1994 Tesla Symposium at Colorado Springs

NIKOLA TESLA,

LIGHTNING OBSERVATIONS,

AND

STATIONARY WAVES

by

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"Repeatedly the instrument played and ceased to play in intervals of nearly half an hour..."
Tesla's Notebook
July 4,1899
Colorado Springs

"No doubt whatever remained: I was observing stationary waves."

Nikola Tesla***

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***Electrical World and Engineer, March 5, 1904.

Introduction

During the summer of 1899, the (now) primitive RF detectors employed by Nikola Tesla were observed to possess a rhythmical pattern of intensity response (with a one-half hour period) whenever electrical storms passed within several hundred kilometers of his experimental station in Colorado. Historian, Leland Anderson has pondered this matter for more than forty years and has posed it to the scientific community as a major issue that must be resolved. "In my opinion, the question of what Tesla was measuring on July 3, 1899 ***must*** be answered."[(1)] The purpose of this paper is to assemble Tesla's scattered remarks into a coherent description and to suggest a physical model, for exploration, as a plausible explanation for Tesla's lightning storm observations.

For a number of years, the authors have been involved with the analysis and reproduction of Tesla's RF work. A major portion of our effort has been to reexpress Tesla's turn-of-the-century physics into the engineering and analytical terms of today. In spite of the fact that his physical explanations often bear the mark of antiquated and faulty theory (he was laboring within the framework of nineteenth century physics), we have been overwhelmed by Tesla's extraordinary physical intuitiveness, his careful power of observation, his uncanny experimental technique, *and the accuracy* of his published data. With regard to his RF work, it has been our experience that *if Tesla said* that he observed something, ***then he saw it!*** He was an honest and careful experimentalist. (Furthermore, we assert that any competent and careful experimentalist today, replicating *any* of Tesla's experiments, will also observe what Tesla *said* that he observed![*]) Having expressed that, let us turn our focus on the mystery before us.

We seek the answers to five basic questions: (a) What was he trying to measure?, (b) How did he describe the experiment?, (c) What equipment did he use?, (d) What did he envisage was going on? (That is, how did he interpret the results?), (e) What, in fact, did he observe on the 3rd of July, and on subsequent dates, in 1899? These will be the topics we bring under consideration.

The Colorado Springs Laboratory

Before turning to the historical evidence, however, let us listen to the descriptive, almost poetical, language that Tesla employs to describe the locale in which his puzzling experiments were made.

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[*]It is impossible for us to state this in any stronger terms!

August 1, 1899

> "In the course of these experiments, and particularly during the past month [July], a number of highly interesting observations have been made which will be presently dwelt upon... First of all, one is struck by noting the extraordinary purity of the atmosphere which is best evident from the clearness and sharpness of outlines of objects at a great distance... The moonlight is of a power baffling description... The number of stars visible and their brilliancy is amazing and the sky presents a truly wonderful sight... The cloud formations are the most marvelous sights that one can see anywhere...more vivid and intense than in the Alps...The shadows on the plain and mountains, thrown by the clouds, appear like big patches of inking blackness hurrying along the ground... I have seen seemingly dense, white clouds appear, as by enchantment, below the mountain peaks... But, the most interesting of all are *the electrical observations* which will be described presently."[2]

Bearing this backdrop for his experiments in mind, we turn to the available technical evidence.

I. THE HISTORICAL DOCUMENTS

We think that sufficient technical information is accessible from Tesla's writings to provide an answer to the questions listed above, and we will propose an elementary hypothesis involving a simple VLF wave propagation model that may be independently examined for validity. We will also report on our initial experimental observations confirming Tesla's declarations. Although this little study will broach physical issues involved in the legal aspects of Tesla's priority in the invention of radio, we will not address the broader concerns required in that investigation. (Readers with concerns for these issues should consult the extensive analyses of Anderson.[3][4][5])

The logical evolutionary path, which Tesla seems to have followed in his thoughts, starts with the discovery of the RF single wire transmission line, proceeds to the contemplation of the impulse excited spherical resonator, and emerges as VLF ground current standing waves (much as one finds in the radial ground screen* of a vertical monopole antenna[6][7][8]). In order to answer the question, "What was he *trying* to measure?", we will require some historical evidence as well as Tesla's own testimony.

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*It is not commonly recognized that the ground currents in the "near zone" around the base of a vertical monopole antenna possess a rippling stationary wave pattern, and do not "fall off" as $1/\sqrt{\rho}$, $1/r$ or $1/r^2$. They may, in fact, even grow in magnitude as one recedes from the base of the antenna. The cited references give experimental measurements, analytical calculations, and computational determinations of the ground screen currents, which are seen to *ripple* as a radial spatial *standing wave*. (The temporal behavior is time-harmonic, of course.) See the comments below.

Tesla's Discovery of Single Wire Electrical Distribution

By 1891 Tesla had developed a powerful* generator of high voltage** RF, and had *discovered* single wire RF transmission. His RF oscillator and "single terminal" lamp apparatus patent (#454,622) issued in the US on June 23, 1891. In this patent he disclosed that he had discovered how to light ordinary incandescent lamps from the single terminal of a special high frequency tuned coil of wire. (This is the first record of a resonant high frequency *coupled* oscillatory circuit, which we now call a Type I Tesla coil.) Tesla demonstrated the single terminal lamp to the AIEE in New York (at Columbia University) on May 20, 1891,

> "A most curious feature of alternate currents of high frequencies and potentials is that they enable us to perform many experiments *by the use of one wire only*. In many respects this feat is of great interest."(9)

Today we describe this in terms of resonant distributed RF circuits, loaded transmission lines, and antennas. When recalling the events of that time frame for his attorney in 1916, Tesla reminisced,

> "I have often been told that [one of] my most important results in invention was the demonstration of the practicability of transmitting energy over one wire; because, once we can transmit energy over one wire we can also use the earth, for the earth is equivalent to a large conductor -- a better conductor than copper wire...
>
> That was in 1891, prior to my going to England to lecture before the scientific societies there... I had already proved in my lecture at Columbia College that I could transmit energy through one wire.... My idea at that time was that I would disturb the electrical equilibrium in the nearby portions of the earth, and the equilibrium being disturbed, this could then be utilized to bring into operation in any way some instrument. That was what we would now call, simply, impressing forced vibrations of very high frequency on an antenna. We have introduced the term 'antenna' since that time."(10)

In February of 1892, almost a year after the Columbia AIEE lecture, the resonant single wire circuits were a significant part of his demonstrations to the IEE (Wednesday, February 2nd) and the

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*This is not an overstatement. When he introduced the coupled tuned transformer, he moved Hertz's energy storage element from the antenna to the primary. Tesla immediately raised the RF *average power* delivered to the antenna from a few milliwatts (in the Hertz apparatus) to more than a kilowatt, and by 1899 to more than 300 kW. We have discussed this in Appendix X of Vacuum Tube Tesla Coils. (Hertz was using peak powers on the order of 10 kW. Tesla's peak powers were in excess of 75 MW!)

The reader should also be aware of another *very* important detail: There are at least four distinct *types* of Tesla coils. Type I (tuned *lumped* coupled circuits) was patented in 1891. This evolved over the next seven years to the Type IV coil, which is a *distributed* helical resonator - not a lumped element.

**He had also developed the high power RF alternator. (See Anderson, 1992, pp. 1-23.)

Royal Institution (Thursday, February 3rd) in London, and to the Society of Electrical Engineers of France and the French Society of Physics in Paris (February 19th). When recalling his European lectures, in 1919, Tesla said,

> "While the spontaneous success*(11) of my lectures was due to spectacular features, its chief import was in showing that all kinds of devices could be operated *through a single wire without return*. This was the initial step in the evolution of my wireless system."(12)

The closing thoughts of these 1892 lectures in Europe were concerned, not with moving charge back and forth on a single wire, but with sloshing the static charge on a large conducting sphere:

> "... The wonder is that, with the present state of knowledge and the experiences gained, no attempt is being made to disturb the electrostatic and magnetic condition of the earth, and transmit, if nothing else, intelligence."(13)

Within a year, Tesla was describing a physical experiment to search for the resonant frequencies of the earth by such a technique:

> "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. In fact, what is there against the carrying out of such a scheme? We now know that electric vibration may be transmitted through a single conductor. Why then not try to avail ourselves of the earth for this purpose?...
>
> It is of the greatest importance to get an idea of what quantity of electricity the earth contains. It is difficult to say whether we shall ever acquire the necessary knowledge, but there is hope that we may, and that is, by means of electrical resonance. **If ever we can ascertain at what period the earth's charge, when disturbed, oscillates,**** we shall know a fact possibly of the greatest importance to the welfare of the human race. ***I propose to seek for the period by means of an electrical oscillator...***

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*Tesla is not taking literary license here. The lectures were applauded in over 36 professional publications in London, Paris, and New York. They were repeatedly published in full in the technical journals of the day both in Europe and the US. And, such prestigious luminaries as Sir William Crookes, Lord Rayleigh, Sir Frederick Bramwell, Sir James Dewer, Lord Kelvin, Sir Oliver Lodge (who was absent), Sir William Preece, Sir John A. Fleming ... all showered appreciation upon Tesla. Reginald Kapp has written, "Although I was not yet seven years old at the time, I can still remember the lecture being talked about by visitors to my father's house.... The theme of Tesla's famous lecture to the Royal Institution was a demonstration of what can be achieved when the principle of resonance is applied to an electric circuit... Small wonder that the lecture triggered off an immense amount of thinking in the British scientific world." (Tribute, pp. A300-A305.)

**This problem was solved analytically by J.J. Thompson and by H. Poincare in 1896, three years after Tesla's remarks. See the comments below. Here, Tesla is formulating the problem and suggesting how to perform the experimental determination.

One of the terminals of the source would be connected to earth, the other to an insulated body of large surface... I would then transform the current to a potential as high as it would be found possible and connect the ends of the high tension secondary to the ground and to the insulated body.* By varying the frequency of the currents and watching for the disturbance at various neighboring points of the earth's surface, resonance might be detected...

Whether this be possible or not, and whether the earth contains a charge or not, and whatever may be its period of vibration, it certainly is possible - for of this we have daily evidence - to produce some electrical disturbances sufficiently powerful to be perceptible by suitable instruments at any point of the earth's surface."[14]

This was in February of 1893. Tesla's proposal was to disturb the uniform charge distribution on the surface of the earth and observe the period of the resultant oscillations as the charge proceeds back to its state of equilibrium.

[Side Note: It is fascinating to notice that, the Irish Physicist G.F. Fitzgerald (1851-1901) examined the possibility of earth resonances also, in 1893.[15][16] It would be interesting to know whether Fitzgerald had knowledge of Tesla's London Lectures of 1892 and whether he had access to the 1893 Tesla Speeches. (The full text of Tesla's IEE Lecture was published serially in London between April 22nd to June 24th of 1892.) Apparently Sir Oliver Lodge (1851-1940), who had missed the London lectures,** even attempted (unsuccessfully) to detect terrestrial resonances.[17] Interestingly, Lodge had obtained oscillations in a 5 centimeter diameter metal sphere as early as 1890.[18] The analytical details for an isolated, charged spherical oscillator were treated by Tesla's contemporaries, J.J. Thompson[19] (who showed that the oscillation from pole to pole of a charge upon a conducting sphere causes heavily damped radiation whose wavelength is 1.4 times the diameter of the sphere[20]), Henri Poincare, American Physical Society founder A.G. Webster,[21] A.H. Love,[22] Peter Debye,[23] and H. Bateman.[24] Subsequently, Max Abraham[25] extended the spherical oscillator treated by Thompson to include the natural oscillations of a conducting prolate spheroid. More modern treatments of the transient oscillations of charged isolated spheres are given by Page and Adams,[26] Stratton,[27] Carslaw and Jaeger,[28] Smythe,[29] Schelkunoff,[30] and Jackson.[31] A brief review is presented in an attached Appendix to this paper. The problem of concentric spherical shell *cavity* resonances was not solved analytically until modern times in the publications of W.O. Schumann,[32][33][34] nor observed experimentally until the work of Konig,[35][36] Balser and Wagner,[37] and others.]

It appears that Tesla's Colorado Springs experiments were specifically intended to carry out his proposal to disturb the earth's charge and observe the oscillation period as the charge distribution goes

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*This is the very technique outlined by Tesla in his RF oscillator and *single terminal* lamp apparatus, US Patent #454,622.

**"I Well remember the time when, as a young man, you aroused the attention and excited the enthusiasm of London scientific men by the demonstration of high tension electricity which you gave at the Royal Institution of Great Britain. Those experiments produced results which exceeded anything previously accomplished up to that time... Unfortunately, I did not see this demonstration, for I was ill at the time, but I saw your apparatus afterwards...", Oliver Lodge, May 26, 1931.

to equilibrium.

Tesla's Own Description Of The Experimental Observations

In 1904, Tesla was invited to contribute an article on his recent research, to be published in a special thirtieth anniversary issue of Electrical World. (It was also republished by McGraw-Hill as an Appendix in Tesla's book, Experiments With Alternate Currents.) Listen as he describes the events building up to the observations which he interpreted as standing waves:

> "Towards the close of 1898 a systematic research, carried on for a number of years with the object of perfecting a method of transmission of electrical energy through the natural medium, led me to recognize three important necessities: First, to develop a transmitter of great power; second to perfect a means of individualizing and isolating the energy transmitted; and, third, to ascertain the laws of propagation of currents through the earth and the atmosphere...
>
> In the middle of June (1899), while preparations for other work were going on, I arranged one of my receiving transformers with the view of determining in a novel manner, experimentally, the electric potential of the globe and studying its periodic and causal fluctuations. This formed part of a plan carefully mapped out in advance. A highly sensitive, self restorative device,* controlling a recording instrument, was included in the secondary circuit, while the primary was connected to the ground and an elevated terminal of adjustable capacity. The variations of potential gave rise to electric surgings in the primary; these generated secondary currents, which in tern affected the sensitive device and recorder in proportion to their intensity. The earth was found to be, literally, alive with electrical vibrations, and soon I was deeply absorbed in this interesting investigation...
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> In the latter part of the same month I noticed several times that my instruments were affected stronger by discharges taking place at great distances than by those nearby. This puzzled me very much. What was the cause? A number of observations proved that it could not be due to the differences in the intensities of the individual discharges, and I readily ascertained that the phenomenon was not the result of a varying relation between the periods of my receiving circuits and those of the terrestrial disturbances. One night, as I was walking home with an assistant, meditating over these experiences, I was suddenly staggered by a thought. Years ago, when I wrote a chapter of my lecture before the Franklin Institute and the National Electric Light Association [see above], it had presented itself to me, but I had dismissed it as absurd and impossible. I banished it again. Nevertheless, my instinct was aroused and *somehow I felt that I was nearing a great revelation.*
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> It was the third of July - the date I shall never forget - when I obtained the first decisive experimental evidence of a truth of overwhelming importance for the advancement of humanity. A dense mass of strongly charged clouds gathered in the west, and towards the evening a violent storm broke loose which, after spending much of its furry in the mountains, was driven away with great velocity over the plains. Heavy and long persisting arcs were formed almost in regular time intervals. My observations were now greatly facilitated and rendered more accurate by the experiences already gained. I was able to handle my

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*Several configurations appear in the Diary: Capacitive multiplication, self excitation, and also a direct conversion (homodyne) receiver employing coherer detection. (See the accompanying paper.)

instruments quickly and I was prepared. The recording apparatus being properly adjusted, **its indications became fainter and fainter with the increasing distance of the storm, until they ceased altogether.** I was watching in eager expectation. Surely enough, in a little while **the indications again began, grew stronger and stronger and, after passing through a maximum, gradually decreased and ceased once more.** Many times, in regularly recurring intervals, the same actions were repeated until the storm which, as evident from simple computations, was moving with nearly constant speed, had retreated to a distance of about 300 kilometers. **Nor did these strange actions stop then, but continued to manifest themselves with undiminished force.** Subsequently, similar observations were also made by my assistant, Mr. Fritz Lowenstein*, and shortly afterward several admirable opportunities presented themselves which brought out, still more forcibly, and unmistakably, the true nature of the wonderful phenomenon. No doubt whatever remained: I was observing stationary waves.

As the source of disturbances moved away the receiving circuit came successively upon their nodes and loops. Impossible as it seemed, this planet, despite its vast extent, behaved like a conductor of limited dimensions."(38)(39)

It is of great fortune that, in addition to these published remarks, we also have the private impressions recorded in his Diary the following day:**

"July 4, 1899

Observations made last night. They were such as not to be easily forgotten, for more than one reason. First of all, a magnificent sight was afforded by the extraordinary display of lightning... The storm began to be perceptible at a distance as it grew dark and continuously increased. An instrument (rotating coherer) was connected to ground and a plate above ground, as in my plane of telegraphy, and a condenser was used to magnify the effects transmitted through the ground. This *method of magnifying* secures much better results and will be described in detail in many modifications... The relay was **not adjusted very sensitively** but it began to play, nevertheless, when the storm was still at a distance of about 80-100 miles, that is judging the distance from the velocity of sound. As the storm got nearer, **the adjustment had to be rendered less and less sensitive** until the limit of the strength of the spring was reached, but even then it played at every discharge...

As the storm receded, the most interesting and valuable observation was made. It happened this way: **the instrument was again adjusted so as to be more sensitive** and to respond readily to every discharge which was seen or heard. It did so for a while, then it stopped. It was thought that the lightning was now too far and it may have been about 50 miles away. All of a sudden, the instruments began again to play, continuously increasing in

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*Concerning Fritz Lowenstein, co-founder and first vice-president of the IRE, inventor of the grid biased Class A amplifier, the shaped plate capacitor, etc., see the comments in our previous papers. There is a photograph showing Lowenstein, Tesla and other IRE dignitaries in the front of Anderson's Nikola Tesla on His Work with AC.

**In the Diary commentary for July 4,1899 (which was omitted in the Commentaries section of the english edition of the Colorado Springs Notes), Dr. Marincic notes that, "...the event which Tesla described on July 4 in the notes took place on July 3." (See Ratzlaff, J.T. and F.A. Yost, Dr. Nikola Tesla: Serbo-Croation Diary Commentary, Tesla Book Company, 1979, pg. 20-21.) By the way, the Diary indicates operation at 20.7 kHz on July 3rd.

strength, although the storm was moving away rapidly. **After some time, the indications again ceased, but half an hour later the instruments began to record again.** When it once more ceased, **the adjustment was rendered more delicate**, in fact very considerably so, still the instrument failed to respond, but half an hour or so it again began to play, and now **the spring on the relay was tightened very much** and still it indicated the discharges. By this time the storm had moved away, far out of sight. **By readjusting the instrument and setting it again so as to be very sensitive**, after some time it again began to play periodically. The storm was now at a distance greater than 200 miles at least. Later in the evening, ***repeatedly the instrument played and ceased to play in intervals nearly of half an hour***, although most of the horizon was clear by that time.

This was a wonderful and most interesting experience from the scientific point of view. It showed clearly the existence of ***stationary waves***, for how could the observations be otherwise explained? How can these waves be stationary unless reflected and where can they be reflected from unless from the point where they started? It would be difficult to believe that they were reflected from the opposite point of the Earth's surface, though it may be possible. But I rather think they are reflected from the point of the cloud where the conducting path began; in this case the point where the lightning struck the ground would be a nodal point. It is now certain that they *can be produced* with an oscillator. (This is of immense importance.)"

Tesla made a remarkable comment of note in a letter sent to George Scherff (who was in charge of Tesla's New York City laboratory during most of 1899) dated the same day as the above Diary entry:[(40)]

"July 4, 1899

We are getting messages from the clouds one hundred miles away, possibly many times that distance. Do not leak it to the reporters.

Yours sincerely, N. Tesla"

Later that month Tesla would also record in his Diary,

"July 28, 1899

In one instance, the devices recorded effects of lightning discharges fully 500 miles away, judging from the *periodical* action of the discharges as the storm moved away."

Stationary waves are alluded to in Tesla's famous Century Illustrated article of June, 1900, but not much embellishment is provided.[(41)] In Tesla's patent application of May 16, 1900, considerably more information, which may be of added help, is disclosed. The patent finally issued on April 18, 1905* as #685,956.

[Side note: As described in the Patent, Tesla reviews the contemporary understanding of ground

*From the Patent Wrappers, it appears that the Patent Examiner was befuddled by the application, and tried to link Tesla's observations to "zones of silence around a fog horn"! (Has anything changed in ninety-four years?!)

current communication and all prior techniques not employing wires between transmitter and receiver. At that time three methods had been used for "wireless telegraphy": conduction systems, induction systems, and Hertzian radiation systems.

(A) Earth Conduction Systems: In 1838 Steinheil was able to telegraph about 50 feet through the earth with a baseband signal using two ground connections at both transmitter and receiver. In 1842 Samuel F.B. Morse did the same thing across a river. Subsequently, James Bowman Lindsay (Dundee, Scotland; patented 1854), Highton, Dering, Stevenson, Preece, Smith and others were able to extend the range of operation up to three miles using the same principle of earth conduction. In the patent application Tesla wrote that the technique "which has been known for many years, is to pass, in any suitable manner, a current through a portion of the ground, by connecting two points of the same, preferably at a considerable distance from each other, the two terminals of a generator, and to energize by a part of the current diffused through the earth, a distant circuit which is similarly arranged and grounded at two points widely apart and which is made to act upon a sensitive receiver."

(B) Induction Systems: Electrostatic induction (baseband capacitive coupling) was used by Dolbear in 1882 between vertical wires - not unlike the 1872 patented system of Mahlon Loomis[42] who also employed vertical wires as early as 1864 (and who introduced the term "aerial"). A similar system was patented by Edison in 1885 to communicate to ships (baseband capacitive coupling) and a magnetic induction system to communicate to trains (baseband magnetic induction). In 1885, Preece was able to use two large rectangular loops to establish baseband magnetic inductive coupling over a transverse distance of almost five miles, between Gloucester and Bristol on the banks of the Severn in England. (He used two parallel rectangular loops, stretched on telegraph poles, fourteen miles long!)

(C) Hertzian Radiation Systems: Hertz published his results in 1887. (Tesla visited with Hertz in Bonn in 1892, and was a friend of Hertz's thesis advisor, Hermann von Helmholtz. In fact Helmholtz sought out Tesla on several occasions when he visited the physics community in the US.) Righi, Popov, Lodge, Bose and others were experimenting with such systems in the 1890's. At that time, Hertzian radiation was conceived to be an "electromagnetic disturbance propagated in straight lines in free-space", and (to quote the patent application) the Hertzian technique involved "directing the radiation upon a receiving apparatus".]

Since the earth connection is so important to what Tesla is about to disclose, he zeroes in on the baseband earth conduction systems. What he states in the patent application is that ground conduction in the lossy earth, "...mainly with the object of dispensing with return conducting wires, has been known and utilized for a long time." He continues on to say that, "It is also well known that electrical currents may be transmitted through portions of the Earth by merely grounding one end of the poles of a source..." The propagation is poor and he states that *this is all common knowledge*:

> "... all experiments and observations heretofore have concurred in confirming the opinion ... that the Earth behaves as a vast ocean which, though it may be locally disturbed ... remains unresponsive and quiescent in a large part or as a whole."

As an experimentalist, he is completely aware that you can't inject signals into the ground and expect significant global propagation!* (But, he is about to announce that he has discovered global terrestrial resonances in the 6 Hz to 20 kHz range.) First, he sets the scene for interpreting his observations:

> "Still another fact, now of common knowledge is that, when electrical waves or oscillations are impressed upon such a conducting path as a conducting wire, reflection takes place, under certain conditions, from the ends of the wire and, in consequence of the interference of the impressed and reflected oscillations, the phenomenon of "stationary waves", with maxima and minima in definite fixed positions is produced. In any case the existence of these waves indicates that some of the outgoing waves have reached the boundaries of the conducting path and have been reflected from the same."

He is ready, and he now proceeds to assert an astonishing discovery, which is related to the lightning observations under consideration:

> "Now, I have discovered that, notwithstanding its vast dimensions and contrary to all observations heretofore made, the terrestrial globe may, in a large part or as a whole, behave toward disturbances impressed upon it in the same manner as a conductor of limited size, this fact being demonstrated by novel phenomena which I shall hereinafter describe.
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> In the course of certain investigations which I carried on for the purpose of studying the effects of lightning discharges upon the electrical conduction of the earth, I observed that sensitive receiving instruments, arranged so as to be capable of responding to electrical disturbances created by the discharges, at times failed to respond when they should have done so. And, upon inquiring into the causes of this unexpected behavior, I discovered it to be due to the character of the electrical waves which were produced in the earth by the lightning discharges, **which had nodal regions following at definite distances the shifting source of the disturbances**. From data obtained in a large number of observations of the maxima and minima of these waves, I found their length to vary approximately from 25 to 70 kilometers [12 kHz** and 4.286 kHz respectively], and these results and theoretical deductions led me to the conclusion that waves of this kind may be propagated in all directions over the globe, and that they may be of still more widely differing lengths, the extreme limits being imposed by the physical dimensions and properties of the earth.
>
> Recognizing in the existence of these waves an unmistakable evidence that the disturbances created had been conducted from their origin to the most remote portions of the planet, and had been thence reflected, I conceived the idea of producing such waves in the earth by artificial means, with the object of using them for many useful purposes for which they are or might be found applicable."[(43)(44)(45)]

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*In US Patent applications filed on August 1, 1899 (#685,954) and November 2, 1899 (#685,956) [both written while he was at Colorado Springs], Tesla discusses the prior art for transmitting signals through natural media [also see Diary, June 4, 1899]: 1) Electromagnetic *radiation* through the air as investigated by Hertz, 2) Electro-magnetic *induction* between large loops [also see Diary June 5, 1899], 3) "Ground currents *diffused* through earth".

**Surprisingly close to Hill's broad spectrum for lightning, with a peak at 11.2 kHz.

On January 7, 1905, Tesla again picks up the thread that lightning observations implied the detection of standing waves, which in turn imply propagation to the antipode and back, and he writes,

> "But the fact that *stationary waves* are producible in the earth is of special and, in many ways, still greater significance in the intellectual development of humanity... It affords a positive and uncontrovertible experimental evidence that the electric current, after passing into the earth travels to the diametrically opposite region of the same and rebounding from there, returns to its point of departure with virtually undiminished force. The outgoing and returning currents clash and form nodes and loops similar to those on a vibrating cord. To traverse the entire distance of about twenty-five thousand miles, equal to the circumference of the globe, the current requires a certain time interval, which I have approximately ascertained. In yielding this knowledge, nature has revealed one of its most precious secrets, of inestimable consequence to man. So astounding are the facts in this connection, that it would seem as though the Creator, himself, had electrically designed this planet just for the purpose of enabling us to achieve wonders which, before my discovery, could not have been conceived by the wildest imagination...
>
> Over five years have elapsed since that providential lightning storm on the third of July, 1899, of which I told in the article before mentioned,* and through which I discovered the terrestrial stationary waves; nearly five years since I performed the great experiment which, on that unforgettable day, the dark God of Thunder mercifully showed me in his vast awe-sounding laboratory."[(46)]

In a 1913 letter to the New York Press, Tesla wrote:

> "Now, the wonderful fact is, that notwithstanding its immense size, the earth responds to a great number of vibrations and can be resonantly excited just like a wire of limited dimensions. When this takes place there are formed on its surface stationary parallel circles of equal electrical activity, which can be revealed by properly attuned instruments."[(47)]

(But alas, how do we create the "properly attuned instruments" to reveal Tesla's observations?) When describing his "World System" of wireless transmission in 1919, Tesla would identify one "important discovery" as:

> "The Terrestrial Stationary Waves: This wonderful discovery popularly explained means that the Earth is responsive to electrical vibrations of definite pitch just as a tuning fork to certain waves of sound. These particular vibrations, capable of powerfully exciting the Globe, lend themselves to innumerable uses of great importance commercially and in many other respects."[(48)]

Again, when describing his "World System of Wireless Transmission of Energy", in 1929, Tesla would write:

> "The chief discovery which satisfied me thoroughly as to the practicability of my plan,

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*"The Transmission of Electrical Energy Without Wires," by Nikola Tesla, Electrical World and Engineer, March 5, 1904, pp. 429-431.

was made in 1899 at Colorado Springs, where I carried on tests with a generator of 1500 KW capacity and ascertained that under certain conditions the current was capable of passing across the entire globe and returning from the antipodes to its origin with undiminished strength. *It was a result so unbelievable that the revelation at first almost stunned me.*

I saw in a flash that by properly organized apparatus at sending and receiving stations, power virtually in unlimited amounts could be conveyed through the earth at any distance, limited only by the physical dimensions of the globe with an efficiency as high as ninety-nine and one-half per cent."[(49)]

This is consistent with his May 16, 1900 Patent Application:

> "The powerful electrical oscillations in the system E'CE [the resonator*], being communicated to the ground, cause corresponding vibrations to be propagated to distant parts of the globe, whence they are reflected and, by interference with the outgoing vibrations, produce stationary waves, the crests and hollows of which lie in concentric circles, relatively to which the ground plate E' may be considered to be the pole. The presence of these waves may be detected in many ways..."[(50)]

At this point we have quoted fairly extensively from his writings over a thirty year period, and believe that we have a fair representation of Tesla's ideas. It should now be clear (a) how *he* envisaged the experiment, (b) what he was attempting to measure, (c) how he proceeded, and (d) what he believed he had discovered. We have discussed the receiving apparatus employed in these experiments, as described in his Diary, in a companion paper presented in these Proceedings. We now turn to the problem of wave propagation in the earth-ionosphere VLF waveguide.

II. RECEIVING CIRCUITS FROM THE DIARY

In a companion Paper presented in these Symposium Proceedings, we treat Tesla's receivers in considerable detail, and so we only call attention to their unique operation here. While Tesla employed a great variety of receivers, some quite advanced for the 1890's, his diary remarks center on circuitry utilizing coherers. For reference purposes, Figure 1 shows a typical Diary receiving circuit. Again, as with most of Tesla's equipment, the circuit is deceptively simple. As discussed in the companion paper, the physics involved in its operation is at the foundation of Armstrong's later

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*"The ground connection should be made with great care... In any event, ...the total length of conductor from the ground plate E' to the elevated terminal E should be equal to one-quarter of the wavelength of the electrical disturbance in the system E'CE, or else equal to that length multiplied by an odd number. This relation being observed, the terminal E will be made to coincide with the points of maximum pressure in the secondary or excited circuit, and the greatest flow of electricity will take place in the same." [US Patent #787,412. Filed: May 16, 1900; Issued: April 18, 1905.]

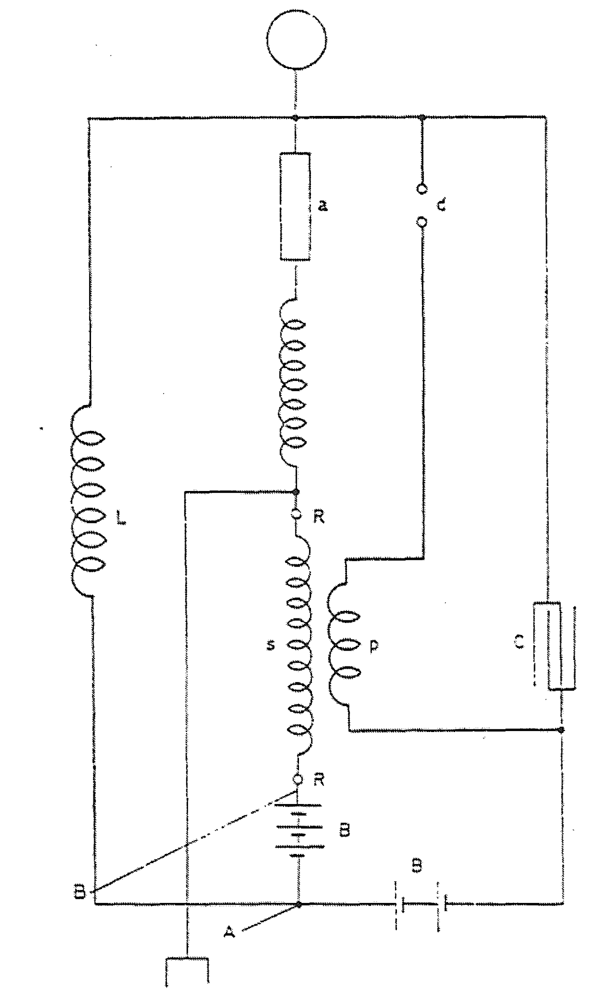

Figure 1. Final version of Tesla's receiver. September 17, 1899. (CSN, pg. 188.)

discovery of the regenerative receiver.

III. LIGHTNING IN THE EARTH-IONOSPHERE WAVE GUIDE

It is clear that Tesla's *receiving* circuits - at least the ones described in the Diary (1899) - were operating in the VLF/LF range: Probably from as low as a few kHz to as high as a few hundred kHz. It is also clear that *he believed* that he was observing a stationary wave pattern anchored to the moving electrical storm.

Standing waves require the interference of a forward and a backward wave or, in the case of the monopole over a radial ground screen, an outward and an inward wave. The presence of this phenomenon on radial ground screens surrounding AM broadcast antennas was pointed out to the authors in 1979 by Allen Christman. We submitted the idea to the AFOSR and a numerical study was subsequently funded at Ohio State. Physically, in the region around the base of a vertical monopole on a circular disk, there exist outwardly radiated waves and waves reflected from the impedance discontinuity at the rim of the groundplane. Consequently, the interference between the two causes an observable SWR pattern on the ground screen (whose modification permits some degree of control of the high angle radiation). The VSWR pattern can be clearly seen in Richmond's publication.[51] (See his Figure 12, where the ground current distribution shows the interference of two counter propagating waves.) While the thought occurs that Tesla may have seen something similar from either lightning discharges or from his own tower, this was probably not the case.

Another form of commonly observed interference also occurs in the medium frequency AM broadcast range. During nighttime hours, the received signal consists of two components - a ground wave signal and a sky wave signal. See Figure 2. At certain distances these two components are of the same order of magnitude and will actually interfere with one another, causing serious fading and distortion. The annular region surrounding the transmitter where this self interference starts to occur, and cause unreliable communication, is called the incipient "fade wall". Merely increasing the transmitter power will not push this "fade wall" further out, since both the ground wave and the sky wave will increase proportionately. Is it possible that Tesla observed a similar interaction of VLF surface waves and skywaves?

The VLF Waveguide

At VLF the lower regions of the ionosphere and the surface of the earth behave as the

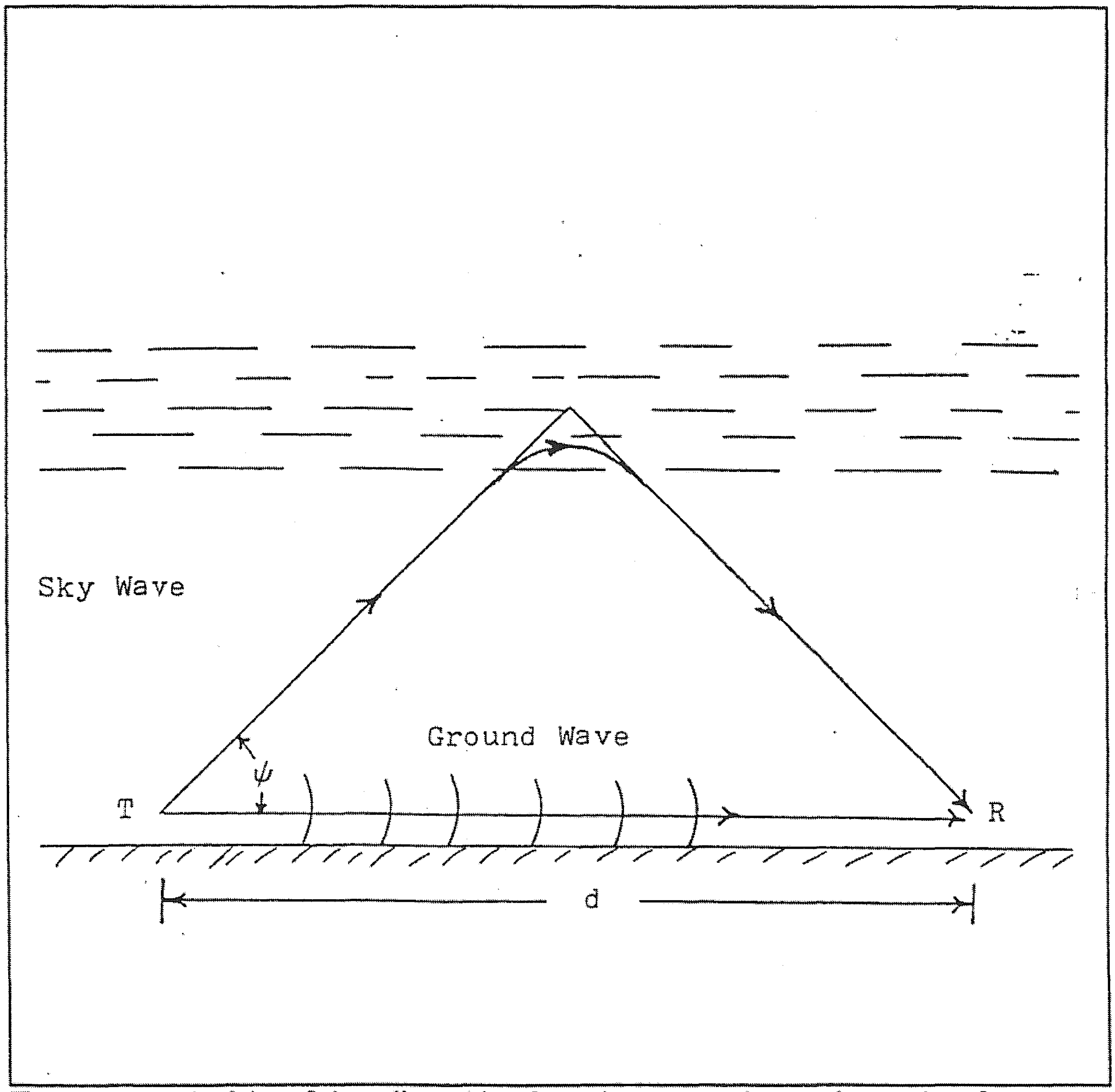

Figure 2. Incipient fade wall resulting from sky wave and ground wave interferrence.

boundaries of a waveguide. The ground conductivity at VLF ranges between .01 millimhos/m (ice sheets in Greenland and Antarctica*) to 5000 millimhos/m (seawater),** and the conductivity of the upper plate (the ionosphere) is on the order of 0.1 millimhos/m.

Apparently the first to formally investigate a concentric spherical shell earth-ionosphere*** waveguide model was G.N. Watson,[52] in 1919. Watson was able to transform his slowly converging series solution of the wave equation, subject to the boundary conditions, into a residue sum corresponding to waveguide modes. Concerning Watson's model, Wait has remarked that, "For frequencies in [the 20-40 kHz] range some 10 to 30 modes would be excited and if the complete mode sum were considered, the calculated field strength verses distance curve using such a model *would show many rapid and violent undulations*."[53] (This would seem to be consistent with Tesla's observations.) However, Wait goes on to note that, "Such a behavior is *not observed***** under normal conditions and this fact alone is sufficient cause to reject this model even from a phenomenological viewpoint."[54] Perhaps this dismissal was, at least for stochastic sources (such as lightning excitation), too hasty. Let us re-examine the model from a somewhat different physical perspective (coherence theory), which will be evident below.

An Informal View of Guided Waves

Consider the limiting case of a simple sharply bounded parallel-plane waveguide with conductors on the top and bottom. The formal solution of the boundary-value problem leads to a superposition of propagating *modes* if the separation distance is greater than a half wavelength at the carrier frequency and the signal is quasi-monochromatic. These modes can also be expressed as a

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*Think of it as "frozen sand".

**The FCC Ground Conductivity Chart, [FCC Rules and Regulations, § 73.190 (Figure R3)], gives the effective ground conductivity for the plains of eastern Colorado as 15 millimhos/m, rising to 30 millimhos/m in central Kansas.

***While the idea of a conducting ionized shell surrounding the earth goes back to Lord Kelvin, and to Tesla's lectures of the early 1890's, it was first employed to explain Marconi's North Atlantic transmission (of December, 1901) by A.E. Kennelly in March of 1902 and later that same year by Oliver Heaviside (and with subsequent modifications by Eccles in 1912). The term was coined by Sir Robert Watson-Watt and its height was experimentally measured by Sir Edward Appleton in 1924, and by Breit and Tuve in 1925. (There is a tragic historical sidelight, concerning the E layer, Lee de Forest and G.W. Pierce circa 1910-1912, in the American Journal of Physics, Vol. 44, 1976, #12, pp. 1219-1220.)

****Apparently this is not quite so. After preparing this paper, we located the paper by Weeks, which evidently supports the observations asserted by Tesla.

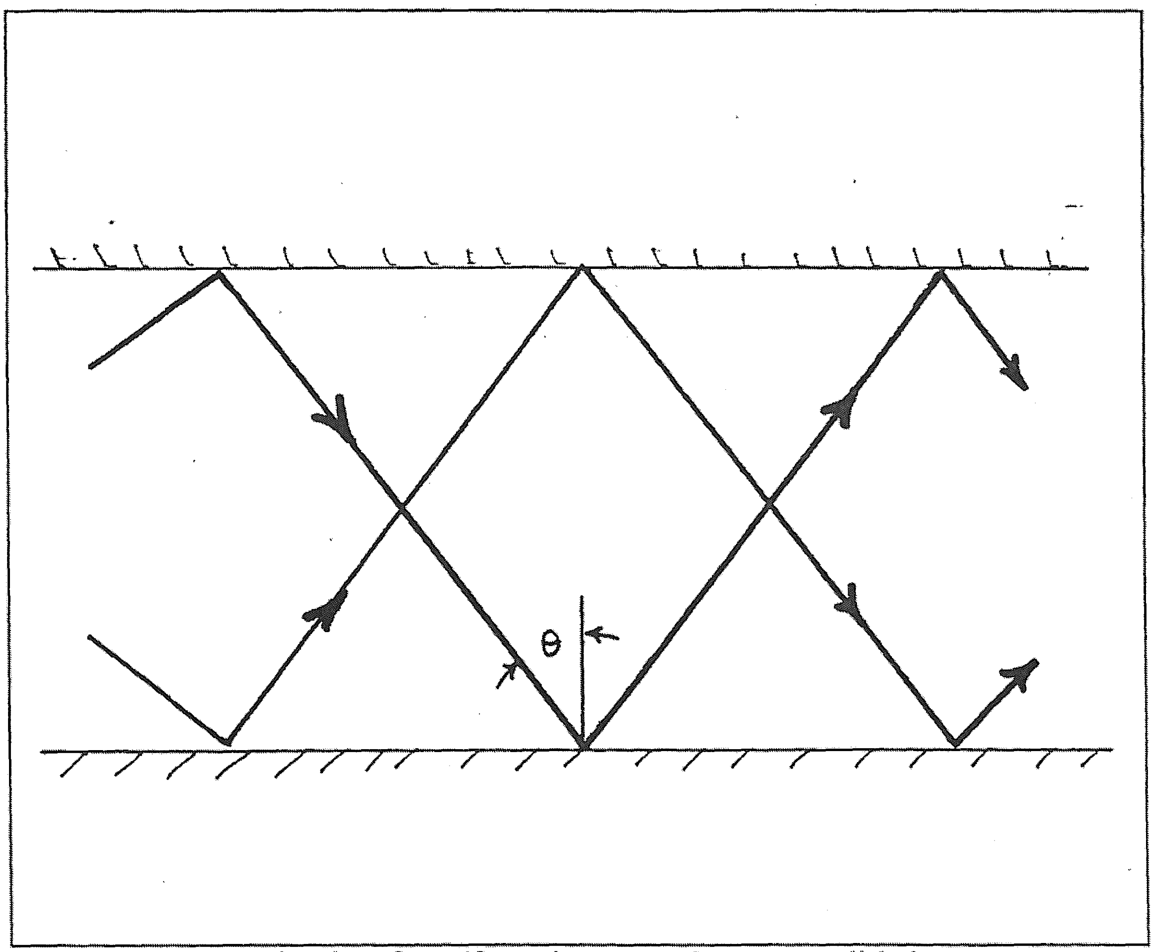

Figure 3. Ray directions for uniform plane waves between parallel planes.

superposition of uniform plane waves propagating along zig-zag paths between the walls.[55][56][57] The TM modes, for example, may be visualized in terms of plane waves bouncing along between the two planes at such an angle that the interference pattern maintains the boundary condition $E_{tan} = 0$ on the upper and lower planes. When the spacing is exactly a half wavelength, the waves travel back and forth across the guide with no longitudinal propagation. This is called "Transverse Resonance". (See Appendix III below.) For shorter wavelengths, longitudinal propagation occurs.

Ramo, Whinnery and Van Duzer demonstrate that the plane waves incident at some angle θ onto a conducting boundary can easily be re-written, in the parallel plane case, as expressions *identical* to those obtained in a formal waveguide solution.[58] (See Figure 3.) This informal approach strengthens our physical picture of propagation in waveguides and lends insight to the formal boundary-value solution of the wave equation in terms of propagating modes.

Propagation Attenuation

Interestingly, the same simple picture also permits the inclusion of propagation attenuation losses. The losses (for the Earth-Ionosphere waveguide) are assumed to exist entirely in the upper (sky) and lower (ground) "walls" of the guide. The current per unit width, flowing axially along the walls, is found from the tangential magnetic field strength at the walls

$$\vec{J} = \vec{n} \times \vec{H} \tag{1}$$

where the unit normal vector is directed inward at the guide walls.[59] When the wall has a finite conductivity, it possesses a surface impedance

$$Z_w = R_s\,(1+j) \tag{2}$$

where the surface resistivity R_s is expressed in terms of the conductivity σ and the skin depth [$\delta = 1/\gamma \approx (\pi f \mu \sigma)^{-1/2}$ for conductors] as

$$R_s = \frac{1}{\sigma\delta} \qquad \textit{Ohms per square} \tag{3}$$

which is the resistance of a square sheet of the medium, of thickness (depth) δ, as measured between two opposite edges. The propagating power falls off as $P(z) = P_o\, e^{-2\alpha z}$ and the power lost per unit length along the guide due to i^2R losses is determined from Joule's law as

$$\frac{dP(z)}{dz} = -2\alpha P(z) = \frac{R_s}{2}\oint_{walls} \vec{J}\cdot\vec{J}^*\, d\ell \tag{4}$$

which may be solved for the attenuation constant α in Np/m.

The model, like physical optics, provides a simple heuristic description for several characteristic features of waveguide transmission lines. It permits a determination of the spatial behavior of the wall surface currents - in our case, the VLF earth-ionosphere waveguide *ground current*. And, it also describes a mechanism for attenuation and wave interference.

Lightning In The Earth-Ionosphere Waveguide

Rather than considering the customary mode theory for lightning excited wave propagation in the earth-ionosphere waveguide, let us attempt to exploit the informal concept just offered. Slater presents a physical picture for the "radiation field" of a dipole in a rectangular waveguide, which utilizes the method of images.(60) A dipole in a parallel plane waveguide has two images, one in each of the two walls, and these images in turn form images. The radiation from the source plus the set of all images will automatically satisfy the boundary conditions on the waveguide walls. (According to Slater, this technique for treating waveguide excitation follows from an unpublished note by J.L. Synge and a memo by Sergi Schelkunoff.(61))

The simple model (letting the source be a short vertical dipole located on the ground, observed at some other point on the ground, and assuming the walls to be perfectly conducting) has been used to represent the lightning excitation of the VLF waveguide. Davies has written, "To an observer on the ground, the signal would appear to come from the dipole plus a whole series of images in the ground and in the ionosphere."(62)(63) According to Wait, "These images are located at ±2H, ±4H, ±6H, etc., and all have equal signs and magnitudes because of the assumed perfect conductivity of the walls."(64) *The ensemble of* ***coherent****, in-phase, time-harmonic (CW), mirror reflected, vertically polarized sources forms a broadside array, radiating down the guide.*

For such an *infinite* array of discrete image elements, the source distribution may be substituted for by an equivalent continuous (uniformly distributed) line element of current stretching from the ground to the ionosphere.(65) Wait points out that the substitution is valid for observation distances which are large compared to the plane separation, H. Such a uniform line source possesses a propagating field proportional to $H_0^{(2)}(\beta\rho)$, the Hankle function of the second kind and argument $\beta\rho$, which asymptotically approaches

$$\sqrt{\frac{2}{\pi\rho}}\, e^{j\frac{\pi}{4}}\, e^{-j\beta\rho} \tag{5}$$

in the far zone. This is recognized as a radially (outward) propagating cylindrical wave, between the planes of the waveguide, that falls off smoothly as $\rho^{-\frac{1}{2}}$.

Returning to the incremental sources, we note that the fields of the classic short vertical element with a time-harmonic uniform electric current distribution are expressed as:

$$H_\varphi = \frac{I_o \ell}{4\pi} e^{-j\beta r} \left[\frac{j\beta}{r} + \frac{1}{r^2}\right] \sin\theta \tag{6}$$

$$E_r = \frac{I_o \ell}{4\pi} e^{-j\beta r} \left[\frac{2\eta}{r^2} + \frac{2}{j\omega\epsilon r^3}\right] \cos\theta \tag{7}$$

$$E_\theta = \frac{I_o \ell}{4\pi} e^{-j\beta r} \left[\frac{j\omega\mu}{r} + \frac{1}{j\omega\epsilon r^3} + \frac{\eta}{r^2}\right] \sin\theta \tag{8}$$

where the symbols have their usual meanings. These expressions are valid *everywhere*, right down to just outside the surface of the source itself. They can be used in the near zone as well as the far zone. We suppose that the images may be described by such sources. Further, we assume the concentric spherical shell waveguide (and images) shown in Figure 4. The magnetic field at point P, a distance d along the earth from the source, will be calculated as a superposition of the fields from the primary source (which we suppose may be attenuated by the Sommerfeld attenuation function, i.e.- a Norton surface wave) plus the array of image sources. To be sure, the conceptual model is crude, but the summation of fields should give results approximating a formal mode analysis. To this point we have been more-or-less in accordance with convention.

The approach is consistent with the geometric optic series presented by Galejs.[66] He notes that the ground wave and a *single* pair of images (sky waves) "approximate quite closely the mode representation of the near fields... and is quite satisfactory for explaining a number of near field measurements."[67] One wonders why this would be so. Why isn't it necessary to perform the doubly infinite sum over *all* the images to obtain useful results? The infinite summation may be required to provide the exact amplitude of the fields, but it appears unnecessary, as Galejs states, for obtaining the characteristic behavior of the observed field variations (Tesla's observed amplitude ripples, for example). We have a suggestion for why this might be so. At this point we break with the conventional VLF lightning model assumed as a superposition of *coherent sources*.

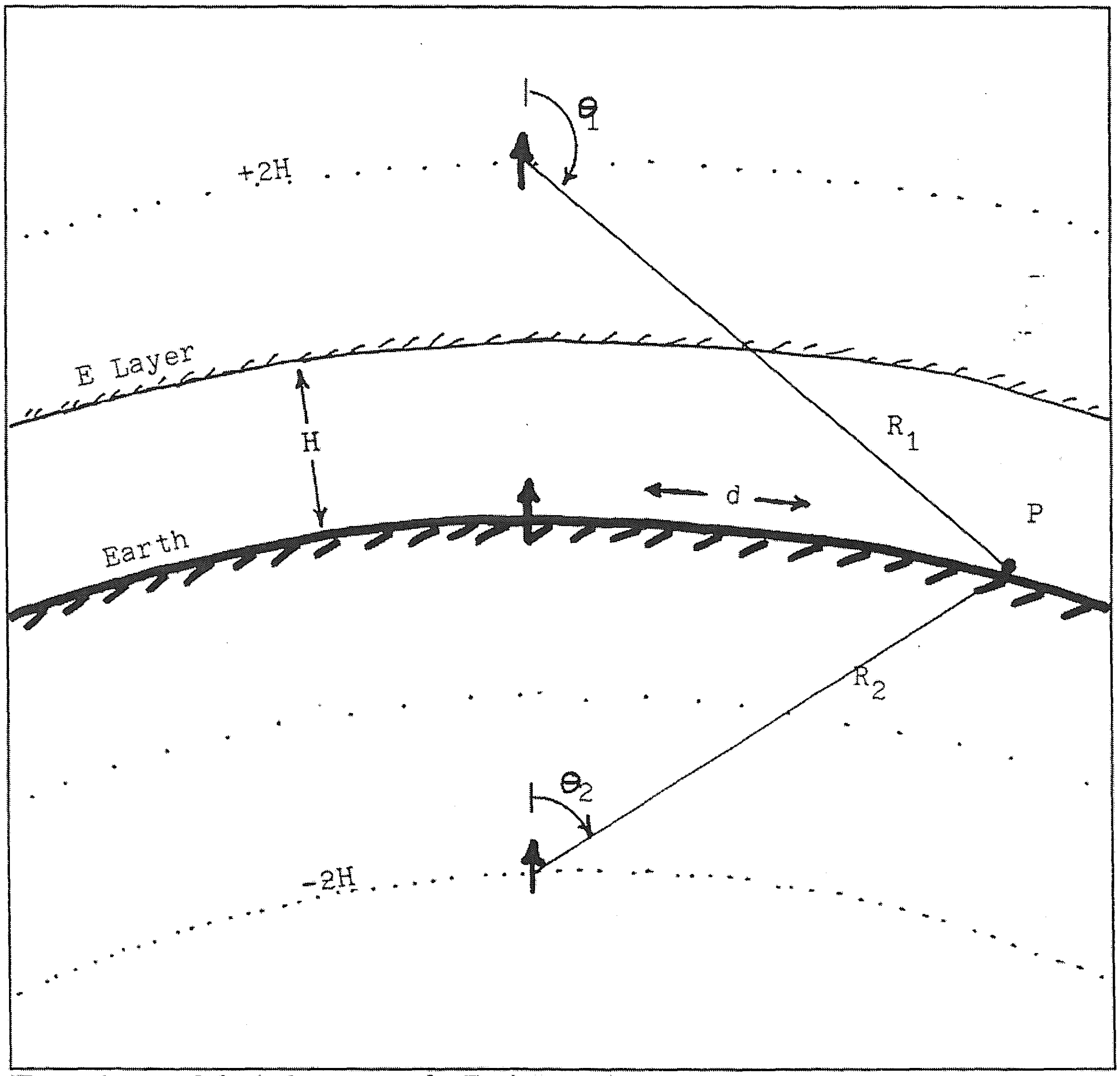

Figure 4. Spherical geometry for Earth-Ionosphere wave guide.

IV. INTERFERENCE AND THE CONCEPT OF COHERENCE

When broad-band or polychromatic radiation fields emanate from two sources, S_1 and S_2 (or a source and its mirror image), and are permitted to superpose at a distant observation point (as in Young's two slit experiment), they will interfere and form grating lobes (an antenna pattern) only if they are mutually coherent. In the theory of partially coherent light, if the wave trains from two separate quasimonochromatic sources propagate to some point P, the resultant field at P is the linear sum

$$\vec{E}(P,t) = K_1\vec{E}_1(P,t - \frac{r_1}{c}) + K_2\vec{E}_2(P,t - \frac{r_2}{c}) \tag{9}$$

and the resultant intensity, I, due to the interference of the two beams is

$$I(P) = \langle \vec{E}(P,t) \cdot \vec{E}^*(P,t) \rangle \tag{10}$$

where the angle brackets denote time average over a finite interval, which is long compared to the coherence time.* (Intensity, or irradiance, is the total power density for the wave.) Equations (9) and (10) lead to the well known general interference law for partially coherent beams:

$$I(P,\tau) = I_1 + I_2 + 2\sqrt{I_1 I_2}\, Re\, \{\gamma_{12}(\tau)\} \tag{11}$$

or, equivalently

$$I(P,\tau) = I_1 + I_2 + 2\sqrt{I_1 I_2}\, |\gamma_{12}(\tau)| \cos\, (\angle\gamma_{12}(\tau)) \tag{12}$$

where I_1 and I_2 are the intensities produced at P *separately* by the sources, τ is the propagation path difference (r_1-r_2) divided by c, and the *complex degree of coherence* is the normalized *mutual coherence function*, which is defined by from a cross-correlation:

$$\gamma_{12}(\tau) = \frac{\Gamma_{12}(P,\tau)}{\sqrt{I_1}\sqrt{I_2}} = \frac{\langle E_1(P,t)\; E_2^*(P,t + \tau)\rangle}{\sqrt{I_1}\;\sqrt{I_2}} \tag{13}$$

---

*Coherence time and natural line-width for a damped wave oscillator obey the reciprocal relation $\delta t \cdot \delta f \geq 1/(4\pi)$, equality holding for gaussian line shapes.

Note that $0 \leq |\gamma_{12}(\tau)| \leq 1$ as the source correlation varies from totally incoherent to perfectly coherent.*

Generally, the spatial distribution of I(P) goes through a series of maxima and minima (the interference fringes) depending on the propagation path difference. If $I_1 = I_2$, then the fringe "visibility" is proportional to the magnitude of the complex degree of coherence:

$$V = |\gamma_{12}| = \frac{I_{Max} - I_{Min}}{I_{Max} + I_{Min}} \tag{14}$$

(See the spectacular photos by Thompson in Born and Wolf,[(68)] also reproduced in Hecht and Zajac.[(69)]) If the beams are totally incoherent, $\gamma_{12}(\tau)=0$ and the intensities add linearly. There is then no interference. If, as in the case of classical antenna theory, the sources are completely coherent then the *intensities* do not add linearly, and the interference implied by Equation (12) is observed.

In general interference can occur only if the source separation is not greater than the *coherence length*, $\delta\ell = c\delta t \sim c/\delta f$ (which is infinite for classical antennas with monochromatic, time-harmonic fields). The disturbance at source 2 would then be strongly correlated with the disturbance at source 1. If the difference in propagation path length is greater than the coherence length, the sources will no longer coherently sum and interference effects will no longer be evident.

Impact of Coherence on Image Theory

The above discussion implies that sources with finite frequency bandwidth δf can interfere and produce phasor sums ("antenna patterns", or grating lobes) only within their correlation time intervals δt. The wave packets of Equation (9) must be present at P within this time window or the wave interference will "wash out". Put another way, "The average duration of a wave packet is δt and so two points on the wave packet of [the RF damped wave associated with the lightning discharge] separated by more than δt must lie on different contributing wave trains."[(70)] These are uncorrelated, and therefore won't produce an interference pattern.

Well, how long is δt for a lightning discharge? The Authors don't know. (The discharge times for Tesla coils are typically 100-300 μs.) We will suppose $\delta t \sim 667$ μs for natural lightning.

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*As an aside, note that the real part of the complex degree of coherence may be experimentally determined by separately measuring I(P), I_1(P), and I_2(P). Equation (11) then gives:

$$Re\{\gamma_{12}(\tau)\} = \frac{I(P) - I_1(P) - I_2(P)}{2\sqrt{I_1(P)}\,\sqrt{I_2(P)}} .$$

This would imply that propagation path *differences* of 200 km for separate rays could result in interference, i.e.- the images could coherently contribute provided their propagation path differences are less than 200 km. Geometrically this means that, for ionospheric heights (H_i) greater than 50 km, *none* of the images greater than n = 2 could coherently contribute to the interference pattern of a broadband source like lightning.* (H_i<200 km for n = 1 terms to remain coherent.) For smaller coherence times, the number of images required would be even less, and this would seem to support Galejs' comment, above, that only a *single* pair of images are satisfactory for explaining a number of measurements. We have used two pairs of images in the calculations below, which is probably more than actually required under these conditions.

Observing Partially Coherent RF Sources

Antennas, RF and partial coherence theory converged during the 1950's in the domain of radio astronomy. Radiation from a partially coherent source distribution (cosmic sources in radio astronomy, lightning and its waveguide images in the present application) may be decomposed into a completely coherent part and a totally incoherent component:

$$\begin{aligned} I(P,\tau) \;=\; & |\gamma_{12}(\tau)|\left[I_1(P) + I_2(P) + 2\sqrt{I_1(P)I_2(P)}\;\cos\left(\angle\gamma_{12}(\tau)\right)\right] \\ & + \left[1 - |\gamma_{12}(\tau)|\,\right]\left[I_1(P) + I_2(P)\right] \end{aligned} \qquad (15)$$

where the terms in the first line arise from the superposition of the beams from the coherent sources and the terms in the second line arise from the incoherent source beams.[71] The disturbance reaching the observation point, P, may be regarded as a *mixture* of coherent and incoherent signals

$$I_{tot}(P) \;=\; I_{coh}(P) + I_{incoh}(P) \qquad (16)$$

with the ratio

$$\frac{|I_{coh}|}{I_{tot}} \;=\; |\gamma_{12}(\tau)| \qquad (17)$$

We hypothesize that, whatever else may have been going on, Tesla's detecting instruments were

*In the monochromatic sinusoidal steady state, a purely time-harmonic source has perfect coherence an infinite coherence length. Consequently, the summation would have to extend over an infinite number of images - unlike the wide-band signals under consideration.

probably responding to the coherent component.

V. OBSERVING BROAD-BAND ENSEMBLES

The RF spectrum of a lightning discharge can hardly be called quasimonochromatic. Now, there are a whole variety of ways in which the broadening of line spectra may arise.(72) Energy-damping will broaden the spectral line-width of a classical oscillator. (This is called lifetime broadening). However random dephasing processes will also broaden the line-width without changing the energy-damping rate at all. The effect of a collection of randomly timed statistically independent RF pulses with the same mean frequency of oscillations will be a smearing out of the collective spectrum. We suppose that similar processes are occurring in lightning discharges.

As mentioned above, the RF spectrum of a lightning discharge is fairly broad. It extends well up into the VHF realm, with a peak in the VLF 5-12 kHz range. (Measured VLF spectra are filtered by the waveguide and, therefore, their low frequency shapes tend to depend upon the observation distance.) An amplitude spectrum based on measured data is given by Fitzgerald.(73) (Also see Hill,(74) Watt,(75) and Dennis and Pierce.(76)) Hill's cloud-ground lightning stroke analysis places the amplitude peak at 11.2 kHz with a half-power bandwidth of 12 kHz. It should be stressed, of course, that the individual spectra, like the discharge paths and currents for lightning strokes, will vary appreciably.

We have spent considerable time on trying to characterize the RF fields associated with wide-band signals. Let us now turn to the calculation of lightning induced ground currents such as Tesla's apparatus might detect.

Surface Current Determination

Without sacrificing too much, we suppose that the radiation component received from the coherent images of the lightning discharge can be represented as a quasimonochromatic, partially polarized radio wave. Letting r_n be the distance from the n^{th} source to the field point on the ground, and θ_n be the angle between the n^{th} incremental source's axis and the vector from the source to the field point, the resultant magnetic field strength, at the field point, is determined from the superposition of propagating waves

$$H_\varphi(P) = \frac{I_o \ell}{4\pi} \sum_{n=-m}^{+m} e^{-\alpha_n} e^{-j\beta r_n} \left[\frac{j\beta}{r_n} + \frac{1}{r_n^2}\right] \sin\theta_n \qquad (18)$$

where for the surface wave n = 0:

$$r_o = d$$
$$\theta_o = \frac{\pi}{2} \qquad (19)$$

and for the images:

$$r_{\pm n}(d) = \sqrt{(R_e)^2 + (R_e \pm 2nH_i)^2 - 2R_e(R_e \pm 2nH_i)\cos\xi}$$
$$\alpha_{\pm n} = 0 \qquad (20)$$
$$\sin\theta_{\pm n} = \frac{d}{r_{\pm n}}$$

where $d = R_e\xi$. The resulting field is seen to be a broadside phased array antenna pattern casting numerous side-lobes (maxima and nulls) along the walls, corresponding to stationary intensity fringes. This is a simple, linearly polarized, plane wave theory, with unity reflection coefficients that do not vary with propagation distance.

The waveguide lower surface (the ground) current density at the observation point may then be determined from the magnetic field strength by Equation (1). A plot of these calculations, for a primary source and *four coherent images* (n = ±2), gives the ground current graphed in Figure 5.

The incoherent images (out beyond the "lateral" coherence length), while contributing to the total intensity (and diminishing the visibility function), contribute nothing to the *interference* pattern. (We walked a long way just to say that!) Furthermore, the field contribution from the images for $n \geq 3$ will not arrive for at least another 2-3 milliseconds after the direct ray is incident on the observer. We believe that a coherer (an RF activated "on-off" switch) would ignore these late-time incoherent signals.

In the Figure, we have included earth curvature but assumed a constant E-layer height, H_i, on the order of 100 km, which is the "effective height" (He) used by the FCC in Part 73.190, Figure 6a, of the standards for good engineering practice published in the Rules and Regulations. (Typical VLF

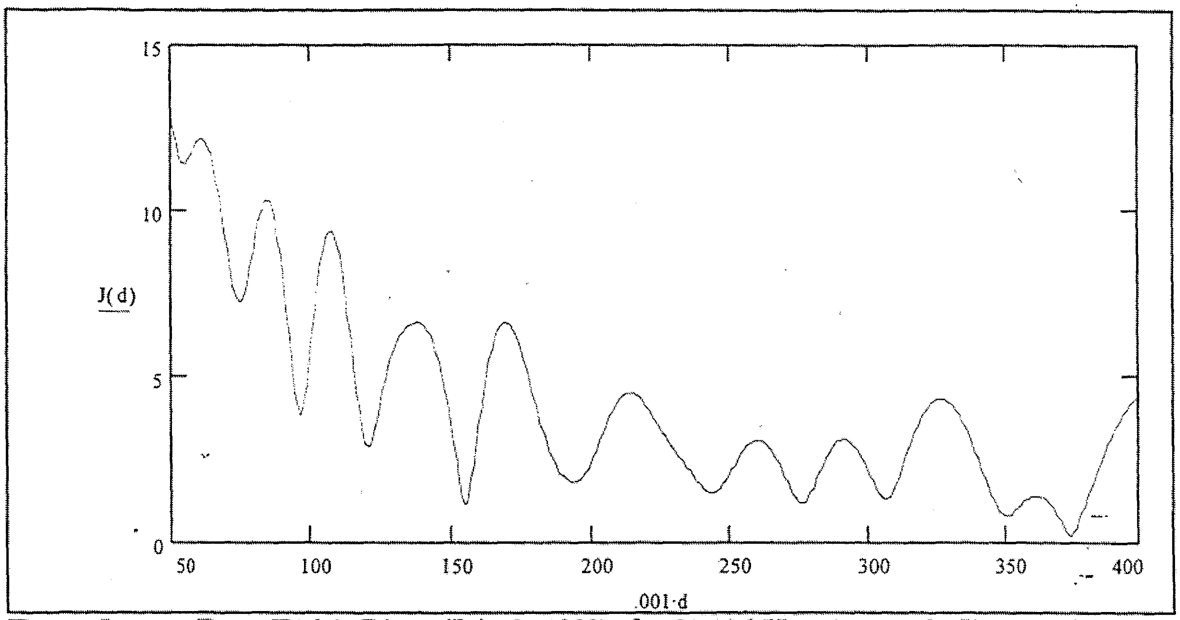

Figure 5. From Tesla's Diary (July 3, 1899): f = 21,136 Hz. Assumed: H_i = 105 km; α = 4.95 dB/Mm. This is a plot of surface current (A/m) vs. distance (in km).

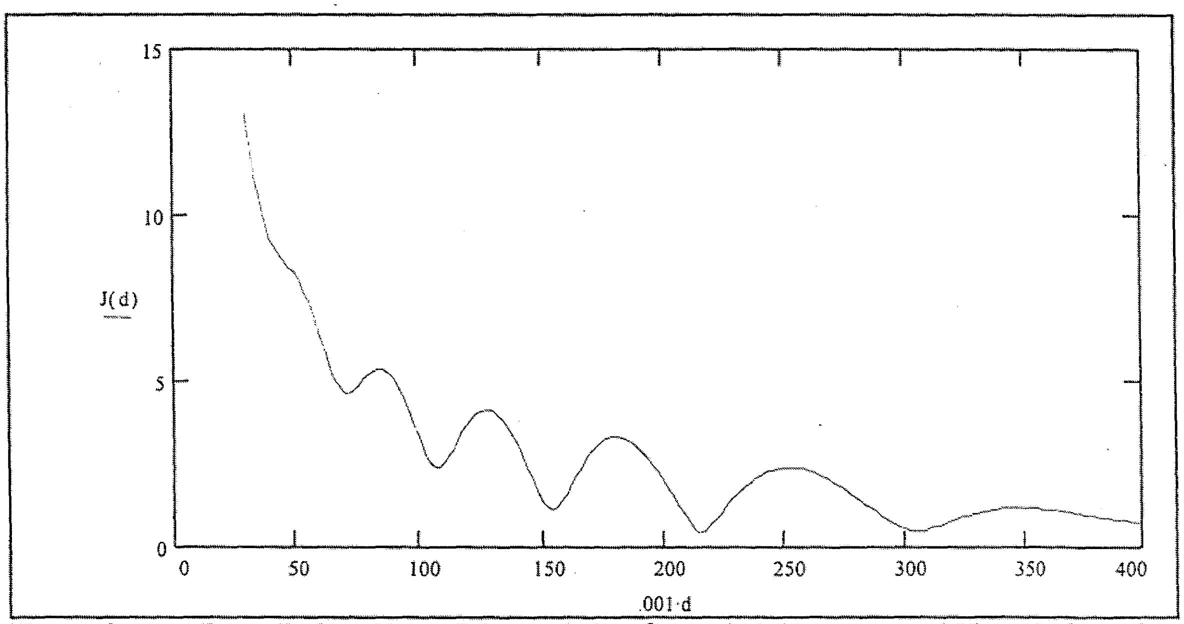

Figure 6. From Tesla's Diary (July 3, 1899): f = 11,800 Hz. Assumed H_i = 125 km; N = 2 image pairs, α = 3.5 dB/Mm. X-axis is distance to storm in km.

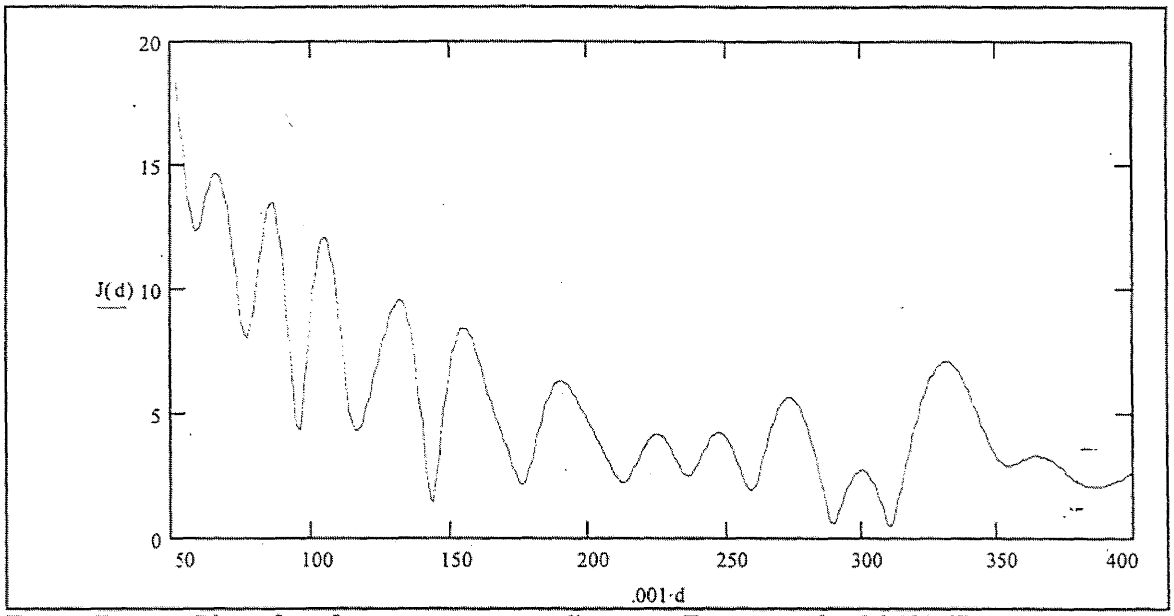

Figure 7. Plot of surface current verses distance. Frequency f = 26,500 Hz. Assumed parameters: H_i = 96 km, α = 5 dB/Mm, N = 4 images.

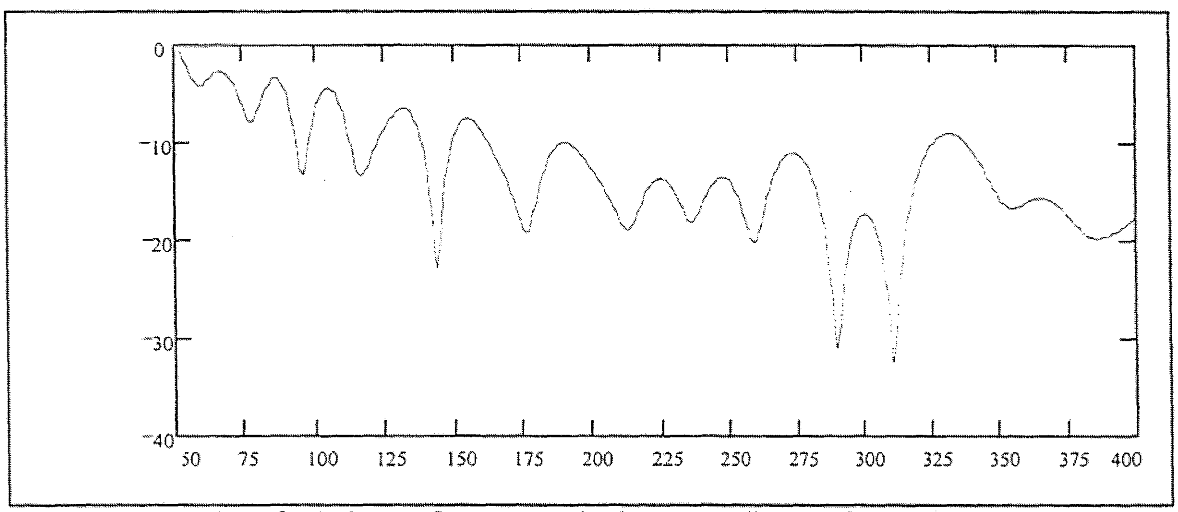

Figure 8. Plot of relative surface current in dB verses distance from reference point.

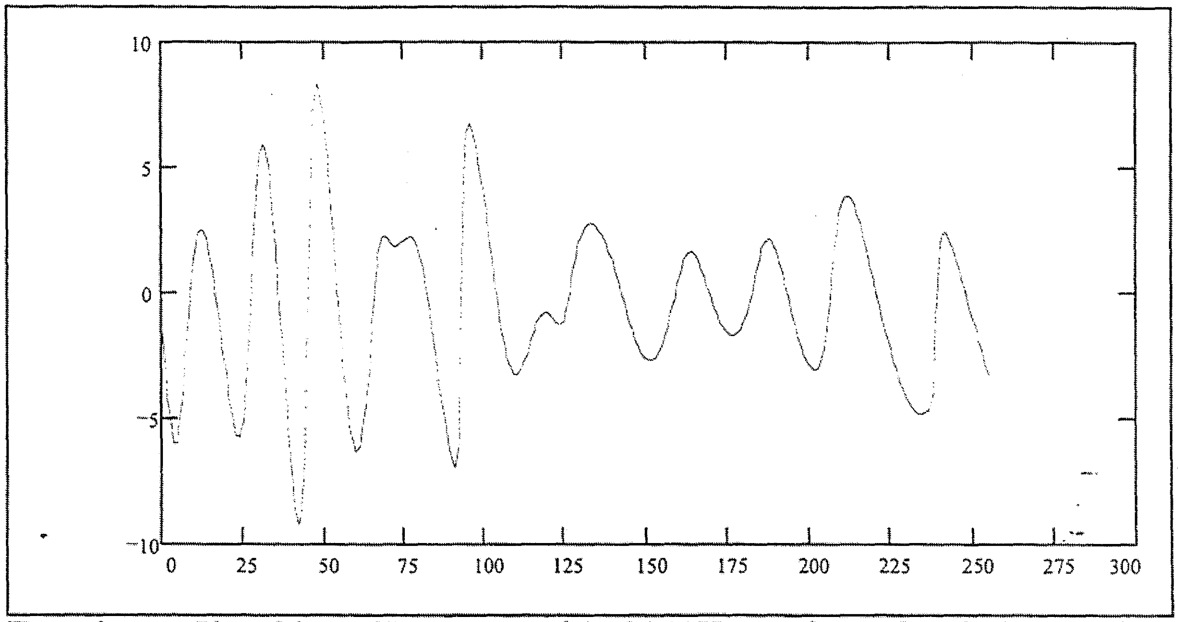

Figure 9. Plot of the "AC" component of the 26.5 kHz waveform. [The horizontal axis is in units of (d - 50) km.]

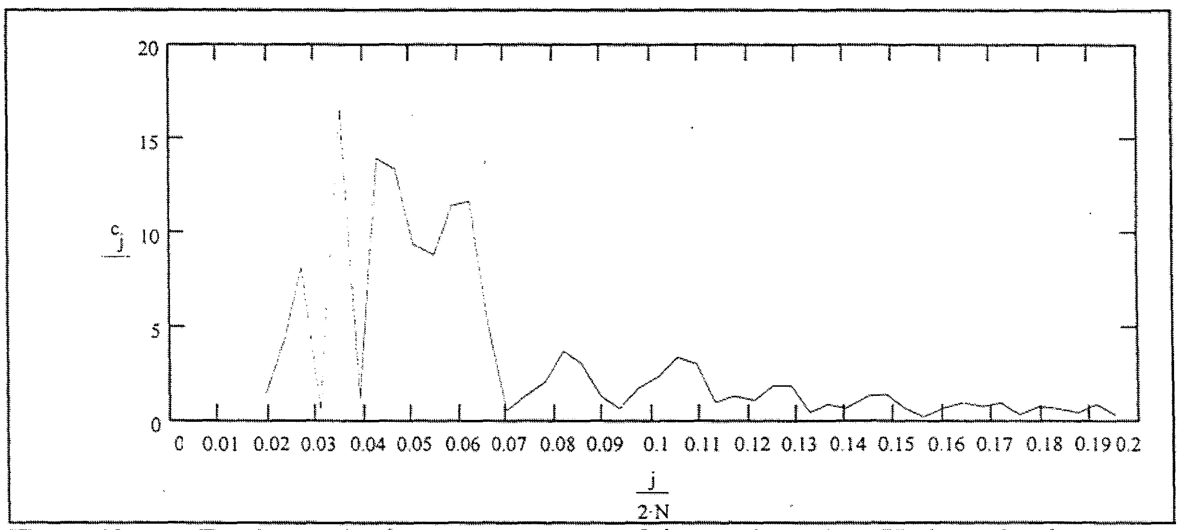

Figure 10. Fourier spatial frequency spectrum of the previous plot. Horizontal units are cycles/km. The distribution's center of gravity appears at x = 0.044.

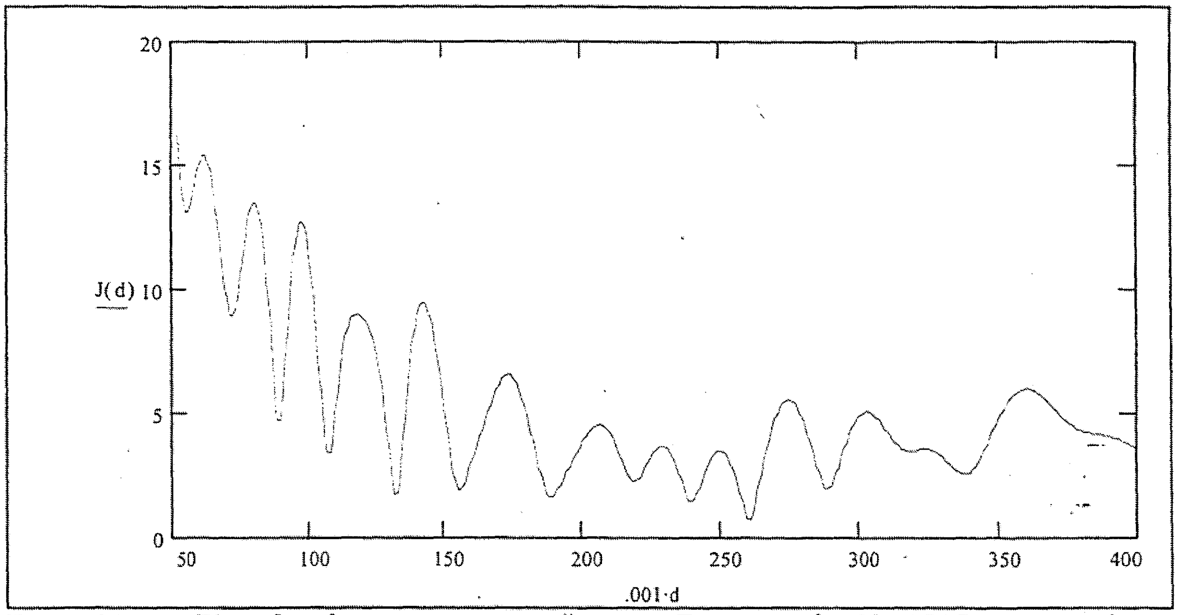

Figure 11. Plot of surface current verses distance. Frequency f = 28,125 Hz. Assumed parameters: H_i = 96 km, α = 15 dB/Mm, N = 4 images.

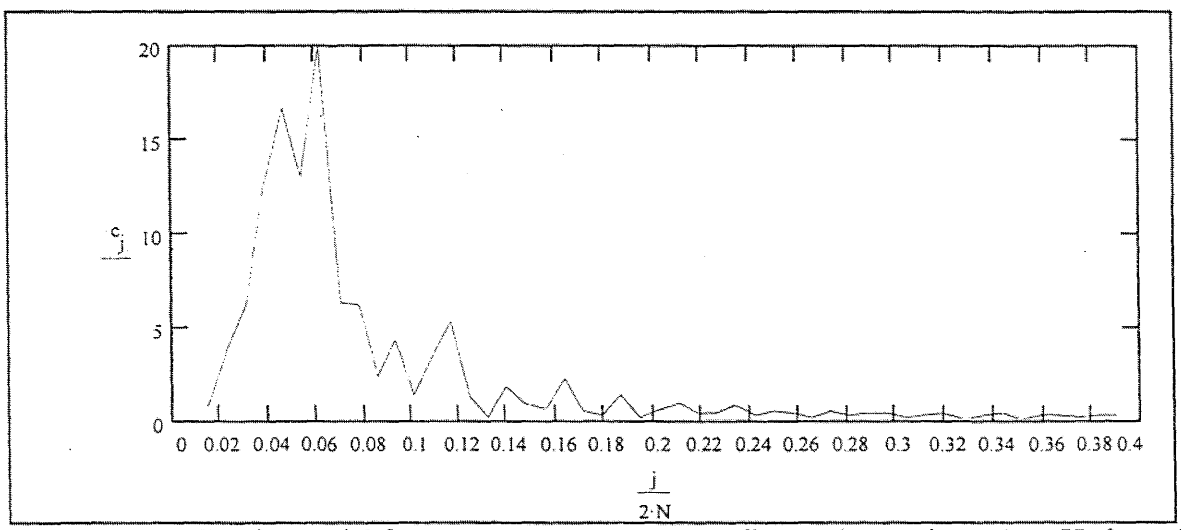

Figure 12. Fourier spatial frequency spectrum corresponding to the previous plot. Horizontal units are cycles/km. The distribution's center of gravity appears at x = 0.055.

authors have used from 65-130 km.) Conceivably, H_i might vary somewhat anisotropically outward from the lightning storm point of excitation, and this would introduce a propagation path-length shift in phase for the image sources. Further, the ionospheric and ground reflection coefficients have been taken as a real constant (unity), and this could be "fine tuned" by the reader in his own investigations.

Figure 5, although it involves the summation of only five terms (two pairs of images plus an attenuated direct ground wave), appears to be consistent with Wait's remark, above, that "... the calculated field strength verses distance curve using such a model *would show many rapid and violent undulations*." Why, then, does Tesla report observing such things (long before they were even predicted), and why are these not observed by others? Perhaps our remarks concerning time delays and the nature of coherer detection will shed some light on this issue. [From a publication that we came across when this paper was being submitted, as mentioned above, it appears that the "undulations" actually have been observed by other investigators. See Weeks.[77]]

Figures 5 and 6 are based on the information presented in Tesla's Diary on July 3, 1899. We believe the assumptions concerning effective E-layer height and propagation attenuation to be consistent with accepted practice. In the Diary, Tesla states that his receiver operated at 20,700 Hz, however the circuit values which he gives (L = 2.52 μH and C = 0.225 μF) would imply a frequency of 21.136 kHz, as employed in the plot of Figure 5. Tesla gives a frequency of 11,800 Hz, which was used in the second example, shown in Figure 6.

Figures 7-10 were calculated at 26.5 kHz, which is another Diary frequency. Figure 8 displays the relative amplitude variation in dB. Figure 9 is a replot of Figure 7 with the "DC" component of the spatially rippling wave removed. Figure 10 is a Fourier transform of Figure 9, to give an appreciation for the periodic spectra associated with the spatial frequency components present in the disturbance. Considered as a group with a center frequency at 0.044 cycles/km, the spatial wave of Figure 7 would have an "average" period of about 23 km. Similarly, the spatial distribution of Figure 11, which corresponds to another Diary frequency, would have an average period on the order of $\Delta x = 1/(0.055) = 18$ km.

Predictions for a Passing Storm

Now let a storm producing ground currents like Figure 7, for example, pass by and recede into the distance over the plains.* Again, we quote Tesla, who interpreted *the observations* to imply

*While the electrical discharges may be occurring randomly in time (but frequently throughout the life of the storm), we will assume that they are (at least with statistical regularity) anchored, more-or-less, to the "center of gravity" of the moving storm system. Meteorologists probably have a more that the lightning "had nodal regions following at definite distances the shifting source of the disturbances" (Patent #787,412). From the Figure it appears that the average distance between minima (or maxima) is approximately 20-30 km so that **such a storm moving with a speed of, say, 50 km/hr (approximately 30 mi/hr) would produce the more-or-less half hour signal phenomenon observed by Tesla.** On average, a set of maxima would be detected about every half hour. To be sure, there would be fluctuations in the observed time: their is "fm" and "phase noise" in the distribution, the storm's radial velocity might be changing, etc. But, we think it reasonable to allow Tesla some experimental literary license here. Is it any wonder that Tesla would write in his diary on July 4, 1899:

> "...repeatedly the instrument played and ceased to play in intervals nearly of half an hour, although most of the horizon was clear by that time."

Many plots like those above can be made for examining the model as frequency, ionospheric height, propagation attenuation, and reflection parameters are varied.

VI. OUR EXPERIMENTAL INVESTIGATION

Well, how do you measure this? How do you repeat Tesla's physical observation? We don't want to fool ourselves by becoming "armchair experimentalists". (There are plenty of those around - virtually none of Tesla's modern critics have ever built a Tesla coil *following the instructions he plainly teaches in his patents*!) As reported in the companion paper on Tesla's receivers, the instruments disclosed in the Diary were remarkably sensitive by early wireless standards, but their unique feature is their inherent sampling window response. This feature, along with the tuned resonators and regenerative feedback that were employed sheds great light on many of the assertions which Tesla published about his Colorado Springs experiments.

Our experimental observations of natural lightning effects, with reproductions of the actual Diary receivers, will be reported at the Symposium. You can expect some surprises.

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appropriate way to describe the situation. At wavelengths of 12-60 km (25 to 5 kHz respectively) random variations in the spatial disposition of the discharges, about the center of gravity, would provide a small "fm" to the spatial waveforms shown in the Figures.

VII. CONCLUSION

Our conclusion is simple. Tesla said, "No doubt whatever remained: I was observing stationary waves."(78) We think that he was, in fact, observing a VLF wave interference phenomenon.

In spite of the fact that many of the most outstanding men in the history of the scientific enterprise have honored Tesla, deeply, it is painful and astonishing to read the scorn and ridicule that, even today, is uttered against him. Taking the events of electrical science into perspective, the following would seem to be a fair and just assessment:

> "He was working in a virgin field. None had gone before him to pave the way or gain experience that would be helpful to him in designing his experiments or his machines. He was entirely on his own, working without human guidance of any kind, exploring a field of knowledge far beyond that which anyone else had reached."(79)

These physical experiments and discoveries were performed prior to the turn of the century! It is difficult to comprehend why, even after almost 100 years, misguided men of comparably smaller creativity would persist in singling out this brilliant engineer for irrational, misconceived, misleading ad hominem attacks.

VIII. A FINAL QUESTION

We conclude this investigation by posing another question similar to the one set forth above, that inspired our little study. In this paper we have tried to resolve the issue of periodic disturbances from electrical storms. Without appealing to the lunatic fringe, there was another enigmatic signal that was received during the summer of 1899. Tesla's description of the signal reception was published in a magazine article and as Chapter XIV in the technical book Polyphase Electric Currents, by British engineer Sylvanus P. Thompson:

> "...Even now, at times, I can vividly recall the incident, and see my apparatus as though it were actually before me... I was alone in my laboratory at night...The changes I noted were taking place periodically, and with such a clear suggestion of number and order that they were not traceable to any cause then known to me. I was familiar, of course, with such electrical disturbances as are produced by the sun,* Aurora Borealis and earth currents, and I was sure as I could be of any fact that these variations were due to none of these causes... Although I

*The sunspot cycle was a minimum in 1901, and the Zurich sunspot number was 10, or less, from 1898 to 1902.

could not decipher their meaning, it was impossible for me to think of them as having been entirely accidental... A purpose was behind these electrical signals; and it was with this conviction that I announced to the Red Cross Society, when it asked me to identify one of the great possible achievements of the next hundred years, that it would probably be the confirmation and interpretation of this planetary challenge to us... Absolute certitude as to the receipt and interchange of messages would be reached as soon as we could respond* with the number 'four,' say, in reply to the signal 'one, two, three.'"[80][81]

In a newspaper interview, Tesla said that his instruments recorded three distinct movements, and this sequence was repeated many times during the course of his observations.[82] [According to his note in the Harvard Illustrated Magazine, Tesla said that the Collier's Weekly and Thompson book statement (just quoted) had been published to "correct an erroneous report which had gained wide circulation".[83]] Twenty years later, Tesla wrote,

"Others may scoff at this suggestion or treat it as a practical joke, but I have been in deep earnest about it ever since I made the first observations at my wireless plant in Colorado Springs from 1899 to 1900... At the time I carried on those investigations there existed no other wireless plant on the globe other than mine, at least none that could produce a disturbance perceptible in a radius more than a few miles... The character of the disturbances recorded precluded the possibility of their being of terrestrial origin... As I then announced, the signals consisted in a regular repetition of numbers."[84]

The reader is cautioned not to blindly ridicule Tesla for these unusual comments. There is no knowledge to be found in that direction: Tesla was a careful experimentalist and observer. As we have asserted before, if he said that he observed something, then he saw *something*. But, what was it that he was he observing? Was it the occurrence of "whistlers"? Was it "the morning chorus"? (Both are natural VLF phenomena, which can be easily observed by anyone in his own home today.) Is there an alternative rational explanation?

Remember the time frame of these remarks. The Lowell Observatory, in Flagstaff, Arizona had been established by Percival Lowell only five years earlier (in 1894), ostensibly for Martian observations.** In 1902, Lord Kelvin, himself a believer in the Martian signals, proclaimed that he was in complete agreement with Tesla on this issue.[85][86] Sir Oliver Lodge was then attempting to detect RF solar emissions.[87] [Twenty years later, even Nobel (by then) Laureate Guglielmo Marconi

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*"One, two, three - but where, my dear Timaeus, is the fourth...?", Socrates, Plato: Timaeus and Critias, translated by D. Lee, Penguin Classics, 1977, p. 29.

**Schiaparelli discovered the "canali" in 1877, and Lowell (on who's 1905 calculations Pluto was discovered in 1930 by Clyde Tombaugh) mapped over 400 canals and published a "map" of Martian canals in 1901. Mars was in opposition, 35 million miles from the earth, during Tesla's Colorado Springs experiments.

would announce that he, too, had heard the signals from Mars.*] In spite of considerable opposition, Tesla would continue to maintain his opinion,

> "I base my faith [in civilized life on Mars] on the feeble planetary electrical disturbances which I discovered in the summer of 1899, and which, according to my investigations, could not have originated from the sun, the moon, or Venus. Further study since has satisfied me that they must have come from Mars."(88)

What are we to make of this? Upon occasion, his receivers registered a regular repetition of disturbances, and Tesla interpreted these as numbers. Now, ***what*** was *that* signal...??

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*Tesla's analysis was that Marconi's instruments were not sensitive enough and that Marconi had only observed undertones and long wave beats of wireless transmitters, in the 500-3500 Hz spectral region, which had been known of since 1906.

APPENDIX I

THE TRANSIENT OSCILLATIONS OF A CONDUCTING SPHERE

"But, the all important question was, how would the planet be affected by the oscillations impressed upon it?" Nikola Tesla*

In this Appendix, we record the transient field and surface (ground) current response of a perfectly conducting isolated sphere. The details of the solution are documented in the References cited above. (We have reviewed Schumann's solution for the Earth-Ionosphere concentric spherical shell resonator in the Appendix to a previous Symposium paper.)

Consider a perfectly conducting sphere which has been immersed in a steady uniform electric field. An initial static spatial charge distribution, of the form $\sigma(a,\theta) = \sigma_o \cos\theta\, \delta(r-a)$, is thus induced upon the conducting sphere. "The field is supposed suddenly destroyed, and the charge then oscillates until equilibrium is attained."(89)

For a sphere of radius a, the *free* oscillation (transient) solution has the following properties:

1. The fields produced by the charge as it returns to equilibrium are those of a damped harmonic oscillator.

2. The fields produced by the transient vibrations of the charge, for $r \geq a$ and $t \geq (r-a)/v$ are of the form(90)

$$E_r(r,\theta,t) = A\sqrt{\frac{\mu}{\epsilon}}\cos\theta\; e^{\frac{(r-vt)}{2a}}\left[-\frac{a}{r^2}\left(1+\frac{a}{r}\right)\cos\frac{\sqrt{3}}{2a}(r-vt) - \frac{\sqrt{3}\,a}{r^2}\left(1-\frac{a}{r}\right)\sin\frac{\sqrt{3}}{2a}(r-vt)\right] \tag{I-1.}$$

$$E_\theta(r,\theta,t) = A\sqrt{\frac{\mu}{\epsilon}}\sin\theta\; e^{\frac{(r-vt)}{2a}}\left[\left(\frac{1}{r}-\frac{a}{2r^2}-\frac{a^2}{2r^3}\right)\cos\frac{\sqrt{3}}{2a}(r-vt) - \frac{\sqrt{3}\,a}{2r^2}\left(1-\frac{a}{r}\right)\sin\frac{\sqrt{3}}{2a}(r-vt)\right] \tag{I-2.}$$

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*Nikola Tesla, Electrical Review and Western Electrician, July, 6, 1912. (Tesla Said, pg. 122)

$$H_\varphi(r,\theta,t) = A \sin\theta \; e^{\frac{(r-vt)}{2a}} \left[\left(\frac{1}{r} - \frac{a}{2r^2}\right) \cos \frac{\sqrt{3}}{2a}(r-vt) - \frac{\sqrt{3}\,a}{2r^2} \sin \frac{\sqrt{3}}{2a}(r-vt)\right] \quad \text{(I-3.)}$$

where the constant A is proportional to $\sigma_o a^3$. Note that the tangential component of the electric field, $E_\theta(a,\theta,t)$, vanishes at the surface of the sphere. Further, in the far zone the fields are the radiation fields of a damped *linear* oscillator.)

3. The charge distribution on the sphere, as a function of time, may be found from Maxwell's jump condition on the normal component of **E** and is of the form

$$\sigma(a,\theta,t) = \frac{A}{2\pi a^3} \; e^{\frac{-vt}{2a}} \left[\cos\left(\frac{\sqrt{3}}{2a}vt\right) - \frac{1}{\sqrt{3}} \sin\left(\frac{\sqrt{3}}{2a}vt\right)\right] \cos\theta \quad \text{(I-4.)}$$

4. The current through any cross-section of the sphere follows from Ampere's law on the surface of the sphere, as

$$i(\theta,t) = A_2 \; e^{-\frac{vt}{2a}} \cos\left[\frac{\sqrt{3}}{2a}vt - \frac{\sqrt{3}}{2} - \frac{\pi}{3}\right] \sin^2\theta \quad \text{(I-5.)}$$

5. The resonant frequencies are complex $s = \alpha + j\omega_d$, where, for the fundamental mode,

$$\begin{aligned}
\alpha &= \frac{v}{2a} \quad \textit{(damping constant } Np/\text{sec)} \\
\omega_d &= \frac{\sqrt{3}\,v}{2a} \quad Rad/\text{sec} \\
\delta &= \frac{\alpha}{f} = \frac{\pi}{Q} = \frac{2\pi}{\sqrt{3}} \quad \textit{(logarithmic decrement)} \\
\lambda &= \frac{4\pi a}{\sqrt{3}}
\end{aligned} \quad \text{(I-6.)}$$

The logarithmic decrement δ is large and the Q rather small for a perfectly conducting sphere of any size (3.62 and 0.866, respectively), and the waves are damped out after about a cycle of oscillation. The damping, of course, is due to energy loss *by radiation* since the sphere is assumed to be perfectly conducting.*

For an infinity conductivity sphere the size of the earth, ($a = 6.36 \cdot 10^6$ meters) these parameters would predict a damped resonant frequency of 6.49 Hz ($\omega_d = 40.78$ rad/sec), a wavelength of $46.143 \cdot 10^6$ meters (exceeding the circumference by about 15.5%),[91] and an attenuation constant *due to radiation loss*, of $\alpha = 23.53$ Np/sec. The case of a sphere with finite conductivity may be treated along the same lines.[92]

Webster points out that, "The above problem corresponds to the lowest possible frequency for a sphere, when the surface density is a zonal surface-harmonic of degree one."[93] Tesla had proposed employing several sources over the surface of the globe.

Conclusions

It is apparent that the terrestrial resonances of a *single* isolated conducting sphere are not what Tesla was observing, since such a model would *radiate* the energy away very rapidly. This was well understood even in Tesla's day. In fact, it is remarkable that Tesla would determine that the response of the earth was underdamped. Clearly, he (unlike many other well known scientists) was not deceived by theory into forcing experimental data to fit with prevailing contemporary doctrine. He was too careful an experimentalist for that.

While his published experimental data and results seem to match with the frequencies and propagation attenuation associated with Schumann's 1950's analyses, and with present experimental measurements, actually exciting such cavity resonator modes would be (even by today's standards) a truly heroic accomplishment for Tesla in 1899.

*The radiation could be eliminated by surrounding the sphere with a concentric conducting shell.

APPENDIX II

THE ZENNECK SURFACE WAVE

(A Fascinating Episode In the History of Radio-Wave Propagation)

"Note, for instance, the mathematical treatment of **Sommerfeld, who shows that my theory is correct**, that I was right in my explanations of the phenomena, and that the profession was completely misled."

Nikola Tesla, 1916*

The trans-Atlantic "over-the-bulge" propagation announced by Marconi as a result of experiments performed the afternoon**(94) of Thursday, December 12, 1901, attracted a great deal of attention - both in the scientific community and from speculators in the financial community. [In regards to the latter, Aitken recognizes Marconi as "the first entrepreneur of the electronic age."(95) Even the founding President of the IRE identified the early attempts to manipulate scientific priority by Marconi's financial backers,*** which, in Aitken's words, were led by the Dublin "whisky

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*Anderson, L.I., Nikola Tesla On His Work With Alternating Currents, Sun Publishers, Denver, Colorado, 1992, pg. 75.

A good deal of controversy has arisen about this. Aitken [Syntony and Spark: The Origins of Radio, pg. 295] observes, "There has always been considerable skepticism as to whether Marconi did in fact receive the Poldhu signals. Belief that he did so is **not made easier by our knowledge of the primitive receiving system used, and by the facts that the time and content of the transmission had been prearranged [the S was transmitted from 3-7 PM GMT]; that, of the three people present, only two (Marconi and his assistant, Kemp) heard the signals, the third being somewhat deaf [there is a gripping photograph of Kemp pressing the phones to his ears, squinting and grimacing to hear the signals while Marconi eagerly stands by - JFC]; and *that the transmission times and frequencies* were, as was later learned, the worst possible in view of propagation conditions on the North Atlantic path. Baker (History of the Marconi Company, pg. 71) points out that anyone who believed that the Poldhu signals had crossed the Atlantic 'did so as an act of faith based on the integrity of one man.' The same is true today. It would be interesting, however, if those who accept Marconi's account uncritically would undertake to repeat the experiment, using the same location, duplicating his receiver and antenna, and attempting to receive signals of approximately the same radiated power *on the same frequencies*." To which we would add *at the same time of day*. By the way, Aitken identifies the frequency as "around 800 kHz." (Pg. 264) Has anyone in Newfoundland ever heard a BC station from England, on a weekday afternoon, using a coherer? And, if all this were not enough, Marconi never claimed to hear the Morse letter "s" (dididit), but rather he asserted that what he heard was the coherer response corresponding to the letter "s", which would have been a stream of clicks.

***IRE President Robert H. Marriott once said that Marconi had "... played the part of a demonstrator and sales engineer. A money getting company was formed, which in attempting to

(continued...)

aristocracy".[96]]

The trans-Atlantic event inspired the hypothesis,[97] by A.E. Kennelly* and by Oliver Heaviside, of the existence of an "upper reflecting-surface" or radio mirror. (Heaviside published later the same year in the Encyclopedia Britannica, and the hypothesis was further developed by Eccles.[98]) However, the concept was not universally immediately accepted. In fact, experimental proof did not exist until Appleton in 1924, and Breit and Tuve in 1925. (See comments above.) At the time of Marconi's announcement a formal solution of Maxwell's equations for the fields a vertical antenna over the surface of a lossy conductor did not exist, and Hertzian waves could not explain the alleged observations. Marconi, in fact, had asserted publicly that he didn't use Hertz waves. As Thompson recalls,

> "When Signor Marconi came to [England], he gave out that he had a new and wonderful discovery. He did not use Hertz waves; Hertz waves would not work with his receiver, and his transmitter would not, he declared, work with Hertz waves!"[99]

Just how was Marconi's England-to-Newfoundland experience to be explained? [An investigation featuring a NEC study of Marconi's base loaded fan-top resonator was recently performed, but was no more convincing than the earlier garbled information.[100] Meanwhile, further apprehension has been raised by yet another scandal associated with Marconi.[101]]

A. Zenneck's Hypothesis

Following on the academic work of several earlier investigators, Johann Zenneck** formulated

***(...continued)
obtain a monopoly, set out to advertise to everybody that Marconi was the inventor and that *they* owned that patent on wireless which entitled them to a monopoly." [Radio Broadcast, Vol. 8, No. 2, December, 1925, pp. 159-162.]

*Recall that Arthur E. Kennelly (1861-1939) was elected as Vice-President of the AIEE at the same time as Tesla: 1892. (Tesla served two years in this capacity.) Kennelly served as President of both the AIEE (1898) and the IRE (1916). He was probably the last Professor of Engineering at Harvard (1902-1930) that never attended a university himself.

**Johann Zenneck, associate of 1909 Nobel Laureate Carl Ferdinand Braun, later became Professor of Physics at Munich. (He is thanked by Sommerfeld in the famous 1909 paper.) Zenneck once wrote to Tesla, "*Your lectures opened a new physical world to me.*" There is a group photo showing Braun, Zenneck, Tesla and others at the 1915 IRE banquet in New York, in the Frontpiece of Anderson's 1992 book. When WWI broke out, Zenneck was in the US, and he was held under arrest at Ellis Island until after the war. To Tesla he wrote, in June of 1931, "The world-war caused me to be in the United States under difficult circumstances. To come in contact with you was a special
(continued...)

a special *surface wave* solution to Maxwell's Equations[102][103] that was fundamentally different from the free-space waves studied by Hertz in 1887. (A surface wave is a guided wave mode propagating parallel to an interface between two media, such as earth and air.) As Burrows puts it,

> "In 1907, Zenneck showed that a plane interface between two semi-infinite media such as the ground and air could support an electromagnetic wave which is exponentially attenuated in the direction of propagation along the surface and vertically upwards and downwards from the interface. *Zenneck did not show that an antenna could generate such a wave*, but because this 'surface wave' seemed to be a plausible explanation of the propagation of radio waves to great distances, it was accepted."[104]

The Zenneck fields were tightly bound to the surface (little or no radiation into space) and they attenuated along the surface in the manner of waves on transmission lines. The distinguishing feature of the Zenneck wave was that the propagating energy didn't spread like radiation, but was concentrated near the guiding surface. Sommerfeld had shown, in 1899, that an electromagnetic wave could be guided along a round wire of finite conductivity,[105] and Zenneck conceived that the earth's *surface* would perform in a manner similar to *a single conducting wire*. (Who do we know that had been preaching that sermon on two continents and throughout the professional literature for over 15 years?) In 1908, Hack[106] reviewed Zenneck's solution and extended the work to include multiple strata for various ground conductivities. Concerning Zenneck's original contribution, Stratton observes,

> "Zenneck recognized the bearing of these researches on the propagation of radio waves and showed that *the field equations admit a solution* that can be interpreted as a surface wave guided by a plane interface separating any two media... He showed that a wave with a forward tilt, following a plane earth and attenuated in the vertical as well as the horizontal direction is compatible with Maxwell's equations, and that such a wave would explain many of the observed phenomena of radio transmission. ***There was no proof** as yet, on the other hand, **that a radio antenna does in fact generate a wave of this type.***"[107]

In a classic 1915 textbook on wireless telegraphy, Zenneck traced the inception of the idea that wireless communication resulted from surface waves:

**(...continued)
event for me. Previously, I had great admiration for you as the original inventor [of wireless telegraphy], I was so enchanted, but now since I've become acquainted with you, you are one of the kindest men I've ever encountered. *The hours which I was permitted to spend together with you will always be among the fondest memories of my life.*" Zenneck served as Vice-President of the IRE in 1933.

"The concept that the waves of radio telegraphy are of the nature of surface waves was probably first presented by Blondel* in 1898, by Lecher,[108] and also Uller[109]."[110]

However, as of 1908 it had not been demonstrated *analytically* that *an antenna* could actually generate such a wave.

B. Sommerfeld's 1909 Paper

In a lengthy article published in March of 1909, Arnold Sommerfeld obtained a formal analytical solution for the radiation from a short vertical monopole over a finitely conducting ground. (Hertz's 1888 paper was concerned, of course, with dipole radiation in free space.) The paper, though a milestone in the history of science, has been the subject of considerable controversy.** In his mind, Sommerfeld saw a clear distinction between Hertzian waves and Zenneck surface waves, and he wanted to find out which physical phenomenon was occurring in real-world wireless telegraphy. Sommerfeld starts his paper by posing the following question:

"Two contrasting concepts arise which may be designated by the terms 'space waves' and 'surface waves.' The Hertzian electrodynamic waves are [space waves]. Electrodynamic waves on wires are typical surface waves... **With which type are the waves utilized in wireless telegraphy to be identified? Are they like Hertzian waves in air or electrodynamic waves on wires?**"[111]

Sommerfeld briefly surveys Zenneck's work, and then identifies the primary purpose of his 1909 paper:

"Heretofore there was no definite proof that such waves [the Zenneck surface waves] could be developed from waves coming from the transmitter. *The main task of the present investigation is to give this proof and to settle the question: space waves or surface waves?"*

As Wait points out in an extensive tutorial review, Sommerfeld obtained exact expressions for

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*Professor Andre Blondel, of course, was an internationally known expert on the Tesla rotating field induction motor. According to Zenneck (1915, pg. 421), Blondel was the one that pointed out that a groundplane bisecting a Hertzian dipole antenna could be treated by the method of images. (See any textbook on antenna engineering.) Recalling Tesla's Paris Lecture before the Society of Electrical Engineers of France and the French Society of Physics, Blondel wrote in 1936, "A summary was given by him in 1892 in the remarkable public conference that he gave in America, then in London, and at Paris. I was an assistant at the great meeting of the Societe des Electriciens in 1892 at Paris, where a grand hall held an enthusiastic audience... Tesla was a veritable magician." [Tribute, pg. A-146] Blondel has published numerous articles on Tesla and on his technology.

**The controversy revolves around the choice of the square root of a complex quantity appearing in the argument of a complex error function.

the field components in the form of integrals which were then evaluated asymptotically.

> "In an attempt to explain the physical nature of his solution, he divided the expressions for the field into a 'space wave' and a 'surface wave'. Both parts, according to Sommerfeld, are necessary in order to satisfy Maxwell's equations and the appropriate boundary conditions. He found that the 'surface wave' part of the solution had almost identical properties to the plane Zenneck surface wave. The field amplitudes varied inversely *as the square root* of the horizontal distance from the source dipole. Furthermore *it was a fast wave* and it decayed exponentially with height above the interface."(112)

Analytically, the issue arose as follows:

> "After Sommerfeld formulated the wave function for a vertical infinitesimal dipole as an infinite integral and noted that the integral around the pole of the integrand is the wave function for a surface wave, which at great distances is identical with the Zenneck wave, no one questioned the reality of Zenneck's surface wave."(113)

The wave propagating over the surface of the earth contained a cylindrical Zenneck surface wave emanating from the oscillating source and, as Burrows states, "... the case for the Zenneck wave seemed complete."(114) Years later Sommerfeld would write:

> "**It was the main point of the author's work of 1909** to show that these fields [the Zenneck waves] are automatically contained in the wave complex, which, according to our theory, is radiated from a dipole antenna."(115)

Sommerfeld appears to have been satisfied with his result, which resolved the question ("space waves or surface waves?") by stating,

> "Zenneck surface waves appear as an important *and occasionally predominant* component of the electromagnetic field accompanied by space waves, which on their part predominate under certain other conditions." (116)

Tesla's ideas were consistent with the composite field mixture idea set forth in this celebrated 1909 analysis.* It is as though Tesla believed that, with his apparatus, one could govern the relative mixture

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*Tesla said, "The apparatus which I devised was an apparatus enabling one to produce tremendous differences of potential and currents in an antenna circuit... By proper design and choice of wavelengths, you can arrange it so that you get, for instance, 5% in these electromagnetic waves and 95% in the current that goes through the earth. That is what I am doing. Or, you can get, as these radio men, 95% in the energy of electromagnetic waves and only 5% in the energy of the current... *The apparatus is suitable for one or the other method.* I am not producing *radiation* in my system; I am suppressing electromagnetic waves. But, on the other hand, my apparatus can be used effectively with electromagnetic waves... The effect at a distance is due to the current energy which flows through the surface layers of the earth. **That has already been mathematically shown, really, by Professor**

(continued...)

of Zenneck surface waves and Hertzian radiated waves launched by the emitter.

C. Tesla Comments

As can be seen from the 1916 quote at the head of this Appendix, Tesla believed that the theoreticians were finally being driven to accept his *observationally based* public assertions concerning terrestrial wave propagation. So thoroughly was Tesla convinced by his own experimental observations that he would maintain,

> "...even at this very day, the majority of experts are still blind to the possibilities which are within easy attainment...
>
> The Hertz wave theory of wireless transmission [inverse square, radiating space waves bouncing off reflectors] 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."(117)

This extraordinary assertion was *not* an entirely irrational statement for a radio scientist to make in 1919. Zenneck, in fact, had said in 1915,

> "As regards the question whether the energy emitted by a transmitting antenna is propagated *by conduction currents* in the ground or by electromagnetic waves in the air, I agree with Mr. Lowenstein* that this is largely a matter of expression... It is therefore a matter of taste whether one describes the propagation of energy as taking place by means of earth currents or whether one describes it as being caused by electromagnetic waves in the air."(118)

This would be acceptable for wave guide propagation, but not for antenna radiation with Hertzian waves.

D. Subsequent Developments

Three significant wave propagation papers were published between 1918 and 1919, two by

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*(...continued)
Sommerfeld. He agrees on this theory. Professor Zenneck took me out and gave me the particulars [on the large Telefunken radio station constructed at Sayville, Long Island]. I went over the calculations and found that at 36 kW they were radiating 9 kW in EM waves." (Anderson, 1992, pp. 132-133).

*Fritz Lowenstein, inventor of the grid biased Class A amplifier, first Vice-President of the IRE, and assistant to Nikola Tesla at the 1899 Colorado Springs experiments.

G.N. Watson,[119][120] and one by Hermann Weyl.*[121] The first of Watson's papers concerned the diffraction of radiation, emitted by a Hertzian oscillator, around an Earth consisting of an imperfectly conducting sphere surrounded by an infinite homogeneous dielectric. Watson showed that "a theory of pure diffraction is insufficient" to account for the distances observed in wireless telegraphy. The second paper investigated the consequences of a perfectly conducting Earth surrounded by a concentric perfect reflector, at a height on the order of 100-150 km, excited by Hertzian waves. Watson concluded that this analysis "afforded a confirmation of the theory put forward by Heaviside and others and modified by Eccles."**

Weyl's paper reformulated the problem of a Hertzian dipole above a conducting half-space, and his far zone results were in a form convenient for numerical calculations. Although his solution was in terms of an angular spectrum of plane waves it should have given results equivalent to Sommerfeld's analysis. But, enigmatically, the radial Zenneck surface wave was *not* present in Weyl's results.

E. Sommerfeld's 1926 Paper

In 1926 Sommerfeld published an extended analysis of vertical and horizontal electric and magnetic radiators above a lossy groundplane. Reviewing Sommerfeld's 1926 paper, Wait says,

> "He gave exact integral expressions for the fields of vertical and horizontal dipoles for both electric and magnetic types. He redeveloped the asymptotic approximations for the infinite integrals which were valid in the far zone, and the resulting field expressions were generalized to permit both source dipole and observer to be at a finite height above the interface. As in the 1909 paper, the asymptotic solution involved an error function whose argument involved the square root of a complex quantity. The prescription for choosing the correct branch of this square root was changed in the 1926 paper. Unfortunately, however, Sommerfeld did not explain his reasons for making this change of sign, which altered the asymptotic behavior of the error function. Consequently, if Sommerfeld had examined the asymptotic expansion of his 1926 formulae he would have found that the radial Zenneck wave fails to emerge as the dominant term...
>
> It appears that the first explicit statement of the error in Sommerfeld's 1909 paper was published by K.A. Norton (1935) in a letter to Nature. It is evident in the exchange of correspondence between Norton and Sommerfeld that **the error was never acknowledged**."[122]

---

*This was 1 year after Professor Weyl's pioneering publication of a Unified Field Theory. [Sitzungsberichte der Preussischen Akademie der Wissenschaften, May 30, 1918.]

**He also concluded that the reflecting layer "places grave obstacles in the way of communications with Mars or Venus" - an obvious reference to the remarks of Nikola Tesla, Lord Kelvin, and Guglielmo Marconi.

[Kenneth Alva Norton, in a brilliant series of radio wave propagation papers,[123][124][125][126][127] provided the practical, yet formal, analysis for the fields radiated by vertical radio antennas over lossy curved earth. (What emerges, instead of the Zenneck wave, is the wave complex responsible for AM broadcasting including a groundwave component, now called the Norton Surface wave which includes the Sommerfeld attenuation function.) His important contributions resulted in the radio wave propagation charts published in the FCC Rules and Regulations, which have been the bread and butter of hundreds of consulting engineers and part of every FCC AM broadcast application since the 1940's. These important charts, from an engineering point of view, are what made possible "the golden age of radio" (and its societal impact) - not the networks and certainly not the entertainers! Few men in history have ever "utilized the resources of the Earth for the benefit of civilization" and impacted humanity to such an extent as Kenneth Norton.]

During the 1930's there was considerable investigation into the "reality" of Zenneck surface waves in radio.[128][129][130] These conflicts between the 1909 Sommerfeld theory (which included a cylindrical Zenneck wave) and the subsequent 1918 analysis of Weyl, and Sommerfeld's 1926 analysis (which did not have the Zenneck wave), culminated in a series of experiments performed at Seneca Lake in New York by Charles Burrows of Bell Labs. (Burrows investigated both vertical and horizontal polarization at a frequency of 150 MHz.) The observations, consistent with Weyl's theory, were *43 dB weaker* than the signal strengths predicted by Sommerfeld's 1909 analysis. Burrows' conclusion:

> "The surface wave component of Sommerfeld is not set up by *simple antennas* on the surface of the earth... The absolute value of the received field strength was found to be less than that predicted by Sommerfeld *by a factor of about a hundred.*"[131]

In 1949, Sommerfeld, in collaboration with Dr. F. Renner, finally commented on the Zenneck surface wave episode in his book on the partial differential equations of physics:

> "It was the main point of the author's work of 1909 to show that these fields [the Zenneck waves] are automatically contained in the wave complex, which, according to our theory, is radiated from a dipole antenna. This fact has, of course, not been changed. What has changed is the weight which we attach to it. At the time it seemed conceivable to explain the overcoming of the earth's curvature by radio signals with the help of the character of *surface waves*; however we know now that this is due to the ionosphere. In any case the recurrent discussion in the literature on the 'reality of the Zenneck waves' seems immaterial to us."[132]

At this point, it might appear that our lead-off quote would indicate that it was Tesla that had been misled. However, we have come to realize that it was his practice not to make assertions without strong experimental evidence. He was an honest investigator, and if he said that he observed some phenomenon, then you can take it to the bank. It may not have been Zenneck's surface wave, but we believe that something other than the Weyl complex was launched and observed in his wave propagation experiments at Colorado Springs.

Clearly, *ordinary* radio antennas don't set up Zenneck waves on the surface of the earth. However, Zenneck's solution does indeed satisfy Maxwell's equations. So, one is led to ask, "Well, what kind of structural geometry *could* be employed to launch this propagation mechanism, which produces such strong signals?" Felsen and Marcuvitz have pointed out that,

> "Because of its inverse $\rho^{1/2}$ radial decay at large distances ... a great deal of discussion has ensued about the independent existence of this wave and its utilization for the transmission of radio waves over long distances."[133]

Banos gives an appreciation for the extensive historical and analytical development.[134] Today there is considerable interest in launching electromagnetic "bullets", "missiles", "non-diffracting beams", "electromagnetic directed energy pulse trains" and other peculiar non-Hertzian solutions of Maxwell's equations. In free-space these propagation mechanisms are, of course, not surface waves. An overview of these fascinating phenomena has been provided by Dr. Jim Daum.[135]

F. Recent Developments

We should call the reader's attention to modern Zenneck wave investigations. While fascinating work was published in the 1950's by Goubau,[136][137][138][139] and more recently (in the 1-10 MHz region) by Wait and his colleagues,[140][141][142] we direct the reader's attention to a series of publications lately appearing in the Russian literature.

Kistovich notes that it is known that the asymptotic expansion of the field of a vertical electric dipole does not manifest a Zenneck wave, "... and it is inferred from this result that a Zenneck surface wave is never generated by sources with a small vertical aperture. This opinion is widely held in radiophysics at the present time."[143] However, he and his colleagues have found, both analytically and experimentally, that it is possible to use small "resonators" to excite a Zenneck wave that is observed to be 10-20 dB stronger than radiation fields. They also found that both travelling and standing Zenneck waves can be excited. [Schelkunoff and Friis clearly delineate the distinction between a quarter wave *resonator* and a quarter wave *radiator* in terms of the in-phase "feed current" (which supplies the radiated power) and the "quadrature current" (which supplies the resonant oscillations of the structure).[144] Without the "feed current" component, the base impedance of an ideal lossless series-resonant quarter wave monopole would drop to zero at resonance despite the fact that the reactive "quadrature current" would be infinite.[145]] The consequences of Kistovich's work for

Tesla research are not yet known.

G. Zenneck Wave Analysis

Perhaps, at this time it would be appropriate to examine Zenneck's solution. The actual analysis of a Zenneck wave can be presented in relatively simple terms. Consider Figure II.1, which shows a plane interface between two media. Zenneck assumed a time-harmonic ($e^{j\omega t}$) TM wave that possessed only a transverse magnetic field component, $H_y(x,z)$ in our Figure, and which propagated along the +z direction with propagation constant β_z which depends upon the constitutive parameters and is to be determined by analysis. Maxwell's equations lead to the Helmholtz equation and boundary conditions to be satisfied in regions 1 and 2:

$$[\frac{\partial^2}{\partial x^2} + k_i^2] E_{zi} = 0 \qquad \textbf{(II-1.)}$$

where the separation constant is

$$k_i^2 = \omega^2 \mu_o \epsilon_i - \beta_z^2 \qquad \textbf{(II-2.)}$$

for i = 1,2 and the normal and tangential components of the electric field strength satisfy

$$\begin{aligned} \epsilon_1 E_{x1} &= \epsilon_2 E_{x2} \\ E_{z1} &= E_{z2} \ . \end{aligned} \qquad \textbf{(II-3.)}$$

The solutions of Helmholtz's equation are as follows.

In region 1 (the ground):

$$\begin{aligned} E_{z1}(x) &= A_1 \, e^{\pm jk_1 x} \, e^{j(\omega t - \beta_z z)} \\ k_1^2 &= \omega^2 \mu_o \epsilon_o \epsilon_g - \beta_z^2 \ . \end{aligned} \qquad \textbf{(II-4.)}$$

where ε_g is complex

$$\epsilon_g = \epsilon_o \epsilon_{gr} - j(\frac{\sigma}{\omega \epsilon_o}) \quad \text{(II-5.)}$$

The ± in the exponent of Equation (4) must be chosen depending upon the imaginary part of k_1. In his discussion of surface waves, Waldron notes that, "The sign to be chosen is that which gives a negative real part of the exponent for negative x, in order to satisfy the boundary condition of vanishing fields at x = -∞."(146) Following Zenneck's original paper, we also assume that no upward waves are coming from below the surface (no sources at x = -∞).

In region 2 (the air):

$$\begin{aligned} E_{z2}(x) &= A_2 e^{\pm jk_2 x} e^{j(\omega t - \beta_z z)} \\ k_2^2 &= \omega^2 \mu_o \epsilon_o - \beta_z^2 \end{aligned} \quad \text{(II-6.)}$$

Again, the ± sign must be chosen such that the real part of the exponent is negative for positive values of x, and following Zenneck, we assume that no downward waves are arriving from x = +∞. (Hack's 1908 solution included the possibility of downward waves.)

As Waldron points out,(147) the transverse components of the fields in the i^{th} region may be found from the longitudinal components by the familiar relations

$$\begin{aligned} k_i^2 \vec{H}_t &= -j\beta \nabla_t H_{zi} - j\omega \epsilon_o \epsilon_i \hat{n} \times \nabla_t E_{zi} \\ k_i^2 \vec{E}_t &= -j\beta \nabla_t E_{zi} + j\omega \mu_o \mu_i \hat{n} \times \nabla_t H_{zi} \end{aligned} \quad \text{(II-7.)}$$

which follow from Maxwell's equations.(148) In our case, $H_z = 0$. Consequently,

$$\begin{aligned} E_{xi} &= -(\frac{j\beta_z}{k_i^2}) \frac{\partial E_{zi}}{\partial x} = \mp \frac{j\beta_z}{k_i} E_{zi} \\ H_{yi} &= -(\frac{j\omega \epsilon_o \epsilon_i}{k_i^2}) \frac{\partial E_{zi}}{\partial x} \end{aligned} \quad \text{(II-8.)}$$

Further, on the plane at x = 0 the boundary conditions stated above give $A_2 = A_1$ and the "characteristic equation"

$$\epsilon_1 k_2 = \epsilon_2 k_1 \quad . \tag{II-9.}$$

Using Equations (2),(4) and (6) gives the complex longitudinal propagation phase constant along the surface as

$$\beta_z = \frac{2\pi}{\lambda_o} \sqrt{\frac{n^2}{1 + n^2}} = \frac{2\pi}{\lambda_o} \sqrt{\frac{\epsilon_{gr} - j60\lambda_o\sigma}{(\epsilon_{gr} + 1) - j60\lambda_o\sigma}} \tag{II-10.}$$

where the complex quantity n is expressed by[149]

$$n = \sqrt{\epsilon_{gr} - j(\frac{\sigma}{\omega\epsilon_o})} = \sqrt{\epsilon_{gr} - j60\,\lambda_o\,\sigma} \tag{II-11.}$$

and, the complex propagation constant is

$$\gamma_z = \left(\frac{2\pi j}{\lambda_o}\right) \sqrt{\frac{n^2(f)}{1 + n^2(f)}} \quad . \tag{II-12.}$$

Equation (10) is the desired result. Further, Equations (4) and (6) permit us to write the transverse (perpendicular to the surface) propagation constants for the Zenneck surface wave as follows.

In earth:

$$k_1 = \frac{2\pi}{\lambda_o} \frac{n^2}{\sqrt{1 + n^2}} \tag{II-13.}$$

In air:

$$k_2 = \frac{2\pi}{\lambda_o} \frac{1}{\sqrt{1 + n^2}} \quad . \tag{II-14.}$$

We can now go back to Equations (8) and (6), and express the vertical component of the

Zenneck surface wave electric field strength in air in the usual form

$$E_x(x,z,t) = E_o\, e^{-(\alpha_x x + \alpha_z z)}\, e^{j(\omega t - \beta_x x - \beta_z z)} \quad . \tag{II-15.}$$

where the attenuation constants are determined from k_1 and β_z as prescribed above. The resulting wave is a surface guided ("single conductor") *transmission line* mode which attenuates exponentially along the guide, and also decays exponentially transverse to the guide. (There is no *inverse square* spreading or diffraction, as with Hertzian waves). The E_z indicates "wave tilt" ($E_{x2}/E_{z2} = jn$) and at VLF a small component of the Poynting vector is directed into the ground, which accounts for the attenuation and transmission loss. The dominant components of E_{x2} and H_{y2} are in phase (and therefore carry most of the power along the surface), while E_{z2} and H_{y2} give reactive power flow in the vertical direction.

In addition to being tightly bound to the interface surface, the Zenneck wave also possesses the property of being a "fast wave". That is, its velocity factor (phase velocity divided by c) is greater than one. The velocity factor in air is given by

$$V(f) = \frac{v}{c} = \frac{\left(\dfrac{\omega}{Re\{\beta_z\}}\right)}{c} = Re\left\{\sqrt{\frac{n^2+1}{n^2}}\right\} \tag{II-16.}$$

which, for the earth, is greater than unity, indicating the "fast wave" nature of the Zenneck wave.

With appropriate constitutive parameters, a pure Zenneck wave would seem to hold out the promise of guided energy propagation with no radiation field to waste energy.

H. Discussion

Now let's put some numbers into the theory and see how it compares with what Tesla said. Using $\varepsilon_r = 80$ and $\sigma = 4$ mhos/m for sea water, we have plotted $\alpha_z(f)$ in dB/Mm, $e^{-\alpha(f)C}$ for round the world propagation in air, $\alpha_x(f)$ in dB/Mm upwards, and $\alpha_x(f)$ in dB/m downwards (notice the units are per meter downward), for frequencies in the VLF/LF Band, in Figures (2), (3), (4) and (5). For comparison purposes, we have also plotted $W = e^{-\alpha d}$ for 10 MHz in Figure (6). [This is the field produced by a Zenneck aperture of infinite extent, and is to be compared with Wait and Hill's[150] Figure 8.] Figure (7) shows the exponential decay, $W(d) = e^{-\alpha d}$, for soil with $\varepsilon_r = 6$ and $\sigma = 10$ mmhos/m at 1.0 MHz. [This is to be compared with the infinitely high ($z_o = \infty$) Zenneck Aperture in

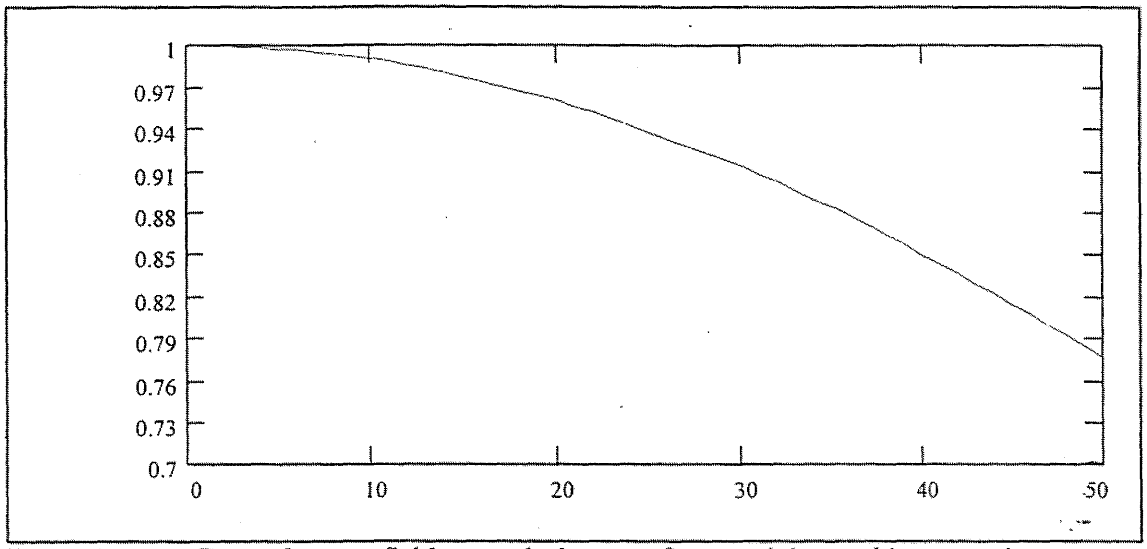

Figure 3. Zenneck wave field strength decrease for round the world propagation as a function of frequency in kHz.

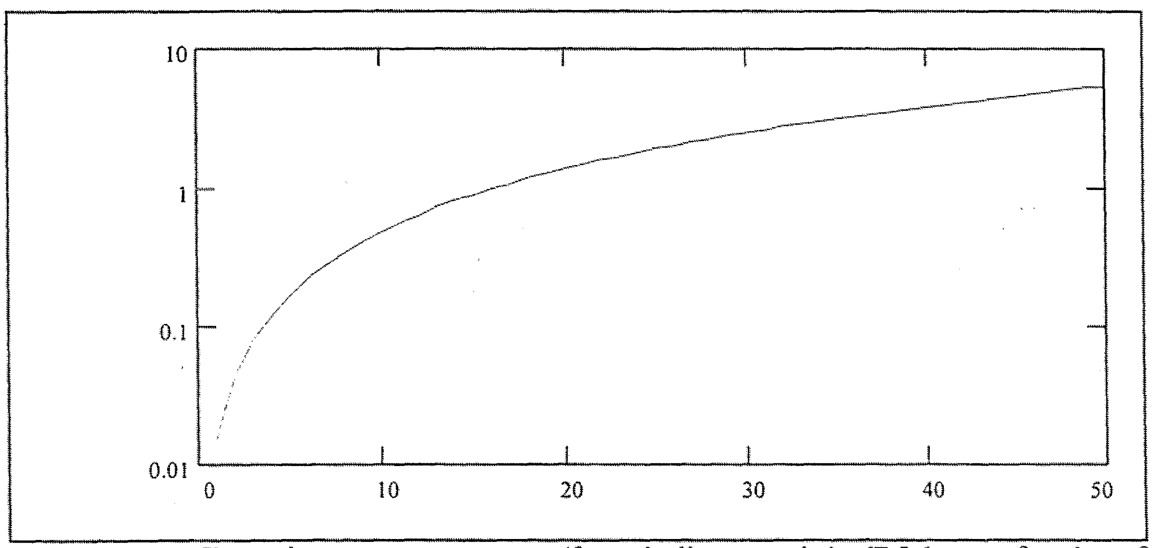

Figure 4. Zenneck wave attenuatuon $\alpha_x(f)$ vertically upwards in dB/Mm as a function of frequency in kHz.

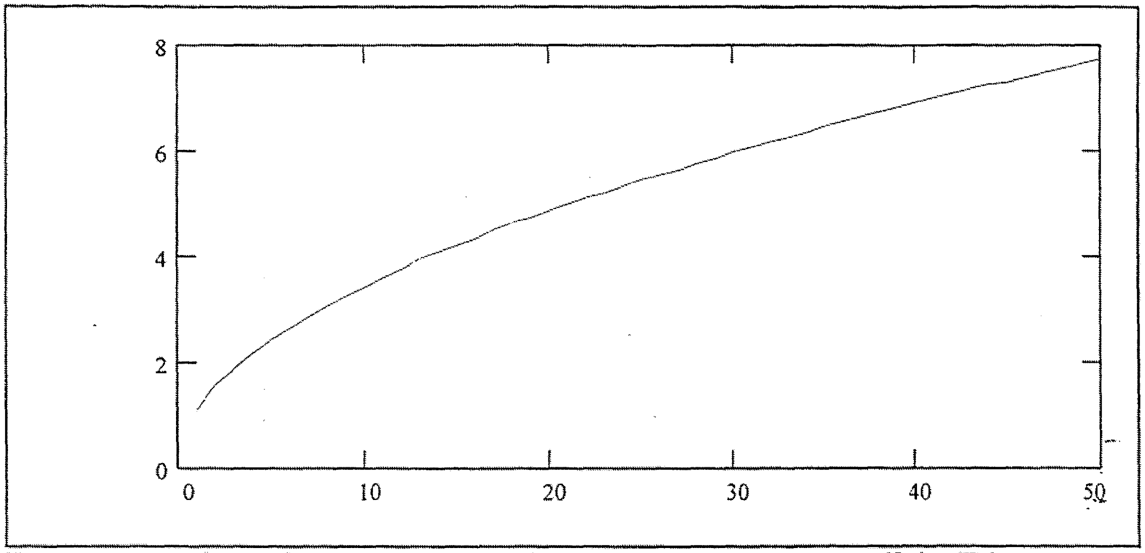

Figure 5. Zenneck wave attenuation downwards, into sea water, $\alpha_x(f)$ in dB/m as a function of frequency in kHz.

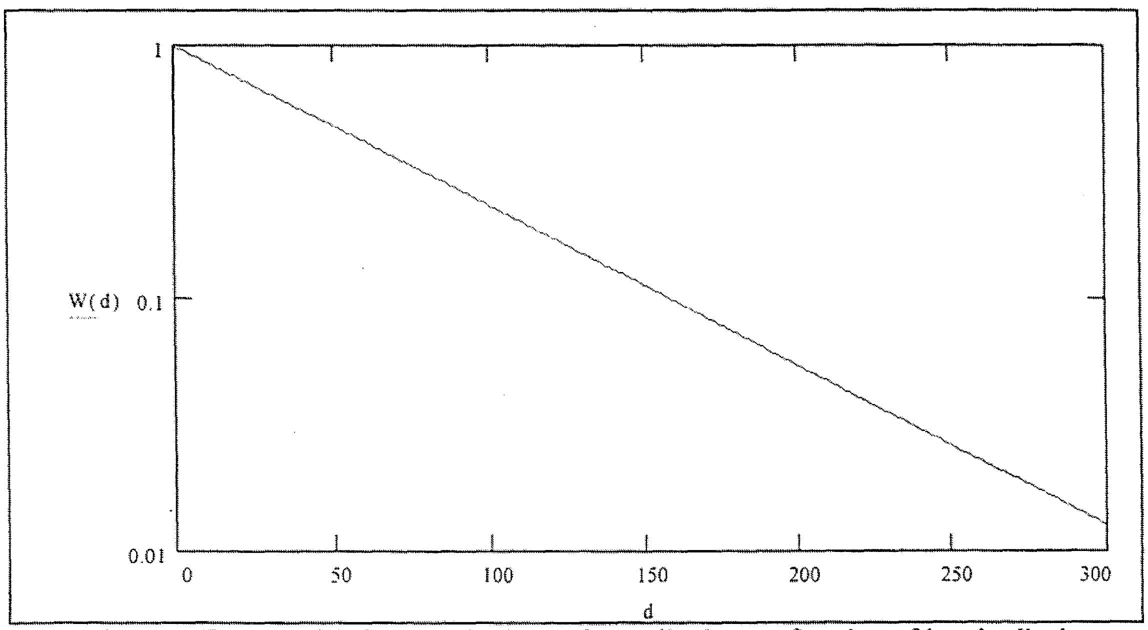

Figure 6. Exponential decrease in Zenneck amplitude as a function of longitudinal propagation over sea water at 10 MHz.

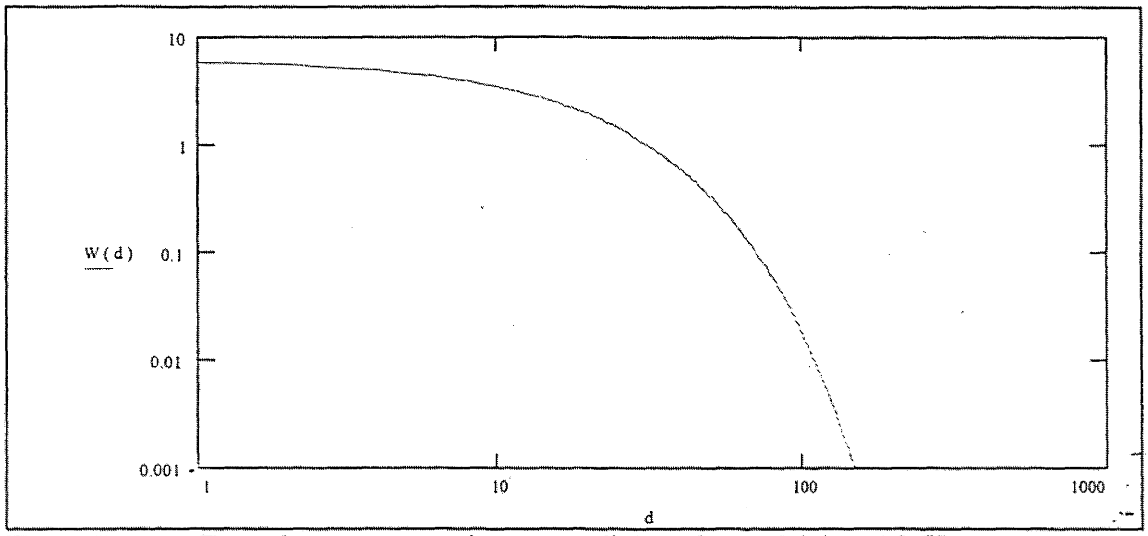

Figure 7. Zenneck wave attenuation over soil ($\varepsilon = 6$; $\sigma = 0.01$) at 1 MHz.

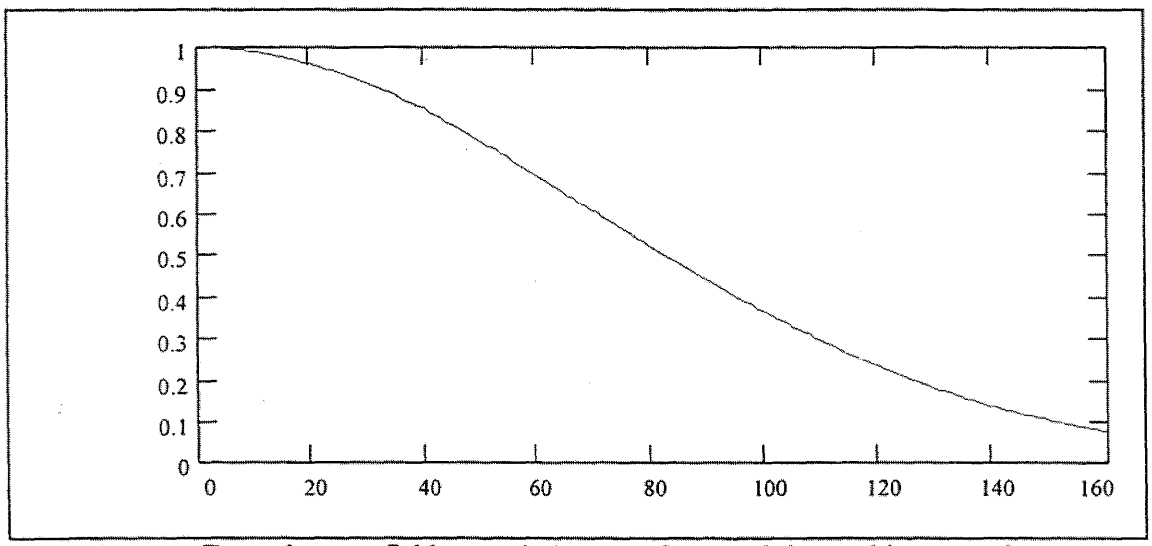

Figure 8. Zenneck wave field strength decrease for round the world propagation as a function of frequency in kHz.

Hill and Wait's[151] Figure 3.]

The Zenneck wave suffers small attenuation, "particularly below 25 kHz" (as Tesla notes), and the Zenneck round the world transmissions would appear to be "as high as 96% or 97%", again as Tesla said. While the Zenneck wave is a "fast wave", it is not 1.57 times faster than c (and so it can't be a rationalization for Tesla's assertion that his measured value for the mean velocity of light was 471,240 km/s[152]). Our explanation for the famous 0.08484 seconds and $V(f) = \pi/2$ were given at the 1986 ITS Symposium.[153] The curves would appear to indicate that a Zenneck wave would loose its advantage as the carrier frequency was raised up into the LF-MF-HF-VHF range, consistent with the comments above of both Wait and Burrows.

G. Speculations

Let us return to the issue expressed by Stratton that *there was no proof that a radio antenna generates a Zenneck wave*. The conclusion of the "great surface wave debate" of the 1930's was that *radio antennas* don't emit Zenneck waves. Hill and Wait have written

> "It is now generally accepted that the radial Zenneck wave is not a major contributor to the total field of a vertical electric dipole over a homogeneous conducting earth."[154]

If Zenneck waves don't emanate from radio antennas then what structures might "launch" them? Hill and Wait go on to discuss this:

> "As it turns out, the Zenneck wave is generally difficult to excite with a realistic source because it has a rather slow decay with height above the earth's surface. But there is still an open question whether other types of sources may not be more favorable... **An infinite vertical aperture with a height variation corresponding to that of the Zenneck wave will excite only the Zenneck surface wave with no radiation field**.. The infinite Zenneck aperture excites *no radiation field* and the pure Zenneck surface wave is the expected result...
>
> A layered or slightly rough surface which results in a more inductive surface impedance could yield a more advantageous situation. A much smaller vertical aperture would then be sufficient. In fact, if the phase angle of the normalized impedance $\Delta = Z/\eta_0$ exceeds $\pi/4$ radians, a trapped (slow) surface wave is excited and then we have a new ball game!"[155]

Is it possible that the ragged mountainous terrain to the west of his laboratory site somehow served as an inductively reactive corrugated surface ($h<\lambda/4$) and launched a Zenneck surface wave in a preferred direction?[156][157] There may be some merit to the idea. Certainly, these could set up the conditions which might established a VLF traveling wave ring power multiplier.[158] For the armchair experimentalists among us, and those looking for a senior project, such a distributed resonator could readily be modeled and examined analytically for technical merit.

The 1978 analysis provided by Hill and Wait examined the fields produced by a vertical sheet of horizontally directed magnetic current with an *exponential variation in the vertical* aperture:

$$m_y(x') = M_o e^{-\gamma_x x'} \qquad \text{(II-17.)}$$

(in the geometry which we employed in Figure 1). This is called an 'infinite Zenneck aperture', and such a source truly "excites a pure Zenneck wave with no radiation field."(159) Effective magnetic current has the units of volts/m. The field produced by this source configuration was a pure Zenneck field over the surface of the earth - with no 'Hertzian radiation'. The analysis of Hill and Wait showed that this field possessed no intrinsic merit at 1 and 10 MHz, and we certainly agree. One wonders, however (and this is pure conjecture at this point), if the disposition of Tesla's Colorado Springs high voltage (10-20 Mv) VLF resonator did, in fact, possess an effective vertical distribution of magnetic current which could launch a similar Zenneck Surface Wave. Certainly, Tesla is on record as stating that the propagation was of little value above 20 kHz.

Is it possible to launch some other kind of non-radiating surface wave? And, is it possible that Tesla, somehow, had configured a geometry which could establish a similar non-Hertzian wave at VLF (or ELF)?

When examining the transient fluctuations of an isolated conducting spherical oscillator, in the previous Appendix, it was seen that the current waves on the sphere were swiftly damped due to the rapid radiation of electromagnetic energy. (As noted in the text, this goes back to the 1892 experiments of Oliver Lodge.) This would *not* be the case if Zenneck surface waves had been excited. Instead, for Zenneck, the sphere would have behaved as a spherical surface-wave resonator. The accompanying ground currents could be found as $\mathbf{J} = \hat{\mathbf{n}} \times \mathbf{H}$, and ring power multiplication would be possible.

The Zenneck analysis presented above was for a planar interface (flat earth), as was the original publication of Zenneck's. It can readily be extended to the case of a surface wave excited on a spherical body (round earth), in which case terrestrial surface wave resonances (unlike Schumann's *cavity* resonator modes) will be manifested.

Furthermore, there appears to be a weak similarity between the Zenneck wave and the "creeping wave" of the geometrical theory of diffraction (GTD). The latter mechanism however sheds radiation as it goes, filling in the "shadow region" of diffracting bodies. In Zenneck's case, depending upon the propagation attenuation, the "Ring Power Multiplication" phenomenon might be excited by spherical surface waves which follow geodesics to the antipode and back.(160)(161)(162) Non-radiating global Zenneck excitation by "resonators" needs to be pursued, particularly at the bottom end of the VLF band.

This leads us to again ask, could it be possible that in his high voltage RF experiments Tesla had discovered some way to launch a form of non-diffracting surface wave? If he did so, then, more than likely, the technique will be shown clearly in many of his published documents as was the case with his production of ball lightning. It is a matter of understanding what you are looking at - this is especially true when examining the photographs.

H. An Earlier Colorado Springs Experiment

Finally, we would like to call attention to a commonly unknown experiment which Tesla performed on Pike's Peak three years prior to the construction of the Colorado Springs experimental station. The details were learned by one of the authors (KLC) during his visit to Beograd as a guest of the Serbian Academy of Sciences and Arts in September of 1993.

As documented in his scrapbooks and papers at the archives of the Tesla Museum, Tesla went to Denver, and on to Colorado Springs where he made radio measurements just below the summit of Pike's peak as early as the summer of 1895. In the newspaper account published in the New York World of March 8, 1896, Tesla, assisted by a friend (a Mr. Ben Bolt), climbed Pike's Peak and positioned two "autoharps" on opposite sides of the mountain, *at the same elevation*, below the summit, about 4 miles circumferentially apart. We don't know what an RF "autoharp" was, nor do we know what frequencies were employed. He detected standing waves (around the circumference of the mountain) and Tesla reports that the two stations were able to communicate as long as they were positioned near SWR maxima. (This would seem to rule out both Hertzian waves and diffraction communication by an "up-over-and-down" path.) This experiment would again support the idea of a surface wave propagation mechanism. It could probably be modeled by surface waves on a cylinder or a cone, and remains to be analyzed.

APPENDIX III

EXPERIMENTAL DETECTION OF FIELD MAGNIFICATION DUE TO TRANSVERSE RESONANCE

During the course of this research we were led to examine many alternative wave propagation and interference mechanisms. In our 1992 ITS paper on physical phenomena which "magnify", we discussed the "Traveling Wave Ring Power Multiplier" in some detail.[163] We looked at both the monochromatic and the double side-band versions of this remarkable "power magnifier". (That's right, the ring power multiplier does indeed magnify *real* average power: $\frac{1}{2}\,\mathrm{Re}\{\iint(\mathbf{E}\times\mathbf{H}^*)\cdot\mathbf{n}\,dA\}$. And, it does so without violating conservation of energy, of course.) The ring multiplier becomes even more interesting when it is excited by a double side-band signal whose $\Delta\lambda$ (a "beat" wavelength") corresponds to exactly one complete circumference of the ring. The analysis is provided in the cited reference. In Part III of the present text above, we casually mentioned that when the plate-to-plate spacing of a parallel plane wave guide is exactly one half wavelength it is possible to excite a "transverse resonance" with the waves up and back, with little or no longitudinal propagation. For the E-layer ($H \approx 100$ km) this would correspond to about 1500 Hz. Surely, one could excite and observe this resonance much easier than Schumann resonances at 7.8 Hz. Needless to say, we were quite excited about this. A brief literature search indicated that a similar phenomenon was first hypothesized by Bliokh, et. al. fairly recently,[164] and discussed with considerable clarity by Gyuninen and Makarov.[165] Simply put, their ideas recognized that while the Schumann cavity resonances occur globally at frequencies of a few tens of hertz, the new "transverse resonances" have fundamentals occurring at tens of kilohertz. However, even 1500 Hz antenna would be a heroic achievement.

Returning to our 1992 ITS paper, we decided to attempt exciting transverse resonance using a 1.8 MHz signal DSB modulated at 1500 Hz, and see if we could observe resonant rise in the signal. We constructed a DSB suppressed carrier transmitter capable of 25 watts for the 160 meter amateur radio band and modulated it with an audio oscillator whose frequency could be varied from 20 to 5000 Hz. The transmitter's modulation response was flat out to 20 kHz (if modulation frequencies that high had been needed). We used a broadband matching network to the antenna and a commercial thru-line RF watt meter, and kept the transmitter output power constant. (A constant power of 25 watts was maintained into the antenna.) We also observed the local RF power level to make sure that any field strength variations could not be attributed to variations in the transmitted power. We employed a Potomac Instruments FIM-41 commercial field strength meter whose calibration is traceable to NIST.

Our antenna was a one wave horizontal loop parallel to the ground, thirty feet above the earth and fed by balanced feeders. The antenna, suggested to us twenty years ago by Clarence Moore (the inventor of the "Cubical Quad" antenna) is a broad-side radiator with a rather bulbous pattern straight up. Our experiments were conducted during both daylight hours and nighttime hours (7:30 PM to 6:30 AM) in mid-December, 1993. The observation point was several miles away.

Now, what we found was astonishing. Transmitting with the full 25 watts all in a monochromatic carrier, the field strength was 67 μV/m. Transmitting 25 watts with 12.5 watts in each side band and the sidebands separated by a total of $\Delta f = 1500$ Hz, the signal strength rose to 300μV/m. Further, as the two side frequencies were brought together or spread apart, one could see the sky wave field strength rise or fall *at three distinct frequencies*. Our night-time unmodulated (key down) carrier signal levels were typically about 67 μV/m RMS, which was acceptable for the required ionospherically reflected signal experiments. (There was no appreciable fading during the time that we collected data.) But as we varied the modulation frequency from 50-5000 Hz we saw ***three*** distinct resonances: one at 300 Hz (with an amplitude two times as great as the carrier alone), one at 1500 Hz (with an amplitude 4.5 times as great as the carrier alone: equivalent to about 13 dB of gain), and one at 2700 Hz (with an amplitude 2 times as great as the carrier alone). The 1500 Hz resonance had $\Delta f \approx 500$ at the .707 points (resonator Q~ 3).

Clearly, the transverse resonances are there. There is a clear, distinct resonant rise in the sky wave field. And, DSB excitation of the resonator is possible without having to resort to using a radiator at the fundamental (1500 Hz). Could this be done for round-the-world propagation using sky-waves (and a directional antenna) to make the Global Ring Power Multiplier that we discussed at the 1992 ITS Symposium? Say, use a carrier frequency of 21 MHz (or 14 MHz, or perhaps even 7 MHz), and modulate at or near 7.5 Hz (the frequency corresponding roughly to the speed of light divided by the circumference of the earth). With even a modest transmitter the signal strengths should build up to significant levels. Was this what was going on back with the Russian "woodpecker"?[166] (Maybe it had nothing to do with OTH radar.) It would even appear possible to utilize the 7.5 Hz separated ring power multiplied DSB signal as an effective AM carrier, if desired.

In our experiments during the day, D region absorption must have kept the sky wave signal from building up. Sweeping over the same modulation frequencies made no change in the received field strength when done during December between 8AM to 5 PM. (The D layer is present during sunshine hours, but absent at night.) At night, one would expect a thin E layer at 100-125 km and an F2 layer in the range of 250-350 km. The observed 1500 Hz peak would correspond to a half-wave resonance for H = 100 km. The 2700 Hz would correspond to a full-wave resonance for H = 110 km.

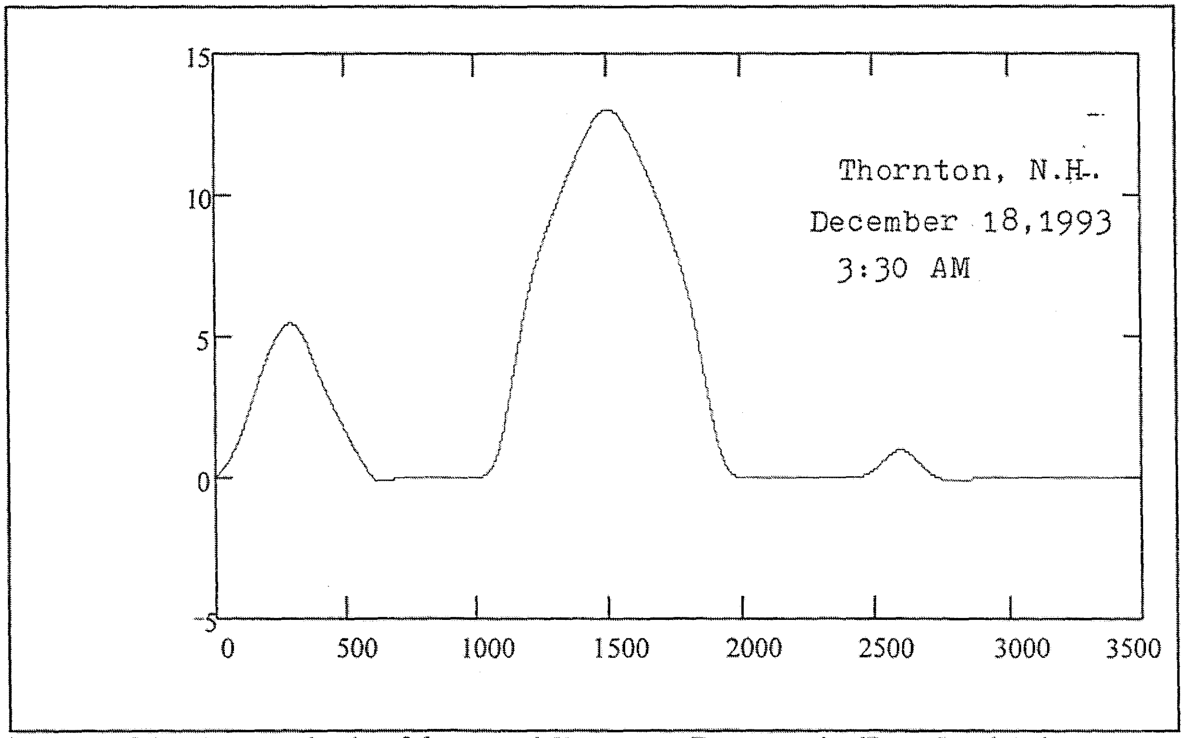

Figure III-1. Measured gain of the natural Transverse Resonator in dB vs. Modulation Frequency in Hz for a 1.8 MHz carrier.

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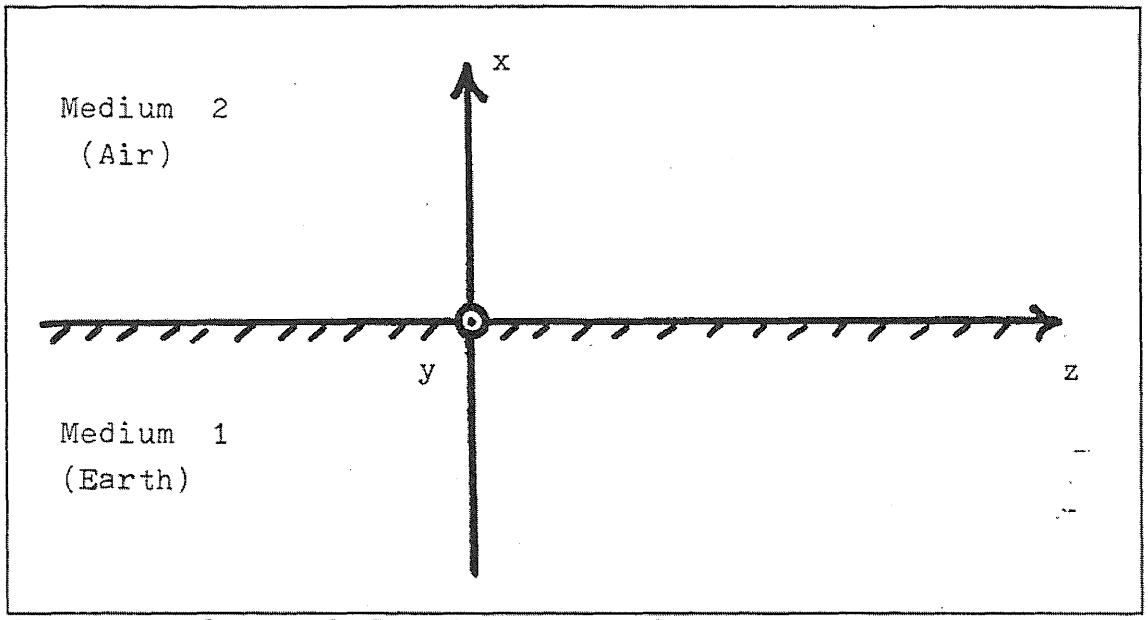

Figure 1. Geometry for Zenneck wave propagation.

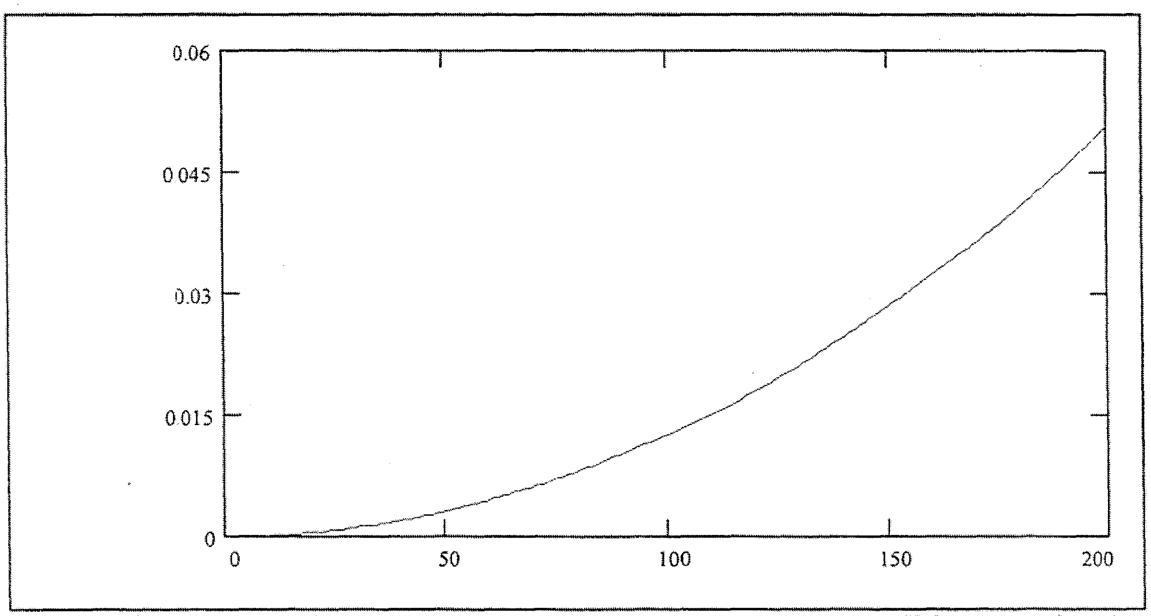

Figure 2. Zenneck longitudinal attenuation $\alpha_z(f)$ over sea water in dB/Mm as a function of frequency in kHz.