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On the origin of "longitudinal electrodynamic waves"

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Abstract – An explanation to the experimental results reported by Monstein and Wesley (*Europhys. Lett.*, **59** (2002) 514), who claimed they had discovered "longitudinal electromagnetic waves", are explained by means of the classical electromagnetic theory. It is proved that the cited authors detected classical TEM waves emitted by currents flowing in the Earth and launched by the ball antenna used in the experiment. A kind of plasma theory is used to describe the behavior of charges in the Earth and the predictions it yields appear to agree with the experiment much better than the original ones presented by Monstein and Wesley.

Introduction. – A few years ago Monstein and Wesley [1] reported that they had generated and detected electrodynamic waves with a longitudinal electric field $\vec{E}$ in the direction of propagation. The experimental results are supported by a theory that claims to justify the existence of longitudinal electrodynamic waves. As the authors use standard equations of classical electromagnetism they believe their theory is "compatible with Maxwell's theory".

While the experimental evidence the authors provide is irrefutable (using a polarizer they clearly demonstrate that the electrodynamic wave they detect has the electric field $\vec{E}$ oriented along the direction from their ball antenna emitter to the observation point), however the explanation on the origin and the nature of these waves is, as we want to show, incorrect.

In 2004 there appeared a critical paper [2] commenting the theory of Monstein and Wesley and some important inconsistency of the theory presented in [1] with Maxwell's theory was pointed out. In a reply [3] to this comment the authors of [1] must finally agree that their solution to the scalar potential equation

$$\nabla^2\Phi - \frac{1}{c^2}\frac{\partial^2\Phi}{\partial t^2} = -4\pi\rho \tag{1}$$

violates Maxwell's equation $\vec{\nabla}\cdot\vec{E} = 4\pi\rho$. But at the same time they claim that it is Maxwell's theory that fails in this particular case of ball antenna they used in experiments.

Unfortunately the essential discrepancy between the theory of [1] and the classical one seems to be overlooked by the authors of [2]. It is well known that the solution to the wave equation (1) is [4]

$$\Phi(\vec{r},t) = \int_{all\ space} \frac{\rho\left(\vec{r}\,',t-\frac{|\vec{r}-\vec{r}\,'|}{c}\right)}{|\vec{r}-\vec{r}\,'|}\mathrm{d}V'. \tag{2}$$

Crucial is that the integration is expanded over the *all space*. If the source of the field is localized, as it is for the experiment described in [1] where we have the ball antenna connected to a car battery, we can replace in the above integral the denominator $|\vec{r}-\vec{r}\,'|$ by $|\vec{r}|\equiv r$ and get from (2)

$$\Phi(\vec{r},t) = \frac{q(t-r/c)}{r}, \tag{3}$$

where q is the total charge of the source. Since the total charge of the localized source is conserved, then the total charge q does not depend on time and the solution to eq. (1) is a *static* field Φ. It follows then that no scalar electrodynamic waves Φ can be produced by a localized source. This is in contradiction to the solution proposed in [1] (see eq. (4) in this work). Erroneous is the assumption that the *total* charge of the localized source the authors use in their experiment changes in time as $q\sin(\omega t)$. It is manifestly *inconsistent with the charge conservation law* and cannot be accepted on the ground of the known experimental evidence.

Despite this explanation, the results presented in [1] still remain intriguing. Recently there appeared some

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alternative theories of electromagnetism (*e.g.* published via internet by Koen van Vlaenderen) promoting the existence of scalar electrodynamic fields and supported by the experimental results of [1]. In this context there is a strong need to give some constructive explanation of the evidently longitudinal orientation of the electric field of the waves detected by Monstein and Wesley, interference effects and dependence of the signal on the distance seeming to be as the inverse square of the distance. From the scientific point of view it is necessary to determine whether these experimental outcomes can be elucidated on the basis of a standard theory or some new approach to electromagnetism is indispensable.

Responding to this need, the aim of our work is to account for the experimental results obtained in [1] by using solely the classical theory of electromagnetism. The crucial observation we make is that the source of the waves described in [1] is not the ball antenna itself but the surface currents induced in the Earth by the antenna. Our theory, which is in fact a plasma theory applied to charges in the Earth, explains the orientation of the detected field $\vec{E}$, the dependence of the signal as a function of distance from the source antenna and the interference effects. The curve representing our theory seems to fit to experimental data much better than that presented by Monstein and Wesley.

Theory. – Let us start from Maxwell's equations we are going to apply to charges (electrons) in the Earth that will move due to the periodic field produced by the ball antenna source. Without loss of generality we can neglect the movement of positive ions. We have then

$$\vec{\nabla}\cdot\vec{E}=\frac{e(n-n_0)}{\epsilon_0}, \tag{4}$$

$$\vec{\nabla}\times\vec{B}-\mu_0\epsilon_0\frac{\partial\vec{E}}{\partial t}=\mu_0 en\vec{v}, \tag{5}$$

$$\vec{\nabla}\times\vec{E}+\frac{\partial\vec{B}}{\partial t}=0, \tag{6}$$

$$\vec{\nabla}\cdot\vec{B}=0, \tag{7}$$

where n is a concentration of electrons (n_0 is the concentration at equilibrium) and $\vec{v}$ is the velocity of the electrons. In the state of equilibrium the charge of electrons is compensated by the charge of positive ions, so that the nonzero charge density occurs due to fluctuations of electrons and is equal to $\rho_e=e(n-n_0)$. The equation of motion for the electrons is

$$\rho_m\frac{D\vec{v}}{dt}=\rho_e(\vec{E}+q\vec{v}\times\vec{B})-\rho_m\nu\vec{v}-\vec{\nabla}p, \tag{8}$$

where

$$\frac{D\vec{v}}{dt}=\frac{\partial\vec{v}}{\partial t}+\vec{v}\,\vec{\nabla}\cdot\vec{v}, \tag{9}$$

and $\rho_m=nm$ (m is the mass of the electron) is the mass density, ν the collision frequency and p the thermal pressure of the gas of electrons. Equation (8) is the well-known *Langevin equation* supplemented by the additional term $\vec{\nabla}p$. The continuity equation has the form

$$\frac{\partial\rho_e}{\partial t}+\vec{\nabla}\cdot(\rho_e\vec{v})=0. \tag{10}$$

Above we have listed all the equations we need to explain the experimental results obtained by Monstein and Wesley. We want to emphasize that these equations of classical theory of electromagnetism suffice to cope with the problem and no extraordinary assumptions are required.

To find the electric field $\vec{E}$ satisfying the above equations, let us first linearize these equations. We assume that the concentration of electrons is

$$n=n_0+n', \tag{11}$$

where n' is a small disturbation from an equilibrium value n_0. Moreover, we consider the velocity $\vec{v}$ and the magnetic field $\vec{B}$ as first-order quantities and neglect second-order terms $\vec{v}\vec{\nabla}\cdot\vec{v}$ and $\vec{v}\times\vec{B}$. As a result we get the equation of motion (8) in the form

$$\frac{\partial\vec{v}}{\partial t}-\frac{e}{m}\vec{E}+\frac{1}{mn_0}\left(\frac{\partial p}{\partial n}\right)_0\vec{\nabla}n'+\nu\vec{v}=0, \tag{12}$$

the continuity equation (10) as follows:

$$\frac{\partial n'}{\partial t}+n_0\vec{\nabla}\cdot\vec{v}=0 \tag{13}$$

and the inhomogeneous Maxwell's equations:

$$\vec{\nabla}\cdot\vec{E}=\frac{en'}{\epsilon_0}, \tag{14}$$

$$\vec{\nabla}\times\vec{B}-\mu_0\epsilon_0\frac{\partial\vec{E}}{\partial t}=\mu_0 en_0\vec{v}. \tag{15}$$

Now we look for the solutions having the form of the spherically symmetrical waves emerging from a center placed just below the ball antenna emitter, *i.e.* we assume proportionality:

$$n',v,E,B\propto\frac{e^{i(kr-\omega t)}}{r}, \tag{16}$$

where $\vec{k}$ is a propagation vector and r is a distance from the source antenna position to a point in the Earth. In effect the equation of motion (12), the continuity equation (13) and Maxwell's equations (14), (15), (6), (7) after neglecting the terms proportional to $1/r^2$ become, respectively,

$$-i\omega\vec{v}-\frac{e}{m}\vec{E}+\frac{1}{mn_0}\left(\frac{\partial p}{\partial n}\right)_0 in'\vec{k}+\nu\vec{v}=0, \tag{17}$$

$$-\omega n'+n_0\vec{k}\cdot\vec{v}=0, \tag{18}$$

$$i\vec{k}\cdot\vec{E}=\frac{en'}{\epsilon_0}, \tag{19}$$

$$i\vec{k}\times\vec{B}+i\omega\mu_0\epsilon_0\vec{E}-\mu_0 en_0\vec{v}=0, \tag{20}$$

$$\vec{k}\times\vec{E}-\omega\vec{B}=0, \tag{21}$$

$$\vec{k}\cdot\vec{B}=0. \tag{22}$$

Combining (20) and (21), we obtain

$$\vec{v}=\frac{i}{\mu_0 en_0\omega}\left[(\omega^2\mu_0\epsilon_0-k^2)\vec{E}+(\vec{k}\cdot\vec{E})\vec{k}\right]. \tag{23}$$

In turn from eqs. (17) and (19) we get

$$(\omega+i\nu)\vec{v}-i\frac{e}{m}\vec{E}-i\frac{\epsilon_0}{en_0}D(\vec{k}\cdot\vec{E})\vec{k}=0, \tag{24}$$

where $D=\frac{1}{m}(\partial p/\partial n)_0$. Eliminating $\vec{v}$ from eqs. (23) and (24) we find

$$\left[\frac{\omega+i\nu}{\mu_0 en_0\omega}(\omega^2\mu_0\epsilon_0-k^2)-\frac{e}{m}\right]\vec{E} + \left[\frac{\omega+i\nu}{\mu_0 en_0\omega}-\frac{\epsilon_0 D}{n_0 e}\right](\vec{k}\cdot\vec{E})\vec{k}=0. \tag{25}$$

It is convenient to separate the electric-field vector into a *longitudinal* component $\vec{E}_\parallel$ (parallel to $\vec{k}$) and a *transverse* component $\vec{E}_\perp$ (perpendicular to $\vec{k}$):

$$\vec{E}=\vec{E}_\parallel+\vec{E}_\perp. \tag{26}$$

As will be explained later, for our purpose it is enough to consider the longitudinal component. Equation (25) yields the following dispersion relation for the longitudinal mode $\vec{E}_\parallel$:

$$(\omega+i\nu)\frac{\epsilon_0\omega}{en_0}-\frac{e}{m}-\frac{\epsilon_0 Dk^2}{n_0 e}=0, \tag{27}$$

or, after some rearrangements,

$$\omega^2+i\nu\omega-{\omega_e}^2-Dk^2=0, \tag{28}$$

where $\omega_e=(e^2n_0/m\epsilon_0)^{1/2}$ is the electron plasma frequency.

Solving (28) for k we obtain

$$k=\beta+\alpha i, \tag{29}$$

where

$$\alpha=\left[\frac{1}{2D}(\sqrt{\omega_e^4+(\nu^2-2\omega_e^2)\omega^2+\omega^4}+\omega_e^2-\omega^2)\right]^{1/2}, \qquad \beta=\frac{\nu\omega}{2D\alpha}. \tag{30}$$

Important is that we have obtained solution for the field $E_\parallel$ *propagating in the Earth* in the form of longitudinal damped waves:

$$E_\parallel\propto\frac{e^{-\alpha r}e^{i(\beta r-\omega t)}}{r}. \tag{31}$$

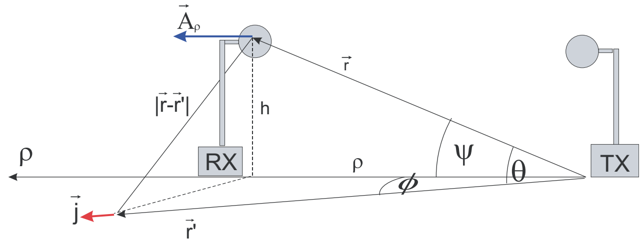

Fig. 1: Surface currents $\vec{j}$, flowing parallely to the surface of the Earth, emit classical TEM waves having the vector $\vec{A}$ (and $\vec{E}$) oriented along the surface of the Earth as well. It may seem that the receiver RX registers "longitudinal" electromagnetic waves emitted directly from the emitter TX.

The same form has the solution for the velocity of electrons parallel to $\vec{k}$. It follows that the antenna used by [1] launches in the Earth *longitudinal current waves*:

$$\vec{j}(r,t)=j_0\hat{k}\frac{e^{-\alpha r}e^{i(\beta r-\omega t)}}{r}, \tag{32}$$

where $\hat{k}$ is a versor pointing to the direction of $\vec{k}$. These currents flowing in the Earth are the source of classical TEM waves. As we are going to show, just these waves were detected by the authors of [1] and incorrectly interpreted by them as "scalar longitudinal electromagnetic waves".

In general the vector potential $\vec{A}$ of the field produced by the currents is

$$\vec{A}(\vec{r},t)=\int_{all\ space}\frac{\vec{j}\left(\vec{r}',t-\frac{|\vec{r}-\vec{r}'|}{c}\right)}{|\vec{r}-\vec{r}'|}\mathrm{d}V'. \tag{33}$$

However, the waves produced by the currents beneath the surface of the Earth will be reflected from the surface and not contribute to the signal detected by the receiver. It suffices then to expand the integration in (33) over a thin layer pertaining the surface of the Earth. Assuming that the longitudinal surface current waves flow *symmetrically* in all directions parallelly to the surface of the Earth, we conclude that the vector potential $\vec{A}$ has only a radial component A_ρ parallel to the surface of the Earth and oriented along the direction from the emitter to the receiver, fig. 1. This explains why Monstein and Wesley detected electromagnetic waves oriented along the direction from emitter and receiver that seemed to be "longitudinal" electromagnetic waves emitted directly by their antenna. Certainly, this also explains the dependence of the registered signal on the angle ϕ between the orientation of wires in the polarizer-analyzer and the "direction of propagation" (*i.e.* the direction from emitter to receiver) as being proportional to $\cos^2\phi$ —see eqs. (7) and (9) in [1].

The symmetry of the experimental situation distinguishes a possible direction of polarization of the transverse field $\vec{E}_\perp$ (eq. (26)) in the direction perpendicular to the surface of Earth. Such a field induces oscillating currents perpendicular to the surface that emit TEM waves polarized also in the direction normal to the Earth surface. But, as stated in [1], the receiver used in experiments registered only longitudinal (*i.e.* horizontal) fields. For this reason the transverse field $\vec{E}_\perp$ need not be considered in our theory aimed to explain the results achieved by [1].

From eqs. (32) and (33) we have for $A_\rho(\rho)$:

$$A_\rho(\rho,t) \propto \int_0^\infty \int_0^{2\pi} \frac{e^{-\alpha r'} \cos(\beta r' + k_a|\vec{r}-\vec{r}'| - \omega t)\cos\phi}{|\vec{r}-\vec{r}'|} \mathrm{d}r' \mathrm{d}\phi, \tag{34}$$

where $k_a = \omega/c$ is a propagation vector of the waves in the air, ρ is the distance between the emitter and the receiver measured along the surface, $\vec{r}'$ the position of the surface current and $\vec{r}$ the position of the receiver. According to fig. 1 we have

$$|\vec{r}-\vec{r}'| = \sqrt{r^2 + r'^2 - 2rr'\cos\theta} = \sqrt{r^2 + r'^2 - 2rr'\cos\psi\cos\phi}, \tag{35}$$

where

$$r = \sqrt{\rho^2 + h^2}, \qquad \cos\psi = \frac{\rho}{r}. \tag{36}$$

Since the radial electric field E_ρ associated with the vector potential A_ρ is $E_\rho = -1/c\,\partial A_\rho/\partial t$, $\vec{B} = \hat{n}\times\vec{E}/c$, then the time averaged Poynting vector $\vec{S} = 1/c\mu_0\,\vec{E}\times\vec{B}$, representing the power of the wave registered by means of the receiver, is

$$\langle S(\rho)\rangle_t \propto \left[\int_0^\infty \int_0^{2\pi} \frac{e^{-\alpha r'} \cos(\beta r' + k_a|\vec{r}-\vec{r}'|)\cos\phi}{|\vec{r}-\vec{r}'|} \mathrm{d}r' \mathrm{d}\phi\right]^2 + \left[\int_0^\infty \int_0^{2\pi} \frac{e^{-\alpha r'} \sin(\beta r' + k_a|\vec{r}-\vec{r}'|)\cos\phi}{|\vec{r}-\vec{r}'|} \mathrm{d}r' \mathrm{d}\phi\right]^2. \tag{37}$$

Relation (37) may be used directly in numerical calculations to reproduce the experimental results presented in [1]. According to [1] the frequency of the emitter is $f = 433,59\,\mathrm{MHz}$, so $k_a = 9,08\,1/\mathrm{m}$. The receiver was kept at the height $h = 4,4\,\mathrm{m}$. For the best fit of our theory to experiment there remains to chose values only of the two parameters α and β.

In fig. 2 the plot from [1] is recalled showing the dependence of the registered signal on the distance between the emitter and receiver and the theoretical curve proposed by Monstein and Wesley. In turn, in fig. 3 a plot of the result of our theory is presented. Values of the parameters are: $\alpha = 0,035\,1/\mathrm{m}$ and $\beta = 8,35\,1/\mathrm{m}$.

There are some important features that should be pointed out to confirm that our theory is correct:

1) The observed signal decreases more rapidly with distance than the inverse square of the distance. The curve obtained by means of our model agrees well with this fact up to the distance of 200 m. The theoretical distance-dependence of the power level presented in fig. 2 by Monstein and Wesley differs significantly from the experimental results.

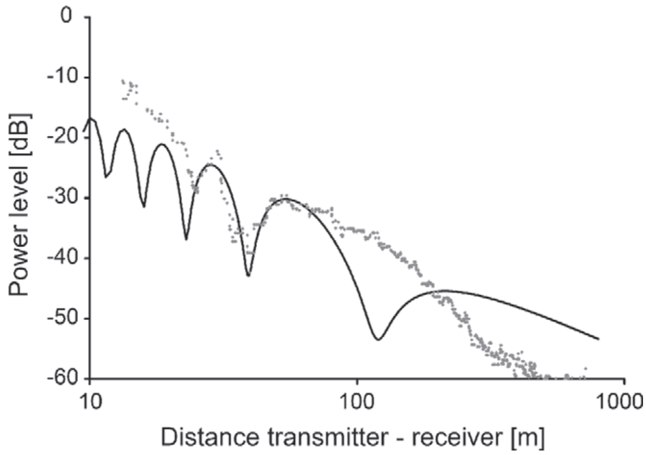

Fig. 2: Experimental results and the curve of the theory by Monstein and Wesley.

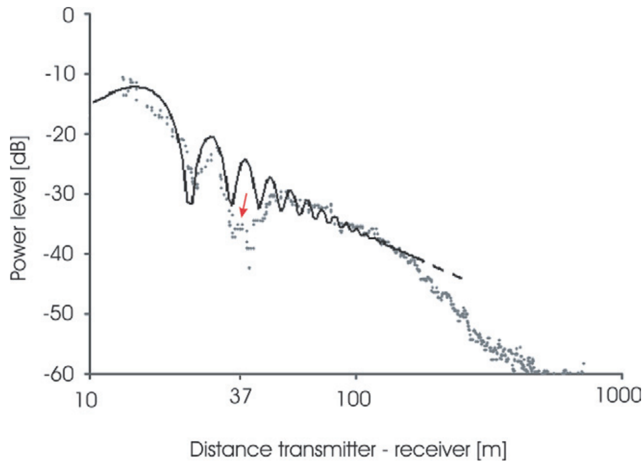

Fig. 3: The solid curve plotted according to eq. (37). A local maximum at the distance of 37 m is pointed out.

2) The experimental data reveal the presence of a local maximum at the distance 37 m separating two close minima at 32 and 39 m, which is correctly reproduced by our theoretical curve. The theory of Monstein and Wesley yields only single minimum at 39 m.

3) The theory by Monstein and Wesley predicts several minima that are not confirmed by the experiment. The plot of our curve reveals no extra extrema comparing to the experimental evidence.

4) Above 200 m our theory does not agree with the experimental results. The reason probably is that due to some reflections of the signal the registered power does not come from all the currents that are taken into account in the integration in (37).

Let us note that the experiment was conducted in uncontrolled environment so that some unknown disturbations influencing the final results are unavoidable. The success of the experiment by [1] consists in the fact that the disturbances did not destroy the interference effects and the general tendency in the distance dependence of the power level was captured. Taking into account these difficulties, the agreement of our theoretical curve with the experimental data is quite satisfactory.

Summarizing, no extraordinary assumptions are required to get an appropriate explanation of the experimental data presented by Monstein and Wesley. In the same way one can explain what registered by them in some other circumstances, *i.e.* a huge signal produced by a nuclear-bomb explosion. Our theory indicates that the signal measured in [1] is an *indirect* signal coming form the currents in the Earth emitting classical TEM waves. There is then no experimental basis to reveal alternative theories promoting the existence of scalar electrodynamic fields. A bit surprising may seem that we had to apply a plasma theory to describe the behavior of charges in the Earth to get the proper predictions for the registered signal. As far as we know, no such approach to the currents in the Earth was reported in literature so far.

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