NIKOLA TESLA AND THE WIRELESS TRANSMISSION OF ENERGY

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Abstract - Nikola Tesla, the inventor of the polyphase-current system, is best known for his contribution regarding induction and other types of alternating-current machines. His patents and his published and unpublished notes about wireless transmission of energy are less known and, if known to some extent, they are usually wrongly interpreted. For many years the author studied Tesla´s works on wireless transmission of energy and that what is given here is a review of relevant documents, unpublished notes and letters from the archives of the Nikola Tesla Museum in Belgrade. An attempt is made to explain Tesla´s physical model on the basis of which he concluded that the wireless transmission of energy on a global scale is possible. His model is critically examined in view of the present day knowledge of extremely low frequency propagation phenomena.

INTRODUCTION

Nikola Tesla, a prolific inventor, well known for his contributions to the present day alternating current system, and less known for his important discoveries in the high frequency field, devoted nearly fifty years to developing his ideas of wireless transmission of energy. When he began to think about it, some time in 1890 - 91, only a few facts were known about electromagnetic waves. Following the publication of Hertz´s research in 1888, which provided confirmation of J. Clark Maxwell´s dynamic theory of the electromagnetic field of 1865, scientists became more and more convinced that electromagnetic waves behaved like light waves, propagating in straight lines. This led to pessimistic conclusions about the possible range of radio stations, which were soon refuted by experiments using the antenna-earth system designed by Tesla in 1893. Tesla invented "open resonant circuit" with one condenser plate in the earth and the other elevated above the earth surface. Such open resonant circuits were used at the transmitting and the receiving sides. Tesla thought that the electric energy could be transmitted through the globe just as through a good conductor. For many years the author searched through Tesla´s written and unpublished notes in order to obtain a complete picture of the Tesla wireless transmission model. That which was published about it at the beginning of this century did more harm than good to Tesla. It was only recently that Tesla´s name reappeared in papers dealing with the propagation of extremely low frequency (ELF) radio waves and the resonance of the earth |1,2,3|. In spite of the fact that Tesla´s model of energy transmission is oversimplified and lacking a mathematical rigor, it is fascinating in that it provides some insight to the very recent development in the ELF field where electromagnetic waves with low attenuation, as predicted by Tesla, are possible.

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SOME EARLY EXPERIMENTS ON WIRELESS TRANSMISSION OF ENERGY

In 1881 Nikola Tesla invented the high frequency, high voltage transformer known since that time as "The Tesla Coil." This transformer contained little or no iron and still could easily, and with a high efficiency, produce extremely high voltages. With this kind of transformer, connected as a part of a coupled oscillatory circuit with a spark gap driven by the low frequency AC or DC source, Tesla produced strong electric field in his laboratory which could produce light in passing through a rarefied gas tube. He was impressed by the efficiency of this kind of light generation and invented several types of gas lamps which produced light that is "soft and agreeable to the eye, closely resembling daylight." The first record of the Tesla coil is to be found in Patent No. 454 622 of June 23, 1891, under the title "System of electric lighting."

The idea that the electric energy could be transmitted through one wire, or no wires, seems to appear for the first time in connection with the Tesla system of electric lighting. Subsequently, Tesla presented much new information about the discharge oscillator and his further research on high frequency currents in the lecture he gave to the IEE in London, February 1892 which he repeated in London and then in Paris |4|. It was there that he gave once again open demonstration of his "single wire" lamps. He noted that HF currents readily passed through slightly rarefied gas and suggested that this might be used for driving motors and lamps at considerable distance from the source, the high frequency resonant transformer being an important component in such a system |3|.

In February 1893 Tesla held a third lecture on high frequency currents before the Franklin Institute in Philadelphia, and repeated it in March before the National Electric Light Association in St. Louis |4|. The most significant part of this lecture is that which refers to a system for "transmitting intelligence or perhaps power, to any distance through the earth or environning medium." What Tesla described here is recognized to be the foundation of some important principles and ideas of radio engineering, viz.: "the idea of inductive coupling between the driving and the working circuits; the importance of tuning both circuits, that is, the idea of an "oscillation transformer", and the idea of a capacitance loaded open secondary circuit |5|".

To Tesla, transmitting intelligence in 1893 seemed to be an established fact as can be judged from his words: "I no longer look upon this plan of energy or intelligence transmission as a mere theoretical possibility, but as a serious problem in electrical engineering, which must be carried out some day." From his numerous experiments he concluded that the transmission of HF currents through a single conductor was possible. The next step in his reasoning was to replace the single conductor with the earth. To him the earth behave as a smooth perfectly conducting ball. In 1893 he wanted to find out the capacity of the earth, and what was its charge if electrified. He thought of disturbing the electric charge of the earth and detecting the period of the charge oscillation. It is fascinating that at that

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moment of radio development he thought of the earth resonance! It was about five years after Hertz's experiments, and at the moment when the radio waves could be detected within the laboratory distance. Tesla, also in 1893, speculated about "the upper strata of the air that are conducting" and their possible role in the transmission process.

In the period 1893 to 1897 Tesla invented and constructed many types of HF spark-gap oscillators and improved the design of his HF transformer. In 1897 he was granted a patent entitled "Electrical Transformer" (No. 593 138, Nov. 2, 1897) in which he thoroughly explained how to design his HF transformer. The transformer had no iron core and the amount of copper was small. The primary coil had few turns of stranded copper wire wound around the secondary coil. Tesla tried cylindrical, conical and spiral coil shapes. For the best results he recommended that the length of the secondary coil of his transformer should approximately be "one quarter of the wave length of the electrical disturbance in the secondary circuit." This was somehow an optimized version of the Tesla coil from 1891, designed to produce a maximum secondary voltage. In the above mentioned patent Tesla described a single wire power transmission system with step up and step down resonant transformers. In fact, it was a single phase transmission system with the ground replacing one wire.

Developing further his "single wire" transmission system, Tesla concluded that the remaining copper conductor, connecting the two high tension terminals, could be removed, providing each terminal was connected to a body of large surface. He thought that by using extremely high voltages applied to the body of large surface (antenna), the current that leaks from the high tension terminal would render higher air strata conductive. Since the limiting pressure at which the gas becomes a good conductor is higher the higher the voltage, he maintained that it would not be necessary to elevate a metal conductor to an altitude of some 15 miles above sea level, but that layers of the atmosphere which could be good conductors could be reached by an antenna at much lover altitudes. Claims like this did not seem much convincing in 1897, so Tesla had to perform an experimental demonstration of power transmission through rarefied gas before an official of the Patent Office. From an original Tesla slide and the Patent No. 645 576, March 20, 1900 (applied Sept. 2, 1897), it was found that Tesla connected the two high tension terminals through an air column under pressure between 120 and 150 mm Hg isolated from the surrounding air by a glass tube. At this air pressure, and with the transformers tuned to resonance, he claimed that efficient power transfer was achieved with a voltage of 2 - 4 million volts on the transmitter antenna. In the aplication, Tesla also claims patent rights to another, similar method of transmission, also using the earth as one conductor, and conductive high layers of the atmosphere as the other.

COLORADO SPRINGS LABORATORY

In the Houston Street laboratory in New York, Tesla made several high voltage Tesla coils but the space was limited there, and in 1898 he began looking for a site for a new laboratory. In mid-1899 he finally decided on Colorado Springs, a plateau about 2000 m above sea level, where he erected a shed large enough to house a high-frequency transformer with a coil diameter of 15 meters [3]! In his article "The transmission of electric energy without wires," written in 1904 in The Electrical World and Engineer (reprinted in [1]), Tesla writes that he came to Colorado Springs with the following goals:

1. To develop a transmitter of great power.
2. To perfect means for individualizing and isolating the energy transmitted.
3. To ascertain the law of propagation of currents through the earth and the atmosphere.

During his eight months stay in Colorado Springs Tesla wrote notes with a detailed day-by-day description of his research. Unlike many other records in the archives of the Nikola Tesla Museum in Belgrade, the Colorado Springs diary is continuous and orderly. Most likely, it was not intended for publication but he kept it as a record of his research. Tesla had an unhappy remembrance of the fire which in 1895 destroyed his laboratory in New York. In Colorado Springs he performed dangerous experiments and he could easily burn his own laboratory. So the Notes could also have been a safety measure.

In Colorado Springs Tesla certainly thought a lot about his wireless transmission of energy but did not write much about it in his diary. He devoted most of his time (56%) to the development, measurements and tests of his huge Tesla coil, about 21% to developing receivers for small signals, about 16% to measuring the capacity of the vertical antenna, and about 6% to miscellaneous other research. Among the latter were some interesting remarks on the fire balls which he claimed to have produced. He described some wireless energy transmission but all one could see in the diary points to transmission over short distances.

One day (July 4, 1899) Tesla recorded unusual behavior of his thunderstrom recording instrument, a rotating coherer device. He noticed periodic recording of the instrument when the storm approached and receded from his laboratory. He concluded that it showed clearly the existence of stationary waves. He speculated about the point of their reflection but, what is most important, he was convinced that the stationary waves could be produced with his oscillator. In his idealized earth model he expected to notice the reflected waves from the opposite side of the earth. However, it was in vain. In Colorado Springs Tesla did not use sufficiently low frequencies so that he could not detect expected peculiar behavior of the electromagnetic waves radiated from his mighty Tesla coil. It will be shown later that he made the necessary correction to the choice of operating frequency, but, unfortunately, he did not perform an experiment that would prove what he claimed.

LONG ISLAND LABORATORY

After returning to New York from Colorado Springs laboratory, Tesla took energetic steps to get backing for the implementation of a system of "World Telegraphy." With the significant financial help of J. Pierpont Morgan and "unselfish and valuable assistance" of his friend Stanford White, architect, Tesla built a laboratory and nearly finished the transmitting tower (capacitively loaded monopole antenna). The work on this plant began in 1900 and was very intensive in the following three to four years.

In a letter to his sponsor J. Pierpont Morgan, early in 1902, Tesla explained in details his research aims, in which he envisaged three "distinct steps to be made: 1) the transmission of minute amounts of energy and the production of feeble effects, barely perceptible by sensitive devices; 2) the transmission of notable amounts of energy dispensing with the necessity of sensitive devices and enabling the positive operation of any kind of apparatus requiring a small amount of power; and 3) the transmission of power in amounts of industrial significance. With the completion of my present undertaking the first step will be made." For the experiments with transmission of large power he envisaged the construction of a plant at Niagara to generate about 100 million volts. In 1904 he wrote to Morgan that "The Canadian Niagara Co. will agree in writting to furnish me 10 000 H.P. for twenty years without charge, if I put up a plant there to transmit this power without wires to other parts of the world..." [6]. As far as is known nothing came out of this plan. At that

moment Tesla was "financially in a dreadfull fix," as he explained his situation to Morgan after he refused to advance more money to Tesla in order to finish his telegraphy plant at Long Island [9].

In searching through the archives of the Nikola Tesla Museum in Belgrade, many notes have been found relative to his Long Island research. The notes are scarce in 1901, more numerous in 1901 to 1903 and again rare in 1904, and hardly any in 1905 and 1906. In 1900 he prepared to work in the new laboratory and had to complete several patent applications. Among these patents is the one submitted on May 16, 1900 which is closely related to his wireless transmission plans. It was renewed June 17, 1902, and issued on April 18, 1905, under the title "Art of transmitting electrical energy through the natural mediums" (No. 787 412). Many of Tesla's complicated explanations in this patent become more clear and even more acceptable, if his Long Island notes are studied. For example, when he states that "the rate

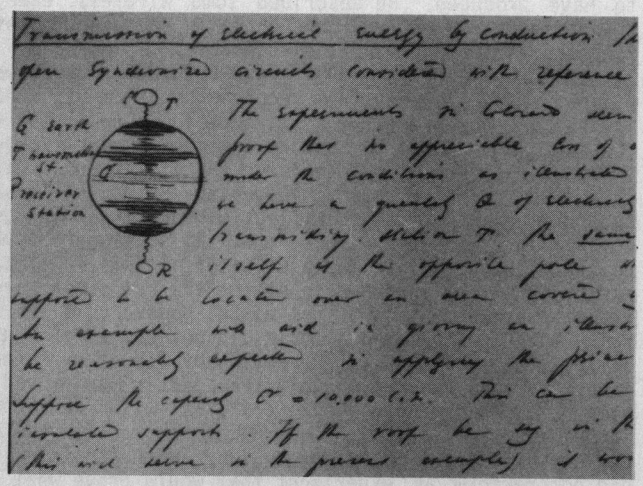


Fig.1. Long Island Notes: (June 2, 1901) showing Tesla's model of transmission through the earth. T, G, R are transmitting station, earth and receiving station, respectively.

of radiation of energy in the form of hertzian or electromagnetic waves is very small," one may think that this is a nonsense. But when one read in his notes that he tried to select the operating frequency in such a way that the dipole formed by the globe and the elevated ball (antenna) radiates little according to Hertz and Maxwell's formulas, one has to reconsider the judgment and think in terms of ELF propagation phenomena [7]. Tesla made calculations for operating frequencies 4, 6, 60 Hz, and at somewhat higher frequencies of 15 and 20 kHz. Particularly at the lower frequencies he expected the resonance of the earth to occur. It is enchanting that he calculated the lowest resonant frequency of the earth to be 6 Hz, while a very elaborate theory of today predicts 10.5 Hz (losses neglected), and the actual measurements gave resonant peak at about 8 Hz. Tesla assumed that the earth behavies like a conducting ball through which the current passes as shown in Fig.1. Tesla also predicted that at the antinodes R, the effects will be pronounced as the current density is the highest there. He also predicted that the standing waves could be set around the globe, and that, in contrast to classical electromagnetic wave propagation, the field at some points may increase with the distance from the transmitter! Just to illustrate that this is possible at ELF a plot is given of the principal fields in the Earth-ionosphere waveguide radiated by a vertical dipole from a recent book [8] on this subject (Fig.2). As is clearly seen, at the operating frequency of 75 Hz,

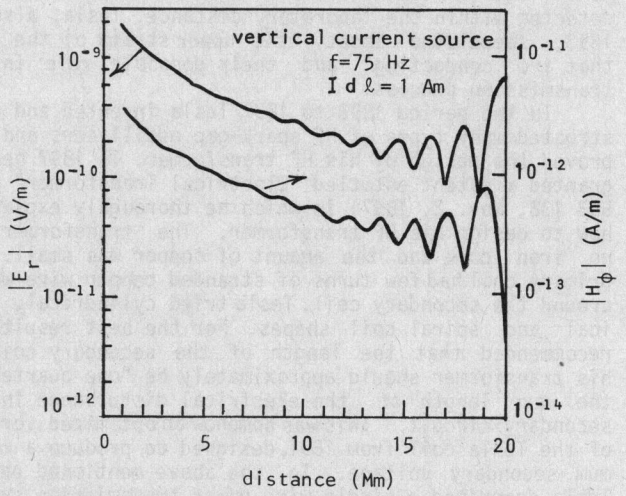


Fig.2. Principal fields in the Earth-ionosphere waveguide radiated by a vertical electric current source [8].

the fields, from about 4 Mm show the characteristic standing wave pattern, most pronounced around the antinode at 20 Mm, and do not decay inversely with distance which is the characteristic of the radiation field.

Unfortunately, the radiating systems at ELF are very inefficient. Tesla thought about that, too. As the radiating antenna he suggested the use of a vertical monopole (15 miles long or so) or two plates burried some distance appart. To illustrate this point some of his drawing, probably prepared for a patent application, are shown in Fig.3. The similarity with some present day ELF antennas cannot be overlooked. However, one knows that the efficiency of ELF atnennas are, in general, very small. As an example let be quoted some relevant data for a typical ELF antenna operating at 45 Hz. For a grid antenna of total length of 10^6m, the efficiency of the antenna is only 0.026 percent! Even a very low attenuation of the electromagnetic wave at this frequency, which is only 0.8 dB/Mm, cannot help much. If another similar antenna is used at the receiving side, the efficiency of the whole system would be, roughly, $(0.0026)^2$percent* As the operating frequency is increased, the efficiency of the transmission system increases, but then the attenuation of the wave in the propagation rapidly increases and the overall efficiency is again very low. From various experimental data, approximate values of attenuation at several frequencies of interest are given in the following table: [7]

Carrier frequency Hz	10	50	100	300	1000
Attenuation dB/Mm	0.25	0.80	1.00	3.00	20.00

If the antenna size is specified, it would be possible to calculate the overall efficiency of ELF system as a function of distance and frequency. Such a calculation is hardly necessary if a large distance system is required. The antenna efficiency of reasonable size is high enough at about 20 kHz, where the attenuation of the wave in propagation is too high. For example, an antenna that is made in the form of two umbrella shaped top loaded monopoles, each of 2 km in diameter and some 250 m high, with the grounding system of some 3000 km

* neglecting attenuation in propagation

of copper wire, has 86% efficiency at 20 kHz and only 0.1% at 100 Hz [8]. Hence, it is possible that the efficiency of the system may vary with frequency and distance but it will be always very low. Thus, at present, ELF systems are used in communication with objects under the sea, where one can make use of the property of ELF waves to penetrate to deeply submerged receiving antennas.

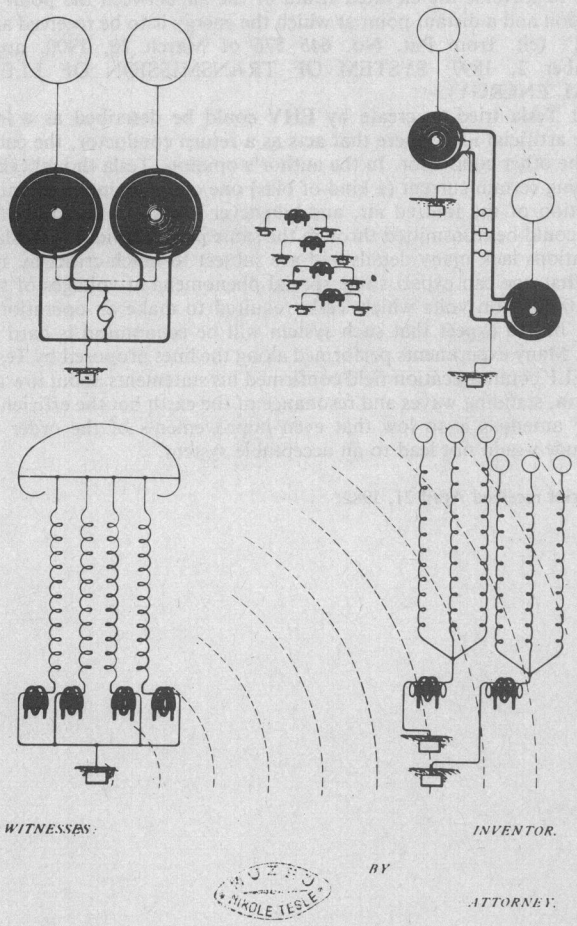


Fig.3. Arrangements of Tesla's antennas. The drawings were, probably, prepared for a patent application (Nikola Tesla Museum, Belgrade).

CONCLUSIONS

For many years Nikola Tesla tried to realize wireless transmission of energy on a large scale. From the initial steps in 1891, when he produced light in single wire or no wire gas tubes within laboratory distance, he gradually improved his wireless energy transmission system. In Colorado Springs he lighted a few lamps some distance apart from the huge transmitter that produced open circuit voltage of about ten million volts. He was convinced that at sufficiently low frequencies, low attenuation and standing waves characterize the behavior of his transmission system. He also predicted that at very low frequency the earth resonances could be set. His concept of energy flow (through the earth!) was peculiar and to some extent misleading. Tesla did not manage to turn attention of the world to his ideas of wireless energy transmission, but some of his statement and visions were proved much later when the research into ELF propagation phenomena began about a half century later. Today is known that Tesla was right in that at low frequencies certain waves can propagate with little attenuation, that the standing waves can be set and that the earth resonates. Regarding energy transmission is known that the overall efficiency of an ELF system is very low for antennas of reasonable sizes irrespective of the fact that the attenuation of electromagnetic waves at very low frequencies is very small. Thus, at present, ELF transmission systems seem to be of use only in some special communication systems with buried receiving antennas.

REFERENCES

[1] J. R. Wait, "Historical background and introduction to the special issue on extremely low frequency (ELF) propagation," IEEE Transactions on Communications, vol. COM-22, pp. 353-354, April 1974.

[2] J. D. Jackson, Classical Electrodynamics. New York: John Wiley, 1975.

[3] A. S. Marinčić, "Introduction and Commentaries" in Nikola Tesla, Colorado Springs Notes 1899-1900, Belgrade: Nolit, 1976.

[4] N. Tesla, Lectures ,Patents, Articles. Belgrade: Museum Nikola Tesla, 1976.

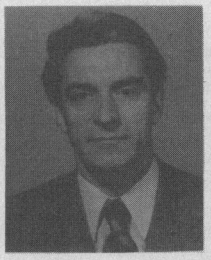
[5] L. P. Wheeler, "Tesla's contribution to high frequency," Electr.Engineering, New York, August 1943.

[6] Letters of Nikola Tesla to J. Pierpont Morgan: Jan. 9, 1902 and Jan. 13, 1904. Belgrade: Archives of Nikola Tesla Museum.

[7] J. R. Wait, "Propagation of ELF electromagnetic waves and project Sanguine/Seafarer," IEEE Journal of Oceanic Engineering, vol. OE-2, pp. 161-172, April 1977.

[8] M. L. Burrows,ELF Communication Antennas.Stevenage Peter Peregrinus, 1978.

[9] G. D. Friedlander, "Tesla: eccentric genius", IEEE Spectrum, pp.26-29, June 1972.



Aleksandar S. Marinčić was born in Sinj, Yugoslavia, on July 9, 1933. He received the Dipl. Ing., and P.G.D. degrees from the University of Belgrade, Yugoslavia, in 1956 and 1957, respectively, and Ph.D. degree from the University of Sheffield, England, in 1963, all in electrical engineering.

From 1958 - 1967 he was with the Department of Electrical Engineering,University of Belgrade; from 1967 - 1971 he was Visiting Professor, UNESCO expert and Actting Chief Technical Adviser at the Middle East Technical University of Ankara, Turkey. From 1971 - 1974 he was an Associate Professor in the Department of Electronics Engineering, University of Niš, Yugoslavia. In 1974 he again joined the Department of Electrical Engineering, University of Belgrade, and is now a Professor of Electrical Engineering. He is editor in chief of Yugoslav electrical engineers´periodical"Elektrotehnika". His areas of interest include antenna and propagation and microwaves fields in which he published numerous papers.

Discussion

G. T. Heydt (Purdue University, West Lafayette, IN): This paper is a fascinating summary of Nikola Tesla's research on the wireless transmission of electric energy. It is somewhat amazing that Tesla could calculate the resonant frequency of the Earth to the 6 Hz which agrees so well with actual modern measurements. What method did Tesla use in this calculation?

I would also like to ask the author to conjecture on the future of wireless transmission of electrical energy at high power levels. Was it the limitation of Tesla's equipment which causes the apparent lack of success in this work?

I hope that Professor Marincic will publish additional papers on this topic through the IEEE Power Engineering Society. On behalf of all power engineers, I would like to thank the author for bringing to us some comments on the very foundations of power engineering and the early history of phenomena which are the basis of our profession.

Manuscript received February 17, 1982.

A. S. Marincic: I would like to thank Mr. G. T. Heydt for the interest shown in Nikola Tesla's research on the wireless transmission of energy and for interesting and stimulating discussion.

The method that Nikola Tesla used in the calculation of the Earth resonance is simple. In his patent ART OF TRANSMITTING ELECTRICAL ENERGY THROUGH NATURAL MEDIUMS (Pat. No. 787 412 of April 18, 1905, appl. May 16, 1900) it is stated that there are three requirements essential to the establishment of the resonating conditions:

1. That the earth's diameter passing through the pole should be an odd multiple of the quarter wavelength;
2. That the oscillation be used in which the radiation is small; and
3. That the wave train should continue for a certain interval of time so that the wave return from the region diametrically opposite the pole.

Based on 1. Tesla calculated that the lowest resonating frequency would be "six per second, in which case there will be but one node, at or near the ground plate, and paradoxical as it may seem, the effect will increase with the distance and will be the greatest in the region diametrically opposite the transmitter."

In the early days of developing the idea of wireless transmission of energy Tesla thought that by placing metal plates in the ground and high in the air (about fifteen miles) one would make a system in which a large amount of energy could be transmitted through a basically "two-wire" system; one conductor in such a system would be the earth and the other rarefied air at high altitudes. Tesla was aware of "the mechanical arts" difficulties and proposed to use extremely high voltages (EHV) "of such character and magnitude as to cause thereby a current to traverse the elevated strata of the air between the point of generation and a distant point at which the energy is to be received and utilized" (cit. from Pat. No. 645 576 of March 20, 1900, appl. September 2, 1897: SYSTEM OF TRANSMISSION OF ELECTRICAL ENERGY).

What Tesla tried to create by EHV could be described as a low altitude artificial ionosphere that acts as a return conductor, the earth being the other conductor. In the author's opinion, Tesla thought that by passing certain current (a kind of bias) one could maintain the high conduction of the ionized air, and whenever necessary an additional energy could be transmitted through the same path. Obviously, Tesla's explanations lack many details and are subject to much criticism. No doubt that one can expect some special phenomena at voltages of the order 100 million volts which Tesla required to make an operational system, but to expect that such system will be economical is hard to believe. Many experiments performed along the lines proposed by Tesla in the ELF communication field confirmed his statements about low attenuation, standing waves and resonance of the earth but the efficiency of ELF antennas is so low that even improvements of the order of magnitude would not lead to an acceptable system.

Manuscript received April 21, 1982.