Thunderbolt Induced Earth Tremors

by R.C. Maglic
Honeywell Solid State Electronics
Colorado Springs, Colorado

A thunderbolt interacts with slightly piezoelectric earth crust setting off an elastic Surface Acoustic Wave (SAW) along with the Bulk Waves. The round trip travel times for reflection of these waves can account for the observations Tesla made in Colorado Springs. No standing EM waves are invoked.

1. Observations

During his short stay in Colorado Springs, Tesla made numerous observations of lightning in the sky. He considered these findings of "immense importance," as can be well understood once his scientific goals in the United States were known. Figure 1a shows the equipment that he used for the measurements.

Tesla's observations made on July 4, 1899, ref. 1, p. 61, read as follows:

> "As the storm receded, the most interesting and valuable observation was made. After adjusting the instrument sensitivity (relay) so that it responds to every discharge, 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 been approximately 50 miles away. All of a sudden, the instrument again began to play . . ."

The above activity repeated with a period of about one-half hour = 1,800 sec., Figure 1b. Tesla's comment:

> "It showed clearly the existence of stationary waves, for how could the observations be otherwise explained? . . ."

2. Difficulties in the Explanation

Tesla offered two alternative explanations for the origin of stationary waves:

a. Reflection of an original EM Wave from the the cloud which generated it (preferred explanation).
b. Reflection of the original Wave from "opposite point of the Earth's surface."

Figure 2 shows his explanation No. 1. A cloud originating a thunderbolt is approximately 1 km high. The round trip time is only six micro-seconds. Clearly, it is hard to imagine formation of a standing wave with periodicity of T = 1800 seconds under these circumstances.

It is also hard to understand Tesla's second explanation of standing wave formation. One possible interpretation of Tesla's explanation No. 2 is that a thunderbolt excites an electromagnetic wave which goes through the earth's center and bounces back from the point on the earth's surface just opposite of the starting point; the travel time for this path is 4R/c = .085 Sec again in disagreement with the observations. Higher harmonics would disagree even worse. The main objection to this model is the propagation of electromagnetic waves through conducting earth. In particular, propagation through metalic center. Consequently, rather than to follow Tesla's vague explanation literally, we calculate the travel time of an EM-Wave, originating at the lightning site (Colorado Springs Lab) and bouncing between conducting earth and the ionosphere around the Earth, Figure 3a. If the wave bounces N times off of the ionosphere, one finds for the travel time:

1) $$T = \frac{2aN}{c}$$

where c is the speed of light, and a is the distance described in Figure 3b.

2) $$a = R\,\frac{\sin\alpha}{\sin\beta}$$

R, the spherical Earth radius is 6,370 km; angle $\alpha = \frac{\pi}{N}$ and ß is found from:

3) $$\operatorname{tg}\beta = \frac{\sin\alpha}{1+\xi-\cos\alpha}$$

ξ = h/R = .0314 since the F2 ionosphere-band is about h = 200 Km high above the ground. For Earth's data see Markus Beth's book, [2]. For N = 100, it follows α = 1.8 degrees and ß = 44.56 degrees. The distance a = 285.2 Km, therefore T = .19 seconds. This certainly is not satisfactory.

Alternatively, one can calculate N to get the desired T-value. For example:

4) $$N = \frac{Tc}{2a} = \frac{Tc}{2R}\left[1+(1+\xi)^2-2(1+\xi)\cos\alpha\right]^{-\frac{1}{2}}$$

since $$\sin\beta = \sin\alpha\left[1+(1+\xi)^2-2(1+\xi)\cos\alpha\right]^{-\frac{1}{2}}.$$

As $$\alpha = \pi/N$$

5) $$B - C\cos\alpha = A^2\alpha^2$$

with $$A = \frac{Tc}{2\pi R} \qquad B = 1+(1+\xi)^2$$

and $$C = 2(1+\xi)$$

Tesla's Observation of Standing Waves, July 1899

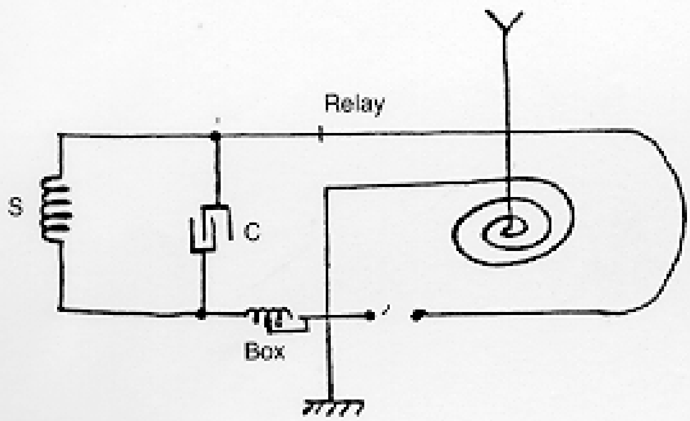


Figure 1a *Equipment Used*

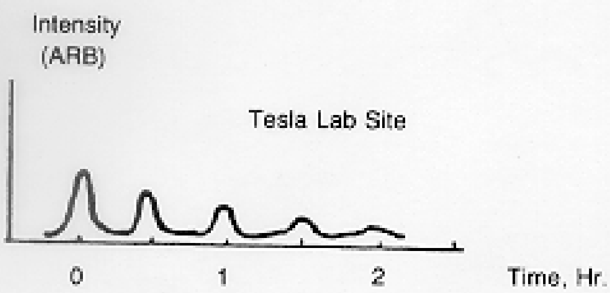


Figure 1b *Results*

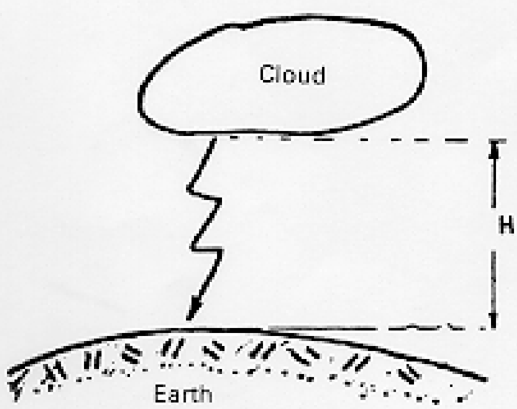


Figure 2 *Tesla's Explanation #1*

So $\frac{c}{B} = 2(1+3)/[1+(1+3)^2] \approx 0.9996$ for this case. Furthermore, for small α

$$1 - \frac{c}{B} = \frac{1}{B}\left(A^2 - \frac{1}{2}C\right)\alpha^2$$

$\therefore \alpha = 2.4 \cdot 10^{-6}\,\text{rad}$, , indeed a small angle.

However, this implies $N = 1.3 \cdot 10^6$ with a bouncing distance (adjacent) $2 \cdot \alpha \cdot R$ = 30m! This is an absurd result and is not worth further discussion.

We could try to "save" this model by assuming "incommensurate bounces." The EM Wave would go several times around the Earth before bouncing off at the right spot in, say, the Colorado Springs Lab. Another way of looking into wave propagation in the ionosphere is to assume wave-guide above the earth's surface. The lowest resonant frequency of this cavity is only approximately 8 Hz which is in disagreement with Tesla. This so-called Schumann Resonance will be discussed at the end.

Rather than pursuing these EM models further, we will examine a model where the Earth vibration may explain the data of Figure 1b. Tesla's observations utilizing the relay may have been sensitive to these.

3. Alternate Model

We propose to investigate the following problem: the Earth's surface, hit with a lightning discharge (about four coulombs, [3]), is instantaneously subjected to high electric field E. This electric field causes atomic displacements in a piezoelectric media of the Earth's crust (the Earth's crust is predominantly $S10_2$ quartz-like). Four types of Earth responses are possible:

a. Generation of Bulk Seismic Waves
b. Generation of Surface Seismic Waves
c. Love waves along discontinuities
d. Free Vibrations of Earth's Sphere

Since the mode is excited only by large earthquakes (energy released in excess of 10^{17} Joule), we do not consider it further here. We estimated the energy release in a thunderbolt as approximately 10^{10} Joule ($Q^2/2C$, C-capacity of a cloud-ground).

Love waves, c, are less frequent and so we disregard them here. The seismological records show high frequency of seismic waves belonging to category b, Figure 4 and reference [2]. These are Rayleigh waves or, called differently, Surface Acoustic Waves (SAW).

Bulk waves are normally excited either as longitudinal or transverse modes.

4. Details

A. *General:* We assume that the Earth's crust is made of $S10_2$ exclusively. This is not completely true, but will be assumed here for the purpose of an order-of-magnitude calculation. $S10_2$ is polycrystalline with a density of S = 2.65 g/cm^3. In the crystalline form, it is trigonal, symmetry class 32. The stress tensor T_J is:

6) $$T_J = C^E_{JK} S_K - e_{Ji} E_i$$

Where index J is contracted i, j symbol; J = 1 to 6. S_K and E_i are strain tensor and electric field in direction K and i respectively. The constant C_{JK}, four-dimensional stiffness tensor is

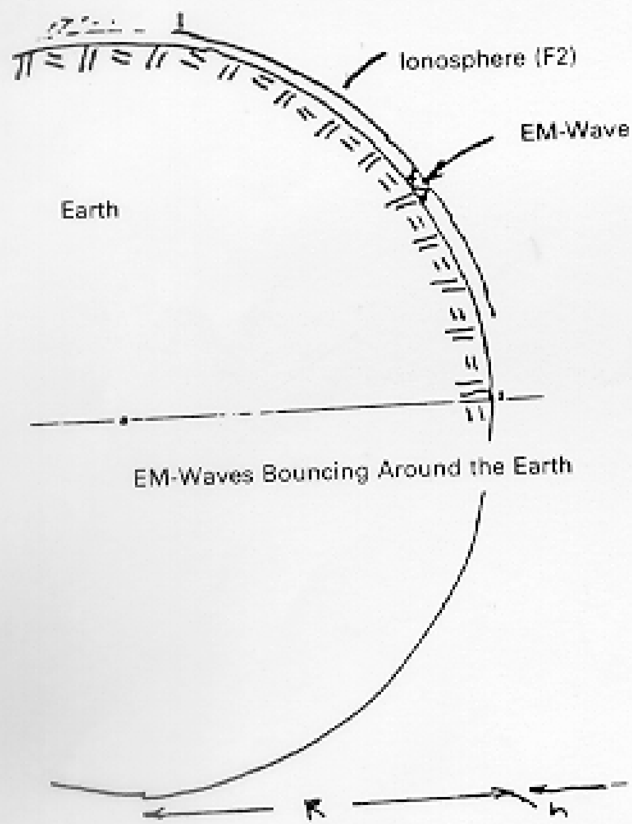


Figure 3a *Tesla's Explanation #2 (Modified)*

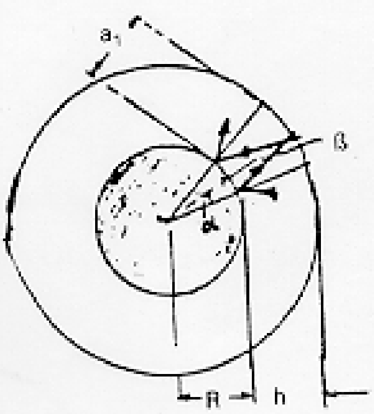


Figure 3b *Reflection Geometry*

symmetric:

C^E =

86.74	6.99	11.91	−17.91	0	0
	86.74	11.91	17.91	0	0
		107.2	0	0	0
			57.94	0	0
				57.94	−12.91
					39.87

C^E is given in GPa while the three dimensional piezoelectric tensor in C/m^2,

7) e =

.171	−.171	0	.044	0	0
.	.	.	.	−.044	−.171
.	.	.	.	.	.

B. *Initial Strain at "Ground Zero":*

Assuming, first, electric interaction only $S_K \neq 0$:

$$T_I \sim -\sum_i^3 e_{Ii} E_i \sim -e_{AVE} E_x = Y S_o$$

for x-direction, say. Y is the average Young modulus. We have:

8) $$S_o = \frac{1}{Y} e_{AVE} E$$

where E is the electric field, volt/m, of the lightning. We estimate the electric field at the impact site as follows: Figure 4b shows an approximate way of calculating the electric field with the following values:

r_1 = 10 cm, r_2 = 50 cm, H = 36 cm

The capacity for this cylindrical symmetry is:

9) $$C = 2\pi\varepsilon \frac{H}{\ln \frac{r_2}{r_1}} = 156 \ \mathrm{pF}$$

assuming an average dielectric constant (ε is also a tensor), $\varepsilon = 4.5\varepsilon_o$. In the above model, we assume a lightning to create highly conducive core of diameter $2r_1$, surrounded by $S10_2$. The field E is in the radial direction.

By using quoted charge Q carried by a lightning, we find $V = Q/C \doteq 2.5 \cdot 10^{10}$ volt and

10) $$E = \frac{V}{r} \sim 5 \cdot 10^{10} \ \mathrm{volt/m}$$

This is the thunderbolt field we will use in this calculation for earth tremor estimates.

Returning now to Eq. (8), we find initial strain of ground:

11) $$S_o = \frac{1}{86.7 \cdot 10^9} \ .171 \ 5 \cdot 10^{10} = .1$$

i.e., 10% local strain. We took here $Y \sim C^E_{11}$. The corresponding stress is, of course, $1.2 \cdot 10^6$ psi. (This is higher than the $S10^2$'s elastic limit.)

Often quoted piezoelectric constant of quartz, reference [4], $d = 3.3 \cdot 10^{-12}$ m/volt agree well with the estimate given above ($e = Yd = 3.3 \cdot 10^{-12} \cdot 86.74\ 10^9 = .286$ C/m^2 to be compared with .171 C/m^2 used above).

C. *Effect of Ground Heating:* From $L = Lo \cdot (1 + \alpha\Delta T)$, one finds the temperature strain to be $\alpha \cdot \Delta T$. If SiO_2 locally melts, T = 1,710 degrees Centigrade, it will expand ($\alpha = 5 \cdot 10^{-6}\ {}^\circ C^{-1}$) so that:

$$S_{oT} = 5 \cdot 10^{-7} (1710 - 300) = 7 \cdot 10^{-4}$$

This is much smaller than S_O calculated before. Therefore, we will neglect it.

D. *Wave Velocities:* Consider a semi infinite medium bounded by an interface plane perpendicular to, say, the z-axis. We have air for $z > 0$, say, and SiO_2 for negative z. Longitudinal and transverse waves propagate in SiO_2 subject to the boundary condition at the interface. This leads to a dispersion relationship:

12) $$\zeta^6 - 8\zeta^4 + 8(3-2\eta^2)\zeta^2 = 16(1-\eta^2)$$

where ζ and η are:

13) $$\zeta = \frac{v_{SAW}}{v_S} \qquad \eta = \frac{v_S}{v_L} < 1$$

v_S is the transverse-wave velocity. Since η is given by:

14) $$\eta = \sqrt{\frac{C_{11}-C_{12}}{2C_{11}}} = .678$$

Equation (12) can be solved for ζ, ζ_0. We find for SiO_2, ζ_0 = .888. As v_L is found in Tables, Reference [5], = 5740 m/sec., both v_S and v_{SAW} are found:

15) $$v_S = \eta v_L = 3892 \frac{m}{sec}$$
$$v_{SAW} = \zeta_0 v_S = 3455 \frac{m}{sec}$$

It can be noted that both ζ_0 and ζ_{SAW} can be calculated approximately according to Ristic [5], p. 95:

16) $$\zeta_0 = \frac{.87 + 1.12\mu}{1+\mu} = .887$$
$$v_{SAW} = \sqrt{\frac{C_{11}-C_{12}}{2\rho}}\left(1 - \frac{.13}{1+2\frac{C_{12}}{C_{11}}}\right) = 3445 \frac{m}{sec}$$

Poisson ratio being μ = .075.

E. *SAW Polarization:* The surface waves have only two components (Sagittal Plane) in the direction of propagation (say x) and perpendicular to interface (z). The ratio of the two for our SAW at ground zero is (Fig. 5):

17) $$\frac{v_x}{v_z} = \frac{1}{\sqrt{1-\frac{C}{D}}}\left[2D-1-2\sqrt{(D-C)(D-1)}\right] = .756$$

with $C = \frac{.5-\mu}{1-\mu}$; $D = \frac{(1+\mu)^2}{(.87+1.12\mu)^2}$

F. *Attenuation:* Seismic waves propagate through the Earth's crust with a frequency f and wavelength λ related by $v = \lambda f$. Longitudinal wave (e.g.) amplitude is:

18) $$\Phi(x,t) = S_0 e^{i(\omega t - kx)} e^{-\alpha x}$$

with $\omega = 2\pi f$, and $k = 2\pi/\lambda$. α is the attenuation constant in the x direction, Figure 5; Φ is amplitude attenuated due to various dissipative mechanisms. The power carried by the wave is:

19) $$P = \mathcal{R}\{P_0 e^{-2\alpha x}\}$$

where R $\{\ldots\}$ denotes "real-part" and P_O, initial power carried by the wave. The attenuation is defined by

20) $$A = -10 \log \frac{\mathcal{R}(P)}{P_0} = 8.68\,\alpha\,\ell$$

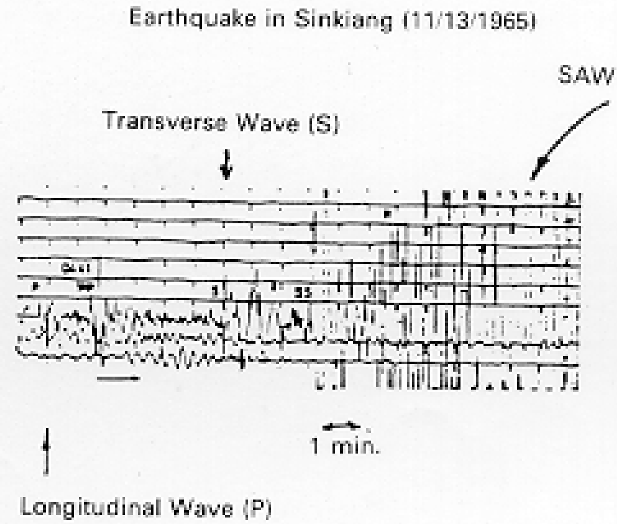


Figure 4a *Typical Seismogramme*

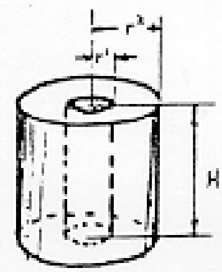


Figure 4b *Electric Field Estimation at "Ground Zero"*

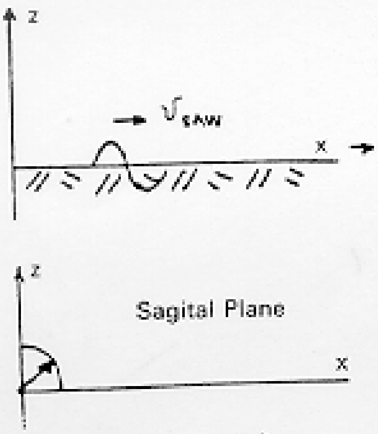
for travel distance, ℓ. A is measured in dB. (For viscous losses α = B · f^2 with $\alpha = \eta w^2/2v^3\rho$). η is the viscosity, P_a · Sec). A has been measured for the Earth: Earth's structure and A are shown on Figure 6 for case when $\ell = \lambda$, as found in literature, [2].

5. Results

We will attempt here to explain Tesla's observations (Figure 1b) using the model of SAW, and perhaps L and S waves propagating through the Earth.

The explanation given here will not be based on standing wave formation. The half-hour peaks may be observed due to wave packet reflection at impedance discontinuities, either for SAW or bulk waves. Multiple peaks in Figure 1b would be due to multiple bouncing of the same wave packet. Tesla's equipment (Figure 1a, notably, the relay) is thought of as earth-shake sensitive.

A. *SAW — Rayleigh Waves:* Colorado Springs is about 1.97 Mm away from the California coast in direct line. Along the surface, this distance may be 50 percent higher, 3.10^6m one-way. If



$$\Phi(x,t) = A e^{i(\omega t - kx)} \cdot e^{\gamma_L z} \cdot e^{-\alpha x}$$

Figure 5 *Surface Acoustic Wave (SAW) Geometry*

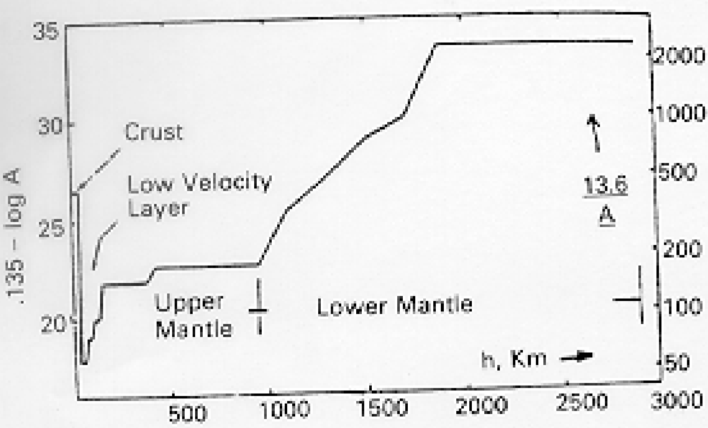


Figure 6 *Attenuation in the Earth*

SAW travels to the shore and back, the travel time would be:

$$T_{SAW} = \frac{6 \cdot 10^6}{3455} = 1737 \text{ sec}$$

NOTE: Typical SAW frequency is approximately .1 Hz, Figure 4.

Attenuation of a SAW with f = .1 Hz. (λ = 3455/.1 = 34.5 Km) is (L/ λ = 174) 4.7 dB or 0.33 in absolute units. This attenuation would be prohibitive for f = 1 Hz.

B. *Bulk Waves:* Seismic Waves (longitudinal L, or transverse, S) may bounce off the discontinuity at the earth's core, 2900km, Figure 6. Results similar to ones for SAW are given in Table I:

Mode	V, m/s	T, s	Attenuation (Hz)
Longitudinal	5740	1010	.12
Transverse	3892	1500	.04
SAW	3455	1737	.33*

*f = .1Hz

Table I

Typical frequency for bulk waves is approximately 1 Hz; for f = 1Hz $\lambda = V/f$ = 5740m for S-waves and 3892m for P-waves.

Table I shows that, in principle, both SAW and S-wave reflections could account for Tesla's findings, if his test was sensitive to Earth tremors. Transverse waves are preferred, however, since their reflection from melted core can account for the multiple peaks Tesla observed.

6. Discussion

The explanation of Tesla's observation made on July 4, 1889, Figure 1b made here does not necessitate standing waves formation. With such low frequency, f = 5.5 · 10^{-4} Hz, it is hard to imagine standing EM-waves. An electromagnetic wave cavity formed by the ionosphere/conducting Earth (Schumann resonance, [6]) cannot form standing waves of this frequency. The lowest Schumann resonance (Reference [6]) is f = c $\sqrt{n(n+1)}$ /(2s – R) = 10.6 Hz for n = 1 (first non-zero mode).

The almost spherical Earth does oscillate with such low frequencies (T = 54 min ⟶ f = 3.1 · 10^{-4} Hz have been observed. For details see Bullen, Ref. [7]. Our model exploits this slower system. To agree with Tesla, we had to *assume* his observations were tremor sensitive.

From a different point of view, one can think of the Earth as a "coupled system": EM cavity (with Schumann energy levels) coupled to seismic subsystem of Earth with its own energy levels. The coupling of two sub-systems is through interaction, perturbation. One form of interaction is piezoelectric, described in this paper. The other is the change of cavity shape due to Seismic waves. If properly done, all energy levels (resonances) of both sub-systems would be shifted:

$$\Delta f = \alpha_1 f_{PE} + \alpha_2 f_{SH}$$

Where PE and SH stand for "piezoelectric" and "shape," respectively, α and α_2 have to be found. Values of α will depend on energy level separation in two sub-systems. Clearly, the seismic subsystem has much larger energies (10^{17} Joule compared to 10^{10} Joule). Effectively, the time-average of these shifts would be observed as energy-levels broadening. This coupling is reminiscent of nucleus/atomic coupling in atoms.

Tesla made such a strong comment in his notes (referred to before) after the record of lightning observation for the obvious reason: it was of central importance for his post-Niagara work. He hoped to pump up the space around the Earth with sufficient RF energy, so that the energy could be used in remote places. Wireless energy transmission was his main project in America, and was the reason for his coming to Colorado Springs (lower air pressure at high altitude; more space for powerful transmitter). Radio and telegraph transmission were only smaller portions of his general dream.

In my opinion, Tesla, in his early ages, made discoveries which triggered an industrial revolution in the world. The revolution (industrial and wide-public utilization of electric power) spread so fast, in fact, that Tesla did not get the credit he deserved. Somewhat misled by his coil-and-bulb experiment, he believed that after he developed all of the utilities for Niagara (and less known, a Teluride, Colorado mine), he could repeat the stunt with the RF power. He failed with his ultimate goal, of course, but while working on it, he developed RF technology as it is known today.

7. Acknowledgement

We wish to thank Roger Knitter of Honeywell's Solid State Product Center for numerous discussions of the subject.

References

[1]A. Marincic, *Nikola Tesla's Colorado Springs Notes*, Nolit, Beograd, 1978.

[2]M. Bath, *Introduction to Seismology*, Halsted Press, John Wiley and Sons, New York, 1973.

[3]Professor V. Ristic, Private Communication.

[4]C. Kittel, *Introduction to Solid State Physics*, John Wiley and Sons, 1953, p. 420.

[5]V. Ristic, *Principles of Acoustic Devices*, p. 165, John Wiley and Sons, New York, 1983.

[6]W.O. Schumann, *Z. Naturforsch*, Teil, 1952, A7.

[7]K.E. Bullen, *An Introduction to the Theory of Seismology*, Cambridge University Press, Cambridge, 1979.