CHEN-PANG YEANG*

The study of long-distance radio-wave propagation, 1900-1919

GUGLIELMO MARCONI' S TESTS of the trans-Atlantic wireless telegraphy made sensational news at the turn of the 20th century. Since the early 1890s, the Italian-born inventor-entrepreneur had established radio communication links spanning as far as the English Channel but what he did in 1901 was unprecedented. He attempted to exchange telegraphic signals between Britain and North America without submarine cables or other mediation. Marconi's moment came on December 12. Sitting in a station on a hill in Newfoundland, Canada, Marconi and his assistant George Kemp heard regular sharp clicks from earphones connected to the receiving apparatus. They had heard a wireless message transmitted from the high antenna tower energized by a spark-gap circuit located at Poldhu, England. The New York Times quickly featured Marconi's story.[1]

* Dibner Institute for the History of Science and Technology, and Program in Science, Technology, and Society, Massachusetts Institute of Technology, 38 Memorial Drive, Cambridge, MA 02139 (cpyeang@mit.edu).

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The following abbreviations are used: *AP, Annalen der Physik;* DM, Deutches Museum Archiv, Munich; (http://www.lrz-muenchen.de/~Sommerfeld/ for the archives Sommerfeld documents); *Obit,* Royal Society of London, *Obituary notices of fellows*; *PRS,* Royal Society of London, *Proceedings.*

1. Orrien E. Dunlap, *Marconi, the man and his wireless* (New York, 1937), 87-102, and Degna Marconi, *My father Marconi* (New York, 1962), 111-120.

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The trans-Atlantic wireless test not only caught the attention of the general public, corporate capitalism, and the electrical industry for its technological implications, but also raised a curious scientific question. To establish a link across a distance as long as one sixth of the earth's perimeter, the wireless waves had to travel along a path conforming to the curved surface of the earth. Why do wireless waves, which behave much like optical and acoustic waves, not follow rectilinear trajectories? Why does the curvature of the earth not block them?

This paper shows how these problems were turned into mathematical representations, and how the empirical observations made by industrial practitioners evolved toward quantitative experimental data. It explores how engineering technologies affected experimental investigations, how traditions of applied mathematicians shaped numerical problems and approaches, and how theoretical tendencies of late-19th-century microphysics directed the formation of physical models. It also discusses how the problem of long-distance transmission emerged as a conjunction of distinct collective cultures, and how these cultures meshed with broader social contexts.

Two alternative theories of the peculiarly long transmission were proposed: the wave propagating along the surface results from diffraction by the body of the earth; and the wave bounces back and forth between the earth's surface and a conducting layer in the upper atmosphere. While theorists discussed these alternatives, experimenters worked on constructing empirical quantitative relations among the physical variables involved in long-distance transmission.

Three communities of researchers may be identified. European mathematical physicists and mathematicians worked on diffraction theories and developed mathematics to convert the diffracted fields into numerically tractable forms. Anglo-American electrical engineers and experimental physicists focused on atmospheric reflection and explored the conducting properties of the air. American wireless telegraphers established the empirical formula governing the relation between received wave intensity and distance for given wavelengths. It proved difficult to decide between the two theoretical models. The quantitative predictions of the diffraction theorists disagreed with the empirical formula. The reflection theorists could explain the bending of the waves and static noise qualitatively, but could not make quantitative predictions. The indeterminacy ended in 1919 when the English mathematician George Neville Watson developed a new mathematical technique for the diffraction theories and used it to demonstrate the superiority of the reflection approach.

The three different practices were significantly shaped by distinct intellectual traditions, purposes, and research styles. The long-distance radio experiments related to pragmatic instrumentality in wireless engineering: to test the validity of high-power transmitters and sensitive radio detectors for the first long-range radio station of the U.S. Navy. The mathematics of series or integral approximations used in the diffraction theories incorporated then recently developed complex-variable analysis in mathematics. The reflection model, which began as a speculation among electrical researchers, became part of the Maxwellian-microphysics agenda.

These communities worked toward different goals, legitimized different methodologies, and gave priority to different technical and social concerns.

Diffraction theorists and the reflection modelers did not compete directly; their practices, and those of the experimenters, exhibited more complementary than competitive elements. Although the three communities were tied together by the same question (the possibility of long-distance radio-wave transmission), the most important aspect of their intertwined history was not the mutually exclusive and competitive answers they reached, but their contributions of different pieces of knowledge eventually subsumed in the solution.

The three communities' essential differences and the intellectual content of their interactions may be understood by analyzing their epistemic status—their judgments about what was known, what was important to know, and possible to know. Here reference to the teachings of Pierre Duhem and Sylvain Bromberg are in order. Duhem distinguished two aims of a physical theory: [to explain] a group of laws experimentally established, and "to *summarize* and *classify logically* a group of experimental laws without claiming to explain these laws. "[2] Duhem's mathematical calculus for organizing scientific knowledge included quantitative and logical reasoning, numerical predictions, and recursive revision. Similarly, Bromberger distinguished theory as an intellectual device that could systematically generate answers to questions from theory as an answer to a why question.[3] Following Duhem's and Bromberger's theories of epistemic status, analyzing what is known, important to know, and possible to know amounts to deciding whether, for the historical actors, a piece of knowledge is explanatory or representational, an answer to a question or a part of a question-answering device.

The essential distinction between the diffraction theorists and the reflection theorists concerned the kinds of questions asked and the kinds of knowledge required, not the mutual exclusiveness of their physical models. The diffraction theorists developed rigorous mathematical theories to represent a physical model that aimed to account for only one wireless phenomenon—long-distance propagation. For this single phenomenon, they could mobilize quantitative reasoning and consolidate numerical predictions from mathematical theories. The reflection theorists constructed elaborate physical models to account for several significant wireless phenomena—not only long-distance transmission but also the diurnal and seasonal variations of signals and atmospheric noise. But their mathematical tools lagged much behind the diffraction theorists'. The diffraction theorists asked questions about mathematical tractability. The reflection theorists asked questions about the causes of various puzzling observations. Their theories were mainly explanations. But until a late stage they did not contain a systematic means for giving qualitative or quantitative predictions.

2. Pierre Duhem, *The aim and structure of physical theory* (Princeton, 1982), 7.
3. Sylvain Bromberger, "A theory about the theory of theory and about the theory of theories," in Bromberger, *On what we know we don't know: Explanation, theory, linguistics, and how questions shape them* (Chicago, 1992), 52-74.

The epistemic approach helps to understand the activities of the experimenters as well. The questions they asked were practical—they wanted to know the performances of transmitters and receivers under operating conditions in order that the U.S. Navy's first long-distance wireless would function properly. They were not motivated by theory-driven questions to conduct experiments. Likewise, their measured results served as reference for engineering specifications rather than as tests of theories. Because, however, the physics-trained experimenters believed that representing the measured results in terms of a mathematical formula, which was much more convenient than raw numbers for the theorists to work with, served engineering, they did provide material for checking theoretical predictions.

1. EMPIRICAL OBSERVATIONS

Guglielmo Marconi invented a transmitter and receiver for wireless telegraphy in the 1890s. Oliver Lodge in Britain, Alexander Popoff in Russia, Edouard Ducretet in France, and Ferdinand Braun in Germany made similar inventions about the same time.[4] The European and American governments, commercial and industrial enterprises, and inventors, engineers, and scientists quickly recognized the potential of these devices. Numerous sophisticated novel technologies of wireless telegraphy were developed between 1895 and 1920.

To the engineering communities, the primary concern with wireless telegraphy was the improvement of transmitters, receivers, and techniques of measurements.[5] They were not as successful in modeling the process of wave transmission as in engineering transmitters and receivers. They had too little information about wave propagation in the real world for which they intended the devices. To proceed, they needed to establish the empirical phenomena of wireless wave transmission. That task began only in the first few years of the 20th century.

The empirical problem may be stated as follows: under what environmental or instrumental conditions does the propagated electromagnetic energy experience a certain amount of change. The relevant major phenomena discovered before 1910 consisted of:

• Marconi's achievement of wireless communications over one sixth of the earth.

• The effect of the terrain. The maximum effective transmission distance of a wireless wave is the longer the greater the ground conductivity; thus a wave over sea usually propagates farther than one over land. The British naval officer Henry Bradwardine Jackson deduced the effect from experiments conducted on his own while serving on British warships between 1899 and 1902.[6]

4. Hugh G.J. Aitken, *Syntony and spark: The origins of radio* (New York, 1976), 198.
5. E.g., Jonathan Adolf Wilhelm Zenneck, *Wireless telegraphy* (New York, 1915); John Ambrose Fleming, *The principles of electric wave telegraphy and telephony* (London, 1916).
6. Henry B. Jackson, "On the phenomena affecting the transmission of electric waves over the surface of the sea and the earth," *PRS, 70* (1902), 254-272.

• A wave goes further in dry than in humid air (Jackson).

• The maximum effective distance at night exceeds that in daytime (Marconi).[7]

• Noise, "static," or "stray wave" is more serious at night than in daytime (Jackson), during the summer than during the winter (Jackson), and at low than at high latitudes (Popoff, Feriyi, and Turpain).[8]

• The received energy generally increases with the length of the wave and the arrangement of the antenna.

• The radiation pattern of an antenna system can be different at different directions. A vertical aerial receives maximum energy when tilted along the transmission direction; several aerials with identical phase delay can give a strongly directional transmission (Marconi, Zenneck, Sigsfeld, Braun).[9]

Until 1905, the antenna consisted of a long vertical conducting wire connected at its lower end to a spark gap. The amplitude of received current is independent of the direction of the receiver's location with respect to the antenna, provided the receiver is on the ground. In 1906, Marconi suggested that a directional effect antenna could be obtained with a horizontal antenna.[10] The received current attains the maximum when the transmitter-receiver direction lies along the direction of the transmitter or the receiver antenna. Typically, reception is a minimum at angles of 110° or 250°. The minimum loci and the shape of the radiation pattern vary with antenna parameters. Figure 1 illustrates two of the radiation patterns Marconi measured.

Many of the empirical observations were qualitative descriptions that made either ontological assertions identifying physical factors relevant to the propagation of electromagnetic waves or quasi-quantitative comparative statements linking propagation with increase or decrease of a physical quantity. Quantitative descriptions of the empirical observations existed as tabulated data, not mathematical formulas. However far this phenomenological knowledge was from ideal sci entific evidence, theorists had no choice but to use them as empirical evidence for their theories. Rigorous and controlled quantitative experiments on long-distance wave transmission remained to be done.

7. Dunlap (ref. 1), 122-127; Guglielmo Marconi, "A note on the effect of daylight upon the propagation of electromagnetic impulses over long distances," *PRS, 70* (1902), 344-347.

8. See Fleming (ref. 5), 851-852.

9. Guglielmo Marconi, "On methods whereby the radiation of electric waves may be mainly confined to certain directions, and whereby the receptivity of a receiver may be restricted to electric waves emanating from certain directions," *PRS, 77* (1906), 413-421; Ferdinand Braun, "On directed wireless telegraphy," *Electrician, 57* (1906), 222-224, 244-248. Cf. Friedrich Kurylo and Charles Susskind, *Ferdinand Braun: A life of the Nobel prizewinner and inventor of the cathode-ray oscilloscope* (Cambridge, 1981), 134, 143, 170.

10. Marconi (ref. 9).

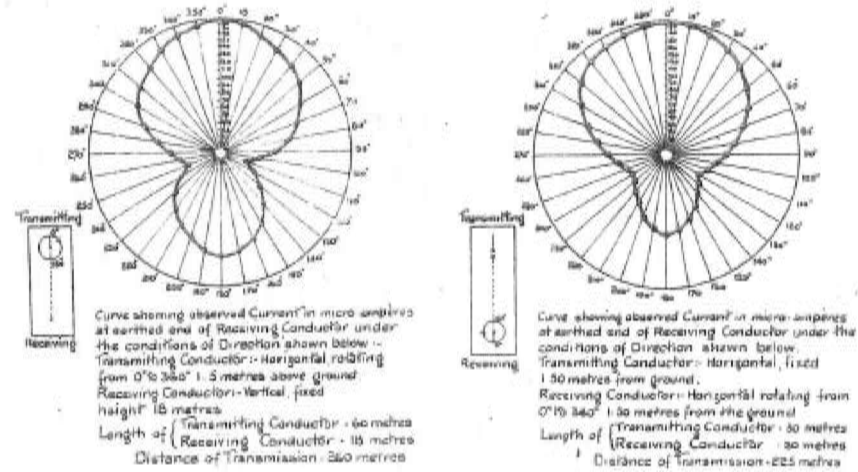

FIG. 1 The radiation patterns of Marconi's directive antenna. Left panel, the transmitter's antenna rotates from 0° to 360°; right panel, the receiver's antenna rotates from 0° to 360°, Marconi (ref. 9), figs. 2, 4.

2. SURFACE DIFFRACTION THEORIES

The British initiative

To the community of physicists in the late 19th century, the phenomenon of long-distance wireless wave transmission was not altogether unfamiliar. The physical picture associated with this phenomenon could be found in the physical optics of diffraction and in acoustic scattering theory. Lord Rayleigh had developed a set of analytic techniques to deal with the acoustic problem.[11]

Between 1901 and 1919, two groups of mathematical physicists and mathematicians developed Rayleigh's approach for application to radio-wave transmission. One was a British group at Cambridge University plus the French mathematician Henri Poincaré. The other group was led by the mathematical physicist Arnold Sommerfeld at the University of Munich and the German electrical engineer Jonathan Zenneck.

Hector Munro Macdonald received a bachelor's degree at the University of Aberdeen before moving to Cambridge University, where he became fourth Wrangler in the Mathematical Tripos of 1889. His research agenda was set by the Adams Prize problem of 1901: to describe the propagation of electromagnetic waves under a number of boundary conditions with simple geometry. Published in 1902 as *Electric waves*, Macdonald's prize-winning essay applied an electromagnetic theory based on an energy expression to study the effect of an antenna on its electrical oscillating frequencies, and to solve the diffraction field at the edge of a perfectly

11. John William Strutt, *The theory of sound* (New York, 1945).

conducting prism.[12] When the news of Marconi's trans-Atlantic transmission spread in 1901, Macdonald was ready to work out a theoretical account of the phenomenon based on diffraction model.

Macdonald's paper of 1903 begins with a simple model that included all the supposedly relevant physical characteristics of wireless wave transmission.[13] The transmission antenna appears as a vertically polarized point current source, the so-called "Hertzian dipole," above the ground. Macdonald treated the atmosphere as free space with uniform dielectric constant and permeability and zero conductivity, and the earth as a perfect conductor (figure 2). The model captured some reality; but also erred seriously in giving the atmosphere no role (different from free space) in wave transmission. All diffraction theorists after Macdonald began their theoretical work by imposing the assumption.[14]

To calculate the intensity of the electric and magnetic fields at any point on the earth, Macdonald solved Maxwell's equations for the electromagnetic fields. He wrote down the wave equation for the azimuthal component of the magnetic field intensity in spherical coordinates (the axis of the azimuth is the radius connecting the earth's center and the dipole's location). Following Rayleigh's *Theory of sound*, Macdonald expressed the solution as a series of Bessel-Hankel functions and Legendre polynomials.[15] He determined the coefficients of the terms in this series from the conditions that the field intensity be infinite at the location of the Hertzian dipole and the tangential component of the electric field at the surface of the perfect conducting earth should vanish.[16]

The diffraction theorists in the first twenty years of the 20th century agreed with all Macdonald's arguments up to this point. They disagreed about how to approximate the analytical solution in a numerically tractable form. Macdonald noticed that the problem had exactly the same form as one dealt with in Rayleigh's *Theory of sound*. Following Rayleigh, Macdonald exploited the asymptotic properties of Hankel functions to establish that when the wavelength λ is much smaller than the radius of the earth a, the field intensity obeys a simple relation. The ratio of the electric field at the sphere's surface at the separation angle θ (the angle between the oscillator P and the point of observation C as seen from the earth's center) to the electric field at $\theta=0°$ is $1-\cos\chi$, χ being the angle between the observer and the earth's center as seen from the dipole.[17]

This overly succinct result implies that the electric field produced by a Hertzian dipole does not vanish at any point on the earth, including the diametrically opposite point, $\chi = 0°$. It means that the earth never casts any shadow on the propa-

12. *Obit., 11* (1935), 553-555.

13. Hector Munro Macdonald, "The bending of electric waves round a conducting obstacle," *PRS, 71* (1903), 251-258.

14. Some of them later assigned the earth a finite conductivity and dielectric constant, but others continued to work on the perfect-conductor case.

15. Strutt (ref. 11), chapt. 17.

16. Ibid, 253.

17. Ibid, 255.

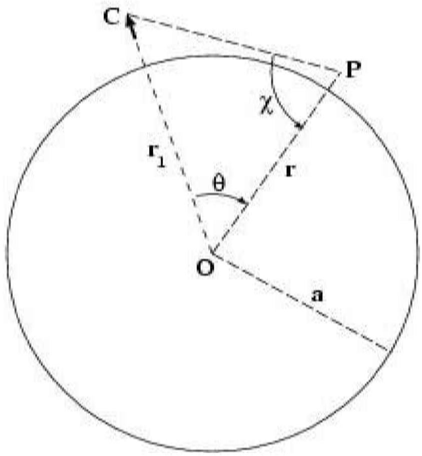

FIG. 2 Spherical boundary condition of the diffraction theory. The sphere represents the earth, the small arrow at C the transmission antenna modeled as a vertically polarized Hertzian dipole; the observer is at P.

gation of the electromagnetic field. The field can travel anywhere on the earth. Thus the magic of trans-Atlantic wireless transmission: the field diffracts across the surface of the earth. Macdonald considered this conclusion to be a complement to Rayleigh's discovery in acoustics.[18]

Unfortunately, Macdonald's approximation scheme had a serious problem, which Rayleigh pointed out. Rayleigh claimed that a shadowless wireless wave could not move around the earth since it would lack analogy to the optical case. The wavelength of the wireless wave (less than 50 kilometers) had about the same ratio to the radius of the earth as the wavelength of visible light had to one inch; but the light shining on a conducting ball one inch in radius does not creep around the ball to illuminate its rear surface. Furthermore, Rayleigh points out that Macdonald's asymptotic approximation did not in fact hold when the wavelength is much smaller than the radius of the sphere owing to a property of the Bessel functions that need not be detailed here.[19] Henri Poincaré also pointed out the difficulty with Macdonald's asymptotic approximation.[20]

In the following decade, the mathematical problem of how to approximate the exact solution of the diffracted field given by Macdonald was widely discussed among mathematicians and mathematical physicists, who proposed new approaches to the notorious Bessel functions. None of these efforts survived criticism. Discus-

18. Ibid, 328.
19. John William Strutt, "On the bending of waves around a spherical obstacle," *PRS, 72* (1904), 40-41.
20. Henri Poincaré, "Sur la diffraction des ondes electriques: Àpropos d'un article de M. Macdonald," *PRS, 72* (1904), 42-52.

sion of the problem was dominated by Cambridge-trained people—and by Henri Poincaré.

Poincaré tried to work out an adequate and rigorous approximate solution for the mathematical problem formulated by Macdonald. He worked at it from 1909 until his death in 1912, publishing nine papers in all, including a 100-page monograph published in 1910.[21] Poincaré's strategy was to convert the infinite series obtained by analytically solving the wave equation into a definite integral and to employ Cauchy's residue theorem to evaluate it. Like Macdonald, Poincaré expressed the analytical solution of the wave equation in terms of a series of spherical harmonics constituted of Bessel functions and Legendre polynomials. In the case of a dipole on the ground, the infinite series can be converted into a sum of integrals associated with the poles of the spherical harmonics. When the size of the conductor is much larger than the wavelength, the term corresponding to the pole with the smallest imaginary part dominates the other terms. Poincaré proved that the dominant-pole contribution to the field intensity on the spherical surface is proportional to $\exp[-\rho(ka)^{1/3}\theta]$, where θ is the angle defined in figure 2, $k=2\pi/\lambda$ is the earth's radius and ρ is an unspecified constant. The field intensity produced by a Hertzian dipole on a spherical conductor has the form of exponential decay with respect to the separation angle.[22]

Poincaré's work involved esoteric theories of Bessel functions and complicated mathematical manipulations. But its conclusion had a clear and straightforward physical meaning: the diffraction field on a conducting sphere decays exponentially: the larger the wavelength, the longer the transmission distance. Four years after Poincaré published his important formula, a debate broke out over whether the field's decay rate varied with $\lambda^{1/3}$, as required by his theory, or with $\lambda^{1/2}$, as revealed from experiment. But Poincaré's result also was incomplete. It did not specify the numerical values of the decay rate γ and the amplitude constant. Without these values, the mathematical theory of diffraction could not produce quantitative results strictly comparable to the experimental data. The task of obtaining the missing numerical value of the decay rate fell to John William Nicholson.

Nicholson, Cambridge Wrangler began to publish on the diffraction problem in 1910. He opened with a criticism of Poincaré's method.[23] Poincaré had not carried out the asymptotic approximation of the Bessel functions correctly, and his procedure for converting the infinite series to an integral was not adequately rigorous. Nonetheless, like Poincaré Nicholson converted the series into an integral and obtained its approximate value by the contribution from the dominant pole. He examined the pole structures of the functions and concluded that for $ka>>1$, the magnetic field intensity is dominated by the contribution from the zero of the de-

21. Henri Poincaré, "Sur la diffraction des ondes hertziennes," Circolo matematico di palermo, *Rendiconti, 29* (1910), 169-259.

22. Ibid, 201.

23. John William Nicholson, "On the bending of electric waves round the earth," *Philosophical magazine, 19* (1910), 276.

rivative of the Hankel function with the smallest imaginary part. The imaginary part of this zero has the form of $\rho(ka)^{1/3}$. Thus the approximate field is proportional to $\exp[-\rho(ka)^{1/3}\theta]$.

This conclusion is the same as Poincaré's. In addition, Nicholson solved for the numerical value of the attenuation coefficient ρ and obtained the value 0.696. Having this numerical information, Nicholson constructed tables providing quantitative predictions of the diffracted electromagnetic waves around the earth.

No quantitative experimental data on wireless wave transmission were available when Nicholson finished his calculation. Still he could make a definitive and surprising statement: "diffraction must be a relatively insignificant agency in the success of experiments such as those of Marconi."[24] Nicholson's confidence came from a dramatic discrepancy between the numerical scale of the diffraction theory and that of Marconi's experiment. The exponential decay at $0.696(ka)^{1/3}$ made the diffracted field diminish much faster than it should have done if diffraction was responsible for long-distance wave transmission. Although Nicholson continued to work on the diffraction theory for a few years, he no longer believed that it could explain long-distance transmission. He thought that reflections from the upper atmosphere offered a more plausible theory.

Nicholson's conclusion did not destroy the diffraction theory. His mathematical solution to Macdonald's predicament was not the final one. Other mathematicians developed different methods that generated numerical results different from his. Also, while the British-French diffraction theorists all stuck to the assumption that the earth can be modeled as a perfect conductor, which guides the diffracted field around the earth, the German diffraction theorists did not focus only on this case.

German follow-up

In Germany, a group of diffraction theorists worked on the problem of wireless-wave transmission over ground. They believed that finite ground conductivity played a role in several wireless phenomena. They assumed that a "surface wave'' would rise above the ground and creep along the ground surface. The finite ground conductivity could modify the polarization of the wave. The German diffraction theorists during the 1900s and the 1910s included an electrical engineer, Jonathan Zenneck, at Braunschweig, the theoretical physicist Arnold Sommerfeld, and his protégés at the University of Munich.

In 1889, while pursuing his doctoral degree at the University of Tübingen, Zenneck became assistant of Ferdinand Braun, a pioneer of radio research in Germany. During their work together (1892 to 1906) Braun's research group competed fiercely with Marconi's team. In 1899, Braun launched experiments on long-distance wireless telegraphy in the Cuxhaven region near Hamburg. Zenneck was

24. John Nicholson, "On the bending of electric waves round a large sphere: III," *Philosophical magazine, 21* (1911), 67-68.

deeply involved in the Cuxhaven project. By 1905, Zenneck had become an authoritative figure in the community of telegraphy engineer. In 1906, he became a professor at the Braunschweig Technical University.[25]

Zenneck's first work of interest here concerned wave propagation along an infinite planar interface between the air and a conductor (figure 3).[26] The novelty of Zenneck's approach in comparison with the British theorists did not lie only in the geometry. In contrast to previous work, he did not use any information about the dipole oscillator to solve the overall field generated by the source and shaped by the boundary condition. He supposed a particular form for the electric and magnetic fields and confirmed that it satisfied Maxwell's equations and the boundary condition. This form was a plane wave with field components containing a factor $\exp[i(\omega t+sx)]$, where ω is the angular frequency and s is the wave number in the horizontal direction. Plugging these expressions into Maxwell's equations and the boundary condition, he found that the field quantities above the surface are pro portional to $\exp[i(\nu t+sx-r_0z)]$, and those below the surface to $\exp[i(\nu t+sx+r_1z)]$, where $r_0=(k_0^2-s^2)^{1/2}$ and $r_1=(k_1^2-s^2)^{1/2}$, and k_0 ands k_1 are the wave numbers in the air and on the ground, respectively. The values of s, r_1, and r_0, all obtained by solving simple algebraic equations, are determined by the dielectric constants and conductivities of the air and the ground. They were complex numbers.

The physical implications of Zenneck's field solution are extraordinary. First, unlike the optical plane waves in free space, Zenneck's wave not only propagates but also attenuates along both the x and z directions. In addition, the polarization of Zenneck's wave is determined by the ground conductivity and dielectric constant. In contrast to free-space plane waves, the polarization of Zenneck's waves cannot be chosen freely.

When the ground conductivity is finite (in the scale of earth, stone, or sand conductivity), the polarization direction of Zenneck's wave inclines along the direction from which the wave comes. Zenneck pointed out that Marconi's experimental results on the directive antenna agreed with this finding. Marconi discovered that the receiving antenna receives maximum power when the aerial inclines along the line of sight between the transmitter and the receiver. According to Zenneck's theory, the finite ground conductivity causes the direction of polarization of the propagating wireless wave to incline toward the direction of propagation; the antenna has maximum efficiency to convert the field into an oscillating current when it aligns with the polarization direction of the field (figure 4).

The attenuation of Zenneck's wave along the propagation direction reaches its maximum at a finite ground conductivity. When the conductivity is either zero or infinite, the attenuation is zero. A ground with high resistance (a dielectric material) could support long-distance propagation. Zenneck also showed that the at-

25. Kurylo and Susskind (ref. 9), 73-74, 130-173.
26. Jonathan A.W. Zenneck, "Über die Fortpflanzung ebener elektromagnetischer Wellen längs einer ebenen Leiterfläche und ihre Beziehung zur drahtlosen Telegraphie," A*P, 23* (1907), 846-866.

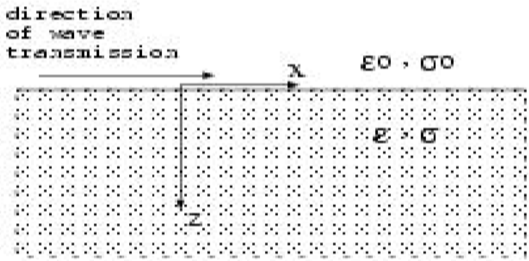

FIG. 3 Zenneck's boundary condition.

tenuation decreases with wavelength and is much more serious along the vertical than along the propagation direction. The field intensity decreases to 1/*e* of the original intensity at z=0 in some centimeters along the vertical and in some kilometers along the horizontal. Most of the energy is concentrated near the air-ground boundary; Zenneck's wave is a "surface wave."

Zenneck's work provided a novel insight. Unlike the British and French diffraction theorists, who held that the shape of the earth enabled long-distance wave propagation, Zenneck suggested that the ground resistance also played a critical role. Nonetheless, his paper of 1907 could not be considered as a complete work. "Zenneck's wave" is only one possible solution of the Maxwell's equations and the boundary conditions, not necessarily the solution describing physical reality. In contrast to the British diffraction theory, Zenneck's approach did not specify the source that generated his wave; we not only have no idea how to generate it, we do not know whether it can be generated at all! Enter Arnold Sommerfeld.

Sommerfeld had worked on optical diffraction before he took up radio waves. His novel approach of converting the solution of a differential equation with a proper boundary condition into a closed-form complex integral suitable for numerical evaluation would become a hallmark of his work.[27] He published his first paper on the Hertzian waves in 1899.[28] It studied the propagation of electromagnetic waves along a conducting wire. Sommerfeld demonstrated that as current flows in the wire, the Hertzian wave it produces also propagates along the wire. Once electrical phenomena were conceived in terms of waves in the aether, there was no essential difference between the wired and the wireless. Since the energy transfer associated with the flow of an electric current in a wire could be understood as the propagation of an aetherial wave along the wire, it was reasonable to understand a wave propagating above ground in terms of a flow of energy guided by the ground.

27. Paul Forman, "Arnold Sommerfeld," in *Dictionary of scientific biography, 12* (New York, 1975), 526-529; Arnold Sommerfeld, "Autobiographische Skizze," in Sommerfeld, *Gesammelte Schriften, 4* (Braunschweig, 1968), 673-682.
28. Arnold Sommerfeld, "Über die Fortpflanzung elektrodynamischer Wellen längs eines Drahtes," *AP, 67* (1899), 233-290.

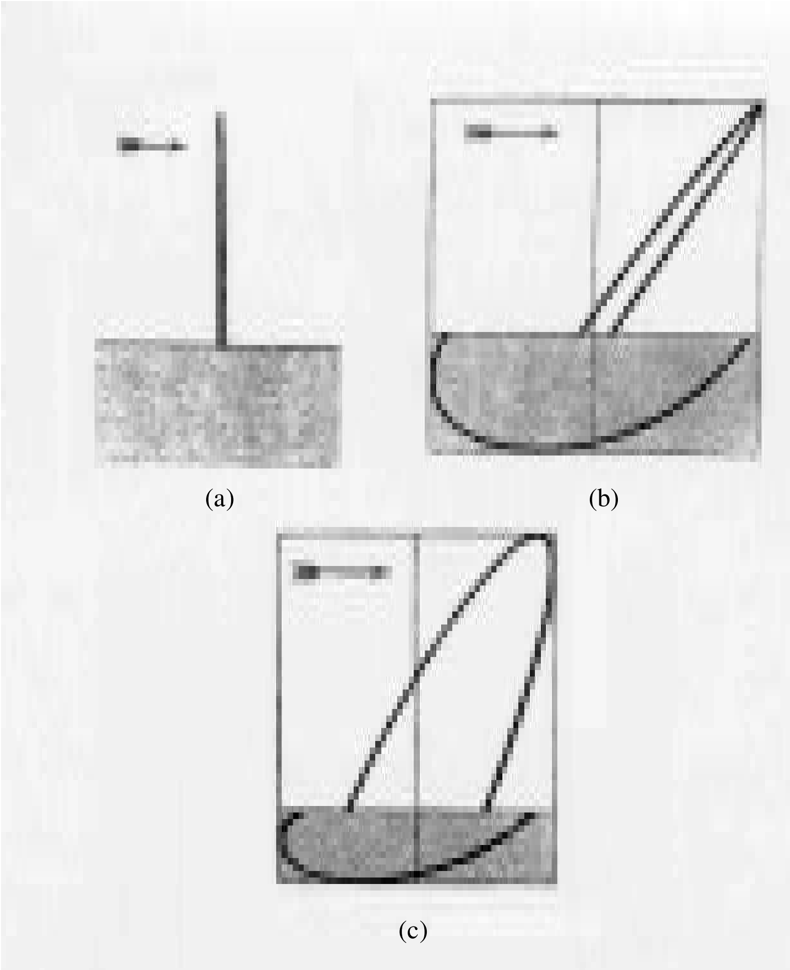

FIG. 4 The polarization diagrams of Zenneck's waves. (a) large ground conductivity; (b) small ground conductivity and dielectric constant; (c) moderate ground conductivity and small ground dielectric constant; The arrows denote the direction of wave transmission. Zenneck (ref. 26), figs. 4-6.

Sommerfeld recognized that he could resolve the questions how or whether Zenneck's surface wave could be produced by the mathematical techniques he had developed in the mid-1890s to tackle diffraction problems and wired waves. In 1909 Sommerfeld showed that Zenneck's "surface wave" could be generated by a vertically polarized Hertzian dipole oscillator located above the flat conducting surface.[29]

29. Arnold Sommerfeld, "Über die Ausbreitung der Wellen in der drahtlosen Telegraphie," *AP, 28* (1909), 665-736.

Sommerfeld's problem has the same geometry condition as Zenneck's: an infinite flat interface separating the conducting material below and the air above. But different from Zenneck, he put a vertical Hertzian dipole on the ground as the source of waves. To solve the problem with his Hertzian radiator, Sommerfeld expanded the Hertzian potential in terms of a set of basis functions more convenient for mathematical manipulations than Macdonald's. However, Sommerfeld's expansion is not a discrete sum of spherical harmonics with various half-integer orders. As was typical of his mathematical approach in the 1890s, it was an integral expansion involving only the Bessel function of order 0. The different choices of expansion led to an essential difference between the British-French and the German theories of diffraction. Sommerfeld noticed that any cylindrical wave in the form of $CJ_0(q\ r)\exp[(q^2-k^2)^{1/2}z]$, is a solution of the wave equation where q is a free parameter and J_0, is the 0th order Bessel function. Sommerfeld's solution of the Hertzian potential has the form of an integral expansion of cylindrical waves over q.

To evaluate this integral, Sommerfeld used Cauchy's residue theorem to convert the integral over the entire real axis into a contour integral over the entire complex plane. The integral came out as the sum of three terms; one of which had the same form as Zenneck's surface wave. Furthermore, the other terms became insignificant at long distance. In short, Sommerfeld proved that Zenneck's surface wave is the asymptotic solution of the diffracted field produced by a vertically polarized Hertzian dipole sitting just above the flat boundary surface.

The German diffraction theory differed from the British-French rival by indirectly showing that not only the geometric shape of the boundary surface but also the resistance of the ground affect the transmission distance. Moreover, Sommerfeld's approach to the diffraction problems created a unique tradition of practices. Expanding the field with respect to an integral of cylindrical waves differed significantly from the common technique that expanded the field over a sum of discrete-order spherical harmonics. Sommerfeld knew that his approach engendered many problems, which he gave to his students at the University of Munich. Herman William March wrote a thesis in 1911 extending Sommerfeld's integral approach to the diffracted wave along a spherical conductor. Witold von Rybczynski wrote on a similar topic in 1913.

3. ATMOSPHERIC REFLECTION HYPOTHESES

A few very important phenomena could not be explained by a surface wave that depends solely upon the characteristics of the ground. The moisture effect, the daylight effect, and "stray rays" all strongly suggested that the propagation of an electromagnetic wave has to do with air as well as ground. This consideration lay behind the theory that extended wave transmission arises from reflection of electromagnetic waves by an electrically conducting layer in the upper atmosphere. Around 1902, Oliver Heaviside, Arthur Edwin Kennelly, André Blondel, Henri

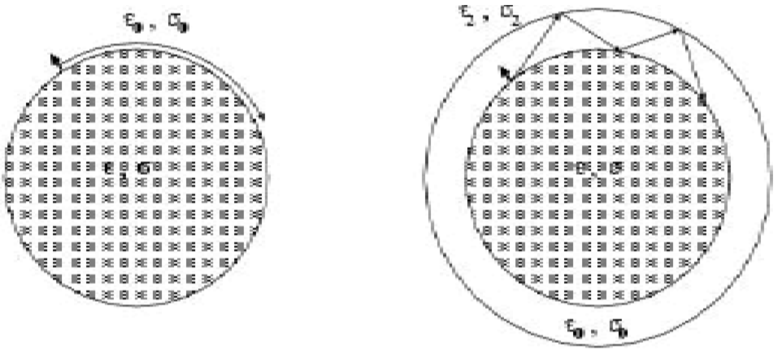

FIG. 5 The surface-diffraction model (left panel) versus the atmospheric-reflection model (right panel); the thicker arrow gives the direction of the Hertzian oscillator, the lighter arrows the direction of wave propagation.

Poincaré, and Charles-Edouard Guillaume all considered the possibility of atmospheric reflection.[30] But only Heaviside and Kennelly published their ideas.

Oliver Heaviside, a self-educated theorist unaffiliated with any academic institute, developed a mathematical model for telegraph-signal transmission, a new formulation of Maxwell's theory, and the technique of operational calculus for solving linear ordinary differential equations.[31] He never studied wireless telegraphy seriously. But his work on wired signal transmission played a significant heuristic role in his thought on the transmission of wireless waves.

In 1901, Heaviside was studying the electromagnetic field patterns produced by an electrical signal transmitted through a coaxial cable. He obtained the electromagnetic field by solving Maxwell's equations for the boundary condition specified. Additionally, he made various geometric metamorphoses of the coaxial cable to other mathematically tractable structures, for example, transformation of the cylindrical condition to a point source sitting on top of a large hemisphere surrounded by another hemisphere.[32] He found that this structure can support the transmission of waves along the curved surfaces and conjectured that the same mechanism accounted for Marconi's wireless signals across the Atlantic Ocean.

He published this idea in 1902, in a short paragraph in an introductory article on telegraphy in the *Encyclopedia Britannica*.[33] In it Heaviside observed that, because both the sea and the land have non-vanishing conductivities, wireless waves could travel along the earth's surface in the same manner as electromagnetic waves

30. Alexander Russell, "The Kennelly-Heaviside layer," *Nature* (24 Oct 1925), 609.
31. Paul Nahin, *Oliver Heaviside, sage in solitude: The life, work, and times of an electrical genius of the Victorian age* (New York, 1987); Ido Yavetz, *From obscurity to enigma: The work of Oliver Heaviside, 1872-1889* (Basel, 1995).
32. Nahin (ref. 31), 279-281.
33. Oliver Heaviside, "The theory of electric telegraphy," *Encyclopedia Britannica* (10th edn., 1902), *33* (1902), 215.

travel along a conducting telegraph wire. He added the possibility that traveling waves are bounded not only by the earth's surface but also by a conducting layer in the upper atmosphere. That was all. He did not discuss the source of the conducting layer, empirical evidence for it, or the behavior of waves propagating between the concentric spherical conductors.

The other man holding the hypothesis of an atmospheric reflection layer was Arthur Edwin Kennelly. Born in India, he left the University of London, where he was a student, to become a full-time telegrapher. After working in the Eastern Telegraph Company for years, he joined Thomas Edison's West Orange laboratory in 1887. The experience transformed him from an operation engineer to a researcher on new electrical technologies. He became a professor of electrical engineering at Harvard University in 1902, and stayed there until 1913.[34] His principal interests were electric circuits and power systems and his contribution to wireless telegraphy was comparatively minor. His primary contribution was popularizing the theories and technologies of wireless telegraphy to the public by providing simple physical explanations of the phenomena encountered in wireless practices. He emphasized physical intuition rather than complicated mathematical theory.

In 1902 Kennelly published a paper with a model similar to Heaviside's.[35] Unlike Heaviside, however, Kennelly explained the existence of the atmospheric conducting layer. The explanation rested on J.J. Thomson's discovery that the air has an electric conductivity when thinned. The more dilute the air, the higher the conductivity. Kennelly evoked the standard dependence of atmospheric pressure on height and Thomson's extrapolated experimental formula to deduce that at the height of 80 kilometers the air conductivity is 20 times that of sea water! After securing the causal explanation of the atmospheric conducting layer, Kennelly argued that if the propagation space is confined by the atmospheric conducting layer and the earth surface, then the wave's energy density diverges as fast as a cylindrical wave's. In the absence of an atmospheric conducting layer, the energy density diverges as fast as a spherical wave's. The argument concerning energy divergence plus the atmospheric reflection model account for a higher field intensity over a given distance.

Kennelly's paper in 1902 gave a causal explanation of the existence of the conducting layer and a more exact estimate of its height. But he did not connect the hypothesis with observed phenomena. Nor did he devise a quantitative theory of wave transmission from Maxwell's equations and the given boundary condition, as the diffraction theorists had done.

34. Karl Willy Wagner, "Arthur Edwin Kennelly, zu seinem 70. Geburtstage," *Elektrische Nachrichten Technik, 8:12* (1931), 1.
35. Arthur E. Kennelly, "On the elevation of the electrically-conducting strata of the earth's atmosphere," *Electrical world and engineer*, 15 Mar 1902; reprinted in "Kennelly-Heaviside ionized layer—a classic of science," *Science news letter, 17* (18 Jan 1930), 45.

4. QUANTITATIVE EXPERIMENTATION
Naval Wireless Telegraphic Laboratory

The experiments done by Louis Austin's team at the U.S. Naval Wireless Telegraphic Laboratory in 1910 were thought to be the only high-quality evidence for long-distance wireless-wave transmission. The mathematical formula synthesized from the experimental results, known as the "Austin-Cohen formula," turned out to be the empirical law governing the relationship between the field intensity and the large transmission distance. Nevertheless, the broad acceptance of the empirical formula made people overlook the fact that the Navy's "experiments" were actually organized not for scientifically investigating long-distance wave transmission phenomena, but for testing the equipment of the Navy's recently installed high-power wireless-telegraphy station.

In 1899 the Bureau of Equipment of the U.S. Navy established a Radio Division to look into replacing flag-and-light signaling with wireless. The plan failed owing to cultural gaps and the associated organizational inertia. Experienced seamen rejected the new gadgets without performance records. Engineering officers living in a conservative military culture clashed with the wireless inventors who preferred flexibility and novelty. The Bureau of Equipment did not have enough power to overcome the opposition. The Navy ended up on-board radio sets rarely used by the combat units and without a system of standardized training in operational and maintenance procedures.[36]

The opposition had much to say for its position. The wireless technology of the early 20th century was unreliable. The mainstream transmitter (spark-gap discharger) suffered from its highly damped oscillation. The mainstream receiver (coherer) could not follow faithfully the continuous variation of a signal and performed unstably. To incorporate the radio into operation, the Navy required reliable data and reliable instruments for which they could develop standard operational-maintenance procedures and systematic procurement schemes. It needed a research establishment for equipment tests, accurate measurements, and technical evaluation of wireless technologies.

The head of the Radio Division, Cleland Davis, and the director of the U.S. National Bureau of Standards Samuel Wesley Stratton, agreed to station the laboratory be stationed within the existing organizational structure of the Bureau. The Naval Wireless Telegraphic Laboratory thus was born.[37] Its first head, Louis Winslow Austin, a physicist then working at the Bureau, had obtained a doctoral degree at

36. Susan Douglas, "Technological innovation and organizational change: The Navy's adoption of radio, 1899-1919," in Merritt Roe Smith, ed., *Military enterprise and technology change: Perspectives on the American experience* (Cambridge, 1985), 117-173; Linwood S. Howeth, *History of communications-electronics in the United States Navy* (Washington, D.C., 1963), chapts. 12, 13.
37. Louis W. Austin, "The work of the U.S. Naval Radio-Telegraphic Laboratory," American Society of Naval Engineers, *Journal, 24* (1912), 122-141.

the University of Strassburg. After graduation, he worked at the Reichsanstalt, the German model for the Bureau of Standards, which he joined on his return to the U.S. in 1904. He was transferred to the Navy Department in 1908 in order to head the Wireless Telegraphic Laboratory. He started with an assistant, George H. Clark, and a few part-time technicians.

In 1908, the Navy issued a tender for its first high-power wireless station in Arlington, Virginia. It specified that the transmitter should be capable of sending messages at all times and at all seasons to a radius of 3000 miles in any navigable direction. The National Electric Signaling Company (NESCO) obtained the contract in 1909. The transmitter would be similar to the 100 kilowatt Fessenden synchronous rotary spark discharger then installed at NESCO's experimental wireless station at Brant Rock, Massachusetts. Both the Navy and NESCO knew that this machine could not meet the long-distance specification in the contract. Nonetheless, the Navy awarded the contract with NESCO in the belief that the Fessenden discharger was the best available. To legitimate the compromise, the Navy required further technical tests and measurements of the existing system at Brant Rock while the construction for the Arlington station proceeded.[38] The task of testing and measuring the 100-kw rotary spark discharger at the Brant Rock station was assigned to the Naval Wireless Telegraphic Laboratory. During the summer and autumn of 1909, the electricians of the Laboratory conducted preliminary measurements on the wireless sets at Brant Rock and on communications from there to the scout cruisers *Birmingham* and *Salem*.[39]

From subsequent field tests done in July, 1910 Austin synthesized the first empirical formula governing the relation between distance and radiation intensity for long-range wave transmission. That realized the major aim of the tests: to evaluate the communication qualities of particular wireless sets, namely the Fessenden rotary-spark transmitters, not to produce an empirical law for the science of wave propagation. Austin paid attention to particular instrumentality rather than general regularity.

The experiments of 1910 were not the first attempts to obtain quantitative relations between received antenna current and distance. William Duddell and J.E. Taylor in Britain and Camille Tissot in France did similar experiments in 1904 and 1906. Within a range of 50 miles, they discovered that the current is inversely proportional to distance.[40] Austin's tests ran to 1000 miles. *Birmingham* sailed about 1200 miles south from Brant Rock, *Salem* about 450 miles southeast; through the voyages the wireless sets at Brant Rock and on the cruisers regularly transmitted and received signals from one another, both day and night. The whole experimen-

38. Hugh G.J. Aitken, *The continuous wave: Technology and American radio, 1900-1932* (Princeton, 1985), 88.
39. Austin (ref. 52), 125, 147-153, and Louis W. Austin,"Some quantitative experiments in long-distance radiotelegraphy," Bureau of Standards, *Bulletin, 7:3* (1911), 315-363.
40. William Duddell and J.E. Taylor, "Wireless telegraphy measurements," *Electrician, 55* (1905), 258-261, and Camille Tissot,"Note on the use of the bolometer as a detector of electric waves," *Electrician, 56* (1906), 848-849.

tal process, including instrument calibration and maintenance, on-site measurements, and data analysis, was executed by electricians hired by the Naval Wireless Telegraphic Laboratory and engineers of NESCO.[41]

Austin carefully documented the instrument specifications in the report he wrote for the Bureau's *Bulletin.* The transmitters were Fessenden synchronous rotary-spark dischargers, powered at 100 kw at the Brant Rock station and 2 kw on the cruisers. The broadcasts occurred at 1000 meters and 3750 meters. When the separation between the transmitter and the receiver exceeded 100 miles, operators used charcopyrite zinkite rectifiers with galvanometers, and shunted telephone circuits, to detect the antenna current. Both kinds of sensors had high sensitivity for weak current.

During the voyage the electricians noticed several unusual phenomena. After the departure of the ships, the signals became too weak for detection by the crystal-rectifier detector. Except for a few signals taken in the first two days, all the data were taken by the shunted telephone. In addition, the electricians observed that the signals received at night were significantly more erratic than those received during the day. The signal level at night was usually stronger, but it had more fluctuation and experienced more disturbance. The nine-day experimental campaign produced five tables of measured data (for example, see figure 6).

The Austin-Cohen formula

Austin at first tried to fit the daytime data with Duddell's formula that made received antenna current inversely proportional to distance. The inverse law gave much higher values than the measured data beyond 200 miles. Then he tried the ad hoc assumption that the received current experiences an additional exponential factor owing to atmospheric absorption. The NESCO engineer Louis Cohen discovered that a fixed damping coefficient A could reproduce all the data for the same wavelength; to capture the data better for both wavelengths, he set $A=\alpha\lambda^{-1/2}$. Thus the exponential factor is $\exp[\alpha\lambda^{-1/2}d]/d$. They specified that $\alpha = 0.0015$, when the distance d and wavelength λ are expressed in kilometers.[42]

The Laboratory also sought an empirical law governing the transmitted antenna current and the heights of the transmitting and receiving antennas. Experiments conducted between Brant Rock and Washington, D.C. after the sea voyage in mid-July 1910 showed that the receiving antenna's current was proportional to the transmitting antenna current and to the heights of both antennas, and inversely proportional to the wavelength (regardless of the exponential decay factor). Combining these relations, Austin obtained the famous empirical "Austin-Cohen formula:"

41. Austin (ref. 39), 320-330.
42. Ibid, 326-327.

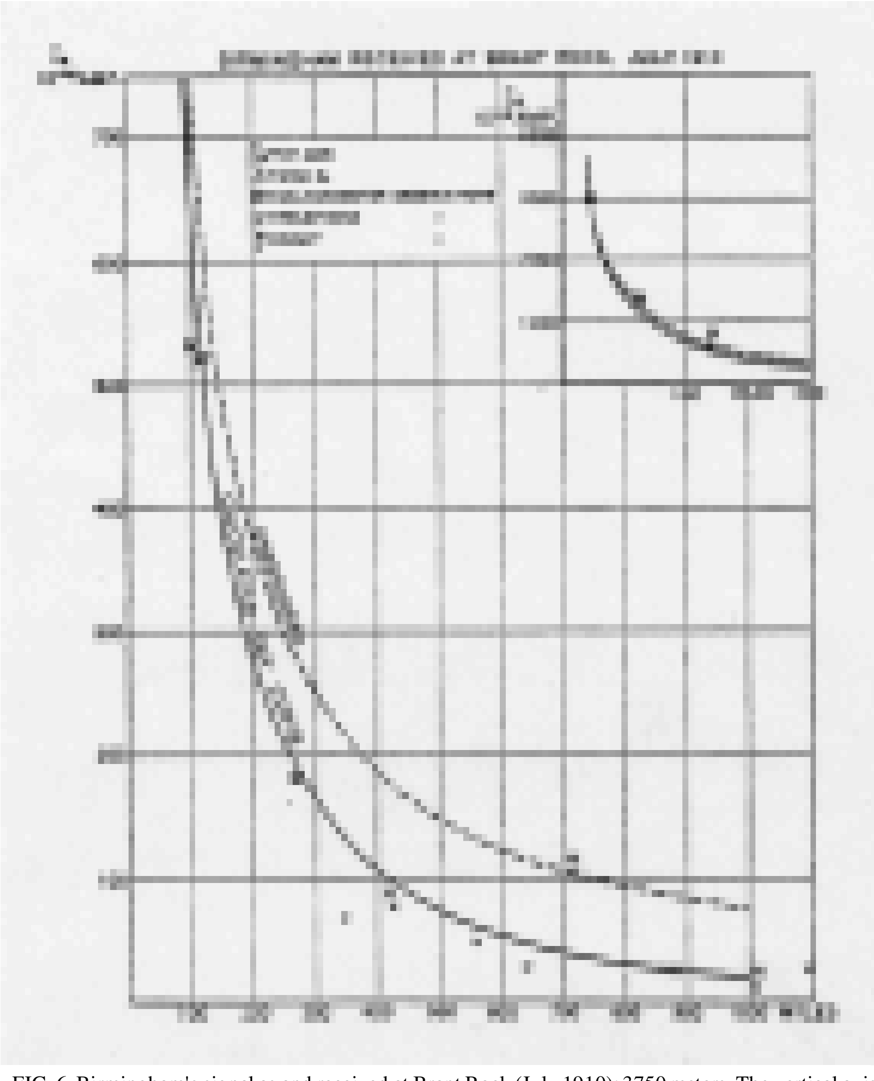

FIG. 6 Birmingham's signal as and received at Brant Rock (July 1910); 3750 meters. The vertical axis represents the received antenna current, the horizontal axis the distance. The solid curve is calculated from the Austin-Cohen formula, the dashed curve from the inverse law "N" denotes data from night-time measurements. Austin (ref. 39), fig. 4.

where I_r is the current received through an antenna with an equivalent resistance of 25 ohm; I_s, the transmitting antenna current; h_1, the height of the transmitting antenna; h_2, the height of the receiving antenna; λ the wavelength; d the distance; and α=0.0015; all the lengths being in kilometers and the current in amperes. According to Austin, the formula is "an equation which will cover the normal day received current over salt water through 25 ohm for two stations with flat-top antennas of any height, with any value of sending current and any wave length, provided the sending station is so coupled as to give but one wave length." It had the further limitation that it had been tested on only the Fessenden rotary spark charger. The coefficient 4.25 in equation (1) is particularly dependent on the instrument. Austin pointed out it applied strictly only to the antennas used in the experiments of 1910.[43]

The Austin-Cohen formula became the most important, and perhaps the only quantitative, empirical basis for all theories of long-distance wireless wave transmission. Before its publication in 1911, scientists worried whether their theories were consistent with physical intuition or wireless know-how, after 1911, they worried whether their numerical results fit Austin's quantitative data or the Austin-Cohen formula. That altered the epistemic situation significantly.

5. DIFFRACTION THEORIES AGAIN

The fit between diffraction theories and the Austin-Cohen formula was far from satisfactory. The theorists adopted several strategies to save the day. The German physicist Witold von Rybczynski showed that his calculations agreed with selected data from Austin's report better than the Austin-Cohen formula did. The English physicist Augustus Edward Hugh Love questioned whether the detector in Austin's experiments had functioned properly. Meanwhile, the experimenters strengthened their position by confirming the Austin-Cohen formula. The test campaign made by the U.S. Naval Radio Telegraphic Laboratory in 1913, which was planned to choose between the rotary-spark discharger and the arc oscillator as the future standard transmission technology, gave an opportunity to produce more measured data. The Austin-Cohen formula survived the tests.

$$I_r = 4.25 \frac{{}_s h_1 h_2}{d\lambda} \exp\left[\frac{-\alpha d}{\sqrt{\lambda}}\right] \qquad (1)$$

The Germans

Sommerfeld assigned the problem of wireless-wave diffraction along the earth surface to an American doctoral student, Hermann William March, who completed the project in 1911.[44] March expressed the fields as the spatial derivatives of a Hertzian potential and the general solution of the wave equation as an expansion in spherical harmonics. The British theorists took such an expansion as a sum over a discrete index. In contrast, March expanded the solution as an integral over a continuous index. He matched the integral with the spherical boundary condition to determine the functional form of the integrand, which turned out to be inversely

43. Ibid, 340-341.
44. Hermann William March, "Über die Ausbreitung der Wellen der drahtlosen Telegraphie auf der Erdkugel," *AP, 37* (1912), 29-50.

proportional to the derivative of the Hankel function with argument *ka*. To evaluate the integral, March developed the Hankel function for large *ka* asymptotically in the same way as Macdonald had done. Then the integral could be calculated analytically. In March's final result, the Hertzian potential is proportional to $\exp[-ika\theta]/(\theta\sin\theta)^{1/2}$ for large *ka* (θ is the usual angle of separation between the transmitter and the receiver). March's solution did not have any exponential decay with respect to θ like $\exp[-\rho(ka)^{1/3}\theta]$; the exponent $\exp[-ika\theta]$ is a sinusoidal function of θ.

March's result, though fresh, had the defect of decaying much more slowly with distance than British theorists predicted and wireless practitioners observed. March's mathematical problem was identical to Macdonald's: in integrating the derivative of a Hankel function for large *ka*, the asymptotic expansion cannot be performed in the usual way. The publication of a new version of this error energized Poincaré, who pointed out the illegitimate approximation in a letter to Sommerfeld.[45] In a short published note on the matter, Poincaré observed that March's predictions disagreed with Austin's experimental data.[46]

Sommerfeld put Rybczinski in the problem. Following Poincaré, Rybczinski took the dominant contribution of the integral from the pole with the smallest imaginary part.[47] He replaced March's integral with another similar in functional form; but the value of Rybczinski's integrand at the projected point of the dominant pole on the real axis equalled that of Poincaré's integrand at the same point. He thus retained the virtues of both March's and Poincaré's approximations: the new integrand was more precise than March's in the region that gives the dominant contribution, and much easier to integrate analytically than Poincaré's. Rybczinski obtained a radiation intensity proportional to $\exp[-0.33(ka)^{1/3}\theta]/(\theta\sin\theta)^{1/2}$.

Rybczinski showed more persuasively than March that the diffraction theory could produce an exponentially damped wave along a large spherical conductor. Rybczinski's factor $\exp[-0.33(ka)^{1/3}\theta]$ differed from Nicholson's factor $\exp[-0.7(ka)^{1/3}\theta]$, and both formulas disagreed with Austin-Cohen's formula in their dependence on wavelength. The diffraction theories stuck with decay rates inversely proportional to $\lambda^{1/3}$, whereas the empirical regularity required $\lambda^{1/2}$. Nicholson's formula decays significantly faster than Rybczinski's, the Austin-Cohen formula significantly slower. As we know, Rybczinski justified his form by appealing to a selected set of data from Austin's paper of 1911 (seven daytime and four nighttime data points for λ= 3750 meters between 400 and 1000 miles). For these cases, Nicholson's predictions were too low, the Austin-Cohen's too high.

Rybczinski's theory met with approval by some wireless telegraphers, especially the German school. They did not think that he had given a complete physical

45. Henri Poincaré to Arnold Sommerfeld, 1 Jan 1912 (DM, HS 1977-28/A,266).
46. Henri Poincaré, "Sur la diffraction des ondes hertziennes," Académie des Sciences, Paris, *Comptes rendus, 154* (1912), 795-797.
47. Witold von Rybczinski, "Über die Ausbreitung der Wellen in der drahtlosen Telegraphie auf der Erdkugel," *AP, 41* (1913), 191-208.

picture of long-distance wireless-wave transmission. Trans-Atlantic radio communications was still not fully explained. But at a minimum Rybczinski's theory gave an approximately correct picture of wave propagation along the earth without atmospheric reflection. Sommerfeld wrote to Wilhelm Wien in November, 1913. that Rybczinski's theory was analytically right and gave a rate of attenuation that matched experiment to some extent. But (Sommerfeld continued) reflection from conducting layers in the upper atmosphere probably played the major role for very long-distance transmission.[48]

Rybczinski's work did not fare as well outside as inside the Sommerfeld school. His ad hoc procedure of approximation lacked mathematical rigor. He did not select the most reliable data. His seven points, taken from the voyage of 1909, were obtained with instruments still under adjustment and under severe weather conditions. And four of his data points came from measurements at night time, when wireless signals are notoriously unstable. In a paper written in 1914, Austin criticized Rybczinski's data points for these reasons.[49]

A new experiment

The results from the test voyages of 1910 did not significantly hinder the promise of the Fessenden rotary-spark discharger. The Arlington station went on line in February, 1913. The Laboratory tested the transmission equipment. The U.S.S. *Salem* proceeded to Gibraltar, 6400 km Washington, D.C.[50] A critical task of the voyage was to compare the signal from the Fessenden rotary-spark transmitter with that from a new technology—the arc transmitter.

The arc transmitter used the negative resistance created by an electric arc in a low-density gas. Because the value of the negative resistance was precise, the electric arc could be used to design an oscillating circuit with a sharp resonance spectrum. The acceptance test for the Arlington station offered a good opportunity to carry out systematic measurements of the arc transmitter's operational conditions. *Salem* simultaneously received signals from the 100 kw Fessenden transmitter. The round trip to Gibraltar took about six weeks. The arc out-performed the spark.[51] Austin: “At distance over 1000 miles the arc waves appear to begin to show advantages over the spark waves.”[52]

The Gibraltar voyage also offered an opportunity to test the Austin-Cohen formula under a set of physical conditions different from those of the 1910 tests: a

48. Arnold Sommerfeld to Wilhelm Wien, 29 Nov 1913 (DM, NL 56, 010).
49. Louis W. Austin,”Quantitative experiments in radiotelegraphic transmission,” Bureau of Standards, *Bulletin, 11* (1914), 69-86.
50. Howeth (ref. 36), 178-183.
51. Austin (ref. 49); John L. Hogan, “Quantitative results of recent radio-telegraphic tests between Arlington, VA., and U.S.S. `Salem' ,” Electrician, 63 (1913), 720-723.
52. Austin to the Chief of the Bureau of Steam Engineering, 3 Apr 1913, in RG 19, Bureau of Ships, E 988, 841(24), Box 1926, National Archives, Washington, D.C.

new (arc) transmitter, a different set of wavelengths (3800 and 2000 meters), and a much longer maximum distance (3500 miles).

Austin and John L. Hogan, an engineer at NESCO, found that the day-time data in 1913 agreed well with the empirical formula. Hogan called the agreement "exceptionally close."[53] Austin went further. He compared Rybczinski's formula, the Austin-Cohen formula, and the new experimental data. Most data points fell closer to the Austin-Cohen formula than to Rybczinski's. Austin again: "There can be no doubt from these results that the theoretical equation [Rybczinski's] gives values too low to be reconciled with the observations, but that they are in very fair agreement with the semi-empirical equation."[54]

Still, something might be retained from the diffraction approach. Austin wrote Zenneck:[55]

> I am becoming quite convinced that the theoretical transmission formula, given in your book, represents approximately the weakest signals observed; while our Navy formula gives a fairly good average. Although I have taken a great many observations, I am still somewhat doubtful regarding the power to which the wave length should be raised in the exponential term. The observations are exceedingly discordant, apparently due to selective reflection.

The British

In January, 1914, Macdonald proposed a new method to approximate the infinite series of his diffraction theory.[56] He introduced a new series, much easier to sum up, that approximated the original series quite well where the spherical harmonic of $n+1/2$ equals ka. Macdonald argued that the new sum well approximated the old one because the dominant contribution of the sum came from this neighborhood. There he replaced the Hankel functions of order $n+1/2$ and its derivatives by Hankel functions of order 1/3 and 2/3. He evaluated the integral via Cauchy's residue theorem. When ka is large, the pole of the Hankel function of order 2/3 with minimum imaginary part dominates. Macdonald found that the resultant field intensity had an exponential decay in the form of $\exp[-\beta(ka)^{1/3}\sin(\theta/2)]$. The functional form of Macdonald's exponential decay differed from both Nicholson's and Rybczinski's factors, $\exp[-\rho(ka)^{1/3}\theta]$.

Enter Augustus Edward Hough Love, still another Cambridge-trained mathematician (second Wrangler, 1885). At the time he contributed to the theory of wireless telegraphy he was a professor of Natural Philosophy at Oxford.[57] In a paper published in 1915, Love gave a comprehensive overview of the research

53. Hogan (ref. 51), 721.
54. Austin (ref. 49), 77-79.
55. Austin to Zenneck, 14 Sep 1916 (DM, NL 053).
56. Hector M. Macdonald, "The transmission of electric waves around the earth's surface," PRS, 90 (1914), 50-61.
57. *Obit., 3* (1939-41), 469-470.

status of long-distance wireless-wave transmission; computed the numerical values of the diffraction series with an approach different from all previous ones; compared his calculations with the values obtained from Macodnald's new formula, found them in agreement, and declared Macdonald's theory the best of the lot; and reinterpreted the long-distance experimental data by correcting the asserted relation between the audibility factor, the results from the shunt-telephone measurements, and the antenna current.[58] That improved the fit with his (and hence Macdonald's) predictions.

Love's method of approximation was numerical. Like Nicholson and Macdonald, Love approximated the terms in the neighborhood of $n+1/2 = ka$. Then he computes the numerical values of a sufficient number of terms, added them up, and compared the numerical results with those he obtained from Macdonald's method at several separation angles.[59]

The Austin-Cohen formula made the field intensity proportional to $[1/\theta]$ exp[-$9.6\lambda^{-1/2}\theta$], which was quite different from all the diffraction formulae, including Macdonald's.[60] Love saved the phenomena by reinterpreting the measured data. Love noticed that Hogan used a "law of device" to convert the data from the measured audibility factor to the antenna current (he made the audibility factor proportional to the square of the antenna current). However, from Austin's 1911 report, this device law did not always hold. Austin's measurements for calibration for weak signals suggested that the audibility factor was proportional to the antenna current. Considering that most data were taken when signals were weak, Love argued that the proper device law was the direct proportion. He modified Hogan's data accordingly and thus gave empirical support to the diffraction theory.

Were Love's conclusions justified? No! His numerical method was based on assumptions about infinite series identical to Macdonald's; it was not a surprise that the two methods gave similar predictions. The real issue, whether the underlying assumptions employed for the purpose of approximation were legitimate, remained unsettled. Moreover, Love's reinterpretation of the data was prblematic. He relied on regularities measured in 1911. Austin reported the same experimental results as Hogan did in 1913, but he did not discover any significant deviation of the measured data from the Austin-Cohen formula.

6. ATMOSPHERIC REFLECTION AGAIN

Atmospheric reflection produced much less literature after 1911 than surface diffraction theories. The wireless communities found it convenient to interpret radio phenomena in terms of atmospheric effects, but much more difficult to elaborate a reflection model via experimental or theoretical means. Still, atmospheric

58. Augustus E.H. Love, "The transmission of electric waves over the surface of the earth," Royal Society of London, *Philosophical transactions A, 215* (1915), 105-131.
59. Ibid, 116-123.
60. Ibid, 127.

reflection theorists managed to go one step further than Heaviside and Kennelly. They wished to understand why static noise is greater at night, and why the transmission efficiency of the wireless signals experiences a diurnal change. Having different research agendas and satisfied with qualitative explanations they did not compete directly with the mathematical physicists working on diffraction theories. Rather, they drew on the intellectual tradition of microphysics, which studied electromagnetic wave propagations in various media in order to reveal the internal molecular structures of materials.[61]

William Henry Eccles, who earned a bachelor's degree in physics from the University of London in physics in 1898, joined Marconi's research team on wireless telegraphy in 1899. It was as a professor at the University of London, where he moved in 1910, that he taught the general wireless communities the empirical ground of the atmospheric-reflection hypothesis.[62]

Eccles discovered that if static was detected at one station, then it was very likely to be detected simultaneously at others some distance away. He deduced that the effect involved a long-distance mechanism, perhaps the discharge of atmospheric electricity at hundreds or thousands of miles away from the receiver stations.[63] In a paper published in 1912, he attempted to explain the cause of diurnal variations of the static intensity. Since trans-Atlantic telegraphic signals and static can be transmitted over long distances, they might propagate in a similar manner.[64] A correct physical model for long-distance wave propagation might explain the data on trans-Atlantic wireless telegraphy and on static.

In Eccles's model, the earth is surrounded by a permanent conducting (Heaviside) layer in the upper atmosphere, and another, concentric layer between the Heaviside and the earth. This new layer corresponds to a region of air with gradually changing physical properties. The ultraviolet component of sunlight ionizes the air in this region.[65] Since sunlight alternates with penetration into this region, the number of charged particles per unit volume in it increases with height.

Eccles evoked a simple microphysical model to describe wave propagation in this medium. When an electric field is applied, the ions move; Eccles deduced the average induced ionized current from Newton's second law of motion. Incorporating the induced current into Maxwell's equations, he expressed the refractive index of the medium in terms of the ions' number density, mass, and charge. From this simple Maxwellian theory, Eccles demonstrated that the phase velocity of an electromagnetic wave increases with the number density of ions.

61. Jed Buchwald, *From Maxwell to microphysics: Aspects of electromagnetic theory in the last quarter of the nineteenth century* (Chicago, 1985).
62. *Obit., 17* (1971), 195-196.
63. William H. Eccles and H. Morris Airey, "Note on the electrical waves occurring in nature," *PRS, 85* (1911), 145-150.
64. William H. Eccles, "On the diurnal variations of the electric waves occurring in nature, and on the propagation of electric waves round the bend of the earth," *PRS, 87* (1912), 79-99.
65. Ibid, 88-89.

Eccles explained three distinct wireless phenomena on his model: the possibility of wave transmission along the surface of the earth, the radiation directivity of Marconi's tilted aerial, and the diurnal variation of static. The theory of ionic refraction suggested that the larger the density of ions, the higher the phase velocity. From Eccles's physical model, the ion density increases with height, as, therefore, does the wave's phase velocity. According to Snell's law, an upgoing radio wave would be gradually drawn downward by the refraction in the gradually varying medium. The wave path would curve. If its curvature equalled that of the earth, the wave could run naturally along the surface without any action of the ground material. Unfortunately the quantitative prediction from ionic refraction disagreed with the Austin-Cohen formula.[66]

Eccles' theory suggested that the amount of refraction decreases with frequency. When the frequency falls low enough, the curvature of the refracted wave path becomes larger than the earth's curvature. In this case, the wave path is obliquely incident to the ground and the direction of wave polarization no longer remains vertical. To match the polarization to the maximum extent, the receiving antenna must be tilted toward the direction of transmitter. Thus Eccles reached the same conclusion as Zenneck's without using the “surface wave.”

The ionized layer results from sunlight and thus does not exist at night. In England, the major source of long-distance static comes from Africa, where thunderstorms and other electrically disturbing weather processes are more severe. In the daytime, long-distance static is controlled by refraction in the ionized layer in the middle and lower atmosphere. During the night, long-distance static is directed by reflection from the conducting Heaviside layer in the upper atmosphere. The waves refracted through the absorptive ionized atmosphere suffer more energy dissipation than the waves reflected by a conducting surface. Hence static during the daytime is weaker than that at night.

Eccles's atmospheric refraction theory contained an essential difference from Heaviside's. In Heaviside's model, radio waves are guided by the concentric spheres of the earth and the permanent conducting layer in the upper atmosphere in accordance with the conductivities of the air and the ground. In Eccles's model, radio waves are directed by the refractive condition of the ionized atmosphere and do not respond to the condition of the ground. For Eccles, ionic refraction alone explains the bending of the wave propagating direction.[67]

Eccle's work of 1912 brought the atmospheric reflection theory from a tentative hypothesis to a sophisticated model. Heaviside and Kennelly attended to only one fact. In contrast, Eccles covered several apparently unrelated phenomena—long-distance wave transmission, tilted polarization, and diurnal variation of static. Eccles's model was essentially a theory of the qualitative behavior of wireless phenomena. Only partial and preliminary results were achieved by efforts to de-

66. Ibid, 91.
67. Eccles to Heaviside, 27 Nov 1912, Heaviside Papers, UK0108 SC MSS 005/I/6/10, Institute of Electrical Engineers Archives, London.

scribe the wave-propagation characteristics mathematically, and these were not consistent with the empirical regularity (the Austin-Cohen formula).

The English physicist John Ambrose Fleming followed up Eccles's work by trying to account for the diurnal variations of wireless signals. But the static patterns seemed too complex for a consistent explanation. In the annual meeting of the British Association for the Advancement of Science (BA) in 1912, Fleming had organized a discussion on “The scientific theory and outstanding problems of wireless telegraphy” and suggested that the BA form a committee to guide and formulate research on them. The committee was formed and planned systematic observations on atmospheric stray rays. It did not achieve significant results.[68]

Kennelly attended Fleming's radio-telegraphic session at the BA meeting in 1912. Kennelly agreed that the boundary between the sunshine and the shadow regions formed a reflecting surface critical to the diurnal variation observed in wireless telegraphy. He proposed a model for the variation of wireless signals around twilight. Two wireless stations sit in an east-west direction and the transitional band moves gradually toward the east station. Before the band crosses when both stations are on the same side of the blocking curtain formed at the transitional band, it does not affect signal transmission between them. When the band moves behind the east station (shortly before the east station's sunrise), the blocking curtain functions as a reflecting surface to bounce the overshoot waves from the west station back to the east station. Hence the received signal strength there is intensified. After sunrise at the east station, the band moves between the stations, wave transmission is blocked, and the received signal strength diminishes significantly. When the sunrise just passes the west station, the band functions again as a reflecting surface behind the west station to enhance the received signal strength there. As the band moves farther away, the reflective enhancement also wanes. The same pattern happens around sunset. Kennelly's mechanism predicts that a wireless signal transmitted along an east-west direction has a maximum just before the twilight of the east station and right after the twilight of the west station, and a minimum in between. The pattern of the signal variation predicted from Kennelly's model agreed with observations made at wireless stations at Nova Scotia and Amesbury, Massachusetts.[69]

These investigations typified the work of the atmospheric-reflection theorists. They paid much more attention to the diurnal variation of wireless energy than to mathematical relation between the signal intensity and the distance, and they emphasized qualitative characteristics rather than quantitative information in the experimental data. Their theoretical work involved sophisticated model-building and simple mathematical theories of wave propagation based on microphysics.

Toward 1920, several young experimental physicists well trained in applied mathematics began to appreciate the physical importance of the ionic-atmosphere

68. Fleming (ref. 5), 860.

69. Arthur E. Kennelly, “The daylight effect in radio telegraphy,” Institute of Radio Engineers, *Proceedings, 1:3* (1913), 12.

model. They tried to bring together the work of all three communities. One of them was Balthasar van der Pol, who worked at the Cavendish Laboratory between 1917 and 1919. In 1918, he tackled the discrepancies among different diffraction formulas (Nicholson, Rybczinski, Macdonald). He reasoned that if he could show that one of them was mathematically rigorous, he could demonstrate that diffraction could not account for the Austin-Cohen formula. The mathematics required was too difficult to him. He turned to a Cambridge-trained mathematician, George Neville Watson, for help.

7. WATSON' S WORK

Like Macdonald, Nicholson, and Love, Watson excelled at the Cambridge training in mathematics, becoming Senior Wrangler, Smith's Prize man, and a Fellow of Trinity College. In 1918, he took up the professorship of mathematics at the University of Birmingham. Unlike the diffraction theorists, Watson was almost detached from physics at Cambridge. He specialized in complex-variable theory applied to Bessel functions. He was also interested in theories of approximation, numbers and computability.[70] He was just the man to solve van der Pol's problem.

Papers of 1918 and 1919

In 1918, Watson gave a rigorous mathematical proof that the field intensity diffracted along the curvature of a large conducting sphere has an exponential factor whose decay rate is proportional to $\lambda^{-1/3}$ rather than $\lambda^{-1/2}$ (as required by the Austin-Cohen formula). In 1919, he showed that the field intensity diffracted in a space bounded by a large conducting sphere and a conducting surface exterior and concentric to the sphere has the $\lambda^{-1/2}$ dependence.[71] The atmospheric reflection theory can explain the empirical regularity.

Watson found the rigorous solution of the diffraction problem without the mathematical problems of previous diffraction theories by working on the Hertzian potential instead of the magnetic field intensity. True to the Cambridge approach, he expanded the Hertzian potential in terms of a discrete sum of spherical harmonics instead of an integral. The result was an infinite series different from Macdonald's, but with a similar angular dependence and pole structure.

Watson's great innovation was to convert the series expansion of the Hertzian potential into an integral expansion without infinities. He interpreted all terms in the diffraction series as residues of a complex function associated with poles on the real axis and so expressed the diffraction series as a contour integral in the complex plane. This procedure, later known as "Watson's transformation," con-

70. *Obit., 12* (1966), 521-522.
71. George N. Watson, "The diffraction of electric waves by the earth," Royal Society of London, Proceedings, 95 (1918-1919), 83-99; and "The transmission of electric waves round the earth," ibid., 546-563.

verted the Hertzian potential from a series to a complex integral. This integral as evaluated by Cauchy's residue theorem contained an exponential decay $\exp[-23.94\lambda^{-1/3}\theta]$, quite close to Nicholson's $\exp[-23.8\lambda^{-1/3}\theta]$.[72] Watson confirmed that the intensity of the field diffracted along the earth's surface was significantly weaker than the Austin-Cohen formula required. The exponential decay of the one contains $\lambda^{-1/3}$, of the other to $\lambda^{1/2}$. The diffraction theory was mathematically consistent, but empirically inadequate.

Watson located the problem in the physical model. All the diffraction theorists assumed that the earth's surface alone diffracts the field radiated by the dipole oscillator. Since the surface diffraction alone cannot account for the empirical observations, the upper reflective regions of the atmosphere might play the dominant role at long distances. Could diffraction theory incorporate the physical assumption of an atmospheric reflective layer? Watson took up the question in his paper of 1919. He took the earth to be a conducting sphere on which the Hertzian dipole sits, and the atmospheric reflective layer to be concentric with the earth.[73]

To evaluate the Hertzian potential in this new boundary condition, Watson expanded the Hertzian potential in a series of spherical harmonics, applied "Watson's transformation" to convert the series into a complex integral, analyzed the pole structure of the integrand, and evaluated the integral in terms of these poles. He discovered that when both the inner and outer conductors are perfect, the field intensity is a superposition of oscillatory modes periodic with the distance, that is, that the field does not decay at all! When both the inner and outer conductors are good but imperfect, the field has an exponential decay proportional to $\lambda^{-1/2}$. By adjusting the conductivity of the ionized layer, Watson could match the numerical value of the decay rate of his theory and the Austin-Cohen formula.

Reception

Watson established a conjunction of mathematical representations, explanatory models, and experiments in the study of long-distance wave transmission. He applied the complex-variable techniques of the diffraction theories to the physical model entertained by the atmospheric-reflection theorists to derive quantitative results consistent with the empirical formula obtained from long-distance experiments. By connecting the mathematical representation with the formulated experimental data, Watson gave the atmospheric-reflection theory the promise of becoming a question-answering device operated and using standard mathematical techniques. When it left his hands, Watson's theory lacked verisimilitude. The physical model of a homogeneous and sharp conducting boundary was an over idealization. Watson did not incorporate a vertical atmospheric profile with gradually varying refractive indices. His theory could not incorporate Eccles's ion-refraction theory in a profound way. Nor was Watson's theory able to marshal em-

72. Watson, "diffraction" (ref. 71), 97.
73. Watson, "transmission" (ref. 71), 547.

pirical evidence beyond the Austin-Cohen formula, for example, the diurnal variation of static.

Appreciation of Watson's contributions came slowly. The first few published papers to mention his work all emphasized the mathematical rather than the empirical implication. Van der Pol stressed Watson's mathematical contribution to clarifying the controversy involving different approximation methods for wave diffraction above a spherical conductor, rather than Watson's theoretical prediction of the Austin-Cohen formula.[74] Macdonald commented on Watson's work without addressing empirical adequacy at all. He concentrated on extending Watson's approach to the general case where single-frequency time-dependence does not hold.[75] Sommerfeld's student Otto Laporte used Watson's results to reconcile the British representation of the diffracted field in terms of a series with the German representation in terms of an integral, not for their own sake.[76]

Most scientists who elaborated the atmospheric-reflection model in the 1920s, studied wave propagation through ionic media. They downplayed Watson's old-fashioned model (the sharply defined "Kennelly-Heaviside layer") and counter-intuitive approach (the complex-variable theory of diffraction). In a classic paper on the subject written in 1924, Joseph Larmor mentioned Watson only at the end of a list of diffraction theorists beginning with Macdonald, and then as the man who demonstrated that surface diffraction cannot account for long-distance wave transmission around the earth.[77] Among these initial responses to Watson's papers, one thing stands out: after Watson had proved the mathematical rigor of Nicholson's predictions, no one attempted to reconcile the experimental data with the surface diffraction theory. Watson's paper in 1918 tilled the diffraction theory as a physical model for long-distance wave transmission.

Watson's fortunes improved in the late 1920s. In 1928, G.W. Kenrick of the University of Pennsylvania reinvestigated the mathematical and empirical significance of Watson's theory. Kenrick pointed out that much work had recently been done to explain short wave transmission by reflection and refraction of electric waves, but "less attention has been given to modifications produced in the classical Hertzian solution for the field at a distant point due to an oscillating doublet."[78] He called for a reexamination of Watson's work in the interest of short-wave analysis. Kenrick calculated the electromagnetic field radiated by a Hertzian dipole

74. Balthasar van der Pol, "On the propagation of electromagnetic waves round the earth," *Philosophical magazine, 38* (1919), 365-380.
75. Hector M. Macdonald, "The transmission of electric waves around the earth's surface," *PRS, 98* (1920), 216-222, 409-410; 108 (1925), 52-76. "On the determination of the directions of the forces in wireless waves at the earth's surface," *PRS, 107* (1925), 587-601.
76. Otto Laporte, "Zur Theorie der Ausbreitung elektromagnetischer Wellen auf der Erdkugel," *AP, 70* (1923), 595-616.
77. Joseph Larmor, "Why wireless electric rays can bend round the earth," *Philosophical magazine, 48* (1924), 1026-1036.
78. Gleason Willis Kenrick, "Radio transmission formulae," *Physical review, 31* (1928), 1040-1050, on 1040.

using the same boundary condition that Watson had. Instead of working on the residue waves, he computed the multiple reflected rays bouncing through the space between the earth and the atmospheric layer, and summed all the reflective terms. He thus reproduced Watson's mathematical formula and hence the Austin-Cohen formula. Watson's work became significant not only for disproving the diffraction model but also for its quantitative predictions of observed phenomena.

The radio scientists and engineers of the 1930s worked intensely on wave propagation under various scenarios specified by atmospheric and terrestrial conditions. A theory of pure refraction without taking into account the effect of the earth was no longer adequate. Their theoretical exercise dealt with wave diffraction above a ground with different possible geometric and material specifications in a heterogeneous atmosphere. "Watson's transformation" proved a very useful technique for analyzing these problems. In 1937, a Harvard professor of physics, Harry R. Mimno reviewed the literature on the physics of the ionosphere.[79] He highlighted the significance of the discrepancy between the $\lambda^{-1/3}$ dependence predicted by all the diffraction theorists before Watson and the $\lambda^{-1/2}$ dependence given by the Austin-Cohen formula, and he stressed Watson's contribution in providing a theoretical account of the empirical $\lambda^{-1/2}$ dependence. Van der Pol's student H. Bremmer wrote that "the pioneering work clearing the way for further investigations was done by Watson in 1918. By a transformation with the aid of an integral in the complex plane, this author succeeded in transforming the rigorous series of zonal harmonics into a new series converging rapidly enough to be of use in the radio problem. As a matter of fact, almost all of the later literature is based upon this transformation of Watson."[80]

Often in the history of science two mutually exclusive theories compete for the answers to the same set of questions. In the case considered here, two mutually exclusive theories address different types of questions. The essential difference between the surface diffraction theories and the atmospheric reflection theories was their distinct epistemic status rather than their different physical models. The surface diffraction theorists began by investigating the possibility of long-distance radio-wave transmission. To answer this question, they constructed a straightforward physical model and attempted to develop a rigorous mathematical solution of the problem described by the physical model. But they soon discovered a mathematical difficulty in obtaining an accurate approximate solution. They switched to a mathematical question—what is an accurate approximation of the diffracted field intensity above a large conducting sphere? Almost all their effort involved proper approximations of the analytic form of the diffracted field.

The atmospheric-reflection theorists asked for causal explanations for a broader realm of wireless phenomena, including long-distance transmission, diurnal variation of signal strength, static, the effect of weather fluctuation, and the directive

79. Harry R. Mimno, "The physics of the ionosphere," Review of modern *physics, 9:1* (1937), 1-43.
80. H. Bremmer, *Terrestrial radio waves: Theory of propagation* (New York, 1949), 7.

antenna pattern. To answer these questions, they constructed elaborate physical models. They were partially successful in offering reasonable causal explanations to observed wireless phenomena. But they failed to develop a mathematical theory for systematic quantitative predictions before 1910, succeeded to a very limited extent after Eccles, and only began to make steady progress after Watson. The reflection theorists had difficulty in formulating answers to numerical-prediction questions. Thus the diffraction theorists and the reflection theorists carried out different agendas: the former tried to resolve a mathematical problem of approximation, the latter aimed to explain newly discovered phenomena. This fact explains why atmospheric-reflection theories rarely engaged in any public debate with the surface-diffraction theorists, why some mathematical physicists kept working on diffraction theories regardless of their dubious empirical adequacy, and why an experimenter strongly supporting the reflection models still gave credit to the diffraction models. The diffraction theories and the reflection theories were not competing worldviews.

From the epistemic viewpoint, long-distance wave-transmission research left unexpected legacies to all the participating communities. They started from what they wanted to know, and found what they did not expect to learn. The diffraction theorists found that approximation can be a critical issue in physical problems in which the analytic solution cannot give meaningful quantitative information and direct numerical computation is intractable. The new condition that the wavelength was much shorter than the scatterer's dimension forced them to develop a repertoire of advanced mathematical techniques other than those developed for acoustic scattering for dealing with the approximations of series or integrals. Sommerfeld's integral and Watson's transformation initiated studies of mathematical questions that would become classical problems in mathematical physics: a vertical or horizontal dipole oscillator above or below a homogeneous or layered horizontal plane, a vertical or horizontal dipole oscillator above or below a homogeneous or heterogeneous sphere within a homogeneous or a concentrically layered medium, and so on. These problems did not necessarily correspond to real physical situations. But the mathematicians contentedly investigated the complex-variable techniques to solve the problems for their own sake. The mathematical theory of complex series and integrals prospered from 1930s to 1950s largely owing to the heritage of the German and the British diffraction theorists in the 1900s and 1910s.[81]

The atmospheric-reflection theorists started from the puzzles associated with radio operations, but ended up with a new science of the atmosphere. Their models of the ionosphere were connected with contemporary electron theories of matter. Thus the study of atmospheric effects on radio became incorporated into one of the largest intellectual movements of physics in the early 20th century: the rise of atomic and molecular physics. The radio scientists benefitted from this incorpora-

81. Alfredo Baños, *Dipole radiation in the presence of a conducting half-space* (Oxford, 1966).

tion: they developed various Maxwellian theories of electromagnetic wave propagation in ionized media. Moreover, the reflection theorists discovered that the radio could be an experimental means to explore atmospheric phenomena. Edward Appleton's experiments of the 1920s, which won him a Nobel Prize, gained "direct" evidence about the physical condition of the ionosphere from radio-interference methods. Meteorology and planetary science became accessible not only through the traditional means of natural history, but also through experiments made possible by efforts of the reflection theorists.[82]

The original goal of the American wireless experimenters was to test equipment for the first long-distance radio station of the U.S. Navy. They had a practical engineering problem to solve, but in pursuing it made an important contribution to pure science. The Navy's questionable decision to settle with NESCO's transmitter, the missionary agenda of the Bureau of Standards, and Austin's technical training in German experimental science incorporated meticulous instrumental design systematic operational procedure, and mathematical representation of the data into the investigation. The outcome of their experiments was an empirical law that served as the only quantitative check on theories of long-distance radio-wave transmission in the 1910s. The U.S. Navy did not gain directly from scientific studies of wave transmission, but from the experimental results: it learned that the arc transmitter performed better than the spark-gap transmitter at long distances. The Austin-Cohen formula provided a primary guide for wireless engineers to design long-distance long-wave wireless stations throughout the 1910s. Engineers relied on this simple mathematical relation to select the wavelength and antenna height of a transmitting station for a signal-strength requirement at a given distance. The other face of the empirical law was an engineering formula.

These drastically diverse post-developments enforce the lesson that our three technical communities, working against with different intellectual backgrounds and toward different goals, created a unified study of long-distance radio-wave transmission. They did so by contributing different elements: one offered empirical evidence, another a physical model, and a third a mathematical tool. This episode might be interpreted as confirmation of Peter Galison's estimates of the strength of the constraints on a scientist or engineer within his own communal tradition or of Andrew Pickering's emphasis on the importance of the contingencies a scientist or engineer might confront.[83] More significantly, it warns us not to assume that the intellectual work of different technical communities apparently concerned with the same general phenomena were alternative answers to the same questions. They might have had their eyes on different, and different kinds of questions.

82. Peter Galison and Alexi Assmus, "Artificial clouds, real particles," in David Gooding, Trevor Pinch, and Simon Schaffer, eds., *The use of experiment: Studies in the natural sciences* (Cambridge, 1989), 225-274.
83. Peter Galison, "Context and constraints," and Andrew Pickering,"Beyond constraint: The temporality of practice and the historicity of knowledge," in Jed Buchwald, ed., *Scientific practice: Theories and stories of doing physics* (Chicago, 1995), 13-55.

CHEN-PANG YEANG

The study of long-distance radio-wave propagation, 1900-1919

ABSTRACT:
At the beginning of the 20th century, scientists and engineers were puzzled by the fact that the long wireless waves could propagate along the earth's curvature without being blocked by the earth. Two explanatory theories were suggested: that the waves are diffracted along the earth's surface and that the waves are reflected back and forth between the earth and a conducting atmosphere. The surface diffraction theory, first proposed by Hector Munro Macdonald in 1901, was continuously elaborated by the British and German mathematical physicists. But its predictions were not consistent with the empirical Austin-Cohen formula obtained from the U.S. Navy's long-distance experiments. The atmospheric reflection theory, first proposed by Arthur Kennelly and Oliver Heaviside in 1901/2, was more commonly believed to be the correct physical model. Yet it had problems yielding quantitative predictions because of its lack of mathematical development. In 1919, the English mathematician, George Neville Watson, developed a mathematical theory of atmospheric reflection that generated predictions consistent with the Austin-Cohen formula based on the analytic techniques established by the surface diffraction theorists.