of a pulse-height technique.[7]

[3] The pulse-height technique was to send short pulses of radio energy toward the ionosphere and to measure the time taken for them to return to Earth. The elapsed travel time of the radio waves gave the apparent height of the ionosphere. Merle A. Tuve, then of Johns Hopkins University, and Gregory Breit of the Carnegie Institution's Department of Terrestrial Magnetism in Washington, first developed the technique in the 1920s and undertook ionospheric research in collaboration with the Naval Research Laboratory and the Radio Corporation of America.[8]

In response to the wartime situation, Wimperis asked Watson-Watt to determine the practicality of using radio waves as a "death ray." Rather than address the proposed "death ray," Watson-Watt's memorandum reply drew upon his experience in ionospheric research. Years later, Watson-Watt contended, "I regard this Memorandum on the 'Detection and Location of Aircraft by Radio Methods' as marking the birth of radar and as being in fact the invention of radar." Biographer Ronald William Clark has termed the memorandum "the political birth of radar."[9] Nonetheless, Watson-Watt's memorandum was really less an invention than a proposal for a new radar application.

The memorandum outlined how a radar system could be put together and made to detect and locate enemy aircraft. The model for that radar system was the same pulse-height technique Watson-Watt had used at Slough. Prior to the memorandum in its final form going before the Committee, Wimperis had arranged for a test of Watson-Watt's idea that airplanes could reflect significant amounts of radio energy, using a BBC transmitter at Daventry. "Thus was the constricting 'red tape' of official niceties slashed by Harry Wimperis, before the Committee for the Scientific Survey of Air Defence had so much as met," Watson-Watt later recounted. The success of the Daventry test shortly led to the authorization of funding (£12,300 for the first year) and the creation of a small research and development project at Orford Ness and Bawdsey

Manor that drew upon the expertise of the Slough Radio Research Station.

From then onwards, guided largely by Robert Watson-Watt, the foundation of the British radar effort, the early warning Chain Home, materialized. The Chain Home began in December 1935, with Treasury approval for a set of five stations to patrol the air approaches to the Thames estuary. Before the end of 1936, and long before the first test of the Thames stations in the autumn of 1937, plans were made to expand it into a network of nineteen stations along the entire east coast; later, an additional six stations were built to cover the south coast.

[4] The Chain Home played a crucial role in the Battle of Britain, which began in July 1940. The final turning point was on 15 September, when the Luftwaffe suffered a record number of planes lost in a single day. Never again did Germany attempt a massive daylight raid over Britain. However, if radar won the day, it lost the night. Nighttime air raids showed a desperate need for radar improvements.

The Magnetron

In order to wage combat at night, fighters needed the

equivalent of night vision--their own on-board radar, but the prevailing technology was inadequate. Radars operating at low wavelengths, around 1.5 meters (200 MHz), cast a beam that radiated both straight ahead and downwards. The radio energy reflected from the Earth was so much greater than that of the enemy aircraft echoes that the echoes were lost at distances greater than the altitude of the aircraft. At low altitudes, such as those used in bombing raids or in air-to-air combat, the lack of radar vision was grave. Microwave radars, operating at wavelengths of a few centimeters, could cast a narrower beam and provide enough resolution to locate enemy aircraft.[10]
Although several countries had been ahead of Britain in microwave radar technology before the war began, Britain leaped ahead in February 1940, with the invention of the cavity magnetron by Henry A. H. Boot and John T. Randall at the University of Birmingham.[11] Klystrons were large vacuum tubes used to generate microwave power, but they did not operate adequately at microwave frequencies. The time required for electrons to flow through a klystron was too long to keep up with the frequency of the external oscillating circuit. The cavity magnetron resolved that problem and made possible the microwave radars of World War II. As Sean Swords asserted, "The emergence of the resonant-cavity magnetron was a turning point in radar history." [12] The cavity magnetron launched a line of microwave research and development that has persisted to this day.

The cavity magnetron had no technological equivalent in the United States, when the Tizard Mission arrived in late 1940 with one of the first ten magnetrons constructed. The Tizard Mission, known formally as the British Technical and Scientific Mission, had been arranged at the highest levels of government to exchange technical information between Britain and the United States. Its head and organizer, Henry Tizard, was a prominent physics professor and a former member of the committee that had approved Watson-Watt's radar project. As James P. Baxter wrote just after the war's end with a heavy handful of hyperbole, though not without some truth: "When the members of the Tizard Mission brought one [magnetron] to America in 1940, they carried the most valuable cargo ever brought to our shores. It sparked the whole development of microwave radar and constituted the most important item in reverse Lease-Lend." [13]

[5] In late September 1940, Dr. Edward G. Bowen, the radar scientist on the Tizard Mission, showed a magnetron to members of the National Defense Research Committee (NDRC), which President Roosevelt had just created on 27 June 1940. One of the first acts of the NDRC, which later became the Office of Scientific Research and Development, was to establish a Microwave Committee, whose stated purpose was "to organize and consolidate research, invention, and development as to obtain the most effective military application of microwaves in the minimum time." [14]

A few weeks after the magnetron demonstration, the NDRC decided to create the Radiation Laboratory at MIT. While the MIT Radiation Laboratory accounted for nearly 80 percent of the NDRC Microwave Division's contracts, an additional 136 contracts for radar research, development, and prototype work were let out to 16 colleges and universities, two private research institutions, and the major radio industrial concerns, with Western Electric taking the largest share. The MIT Radiation Laboratory personnel skyrocketed from thirty physicists, three guards, two stock clerks, and a secretary for the first year to a peak employment level of 3,897 (1,189 of whom were staff) on 1 August 1945. The most far-reaching early achievement, accomplished in the spring of 1941, was the creation of a new generation of radar equipment based on a magnetron operating at 3 cm. Experimental work in the one cm range led to numerous improvements in radars at 10 and 3 cm.[15]
Meanwhile, research and development of radars of longer wavelengths were carried out by the Navy and the Army Signal Corps, both of which had had active ongoing radar programs since the 1930s. The Navy started its research program at the Naval Research Laboratory (NRL) before that of the Signal Corps, but radar experimenters after the war used Signal Corps equipment, especially the SCR-270, mainly because of its wide availability. A mobile SCR-270, placed on Oahu as part of the Army's Aircraft Warning System, spotted incoming Japanese airplanes nearly 50 minutes before

they bombed United States installations at Pearl Harbor on 7 December 1941. The warning was ignored, because an officer mistook the radar echoes for an expected flight of B-17s.[16]

Historians view the large-scale collection of technical and financial resources and manpower at the MIT Radiation Laboratory engaged in a concerted effort to research and develop new radar components and systems, along with the Manhattan Project, as [6] 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 that 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 1926 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. After building Nashville's first broadcasting station, in 1929 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 [7] 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.

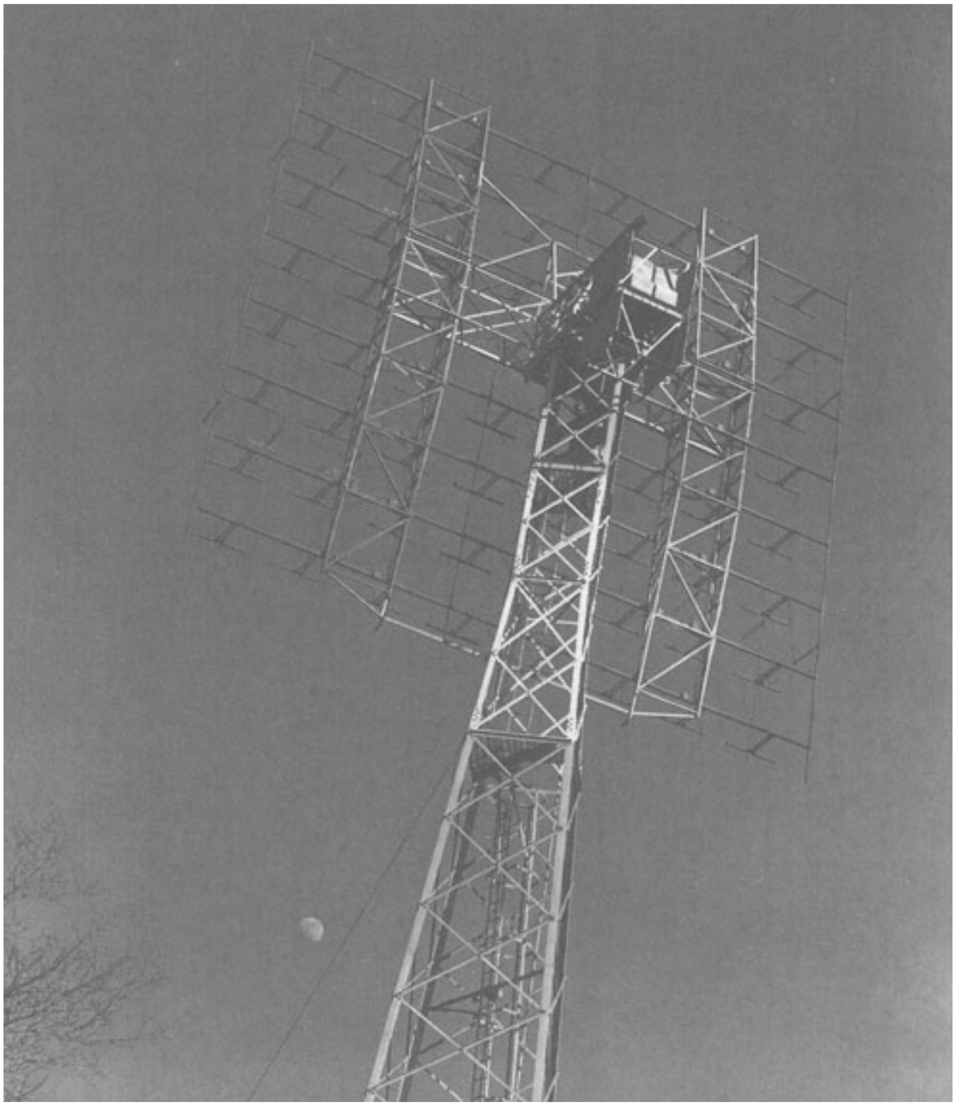

Figure 1. The "bedspring" mast antenna, U.S. Army Signal Corps, Ft. Monmouth, New Jersey, used by Lt. Col. John H. DeWitt, Jr., to bounce radar echoes off the Moon on 10 January 1946. Two antennas from SCR-271 stationary radars were positioned side by side to form a 32-dipole array aerial and were mounted on a 100-ft (30-meter) tower. (Courtesy of the U.S. Army Communications-Electronics Museum, Ft. Monmouth, New Jersey.)

[9] 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 meters) 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 [10] 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 [11] to return from the Moon in less than three seconds, so the rotating switch made a sweep of the ten coulometers every three seconds. The release of hydrogen gas left a record of both the echo signal and the receiver noise. As the number of signal echoes and sweeps of the coulometers added up, the signal-to-noise ratio improved. By increasing the total number of signal echoes, Bay believed that any signal could be raised above noise level and made observable, regardless of its amplitude and the value of the signal-to-noise ratio.[26] Because the signal echoes have a more-or-less fixed structure, and the noise varies from pulse to pulse, echoes add up faster than noise.

Despite the conceptual breakthrough of the coulometer integrator, the construction and testing of the apparatus remained to be carried out. The menace of air raids drove the Tungsram research laboratory into the countryside in the fall of 1944. The subsequent siege of Budapest twice interrupted the work of Bay and his team until March 1945. The Ministry of Defense furnished Bay with war surplus parts for a 2.5-meter (120-MHz) radar manufactured by the Standard Electrical Co., a Hungarian subsidiary of IT&T. Work was again interrupted when the laboratory was dismantled and all equipment, including that for the lunar radar experiment, was carried off to the Soviet Union. For a third time, construction of entirely new equipment started in the workshops of the Tungsram Research Laboratory, beginning August 1945 and ending January 1946.

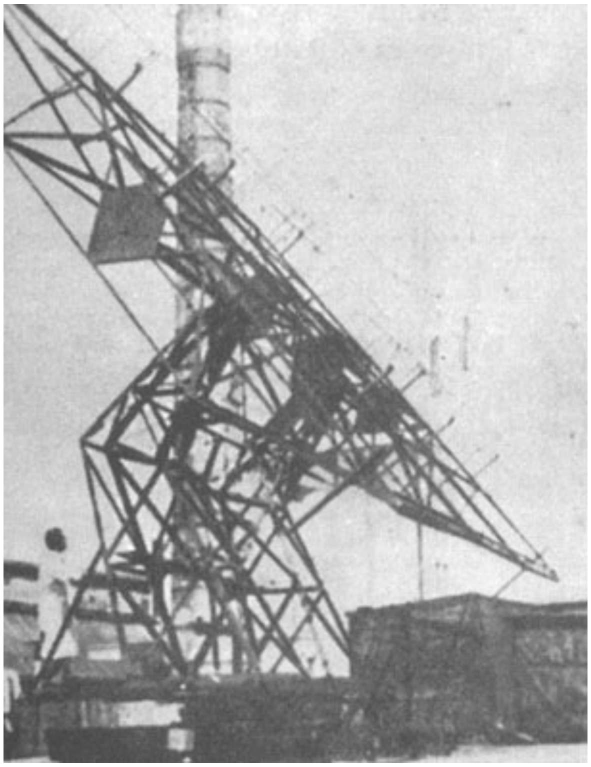

Figure 2. Antenna built and used by Zoltán Bay to bounce radar echoes off the Moon in February and May 1946. (Courtesy of Mrs. Julia Bay.)

Electrical disturbances in the Tungsram plant were so great that measurements and tuning had to be done in the late afternoon or at night. The experiments were carried out on 6 February and 8 May 1946 at night by a pair of researchers. Without the handicap of operating in a war zone, Bay probably would have beaten the Signal Corps to the Moon, although he could not have been aware of DeWitt's experiment. More importantly, though, he invented the technique of [12] long-time integration generally used in radar astronomy. As the American radio astronomers Alex G. Smith and Thomas D. Carr wrote some years later: "The additional tremendous increase in sensitivity necessary to obtain radar echoes from Venus has been attained largely through the use of long-time integration techniques for detecting periodic signals that are far below the background noise level. The unique method devised by Bay in his pioneer lunar radar investigations is an example of such a technique."[27]

Both Zoltán Bay and John DeWitt had fired shots heard round the world, but there was no revolution, although others either proposed or attempted lunar radar experiments in the years immediately following World War II. Each man engaged in other projects shortly after completing his experiment. Bay left Hungary for the United States, where he taught at George Washington University and worked for the National Bureau of Standards, while DeWitt re-entered radio broadcasting and pursued his interest in astronomy.[28]

As an ongoing scientific activity, radar astronomy did not begin with the spectacular and singular experiments of DeWitt and Bay, but with an interest in meteors shared by researchers in Britain, Canada, and the United States. Big Science, that is, ionospheric physics and secure military communications, largely motivated that research. Moreover, just as the availability of captured V-2 parts made possible rocket-based ionospheric research after the war,[29] so war-surplus radars facilitated the emergence of radar astronomy. Like the exploration of the ionosphere with rockets, radar astronomy was driven by the availability of technology.

Meteors and Auroras

Radar meteor studies, like much of radar history, grew out of ionospheric research. In the 1930s, ionospheric researchers became interested in meteors when it was hypothesized that the trail of electrons and ions left behind by falling meteors caused fluctuations in the density of the ionosphere.[30] Edward Appleton and others with the Radio Research Board of the British Department of Scientific and Industrial Research, the same organization with which Watson-Watt had been associated, used war-surplus radar furnished by [13] the Air Ministry to study meteors immediately after World War II. They concluded that meteors caused abnormal bursts of ionization as they passed through the ionosphere.[31]

During the war, the military had investigated meteor trails with radar. When the Germans started bombarding London with V2 rockets, the Army's gun-laying radars were hastily pressed into service to detect the radar reflections from the rockets during their flight in order to give some warning of their arrival. In many cases alarms were sounded, but no rockets were aloft. James S. Hey, a physicist with the Operational Research Group, was charged with investigating these mistaken sightings. He believed that the false echoes probably originated in the ionosphere and might be associated with meteors.

Hey began studying the impact of meteors on the ionosphere in October 1944, using Army radar equipment at several locations until the end of the war. The Operational Research Group, Hey, G. S. Stewart (electrical engineer), S. J. Parsons (electrical and mechanical engineer), and J. W. Phillips (mathematician), found a correlation between visual sightings and radar echoes during the Giacobinid meteor shower of October 1946. Moreover, by using an improved photographic technique that better captured the echoes on the radar screen, they were able to determine the velocity of the meteors.

Neither Hey nor Appleton pursued their radar investigations of meteors. During the war, Hey had detected radio emissions from the Sun and the first discrete source of radio emission outside the solar system in the direction of Cygnus. He left the Operational Research Group for the Royal Radar Establishment at Malvern, where he and his colleagues carried on research in radio astronomy. Appleton, by 1946 a Nobel Laureate and Secretary of the Department of Scientific and Industrial Research, also became thoroughly involved in the development of radio astronomy and became a member of the Radio Astronomy Committee of the Royal Astronomical

Society in 1949.[32]

Instead, radar astronomy gained a foothold in Britain at the University of Manchester under A. C. (later Sir) Bernard Lovell, director of the University's Jodrell Bank Experimental Station. During the war, Lovell had been one of many scientists working on microwave radar.[33] His superior, the head of the Physics Department, was Patrick M. S. Blackett, a member of the Committee for the Scientific Survey of Air Defence that approved Watson-Watt's radar memorandum. With the help of Hey and Parsons, Lovell borrowed some Army radar equipment. Finding too much interference in Manchester, he moved to the University's botanical research gardens, which became the Jodrell Bank Experimental Station. Lovell equipped the station with complete war-surplus radar systems, such as a 4.2-meter gun-laying radar and a mobile Park Royal radar. He purchased at rock-bottom prices or borrowed the radars from the Air Ministry, Army, and Navy, which were discarding the equipment down mine shafts.

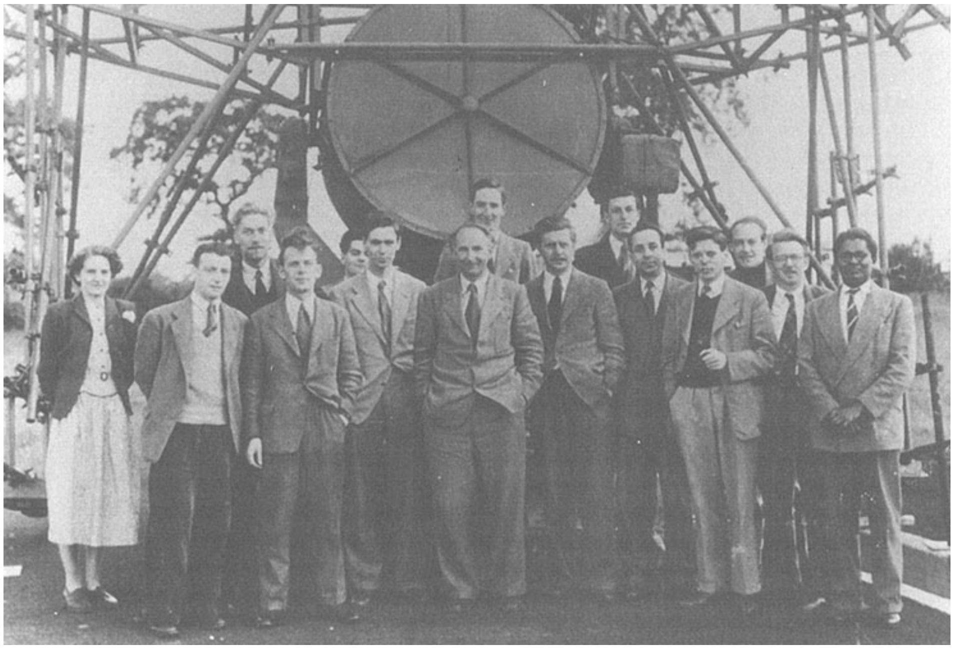

Figure 3. The Jodrell Bank staff 1951 in front of the 4.2-meter searchlight aerial used in some meteor radar experiments. Sir Bernard Lovell is in the center front. (Courtesy of the Director of the Nuffield Radio Astronomy Laboratories, Jodrell Bank.)

Originally, Lovell wanted to undertake research on cosmic rays, which had been Blackett's interest, too. One of the primary research objectives of the Jodrell Bank facility, as well as one of the fundamental reasons for its founding, was cosmic ray research. Indeed, the interest in cosmic ray research also lay behind the design and construction of the 76-meter (250-ft) Jodrell Bank telescope. The search for cosmic rays never succeeded, however; Blackett and Lovell had introduced a significant error into their initial calculations.

Fortuitously, though, in the course of looking for cosmic rays, Lovell came to realize that they were receiving echoes from meteor ionization trails, and his small group of Jodrell Bank investigators began to concentrate on this more fertile line of research. Nicolai Herlofson, a Norwegian meteorologist who had recently joined the Department of Physics, put Lovell in contact with the director of the Meteor Section of the British Astronomical Association, J. P. Manning Prentice, a lawyer and amateur astronomer with a passion for meteors. Also joining the Jodrell Bank team was John A. Clegg, a physics teacher whom Lovell had known during the war. Clegg was a doctoral candidate at the University of Manchester and an expert in antenna design. He remained at Jodrell Bank until 1951 and eventually landed a position teaching physics in Nigeria. Clegg converted an Army searchlight into a radar antenna for studying meteors.[34]

[15] The small group of professional and amateur scientists began radar observations of the Perseid meteor showers in late July and August 1946. When Prentice spotted a meteor, he shouted. His sightings usually, though not always, correlated with an echo on the radar screen. Lovell thought that the radar echoes that did not correlate with Prentice's sightings might

have been ionization trails created by cosmic ray showers. He did not believe, initially, that the radar might be detecting meteors too small to be seen by the human eye.

The next opportunity for a radar study of meteors came on the night of 9 October 1946, when the Earth crossed the orbit of the Giacobini-Zinner comet. Astronomers anticipated a spectacular meteor shower. A motion picture camera captured the radar echoes on film. The shower peaked around 3 A.M.; a radar echo rate of nearly a thousand meteors per hour was recorded. Lovell recalled that "the spectacle was memorable. It was like a great array of rockets coming towards one."[35]

The dramatic correlation of the echo rate with the meteors visible in the sky finally convinced Lovell and everyone else that the radar echoes came from meteor ionization trails, although it was equally obvious that many peculiarities needed to be investigated. The Jodrell Bank researchers learned that the best results were obtained when the aerial was positioned at a right angle to the radiant, the point in the sky from which meteor showers appear to emanate. When the aerial was pointed at the radiant, the echoes on the cathode-ray tube disappeared almost completely.[36]

Next joining the Jodrell Bank meteor group, in December 1946, was a doctoral student from New Zealand, Clifton D. Ellyett, followed in January 1947 by a Cambridge graduate, John G. Davies. Nicolai Herlofson developed a model of meteor trail ionization that

Davies and Ellyett used to calculate meteor velocities based on the diffraction pattern produced during the formation of meteor trails. Clegg devised a radar technique for determining their radiant.[37]

At this point, the Jodrell Bank investigators had powerful radar techniques for studying meteors that were unavailable elsewhere, particularly the ability to detect and study previously unknown and unobservable daytime meteor showers. Lovell and his colleagues now became aware of the dispute over the nature of meteors and decided to attempt its resolution with these techniques.[38]

Astronomers specializing in meteors were concerned with the nature of sporadic meteors. One type of meteor enters the atmosphere from what appears to be a single point, the radiant. Most meteors, however, are not part of a shower, but appear to arrive irregularly from all directions and are called sporadic meteors. Most astronomers believed that sporadic meteors came from interstellar space; others argued that they were part of the solar system.

The debate could be resolved by determining the paths of sporadic meteors. If they followed parabolic or elliptical paths, they orbited the Sun; if their orbit were hyperbolic, they had an interstellar origin. The paths of sporadic meteors could be determined by an accurate measurement of both their velocities and radiants, but optical means were insufficiently precise to give unambiguous results. Fred L. Whipple, future director of the [16] Harvard College Observatory, a leading center of United States meteor research, attempted state-of-the-art optical studies of meteors with the Super Schmidt camera, but the first one was not operational until May 1951, at Las Cruces, New Mexico.[39]

Radar astronomers, then, attempted to accomplish what optical methods had failed to achieve. Such has been the pattern of radar astronomy to the present. Between 1948 and 1950, Lovell, Davies, and Mary Almond, a doctoral student, undertook a long series of sporadic meteor velocity measurements. They found no evidence for a significant hyperbolic velocity component; that is, there was no evidence for sporadic meteors coming from interstellar space. They then extended their work to fainter and smaller meteors with similar results.

The Jodrell Bank radar meteor studies determined unambiguously that meteors form part of the solar system. As Whipple declared in 1955, "We may now accept as proven the fact that bodies moving in hyperbolic orbits about the sun play no important role in producing meteoric phenomena brighter than about the 8th effective magnitude."[40] Astronomers describe the brightness of a body in terms of magnitude; the larger the magnitude, the fainter the body.

The highly convincing evidence of the Jodrell Bank scientists was corroborated by Canadian radar research carried out by researchers of the Radio and Electrical Engineering Division of the National Research Council under Donald W. R. McKinley. McKinley had joined the

Council's Radio Section (later Branch) before World War II and, like Lovell, had participated actively in wartime radar work.

McKinley conducted his meteor research with radars built around Ottawa in 1947 and 1948 as part of various National Research Council laboratories, such as the Flight Research Center at Arnprior Airport. Earle L. R. Webb, Radio and Electrical Engineering Division of the National Research Council, supervised the design, construction, and operation of the radar equipment. From as early as the summer of 1947, the Canadian radar studies were undertaken jointly with Peter M. Millman of the Dominion Observatory. They coordinated spectrographic, photographic, radar, and visual observations. The National Research Council investigators employed the Jodrell Bank technique to determine meteor velocities, a benefit of following in the footsteps of the British.[41]

Their first radar observations took place during the Perseid shower of August 1947, as the first radar station reached completion. Later studies collected data from the Geminid shower of December 1947 and the Lyrid shower of April 1948, with more radar stations brought into play as they became available. Following the success of Jodrell Bank, [17] McKinley's group initiated their own study of sporadic meteors. By 1951, with data on 10,933 sporadic meteors, McKinley's group reached the same conclusion as their British colleagues: meteors were part of the solar system. Soon, radar techniques became an integral part of Canadian meteor research with the establishment in 1957 of the National Research Council Springhill Meteor Observatory outside Ottawa. The Observatory concentrated on scientific meteor research with radar, visual, photographic, and spectroscopic methods.[42]

These meteor studies at Jodrell Bank and the National Research Council, and only at those institutions, arose from the union of radar and astronomy; they were the beginnings of radar astronomy. Radar studies of meteors were not limited to Jodrell Bank and the National Research Council, however. With support from the National Bureau of Standards, in 1957 Harvard College Observatory initiated a radar meteor project under the direction of Fred Whipple. Furthermore, radar continues today as an integral and vital part of worldwide meteor research. Its forte is the ability to determine orbits better than any other technique. In the last five years, a number of recently built radars have studied meteors in Britain (MST Radar, Aberytswyth, Wales), New Zealand (AMOR, Meteor Orbit Radar, Christchurch), and Japan (MU Radar, Shigaraki), not to mention earlier work in Czechoslovakia and Sweden.[43]

Unlike the Jodrell Bank and National Research Council cases, the radar meteor studies started in the United States in the early 1950s were driven by civilian scientists doing ionospheric and communications research and by the military's desire for jam-proof, point-to-point secure communications. While various military laboratories undertook their own research programs, most of the civilian U.S. radar meteor research was carried out at Stanford University and the National Bureau of Standards, where investigators fruitfully cross-fertilized ionospheric and military communications research. The Stanford case is worth examining not only for its later connections to radar astronomy, but also for its pioneering radar study of the Sun that arose out of an interest in ionospheric and radio propagation research.

In contrast to the Stanford work, many radar meteor experiments carried out in the United States in the 1940s were unique events. As early as August and November 1944, for instance, workers in the Federal Communications Commission Engineering Department associated visual observations of meteors and radio bursts. In January 1946, Oliver Perry Ferrell of the Signal Corps reported using a Signal Corps SCR-270B radar to detect meteor ionization trails.[44] The major radar meteor event in the United States and elsewhere, [18] however, was the spectacular meteor shower associated with the Giacobini-Zinner comet.

On the night of 9 October 1946, 21 Army radars were aimed toward the sky in order to observe any unusual phenomena. The Signal Corps organized the experiment, which fit nicely with their mission of developing missile detection and ranging capabilities. The equipment was operated by volunteer crews of the Army ground forces, the Army Air Forces, and the Signal Corps located across the country in Idaho, New Mexico, Texas, and New Jersey. For mainly meteorological reasons, only the Signal Corps SCR-270 radar successfully detected meteor ionization trails. No attempt was made to correlate visual observations and radar echoes. A Princeton University undergraduate, Francis B. Shaffer, who had received radar training in the Navy, analyzed photographs of the radar screen echoes at the Signal Corps laboratory in Belmar, New Jersey. This was the first attempt to utilize microwave radars to detect astronomical objects. The equipment operated at 1,200 MHz (25 cm), 3,000 MHz (10 cm), and 10,000 MHz (3 cm), frequencies in the L, S, and X radar bands that radar astronomy later used. "On the basis of this night's experiments," the Signal Corps experimenters decided, "we cannot conclude that microwave radars do not detect meteor-formed ion clouds."[45]

In contrast to the Signal Corps experiment, radar meteor studies formed part of ongoing research at the National Bureau of Standards. Organized from the Bureau's Radio Section in May 1946 and located at Sterling, Virginia, the Central Radio Propagation Laboratory (CRPL) division had three laboratories, one of which concerned itself exclusively with ionospheric research and radio propagation and was especially interested in the impact of meteors on the ionosphere. In October 1946, Victor C. Pineo and others associated with the CRPL used a borrowed SCR-270-D Signal Corps radar to observe the Giacobinid meteor shower. Over the next five years, Pineo continued research on the effects of meteors on the ionosphere, using a standard ionospheric research instrument called an ionosonde and publishing his results in Science.

Pineo's interest was in ionospheric physics, not astronomy. Underwriting his research at the Ionospheric Research Section of the National Bureau of Standards was the Air Force Cambridge Research Center (known later as the Cambridge Research Laboratories and today as Phillips Laboratory). His meteor work did not contribute to knowledge about the origin of meteors, as such work had in Britain and Canada, but it supported efforts to create secure military communications using meteor ionization trails.[46] Also, it related to similar research being carried out concurrently at Stanford University.

The 1946 CRPL experiment, in fact, had been suggested by Robert A. Helliwell of the Stanford Radio Propagation Laboratory (SRPL). Frederick E. Terman, who had headed the Harvard Radio Research Laboratory and its radar countermeasures research during the war, "virtually organized radio and electronic engineering on the West Coast" as [19] Stanford Dean of Engineering, according to historian C. Stewart Gillmor. Terman negotiated a contract with the three military services for the funding of a broad range of research, including the SRPL's long-standing ionospheric research program.[47]

Helliwell, whose career was built on ionospheric research, was joined at the SRPL by Oswald G. Villard, Jr. Villard had earned his engineering degree during the war for the design of an ionosphere sounder. As an amateur radio operator in Cambridge, Massachusetts, he had noted the interference caused by meteor ionizations at shortwave frequencies called Doppler whistles.[48]

In October 1946, during the Giacobinid meteor shower, Helliwell, Villard, Laurence A. Manning, and W. E. Evans, Jr., detected meteor ion trails by listening for Doppler whistles with radios operating at 15 MHz (20 meters) and 29 MHz (10 meters). Manning then developed a method of measuring meteor velocities using the Doppler frequency shift of a continuous-wave signal reflected from the ionization trail. Manning, Villard, and Allen M. Peterson then applied Manning's technique to a continuous-wave radio study of the Perseid meteor shower in August 1948. The initial Stanford technique was significantly different from that developed at Jodrell Bank; it relied on continuous-wave radio, rather than pulsed radar, echoes.[49]

One of those conducting meteor studies at Stanford was Von R. Eshleman, a graduate student in electrical engineering who worked under both Manning and Villard. While serving in the Navy during World War II, Eshleman had studied, then taught, radar at the Navy's radar electronics school in Washington, DC. In 1946, while returning from the war on the U.S.S. Missouri, Eshleman unsuccessfully attempted to bounce radar waves off the Moon using the ship's radar. Support for his graduate research at Stanford came through contracts between the University and both the Office of Naval Research and the Air Force.

Eshleman's dissertation considered the theory of detecting meteor ionization trails and its application in actual experiments. Unlike the British and Canadian meteor studies, the primary research interest of Eshleman, Manning, Villard, and the other Stanford investigators was information about the winds and turbulence in the upper atmosphere. Their investigations of meteor velocities, the length of ionized meteor trails, and the fading and polarization of meteor echoes were part of that larger research interest, while Eshleman's dissertation was an integral part of the meteor research program.

Eshleman also considered the use of meteor ionization trails for secure military communications. His dissertation did not explicitly state that application, which he took up after completing the thesis. The Air Force supported the Stanford meteor research mainly to use meteor ionization trails for secure, point-to-point communications. The Stanford meteor research thus served a variety of scientific and military purposes simultaneously.[50]

[20] The meteor research carried out at Stanford had nontrivial consequences. Eshleman's dissertation has continued to provide the theoretical foundation of modern meteor burst communications, a communication mode that promises to function even after a nuclear holocaust has rendered useless all normal wireless communications. The pioneering work at Stanford, the National Bureau of Standards, and the Air Force Cambridge Research Laboratories received

new attention in the 1980s, when the Space Defense Initiative ("Star Wars") revitalized interest in using meteor ionization trails for classified communications. Non-military applications of meteor burst communications also have arisen in recent years. [51]

Early meteor burst communications research was not limited to Stanford and the National Bureau of Standards. American military funding of early meteor burst communications research extended beyond its shores to Britain. Historians of Jodrell Bank radio astronomy and meteor radar research stated that radio astronomy had surpassed meteor studies at the observatory by 1955. However, that meteor work persisted until 1964 through a contract with the U.S. Air Force, though as a cover for classified military research.[52]

Auroras provided additional radar targets in the 1950s. A major initiator of radar auroral studies was Jodrell Bank. As early as August 1947, while conducting meteor research, the Jodrell Bank scientists Lovell, Clegg, and Ellyett received echoes from an aurora display. Arnold Aspinall and G. S. Hawkins then continued the radar auroral studies at Jodrell Bank in collaboration with W. B. Housman, Director of the Aurora Section of the British Astronomy Association, and the aurora observers of that Section. In Canada, McKinley and Millman also observed an aurora during their meteor research in April 1948.[53]

The problem with bouncing radar waves off an aurora was determining the reflecting point. Researchers in the University of Saskatchewan Physics Department (B. W. Currie, P. A. Forsyth, and F. E. Vawter) initiated a systematic study of auroral radar reflections in 1948, with funding from the Defense Research Board of Canada. Radar equipment was lent by the U.S. Air Force Cambridge Research Center and modified by the Radio and Electrical Engineering Division of the National Research Council. Forsyth had completed a dissertation on auroras at McGill University and was an employee of the Defense Research Board's Telecommunications Establishment on loan to the University of Saskatchewan for the project. The Saskatchewan researchers discovered that the echoes bounced off small, intensely ionized regions in the aurora.[54]

Other aurora researchers, especially in Sweden and Norway, took up radar studies. In Sweden, Götha Hellgren and Johan Meos of the Chalmers University of Technology [21] Research Laboratory of Electronics in Gothenburg decided to conduct radar studies of auroras as part of their ionospheric research program. Beginning in May 1951, the Radio Wave Propagation Laboratory of the Kiruna Geophysical Observatory undertook round-the-clock observations of auroras with a 30.3-MHz (10-meter) radar. In Norway, Leiv Harang, who had observed radar echoes from an aurora as early as 1940, and B. Landmark observed auroras with radars lent by the Norwegian Defense Research Establishment and installed at Oslo (Kjeller) and Tromsö, where a permanent center for radar investigation of auroras was created later.[55]

These and subsequent radar investigations changed the way scientists studied auroras, which had been almost entirely by visual means up to about 1950. Permanent auroral observatories located at high latitudes, such as those at Oslo and Tromsö in Norway, at Kiruna in Sweden, and at Saskatoon in Saskatchewan, integrated radar into a spectrum of research instruments that included spectroscopy, photography, balloons, and sounding rockets. The International Geophysical Year, 1957-1958, was appropriately timed to further radar auroral research; it coincided with extremely high sunspot and auroral activity, such as the displays visible from Mexico in September 1957 and the "Great Red Aurora" of 10 February 1958. Among those participating in the radar aurora and meteor studies associated with the International Geophysical Year activities were three Jodrell Bank students and staff who joined the Royal Society expedition to Halley Bay, Antarctica.[56]

To the Moon Again

The auroral and meteor radar studies carried out in the wake of the lunar radar experiments of DeWitt and Bay were, in essence, ionospheric studies. While the causes of auroras and meteor ionization trails arise outside the Earth's atmosphere, the phenomena themselves are essentially ionospheric. At Jodrell Bank, meteor and auroral studies provided the initial impetus, but certainly not the sustaining force, for the creation of an ongoing radar astronomy program. That sustaining force came from lunar studies. However, like so much of early radar astronomy, those lunar studies were never far from ionospheric research. Indeed, the trailblazing efforts of DeWitt and Bay opened up new vistas of ionospheric and communications research using radar echoes from the Moon.

Historically, scientists had been limited to the underside and lower portion of the ionosphere. The discovery of "cosmic noise" by Bell Telephone researcher Karl Jansky in 1932 suggested that higher frequencies could penetrate the ionosphere. The experiments of DeWitt and Bay suggested radar as a means of penetrating the lower regions of the ionosphere. DeWitt, moreover, had observed unexpected fluctuations in signal strength that lasted several minutes, which he attributed to anomalous ionospheric refraction.[57] His observations invited further investigation of the question.

The search for a better explanation of those fluctuations was taken up by a group of ionosphericists in the Division of Radiophysics of the Australian Council for Scientific and Industrial Research: Frank J. Kerr, C. Alex Shain, and Charles S. Higgins. In 1946, Kerr and Shain explored the possibility of obtaining radar echoes from meteors, following the [22] example of Lovell in Britain, but Project Diana turned their attention toward the Moon. In order to study the fluctuations in signal

strength that DeWitt had observed, Kerr, Shain, and Higgins put together a rather singular experiment.
For a transmitter, they used the 20-MHz (15-meter) Radio Australia station, located in Shepparton, Victoria, when it was not in use for regular programming to the United States and Canada. The receiver was located at the Radiophysics Laboratory, Hornsby, New South Wales, a distance of 600 km from the transmitter. Use of this unique system was limited to days when three conditions could be met all at the same time: the Moon was passing through the station's antenna beams; the transmitter was available; and atmospheric conditions were favorable. In short, the system was workable about twenty days a year.[58]
Kerr, Shain, and Higgins obtained lunar echoes on thirteen out of fifteen attempts. The amplitude of the echoes fluctuated considerably over the entire run of tests as well as within a single test. Researchers at IT&T's Federal Telecommunications Laboratories in New York City accounted for the fluctuations observed by DeWitt by positing the existence of smooth spots that served as "bounce points" for the reflected energy. Another possibility they imagined was the existence of an ionosphere around the Moon.[59] The Australians disagreed with the explanations offered by DeWitt and the IT&T researchers, but they were initially cautious: "It cannot yet be said whether the reductions in intensity and the long-period variations are due to ionospheric, lunar or inter-planetary causes."[60]
During a visit to the United States in 1948, J. L.

Pawsey, a radio astronomy enthusiast also with the Council for Scientific and Industrial Research's Division of Radiophysics, arranged a cooperative experiment with the Americans. A number of U.S. organizations with an interest in radio, the National Bureau of Standards CRPL, the Radio Corporation of America (Riverhead, New York), and the University of Illinois (Urbana), attempted to receive Moon echoes simultaneously from Australia, beginning 30 July 1948. Ross Bateman (CRPL) acted as American coordinator. The experiment was not a great success. The times of the tests (limited by transmitter availability) were all in the middle of the day at the receiving points. Echoes were received in America on two occasions, 1 August and 28 October, and only for short periods in each case.

Meanwhile, Kerr and Shain continued to study lunar echo fading with the Radio Australia transmitter. Based on thirty experiments (with echoes received in twenty-four of them) conducted over a year, they now distinguished rapid and slow fading. Kerr and Shain proposed that each type of fading had a different cause. Rapid fading resulted from the Moon's libration, a slow wobbling motion of the Moon. Irregular movement in the ionosphere, they originally suggested, caused the slower fading.[61] Everyone agreed that the rapid fading of lunar radar echoes originated in the lunar libration, but the cause of slow fading was not so obvious.

The problem of slow fading was taken up at Jodrell

Bank by William A. S. Murray and J. K. Hargreaves, who sought an explanation in the ionosphere. Although Lovell had proposed undertaking lunar radar observations as early as 1946, the first worthwhile results were not obtained until the fall of 1953. Hargreaves and Murray photographed and analyzed some 50,000 lunar radar echoes at the Jodrell Bank radar telescope in October and November 1953 to determine the origin of slow fading.

[23] With rare exceptions, nighttime runs showed a steady signal amplitude, while daytime runs, especially those within a few hours of sunrise, were marked by severe fading. The high correlation between fading and solar activity strongly suggested an ionospheric origin. However, Hargreaves and Murray believed that irregularities in the ionosphere could not account for slow fading over periods lasting up to an hour. They suggested instead that slow fading resulted from Faraday rotation, in which the plane of polarization of the radio waves rotated, as they passed through the ionosphere in the presence of the Earth's magnetic field.

Hargreaves and Murray carried out a series of experiments to test their hypothesis in March 1954. The transmitter had a horizontally polarized antenna, while the primary feed of the receiving antenna consisted of two dipoles mounted at right angles. They switched the receiver at short intervals between the vertical and horizontal feeds so that echoes would be received in both planes of polarization, a technique that is a standard planetary radar practice today.

As the plane of polarization of the radar waves rotated in the ionosphere, stronger echo amplitudes were received by the vertical feed than by the horizontal feed. If no Faraday rotation had taken place, both the transmitted and received planes of polarization would be the same, that is, horizontal. But Faraday rotation of the plane of polarization in the ionosphere had rotated the plane of polarization so that the vertical feed received more echo power than the horizontal feed. The results confirmed that slow fading was caused, at least in part, by a change in the plane of polarization of the received lunar echo.[62]

Murray and Hargreaves soon took positions elsewhere, yet Jodrell Bank continued to feature radar astronomy through the persistence of Bernard Lovell. Lovell became entangled in administrative affairs and the construction of a giant radio telescope, while John V. Evans, a research student of Lovell, took over the radar astronomy program. Evans had a B.Sc. in physics and had had an interest in electronics engineering since childhood. He chose the University of Manchester Physics Department for his doctoral degree, because the department, through Lovell, oversaw the Jodrell Bank facility. The facility's heavy involvement in radio and radar astronomy, when Evans arrived there on his bicycle in the summer of 1954, assured Evans that his interest in electronics engineering would be sated.

With the approval and full support of Lovell, Evans renewed the studies of lunar radar echoes, but first he rebuilt the lunar radar equipment. It was a "poor instrument," Evans later recalled, "and barely got echoes from the Moon." After he increased the power output from 1 to 10 kilowatts and improved the sensitivity of the receiver by rebuilding the front end, Evans took the lunar studies in a new direction. Unlike the majority of Jodrell Bank research, Evans's lunar work was underwritten through a contract with the U.S. Air Force, which was interested in using the Moon as part of a long-distance communications system.

With his improved radar apparatus, Evans discovered that the Moon overall was a relatively smooth reflector of radar waves at the wavelength he used (120 MHz; 2.5 meters). Later, from the way that the Moon appeared to scatter back radar waves, Evans speculated that the lunar surface was covered with small, round objects such as rocks and stones. Hargreaves proposed that radar observations at shorter wavelengths should be able to give interesting statistical information about the features of the lunar surface.[63] That idea was [24] the starting point for the creation of planetary radar techniques that would reveal the surface characteristics of planets and other moons.

Experimenters prior to Evans had assumed that the Moon reflected radar waves from the whole of its illuminated surface, like light waves. They debated whether the power returned to the Earth was reflected from the entire visible disk or from a smaller region. The question was important to radar astronomers at

Jodrell Bank as well as to military and civilian researchers developing Moon-relay communications.
In March 1957, Evans obtained a series of lunar radar echoes. He photographed both the transmitted pulses and their echoes so that he could make a direct comparison between the two. Evans also made range measurements of the echoes at the same time. In each case, the range of the observed echo was consistent with that of the front edge of the Moon. The echoes came not from the entire visible disk but from a smaller portion of the lunar surface, that closest to the Earth and known as the subradar point.[64] This discovery became fundamental to radar astronomy research.
Because radar waves reflected off only the foremost edge of the Moon, Evans and John H. Thomson (a radio astronomer who had transferred from Cambridge in 1959) undertook a series of experiments on the use of the Moon as a passive communication relay. Although initial results were "not intelligible," because FM and AM broadcasts tended to fade, Lovell bounced Evans' "hello" off the Moon with a Jodrell Bank transmitter and receiver during his BBC Reith Lecture of 1958. Several years later, in collaboration with the Pye firm, a leading British manufacturer of electronic equipment headquartered in Cambridge, and with underwriting from the U.S. Air Force, a Pye transmitter at Jodrell Bank was used to send speech and music via the Moon to the Sagamore Hill Radio Astronomy Observatory of the Air Force Cambridge Research Center, at Hamilton, Massachusetts. The U.S. Air Force thus obtained a

successful lunar bounce communication experiment at Jodrell Bank for a far smaller sum than that spent by the Naval Research Laboratory.[65]

The Moon Bounce

The lunar communication studies at Jodrell Bank illustrate that astronomy was not behind all radar studies of the Moon. Much of the lunar radar work, especially in the United States, was performed to test long-distance communication systems in which the Moon would serve as a relay. Thus, the experiments of DeWitt and Bay may be said to have begun the era of satellite communications. Research on Moon-relay communications systems by both military and civilian laboratories eventually drew those institutions into the early organizational activities of radar astronomers. After all, both communication research and radar astronomy shared an interest in the behavior of radio waves at the lunar surface. Hence, a brief look at that research would be informative.

Before the advent of satellites, wireless communication over long distances was achieved by reflecting radio waves off the ionosphere. As transmission frequency increased, the ionosphere was penetrated. Long-distance wireless communication at high frequencies had to depend on a network of relays, which were expensive and technically complex. Using the Moon as a

relay appeared to be a low-cost alternative.[66]
[25] Reacting to the successes of DeWitt and Bay, researchers at the IT&T Federal Telecommunications Laboratories, Inc., New York City, planned a lunar relay telecommunication system operating at UHF frequencies (around 50 MHz; 6 meters) to provide radio telephone communications between New York and Paris. If such a system could be made to work, it would provide IT&T with a means to compete with transatlantic cable carriers dominated by rival AT&T. What the Federal Telecommunications Laboratories had imagined, the Collins Radio Company, Cedar Rapids, Iowa, and the National Bureau of Standards CRPL, accomplished.
On 28 October and 8 November 1951, Peter G. Sulzer and G. Franklin Montgomery, CRPL, and Irvin H. Gerks, Collins Radio, sent a continuous-wave 418-MHz (72-cm) radio signal from Cedar Rapids to Sterling, Virginia, via the Moon. On 8 November, a slowly hand-keyed telegraph message was sent over the circuit several times. The message was the same sent by Samuel Morse over the first U.S. public telegraph line: "What hath God wrought?"[67]
Unbeknownst to the CRPL/Collins team, the first use of the Moon as a relay in a communication circuit was achieved only a few days earlier by military researchers at the Naval Research Laboratory (NRL). The Navy was interested in satellite communications, and the Moon offered itself as a free (if distant and rough) satellite in the years before an artificial satellite could be launched.

In order to undertake lunar communication studies, the NRL built what was then the world's largest parabolic antenna in the summer of 1951. The dish covered over an entire acre (67 by 80 meters; 220 by 263 ft) and had been cut into the earth by road-building machinery at Stump Neck, Maryland. The one-megawatt transmitter operated at 198 MHz (1.5 meters). The NRL first used the Moon as a relay in a radio communication circuit on 21 October 1951. After sending the first voice transmission via the Moon on 24 July 1954, the NRL demonstrated transcontinental satellite teleprinter communication from Washington, DC, to San Diego, CA, at 301 MHz (1 meter) on 29 November 1955 and transoceanic satellite communication, from Washington, DC, to Wahiawa, Oahu, Hawaii, on 23 January 1956.[68]

Later in 1956, the NRL's Radio Astronomy Branch started a radar program under Benjamin S. Yaplee to determine the feasibility of bouncing microwaves off the Moon and to accurately measure both the Moon's radius and the distances to different reflecting areas during the lunar libration cycle. Aside from the scientific value of that research, the information would help the Navy to determine relative positions on the Earth's surface. The first NRL radar contact with the Moon at a microwave frequency took place at 2860 MHz (10 cm) and was accomplished with the Branch's 15-meter (50-ft) radio telescope.[69]

Although interest in bouncing radio and radar waves off the Moon drew military and civilian researchers to early radar astronomy conferences, lunar communication schemes failed to provide either a theoretical or a funding framework within which radar astronomy could develop. The rapidly growing field of ionospheric research, on the other hand, provided both theoretical and financial support for radar experiments on meteors and the Moon. Despite the remarkable variety of radar experiments carried out in the years following World War II, radar achieved a wider and more permanent place in ionospheric research (especially meteors and auroras) than in astronomy.

[26] All that changed with the start of the U.S./U.S.S.R. Space Race and the announcement of the first planetary radar experiment in 1958. That experiment was made possible by the rivalries of the Cold War, which fostered a concentration of expertise and financial, personnel, and material resources that paralleled, and in many ways exceeded, that of World War II. The new Big Science of the Cold War and the Space Race, often indistinguishable from each other, gave rise to the radar astronomy of planets.

The Sputnik and Lunik missions were not just surprising demonstrations of Soviet achievements in science and technology. Those probes had been propelled off the Earth by ICBMs, and an ICBM capable of putting a dog in Earth-orbit or sending a probe to the Moon was equally capable of delivering a nuclear bomb from Moscow to New York City. Behind the Space Race lay the specter of the Cold War and World War III, or to paraphrase Clausewitz, the Space Race was the Cold

War by other means. Just as the vulnerability of Britain to air attacks had led to the creation of the Chain Home radar warning network, the defenselessness of the United States against aircraft and ICBM attacks with nuclear bombs and warheads led to the creation of a network of defensive radars. The development of that network in turn provided the instrument with which planetary radar astronomy, driven by the availability of technology, would begin in the United States.

Notes

1. Guglielmo Marconi, "Radio Telegraphy," Proceedings of the Institute of Radio Engineers 10 (1922): 237.
2. Charles Süsskind, "Who Invented Radar?" Endeavour 9 (1985): 92-96; Henry E. Guerlac, "The Radio Background of Radar," Journal of the Franklin Institute 250 (1950): 284-308.
3. Swords, A Technical History of the Beginnings of Radar (London: Peter Peregrinus Press, 1986), pp. 270-271.
4. Guerlac, "Radio Background," p. 304.
5. Alfred Price, Instruments of Darkness: The History of Electronic Warfare, 2d. ed. (London: MacDonald and Jane's, 1977); Tony Devereux, Messenger Gods of Battle, Radio, Radar, Sonar: The Story of Electronics in

War (Washington: Brassey's, 1991); David E. Fisher, A Race on the Edge of Time: Radar - the Decisive Weapon of World War II (New York: McGraw-Hill, 1988).
6. H. Montgomery Hyde, British Air Policy Between the Wars, 1918-1939 (London: Heinemann, 1976), p. 322. See also Malcolm Smith, British Air Strategy Between the Wars (Oxford: Clarendon Press, 1984).
7. Swords, p. 84; Edward G. Bowen, Radar Days (Bristol: Adam Hilger, 1987), pp. 4-5, 7 & 10; Robert Watson-Watt, The Pulse of Radar: The Autobiography of Sir Robert Watson-Watt (New York: Dial Press, 1959), pp. 29-38, 51, 69, 101, 109-110, 113; A. P. Rowe, One Story of Radar (Cambridge: Cambridge University Press, 1948), pp. 6-7; Reg Batt, The Radar Army: Winning the War of the Airwaves (London: Robert Hale, 1991), pp. 21-22. The Radio Research Board was under the Department of Scientific and Industrial Research, created in 1916.
Born Robert Alexander Watson Watt in 1892, he changed his surname to "Watson-Watt" when knighted in 1942. See the popularly-written biography of Watson-Watt, John Rowland, The Radar Man: The Story of Sir Robert Watson-Watt (London: Lutterworth Press, 1963), or Watson-Watt, Three Steps to Victory (London: Odhams Press Ltd., 1957). An account of Watson-Watt's research at Slough is given in Watson-Watt, John F. Herd, and L. H. Bainbridge-Bell, The Cathode Ray Tube in Radio Research (London: His Majesty's Stationery Office, 1933).
8. By "apparent height of the ionosphere," I mean what

ionosphericists call virtual height. Since the ionosphere slows radio waves before being refracted back to Earth, the delay is not a true measure of height. The Tuve-Breit method preceded that of Watson-Watt and was a true send-receive technique, while that of Watson-Watt was a receive-only technique.
Tuve, "Early Days of Pulse Radio at the Carnegie Institution," Journal of Atmospheric and Terrestrial Physics 36 (1974): 2079-2083; Oswald G. Villard, Jr., "The Ionospheric Sounder and its Place in the History of Radio Science," Radio Science 11 (1976): 847-860; Guerlac, "Radio Background," pp. 284-308; David H. DeVorkin, Science With a Vengeance: How the Military Created the U.S. Space Sciences after World War II (New York: Springer-Verlag, 1992), pp. 12, 301 & 316; C. Stewart Gillmor, "Threshold to Space: Early Studies of the Ionosphere," in Paul A. Hanle and Von Del Chamberlain, eds., Space Science Comes of Age: Perspectives in the History of the Space Sciences (Washington: National Air and Space Museum, Smithsonian Institution, 1981), pp. 102-104; J. A. Ratcliffe, "Experimental Methods of Ionospheric Investigation, 1925-1955," Journal of Atmospheric and Terrestrial Physics 36 (1974): 2095-2103; Tuve and Breit, "Note on a Radio Method of Estimating the Height of the Conducting Layer," Terrestrial Magnetism and Atmospheric Electricity 30 (1925): 15-16; Breit and Tuve, "A Radio Method of Estimating the Height of the Conducting Layer," Nature 116 (1925): 357; and Breit and Tuve, "A Test of the Existence of the

Conducting Layer," Physical Review 2d ser., vol. 28 (1926): 554-575; special issue of Journal of Atmospheric and Terrestrial Physics 36 (1974): 2069-2319, is devoted to the history of ionospheric research.
9. Watson-Watt, Three Steps, p. 83; Ronald William Clark, Tizard (London: Methuen, 1965), pp. 105-127.
10. Swords, pp. 84-85; Bowen, pp. 6, 21, 26 & 28; Batt, pp. 10, 21-22, 69 & 77; Rowe, pp. 8 & 76; R. Hanbury Brown, Boffin: A Personal Story of the Early Days of Radar, Radio Astronomy, and Quantum Optics (Bristol: Adam Hilger, 1991), pp. 7-8; P. S. Hall and R. G. Lee, "Introduction to Radar," in P. S. Hall, T. K. Garland-Collins, R. S. Picton, and R. G. Lee, eds., Radar (London: Brassey's, 1991), pp. 6-7; Watson-Watt, Pulse, pp. 55-59, 64-65, 75, 113-115 & 427-434; Watson-Watt, Three Steps, pp. 83 & 470-474; Bowen, "The Development of Airborne Radar in Great Britain, 1935-1945," in Russell W. Burns, ed. Radar Development to 1945 (London: Peter Peregrinus Press, 1988), pp. 177-188. For a description of the technology, see B. T. Neale, "CH--the First Operational Radar," in Burns, pp. 132-150.
11. Boot and Randall, "Historical Notes on the Cavity Magnetron," IEEE Transactions on Electron Devices ED-23 (1976): 724-729; R. W. Burns, "The Background to the Development of the Cavity Magnetron," in Burns, pp. 259-283.
12. Swords, p. xi.
13. Baxter, Scientists Against Time (Boston: Little, Brown and Company, 1946), p. 142; Swords, pp. 120,

259 & 266; Clark, especially pp. 248-271.
14. Guerlac, Radar in World War II, The History of Modern Physics, 1800-1950, vol. 8 (New York: Tomash Publishers for the American Institute of Physics, 1987), vol. 1, p. 249; Swords, pp. 90 & 119; Batt, pp. 79-80; Bowen, pp. 159-162: Watson Watt, Pulse, pp. 228-229 & 257; Watson-Watt, Three Steps, 293.
In addition to Tizard and Bowen, the Mission team consisted of Prof. J. D. Cockcroft, Col. F. C. Wallace, Army, Capt. H. W. Faulkner, Navy, Capt. F. L. Pearce, Royal Air Force, W. E. Woodward Nutt, Ministry of Aircraft Production, Mission Secretary, Prof. R. H. Fowler, liaison officer for Canada and the United States of the Department of Scientific and Industrial Research, and Col. H. F. G. Letson, Canadian military attache in Washington.
15. Guerlac, Radar in World War II, 1:258-259, 261, 266 & 507-508, and 2:648 & 668. See also the personal reminiscences of Ernest C. Pollard, Radiation: One Story of the MIT Radiation Laboratory (Durham: The Woodburn Press, 1982). Interviews (though not all are transcribed) of some Radiation Laboratory participants are available at the IEEE Center for the History of Electrical Engineering (CHEE), Rutgers University. CHEE, Sources in Electrical History 2: Oral History Collections in U.S. Repositories (New York: IEEE, 1992), pp. 6-7. The British also developed magnetrons and radar equipment operating at microwave frequencies concurrently with the MIT Radiation Laboratory effort.

16. Guerlac, Radar in World War II, 1:247-248 & 117-119. For the Navy, see L. A. Hyland, "A Personal Reminiscence: The Beginnings of Radar, 1930-1934," in Burns, pp. 29-33; Robert Morris Page, The Origin of Radar (Garden City, NY: Anchor Books, Doubleday & Company, 1962); Page, "Early History of Radar in the U.S. Navy," in Burns, pp. 35-44; David Kite Allison, New Eye for the Navy: The Origin of Radar at the Naval Research Laboratory (Washington: Naval Research Laboratory, 1981); Guerlac, Radar in World War II, 1:59-92; Albert Hoyt Taylor, The First Twenty-five Years of the Naval Research Laboratory (Washington: Navy Department, 1948). On the Signal Corps, see Guerlac, Radar in World War II, 1:93-121; Harry M. Davis, History of the Signal Corps Development of U.S. Army Radar Equipment (Washington: Historical Section Field Office, Office of the Chief Signal Officer, 1945); Arthur L. Vieweger, "Radar in the Signal Corps," IRE Transactions on Military Electronics MIL-4 (1960): 555-561.

17. Gillmor, "Geospace and its Uses: The Restructuring of Ionospheric Physics Following World War II," in De Maria, 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.
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 Mofenson, "Radar Echoes from the Moon," Electronics 19 (1946): 92-98; and Herbert Kauffman, "A DX Record: To the Moon and Back," QST 30 (1946): 65-68.
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 & 382 and 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.

24. "Diana," Time col. 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 & 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.

26. Bay, "Reflection of Microwaves from the Moon," Hungarica Acta Physica 1 (1947): 1-6; Bay, Life is Stronger, pp. 20, 29; Wagner, Zoltán, pp. 39-40; Wagner, Fifty Years, pp. 1-2.

27. Smith and Carr, Radio Exploration of the Planetary System (New York: D. Van Nostrand, 1964), p. 123; Bay, "Reflection," pp. 2, 7-15 & 18-19; P. Vajda and J. A. White, "Thirtieth Anniversary of Zoltán Bay's Pioneer Lunar Radar Investigations and Modern Radar Astronomy," Acta Physica Academiae Scientiarum Hungaricae 40 (1976): 65-70; Wagner, Zoltán, pp. 40-41. Bay, Life is Stronger, pp. 103-124, describes the

looting and dismantling of the Tungsram works by armed agents of the Soviet Union.
28. DeWitt, telephone conversation, 14 June 1993; DeWitt biographical sketch, HL Diana 46 (04), HAUSACEC; Wagner, Zoltán, p. 49; Wagner, Fifty Years, p. 2.
Among the others were Thomas Gold, Von Eshleman, and A. C. Bernard Lovell. Gold, retired Cornell University professor of astronomy, claims to have proposed a lunar radar experiment to the British Admiralty during World War II; Eshleman, Stanford University professor of electrical engineering, unsuccessfully attempted a lunar radar experiment aboard the U.S.S. Missouri in 1946, while returning from the war; and Lovell proposed a lunar bounce experiment in a paper of May 1946. Gold 14/12/93, Eshleman 9/5/94, and Lovell, "Astronomer by Chance," manuscript, February 1988, Lovell materials, p. 183.
Even earlier, during the 1920s, the Navy unsuccessfully attempted to bounce a 32-KHz, 500-watt radio signal off the Moon. A. Hoyt Taylor, Radio Reminiscences: A Half Century (Washington: NRL, 1948), p. 133. I am grateful to Louis Brown for pointing out this reference.
29. See DeVorkin, passim.
30. A. M. Skellett, "The Effect of Meteors on Radio Transmission through the Kennelly-Heaviside Layer," Physical Review 37 (1931): 1668; Skellett, "The Ionizing Effect of Meteors," Proceedings of the Institute of Radio Engineers 23 (1935): 132-149. Skellett was a part-time graduate student in astronomy

at Princeton University and an employee of Bell Telephone Laboratories, New York City. The research described in this article came out of a study of the American Telegraph and Telephone Company transatlantic short-wave telephone circuits in 1930-1932, and how they were affected by meteor ionization. DeVorkin, p. 275.

31. Appleton and R. Naismith, "The Radio Detection of Meteor Trails and Allied Phenomena," Proceedings of the Physical Society 59 (1947): 461-473; James S. Hey and G. S. Stewart, "Radar Observations of Meteors," Proceedings of the Physical Society 59 (1947): 858; Lovell, Meteor Astronomy (Oxford: Clarendon Press, 1954), pp. 23-24.

32. Hey, The Evolution of Radio Astronomy (New York: Science History Publications, 1973), pp. 19-23 & 33-34; Lovell, The Story of Jodrell Bank (London: Oxford University Press, 1968), p. 5; Hey, Stewart, and S. J. Parsons, "Radar Observations of the Giacobinid Meteor Shower," Monthly Notices of the Royal Astronomical Society 107 (1947): 176-183; Hey and Stewart, "Radar Observations of Meteors," Proceedings of the Physical Society 59 (1947): 858-860 & 881-882; Hey, The Radio Universe (New York: Pergamon Press, 1971), pp. 131-134; Lovell, Meteor Astronomy, pp. 28-29 & 50-52; Peter Robertson, Beyond Southern Skies: Radio Astronomy and the Parkes Telescope (New York: Cambridge University Press, 1992), p. 39; Dudley Saward, Bernard Lovell, a Biography (London: Robert Hale, 1984), pp. 142-145; David O. Edge and Michael J.

Mulkay, Astronomy Transformed: The Emergence of Radio Astronomy in Britain (New York: Wiley, 1976), pp. 12-14. For a brief historical overview of the Royal Radar Establishment, see Ernest H. Putley, "History of the RSRE," RSRE Research Review 9 (1985): 165-174; and D. H. Tomin, "The RSRE: A Brief History from Earliest Times to Present Day," IEE Review 34 (1988): 403-407. This major applied science institution deserves a more rigorously researched history.

33. See Lovell, Echoes of War: The Story of H_2S Radar (Bristol: Adam Hilger, 1991). Lovell's wartime records are stored at the Imperial War Museum, Lambeth Road, London.

34. Lovell 11/1/94; Lovell, Jodrell Bank, pp. 5-8, 10; Lovell, Meteor Astronomy, pp. 55-63; Edge and Mulkay, pp. 15-16; Saward, pp. 129-131; R. H. Brown and Lovell, "Large Radio Telescopes and their Use in Radio Astronomy," Vistas in Astronomy 1 (1955): 542-560; Blackett and Lovell, "Radio Echoes and Cosmic Ray Showers," Proceedings of the Royal Society of London ser. A, vol. 177 (1941): 183-186; and Lovell, "The Blackett-Eckersley-Lovell Correspondence of World War II and the Origin of Jodrell Bank," Notes and Records of the Royal Society of London 47 (1993): 119-131. For documents relating to equipment on loan from the Ministry of Aviation, the War Office, the Royal Radar Establishment, the Admiralty, and the Air Ministry as late as the 1960s, see 10/51, "Accounts," JBA.

35. Lovell 11/1/94; Lovell, Jodrell Bank, pp. 7-8, 10.

36. Lovell 11/1/94; Lovell, Jodrell Bank, pp. 8-10;

Lovell, Clegg, and Congreve J. Banwell, "Radio Echo Observations of the Giacobinid Meteors 1946," Monthly Notices of the Royal Astronomical Society 107 (1947): 164-175. Banwell was a New Zealand veteran of the Telecommunications Research Establishment wartime radar effort and an expert on receiver electronics.
37. Saward, p. 137; Herlofson, "The Theory of Meteor Ionization," Reports on Progress in Physics 11 (1946-47): 444-454; Ellyett and Davies, "Velocity of Meteors Measured by Diffraction of Radio Waves from Trails during Formation," Nature 161 (1948): 596-597; Clegg, "Determination of Meteor Radiants by Observation of Radio Echoes from Meteor Trails," Philosophical Magazine ser. 7, vol. 39 (1948): 577-594; Davies and Lovell, "Radio Echo Studies of Meteors," Vistas in Astronomy 1 (1955): 585-598, provides a summary of meteor research at Jodrell Bank.
38. Lovell, Jodrell Bank, p. 12; Lovell, Meteor Astronomy, pp. 358-383.
39. Ron Doel, "Unpacking a Myth: Interdisciplinary Research and the Growth of Solar System Astronomy, 1920-1958," Ph.D. diss. Princeton University, 1990, pp. 33-35, 42-44 & 108-111; DeVorkin, pp. 96, 273, 278 & 293; Luigi G. Jacchia and Whipple, "The Harvard Photographic Meteor Programme," Vistas in Astronomy 2 (1956): 982-994; Whipple, "Meteors and the Earth's Upper Atmosphere," Reviews of Modern Physics 15 (1943): 246-264; Ibid., "The Baker Super-Schmidt Meteor Cameras," The Astronomical Journal 56 (1951): 144-145, states that the first such camera was

installed in New Mexico in May 1951. Determining the origin of meteors was not the primary interest of Harvard research.

40. Whipple, "Some Problems of Meteor Astronomy," in H. C. Van de Hulst, ed., Radio Astronomy (Cambridge: Cambridge University Press, 1957), p. 376; Almond, Davies, and Lovell, "The Velocity Distribution of Sporadic Meteors," Monthly Notices of the Royal Astronomical Society 111 (1951): 585-608; 112 (1952): 21-39; 113 (1953): 411-427. The meteor studies at Jodrell Bank were continued into later years. See, for instance, I. C. Browne and T. R. Kaiser, "The Radio Echo from the Head of Meteor Trails," Journal of Atmospheric and Terrestrial Physics 4 (1953): 1-4.

41. W. E. Knowles Middleton, Radar Development in Canada: The Radio Branch of the National Research Council of Canada, 1939-1946 (Waterloo, Ontario: Wilfred Laurier University Press, 1981), pp. 18, 25, 27, 106-109; Millman and McKinley, "A Note on Four Complex Meteor Radar Echoes," Journal of the Royal Astronomical Society of Canada 42 (1948): 122; McKinley and Millman, "A Phenomenological Theory of Radar Echoes from Meteors," Proceedings of the Institute of Radio Engineers 37 (1949): 364-375; McKinley and Millman, "Determination of the Elements of Meteor Paths from Radar Observations," Canadian Journal of Research A27 (1949): 53-67; McKinley, "Deceleration and Ionizing Efficiency of Radar Meteors," Journal of Applied Physics 22 (1951): 203; McKinley, Meteor Science and Engineering (New York: McGraw-Hill,

1961), p. 20; Lovell, Meteor Astronomy, pp. 52-55.
42. Millman, McKinley, and M. S. Burland, "Combined Radar, Photographic, and Visual Observations of the 1947 Perseid Meteor Shower," Nature 161 (1948): 278-280; McKinley and Millman, "Determination of the Elements," p. 54; Millman and McKinley, "A Note," pp. 121-130; McKinley, "Meteor Velocities Determined by Radio Observations," The Astrophysics Journal 113 (1951): 225-267; F. R. Park, "An Observatory for the Study of Meteors," Engineering Journal 41 (1958): 68-70.
43. Whipple, "Recent Harvard-Smithsonian Meteoric Results," Transactions of the IAU 10 (1960): 345-350; Jack W. Baggaley and Andrew D. Taylor, "Radar Meteor Orbital Structure of Southern Hemisphere Cometary Dust Streams," pp. 33-36 in Alan W. Harris and Edward Bowell, eds., Asteroids, Comets, Meteors 1991 (Houston: Lunar and Planetary Institute, 1992); Baggaley, Duncan I. Steel, and Taylor, "A Southern Hemisphere Radar Meteor Orbit Survey," pp. 37-40 in ibidem; William Jones and S. P. Kingsley, "Observations of Meteors by MST Radar," pp. 281-284 in ibidem; Jun-ichi Wattanabe, Tsuko Nakamura, T. Tsuda, M. Tsutsumi, A. Miyashita, and M. Yoshikawa, "Meteor Mapping with MU Radar," pp. 625-627 in ibidem. The MST Radar and the AMOR were newly commissioned in 1990. The MU Radar is intended primarily for atmospheric research.
For the meteor radar research in Sweden and Czechoslovakia, see B. A. Lindblad and M. Simek,

"Structure and Activity of Perseid Meteor Stream from Radar Observations, 1956-1978," pp. 431-434 in Claes-Ingva Lagerkvist and Hans Rickman, eds., Asteroids, Comets, Meteors (Uppsala: Uppsala University, 1983); A. Hajduk and G. Cevolani, "Variations in Radar Reflections from Meteor Trains and Physical Properties of Meteoroids," pp. 527-530 in Lagerkvist, H. Rickman, Lindblad, and M. Lindgren, Asteroids, Comets, Meteors III (Uppsala: Uppsala University, 1989); Simek and Lindblad, "The Activity Curve of the Perseid Meteor Stream as Determined from Short Duration Meteor Radar Echoes," pp. 567-570 in ibidem.
44. Ferrell, "Meteoric Impact Ionization Observed on Radar Oscilloscopes," Physical Review 2d ser., vol. 69 (1946): 32-33; Lovell, Meteor Astronomy, p. 28.
45. Signal Corps Engineering Laboratories, "Postwar Research and Development Program of the Signal Corps Engineering Laboratories, 1945," (Signal Corps, 1945), "Postwar R&D Program," HL R&D, HAUSACEC; John Q. Stewart, Michael Ference, John J. Slattery, Harold A. Zahl, "Radar Observations of the Draconids," Sky and Telescope 6 (March 1947): 3-5. They reported their later results in a paper, "Radar Observations of the Giacobinid Meteors," read before the December 1946 meeting of the American Astronomical Society in Boston. HL Diana 46 (26), HAUSACEC.
46. Wilbert F. Snyder and Charles L. Bragaw, Achievement in Radio: Seventy Years of Radio Science, Technology, Standards, and Measurement at the

National Bureau of Standards (Boulder: National Bureau of Standards, 1986), pp. 461-465; Ross Bateman, A. G. McNish, and Pineo, "Radar Observations during Meteor Showers, 9 October 1946," Science 104 (1946): 434-435; Pineo, "Relation of Sporadic E Reflection and Meteoric Ionization," Science 110 (1949): 280-283; Pineo, "A Comparison of Meteor Activity with Occurrence of Sporadic-E Reflections," Science 112 (1950): 50-51; Pineo and T. N. Gautier, "The Wave-Frequency Dependence of the Duration of Radar-Type Echoes from Meteor Trails," Science 114 (1951): 460-462. Other articles by Pineo on his ionospheric research can be found in Laurence A. Manning, Bibliography of the Ionosphere: An Annotated Survey through 1960 (Stanford: Stanford University Press, 1962), pp. 421-423.

47. Gillmor, "Federal Funding and Knowledge Growth in Ionospheric Physics, 1945-1981," Social Studies of Science 16 (1986): 124.

48. Oswald G. Villard, Jr., "Listening in on the Stars," QST 30 (January, 1946): 59-60, 120 & 122; Helliwell, Whistlers and Related Ionospheric Phenomena (Stanford: Stanford University Press, 1965), pp. 11-23; Leslie, p. 58; Gillmor, "Federal Funding," p. 129.

49. Manning, Helliwell, Villard, and Evans, "On the Detection of Meteors by Radio," Physical Review 70 (1946): 767-768; Manning, "The Theory of the Radio Detection of Meteors," Journal of Applied Physics 19 (1948): 689-699: Manning, Villard, and Peterson, "Radio Doppler Investigation of Meteoric Heights and

Velocities," Journal of Applied Physics 20 (1949): 475-479; Von R. Eshleman, "The Effect of Radar Wavelength on Meteor Echo Rate," Transactions of the Institute of Radio Engineers 1 (1953): 37-42. DeVorkin, pp. 287-288, points out that, when given an opportunity to make radio observations in coordination with rocket flights, Stanford declined.

50. Eshleman 9/5/94; Eshleman, "The Mechanism of Radio Reflections from Meteoric Ionization," Ph.D. diss., Stanford University, 1952; Eshleman, The Mechanism of Radio Reflections from Meteoric Ionization, Technical Report no. 49 (Stanford: Stanford Electronics Research Laboratory, 15 July 1952), pp. ii-iii & 3; Manning, "Meteoric Radio Echoes," Transactions of the Institute of Radio Engineers 2 (1954): 82-90; Manning and Eshleman, "Meteors in the Ionosphere," Proceedings of the Institute of Radio Engineers 47 (1959): 186-199.

51. Robert Desourdis, telephone conversation, 22 September 1994; Donald Spector, telephone conversation, 22 September 1994; Donald L. Schilling, ed., Meteor Burst Communications: Theory and Practice (New York: Wiley, 1993); Jacob Z. Schanker, Meteor Burst Communications (Boston: Artech House, 1990). For a civilian use of meteor burst communications, see Henry S. Santeford, Meteor Burst Communication System: Alaska Winter Field Test Program (Silver Spring, MD: U.S. Dept. of Commerce, National Oceanic and Atmospheric Administration, National Weather Service, Office of Hydrology, 1976.

52. Lovell 11/1/94; 7 & 8/55, "Accounts," JBA; Lovell,

"Astronomer by Chance," typed manuscript, February 1988, p. 376, Lovell materials; Lovell, Jodrell Bank, p. 157; G. Nigel Gilbert, "The Development of Science and Scientific Knowledge: The Case of Radar Meteor Research," in Gerard Lemaine, Roy Macleod, Michael Mulkay, and Peter Weingart, eds., Perspectives on the Emergence of Scientific Disciplines (Chicago: Aldine, 1976), p. 191; Edge and Mulkay, pp. 330-331.
53. Lovell, Clegg, and Ellyett, "Radio Echoes from the Aurora Borealis," Nature 160 (1947): 372; Aspinall and Hawkins, "Radio Echo Reflections from the Aurora Borealis," Journal of the British Astronomical Association 60 (1950): 130-135; various materials in File Group "International Geophysical Year," Box 1, File 4, JBA; McKinley and Millman, "Long Duration Echoes from Aurora, Meteors, and Ionospheric Back-Scatter," Canadian Journal of Physics 31 (1953): 171-181.
54. Currie, Forsyth, and Vawter, "Radio Reflections from Aurora," Journal of Geophysical Research 58 (1953): 179-200.
55. Hellgren and Meos, "Localization of Aurorae with 10m High Power Radar Technique, using a Rotating Antenna," Tellus 3 (1952): 249-261; Harang and Landmark, "Radio Echoes Observed during Aurorae and Geomagnetic Storms using 35 and 74 Mc/s Waves Simultaneously," Journal of Atmospheric and Terrestrial Physics 4 (1954): 322-338; ibidem Nature 171 (1953): 1017-1018; Harang and J. Tröim, "Studies of Auroral Echoes," Planetary and Space Science 5 (1961): 33-45 & 105-108.

56. Jean Van Bladel, Les applications du radar à l'astronomie et à la météorologie (Paris: Gauthier-Villars, 1955), pp. 78-80; Neil Bone, The Aurora: Sun-Earth Interactions (New York: Ellis Horwood, 1991), pp. 36, 45-49; Alistair Vallance Jones, Aurora (Boston: D. Reidel Publishing Company, 1974), pp. 9, 11 & 27; Lovell, "Astronomer by Chance," manuscript, February 1988, p. 201, Lovell materials.
57. DeWitt and Stodola, p. 239.
58. Kerr, Shain, and Higgins, "Moon Echoes and Penetration of the Ionosphere," Nature 163 (1949): 310; Kerr and Shain, "Moon Echoes and Transmission through the Ionosphere," Proceedings of the IRE 39 (1951): 230; Kerr, "Early Days in Radio and Radar Astronomy in Australia," pp. 136-137 in Sullivan. Kerr and Shain, pp. 230-232, contains a better description of the system. See also Kerr, "Radio Superrefraction in the Coastal Regions of Australia," Australian Journal of Scientific Research, ser. A, vol. 1 (1948): 443-463.
59. D. D. Grieg, S. Metzger, and R. Waer, "Considerations of Moon-Relay Communication," Proceedings of the IRE 36 (1948): 660.
60. Kerr, Shain, and Higgins, p. 311.
61. Kerr and Shain, pp. 230-242.
62. Murray and Hargreaves, "Lunar Radio Echoes and the Faraday Effect in the Ionosphere," Nature 173 (1954): 944-945; Browne, Evans, Hargreaves, and Murray, p. 901; 1/17 "Correspondence Series 7," JBA; Lovell, "Astronomer by Chance," p. 183.
63. Evans 9/9/93; Hargreaves, "Radio Observations of

the Lunar Surface," Proceedings of the Physical Society 73 (1959): 536-537; Evans, "Research on Moon Echo Phenomena," Technical (Final) Report, 1 May 1956, and earlier reports in 1/4 "Correspondence Series 2," JBA.

64. Evans 9/9/93; Evans, "The Scattering of Radio Waves by the Moon," Proceedings of the Physical Society B70 (1957): 1105-1112.

65. Evans 9/9/93; Edge and Mulkay, p. 298; Materials in 1/4 "Correspondence Series 2," and 2/53 "Accounts," JBA. With NASA funding, Jodrell Bank later participated in the Echo balloon project.

66. Harold Sobol, "Microwave Communications: An Historical Perspective," IEEE Transactions on Microwave Theory and Techniques MTT-32 (1984): 1170-1181.

67. Grieg, Metzger, and Waer, pp. 652-663; "Via the Moon: Relay Station to Transoceanic Communication," Newsweek 27 (11 February 1946): 64; Sulzer, Montgomery, and Gerks, "An U-H-F Moon Relay," Proceedings of the IRE 40 (1952): 361. A few years later, three amateur radio operators, "hams" who enjoyed detecting long-distance transmissions (DXing), succeeded in bouncing 144-Mhz radio waves off the moon, on 23 and 27 January 1953. E. P. T., "Lunar DX on 144 Mc!" QST 37 (1953): 11-12 & 116.

68. Gebhard, pp. 115-116; James H. Trexler, "Lunar Radio Echoes," Proceedings of the IRE 46 (1958): 286-288.

69. NRL, "The Space Science Division and E. O. Hulburt Center for Space Research, Program Review," 1968, NRLHRC; Yaplee, R. H. Bruton, K. J. Craig, and Nancy G.

Roman, "Radar Echoes from the Moon at a Wavelength of 10 cm," Proceedings of the IRE 46 (1958): 293-297; Gebhard, p. 118.

INDEX PAGE