Paradigm Lost: Nikola Tesla's True Wireless

We examine an article written by Nikola Tesla entitled "The True Wireless," which appeared in the *Electrical Experimenter* magazine in May of 1919. His essay is analyzed as an example of the inability of a scientist or inventor to assimilate a paradigm shift in his discipline, and we use the language and thought of Thomas Kuhn in this discussion. The paradigm shift in question was created by Maxwell and Hertz in the latter third of the 19th century, a shift that explained the existence and generation of electromagnetic waves—the basis for wireless telegraphy and eventually radio. We also focus on the magazine in which Tesla's piece appeared and consider why the article might have been written and accepted for publication.

"The Hertz wave theory of wireless transmission may be kept up for a while, but I do not hesitate to say that in a short time it will be recognized as one of the most remarkable and inexplicable aberrations of the scientific mind which has ever been recorded in history."

—Nikola Tesla, "The True Wireless" 1919

"… the man who continues to resist after his whole profession has been converted has ipso facto ceased to be a scientist."

—Thomas Kuhn, *The Structure of Scientific Revolutions* 1962

The Paradigm

For historians of radio and the wireless telegraph, one of the strangest documents they are apt to encounter is an article entitled "The True Wireless" that was published in the May 1919 issue of the popular magazine, the *Electrical Experimenter*. The author was the renowned Serbian-born inventor, Nikola Tesla (1856–1943). Tesla spent most of his professional life in the United States, and by 1919 he was just past the peak of his fame—a man as nearly well known to the general public as Edison. He was a contributor to the Sunday supplements of newspapers, where he described his latest proposed inventions such as a weapon that would make war obsolete by creating an enormous tidal wave.[1]

Although his reputation as an inventor may have faded, he persists today as a cult figure. A web search will lead to sites proclaiming that he invented radio, radar, x-rays, alternating current, the laser, the transistor, and limitless free energy. His name also endures as the brand of a pioneering high-priced electrical automobile.

There is some irony in this—the car is powered by batteries that supply direct current (DC), while Tesla's great accomplishment resides in his contribution to the generation and distribution of polyphase alternating current (AC). He developed an ingenious device, the induction motor, that is ideally suited to polyphase AC because of the ease with which such current creates the rotating magnetic field required by many motors.

Readers of this paper should have at their disposal a copy of "The True Wireless," which can be found on the Internet.[2] Note that the insert appearing in the article was written by the magazine's editor, Hugo Gernsback, who asserted, "Dr. Tesla shows us that he is indeed the 'Father of wireless.'" Tesla is referred to variously as an engineer, physicist, scientist, and inventor on many websites, including the Wikipedia, which contain his biography. Historically, this blurring of occupations has a distinguished lineage: Galileo, for example, invented telescopes and other instruments and was also an astronomer, and the transistor was invented by men trained as scientists, not engineers.

A Paradigm Missed

Had Tesla's paper appeared fifteen years before—*circa* 1904—its content would be unremarkable. Coming as it does in 1919, just before the era of broadcast radio, it becomes useful as a notable example, in the field of science and technology, of an inventor's failure to grasp what the distinguished historian of science Thomas Kuhn has described as a "paradigm shift."

This term first appears in Kuhn's book *The Structure of Scientific Revolutions* published in 1962. The work is among the most cited scholarly books produced in the last half of the 20th century and has been in print in various editions for over 50 years. We refer here to the 3rd edition of 1996.[3] The expression *paradigm shift* has entered everyday language, and its use has steadily increased since Kuhn coined the phrase. The concept will be employed here in the discussion of Tesla's paper.

What does Kuhn mean by this term? In the sciences, he asserts that a *paradigm* derives from "universally recognized scientific achievements that for a time provide model problems and solutions to a community of practitioners." The word "*model*" is key here. The Greek-Egyptian astronomer Ptolemy (100–170 AD) had a model of what we now call our solar system: his earth was at its center, and the sun revolved around the earth. The concept has a limited use—it does explain sunrise and sunset, but as mankind's knowledge of the planets and stars increased, it became unworkable. Copernicus, Galileo, Kepler, and Newton killed the old model—their work, which began *circa* 1540 and occupied nearly two centuries, led to a classic paradigm shift. The shift describes the discarding of an old model whose use is unfruitful and untenable in favor of a new paradigm that more gracefully and convincingly describes recent experimental evidence.

For our present discussion, the important paradigm shift began with the Scotsman James Clerk Maxwell (1831–1879). Consider what Nobel Laureate Richard Feynman said about Maxwell's work of the period 1860–1873: "From a long view of the history of mankind—seen from, say, ten thousand years from now—there can be little doubt that the most significant event of the 19th century will be judged as Maxwell's discovery of the laws of electrodynamics."[4]

Maxwell produced a paradigm, or a model, for light: it was an electromagnetic wave having transverse electric and magnetic fields. The theory described a wave moving at the speed of light that could be generated by electrical means, and it did not specify a wavelength—it could be, for example, 700 nanometers (like visible light, whose wavelengths were known in Maxwell's era), or around 300 meters (like broadcast AM radio of our time).

In the late 17th century, Newton had maintained that light consisted of streams of particles, which he named *corpuscles*; his prestige was such that his model still had some adherents as late as Maxwell's era, although there was much evidence favoring a wave theory. To further complicate matters, others analyzed light as a *ray* that describes the path of the light energy.[5]

We now come to a narrative familiar to many readers. In the period 1886–1889, the German physicist Heinrich Hertz carried out a series of experiments in which he generated a wave that exhibited wavelengths on the order of meters, possessed a measurable electromagnetic field, and to a fair approximation moved at the known speed of light.[6] These waves could be reflected, polarized, and diffracted—just as visible light, whose properties had been studied for several centuries. Had the Nobel Prize been awarded in the lifetimes of Maxwell and Hertz, they would surely have been winners. Hertz's work was published in the period 1887–1891 and served as a stimulus to such people as Guglielmo Marconi, Oliver Lodge, and Karl F. Braun, who sought to employ Hertz's discovery in the field of wireless telegraphy. The story is well told in the book by Aitken.[7]

Tesla recounts a meeting with Hertz in the document we are studying: he traveled to Hertz's laboratory in Bonn, Germany, in 1892 and describes in "The True Wireless" an unfruitful encounter where he informs Hertz that he had been unable to reproduce his results. If we believe Tesla, the two parted "sorrowfully" with our narrator subsequently regretting his trip.[8] He also informs us that later, even having developed a "wireless transmitter which enabled me to obtain electromagnetic activities of many millions [sic] of horse-power," he was unable to "prove that the disturbances emanating from the oscillator were ether vibrations akin to those of light…" Unable to generate what soon became known as Hertzian waves, and having read articles describing such waves over the eighteen-year period preceding this article, he remarks, "The Hertz-wave theory, by its fascinating hold on the imagination, has stifled creative effort in the wireless art and retarded it for twenty-five years."

By the time Tesla wrote his article, wireless telegraphy had been a business for nearly 20 years—and had grown into a very big one at that. When the United States entered World War I in 1917, the Marconi Wireless Telegraphy Company of America (American Marconi) had outfitted 582 wireless stations on ships and possessed 45 coastal stations for ship-to-shore and international communication.[9] The Navy took these over at the beginning of the war. At the cessation of the war, British Marconi was eager to buy exclusive rights to the Alexanderson alternators from General Electric; these were powerful and efficient successors to the spark gap and arc transmitters used earlier in wireless telegraphy. Initially, they planned to spend over $3M on 24 alternators and employ them both in their own corporation and in American Marconi.[10] If, as Tesla alleges, the big business of wireless telegraphy did not employ Hertzian waves, how did it operate? He specifically denies that the "disturbances" (a name he uses in lieu of Hertz's waves) emanating from an oscillator "were ether vibrations akin to that of light."

It is interesting to examine the language of his paper. He speaks of "some kind of space waves" and "transversal vibrations in the ether," and except to disparage them, he does not refer to Hertz's (or Hertzian) waves. By 1919, his words and thinking were archaic. The terminology in the discourse of radio and wireless telegraphy engineering had evolved since Hertz's work and the growth of international wireless telegraphy.

We now employ the Google Book's Ngram Viewer, a piece of free Internet software that quantifies how frequently a word turns up in a large number of books during a specified time period. The output of this software is a graph showing the number of mentions in books versus time (in years) for a word or phrase supplied. The frequency of use of the term *Hertzian waves* over more than a century is shown in Fig. 1. We see the term gaining currency beginning with Hertz's famous experiments and reaching a peak at about the time of Tesla's paper. It is not hard to understand that it subsequently lost popularity. A search of the term *electromagnetic waves*, which ultimately replaced *Hertzian waves*, is shown in Fig. 2.

As it became clear to the engineering community that the waves generated by Hertz were merely a part of the electromagnetic spectrum—one which was to become increasingly exploited by broadcast AM radio, television, and FM broadcasting—the locution *Hertzian waves* would have seemed anachronistic. It is evident that at the time of Tesla's writing, the term "Hertzian waves" had already been eclipsed by "electromagnetic waves." Incidentally, an Ngram of the term "radio waves" displays a curve much like that for electromagnetic waves. Both gained favor at the same time.

Fig. 1. Frequency of use of the term "Hertzian waves." (Google Ngram)

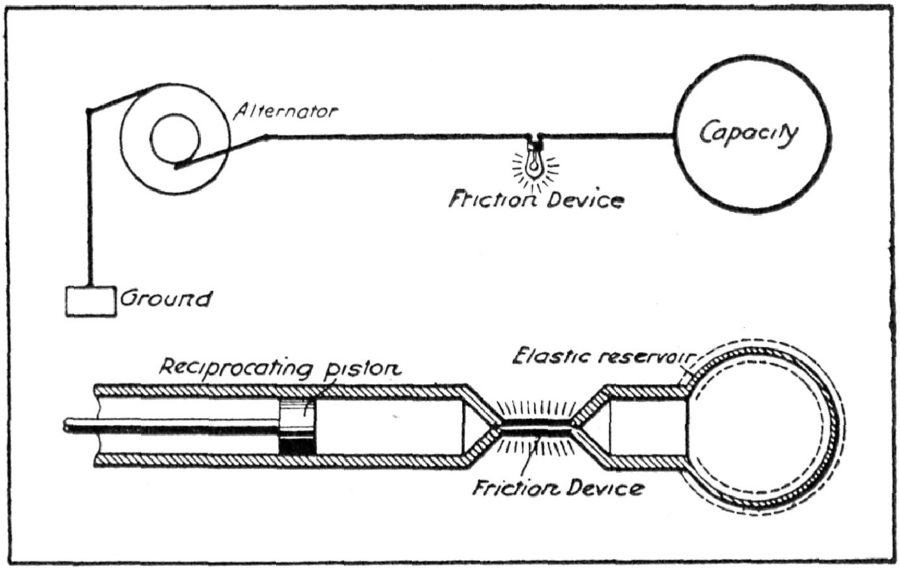
Fig. 2. Frequency of use of the term "electromagnetic waves." (Google Ngram)

Tesla "Disproves" Hertzian Theory

Electricity and Hydraulic Analogies

How did Tesla explain wireless communication without Hertzian waves or its synonyms? The answer is fascinating. He used a fishy version of alternating circuit theory. A close reading of "The True Wireless" reveals that he promoted a form of circuit theory employing but a single wire—in other words, there is no real circuit such as those who understood the subject are accustomed to. He also maintains that the earth itself can function—*must* function—as this lone wire. He seeks to explain this with a labored hydraulic (fluid) analogy that is illustrated in Fig. 4 of his paper, which is reproduced here as Fig. 3.

Of course, you can send a disturbance down a water filled pipe without employing a return circuit—just strike one end with a hammer. His analogy proves nothing, but its use is understandable. When Tesla was in college in the late 1870's and early 1880's, alternating current theory was a new and difficult subject.[11] If he learned



Electric Transmission Thru a Single Wire Hydraulic Analog.

Fig. 3. Tesla's fluid "circuit." (*True Wireless*, Fig. 4)

it there, or, as seems likely, on his own after college, he would have encountered textbooks that sought to treat this discipline using analogies drawn from hydraulics—a much older and better-understood subject.[12] It was not uncommon then to use the word "pressure," taken from fluid mechanics, where we now use "voltage" or "electrical potential." Such analogies, which might employ water wheels to represent inductors and elastic diaphragms as proxies for capacitors, convey only an intuitive feeling for AC circuits and are of no use for communication systems employing electromagnetic waves.[13]

Thus, Tesla attempted to apply a dubious electric circuit approach where it had no validity. In fact, one wonders why no one asked him if the return wire in the circuit could be eliminated, then why not also the wire that carries the current that is outgoing from the generator. Had he taken that radical step, he might have been on his way to understanding communication between two antennas in the absence of any earth.[14]

In criticizing Tesla for his wrong-headed model, are we in fact guilty of what has become known as Whig history? The term Whig history was introduced by the distinguished English historian Sir Herbert Butterfield in 1931. It can refer to an unfair judgment of historical figures and their actions that are based on our present knowledge of what is humane and progressive and acceptable. For example, to condemn Thomas Jefferson for writing in the Declaration of Independence "All men are created equal" (where are the women?) would be to engage in Whig history. In the sciences, Whig history has a similar meaning: it would be to criticize a scientist or inventor of the past for failing to use concepts that we now take for granted.[15]

From our present perspective, Tesla's not using a wave model to explain radio seems bizarre, but given what was known in 1919, are we being unfair and leaving ourselves open to the accusation of Whiggishness? An example of Whig history of science would be to condemn Ptolemy for his earth centered view of astronomy. Given the tools at his disposal, his mistake is understandable. And to disparage Maxwell for his frequent use of the term ether—when we know that the concept is not valid—would be Whig history. I will seek to explain in what follows that I have not fallen into the trap of Whig history in discussing Tesla.

Influence of Mountains or Obstacles

Tesla seeks to disprove Hertzian wave theory as a means of communication with several examples. Consider his Fig. 17, reproduced here as Fig. 4. Tesla claims that "unless the receiver is within the *electrostatic* influence of the mountain range"—in what we would now call "the near field of the antenna"—the signals at the receiver "are not appreciably weakened by the presence of the latter because the signal passes *under it* [italics added]

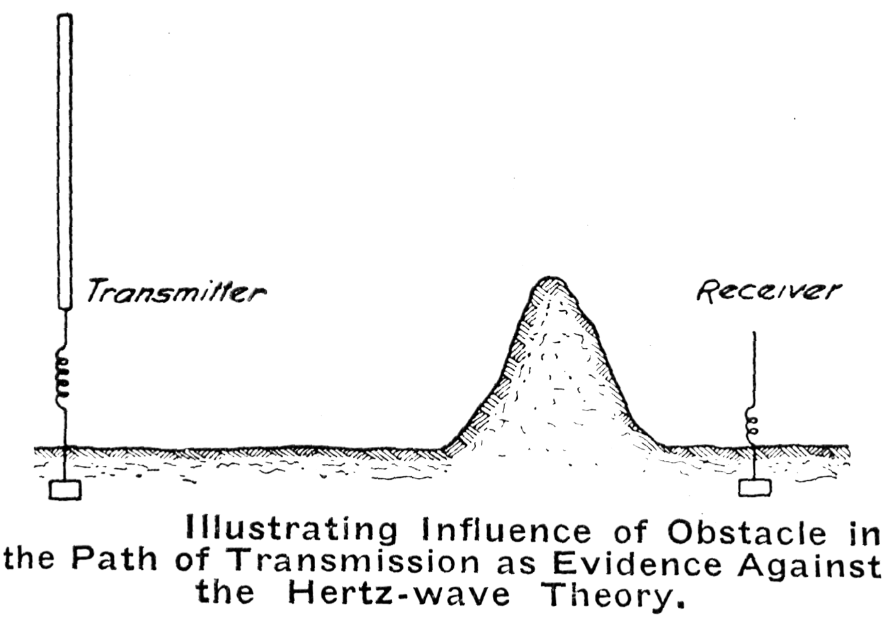


Fig. 4. Tesla analyzes the effect of an obstacle. (*True Wireless*, Fig. 17)

and excites the [receiving] circuit in the same way as if it is attached to an energized wire." No radio propagation engineer would have accepted such an argument in 1919. Indeed, the receiver might well detect the transmitted signal, but not for the reasons stated by Tesla. No model of wave propagation asserts that the signal goes *under* the mountain.[16]

Following the work of Hertz, it was apparent that laws of optics could be applied to electrically generated waves. There would have been no problem in explaining the reception of waves by a detector lying on the shaded side of the mountain—it would be described as Fresnel diffraction, a theory put forth by the eponymous French physicist in the period 1815–1818.[17] The theory asserts, in part, that the greater the wavelength used, the stronger the signal that makes its way into the optical "dark side," provided the distance from the diffracting edge (here, the mountain top) is small measured in wavelengths.[18] Given the long wavelengths employed by Tesla (10 kHz => 30 km. => 18 miles), a number taken from Fig. 1 in his article, there is no trouble in explaining wireless reception on the far side of the mountain. By the time Tesla published this piece, the subject of diffraction of electromagnetic waves had become sophisticated and had engaged the attention of a number of distinguished mathematicians.

If the mountain is modeled as a hemispherical impediment to the wave, and if the earth is a good conductor, then the problem of scattering by the mountain can be attacked using the method of images. The problem becomes that of a plane wave incident upon a sphere. This problem had been solved in the period 1908–9 by Debye and Mie and would also show a signal in the optical shadow cast by the hemispherical mountain.[19]

In the period beginning in 1889 and ending in the era of Tesla's writing, the Scottish mathematician H. M. Macdonald had treated waves from a Hertzian dipole diffracted from the earth, which he modeled as a perfectly conducting sphere.[20] His work was improved by the great French scientist and philosopher, Henri Poincaré, who in the period 1909–1912 converted Macdonald's series of Bessel functions into a definite integral that could be better evaluated. The German mathematical physicist Arnold Sommerfeld, unlike his predecessors, treated the earth as an imperfectly conducting surface, although he simplified matters by making the earth flat. He placed a vertical, electrically short dipole above the earth and derived an expression for the resulting electric and magnetic fields. His results of 1909 were expressed in terms of an integral that he evaluated asymptotically for an observer far from the antenna. He found that a surface wave had been generated, and his theory nicely supported that of another German, Jonathan Zenneck, whose less rigorous work had led to what became known as the Zenneck wave, which existed on the ground at some distance from the antenna. The latter turned out to be the asymptotic solution of Sommerfeld's theory. In 1919, the German mathematician Herman Weyl solved Sommerfeld's configuration and ended up with a different approach that did not contain Zenneck's wave. This result caused Sommerfeld to rework his solution, and his new findings did not agree with Zenneck.

In short, the first two decades of the 20th century was a lively and sometimes contentious period in the theory of radio wave propagation, but there is no hint of this in Tesla's paper. Nor is there any indication in anything he wrote that he had the sophisticated mathematical skills to comprehend what was being written by the people cited above. There were, of course, great inventors with minimal knowledge of higher mathematics (think of Edison, Morse, Bell) but these largely belonged to the 19th century, and one does see Tesla as part of that tradition. His clinging to a sketchy circuit theory explanation seems pathetic. Incidentally, as early as 1904, a textbook of Henri Poincaré had addressed the primacy given to currents flowing through the earth in Tesla's model of wireless telegraphy. He points out that if a coherer is placed in a hole in the ground "it will operate [as a detector of wireless telegraphy] when uncovered; if the hole be filled with earth, the oscillations produce no effect. We must look for something more than earth currents to explain the phenomena."[21] Recall that the most common detector in use at that time was the Branly coherer.

Putting aside theoretical considerations, Tesla's paper is notable for the omission of major empirical findings contained in the famous and practical Austin-Cohen formula, a concise expression that describes the strength of the electric field experienced by a receiving antenna when both receiver and transmitter are over the ocean. Louis Winslow Austin and Louis Cohen had worked for the U.S. Navy in the early 1910's, making shipboard electrical measurements of the field radiated from various transmitters manufactured by Reginald Fessenden's company, the National Electric Signaling Company, or NESCO. By 1911, the two men had devised a successful empirical formula that gives the received field.[22]

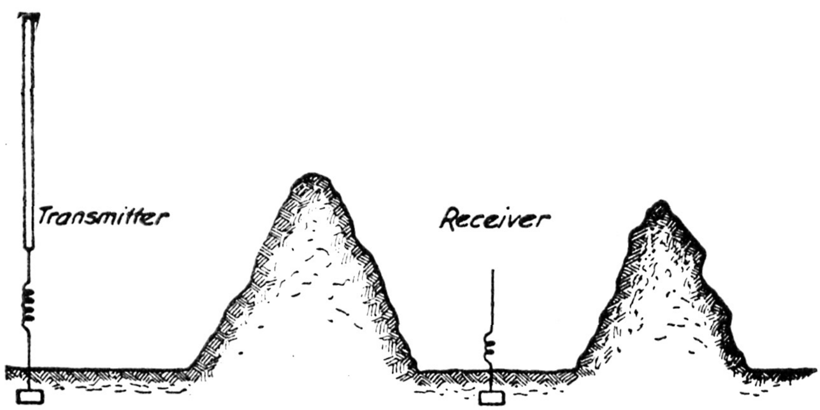
$$I_r = 4.25 \frac{I_s h_1 h_2}{d\lambda} e^{-ad/\sqrt{\lambda}}.$$

Here I_r is the current received by an antenna driving an impedance of 25 ohms, I_s is the transmitting antenna's current, h_1 and h_2 are the lengths of the two vertical antennas, λ is the wavelength, d is the distance separating the antennas, and $\alpha = .0015$. Lengths are in kilometers and currents in amperes. The formula was effective only during the day and was so useful that it became the basis for testing new theoretical predictions of received fields. The presence of the square root of the wavelength in the exponent was later derived theoretically by the English mathematician G. N. Watson and published in 1919, only a few months after Tesla's paper.[23] Interestingly, Tesla, speaking of the formula, states unequivocally "… the actions at a distance cannot be proportionate to the height [length] of the antenna and the current in the same," which is in direct contradiction to what the much-used equation asserts. Tesla's statement "the current in the same" is especially puzzling, not only because it had been established experimentally but also because he has essentially been using alternating circuit theory, in a strange form, and the device he is employing—an antenna, and a conducting earth—are mathematically linear and should, according to linear circuit analysis, create a response in linear proportion to the current exciting the antenna.

Strange to say, Tesla then uses Austin-Cohen to reject Hertzian waves, saying that, "...I cannot agree with him [Austin] on this subject. I do not think that if his receiver was affected by Hertz waves he could ever establish such relations as he has found." So, on the one hand, he rejects the famous formula but then embraces it as a means to argue against Hertzian wave theory.

Let us now study Fig. 18, in Tesla's paper, reproduced here in Fig. 5. He has now introduced a second mountain that is further from the transmitter than the one in the previous figure. He argues that if Hertzian wave theory were true, then the second mountain "could only strengthen the Hertz wave [at the receiver] by reflection, but as a matter of fact it detracts greatly from the received impulses because the electrical *niveau* between the mountains is raised..." [*niveau* is a French word for level surface].

What Tesla fails to understand here is that without knowing the wavelength of the radiation, the separation of the two mountains, and the position of the antenna between them, we can make



Showing Effect of Two Hills as Further Proof Against the Hertz-wave Theory.

Fig. 5. Tesla considers the effect of two hills. (*True Wireless*, Fig. 18)

no statement about the enhancement or reduction of the signal at the receiver caused by the presence of the second mountain. In fact, using elementary wave theory or a transmission line analog, we can argue that if the two mountains are separated by half a wavelength and if the receiver is midway between them, and if the soil is of reasonably high conductivity, then we have what is called a standing wave between the mountains. In this case, the effect of the more distant mountain is to enhance the signal at the receiver. There are waves moving from right to left and vice-versa between the mountains. Such an arrangement, when set up in a room, as Hertz did in his famous experiment published in 1888, is known as an interferometer.[24]

Kuhn tells us that if we want to see what constitutes "normal science" and the paradigms it embraces, we should look at the textbooks of that era.[25] By 1904, we can say confidently that the paradigm shift created by Maxwell and Hertz had taken hold and was part of normal science. This was the date of publication of Poincaré's book, whose chapters 7, 8 and 9 are devoted to the propagation of waves along wires, dielectrics, and air. It seems evident that Tesla was not reading the textbooks of his epoch.

Tesla and Antenna Theory

Another puzzling segment of Tesla's anti-Hertz diatribe is his Fig. 16, shown below as Fig. 6. Tesla would have us believe that the antenna on the right

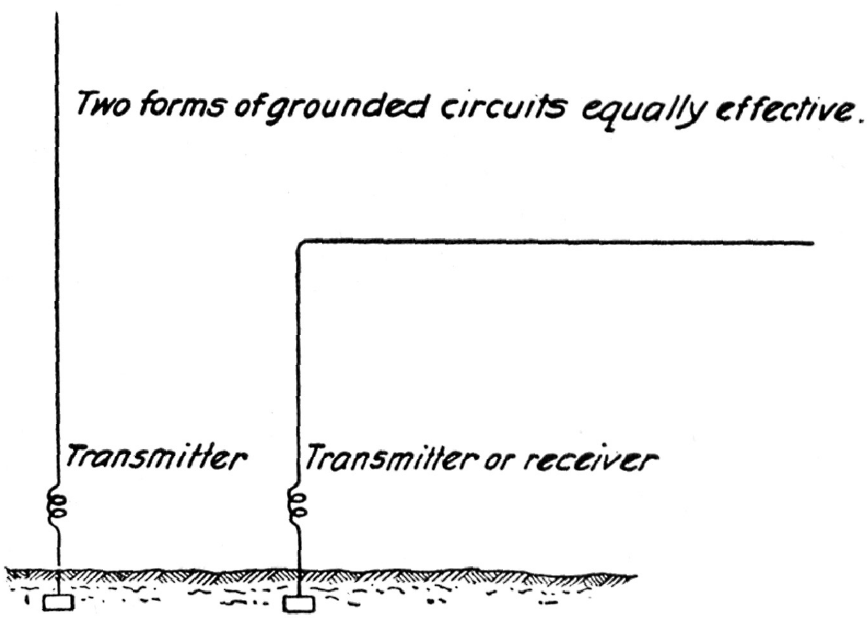


Fig. 6. Tesla considers a straight and bent antenna. (*True Wireless*, Fig. 16)

(which nowadays is called "an inverted L") is just as effective as a receiver or transmitter as the straight antenna on the left. He claims that he has performed an experiment that supports this conclusion. He also asserts that the experiment proves that "currents propagated through the ground, and not … space waves" is the reason for true wireless telegraphy.

In 1919, an understanding of the theory of receiving antennas was still fairly primitive.[26] And it was only in 1924, with the work on reciprocity of John R. Carson at Bell Labs, that the tools that had been developed to analyze transmitting antennas could be brought to bear on receiving antennas.[27] So, we must not be harsh in condemning Tesla for his wrongful assertion. However, it was known as early as 1898 that if antennas are placed above a flat highly conducting earth, one can invoke the method of images for analyzing them.[28] It was well known before 1919 that if the earth is a good conductor, the electric field of a propagating radio wave would be primarily perpendicular to the earth, and the field strength would be proportional to an integral of the current along the vertical portion of the antenna.

It should have been apparent to Tesla that if a transmitting vertical wire antenna is small, measured in wavelengths, and has the shape of the antenna on the left of Fig. 6, and if it is now bent into the shape shown on the right, then the electric field normal to a flat highly conducting earth is reduced.[29] However, the situation here is potentially quite complicated. The difficulty occurs with an *imperfectly* conducting earth. Marconi, in 1906, described to the Royal Society an array he built consisting of inverted L antennas and observed that the array broadcasts most effectively in the direction of the arrow shown below, i.e., *away from* the horizontal element.[30] Fig. 7 is taken from *Principles* of *Wireless Telegraphy* by G. W. Pierce, published in 1910.[31]

Jonathan Zenneck, in the same era as Pierce, describes the work of H. von Hoerschelmann, a student of Arnold Sommerfeld, who apparently was the first to explain the directive properties of Marconi's antenna. His earth is assumed to be imperfectly conducting. He includes the vertical portions of the current induced in the earth directly under the horizontal wires of the array.[32] The upshot is that whether one assumes a highly conducting earth or one of imperfect conductivity (as is required for Marconi's antenna), Tesla's assertion "that the antennas can be put out of parallelism without noticeable change in action on the receiver" is utterly wrong. Marconi's inverted L was constructed in the year 1905, and the explanation by Hoerschelmann was

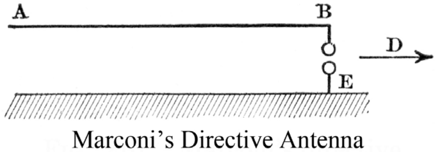


Fig. 7. Marconi's directional inverted L antenna. (G. W. Pierce, *Principles* of *Wireless Telegraphy*, 1910, p. 298)

published in Zenneck's book, which came out in German in 1912, both well before Tesla's paper.[33]

Skin Effect

Tesla repeatedly speaks of his system of wireless telegraphy implemented by sending messages *through* the earth. Here he displays his ignorance of what is now referred to as "skin effect": that alternating currents have a marked tendency to cling to the outside (skin) of conductors. Knowledge of this goes back to the work of the Englishman, Sir Horace Lamb, in 1883 and was advanced further by his countryman, Oliver Heaviside, in 1885.[34] The results showed that the higher the frequency in use, the greater the tendency for the current to adhere to the outside of the conductor.

It is especially puzzling that Tesla does not mention this phenomenon as he took advantage of it in arranging for photographs of himself enveloped by sparks.[35] The frequency of the generator he was using was such that the energy would not penetrate deeply into his body, which meant that although he might have been burnt, he would not have been electrocuted. In an 1893 lecture before the Franklin Institute in Philadelphia, he sought to explain his not being shocked with a confused discussion.[36]

By 1919, skin effect and the concept of skin depth (the depth of penetration of the current) would have been in the better electrical engineering textbooks.[37] We can calculate how far a wave might penetrate into a mountain in the United States where typical soil conductivity, $\sigma = .005$ mhos/meter and the relative permittivity, $\varepsilon_r = 10$.[38] We will assume a frequency $f = 100$ kHz. Using the standard formula for skin depth that applies when conduction current greatly exceeds displacement current,[39] we have

$$\delta = \sqrt{\frac{1}{\pi f \mu \sigma}}$$

Here δ is the skin depth and μ is the permeability of the soil, assumed here to be nonmagnetic. The skin depth for the numbers chosen here is about 22 meters. It is virtually impossible for the signal that Tesla imagines to penetrate a mountain having these typical parameters.

Dismissal of Gliding Waves

Let us now focus on Tesla's Fig. 13 (shown here as Fig. 8) and his accompanying discussion. At the very top of his figure Tesla has the caption, "Hertz's waves passing off into space through the earth's atmosphere." To someone acquainted with even elementary antenna theory, the picture is a puzzle. It depicts what appears to be a vertical antenna fed by a generator connected between the base of the antenna and the earth. In 1919, such an antenna would likely be of small height when measured in the wavelengths in use. Using the method of images and antenna analysis dating from the turn of that century, it should have been apparent that no radiation propagates along the axis of the antenna; instead, the radiation

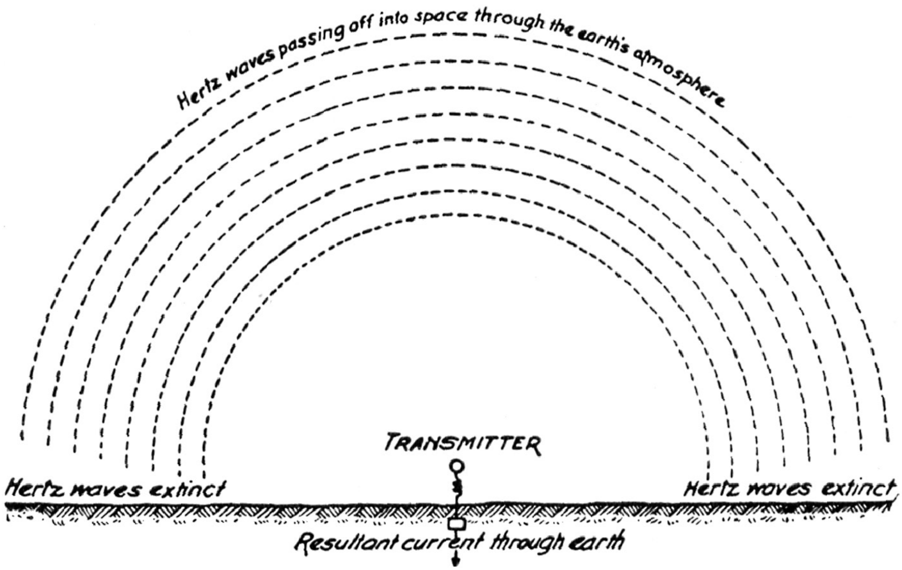


Fig. 8. Tesla condemns the "Gliding Wave." (*True Wireless*, Fig. 13)

tends to be focused along the ground. In fact, if the current in amperes along the antenna is I_0, then elementary antenna theory establishes that the strength of the electric field is at a distance *r* from the antenna, above the earth, is given by

$$E_\theta = \frac{I_0 120\pi h}{\lambda r} \sin\theta \text{ for } 0 \le \theta \le \pi / 2 ,$$

where *h* is the length of the antenna, *l* is the wavelength in use and *r* is the distance of the observer from the antenna.[40] All the distances are in meters. The meanings θ and E_θ should be evident from Fig. 9.

Observe that directly above the antenna corresponds to θ =0, so that sinθ = 0, which indicates there is no radiation normal to the earth, while along the earth θ = 90 degrees, and the radiation is maximum, which might suggest a wave gliding along the surface of the earth, provided we are close enough to the antenna to neglect the earth's curvature. This result would have certainly been known well before 1919. The book *Robison's Manual of Radio Telegraphy and Telephony for*

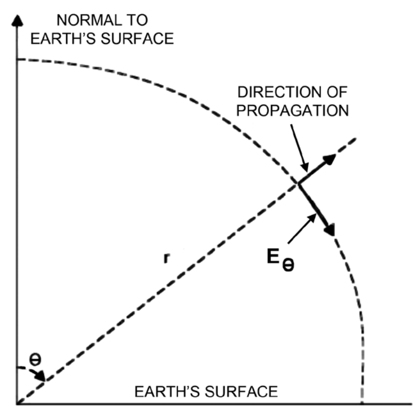


Fig. 9. Electric field and spherical coordinates.

the use of Naval Electricians, published in 1918, contains the following diagram showing the direction of electric lines (see Fig. 10).[41] It illustrates that a monopole antenna radiating above a flat perfectly conducting ground tends to radiate in a direction parallel to the ground and not in a direction along the axis of the antenna. This is not a polar plot of the field strength *vs.* angle but a picture showing the direction of the electric field at various locations. Incidentally, one can argue that there is no radiation along the axis of the antenna even if the ground has imperfect conductivity.[42]

Tesla specifically condemns any theory that claims "[space waves] pass along the earth's surface and thus affect the receivers. I can't think of anything more improbable than this 'gliding wave' theory which… [is] contrary to all laws of action and reaction." Of course, this gliding wave concept that we would now call a "surface wave" did describe daytime radio propagation and was central to the work of such theorists as Sommerfeld, Zenneck, and Watson.[43]

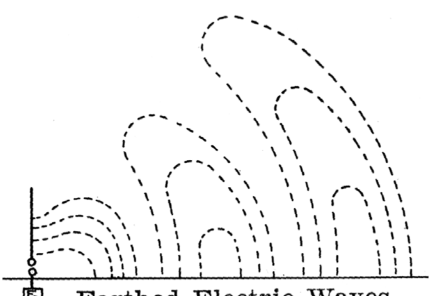


Fig. 10. Electric field lines of a short monopole antenna. (*Manual for U.S. Navy Electricians,* 1918)

Tesla Debunks the Ionosphere

Warming to the task of diminishing other theorists, Tesla then damns what was then only a conjecture: the belief in what was then known as the Kennelly-Heaviside layer. We now call this the ionosphere—a set of layers of three or more ionized gases in the earth's upper atmosphere. It was first postulated, as a single layer, in 1902 by Arthur Kennelly and Oliver Heaviside, working independently, as a way of explaining how radio waves propagate beyond the horizon.[44] Although its existence and height were not verified experimentally until 1924 by the Englishman Edward Appleton, for which he was later awarded the Nobel Prize, its presence was generally accepted in 1919, especially as a means to explain the long distances that radio waves would propagate at night.[45] Tesla tells us, "I have noted conclusively that there is no Heaviside layer, or if it exists it is of no effect." One wonders if he recanted this statement after Appleton's experiment.

Communication with Airplanes

Among the more perplexing aspects of Tesla's article is his discussion tied to his Fig. 15. He is showing here in Fig. 11 a "Hertz oscillator" suspended in the air, and uses this arrangement to explicate something that became well known during World War I: an airplane could communicate with a wireless receiver on the ground. Also known, but not discussed by Tesla, was that two airplanes in the air might experience radio contact with each other.

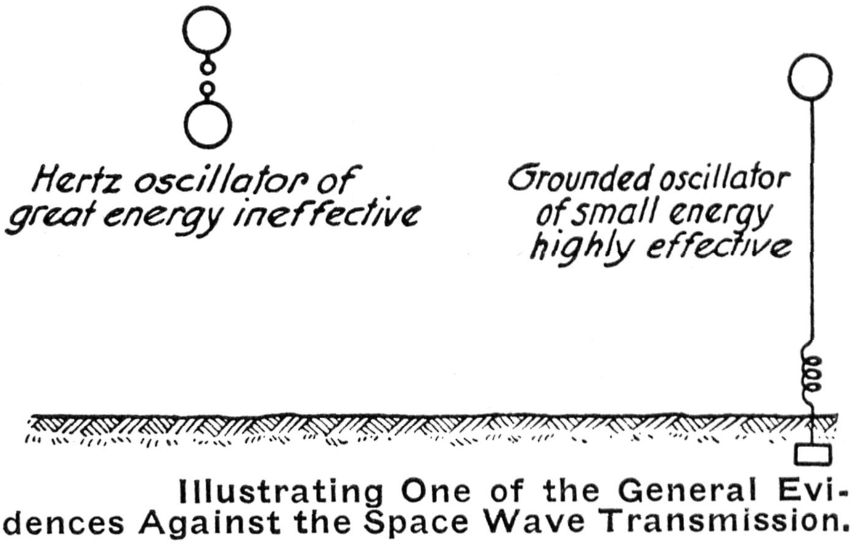


Fig. 11. Tesla denies there is "Space Wave" transmission in wireless telegraphy. (*True Wireless*, Fig. 15)

What Tesla must explain is how his transmitter in the air might communicate with the receiver on the ground in spite of its not having a direct connection to the earth that would be capable of effectively launching his crucial earth currents. His explanation is that "we are merely working through a condenser." Stating incorrectly there is a capacity that "is a function of a logarithmic ratio between the length of the conductor and the distance from the ground," he says the receiver is affected in the same manner as with an ordinary transmitter. Evidently, we are to believe that the capacitance between earth and ground makes possible the earth currents crucial to his argument.

The formula for the capacity of a wire that he is most likely referring to would have been well known by the 1910s when it already had appeared in textbooks and handbooks:[46]

$$C = \frac{1.111\ L}{2\ \ln\left(\frac{2h}{r}\right)} \text{ picofarads.}$$

This expression is the capacity of a wire of length L above, and parallel to, the earth's surface, which is assumed to be highly conducting. An airplane in flight dragging a wire antenna behind itself would create this situation. The wire is at height h above the earth, and its radius is r. All dimensions are in centimeters, and the logarithm is base e. Note that the capacity is proportional to the wire length L, not to the logarithm of L as Tesla asserted.[47] Using the well-known formula for capacitive reactance $X = 1/(2\pi f C)$, where f is the operating frequency, we could in principle obtain the impedance between the wire and earth. Dividing the voltage of the antenna, with respect to the earth, by this impedance, we might think we have obtained the current on the earth.

But what voltage are we to use? Because the antenna illuminates the earth with an electromagnetic wave, the concept of voltage difference or potential difference cannot be applied. It was known in the late 19th century that electric potential difference between two points is calculated by the line integral of the electric field along a path between those points. When there is a time varying electromagnetic field between these points the result will depend on the path taken and so the concept of voltage difference ceases to be of use.[48]

Note that Tesla skirts entirely the phenomenon of airplane-to-airplane wireless communication, which had been observed during the war.[49] Such communication could not possibly involve earth currents if the transmission took place over a desert or dry sandy soil.

The Hertzian Wave Discourse

The publication of Maxwell's *Treatise on Electricity and Magnetism* in 1873, which described his work of the previous decade, together with Hertz's experiments of 1886–9, created the paradigm shift which Tesla was unable to accept. We might be a little indulgent here—the new paradigm was slow to be accepted—consider Marconi for example.

By the late 19th century Marconi was being lionized in the British press because of his demonstrations of wireless telegraphy, but an interview in McClure's magazine from 1899 has him declining to say what sort of waves he was using: "What kind of waves they were Marconi did not pretend to say; it was enough for him that they did their business well."[50] When asked about the difference between his waves and those used by Hertz he replied "I don't know. I am not a scientist, but I doubt if any scientist can tell you..."[51] What seemed to impede the connection of Marconi's waves to those of Hertz's was that it was known by 1897 that the former's radiation could pass through the walls of a building while Hertz's, which was based on a model of radiation as visible light, would apparently not perform such a feat.[52]

Marconi's first British patent, number 12039, which was filed in 1896, speaks of an arrangement that he calls "a Hertz radiator" producing effects "which propagate through space [as] Hertzian rays." But he also talks of electrical actions or manifestations "…transmitted through the air, earth, or water by means of electrical oscillations of high frequency." For a while, Marconi's manifestations in the ether were known in some circles as Marconi waves, but the term soon died. Some further indication of the confusion, *circa* 1900, is a question raised by the historian of early wireless, J. J. Fahie, in his publication of 1901, "… is the Marconi effect under all circumstances truly Hertzian…?"[53]

After 1899, we find that Marconi began to refer more frequently in his work to "Hertzian waves." In a speech given before the Institution of Electrical Engineers (now the IET) in

England on March 2, 1899, he says, "I think it desirable to bring before you some observations and results I have obtained with a system of Hertzian wave telegraphy, which was the first with which I worked…."[54] His U.S. patent 676,332 of 1901 refers to "a transmitter producing Hertz oscillations." And, following Kuhn, we can say that Hertzian waves entered the discourse of "normal science" because we find extensive references to them in a textbook, e.g., Poincaré, cited above. In fact, studying the index of Poincaré, we find that he uses Hertzian waves and electromagnetic waves as synonyms. John Ambrose Fleming, who was the first Professor of Electrical Engineering at University College, London, and who did major work for Marconi beginning in 1899, published a textbook titled *Hertzian Wave Wireless Telegraphy* in 1903, in which there is not the slightest doubt that wireless telegraphy relies on the waves of the title.

Interestingly, Tesla, in certain of his turn-of-the-century U.S. wireless patents, refers to Hertzian waves, or "radiations," being "brought into prominence" by Heinrich Hertz.[55] In all of these instances, such waves are disparaged as being of an outmoded or less desirable way of transmitting signals, or energy, which should be discarded in favor of one that either uses extremely strong electric fields and high antennas to ionize a layer of the earth's atmosphere which is to then act as a conductor of a transmission system (which includes the earth's crust)—or of another that uses wavelengths so long as to make the earth into a conducting sphere that has been brought to a resonant condition. In the later case, he recommends using frequencies lower than 20,000 cycles per second (cps) and asserts one might go as low as 6 cps (patent 787,412, lines 260–270).

Maxwell and Einstein: Difficulties for Tesla

When Tesla wrote his True Wireless paper he was not a young man—he was 63. Male life expectancy in the United States was then 54. His formal education in science and engineering had taken place many years before. He had studied for somewhat less than three years at the Austrian Polytech in Graz Austria in the late 1870's. In 1880 he audited courses at Charles Ferdinand University in Prague but was not enrolled. His course work should have given him a solid grounding in electric circuit theory, and it was in school that he developed a great interest in alternating currents, especially for motors.[56] It is highly unlikely that Tesla would have studied Maxwell's theory while at school. As first presented in 1873, it was so difficult that few could understand it; nowhere will you find in Maxwell's treatise the four succinct equations studied today by all electrical engineering and physics students. His analysis is based entirely on potentials, not the electric and magnetic fields used now. He used 20 equations and 20 variables, and it was only through the efforts of such people as Hertz, Heaviside, and Willard Gibbs in the late nineteenth century that the equations were to assume the form we find them in today.[57] Even with their simplifications, we know that Maxwell's theory was not systematically taught at Cambridge University until after around 1900.[58] Because Hertz's famous experiment was inspired by Maxwell's work, which Tesla most likely did not understand, it seems plausible that Tesla might cling to an electric circuit theory paradigm in explaining what was called wireless communication. Note however, this was not canonical circuit theory—Tesla had added some bizarre features of his own to force it to explain wireless telegraphy.

Maxwell's theory and its experimental verification by Hertz is not the only paradigm shift in Tesla's era that he was unwilling to accept and understand. Throughout his life, he spoke often of particles that moved faster than light—a direct contradiction of Einstein's theory of relativity.[59] In an interview with *Time* magazine on the occasion of his 75th birthday in 1931, he claimed to have "split atoms" with *no release* of energy—again a contradiction of relativity. He also asserted that he had, using "pure mathematics," come up with a theory that "tend[s] to disprove the Einstein theory." There is no indication that Tesla ever had the knowledge to derive a competing theory.

Circa 1930, Tesla wrote a poem for his friend George Sylvester Viereck in which he muses about science.[60] One stanza addresses Newton and contains these lines:

"Too bad, Sir Isaac, they dimmed your renown
And turned your great science upside down.
Now a long haired crank, Einstein by name,
Puts on your high teaching all the blame.
Says: matter and force are transmutable
And wrong the laws you thought immutable."

Note the "long haired crank"—Tesla's name for the man who overthrew the Newtonian paradigm of mechanics.

Much has been written about opposition to Einstein's theory of relativity; this hostility reached its peak in the two decades following the confirmation of the general theory of relativity via the measurement of the bending of starlight by the sun's gravitational field in 1919.[61] Some of this opposition was rooted in anti-Semitism, as the preceding reference shows, and we do know that Tesla had anti-Jewish tendencies.[62] In addition, Hertz, whom he diminishes, was, like Einstein, of Jewish origin,—only partly in Hertz's case—but it seems more likely that the statement to *Time* magazine derives more from an almost pathological narcissism that compelled him to be in the public eye.

Tesla has been called a scientist, engineer, and inventor. While the confusion and angst that can befall a scientific community having difficulty in adapting to a paradigm shift has been much written about, especially after Kuhn's seminal publication, the effect of a scientific paradigm shift on inventors, as opposed to scientists, has been less explored.[63] When we study the lives of individual inventors or engineers we can find failure to adapt to a paradigm change.

Shifting Paradigms in Invention

Besides Tesla, whose inability to absorb a new paradigm should be evident, we have the example of yet another great inventor, Thomas A. Edison. Edison had little formal teaching in schools and was largely educated by his mother and by his own readings. His first important work experiences and inventions were in the field of the [wired] telegraph, which operates using direct currents, and it is clear that he obtained a strong intuitive grasp of DC theory. It is understandable that his subsequent system of generating and distributing electric power was all based on DC. Paul Israel, the esteemed biographer of Edison and editor of the Thomas Edison papers, remarks, "While experimenting with generators, Edison again relied on his experience with telegraph technology to provide a useful analogy that guided laboratory research." Israel points out how Edison and his workers sometimes envisioned direct current generators as "carbon battery elements."[64]

Historians have written about Edison's unwillingness to adapt to the newly introduced system of AC electric power, which posed a direct economic threat to his own DC system.[65] We will probably never know for sure if his objection to AC was truly based on his concern that it was more lethal than DC, or whether he was acting out of pride, inertia, economic self-interest, or an inability to grasp a phenomenon requiring some mathematical sophistication that eluded him. His statement in 1891 to Henry Villard, President of Edison GE, "The use of alternating current instead of direct current is unworthy of practical men," has proved to be as fatuous as Tesla's notion that Hertzian wave theory is "an aberration of the scientific mind."[66]

Age and Vanity

We are left to wonder why Tesla wrote this long paper displaying a wealth of ignorance. One clue might come from an article about him that appeared in the *New York Times* of January 9, 1943, a few days after the inventor's death. The generally admiring piece observes, "His practical achievements were limited to the short period that began in 1886 and ended in 1903. And what achievements they were." By 1919, Tesla's last important work had taken place more than half a generation before. Studying a list of Tesla's patents, we find that about 90% of them were filed on or before 1903, and all of his important ones were granted before this date.[67]

Resurrecting Tesla's Reputation

His *Electrical Experimenter* piece can be read as a rather sad effort to resurrect his reputation. Moreover, his denigration of Hertzian waves and promotion of the primacy of earth currents may be seen as an attempt to preserve respect for his construction of a 187-foot tower (capped with a sphere) in 1901–1903 on

Shoreham, Long Island, whose purpose was to produce a "World Wireless System" that would radiate "several thousands of horsepower" and permit the connectedness of all the telephone and telegraph exchanges in the world by wireless means. The system was to use currents in the earth but was never demonstrated.[68]

Consider his allusion in "The True Wireless" to a speech he gave in 1893 at the Franklin Institute where there is a portion entitled "Electrical Resonance." He remarks in 1919, "This little salvage from the wreck has earned me the title of 'Father of Wireless' from many well-disposed workers …" Perusing the speech, we wonder who these well-disposed workers are.

In his Institute lecture he asserted, "I do firmly believe that it is practicable to disturb by means of powerful machines the *electrostatic* condition of the earth and thus transmit intelligible signals and perhaps power… We know now that electrical vibration may be transmitted through a single conductor. Why then not try to avail ourselves of the earth for this purpose [italics added]?"[69] Notice the use of the word *electrostatic*. His proposal is not based on any use or understanding of electromagnetic waves. As further proof of this, he goes on to wonder what the electrical capacitance of the earth might be and "the quantity of electricity the earth contains." None of this thinking proved germane to communication by wireless telegraphy nor is his obsession in the article with determining the period of oscillation of currents that might be induced in a resonant earth.

Strengthening Tesla's Claims

In a further attempt to strengthen his claims to invention in wireless, Tesla lays claim to discovering the forerunner of the Audion in the caption to his Fig. 9 (reproduced here as Fig. 12). The captions reads, "The Forerunner of the Audion—the Most Sensitive Wireless Detector Known, as described by Tesla in His Lectures Before the Institution of Electrical Engineers, London, February, 1892." It is instructive to read the text of the talk where he discusses his "forerunner."[70] He begins by paying homage to Professor Crookes and his invention, the Crookes tube. Like Crookes, Tesla is not using thermionic emission. He employs a cold evacuated glass bulb, like a lamp bulb, but with no filament. The bulb, which has a "high vacuum," contains some conducting powder, which in turn is connected by a wire to one terminal of a high frequency, high voltage induction coil. The bulb has a sheet of metal foil on its surface that is also connected to the coil for some experiments, but not others. The

The Forerunner of the Audion—the Most Sensitive Wireless Detector Known, as Described by Tesla in His Lecture Before the Institution of Electrical Engineers, London, February, 1892.

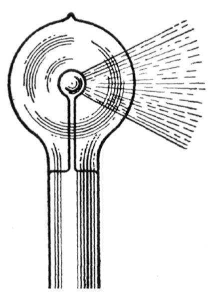


Fig. 12. Tesla's "Forerunner of the Audion." (*True Wireless*, Fig. 9)

straight lines that you see in the figure he calls a "brush"; it gives off a glow that he calls luminosity—whose shape and form he reports is very sensitive to the presence of objects or nearby electric or magnetic fields.

However fascinating his demonstration, Tesla still has not produced the forerunner of the Audion. The latter, we recall, was invented by Lee de Forest, and was the first working three-element vacuum tube. His patent application is dated January 29, 1907, and it issued on February 18, 1908. Despite de Forest's confused understanding of his invention, within the next half dozen years it was proving its worth as both an amplifier and an oscillator. If we want to see the forerunner of the Audion we must look to the work of Fleming and Edison, whose devices, like de Forest's, relied on *thermionic emission*. The distinguished historian of the vacuum tube, Gerald Tyne, makes no mention of Tesla in his well-regarded opus.[71] This is not surprising—Tesla's bulbs responded by glowing only in the presence of strong, quasi-electrostatic fields produced by his machines.

It is regrettable that Tesla's narcissism caused him to write this paper—it can only provide difficulty for his acolytes and apologists. The ignorance he displays of classical electromagnetic theory, which by 1919 was a mature subject, can only diminish his reputation.

Gernsback and His Magazine

If Tesla's True Wireless is so utterly wrong, and if it conflicts with the paradigms used by engineers and scientists of 1919, how did he get his article published? To answer this, we must focus on the magazine where it appeared and its editor/publisher Hugo Gernsback (1884–1967).[72] Almost a generation younger than Tesla, Gernsback had certain things in common with him: they were both inventors with substantial lists of patents—Gernsback had 22, Tesla 112; both came from groups that placed them in small minorities in the United States (Gernsback was a Jew from Luxemburg); both studied science and engineering on the European continent; and both occupied a kind of nether world bridging science and fantasy.[73] They apparently had a lasting friendship that would tend to counter suspicions that Tesla was an anti-Semite. Gernsback pressured the Westinghouse Company, which had benefited greatly from Tesla's work in three phase power and induction motors, to give the near destitute inventor a pension in 1934.[74]

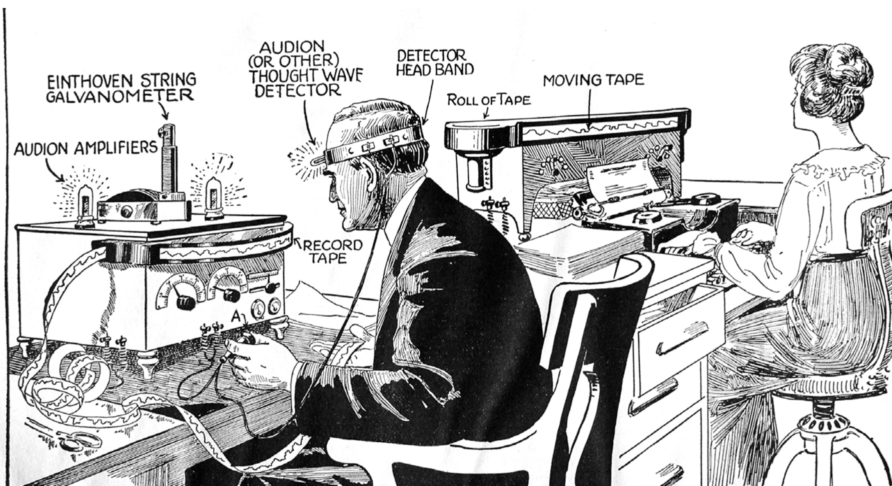
Gernsback's Electrical Experimenter

The *Electrical Experimenter,* started by Gernsback in 1913, is where we find Tesla's article six years later.[75] Although the term "science fiction" did not exist until coined by Gernsback in 1929, his magazine *Modern Electrics* carried a serialized story of that genre in 1911–12, written by Gernsback—something to keep in mind when we look at the *Electrical Experimenter,* where Tesla was to publish abundantly in the 7-year life of that magazine.[76]

What sort of magazine was the *Electrical Experimenter*? It was dense with ads for radio hardware, e.g., Murdock headphones and audio interstage transformers as well as Grebe and De Forest radios. Mainly, it carried stories of new inventions, especially those with an electrical basis, such as a new radio compass, a method of abolishing smoke electrically, new electric stoves, and quack medicine—anesthesia via electricity and an electrical cure for tuberculosis using the Tesla coil.[77] Much of the magazine was given over to what we would now call “techno-euphoria”—a belief that technology would bring us wonderful things in the not-too-distant future. One example was the Thought Recorder, shown in Fig. 13.

The author of the article is none other than Gernsback himself. He imagines a man in an office who is connected to a halo on his forehead. The halo is supporting an Audion amplifier tube that detects and amplifies the man’s thoughts. They are then sent to an instrument on his desk that converts his thoughts to an inscription on a moving tape. The latter is supplied to the man’s secretary who is capable of reading the information on the tape and who can now write letters or memos based on what the boss has been thinking. The article appears in the same issue as Tesla’s, and Tesla, in an introduction, gives some measured support to the idea. Interestingly, Greenleaf Whittier Pickard, a distinguished electrical engineer who helped develop what we would now call the crystal radio, *circa* 1904, also comments and employs the term “Hertzian waves,” illustrating how commonly the phrase was used.

The *Electrical Experimenter* does seek to explain legitimate recent advances in the sciences. For example, Einstein’s special and general theory of relativity and the general theory’s



The Thought Recorder is an Instrument Recording Thoughts Directly by Electrical Means, On a Moving Paper Tape. Our Illustration Shows What a Future Business Office Will Look Like When the Invention, Which as Yet Only Exists in the Imagination, Has Been Perfected. By Pushing the Button A, the Tape is Started and Stopt Automatically So That Only Thoughts That Are Wanted Are Recorded.

Fig. 13. The “Thought Recorder.” (*Electrical Experimenter*, May 1919)

confirmation by the observed bending of light are carefully described in the January 1920 issue by an unusual person for the era: a female astronomer, Isabel M. Lewis, M.A, who was a regular contributor and the first woman astronomer to be hired at the U.S. Naval Observatory.[78] The magazine also published pure science fiction stories, such as "At War with the Invisible" appearing in the March and April 1918 issues, which described a war between the planets Mars and Earth in the 21st century.[79]

Science Fiction, Nostalgia for the Future

Unfortunately, a magazine mixing techno-euphoria, future studies, science fiction and real science is playing dangerous games: the boundaries became diffuse. The March 1918 *Electrical Experimenter* has an article by Gernsback starting on page 743 entitled "Can Electricity Destroy Gravitation?" The author asserts it can, and describes the work of a Prof. Francis E. Nipher of the Saint Louis Academy of Science. The professor's experiment is described thusly: He suspends a small lead ball from a string. It is placed in proximity to a very heavy lead ball that rests on a bench. The small ball and string are seen to be deflected toward the heavy ball because of the force of gravitational attraction—a straightforward replication of the famed Cavendish experiment of 1797–8.[80] The professor then passes a direct current through the large ball. Nothing has changed. But then he applies an AC current, *et voilà,* the small ball moves away from the large one, thereby proving that gravity has been weakened by electricity.

Anyone with a modicum of knowledge of electromagnetic theory would see what was happening here. The AC creates a time varying magnetic field that induces eddy currents in the small ball. These currents interact with the magnetic field to push the small ball away from the large one. The clue that Faraday's law of induction and the induced current serve as the explanation should have been the failure of the experiment to work with a direct current. The gravitational field, like DC and its resulting fields, is static. A direct current cannot induce a voltage or current in a neighboring circuit, while alternating currents have that ability. Eddy currents were well understood by 1919. One wonders how much real science Gernsback knew; it is no surprise that he permitted another paper based on dubious physics to be published the next year: Tesla's "The True Wireless."

The *Electrical Experimenter* morphed into another Gernsback magazine: *Science and Invention,* in 1920.[81] This publication, although it did in some ways live up to its title, increasingly carried science fiction and proved so successful that Gernsback was able to introduce more magazines (e.g., *Amazing Stories, Wonder Stories*) that were wholly devoted to the science fiction genre, and he is best known as a publisher of science fiction. At least one historian has suggested that many of the ideas in Gernsback's science-fiction stories promoted Tesla's "still unrealized ideas" for inventions.[82]

Endnotes

1. Nicholson Baker and Margaret Brentano, *"The World on Sunday: Graphic Art and Joseph Pulitzer's Newspaper (1898–1911),"* (Bullfinch Press, Boston, 2005) pp. 102–103.
2. Nikola Tesla, "The True Wireless," *Electrical Experimenter*, vol. 7, no. 3, May 1919, pp.22–23, 61–63, 87. The following website has images of the original pages: http://www.free-energy-nfo.com/Tesla TrueWireless.pdf. Other sources of the paper can be found by Googling the search term *"Tesla True Wireless."* Vendors of CD's having a complete run of the issues of *the Electrical Experimenter* can be found on eBay.
3. Thomas Kuhn, *The Structure of Scientific Revolutions, 3rd ed.*, (University of Chicago Press, Chicago, 1996).
4. R.P. Feynman, R. B. Leighton, and M. Sands, "The Feynman Lectures on Physics, vol. 2," (Addison-Wesley, Reading, MA, 1964) pp. 1–6.
5. Jed Buchwald, *The Rise of the Wave Theory of Light,* (University of Chicago Press, Chicago, 1989); With the birth of quantum theory *circa* 1900–26, a particle theory of light based on photons was to reemerge, but it did not undermine Maxwell's work thanks to the concept of the wave-particle duality. See for example Ian Walmsley, *Light: A Very Short Introduction,* (Oxford University Press, Oxford, 2015).
6. Hugh Aitken, *Syntony and Spark: The Origins of Radio*, (Princeton University Press, Princeton, 1985), Chapter 3.
7. Hugh Aitken, *Syntony and Spark.*
8. Interestingly, we have only Tesla's word that this meeting took place. There is no supporting entry in *Heinrich Hertz: Memoirs, Letters, Diaries* by Mathilde Hertz and Charles Süsskind, 2nd edition (San Francisco Press, San Francisco, 1977). As Tesla was a famous inventor by the time of the meeting, it is puzzling that he was not mentioned by Hertz. Also, no meeting is described by Bernard W. Carlson in his definitive biography of Tesla: *Tesla: Inventor of the Electrical Age*, (Princeton University Press, Princeton, 2013).
9. Tom Lewis, *Empire of the Air: The Men Who Made Radio*, (Harper-Collins, New York, 1991), p 136.
10. Paul Schubert, *The Electric Word: The Rise of Radio,* (Macmillan, London, 1928) pp. 166–168.
11. It was not until 1893, well after Tesla had completed his education, that the great simplification in AC circuit analysis made possible by the use of complex quantities began to be adopted, thanks to the work of C. P. Steinmetz. See, for example, Charles Proteus Steinmetz, "Complex Quantities and their Use in Electrical Engineering," *AIEE Proceedings of International Electrical Congress*, July 1893, pp. 33–74.
12. Alfred Hay, *The Principles of Alternate Current Working,* (Biggs and Co, Boston, 1897) pp. 137–148. Available at Google Books; for other 19th century engineers who used fluid analogies—or rejected them—see Paul J. Nahin. *Oliver Heaviside: Sage in Solitude,* (IEEE Press, Hoboken, NJ) *1988, p.* 59 (note his footnote 3 and the derisive comment "drainpipe theory").
13. There is a stern critique of using mechanical explanations for explaining electrical phenomena in Henri Poincaré, *Maxwell's Theory and Electrical Oscillations, (*McGraw-Hill, NY, 1904) Chapter 1, pp. 1–2. This book is available at Google Books. Tesla was so committed to hydraulic analogies that he supplied one for his high voltage, high frequency invention, the Tesla coil. See N. Tesla, *My Inventions*. This series of articles originally appeared in the *Electrical Experimenter* in 1919. They have been republished in his book *My Inventions (*Barnes and Noble, NY, 1995). See especially pp. 76–77. The analogy is so complicated that one is better served by studying the original electrical device and applying the laws of AC circuit theory and resonance.
14. Interestingly, in U.S. patent 645,576, Tesla has not yet discarded the return wire in a communication/power distribution system he is proposing. Part of his circuit consists of a path through an atmospheric layer that his powerful transmitter will, he asserts, succeed in ionizing. The earth is also employed in the circuit. The patent was granted in 1900, but by 1919 he has dispensed with the return part of the circuit.
15. For an explanation of the concept of Whig history, as it applies to the history of science, see Steven Weinberg, "Eye on the Present, The Whig History of Science," *New York Review of Books,* vol. 62, no. 20, Dec. 17, 2015.
16. J. Zenneck and A. E. Seelig (translation), *Wireless Telegraphy*, (McGraw-Hill, NY 1915)

pp. 258–259. This book provides an idea of how textbooks, *circa* 1910–1920, explained waves received on the far side of the mountain.

17. See the article on diffraction in the 11th edition of the *Encyclopedia-Britannica, vol. 8, 1911.* https://en.wikisource.org/wiki/1911_Encyclop%C3%A6dia_Britannica/Diffraction_of_Light/11. Also, for a modern treatment see Y. T. Lo, Y. T and S. W. Lee, *Antenna Handbook*, (Van Nostrand-Reinhold, NY, 1988) sec. 29.
18. R. W. P King and S. Prasad, *Fundamental Electromagnetic Theory and Applications,* (Prentice Hall, Upper Saddle River, New Jersey 1986) chapter 7.
19. Jules Stratton, *Electromagnetic Theory,* (McGraw-Hill, New York. 1941), secs. 9.22–9.24.
20. Chen-Pang Yeang, *Probing the Sky with Radio Waves* (University of Chicago Press, Chicago. 2013). I am greatly indebted to this source.
21. Henri Poincaré and F. King Vreeland (translation), *Maxwell's Theory and Wireless Telegraphy*, (McGraw-Hill, New York, 1904) p. 161. Tesla might have countered by asserting that the Branly coherer responds to the electric field—not the magnetic field—and the earth weakens the former.
22. L. W. Austin, "Some Quantitative Experiments in Long Distance Radio Telegraph," Reprint No. 159, *Bulletin of Bureau of Standards*, vol. 7, no. 3, Feb. 1, 1911; see also Robison, 1918, p. 228.
23. Watson, G. N. "The Transmission of Electric Waves Around the Earth," *Proc Royal Society (London) Series A*, vol. 95, July 15, 1919, pp. 546–553.
24. Heinrich Hertz, *Electric Waves*, (Dover Books, Mineola NY, reprint of Macmillan book 1893) chapter 8 (dating from 1888, especially Fig. 26).
25. Kuhn, page 43.
26. Samuel Robison, *Robison's Manual of Radio Telegraphy and Telephony for Naval Electricians* (U.S. Naval Institute, Annapolis, MD, 1918) p.131. He asserts that the directivity behavior of the "flat top antenna" attributed to Marconi, which involves a long piece of wire or wires parallel to the ground, is still not understood.
27. L. J. Chu, "Growth of the Antennas and Propagation Field Between World War 1 and World War 2. Part 1, Antennas," *Proceedings of the IRE,* vol. 50, no. 5, May 1962, pp. 685–7.
28. Charles Burrows, "The History of Radio Propagation up to the End of World War I," *Proceedings of the IRE*, vol. 50, no. 5, May 1962, pp. 682–684.
29. Note that Marconi had described arrays formed from inverted L antennas as early as 1906, as noted in G. W. Pierce below. The horizontal elements were much longer than the vertical ones, a configuration not suggested in Tesla's Fig. 16. G. W. Pierce, *Principles of Wireless Telegraphy*, (McGraw-Hill, New York, 1910) Chapter 25. See also *Practical Wireless Telegraphy*, Elmer Bucher, Wireless Press, 1917, sec. 233. Here, the horizontal portion of the antenna is nearly a mile long.
30. See G. Marconi, "On Methods Whereby the Radiation of Electric Waves May Be Mainly Confined to Certain Directions, and Whereby the Receptivity of a Receiver May Be Restricted to Electric Waves Emanating from Certain Directions," *Proceedings of the Royal Society of London. Series A,* Containing Papers of a Mathematical and Physical Character 77.518 (1906): 413–21; *Electrician*, vol. 60, 1908, p. 883.
31. Pierce, p. 298.
32. Zenneck and Seelig, Sec. 202–204. The book contains the reference to Von Hoerschelmann, which was published in German as a dissertation in 1911.
33. Aitken, p. 267.
34. Nahin, pp. 142–143.
35. Bernard Carlson, *Tesla: Inventor of the Electrical Age*, (Princeton U. Press, Princeton NJ, 2013) p. 200–202; note that some images were the result of multiple exposures where Tesla was not present when the sparks were being generated, see pp. 297–299.
36. T. C. Martin, editor, *The Inventions, Researches and Writings of Nikola Tesla*, 1893; republished by (Barnes and Noble, NY, 1992) Chapter 6. From the lecture: "The reason why no pain in the body is felt, and no injurious effect noted, is that everywhere, if a current be imagined to flow through the body, the direction of its flow would be at right angles to the surface; hence the body of the experimenter offers an enormous section to the current, and the density is very small, with the exception of the arm, perhaps, where the density may be considerable…The expression of these views, which are the result of long continued experiment and observation, both with steady and

varying currents, is elicited by the interest which is at present taken in this subject, and by the manifestly erroneous ideas which are daily propounded in journals on this subject." Tesla misses the essential point here—the very shallow depth of penetration of the energy. The arm plays no special role. Notice that he takes a swipe at other workers' "erroneous ideas."

37. Indeed, it was in Poincaré's book of 1904 (see above).
38. E. C. Jordan and K. Balmain, *Electromagnetic Waves and Radiating Systems*, 2nd ed., (Prentice-Hall. NJ, 1968) p. 655.
39. Note that this is a simplification of a formula derived by Heaviside in 1888. See Nahin, who also gives the formula we are using here, p. 176
40. King and Prasad, section 5.9. The sinθ variation was derived by Hertz in the 19th century (see Hertz, *Electric Waves,* p. 143 above) and was popularized by Louis Cohen in a paper written for engineers in 1914. See his "Electromagnetic Radiation," *Journal of the Franklin Institute*, April 1914, vol. 177, no. 4, pp. 409–418.
41. Robison, 1918, p. 62. Notice that the same picture appears in an even earlier edition of Robison, dating from 1911, on page 76. This book is available from Google Books.
42. R.W.P King, Theory of Linear Antennas, (Harvard University Press, Cambridge, MA, 1956) chapter 7. Note that this work is based in part on Sommerfeld's work of 1909.
43. Burrows.
44. Ibid.
45. The ionosphere, although not called by that name, could be found in electrical engineering handbooks as early as 1915; see for example W. H. Eccles, *Wireless Telegraphy and Telephony: A Handbook of Formulae, Data and Information.* (*Electrician*, London, 1915), pp. 162–3.
46. Eccles, p. 120.
47. In the unlikely event that the wire hangs straight down from the aircraft, the preceding formula does not apply. However, it would still be incorrect to say that the capacitance varies with the logarithm of the length of wire. The required formula shows a more complicated behavior. See Eccles p. 120.
48. James Clerk Maxwell*, A Treatise on Electricity and Magnetism*, vol. 1.(Clarendon Press, Oxford 1891) p. 76. This has been reprinted by Dover Books, NY, 1954. For a modern treatment that emphasizes the limitations of the concept of voltage difference see Edward.C. Jordan and Kenneth. Balmain, *Electromagnetic Waves and Radiating Systems,* second ed., (Prentice-Hall, New Jersey 1968) p. 36.
49. http://blogs.mhs.ox.ac.uk/innovating incombat/ See also R. W. Burns, *Communications: An International History of the Formative Years,* (IEE Press, UK, 2004) p. 407.
50. http://earlyradiohistory.us/1899marc.htm, *McClure's Magazine*, (London), June 1899, pp. 99–112.
51. Sungook Hong, *Wireless: From Marconi's Black Box to the Audion*, (MIT Press, Cambridge, MA, 2001) p. 205. See Aitken, his footnote 12 page 195. Note (same page) that even Fleming, Marconi's well-regarded consulting engineer, was at first misled by the misuse of analogies drawn from the theory of light.
52. Aitken, pp. 285–286 and Hong p. 42, footnote 48.
53. J. J Fahie, *A History of Wireless Telegraphy*, (Blackwood, Edinburgh, 1901) p. 216.
54. Guglielmo Marconi, "Wireless Telegraphy," *Journal of the Institution of Electrical Engineers,* vol. 28, 1899, pp. 273–291.
55. U.S. Patent 685,955 of 1901, 685,954 of 1901, 685,956 of 1901, 787,412 of 1905.
56. Carlson, chapter 2.
57. Nahin, chapters 7 and 9.
58. Bruce Hunt, The *Maxwellians,* (Cornell U. Press, Ithaca, NY, 1991) p. 202.
59. Marc Seifer, *Wizard: The Life and Times of Nikola Tesla*, (Citadel Press. New York, 1998) p. 423.
60. Margaret Cheney & Robert Uth, *Tesla: Master of Lightning,* (Barnes and Noble/Metro Books, NY, 2001) pp. 138–139.
61. Milena Wazeck , *Einstein's Opponents, The Public Controversy about the Theory of Relativity in the 1920's.* (Cambridge University Press, Cambridge, UK, 2014).
62. Seifer, p. 212.
63. For an example of writing on the subject of paradigm shifts in physics after Kuhn, see Jaume Navarro, "Electron Diffraction Chez Thomson: Early Responses to Quantum Physics in Britain." *The British Journal for the History of Science,* vol. 43, 2010, pp. 245–275.
64. Paul Israel, *Edison: A Life of Invention*, (John Wiley & Sons, New York, 1998) p. 176.
65. Thomas Parke Hughes, *Networks of Power: Electrification in Western Society*, (Johns Hopkins University Press, Baltimore, 1983).

66. Matthew Josephson, *Edison: A Biography,* (Wiley, New York, 1992) p. 359.
67. The web site https://en.wikipedia.org/wiki/List_of_Nikola_Tesla_patents lists 111 or 112 U.S. Tesla patents (depending on how they are counted).
68. Nikola Tesla, "My Inventions," *Electrical Experimenter, 1919,* see chapter 5, available on the Internet http://www.teslasautobiography.com/ See also Carlson, chapter 15.
69. T. C. Martin, pp. 346–7. In the late 19th century, Tesla spoke repeatedly of disturbing the electrostatic condition of the earth as a means of sending intelligence. See also Martin p. 292 for an example used in a speech before the British IEE in 1892.
70. This tube appears in a speech he gave in 1892 to the Institution of Electrical Engineers (London). See T. C. Martin ed. pp. 225–229.
71. Gerald Tyne, *Saga of the Vacuum Tube*, (Antique Electronic Supply, Tempe AZ. 1977).
72. Mike Adams, "Hugo Gernsback: Predicting Radio Broadcasting, 1919–1924," *Antique Wireless Association Review*, vol. 27, August 2014, pp. 165–192.
73. For a listing of the Tesla U.S. patents see http://web.mit.edu/most/Public/Tesla1/alpha_tesla.html. The number for Gernsback was obtained from a search of Google Patents using his name as the inventor. Footnote 64 above also gives a source of Tesla's patents.
74. Carlson, p. 379.
75. K. Massie, and Stephen Perry, "Hugo Gernsback and Radio Magazines: An Influential Intersection in Broadcast History," J*ournal of Radio Studies*, vol. 9, no. 2, 2002. Note that the magazine was originally titled *The Electrical Experimenter*. The title was shortened during 1917.
76. The term was apparently first used in Gernsback's magazine *Wonder Stories* in the issue of June 1929; Gernsback had earlier coined the term "scientifiction." See Leon Stover, *Science Fiction from Wells to Heinlein*, (McFarland Publishers, Jefferson, NC, 2002) p. 9.
77. Frederick Strong, "The Home Treatment of Tuberculosis by High Frequency Currents," *The Electrical Experimenter*, vol. 5, no. 10, Feb. 1918.
78. http://maia.usno.navy.mil/women_history/lewis.html.
79. M Ashley and R. Lowndes, *The Gernsback Days,* (Wildside Press, Rockville, MD, 2004) p. 51–2.
80. https://en.wikipedia.org/wiki/Cavendish_experiment.
81. Ashley, above, p. 53.
82. Stover, p. 175. In 1923 Gernsback produced a book, *Radio for All*, published by Lippincott. The work was designed to introduce people to what was still in many ways a hobby. Thus, there were instructions for building simple radios—crystal and one-or two-tube sets, as well as transmitters. It is puzzling that the book makes no mention of the work of Tesla, given his friendship with Gernsback, although there are numerous allusions to Marconi as well as single references to such inventors as Poulsen, Pickard, Fessenden, and Dunwoody.

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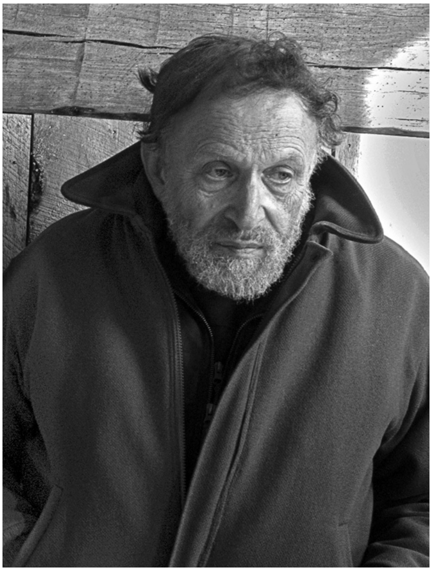
David is the book review editor of the IEEE Magazine *Technology and Society*. He is the author of two textbooks: *Complex Variables with Applications* (Pearson), currently in its third edition, and the recently published *A MATLAB Companion to Complex Variables* (Taylor and Francis).

David recently rebuilt the Heathkit oscilloscope that he constructed in 1957. He thought it would make him 17 again but his beard remains white.



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