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The Origin of Waveguides*: A Case of Multiple Rediscovery

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Abstract—**The early history of hollow tube waveguides is described. Conceived by Lord Rayleigh in 1897, they were little used and the idea forgotten. Almost 40 years later, G. C. Southworth and W. L. Barrow rediscovered the concept, each working independently for almost five years with no knowledge of the other. This work culminated in almost simultaneous public presentations in 1936. The significance of these events for gaining insight into the interactions of science, mathematics, and engineering is discussed.**

I. Introduction

THE HISTORY of the development of waveguides from the earliest conceptual exploration extends over virtually the full extent of the 100-year history of the IEEE. It is only the past half century, however, that has witnessed the extensive application of this technology and its conceptual enrichment. The technical advances during this later period are generally well known to most of the readers of this journal, but the earlier half of the period has not been treated as a topic in either technical or historical literature. Nevertheless, it holds a fascinating story of struggles with technical ideas, and offers many insights into how such ideas are developed. It is this earlier period that will be considered here.

With the acceptance of the electromagnetic theory of Faraday and Maxwell and its experimental verification by Hertz in the late 19th century, electromagnetic phenomena assumed a leading position among the concerns of contemporary physicists. The wave theory of light had been firmly established, and the nature of light had been shown to be electromagnetic; it now appeared that these concepts might explain much of the physical world. With recognizable practical applications in the growing field of electrical communication, these phenomena were also of great interest to engineers.

Work on the transmission of electrical signals was concentrated at the low-frequency end of the electromagnetic spectrum, and the technology was limited to the use of multiple-wire lines (usually two) or a single wire with the earth as a return. In these cases, the dominant mode of propagation, the only one recognized at first, is a transverse electromagnetic (TEM) wave with its electric- and magnetic-field components in a plane perpendicular to the wire, corresponding to the optical model accepted for lightwaves in free space. Thus, the concept of propagating electromagnetic waves, whether in space or along wires, was effectively concentrated on the transverse plane-wave paradigm. Although it was recognized that a point source radiates spherical waves and a line source cylindrical waves, at great distances from the source these are approximated by plane waves.

During this period, Oliver Heaviside engaged in a vigorous development of the theory of transmission of electromagnetic energy. His purpose was the creation of a theory useful for practical purposes, and he introduced many of the concepts that have since proven useful in electrical engineering. He developed the essential basis of modern transmission-line theory. Furthermore, Heaviside first introduced the concept that metallic conductors act to *guide* an electromagnetic wave.

In 1893, Heaviside considered various possibilities for waves along wire lines from a theoretical standpoint and concluded that single conductor lines were not feasible. He convinced himself that guided waves needed "two leads as a pair of parallel wires; or if but one be used, there is the earth, or something equivalent, to make another" [1]. Speculating on propagation within hollow tubes, Heaviside concluded that:

> It does not seem possible to do without the inner conductor, for when it is taken away we have nothing left upon which the tubes of displacement can terminate internally, and along which they can run....
>
> It would appear that the only way of completely solving the problem of the automatic transmission of plane waves within a single tube is a theoretical one, employing magnetic as well as electric conductance [2].

At about the same time, J. J. Thomson gave a theoretical analysis of electric oscillations within a conducting cylindrical cavity of finite length. He found that there were permissible normal modes that were a function of the radius of the cylinder [3]. Shortly thereafter, J. Larmor similarly investigated the theory of resonant structures such as coaxial metallic cylinders and a single dielectric cylinder [4].

The definitive treatise that extended the theory of transmission of electromagnetic waves, however, was that by Lord Rayleigh in 1897 [5]. Rayleigh had a broad interest in all aspects of the theory of waves and had contributed greatly to the theory of sound, waves in fluids, and lightwaves. He now turned his attention to the propagation of

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*The term *waveguide* will be used in its common sense of a single conductor of essentially hollow cylindrical form of an arbitrary cross-sectional shape.

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electromagnetic waves on cylindrical structures. Solving the boundary value problem for Maxwell's equations in a space bounded by a cylindrical surface of arbitrary cross-sectional shape, he showed that waves could indeed propagate within a hollow conducting cylinder. He found that such waves existed only in a set of well-defined normal modes, such as is the case for vibrations of a membrane. Furthermore, the waves were of two types: one with a longitudinal component of electric intensity only, while the other had a longitudinal component of magnetic intensity only. Both types had transverse components of both electric and magnetic intensity. He found that a fundamental limitation on the existence of such waves was that the frequency must exceed a lower limit depending on mode number and the cross-sectional dimensions of the cylinder. Rayleigh gave specific solutions for the cases of cylinders of rectangular and circular cross section. Because the cutoff wavelength was of the same order of magnitude as the largest cross-sectional dimension of the cylinder, it was obvious that the phenomena would only be of practical value at high frequencies, and at the time such frequencies were only used in research work.

Some contemporary research work did indeed make use of electromagnetic waves in hollow cylinders, but this work involved resonators rather than long propagating structures [6]. Propagation in hollow tubes did receive some further attention, however, and R. H. Weber, in 1902, proposed an interesting physical interpretation for the fact that the wave velocity in the tube was less than the velocity of light in the medium [7]. He suggested that the wave is equivalent to a plane wave traveling in a zig-zag path, being reflected from the walls of the tube, a concept revived some thirty-five years later. After this brief period of attention, work on electromagnetic propagation in hollow tubes virtually disappeared from the scientific and technical literature. An exception is an isolated paper by L. Silberstein in 1915 wherein he recognized that propagation in a hollow tube is dispersive, thus broadening an electromagnetic pulse, and he proposed that this effect would soften "hard" Roentgen rays [8].

A different type of guided electromagnetic wave propagation began to receive attention around the turn of the century. This type is based on the fact that the discontinuity surface between two media having different electrical properties acts to bind a wave to that surface, thus guiding the wave, which is thereby termed a *surface wave*. A simple form of structure that can support such a surface wave is a single wire in space, and this case was first analyzed by A. Sommerfeld in 1899, obtaining only the principal mode [9]. Sommerfeld's work was extended by D. Hondros in 1909 to obtain the complete solution [10].

An isolated single wire is only of theoretical interest, however, as it cannot be realized in practice. A far more interesting and useful form is either a pure dielectric rod or slab, or a dielectric on a conducting surface. Hondros turned his attention to the dielectric rod and, with P. Debye, obtained a theoretical solution in 1910 [11]. Experimental work on dielectric rods was begun by Rüter and Schriever in 1914, but this was interrupted by the war. The work was continued by H. Zahn, who published some preliminary results in 1916 [12]. After the war, Schriever returned to his investigations on dielectric rods for his doctoral dissertation at the University of Kiel. This encompassed a comprehensive theoretical and experimental exposition, and the essential points were summarized in a paper published in 1920 [13]. As will become apparent below, this particular paper played an influential role when work on hollow tube waveguides was revived.

The above account demonstrates how research interest in guided waves changed over the years from wire lines to dielectric wires and surface waves with only a brief and ephemeral interlude devoted to hollow tube waveguides. The textbooks published in the first several decades of this century, whether for physicists or engineers, treat, at most, electromagnetic waves in space or on wire lines. This is not too surprising when one considers that the major application for propagating electromagnetic waves (other than light) was in radio communication, and the frequencies used were relatively low—too low for hollow tube waveguides to be practical.

There are several reasons why low frequencies were preferred for radio communication. For long distance propagation along the earth's surface, the ground wave is only useful at relatively low frequencies, and the sky wave is not reflected from the ionosphere above 15 to 20 MHz. Under the influence of Marconi, developments in components for radio emphasized higher power at lower frequencies in order to obtain the greatest distance of communication [14]. This emphasis focused attention on power sources that would provide these characteristics, such as arc generators and the "high-frequency" alternator, the latter being limited to frequencies of a fraction of a megahertz. Throughout the development of electromagnetism, the state of the art has been limited by the available power sources.

As a result of this course of events, the concept of electromagnetic waves propagating in hollow tubes having dimensions on the order of a wavelength effectively disappeared from the working body of scientific and technical knowledge. That this was so is illustrated by a speculative article by E. Karplus in 1931 on the possibility of communicating at any wavelength down to the infrared region [15]. He discussed all components of such communications systems, and concluded they were feasible. In discussing applications, he suggested communications from one end of a railroad train to the other, but cautioned—"It is easily understood that in a narrow tunnel wave propagation and radiation are only possible at waves short compared to the diameter of the tunnel." Clearly, Karplus was thinking in optical terms and was not aware of Rayleigh's 1897 paper, where it was shown that, for conducting walls, the wavelength only need be less than 1.7 times the diameter! In the developments discussed below, there will be further evidence that other highly competent persons directly questioned the feasibility of wave propagation in hollow tubes at about the same time.

The development of vacuum tube sources of electromagnetic energy proceeded steadily following Lee deForest's invention of the triode in 1906. This led to the

Barkhausen-Kurz oscillator in 1920, which produced detectable power up to frequencies as high as 10 GHz. Another new form of oscillator was the magnetron, discovered by A. W. Hull in 1921. This type of vacuum tube underwent considerable development in succeeding years so that by the mid-1930's useful power output was obtained at frequencies as high as 30 GHz. These power sources were only used for research purposes, as there were no practical applications at such high frequencies. Their existence, however, did provide a technology needed for a revived interest in hollow tube waveguides.

There had been a harbinger of a new technology involving electromagnetic waves of very short wavelength. A line-of-sight radio link operating at a wavelength of 18 cm, from Calais to Dover, had been demonstrated on March 31, 1931 [16]. With a beamed radiation pattern formed by parabolic reflectors, this experimental link was the forerunner of most present-day communication systems.

It was against this background that in the spring of 1936 in Washington, DC, two men independently announced on successive days that they had discovered that electromagnetic waves would propagate in hollow tubes and had experimentally demonstrated the practicality of this phenomenon. These men, George C. Southworth of Bell Telephone Laboratories (BTL), and Wilmer L. Barrow of the Massachusetts Institute of Technology (M.I.T.), had each been working on these developments for more than four years. During this time, knowledge of the work had not diffused beyond those associated with each project at each institution. The principals had only become aware of each other's work about one month prior to the announcements, after publication of the programs for the meetings at which the presentations were to be made.

This instance of simultaneous discovery provides a number of interesting parallels and contrasts, as well as insight into several aspects of the interaction of science and technology. The fact that it is also a case of rediscovery introduces conditions that are not usually present in multiple discoveries.

II. George C. Southworth

A major figure in the rediscovery of hollow tube waveguides is George C. Southworth. He was born on August 24, 1890 and grew up on a farm in Little Cooley, PA [17]. He became interested in radio during his last year in high school and began to experiment, reading everything he could find on the subject. Following graduation, he taught grade school for two years, then enrolled at Grove City College, graduating with a major in physics in 1914. His interest in radio had persisted, and he continued at Grove City as a graduate student majoring in the physics of radio.

In 1916, Southworth decided that he wished to teach on a university level and realizing that his education needed strengthening, he enrolled as a graduate student at Columbia. After a year, however, influenced by the need for technical help for the war effort, he joined the Bureau of Standards to work in the Radio Section. In late summer 1918, he moved to Yale to train Signal Corps officers. Following the end of the war, he was asked to remain at Yale and teach first year physics and assist in a graduate laboratory course, largely because of his unique experience with radio.

Recognizing the need for a doctoral degree if he was to progress as a faculty member, Southworth began preparation in 1920, receiving the degree in 1923. His dissertation subject was the measurement of the dielectric constant of water at radio frequencies (about 15 MHz), measured by continuous waves. The method he used was to compare the wavelength measured by a Lecher wire frame, first in air, then when immersed in water. The measurement in water produced an unusual standing-wave pattern, indicating unexplained resonances. Upon removing the Lecher wire frame, Southworth found that the trough of water still exhibited these perturbing waves. Hearing a report on Schriever's article [13] on waves on dielectric wires, he concluded that this was the explanation. He finally eliminated the spurious influence by making his apparatus sufficiently small.

Upon graduation from Yale, Southworth, already married for more than eight years and having children, decided that he could not make do on a faculty salary. He sought a position in industry and accepted an offer from the American Telephone and Telegraph Company in New York. He was assigned to help edit the newly started *Bell System Technical Journal*, and to write semipopular articles on technical subjects. This work was not to his liking, and, in late 1924, he arranged to be transferred to the Development and Research Department. Here he engaged in field measurements of equipment for short-wave radio transmission.

Southworth did not find the assigned work very inspiring, as, despite the name of the department, there was no research being conducted. He had been continually reflecting on those spurious resonances he had found in his work at Yale. Finally, in the summer of 1931, he prevailed on an associate to make a translation of Schriever's article, and he found that, while suggestive, it did not really explain the phenomena he had observed. He decided, therefore, that he would resume his investigation of the unexplained waves, and on November 10, 1931, he began to record his ideas in a personal notebook [18]. Over the next few weeks he described dielectric rod waveguide, methods of exciting and detecting dielectric waves, and speculations regarding long distance transmission.

The first problem Southworth faced was that of obtaining apparatus with which to experiment. Members of his department were not to engage in research, but could make tests of existing telephone equipment. He decided he would stretch this policy to make some "tests" of his ideas which, after all, could be related to short-wave transmission. Because the concept of a transmission line without a return conductor might appear ridiculous to some, he sought to make initial tests before he disclosed his ideas to management. On December 14, 1931, he visited the Netcong Radio Station test facility of the department to arrange for the building of test apparatus similar to that he had used at Yale ten years earlier [19].

As the work progressed, it was necessary to make some minor purchases of materials, and this required supervisory approval, fortunately granted without question by his immediate supervisor, Ralph Bown. Southworth's request to the company library for translation of one of the articles among Schriever's citations, however, led to the exposure of his interests to higher levels of supervision [20]. The matter came to the attention of Lloyd Espenschied, Bown's supervisor, who met with Southworth on March 18, 1932 to discuss the project [21]. Espenschied encouraged Southworth and asked him to provide a written exposition of his ideas. By April 11, 1932, he had completed a memorandum entitled "Transmission Through Dielectric Cylinders," and sent a number of copies, which Espenschied then forwarded to potentially interested individuals [22]. In his letter of transmittal, Espenschied expressed some skepticism, but took the view that Southworth should be afforded the opportunity to investigate his ideas a little further before any formal decisions were made regarding company support.

Fortunately, tests with the apparatus in Netcong were successful when, on March 28–30, 1932, waves were first observed in the water-filled copper pipe used as the dielectric cylinder. Fortunate because one of the recipients of Southworth's memorandum was John R. Carson, one of the leading mathematicians in the company, who analyzed Southworth's scheme in a memorandum dated May 6, 1932 and concluded in a transmittal memorandum dated May 9, 1932 that the "proposed system of transmission is not practicable" [23]. As a result of this conclusion, Epsenschied, his skepticism confirmed, was reluctant to authorize further work, and Southworth so recorded this in his notebook on June 15, 1932 [24].

Meanwhile, Carson had reexamined his analysis and found an error. He sent a memorandum to Southworth, dated June 22, 1932, admitting his prior mistake and supporting the feasibility of dielectric waves of the type Southworth was proposing [25]. He apparently also assigned one of the mathematicians on his staff, Sallie P. Mead, to further analyze the structures. She prepared a memorandum, "Dielectric Cylinders: Transmission Characteristics," dated August 11, 1932 and another dated August 23, 1932, deriving the equations given in the first. These were forwarded to Espenschied on September 14, 1932, providing support for the future establishment of a formal project [26].

Southworth, meanwhile, had continued his measurement program and also had undertaken his own theoretical analysis, largely following the approach used by Schriever. Schriever had been interested in dielectric wires and his only cited references were to Sommerfeld, Hondros, Debye, and Zahn [9]–[12]. Consequently, Southworth was unaware of the work of Rayleigh and others, and viewed the phenomenon in Schriever's terms. Carson and Mead were also apparently unaware of Rayleigh's work and had started from basic principles, but influenced by Southworth's conceptualization in terms of dielectric waves. They were joined shortly by Sergei A. Schelkunoff, a mathematician at Bell Laboratories, who heard of the work going on and began his own analysis [27]. Schelkunoff prepared a 38-page memorandum entitled "The Propagation of Electromagnetic Waves in Dielectric Plates and Wires," dated November 3, 1932 [28].

In August 1932, Southworth lost the services of his technical assistant in Netcong due to a company retrenchment [29]. He had been working without any company authorization, and he continued to do so for some time. Yet his activities were known to many in the company, and he had attracted some highly competent mathematical support despite the lack of an authorized project. With both experimental and theoretical justification of his ideas accomplished, Southworth adopted a new strategy to gain company funding for further development. After writing two drafts in September 1932, he sent a memorandum, "Communication Over Dielectric Wave-Guides," dated October 19, 1932, to the patent department, and followed this with another, "Preliminary Experiments with Electric Waves in Dielectric Guides," dated November 2, 1932 [30].

We can identify two parallel processes at work during this period. First, there is the growth of an informal group attracted to a new scientific idea. They were, with the exception of Southworth, oriented toward theory. While Southworth carried out the experimental investigation, the others sought to establish the theoretical basis for the results, and the prediction of new phenomena. The activities of the group were essentially scientific up to this point.

The other process at work is the shifting of attention to technological considerations associated with application of the phenomenon to practical purposes. Nothing had been undertaken as yet, but Southworth recognized that he would have to demonstrate a potential use before he could expect significant financial support. His memorandum to the patent department was intended to arouse interest in such uses. This should not be confused with a strong interest on Southworth's part to engineer a communications system using waveguides. His subsequent career amply demonstrates that his primary interests lay in the development of basic waveguide technology, i.e., applied research. In any event, his memorandum did cause the patent department to begin investigating the matter.

Under the influence of the Schriever article, work up to this time had dealt only with the circular transverse magnetic wave (TM_{01}), and in December 1932, Southworth's bibliography on the subject contained only references to papers on dielectric waves. On December 8, 1932, Mead finished a memorandum entitled "Dielectric Cylinder with Metallic Sheath," which was the first quantitative analysis of the behavior of metal pipes, and then followed this with calculations for practical sizes of waveguide on December 19, 1932 [31]. These still dealt only with the TM_{01} mode, but shortly thereafter it became evident that a dielectric was superfluous, and this point represents a conceptual shift to hollow tube waveguide.

On February 3, 1933, Southworth described an experimental identification of the dominant mode, the lowest transverse electric mode (TE_{11}), while on March 6, 1933, Mead wrote a memorandum pointing out that there was a double infinity of such "unsymmetrical" modes in a hollow tube [32]. Over the next few months, a number of memoranda by Mead and Schelkunoff treated the different modes in tubes and dielectric cylinders, and their propagation characteristics. By the middle of 1933, the modal properties of hollow tubes outlined by Rayleigh in 1897 had been quite well re-established. The work had also gone far beyond that of Rayleigh in considering the propagation characteristics, including attenuation due to imperfect conductors, and recognition of the unique character of the TE_{01} mode, which has decreasing attenuation with increasing frequency. It was very soon thereafter that Rayleigh's early paper was discovered.

An entry in Southworth's notebook, dated November 11, 1933, relates that he asked Harvey E. Curtis on August 28, 1933 to calculate the design of a transformer from coaxial line to circular waveguide, and records the details of the resulting design [33]. On November 27, 1933, Southworth sent a memorandum to Carl A. Richmond, the patent attorney preparing the waveguide patents, stating that H. E. Curtis had discovered "an early article on hollow pipe guides by Lord Rayleigh" and gave the reference to his 1897 paper [34]. Presumably there was concern that this article might affect the patentability of waveguides.

The issue of patent priority within AT&T itself was not a straightforward matter. So many had been involved in various theoretical and conceptual aspects of the subject that there were numerous patent disclosures made by different individuals. These issues were largely resolved by C. A. Richmond in the fall of 1933, generally in favor of Southworth, who had certainly originated the basic idea and carried out the "reduction to practice" [35].

Considerable experimental progress also was made during 1933. Using triodes made in France, Southworth developed, starting in March, a Barkhausen oscillator operating at 16 cm and mounted in an air-filled tube of 4-in diameter. This now avoided the inconvenience of water-filled guides, and subsequent work was done with air-filled pipes having diameters from 2 to 5 in. On July 25, 1933, Southworth demonstrated the fundamental characteristics of waveguides to L. Espenschied and E. I. Green [36]. This demonstration resulted in authorization to build a long transmission line at Netcong, starting in August, the first official company-authorized project.

A comprehensive program of development of waveguide technology was formulated by Southworth in a memorandum, dated November 29, 1933, revised December 22, 1933, and finally forwarded through management channels on March 12, 1934 [37]. This program was to be under the auspices of Bell Laboratories and involved Southworth's transfer to that organization. Final authorization was given on July 12, 1934, with the stated objective being to study "the use of waveguides as a means of communication" [38]. Because the application would be at ultra-high frequencies and beyond, this implies "an exceedingly large number of telephone channels." It was explicitly recognized that waveguides offered possibilities for a variety of components, such as filters and directive antennas in addition to acting as transmission lines. It was pointed out that the work would require mathematical support, new materials, and the development of new electron devices, i.e., vacuum tube oscillators as energy sources. This project, renewed annually for many years, became the vehicle for developing many of the concepts that came to form the core of microwave technology.

This event signals a clear shift to emphasis on the development of technology with a specific practical application in mind. Whereas during the first two years, 1932 and 1933, the activities were essentially of a scientific nature, with technological developments going to support the scientific investigation, after mid-1934 the roles were reversed. This transition appears abrupt, but slowly evolved over a period of about one year.

After mid-1934, the activities were of a different character. The project was moved to a new location, Holmdel, NJ, where it remained for many years. The expenditures increased substantially. Most significant, however, was the addition of new personnel, A. P. King and A. Bowen, both of whom were skilled development engineers [39]. Over the next four years, this team developed much of the basic technology of waveguides, making a major contribution to the application of electromagnetic waves above 1 GHz. Further developments in theory were generally in support of these technological developments.

On January 15, 1934, Southworth, naturally wanting public recognition for his achievement, wrote a memorandum to Espenschied suggesting publication of a paper on waveguides, and on February 8, he prepared a note for the AT&T annual report [40]. It was decided, however, that it was too early for publication because of the uncertainty and relatively undeveloped state of the technology. Finally, a year and half later, a paper was prepared by Southworth, the first draft being dated July 11, 1935, then revised November 25, 1935, while the final version was dated March 10, 1936. [41]. This was accepted and scheduled for publication in the April issue of the *Bell System Technical Journal*, and an oral presentation was scheduled before a joint meeting of the American Physical Society (APS) and the Washington (DC) Section of the Institute of Radio Engineers (IRE) on the evening of April 30, 1936.

With the work that began almost 15 years earlier about to culminate in well-deserved public recognition, Southworth learned the disturbing news that someone else had also been working on hollow tube waveguides. Toward the end of March, Arthur L. Samuel, a coworker at BTL and a graduate of M.I.T., returned from a visit to the latter institution with word that such work was being conducted there. At about the same time, Southworth received the program for a coming joint meeting of the American Section of the International Scientific Radio Union and the IRE in Washington, DC. This included a paper by W. L. Barrow of M.I.T., entitled "Transmission of Electromagnetic Waves in Hollow Tubes," to be presented at the afternoon session on May 1, 1936. As this was the day following his own presentation in the same city, there was a potentially awkward situation developing.

On April 3, 1936, Southworth wrote a letter to Barrow informing him of the circumstances [42]. He enclosed drafts of his own paper and that of a companion paper by J. R.

Carson, S. P. Mead, and S. A. Schelkunoff on the mathematical theory of waveguides. He also informed Barrow that he would be presenting much of the material at the joint APS/IRE meeting on the evening before Barrow's presentation. He offered to avoid anticipating Barrow's subject matter to the extent possible if Barrow would advise him of where duplication might be present. Barrow responded by telegram on April 6, 1936, and followed this with a letter on April 7, 1936 [43]. In this letter, Barrow confirmed that they had been working in the same field, indicated that he was sending a draft of the first part of his paper under separate cover, and would forward the remainder in a few days. He also informed Southworth that he was submitting the paper to the IRE for publication. He offered to arrange his talk to be supplementary to Southworth's and asked for suggestions in this regard.

In the months following public release of the waveguide work, Southworth gave numerous talks before other technical audiences, and on February 1, 1938 gave a public demonstration. Visitors came from many other laboratories, including some from England and Germany, to see the equipment in Southworth's laboratory, and to discuss, at first hand, the significance of this new form of transmission medium.

From the beginning, the most obvious application of waveguides had been as a communications medium. It had been determined by both Schelkunoff and Mead, independently, in July 1933, that an axially symmetric electric wave (TE_{01}) in circular waveguide would have an attenuation factor that decreased with increasing frequency [44]. This unique characteristic was believed to offer a great potential for wide-band, multichannel systems, and for many years to come the development of such a system was a major focus of work within the waveguide group at BTL. It is important to note, however, that the use of waveguide as a long transmission line never did prove to be practical, and Southworth eventually began to realize that the role of waveguide would be somewhat different than originally expected. In a memorandum dated October 23, 1939, he concluded that microwave radio with highly directive antennas was to be preferred to long transmission lines. "Thus," he wrote, "we come to the conclusion that the hollow, cylindrical conductor is to be valued primarily as a new circuit element, but not yet as a new type of toll cable" [45]. It was as a circuit element in military radar that waveguide technology was to find its first major application and to receive an enormous stimulus to both practical and theoretical advance.

III. WILMER L. BARROW

During much of the period that Southworth and his associates were developing the technology of hollow waveguides, Wilmer L. Barrow, a professor of electrical engineering at the Massachusetts Institute of Technology (M.I.T.), was also working on the same subject. Barrow's interest in high-frequency electromagnetic waves dates from about the same time as Southworth's revived interest, and, as in Southworth's case, his work was conducted over an extended period without external communication.

Wilmer L. Barrow was born October 25, 1903, in Baton Rouge, LA [46]. He received a B.S.E.E. degree from Louisiana State University, followed by an M.S. degree in electrical communications from M.I.T. in 1929. He then attended the Technische Hochschule in Munich as a Redfield Proctor Fellow in physics, receiving the Sc.D. degree at the end of January 1931. His purpose in going to Germany was to gain a "better grounding in basic physical principles and in mathematics" than was available in the United States [47]. His dissertation was in acoustics, but his studies included theoretical electrodynamics under A. Sommerfeld and applications of Maxwell's equations under Schumann [48].

Barrow had planned to return to a faculty position at M.I.T. upon completing his studies in Germany. Corresponding with Professor D. C. Jackson of the Electrical Engineering Department with regard to such a position, Barrow revealed that his German experience had kindled a new interest. He wrote:

> A new and especially promising field for research is that of ultra-short radio waves, by which I mean those at least below a meter in wavelength... this is really a most fertile field for new and valuable work. It is also one which is finding more attention in Germany than in our own country.... I am most interested in the many questions in this upper frequency band of radio transmission and I would enjoy enormously doing research in it [49].

Barrow indicated an appreciation of the need for better means of generating signals at these shorter wavelengths, the primitive state of measurement technique, and the need for advancing both theoretical and experimental knowledge of wave propagation in various media. He further recognized the unusual nature of this field, "representing as it does the solution of problems vital to the advancement of industry, technology, and applied science which are however also contributions to physics as a pure science...." [50]. It required that combination of electrical engineering, physics, and mathematics for which he had been so assiduously preparing himself.

In the fall of 1931, Barrow joined the faculty of the Communications Division at M.I.T. While probably too absorbed in his new teaching duties to undertake any research during the first semester, he did begin during January 1932 to develop an oscillator that would provide signals at short wavelengths [51]. By the end of January he had obtained reliable oscillations over a range of wavelengths in the region of 2 m.

Barrow's primary research interests lay in the radiation characteristics of antennas and electromagnetic propagation at short-wave lengths, and he was soon involved in research on this subject. He was working within the general framework of a departmental research program addressing the problem of aircraft navigation in fog [52]. His specific research subject was the development of new forms of antenna that would provide narrow beams in order to locate aircraft by means of radio under conditions of poor visibility. To keep the physical size within practical limits and to achieve high resolution, the work was being carried out at short wavelengths.

Barrow's research on antennas included the investigation of shaped reflectors which led him to the idea of an electromagnetic horn. In considering means of coupling energy to the horn, he thought naturally of a hollow tube. He then "saw that the interior of a hollow-metal tube could be used to transmit electromagnetic waves, of length comparable to tube dimensions, from one point to another" [53]. This was in the latter part of 1933, and he stated that his "first written statement concerning the hollow-tube system" was dated November 3, 1933 [54]. Thus, Barrow's concept of propagation in hollow tubes was inspired by recognition of a technological possibility, probably in analogy to his acoustical experience. A signal source at sufficiently short wavelength was not available at this time for conducting experiments to test his idea.

An appropriate signal source was obtained in 1934, but due to several pressing matters Barrow did not return to investigation of propagation in hollow tubes until the following year. An entry in his notebook, dated May 7, 1935, states that he "tried out experiments to demonstrate existance [sic] of waves in hollow tubes. Results were all negative" [55]. In this experiment, the source wavelength was 50 cm and the waveguide was a long brass pipe with an inner diameter of 4.5 cm, a dimension too small to support propagation. Clearly, Barrow had not yet fully developed the theory of propagation in hollow tubes at this time, but within a few months he had completed this essential step. He stated that "During the summer, the theory was completed. During the fall, in spare moments, numerical curves were plotted and a paper was written (during the Christmas holidays, December 28, 1935)..." [56].

By March 16, 1936, Barrow had located a hollow tube waveguide suitable for his 40-cm source. This was an old section of air duct, 18 inches in diameter and 16 feet long [57]. On March 24, 1936, the first successful tests of the propagation of radio waves through the tube were made [58]. Calculations, dated March 16, 1936, show that he now had a comprehensive theoretical base, including both transverse electric and transverse magnetic modes, and formulation of the cutoff wavelength for these modes, beyond which they would not propagate.

Within the space of a few months, Barrow had made great progress, completing the basic theory, preparing a paper for publication, and obtaining experimental verification. Even prior to the latter step, he had submitted a short theoretical paper for presentation before a joint meeting of the American Section of the International Scientific Radio Union (URSI) and the IRE at the National Academy of Sciences on May 1, 1936. A rather disappointing turn of events was about to unfold, however, and on March 28, 1936 he made the following notebook entry:

> Mr. [space] Samuel of Bell Tel. Laboratories, who was here as a speaker before I.R.E., came into Com. Lab. to discuss vacuum tube for $\lambda < 1$m. with me. He saw my set-up and we discussed the experiments a bit. He intimated that related work was being carried out at Bell Labs. and that a paper from there would be presented at Washington May 1st URSI-IRE meeting [59].

On the following day, a Sunday, Barrow, now feeling pressure to make rapid progress, investigated a different method of exciting the wave and found that a different mode was established in the tube. On Monday, he discussed the matter of the BTL work with Professor E. L. Bowles, and it was decided that the Institute Patent Committee should be notified. A memorandum describing the chronology of the development of the hollow tube transmission system and its current status was written on April 1, 1936, although it was not finally typed until May 25, 1936 [60].

On April 4, 1936, Barrow recorded in his notebook that he had received a letter from Dr. G. C. Southworth of Bell Telephone Laboratory. He discussed the letter with Professors E. L. Bowles and Vannevar Bush, who advised him to cooperate fullly with Southworth, and on April 6, 1936, he recorded that he had wired Southworth to this effect [67].

With a public announcement imminent and an awareness of work done elsewhere, the work could now be discussed with outsiders. Visitors were received in significant numbers at this time, and the level of interest was high. On April 10, 1936, a group from RCA, including V. K. Zworykin, I. Wolff, E. G. Linder, and B. J. Thompson, were shown the experimental setup, and the concepts were discussed with them [62]. Later that same day, Hull of General Electric also visited the laboratory. On April 23, 1936, F. B. Llewellyn of BTL visited Barrow and discussed the hollow tube waveguide, and on the following day, E. Bruce, also from BTL, made a visit [63].

During the month preceding the talk in Washington and for some time thereafter, Barrow was busily engaged in experimental measurements, particularly the radiation patterns from the open end of his waveguide apparatus. On April 27, 1936, he wrote a patent disclosure on a multiplexed communications system based on the use of different waveguide modes to carry different signals [64]. This was demonstrated publicly on May 22, 1936 before a meeting of the Boston Section of the IRE.

There was concern about the status of possible patents, and on June 5, 1936, V. Bush wrote to F. B. Jewett, president of BTL, suggesting that representatives of M.I.T. and BTL meet and try to decide who had priority in which areas. On June 12, 1936, Jewett replied that they were willing to discuss the matter, but thought that both parties should file in the normal manner and then settle matters in a friendly way in an interference proceeding [65]. Barrow was informed of this decision in early August and asked to get his records and notes together in preparation for working with M.I.T.'s patent counsel [66]. These issues were ultimately resolved without any significant conflict.

As mentioned above, Barrow's primary interest was in electromagnetic horn radiators, and the principal application of this component was expected to be in an instrument landing system for aircraft. This project, under E. L. Bowles, and partially funded by the Civil Aeronautics Authority, was successfully completed in late 1939, but further development was delayed by the war. This work did, however, provide the foundation for the M.I.T. Radar School and the M.I.T. Radiation Laboratory. Barrow became Director of the Radar School, and served in several other capacities under the National Defense Research Committee during World War II. The M.I.T. Radiation Laboratory became the center for the rapid development of waveguide technology during this period; BTL, through its parent Western Electric Co., was one of the major contractors in this effort [67].

IV. DISCUSSION

The history of the technology of cylindrical waveguides provides an unusual opportunity for insight into the interaction of science and technology, including the role of mathematics. The individuals involved in this development were professional scientists, engineers, or mathematicians. The two principal investigators, though having training in physics, were strongly oriented toward engineering rather than theoretical analysis, yet mathematical analysis played a crucial role in their work. There was a close interplay of physical concepts, mathematical analysis, inventive engineering, and experimental investigation that was critical to success in this episode. The position of waveguide technology on the borderline between conventional electrical engineering and optical physics undoubtedly influenced this admixture.

The science–technology relations are substantially different in the two cases described above, and in neither case are they represented by a linear sequential process. Southworth and Barrow started on their respective courses of development from completely different points of departure. The dominant paradigm that guided each of them was different, and in each case it was necessary to make a significant change in their conceptualization before reaching a satisfactory understanding of the phenomenon that they were investigating.

Southworth was proceeding from an observed anomaly, the tentative explanation for which never really satisfied him. This explanation did, however, provide the concept that guided him when he resumed his investigation. Being incorrect it actually misguided him, and Southworth long labored under the mistaken notion that he was dealing with a phenomenon that could be described in terms of waves on dielectric cylinders, using the analytic methods of Schriever and Hondros. Through 1933, his notebooks were entitled *Dielectric Waves*, and this term was used in the titles of memoranda by Southworth and those working on the theory. After the work of S. P. Mead in December 1932 and early 1933, and that of S. A. Schelkunoff in early 1933, on metal sheathed dielectric cylinders and hollow tubes, it became clear that the dielectric was unnecessary and the wave was supported by the metal tube. This change in conceptualization was not immediate, however, and S. P. Mead was still using the term "dielectric waves" as late as July 1933. By August of that year, everyone was writing in terms of "waves in hollow tubes." The change was of such significance, moreover, that Carson claimed, in an internal memorandum, that he and Mead had invented hollow waveguide [68].

These events, all of a theoretical nature, were proceeding in parallel with experimental work. The switch in theoretical viewpoint did not influence the experimental work, which received little guidance from the extensive development of theory during the early stages. During this phase, it was more a question of making sure that theory fitted the facts. This relation changed dramatically with the discovery, in July 1933, that the TE_{01} mode had decreasing attenuation with increasing frequency. This theoretical fact appeared to offer a significant technological opportunity, and thereafter it strongly influenced the development program. Ultimately, it proved illusory because of practical difficulties. The important point, however, is the fact that over the course of this development the relation between theory and practice changed its direction of influence.

In contrast to Southworth's path to waveguides through scientific explanation of an observed phenomenon, Barrow's approach was technological. Engaged in a program of related technological development, he perceived the technical possibility of transmitting electromagnetic waves through a hollow tube. This perception was the result of inspiration and was seen as a whole in phenomenological terms. Barrow was probably influenced analogically by his acoustic experience. He did not immediately recognize the low-frequency cutoff property of electromagnetic waves in hollow tubes because no such phenomenon exists in acoustics. His first experiment in May 1935 failed to produce transmission through the tube, and this result would have been expected given the source wavelength and tube diameter used, had the theory been available to him.

Here again is an example of an existing scientific paradigm misleading an investigator when applied to a new and inappropriate phenomenon. This failure stimulated Barrow to carefully analyze the problem, and construct a theory that was valid for his experimental apparatus. The analysis made him aware of the cutoff property, and led him to obtain a tube of sufficiently large diameter so that he was able to conduct a successful experiment. Thus, in Barrow's case, we find that starting from a technological idea, experimental failure stimulated creation of a scientific theory that then led to technological success.

If Rayleigh's work had not been forgotten, the course of events leading to waveguide technology would have been quite different, and could well have followed a linear sequential process with technology resulting from the application of science. In actuality, each of the later developments had to reach a reconstruction of that theory before they could make real progress. In each of these later cases, however, a technology came into being, physically in one case, intellectually in the other, before that theory was reconstructed. Nominally, one case had a scientific origin, the other technological.

With these different and varying relations between science and technology present in the development of one basic technology, it is not reasonable to expect any simple model to represent the circumstances. It is clear that there is a close relationship between the science and the technology involved. It is equally clear that the technology is not merely an application of that science. The science is both an explanation of and a guide to further development of the technology. It is difficult to separate them, and only possible on a detailed technical level, at which point it is questionable whether anything has been gained by the distinction because it becomes impossible to generalize usefully.

It seems more useful, in cases such as waveguide technology, and many others of the modern technical areas, to avoid attempting sharp distinctions between science and technology, while recognizing that they are two aspects of the same whole. They are two viewpoints, one theoretical, the other practical, but only in combination are they completely meaningful.

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