CHEN-PANG YEANG

PROBING THE SKY *WITH* RADIO WAVES

FROM WIRELESS TECHNOLOGY TO THE DEVELOPMENT OF ATMOSPHERIC SCIENCE

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The University of Chicago Press CHICAGO & LONDON

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The University of Chicago Press, Chicago 60637
The University of Chicago Press, Ltd., London

Printed in the United States of America

22 21 20 19 18 17 16 15 14 13   1 2 3 4 5

ISBN-13: 978-0-226-01519-4 (cloth)
ISBN-13: 978-0-226-03481-2 (e-book)

Library of Congress Cataloging-in-Publication Data
Yeang, Chen-Pang.
Probing the sky with radio waves : from wireless technology to the development of atmospheric science / Chen-Pang Yeang.
pages cm
Includes bibliographical references and index.
ISBN 978-0-226-01519-4 (cloth : alk. paper)—ISBN 978-0-226-03481-2 (e-book)
1. Radio waves. 2. Radio waves—Research—History. 3. Atmospheric physics—History. 4. Amateur radio stations—History. I. Title.
QC676.4.Y43 2013
538′.767—dc23
2013009936

♾ This paper meets the requirements of ANSI/NISO Z39.48-1992 (Permanence of Paper).

To my parents, wife, and brother

CONTENTS

PART 2 Discovering the Ionosphere, 1920–26

PART 3 Theory Matters, 1926–35

PART 4 Conclusion

ACKNOWLEDGMENTS

This book originated from a paper I wrote when I was a graduate student at MIT Science, Technology, and Society (STS) Program in the early 2000s. In that paper, I attempted to investigate a turn-of-the-century debate regarding whether the electromagnetic waves of Marconi's first transatlantic wireless signals crept along the sea or bounced between the earth and the sky, a debate I had heard about in my undergraduate electromagnetics course. Over the following decade, the paper expanded into ten talks and conference presentations, two journal articles, and eventually a monograph. And my initial curiosity about the surface-wave-vs.-sky-wave controversy led to an exploration of the epistemic status of scientific theories, the activities of radio amateurs, the discovery of the ionosphere, the nature of field experiments, the microphysics of radio wave propagation in ionic media, and the significances of active sensing in general. It is fair to state that the book project has grown with and spanned my humble academic path in the history of science and technology. Thus, I would like to thank not only those who helped me directly with the book, but also those who helped me with my career.

Above all, I am grateful to my mentors at graduate school: Jed Buchwald, George Smith, and David Mindell. Jed was my eye opener to the history of science. From his teaching, I learned the value and pleasure of parsing out technical details with the reasoning of historical actors themselves. He also gave me intellectually stimulating and pragmatically important suggestions at every stage of my book project. I am very fortunate to have him as an adviser. George guided me to the world of philosophy. His enlightening pedagogy and crystal-clear explications refreshed my understanding of the philosophy of science. He taught me one thing that I consider perhaps the most important research guideline: think hard of the nature of questions and their answers. David was a great adviser. He urged me to pay close attention to the coherence of narratives and the arts of studying and writing the history of technology. He also coached me in various aspects of my professional preparation.

In addition, I am indebted to David Kaiser's tremendous help. He read carefully an earlier work on this project and a draft of several chapters of this book. His comments and critiques on the structures, concepts, and contents of my writings were always insightful. I also appreciate that he brought my book project to the attention of the University of Chicago Press.

I developed and wrote this book at six institutions: MIT STS Program; the Division of Humanities and Social Sciences at California Institute of Technology; the former Dibner Institute for the History of Science and Technology in Cambridge, Massachusetts; the Max Planck Institute for the History of Science in Berlin; the Institute for the History and Philosophy of Science and Technology (IHPST) at the University of Toronto; and the Institute for Modern History at Academia Sinica in Taipei. I was fortunate to befriend the faculty, fellows, students, and staff at these institutions and to receive their generous support in various ways. At MIT, Sam Schweber, Evelyn Fox Keller, Merritt Roe Smith, and Larry Bucciarelli mentored me on the history of physics, philosophy of science, history of technology, social studies of engineering, and the nuts and bolts of academia. I also thank my fellow graduate students for their warm friendships: Tim Wolters, David Lucsko, Shane Hamilton, Sandy Brown, Wen-Hua Kuo, Rob Martello, Rachel Prentice, Eden Medina, Rebecca Slayton, Anne Pollock, and Kaushik Sunder Rajan. Tim read an early draft of this book's chapters 2–4 and provided brilliant comments. He and his wife Karen nicely offered me lodging at their house when I visited Washington, D.C., for archival research. My office mate David (Lucsko) helped me considerably with my writing. I also benefited from the writing workshops organized by David (Kaiser), Susan Silbey, Rachel, Rebecca, and Kaushik.

At the Dibner Institute, I received invaluable advice from senior fellows including Bruce Sinclair, Deborah Cramer, Conevery Bolton Valencius, Edith Sylla, David Cahan, Karine Chemla, Bruce Belhoste, Tom Archibald, Olival Freire, Giora Hon, James Voelkel, Sara Wermiel, and Emily Thompson. Bruce discussed my research project with me, read an earlier work on this project, and gave me useful and detailed suggestions on how to turn it into a book. Deborah helped me to craft my book proposal and book plan. Conevery gave me fabulous encouragement. In addition, I enjoyed the company of my cohort postdoctoral fellows: David Pantalony, Jeremiah James, Elizabeth Cavicchi, Takashi Nishiyama, Claire Calcagno, Martin Niss, Dane Daniel, Yunli Shi, Arne Hessenbruch, Mathew Harpster, Ben Marsden, Kristine Harper, Peter Bokulich, Sandro Caparrini, Alberto Martinez, and Gerard Fitzgerald. In particular, David was kind enough to proofread many of my writings. We all miss the beautiful, cozy, and productive environment of the Dibner Institute, and deeply regret that it no longer exists.

While my stays at Caltech, the Max Planck Institute, and Academia Sinica were shorter, they too were fruitful and critical to my book project. I am grateful to Jed Buchwald, Otto Sibum, and Yung-fa Chen for arranging my visits at these three institutions, respectively. At Caltech, Diana Kormos-Buchwald and James Lee talked with me about my career plans in general. At the Max Planck Institute, David Bloor read a draft of my book's chapter 5 and provided me with excellent suggestions.

At the IHPST, I am privileged to have wonderful colleagues: Trevor Levere, Bert Hall, Janis Langins, Craig Fraser, Marga Vicedo, and Mark Solovey, who offered me their advice and shared with me their experiences in research, teaching, professional development, and the details of book publishing. In Toronto, I also enjoy the company and suggestions of Edward Jones-Imhotep, who shares my interest in the history of radio ionospheric propagation studies.

I would also like to thank the staffs of the six institutions for their unreserved support: Chris Bates, Deb Fairchild, Debbie Meinbresse, May Maffel, Shirin Fozi, Kris Kipp, and Judy Spitzer at MIT STS; Rita Dempsey, Carla Chrisfield, Trudy Kontoff, Bonnie Edwards, and Evelyn Simha at the Dibner Institute; Gail Nash and Susan Davis at Caltech; Nina Ruge at the Max Planck Institute; Hsiuchuan Lin at Academia Sinica; and Muna Salloum and Denise Horsley at the IHPST.

As an engineer turned historian, I owe much to my former advisers and friends in electrical engineering. The training and mentorship they provided enabled me to engage the technical history of radio ionospheric propagation, and their interest in my project motivated me to finish the book. I would like to express my gratitude to four faculty members at MIT Department of Electrical Engineering and Computer Science. Hermann Haus was a reader of my earlier work in the history of science before he passed away. He was most concerned with my writing. I am grateful that he went through my chapters line by line with corrections and gave me useful critiques on my English. The late Jin Au Kong was the supervisor for my Master of Science in electrical engineering. He taught me the beauty and intricacy of electromagnetic theory, which I needed to write this book. I really wish they could have lived to see this book

in print. Jeffrey Shapiro was the supervisor of my ScD in electrical engineering, and Gregory Wornell supervised my engineering postdoctoral research. I appreciate their open-mindedness to my digression to history and their curiosity about my book project. In addition, I presented several chapters of this book at David Rutledge and William Bridges's group meeting at Caltech and Frank Kschischang's group meeting at the University of Toronto.

I am very thankful to three referees who reviewed my book manuscript; I came to know later that they were David Wunsch, Sungook Hong, and Suman Seth. Their frank but positive comments were extremely useful for me in reshaping and revising my manuscript. I also appreciate the enormous help of my editors, Jennifer Howard and Karen Darling at the University of Chicago Press. Jennifer launched the review process for my manuscript; Karen has taken over since Jennifer left the press. Without their efforts, this book would not exist.

I would also like to thank my research assistants Chris Conway and Nicolas Sanchez Guerrero at the University of Toronto and my copyeditor John Parry. Chris and Nicolas helped me to prepare the figures and tables and to acquire copyright permissions. John went through my manuscript relentlessly and made a lot of stylistic modifications. While I hold responsibility for any stylistic awkwardness, he contributed to making this book much more readable than it was. In addition, I express my gratitude to Michael Koplow, a manuscript editor at the University of Chicago Press, for his work on my book.

My book project could not be done without the generous assistance of the staff at the archives and libraries I had accessed: American Radio Relay League Archives, Newington, CT; Arnold Sommerfeld Papers (NL 056) and Jonathan Zenneck Papers (NL 053), Deutsches Museum Archives, Munich; AVIA Records and DSIR Records, Public Record Office, London; Bureau of Ships Records (RG 19), U.S. National Archives I and II, Washington and College Park, MD; Edward Appleton Papers (H37), Special Collections, University of Edinburgh Libraries; General Collection, Philips Research Public Relations Department, Eindhoven; George Neville Watson Papers, Special Collections, University of Birmingham Libraries; Hiram Percy Maxim Papers, RG 69:12, Connecticut State Library, Hartford; Historical Archives, Naval Research Laboratory, Anacostia, Washington; Historical Records, Rutherford Appleton Laboratory (Space Science Department), Didcot, England; Ionospheric Section Records, 1927–59, Department of Terrestrial Magnetism Archives, Carnegie Institution, Washington; Joseph Larmor Papers, Special Collection, St. John's College Library, Cambridge University; Merle Tuve Papers, Li-

brary of Congress, Washington; Oliver Heaviside Papers (UK0108 SC MSS), Institution of Electrical Engineers (IEE) Archives, London; Radio Pioneers, Columbia University Oral History Collection, New York; Rayleigh Papers, Rare Book Collection, Air Force Research Laboratory, Hanscom Air Force Base, Lexington, MA; Service Historique de l'Armée de Terre, Paris; Special Collection, Libraries of Radio France, Paris; Special Collection, University of Aberdeen Libraries, Aberdeen. I am especially grateful to Chris Davis at the Rutherford Appleton Laboratory, Sylvain Alzial at Radio France, Wilhelm Füßl at Deutsches Museum, William Perry at the American Radio Relay League, Marjery Ciarlante and Tab Lewis at the National Archives II, the late David van Keuren at the Naval Research Laboratory, Sheila Noble at the Edinburgh University Libraries, and Shaun Hardy at the Carnegie Institution.

My research and writing for this book project were sponsored by the MIT STS fellowship (1999–2001), fellowship at the Caltech History Program (2002), the Dibner Graduate Fellowship (2002–4), the Dibner Sloan Project for the History of Recent Sciences and Technologies (2002–4), the MIT Kelly-Douglass Fund (2001–3), the MIT Siegel Prize (2003), the Dibner Postdoctoral Fellowship (2004–5), the IEEE Life Member Fellowship in Electrical History (2004–5), the postdoctoral fellowship at the Max Planck Institute for the History of Science (2006), the Connaught Start-Up Fund at the University of Toronto (2006–8), and the Connaught New Staff Matching Fund at the University of Toronto (2007–10). Jed Buchwald arranged the Caltech fellowship; Buchwald and David Mindell arranged the grants from the Dibner Sloan Project; Otto Sibum arranged the fellowship at the Max Planck Institute.

Portions of this book have appeared previously in two articles. Sections of chapters 2 and 4 originally appeared in Chen-Pang Yeang, "The study of long-distance radio-wave propagation: 1900–1919," *Historical Studies in the Physical and Biological Sciences*, 33:2 (2003), 369–403. Most of chapter 3 originally appeared in Chen-Pang Yeang, "Scientific fact or engineering specification? The U.S. Navy's experiments on long-range wireless telegraphy circa 1910," *Technology and Culture*, 45:1 (2004), 1–29. I thank the editors of each journal for permission to use the material here.

Above all, I owe great debt to my family: my father Chia-Chiu Yeang, my mother Lan-Chun Hsu, my sisters Hui-Shan and Hui-Chi, my brother Chen-Hsiang, who accompanied me during my long life as a graduate student in Cambridge, Massachusetts, and my wife, Wen-Ching Sung, who has given me love and support all the time.

CHAPTER 1

Introduction: From Propagation Studies to Active Sensors

On 26 October 2004, the *Cassini* Orbiter had its first close flyby of Titan, Jupiter's largest moon. Under the control of the Jet Propulsion Laboratory (JPL) at California Institute of Technology in Pasadena, the spacecraft had undertaken a seven-year cosmic odyssey since its launch from the Kennedy Space Center in Florida. The JPL staff and participating researchers around the world had waited for this day, since one of the project's major missions—arguably its primary task—was to explore Titan. As an exploratory platform, the *Cassini* boasted a dozen detectors, including two state-of-the-art cameras that had captured stunning images of Saturn and its rings and a cadre of spectrometers to monitor the chemical composition of any radiating celestial body.

But Titan posed a particular challenge to the instrument designers. It is the only satellite of the solar system possessing an atmosphere, and a thick, yellow haze of hydrocarbons almost perpetually blocks it to cameras and spectrometers. Even the onboard *Huygens* probe—the landing unit that the European Space Agency had made for exploring Titan's surface—was not the complete solution, as it could take measurements only near its landing site. To reveal the yellow moon's macroscopic geological characteristics, the *Cassini* team rested its hopes on imaging radar. Unlike cameras and spectrometers, which received light, energy, or particles that emanated from the observed object, the radar bounced microwaves off the object and timed their return. This apparatus did not disappoint the JPL staff. During the flyby, it scanned 1 percent of Titan's overall surface and relayed the echoed signals back to earth. Three days later, JPL's Media Relations Office proudly displayed the first radar images of Titan, which unveiled such novel features as the active surface, complex terrains, and the possible existence of lakes. The Titan radar had made its début.[1]

The mapping of Titan's geology signified a mode of seeing that has permeated our world, ranging from the spectacular weather-radar images of ash out of the recently erupting Eyjafjallajökull volcano in Iceland and the underwater sounding of the *Titanic*'s debris in the North Atlantic, through the mundane altimeters every aircraft now carries and acoustic pulse-echo devices popular among oil-drilling stations, to the ubiquitous magnetic-resonance imaging (MRI), ultrasound, and X-ray machines that adorn modern hospitals. In none of these endeavors do instruments passively observe and measure objects in a nonintervening manner; rather, an acoustic wave, electronic beam, electromagnetic wave, or other form of energy or particle flow "pokes" the objects and then reconstructs their properties from their modification of the flow. This is the principle of the *active sensor*, one of the most powerful scientific instruments since the early twentieth century.

Instruments are never "just" instruments. Introducing a new instrument is not simply the addition of more advanced hardware to enhance human capacity. As history shows, it often accompanies a sea change of understanding and doing things: the telescope initiated the Scientific Revolution; the air pump nurtured laboratory science; the thermometer pioneered quantitative experimentation; the microscope redefined diseases; the particle accelerator made "big science"; the polymerase chain reaction heralded the genetic worldview. Likewise, the employment of active sensors represents a distinct approach to probing nature, the body, and artifacts that involves not only instrument design but also the making of theories and experimentation.

How did the approach of active sensing come into existence? What characterized this approach as it was developing? How did such a novel mode of seeing change the meanings of experimentation and the patterns of experimental practice? How did it affect the standard of legitimate evidence? How did theories of wave or particle propagation help form and refine active sensing? What kinds of epistemic functions did these theories aim to undertake? Why did this mode of seeing prevail?

While the complete answers to these questions require an overwhelming

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[1] Jet Propulsion Laboratory news releases, "First close encounter of Saturn's hazy moon Titan" (25 Oct. 2004), "Cassini's radar shows Titan's young active surface" (29 Oct. 2004), "Cassini radar sees bright flow-like features on Titan" (9 Nov. 2004), all from Cassini Equinox Mission homepage (http://saturn.jpl.nasa.gov/news/newsreleases/, last accessed on 3 December 2012).

comparative analysis and synthesis of all active sensors that easily go beyond the scope of a monograph, investigation of an informative case may shed some light on such vexing puzzles. This book examines research on radio ionospheric propagation between 1900 and 1935. It is a story of mutual shaping between wireless technology and atmospheric science. After Guglielmo Marconi's first successful transatlantic test in 1901, scientists were curious about why and how radio waves could propagate over such a long distance without the earth's blocking them. From 1901 to 1925, European theoreticians and American engineers grappled with this problem. Its solution led to the discovery of an electrically active region in the upper atmosphere, which they named the "ionosphere."

This revelation opened a new field in earth sciences, and, with the assistance of propagation studies, initiated a novel method of experimentation based on manipulating waves: sending radio waves to the ionosphere and detecting their return. Known as "radio sounding," this method transformed atmospheric studies from passive observation to active experimentation, undercutting the traditional distinction between field and laboratory sciences. From wireless to geophysics, the emergence of studies of radio ionospheric propagation occupies a significant position in the history of active sensing: it began this mode of seeing with electromagnetic waves and led directly to radar during World War II and various sensors in space exploratory programs since *Sputnik* and *Apollo*.

FROM PROPAGATION STUDIES TO ACTIVE SENSING: EXPERIMENT AND THEORY

Similar to the emergence of some other active sensors, the history of radio ionospheric propagation displays a transformation from studies of wave propagation to development of active-sensing systems. Looking at images or data from a lidar, radar, seismic sounder, sonar, or X-ray machine, we may assume that the stream of energy that the instrument sends to observed objects is a transparent medium that merely helps to illuminate the invisible, like a spotlight on a dark stage. But that is not the case. Far from being transparent, that medium is usually complex, entangles itself with imaging and measuring, attracts researchers' attention for its own sake, and thus has a rich history.

The origin of radio ionospheric sounding attests to the importance of wave-propagation research. What spurred radio echo-sounding probes of the ionosphere in the mid-1920s was not geoscientists' pressing need to measure the upper atmosphere, but physicists and engineers' desire to understand how radio waves propagated over long distances above the earth. Only after the discovery of the ionosphere and the invention of the sounding-echo scheme during wave-propagation research did scientists refocus from the waves to the upper atmosphere.

Along this axis of transformation, the history of radio ionospheric propagation epitomizes the challenges that active sensing has brought to our understanding of modern science and technology. In its first thirty years—from Marconi's wireless test to the establishment of the so-called magneto-ionic theory—which constitutes the scope of this book, such a history raises at least three major issues in experiment and theory: Is it possible to experiment outside laboratories? How do we define direct evidence? What role does theory play at different stages of research?

In a subsequent book, I will examine the development and ramification of the automatic ionospheric sounders in the 1930s based on the theoretical and experimental work on radio propagation, and the establishment of radio ionospheric forecasting services around the world during World War II. This forthcoming work will address more closely the issues of instrumentation and technology in radio ionospheric research.

The issues of experiment and theory raised in the development of active sensing were embedded in a broader context of changing senses of reality at the turn of the twentieth century. Historians have found that scientists during this period were increasingly concerned with the epistemic ground of various experiments, observations, and instruments that promised to make the invisible visible: Do scientific instruments uncover phenomena, or create them? What is the role of sensory experiences in the process of generating empirical knowledge? How does one make claims about microscopic or hidden entities based on macroscopic or observable effects? While the scientists' views on these questions diverged, they were all aware of the instrument-mediating character of scientific evidence, and the shaping force of instruments on experiment and theory.[2]

Field Experiments and Direct Evidence

Above all, studies of radio ionospheric propagation in the early twentieth century broaden our historical understanding of experiment. The empiri-

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[2] See Sibum, "Science and the changing senses of reality circa 1900" (2008), 295–97, and the special issue *Studies in History and Philosophy of Science A*, 39:3 (2008). (Sibum's article is the introduction to the issue's theme.)

cal investigations on wave propagation and the ionosphere, like the research and development relating to many other active sensors, had to take place outdoors. The scale could be as large as several thousand miles, and the objects of interest were geophysical in nature. These outdoor measurements and tests were by no means feasible in any laboratory. Therefore, we may not be able to understand them in terms of the laboratory studies that historians have explored in the past. For example, measurements of wave propagation and radio sounding of the ionosphere hardly followed what historians Steven Shapin and Simon Schaffer have called the "laboratory form of life":[3] Control and manipulation of material conditions and relevant variables were often very challenging; replication was usually almost impossible; authoritative eyewitnesses of results were rare; and investigators aimed not so much to generate novel "matters of fact" or "scientific effects" as to figure out how those scientific effects interacted with large-scale nature.

Rather, the empirical work in this story resembled more the tradition of field sciences such as astronomy, botany, geology, geodetics, meteorology, and zoology. What characterized these sciences and radio ionospheric propagation alike were comprehensive and extensive fieldwork, careful preparation for expeditions, meticulous collection of data, and precise instrumentation for observations. The "Humboldtian approach" marked an apex of efforts to turn natural history into integrated, modern field science.[4]

Nevertheless, calling radio ionospheric propagation Humboldtian may downplay its experimental features. Throughout the first half of the twentieth century, the physicists and engineers measuring wave propagation and sounding the ionosphere frequently called their activities "experiments." Much of their practice closely resembled experimentation rather than field observation: their instruments, not nature, produced the radio waves. Although they could not control the macroscopic geophysical structures that shaped the propagation of radio waves over distance, they could manipulate radio waves, including their frequencies, power, polarizations, and waveforms.

Such delicate control encouraged them to tinker with devices, redesign procedures, coordinate measurements, and manipulate signals. For example, military engineers tested wireless equipment between warships, radio amateurs demonstrated long-range radio communications with coordinated voluntary actions all over Europe and the Americas, physicists explored scientific effects between ground and sky at particular experimental sites, and

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[3] Shapin and Schaffer, *Leviathan and the Air Pump* (1989), 22.

[4] Humboldt, *Cosmos*, vol. 1, (1997), vii–xxxv, 7–12, 23–34.

geoscientists acquired data from networks of observing stations (which resembled labs) and interpreted them. These were not laboratory but rather field experiments in our eyes and in theirs. Instead of working indoors, they experimented outdoors and turned nature into a laboratory.

How credible was their empirical evidence? While wave propagation studies had suggested the possibility of an electrically active upper atmosphere, general acceptance of the ionosphere's existence occurred only after the sounding-echo experiments in the 1920s. Why? Many scientists believed that the sounding-echo experiments generated "direct" evidence for the ionosphere. But what was direct about the evidence produced by this particular approach? Control in field experiments, I believe, offers the answer: unlike propagation experiments, which only changed the transmitting radio waves' power and frequency, the sounding-echo tests relied on more elaborate control of waveforms. Instead of sinusoids modulated by Morse code dots and dashes, radio waves now could be chirps, pulses, or other patterned undulations, which scientists designed so that their return, scattering, or deflection from an unknown entity would exhibit their properties more clearly.

Here Nancy Cartwright and Ian Hacking's concept of entity realism may help us: a scientific object is real if we can manipulate it.[5] Sounding-echo experimenters in the 1920s could not modify the ionosphere, yet they could tinker with the transmitting radio waveforms as malleable signals and observe the corresponding changes at the receivers. The introduction of waveform control in propagation experiments made the ionosphere seem more "real" and transformed propagation studies into active sensing.

Epistemic Status of Theories

A central desideratum of research on radio ionospheric propagation was to understand how radio waves traveled above the ground, across water, within the atmosphere, around geographical obstacles, or in any other open environment on the earth. Through the first half of the twentieth century, scientists and engineers proposed, elaborated, and fought over several theories: surface diffraction, atmospheric reflection, ionic refraction, and magneto-ionic refraction. The contest between these theories spurred studies of radio ionospheric propagation, especially up to 1930.

However, it is misleading to interpret the story as one theory replacing

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[5] Cartwright, *How the Laws of Physics Lie* (1983), 1–20; Hacking, *Representing and Intervening* (1983), 262–75.

another, like Hempel-style expansion of covering laws or Kuhnian paradigm change. Scientists devised these theories for different purposes, and they served different functions. Although they did generate mutually incompatible predictions on some empirical questions, and although researchers fiercely debated such forecasts, more often they operated within their own realms and were either irrelevant or marginal to others.

This plurality becomes clear as we examine the epistemic status of wave-propagation theories. At least six questions are germane here. What was a theory's aim and function? What was its most important intellectual virtue? What was the empirical knowledge essential to the theory? What were the central questions it meant to answer? What was its method for tackling these questions? What sort of answers did scientists expect?

The two dominant theories of wave propagation between 1900 and 1920, for instance, differed in nature, even though they both attempted to explain the possibility of long-distance radio. Consistent with Pierre Duhem's two types of scientific theories,[6] the hypothesis of surface diffraction aimed at *formal representation* of an empirical fact, whereas atmospheric reflection proposed *causal explanations* for a broader set of wireless phenomena.

Mathematical physicists worked on surface diffraction and sought a mathematical model to represent long-distance propagation of radio waves along the earth's curvature. Their model comprised a wave equation and a simple boundary condition and gained a life of its own. It became more and more a platform to develop approximating techniques in solving differential equations instead of a reference point for empirical observations. In other words, mathematics was replacing physics.

By contrast, radio engineers were the main explorers of atmospheric reflection. The theory's mathematical structure was much cruder and simpler than surface diffraction before 1919. It boasted no differential equations, no Bessel functions, no asymptotic approximations; it worked with just naïve ray tracing and geometric optics. But formal refinement was never the point. Rather, radio engineers sought to explain numerous wireless phenomena from daily practice—not only long-distance propagation, but also diurnal, geographical, and seasonal variations of ambient noise from the atmosphere. Even though the explanations that they generated were only partly quantitative, their broad but rough theory of atmospheric reflection explained their field observations much better than the precise but narrow theory of surface diffraction.

The magneto-ionic theory, which evolved from the model of atmospheric

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[6] Duhem, *The Aim and Structure of Physical Theory* (1982), 1–54.

reflection, originally served to explain new short-wave propagation phenomena in the early 1920s. As wave-propagation studies were evolving into ionospheric sounding in middecade, however, the epistemic status of the magneto-ionic theory was changing, too. The new radio echo sounding absorbed this theory (thanks to its dependence on the atmospheric structure), which came to be neither strictly mathematical nor exclusively causal.

Recent horizon-expanding literature on scientific theories sheds light on the magneto-ionic model after the 1920s. Historians and philosophers have identified other functions for theories than the conventional ones such as facilitating hypothetical deduction, establishing natural laws, and providing ontological assurance. Andrew Warwick, Ursula Klein, and David Kaiser have stressed theories' use as "paper tools" for computation and supplying information to experimenters. Similarly, Suman Seth has characterized German physicist Arnold Sommerfeld's approach as "physics of problems," which used certain core mathematical techniques to (somehow opportunistically) formulate and solve various physical problems. George Smith has highlighted their roles in building a recursive convergence between predictions and empirical observations and thus achieving "more secure arguments." Sylvain Bromberger has pinpointed their utility as generators of unexpected puzzles and solutions.[7] The magneto-ionic model, it turned out, became "theoretical machinery" that helped radio sounders generate systematic information about the ionosphere as they used echoing radio signals to infer the upper atmosphere's electron density. From the mid-1920s on, the theory's utilitarian value dominated over other goals. Scientists worried less about explaining radio-wave propagation while imposing the ionosphere as part of that explanation; they looked more to unveiling the ionosphere's nature by employing radio-wave propagation. Means and end swapped places.

That conclusion nonetheless does not imply that all scientists after the mid-1920s treated the magneto-ionic theory as a totally black-boxed tool and ceased to think about its accuracy or physical foundation. In the 1920s and 1930s, some physicists still paid attention to the microscopic basis of the magneto-ionic theory and tried to revise it according to such microphysical arguments. These attempts did not succeed, for one reason or another. Yet

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[7] Warwick, *Masters of Theory* (2003); Klein, "Paper tools in experimental cultures" (2001), 265–302; Kaiser, *Drawing Theories Apart* (2005); Seth, *Crafting the Quantum* (2010); Smith, "The methodology of the *Principia*" (2002), 138–73; Bromberger, *On What We Know We Don't Know* (1992).

they remind us of the ambiguity and ontological complexity of theoretical machinery or paper tools.

WHERE THIS BOOK FITS IN

An interdisciplinary subject connotes a pluralistic historiography. Examining research on radio ionospheric propagation as the emergence of a mode of seeing via active sensing can bring new perspectives to the existing literature on the history of physics, history of radio, and history of geoscience. In the history of physics, scholars usually assume a massive change about 1900. Before then, there were elaborations and extensions of Newton's doctrines in mechanics and centuries-long inquiries into light, electricity, and magnetism, culminating in Maxwell's theory. Afterwards, the revolutions of relativity and quantum mechanics dominated modern physics.[8]

In electromagnetism, a subarea of physics, historians have rarely considered anything after 1900 interesting unless it related to quantum mechanics or relativity. Thus, most historical writing has concentrated either on pre-1900 optics, electricity, and magnetism—as in the pivotal works of Jed Buchwald, Bruce Hunt, Daniel Siegel, and Crosbie Smith and Norton Wise[9]—or on quantum and relativistic electrodynamics—as with the renowned studies by Olivier Darrigol, Gerald Holton, and Sylvan Schweber. [10] The most recent overview of electrodynamics, Darrigol's *Electrodynamics from Ampère to Einstein*, has stopped at Einstein, too.[11] This book attempts to remedy exactly this historiographical blind spot. It examines research on electromagnetic waves, but not in relation to quantum physics or relativity, in the early twentieth century. It is clear from this case that novelty in "classical" electromagnetism did not end with Maxwellians, nor were quantum mechanics and relativity the only noteworthy developments of twentieth-century physics. The discoveries regarding wave propagation in the ionosphere formed a breakthrough in

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[8] Recently, some historians have challenged this clear-cut demarcation between "classical physics" and "modern physics" and started to examine the historical orgin of the discourses on this demarcation. For example, see Staley, *Einstein's Generation* (2008), 345–422.

[9] Buchwald, *From Maxwell to Microphysics* (1985), *The Creation of Scientific Effects* (1994), and *The Rise of Wave Theory of Light* (1989); Hunt, *The Maxwellians* (1991); Siegel, *Innovation in Maxwell's Electromagnetic Theory* (1992); and Smith and Wise, *Energy and Empire* (1989).

[10] Darrigol, *From C-Numbers to Q-Numbers* (1992); Holton, *Thematic Origins of Scientific Thoughts* (1988); Schweber, *QED and the Men Who Made It* (1994).

[11] Darrigol, *Electrodynamics from Ampère to Einstein* (2000).

twentieth-century physics. And the history of these findings is more interdisciplinary and involves broader contexts than the above works.

Most literature on the history of radio has focused on devices and their technological systems, not on the effects of propagation of immaterial waves on devices and systems. In recent writing about the technical development of the key devices in radio technology, Hugh Aitken and Sungook Hong have offered the most comprehensive accounts. They have traced Marconi and others' invention of tuning, the transformation of wireless from laboratory apparatus to powerful machinery, and the emergence of electronic tubes. While they have connected the early development of wireless to physicists' research on electromagnetic waves, they have not addressed radio-wave propagation after 1900, which, as this volume shows, helped shape wireless technology.[12] Among the abundant cultural, political, and social histories of radio broadcasting, Susan Douglas and Linwood Howeth's works have stood out, as they have stressed the institutional processes that transformed radio from novel machines into a prevalent technological system. While Howeth has discussed the U.S. Navy's adoption of radio, Douglas has explored inventor-entrepreneurs, the navy, and radio amateurs as incubators of American broadcasting.[13] They have focused on social dimensions of the construction of *hardware* and *applications*—how these people invented devices, improved machines, promoted new services, and established organizations for these purposes. By contrast, this book looks at the immaterial agent of radio technology—electromagnetic waves—as it examines how these parties worked together on radio-wave propagation.

Writings on the history of geoscience have been fewer than those on electromagnetism and radio. Recently, growing interest in environmental history and awareness of big science's interdisciplinary nature have inspired more research on this subject. One common trend is emphasis on how the methods of laboratory physical sciences diffused throughout and changed the practices of geoscience in the last two centuries. Naomi Oreskes's *Rejection of Continental Drift* (on geology) and Helen Rozwadowski's *Fathoming the Ocean* (on oceanography) are the leading products of such a trend.[14] *Probing*

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[12] Aitken, *Syntony and Spark* (1976), and *The Continuous Wave* (1985); Hong, *Wireless* (2001).

[13] Douglas, "Technological innovation" (1985), 117–73, and *Inventing American Broadcasting* (1987); Howeth, *History of Communications-Electronics* (1963).

[14] Oreskes, *The Rejection of Continental Drift* (1999); Rozwadowski, *Fathoming the Ocean* (2005).

the Sky with Radio Waves complements these books by concentrating on how the introduction of active sensing facilitated the rise of ionospheric science.

Of course, this is not the only historical work on the subject. Decades ago, Stewart Gillmor and Bruce Hevly wrote on different aspects of the field's history, including the discovery of the ionosphere, the mathematical formulation of the magneto-ionic theory, and the institutional framework of early radio ionospheric research. Recently, Edward Jones-Imhotep and Dominique Pestre have studied ionospheric research during and after World War II. Although all these and other writings provide valuable insights, they deal with only part of the story: either conspicuous discoveries (the early works), or the institutional and political contexts of ionospheric studies *after* their major development (the later efforts). An exception is Aitor Anduaga's *Wireless and Empire*, perhaps the most comprehensive examination on the topic in recent years. It offers a careful and detailed account of interwar research on radio ionospheric propagation in Britain, Australia, Canada, and New Zealand, with the intention of illuminating the geopolitical and commercial structure of the British Empire that nurtured these endeavours. It therefore does not touch on developments in France, Germany, and the United States, or the pioneer era 1900–1920.[15]

This volume presents a longue-durée conceptual, epistemic, and technical history of radio ionospheric propagation and situates it in the emergence of a new mode of sensing the world.

OUTLINE OF CHAPTERS

I have divided this book into three parts. Part I (chapters 2–4) concerns the early studies of long-distance radio-wave propagation between 1901 and 1919. The success of Marconi's transatlantic wireless trial in 1901 immediately raised a question: how did radio waves traverse the earth's curvature? Chapter 2 is about the introduction of the first theory to account for long-distance propagation of waves—the theory of "surface diffraction" contended that radio waves crept along the earth's surface like sound or light flowed around an obstacle. Hector Macdonald at Cambridge first proposed this model in 1901.

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[15] Gillmor, "The big story" (1994), 133–41, "Threshold to space" (1981), 101–14, and "Wilhelm Altar, Edward Appleton, and the magneto-ionic theory" (1982), 395–440; Hevly, "Building a Washington network for atmospheric research" (1994), 143–48; Jones-Imhotep, "Nature, technology, and nation" (2004), 5–36; and Pestre, "Studies of the ionosphere and forecasts for radiocommunications" (1997), 183–205; Anduaga, *Wireless and Empire* (2009).

In the decade that followed, the French mathematician Henri Poincaré, Macdonald's colleague John Nicholson, the German engineer Jonathan Zenneck, and the German physicist Arnold Sommerfeld revised Macdonald's model and turned it into a tour de force of mathematical exercises.

Yet those proponents of the theory lacked quantitative empirical evidence. Chapter 3 deals with the U.S. Navy's construction of the first empirical formula for radio-wave propagation. From 1909 to 1913, the U.S. Naval Radiotelegraphic Laboratory in Washington, directed by Louis Austin, performed a series of transatlantic wireless measurements to test the navy's new high-power transmitting station, and these engineering tests became scientific experiments. Austin and his colleague Louis Cohen's resulting Austin-Cohen formula constituted substantial empirical evidence for propagation theorists. Its wavelength dependence, however, contradicted the surface-diffraction theory.

Chapter 4 looks at how scientists and engineers resolved this discrepancy. When Macdonald developed his theory, the English physicist Oliver Heaviside and the American engineer Arthur Kennelly proposed "atmospheric reflection" to explain long-distance propagation, whereby radio waves bounced back and forth between a conducting layer in the upper atmosphere and the earth. This simple model was not even quantitative, let alone capable of making predictions consistent with Austin-Cohen. In the mid-1910s, the British radio experimenter William Eccles revised the model by suggesting that the upper layer consisted of free electrons that emerged as sunlight ionized the atmosphere. The ionized layer did not directly reflect radio waves but rather "refracted" them by deflecting their trajectories, just as water deflected light from air. Although Eccles's theory provided quantitative predictions on wave propagation, the results did not match the empirical formula either. Predictions and data eventually fitted each other in 1919, when the Cambridge mathematician George Watson built a formal theory of atmospheric reflection that could reproduce the Austin-Cohen formula. A long-distance radio experiment by the Marconi Wireless Company corroborated the theory and ended the debate.

Austin-Cohen's most valuable prediction was that radio waves traveled farther at longer wavelengths (i.e., lower frequencies). Before 1920, therefore, all the military and commercial long-range wireless systems used long wavelengths. During the early 1920s, however, the situation changed entirely: shortwave systems marginalized long-wave radio and came to dominate long-range wireless communications, which led to discovery of the ionosphere—the focus of part II (chapters 5–8). Chapter 5 delves into a major finding by radio amateurs: contrary to Austin-Cohen, radio waves shorter than 300 meters could travel up to several thousand miles. At the time, laws restricted radio amateurs to operating at "useless" short wavelengths, a disadvantage that turned them into pioneers. In the early 1920s the amateur American Radio Relay League undertook large-scale wireless experiments that involved hundreds of hobbyists on both sides of the Atlantic. The results showed that waves as short as 100–200 meters could cross the ocean. This launched a "gold rush" to explore shorter waves.

The short-wave bandwagon led to identification of another aspect of propagation and modification of the theory of ionic refraction, as we see in chapter 6. Among the explorers was the U.S. Naval Research Laboratory. Albert Taylor, the head of its radio department, collaborated with American amateurs to experiment with short-wave propagation. They kept on decreasing the wavelength and measured the change in the range of propagation. It turned out that radio waves shorter than 50 meters behaved strangely: instead of diminishing steadily with distance, their signal strength became zero in some intermediate region but then rose again, as if they "skipped" over this region. These three phenomena—transatlantic short waves, the skip zone, and the variation of propagating range with wavelength—all called for explanation. Eccles's model (ionic refraction) explained them better than Watson's (earth-sky reflection). In 1924, the Cambridge physicist Joseph Larmor reformulated Eccles's theory. Then Taylor and E. O. Hulburt at the Naval Research Laboratory modified ionic refraction and explained the skip zones. Finally, Edward Appleton of the Cavendish Laboratory and Harold Nichols and John Schelleng of American Telephone and Telegraph (AT&T) incorporated geomagnetism into ionic refraction to account for some features in the range-wavelength data. All these experimental and theoretical efforts led to the conclusion that short radio waves propagated over long distances because an ionized layer in the upper atmosphere refracted them and the earth's magnetic field affected their velocity, intensity, and polarization.

Nevertheless, no one had actually seen this layer. Was it a hypothetical entity to explain some observations, or a real object? Again, studies of radio-wave propagation offered answers. Between 1924 and 1928, as chapter 7 details, wireless experiments by British physicists yielded what seemed to be direct evidence for the ionosphere. In 1920, the English engineer Thomas Eckersley suggested, from his experience in the British army with wireless direction finders, that radio waves often traveled great distances, going into the sky and returning to the ground. The existence of such sky waves indicated to him the existence of a wave-deflecting boundary in the sky, without evoking specific propagation theories. And one could determine the height of this boundary by measuring sky waves, whose detection became the primary route to direct evidence for the ionosphere. This endeavor preoccupied three groups of researchers—two in Britain and one in the United States. Reginald Smith-Rose and R. H. Barfield of Britain's National Physical Laboratory followed Eckersley's approach of looking for sky waves by tracing the polarizations of incoming waves. Before they could obtain positive results, however, Appleton and his assistant, Miles Barnett, under the aegis of Britain's Radio Research Board, claimed success in 1924. In contrast to the polarization method, they changed radio signals' frequencies to produce interference between sky waves and waves propagating from transmitter to receiver along the ground. They could also easily determine the ionosphere's height from their measurements of interference.

The four British researchers' radio experiments triggered a series of investigations that harnessed echo sounding to probe the upper atmosphere—the subject of chapter 8. About the same time as Appleton and Barnett's frequency-change trials, Gregory Breit and Merle Tuve at the Carnegie Institution of Washington began sending narrow radio pulses to the sky and observing whether they bounced back, and they used the time delay between a pulse and its echo to determine the ionosphere's height. Unlike previous propagation experiments that passively measured radio-wave intensity, Appleton-Barnett and Breit-Tuve actively changed signal patterns at transmitters and inferred properties from corresponding changes at receivers. In so doing, they generated evidence for the ionosphere that contemporaries considered direct. Furthermore, their method of active experiments using radio waves allowed scientists to explore the physical state of the ionosphere. For example, Appleton soon claimed that it possessed a second layer. Propagation studies were revolutionizing atmospheric science.

The discovery of the ionosphere offered new clues to some long-standing problems in geoscience, and radio waves became a tool to help solve these problems. Yet turning radio measurements into ionospheric data required better understanding of radio-wave propagation. Part III (chapters 9–10) examines physicists and engineers' efforts between the world wars to explain wave propagation in the ionosphere. Chapter 9 concentrates on the incorporation of the geomagnetic effect into ionic refraction. Extending Appleton, Nichols, and Schelleng's earlier work, a few Germans, an Austrian, and a few English associated with Appleton deduced and elaborated a generalized magneto-ionic theory (the Appleton-Hartree formula), which gained empirical support from the Cavendish Laboratory's polarization measurements in England and Australia. The English researchers also developed computational methods to turn the general theory into a paper tool to help echo-sounding experimenters uncover the structural characteristics of the ionosphere.

Domesticating the magneto-ionic theory did not stop scientists from worrying about its physical foundation. Chapter 10 addresses physicists' interwar debates on the theory's ontological—or, more precisely, microscopic—status. American, British, Danish, and French researchers contended over whether to include two extra terms in Appleton-Hartree because of intermolecular interactions: the Lorentz correction, proposed by the Cambridge mathematician Douglas Hartree, and the quasi-elastic force, advocated by the French physicist Camille Gutton and his disciples in Nancy. Although these microphysical debates did not get settled until the 1950s and did not much affect practical application of the theory, they reflected physicists' concern about the ultimate basis of a theory and the technical difficulty of exploring that conundrum.

Chapter 11 concludes the book. It sketches later research in radio ionospheric propagation, summarizes key themes and crucial developments between 1900 and 1930, and compares this story with other ones relating to the rise of active sensing.

A NOTE ON UNITS

Scientists and engineers in the first half of the twentieth century did not settle on a single system of units for measurement. While those in Continental Europe had adopted the metric units of meter and kilometer for length and gram and kilogram for weight, the Anglo-American researchers stayed with the imperial units of inch, foot, mile, and pound. In electromagnetics, a widely used system of units, which is the only one most scientists and engineers know today, was the rationalized MKS system comprising meter, kilogram, second, coulomb (for electric charge), ampere (for electric current), and other common technical units. At the time, however, another system of units was also popular: the Gaussian system comprising CGS (centimeter, gram, second), the electrostatic unit (esu) of charge, and the electromagnetic unit (emu) of current. And there were at least two additional systems: the Heaviside-Lorentz system that eliminated the constants of permittivity and permeability in Maxwell's equations, and the "natural" units that equaled the speed of light and reduced Planck constant to 1.[16] In this book, I do not convert all the physical units into today's standard system such as metric or rationalized MKS. Rather, I follow historical actors' own use of units. When a scientist or engineer in the story chose to express physical quantities in terms of a specific system of units, I present the same figures and units.

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[16] Panofsky and Phillips, *Classical Electricity and Magnetism* (1962), 459–69.

* 1 *

Conceiving Long-Range Propagation: 1901–19

CHAPTER 2

Theorizing Transatlantic Wireless with Surface Diffraction

It was a chilly winter day. The freezing Arctic winds blew on the rocky coast, not pleasant for the men on the hill, but good for flying kites, which they were doing. The young *signor* sat in a room of an abandoned hospital nearby, with drums, knobs, tubes, and wires on the table. Outside with the local laborers were his two moustached, hard-working assistants. The signor had planned for his "big thing" for years; this expedition was its culmination. Before departing for Newfoundland, the assistants shipped six 500-foot-long kite antennae, two balloons, and various receiving apparatuses. On arrival, the signor cabled his experimental station in England to transmit the Morse code of "SSS" (dot-dot-dot) to him every day between 11:30 a.m. and 2:30 p.m., his time. Keeping their real goal secret, team members pretended that they were just studying the influence of rocks on Hertzian waves.

The historical moment came at 12:30 p.m. The signor was the first to hear the three sharp clicks from the earphone. He then fetched one of his assistants, who heard the same thing. The pattern repeated itself at 1:10 and 2:20 p.m. and the next day at 1:38 p.m. Deteriorating weather forbade further testing. But that was enough. The signor informed his business partner in London and issued a brief press statement. Two days later, the *New York Times* featured the story: "St. John's, Newfoundland, December 14 [1901]—Guglielmo Marconi announced tonight the most wonderful scientific development of recent times. He stated that he had received electric signals across the Atlantic Ocean from his station in Cornwall."[1] The world beheld the wireless.

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[1] Dunlap, *Marconi* (1937), 99; anonymous, "Wireless signals across the ocean" (1901). There are many accounts of Marconi's transatlantic wireless test of 1901. For example, see Dun-

Like all telecommunications technologies, wireless has been a project of conquering space. When Heinrich Hertz discovered the spark-induced electric waves in 1886–88, the phenomenon was a curiosity interesting only to physicists. A series of efforts by scientists and engineers in the 1890s turned this scientific effect into a workable means of telegraphy. A major development took the experimental sets outside the laboratory. In Hertz's original experiment in Karlsruhe, the whole apparatus was indoors, and the maximum distance to detect electric waves was 12 m. In 1891, the Briton George Minchin detected the waves at 130 feet (39.65 m). In 1894, the Maxwellian physicist Oliver Lodge claimed success in detecting electric waves between a spark-gap transmitter in the Clarendon Laboratory and a coherer receiver 180 feet (54.9 m) away in the Oxford Museum. From that time on, experimenters no longer stationed the transmitter and receiver in the same room, and the development of wireless became a race of expanding distances: in 1895–96, Captain Henry Jackson of the British Royal Navy reached 100 yards (91.4 m). In 1896, the New Zealander Ernest Rutherford reached 0.5 miles (800 m) at Cambridge's Cavendish Laboratory. In 1894, the Italian-Briton inventor Guglielmo Marconi reached 2 miles (3.2 km) in Bologna, and his reproduction of this result in 1896 at a demonstration to the British Post Office marked the beginning of his enterprise in wireless.[2]

Marconi's career in the late 1890s rose with his further increase of the Hertzian waves' communications range. From May to November 1897, he experimented across the Bristol Channel and achieved first 3.3 miles (5.28 km) and later 7.3 miles (11.68 km). At the same time, his demonstration for the Italian navy reached 12 miles (19.2 km). In March 1899, he sent wireless signals across the English Channel, between the South Foreland Lighthouse near Dover and Wimereux near Boulogne. The distance was about 30 miles (48 km), at which the receiver was significantly below the transmitter's earth horizon.[3]

Could the traveling distance of the Hertzian wave increase indefinitely? What was the spatial limit of wireless telegraphy? Was it possible to transmit signals across, say, the entire ocean? To Marconi, these were technological

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lap, *Marconi*, 87–102; Bussey, *Marconi's Atlantic Leap* (2000), 43–52; Hong, *Wireless* (2001), 77–80; and Marconi, *My Father Marconi* (1962), 111–20. For the historiography of this event, see Hong, *Wireless* (2001), 213.

[2] Aitken, *Syntony and Spark* (1976), 118–20; Buchwald, *The Creation of Scientific Effects* (1994), 297; Hong, *Wireless*, 5, 14, 16, 20, 34.

[3] Hong, *Wireless* (2001), 53–58; Jolly, *Marconi* (1972), 33–67.

rather than scientific questions. After the successful test across the Channel, he was confident that elevating the power of spark-gap machines, refining the sensitivity of detectors, and improving antennae could overcome distance, regardless of any laws of wave propagation. So he aimed at a much more ambitious range: the 2,000 miles (3,200 km) of the North Atlantic between Ireland and Newfoundland.

Marconi clandestinely prepared for the transatlantic experiment throughout 1900 and 1901. With the help of John Ambrose Fleming, a physics professor at University College, London, he established a high-power transmitting station in Poldhu near Cornwall, England. In September 1901, a test between there and a receiver 200 miles (320 km) away in Crookhaven, Ireland, was successful. Marconi considered several receiving sites in North America and first picked Cape Cod, Massachusetts. But a storm destroyed the aerial mast there, which forced him to move the effort to Newfoundland.[4] The rest of the story is familiar: Marconi achieved the first wireless communication across the Atlantic on 12 December 1901. Some experts reasonably suspected the reliability of the 1901 test—only Marconi and his assistant George Kemp witnessed SSS, the signals appeared just four times, and the result was not repeatable. But the doubt evaporated in February 1902, as Marconi, his assistants, and their apparatuses boarded SS *Philadelphia* in Southampton, England, to sail to New York. Their ability to receive signals from Poldhu in the course of the voyage demonstrated the actuality of long-range wave transmission. By the end of 1902, Marconi had managed to enact a receiving station in Glace Bay, Nova Scotia, and launched a regular transatlantic service.[5]

Marconi's transatlantic wireless tests caught the public's attention for their technological implications and also raised a scientific question about how electric waves traverse space. Despite the enthusiastic late-century competition to increase the effective range of Hertzian waves, attempts to understand the variation of the electric-wave intensity with distance were scarce. Hertz's work remained the gold standard. In 1889, he proposed a theory for his spark-gap experiment: he modeled the spark gap as a tiny radiating dipole source and solved Maxwell's equations under spherical symmetry. The solution was

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[4] Jolly, *Marconi* (1972), 103.

[5] For the reception of Marconi's 1901 test, see Hong, *Wireless* (2001), 79–80. For Marconi's experiment on SS *Philadelphia* and the creation of the Glace Bay station, see Bussey, *Marconi's Atlantic Leap* (2000), 71–87. There has been a controversy regarding whether Marconi "really" received the letters "SSS" transmitted from Britain in December 1901. For a skeptical view about the reality of Marconi's claimed success in receiving "SSS," see Sarkar et al., *History of Wireless* (2006), 392–94.

classical: if the whole space contained nothing but the source, then the radiated field intensity E observed far from the source attenuated with distance r; in other words, $E \sim 1/r$.[6]

In Hertz's theory, the electric-wave intensity decreased with distance. And the decreasing rate of $1/r$ was identical to that of a point source spreading energy spherically to the surrounding space, which was consistent with the picture of the pointlike Hertzian dipole. So an electromagnetic wave *spread out rectilinearly* from the radiating source, and therefore Hertz applied the German *Ausbreitung* (spreading out); the English *propagation* connotes the same meaning.

Hertz's theory claimed that electromagnetic waves propagated along straight lines. But in wireless communications farther than 20 km (such as Marconi's 1899 trial across the English Channel), the transmitter and receiver were below each other's horizons, and the earth blocked line-of-sight propagation. What mechanism delivered electromagnetic energy in those cases? Marconi suspected that the ground, like a huge cable, carried the electric signals. The Serbian-American inventor Nikola Tesla held the same belief. The idea of ground-creeping Hertzian waves did not receive much attention in the 1890s; the effect seemed minor for the distances of experimentation, at which Hertzian radiation still behaved like light. Nor were Marconi and his fellow technologists looking for scientific explanations. For a while, how the Hertzian waves propagated remained a not particularly interesting question.

The success of the transatlantic wireless in 1901 altered the nature of this question. The distance of 3,200 km was much beyond the line of sight. Why could the signals travel this far? To traverse one-sixth of the earth's perimeter, the waves had to conform to the curving surface of the earth. Why did they, unlike optical and acoustic waves, not follow rectilinear trajectories? Why did the earth's curvature not block their propagation? After Marconi's triumph, scientists could no longer ignore this problem or pretend it was the result of some minor physical effect.

Starting in 1901, the theoretical physicists and mathematicians in Britain, France, and Germany took on the theoretical problem of long-range propagation of radio waves, the new name for the Hertzian, or electric, waves.[7] They

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[6] Hertz, "The forces of electric oscillations" (1900), 137–59; Buchwald, *The Creation of Scientific Effects* (1994), 312–14.

[7] The term "radio" began to replace the scientific "Hertzian effect" and technological "wireless" after about 1905. In the rest of the book, I follow today's convention by using "radio waves" to refer to electromagnetic waves longer than 1 mm.