Interpretation of the solution of Maxwell's equations for a moving Hertzian dipole

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October 30, 2023

Abstract

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Index Terms—**Maxwell equations, Electromagnetic forces, Electromagnetic propagation, Radio communication, Lorentz covariance, Quantum mechanics, Doppler effect**

I. Introduction

The solution of Maxwell's equations for the *resting* Hertzian dipole has long been well known (e.g. [1]). The Hertzian dipole is an extremely important model in electrical engineering, because it represents an elementary electromagnetic transmitter. The Hertzian dipole can be thought of as being composed of two point charges with charge quantities $+q$ and $-q$, both moving in proximity to the coordinate origin. This motion produces a time-dependent spatial displacement of the two charges with respect to each other and can be expressed mathematically by the time-dependent displacement vector $\boldsymbol{s}(t)$, where the magnitude $\|\boldsymbol{s}(t)\|$ is assumed to be very small for all times t with respect to the distance r of the receiver from the transmitter. Usually for $\boldsymbol{s}(t)$, only sinusoidal functions are found in textbooks. However, this restriction is not necessary.

As can be easily seen, the Hertzian dipole is a model of an electrically neutral, compound particle, which oscillates within itself. The Hertzian dipole therefore has a similar important role in electrical engineering to that of the hydrogen atom in atomic physics, because the model on the one hand is quite simple and on the other hand correctly describes many essential characteristics of electromagnetic waves. Furthermore, this elementary solution can be integrated along current paths, thus allowing the radiation fields of antennas of arbitrary shape to be obtained.

The formula for the field of the electromagnetic force $\boldsymbol{F}$ in the far field of a *resting* Hertzian dipole at time t on a *resting* test charge q_d at location $\boldsymbol{r}$ at distance $r := \|\boldsymbol{r}\|$ is not complicated and is as follows:

$$\boldsymbol{F}(\boldsymbol{r},t) = \frac{q_d\, q}{2\,\pi\,\varepsilon_0\, c^2\, r}\left(\frac{\boldsymbol{r}}{r}\times\left(\frac{\boldsymbol{r}}{r}\times\ddot{\boldsymbol{s}}\left(t-\frac{r}{c}\right)\right)\right). \tag{1}$$

This solution is found in numerous textbooks, but usually in polar coordinates and decomposed into electric and magnetic fields. In that case, the magnetic field $\boldsymbol{B}$ has no meaning for a *resting* test charge q_d, because, in the Lorentz force, the term $q_d\,\boldsymbol{v}\times\boldsymbol{B}$ is ineffective, given that $\boldsymbol{v} = \boldsymbol{0}$. As can be immediately seen from equation (1), the information contained in $\boldsymbol{s}(t)$ propagates at the speed of light c, because the force depends not on $\ddot{\boldsymbol{s}}\,(t)$ but on $\ddot{\boldsymbol{s}}\left(t-\frac{r}{c}\right)$.

The field of the electromagnetic force of a uniformly moving Hertzian dipole onto a resting test charge at location $\boldsymbol{r}$ is more complicated and was only recently calculated for the first time [2]. Solving Maxwell's equations in the rest frame of the receiver is uncommon but explicitly allowed, because of the principle of relativity. This process circumvents the use of Lorentz force and Lorentz transformation. In contrast, the usual procedure for solving Maxwell's equations is to assume that both the transmitter and receiver are at rest. Afterward, the calculated magnetic field is used to generalize the solution to moving receivers by inserting it together with the electric field into the Lorentz force. To finally obtain the force in the rest frame of the receiver, a Lorentz transformation is performed.

This article analyzes the newly calculated solution. Owing to the novelty, new scientific ground is broken in this old subject.

II. The solution of Maxwell's equations for a uniformly moving Hertzian dipole

The far-field solution of Maxwell's equations of a *uniformly moving* Hertzian dipole from the perspective of a *resting* receiver was only recently calculated for the first time [2]. The result of the calculation for the field of the electromagnetic force $\boldsymbol{F}$ of a Hertzian dipole moving with trajectory $\boldsymbol{r}_s(t) = \boldsymbol{v}\,t$ is

$$\begin{aligned}\boldsymbol{F}(\boldsymbol{r},t) = {} & \frac{q_d\,q\left(1+\frac{\boldsymbol{v}}{c}\cdot\frac{\boldsymbol{R}}{R}\right)}{2\,\pi\,\varepsilon_0\,c^2\,R}\left\{\frac{\boldsymbol{R}}{R}\times\left(\frac{\boldsymbol{R}}{R}\times\ddot{\boldsymbol{s}}\,(t-\tau)\right)+\right.\\ & \left.\left(\frac{\boldsymbol{v}}{c}\times\frac{\boldsymbol{R}}{R}\right)\times\ddot{\boldsymbol{s}}\,(t-\tau)\right\},\end{aligned} \tag{2}$$

where, for convenience, the time constant

$$\tau := \frac{\boldsymbol{R}\cdot\boldsymbol{v}+\sqrt{c^2\,R^2-\|\boldsymbol{R}\times\boldsymbol{v}\|^2}}{c^2-v^2} \tag{3}$$

and the time dependent distance vector

$$\boldsymbol{R} := \boldsymbol{r} - \boldsymbol{r}_s(t) \tag{4}$$

were defined. As can easily be verified, solution (2) for velocity $\boldsymbol{v} = \boldsymbol{0}$ turns into the already known solution (1). In the following, several special cases are studied to verify whether the solution (2) agrees with the expectations and is plausible.

III. Examples

Solution (2) is significantly more valuable than the well-known solution (1) because it enables analysis of how electromagnetic waves that are emitted by fast-moving radio transmitters, such as satellites, propagate. For illustration purposes, Figure 1 shows the field $\boldsymbol{F}$ of a 50 MHz transmitter in the x-z plane, which moves with velocity $\boldsymbol{v} = 1/3\, c\, \boldsymbol{e}_x$ and oscillates in the z-direction. The function $\boldsymbol{s}(t)$ for this special case is

$$\boldsymbol{s}(t) = s\, \boldsymbol{e}_z \, \sin\left(2\,\pi\, f\, t\right), \tag{5}$$

where $f = 50\,\text{MHz}$ represents the frequency of the transmitter.

As can be seen in Figure 1, solution (2) contains many essential properties of electromagnetic waves. Some are already known from the resting Hertzian dipole and thus are not discussed herein. The new aspects are the blue and red shift in front of and behind the transmitter. Furthermore, a red shift is accompanied by a weakening of the electromagnetic field strength, and a blue shift increases the field strength. These phenomena are well known from experiments, because blue-shifted electromagnetic waves transmit more energy than red-shifted waves.

Furthermore, the centers of the circles are always located where the transmitter was located when the wave crest or wave trough was emitted. Therefore:

1) The receiver perceives the transmitter not at the position where the transmitter is actually located but at the position where it was located when the signal was emitted.
2) The wave propagates as if the resting receiver were inside a resting transmission medium. Remarkably, this aspect is true for *every* receiver. Therefore, every receiver always perceives a virtual resting transmission medium independently of the relative velocity between it and the transmitter.

Interestingly, point 1) does not apply to electrically charged particles surrounded by an electrostatic field. An electrostatic field is not a wave and, for a uniformly moving point charge, always propagates so that the gradient of the field strength points exactly to the direction where the point charge is currently located. This does not represent a contradiction, because also in this case, the electromagnetic force is moving in the rest frame of each receiver with the speed of light. However, such a demonstration is not relevant to the topic of this article. More information can be found in [2].

Point 2) is also very interesting, because it seems paradoxical and finally led to the development of the Lorentz transformation. That the electromagnetic wave propagates exactly with speed of light c is even more clearly recognized if for

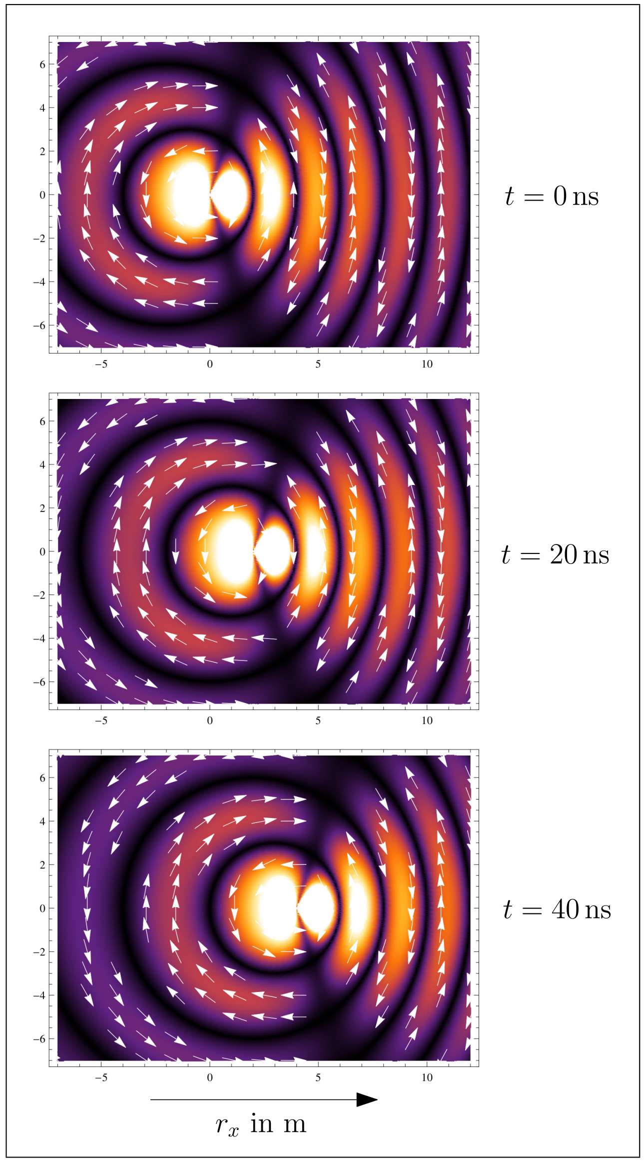

Figure 1. The time evolution of the field of a 50 MHz transmitter moving along the x-axis at speed $v = 1/3\, c$. The brightness of the background color is proportional to the magnitude of the field strength. The arrows mark the direction of the force that would act on a positive test charge.

$\boldsymbol{s}(t)$, one assumes not a sinusoidal but a pulse-like function, for example,

$$\boldsymbol{s}(t) = s\, \boldsymbol{e}_z \, \exp\left(-\left(\frac{t}{3\,\text{ns}}\right)^2\right), \tag{6}$$

which is nonzero only at the time period $t \approx 0$. This corresponds to a short and unique separation of the two charges inside the Hertzian dipole.

Figure 2 illustrates the temporal propagation of the signal. The single pulse (6) does not travel as a single wave crest. This finding is not unexpected, because in formula (2), only the second time derivative of signal (6) appears. As can be clearly seen, the signal propagates exactly as if it were traveling in a resting medium. The speed of propagation corresponds to the speed of light c. That the transmitter is actually moving and not resting can be recognized only by means of the Doppler effect.

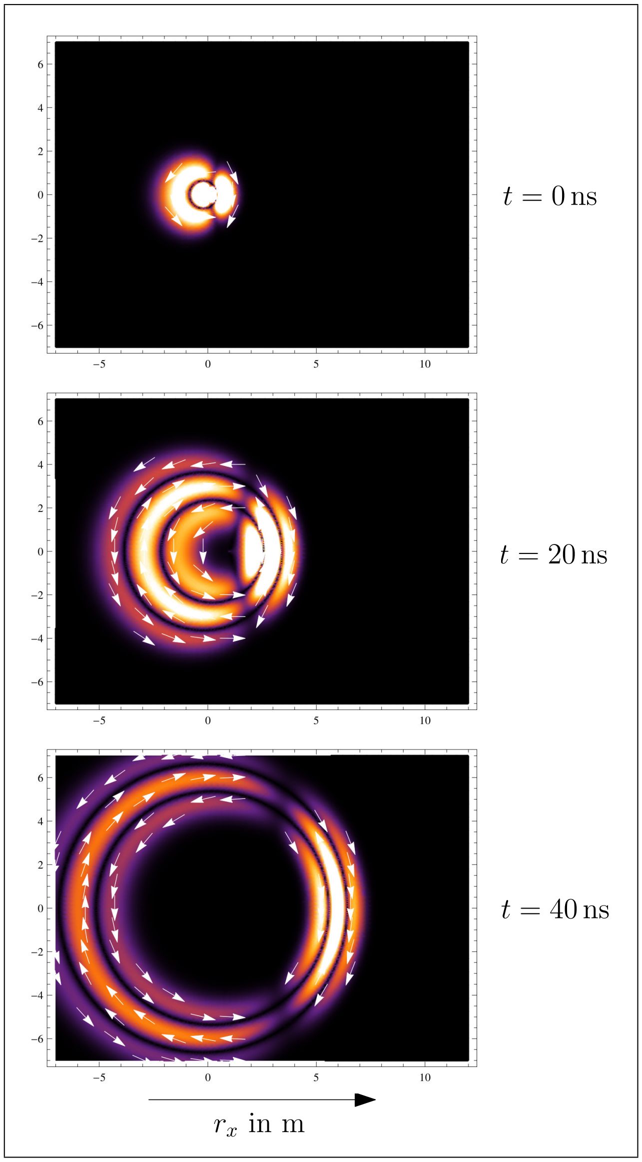

Figure 2. Propagation of a pulse-like signal emitted by a moving transmitter at time $t = 0$ at location $\boldsymbol{r} = \boldsymbol{0}$. The transmitter moves along the x-axis with speed $v = 1/3\,c$. For resting receivers, the electromagnetic wave propagates in all directions at the speed of light.

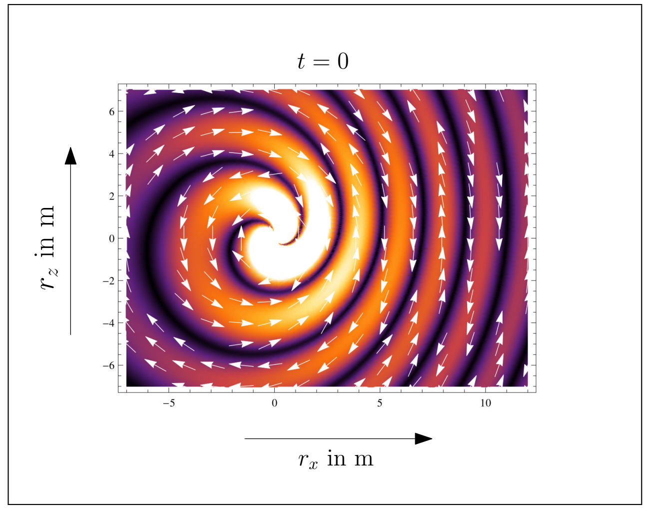

Figure 3. Field of a rotating dipole with static dipole moment moving along the x-axis with speed $1/3\,c$. The rotational frequency is 50 MHz. The plot shows the field at time $t = 0$.

Of note, solution (2) can also be used to represent more uncommon electromagnetic fields. For example, the field of a dipole rotating around the y-axis with static dipole moment can be modeled by means of

$$\boldsymbol{s}(t) = s\,\boldsymbol{e}_x \sin(2\pi f t) + s\,\boldsymbol{e}_z \cos(2\pi f t)\,. \tag{7}$$

The corresponding field at time $t = 0$ is shown in Figure 3. As expected, a spiral field is now obtained, where the Doppler effect is again clearly visible.

The presented examples illustrate that solution (2) is a rather useful model for the analysis of electromagnetic waves radiated by fast moving transmitters. In particular, the postulates of special relativity are clearly satisfied, because the propagation speed of the wave is equal to c and does not depend on the relative velocity $\boldsymbol{v}$ in the rest frame of the receiver. That solution (2) is not limited to the one-dimensional special case, but allows for analysis of the propagation of information in three dimensions, is also highly advantageous. Here, the function $\boldsymbol{s}(t)$ can be interpreted as a signal from the communication engineering point of view.

IV. The Doppler effect in the solution

In the previous section, the solution of Maxwell's equations for the uniformly moving Hertzian dipole in the rest frame of a receiver was analyzed and explained through several examples. From the perspective of a receiver in a vacuum, electromagnetic waves were shown to always propagate at the speed of light, and each receiver perceives a virtual transmission medium that is at rest with respect to itself. This is seemingly paradoxical, because a real transmission medium cannot be at rest simultaneously for receivers traveling at different speeds. However, it corresponds exactly to the expectations due to the special theory of relativity.

However, an aspect does not match special relativity, because the solution to Maxwell's equations (2) contains a classical instead of a relativistic Doppler effect. For illustrative purposes, we reduce formula (2) to a one-dimensional case by choosing $\boldsymbol{v} = v_x\,\boldsymbol{e_x}$ and $\boldsymbol{r} = r_x\,\boldsymbol{e}_x$. Therefore, we analyze the situation only on the x-axis, which corresponds exactly to the axis of motion of the Hertzian dipole. Moreover, we want to assume that the Hertzian dipole oscillates only in the z-direction, that is, transverse to the direction of motion. In this case $\boldsymbol{s}(t) = s_z(t)\,\boldsymbol{e}_z$.

Solution (2) simplifies considerably for this special case, because $\boldsymbol{R} \times \boldsymbol{v} = \boldsymbol{0}$, and, except for the z-component of the force

$$F_z(r,t) = -\frac{q_d\,q\left(1 + \frac{v_x}{c}\,\frac{r_x - v_x t}{|r_x - v_x t|}\right)}{2\pi\,\varepsilon_0\,c^2\,|r_x - v_x\,t|}\,\ddot{s}_z\,(t-\tau)\,, \tag{8}$$

all other force components become 0. Moreover, the equation (3) substantially simplifies, and we obtain

$$\tau = \frac{|r_x - v_x\,t|}{c - \operatorname{sgn}(r_x - v_x\,t)\;v_x}\,. \tag{9}$$

In the blue-shifted region, $r_x - v_x t > 0$, and we have

$$\ddot{s}_z(t-\tau) = \ddot{s}_z\left(D_c\left(t - \frac{r_x}{c}\right)\right) \tag{10}$$

with D_c being the Doppler factor

$$D_c := \frac{c}{c - v_x}. \tag{11}$$

As can be seen from the factor $t - r_x/c$ in equation (10), the signal $\ddot{s}_z$ propagates at the speed of light c. However, the Doppler factor D_c does *not* correspond to the Doppler factor in special relativity, because

$$D_r := \sqrt{\frac{c+v_x}{c-v_x}} = \frac{D_c}{\gamma(v_x)}, \tag{12}$$

with γ being the Lorentz factor

$$\gamma(v) := \frac{1}{\sqrt{1 - v^2/c^2}} = \frac{c}{\sqrt{c-v}\,\sqrt{c+v}}. \tag{13}$$

That the application of the Lorentz transformation produces a different Doppler effect becomes clear when the one-dimensional Lorentz transformation

$$\mathcal{L}\Big\{f(r_x,t)\Big\} := f\left(\gamma(v_x)\,(r_x - v_x\,t)\,,\gamma(v_x)\left(t - \frac{v_x}{c^2}\,r_x\right)\right), \tag{14}$$

is applied to the term $\ddot{s}_z(t - r_x/c)$. It can be verified that

$$\mathcal{L}\left\{\ddot{s}_z\left(t - \frac{r_x}{c}\right)\right\} = \ddot{s}_z\left(D_r\left(t - \frac{r_x}{c}\right)\right). \tag{15}$$

The term $t - r_x/c$ on both sides shows that the Lorentz transformation ensures that the signal still moves at the speed of light after the transformation. However, the Doppler effect does not coincide with that which follows when we solve Maxwell's equations, because $D_c \neq D_r$.

Therefore we reach the following conclusion: if we solve Maxwell's equations for the Hertzian dipole directly in the receiver's rest frame, we obtain a different solution from that when we use the standard procedure, which consists of solving Maxwell's equations in the transmitter's rest frame and then transforming the force into the receiver's rest frame by using the Lorentz transformation. Clearly, some aspects are inconsistent or poorly comprehended, because to obtain a result consistent with special relativity, one would need to make the substitution

$$\ddot{\mathbf{s}}(t-\tau) \rightarrow \ddot{\mathbf{s}}\left(\frac{t-\tau}{\gamma(v)}\right) \tag{16}$$

in solution (2), which corresponds to a *time dilation* of the transmitter with respect to the receiver, and indicates that all physical and chemical processes are slower in the transmitter than in the receiver.

V. Is time dilation due to a relative velocity actually possible?

The additional red shift due to a time dilation of moving transmitters can almost always be neglected from an engineering point of view, because the Lorentz factor is de facto 1, even at high technical velocities. For example, GPS satellites move with respect to a receiver at rest on the Earth's surface at a maximum speed of 5000 m/s, which corresponds to a velocity of $1/60000\,c$, and we obtain $1/\gamma \approx 1 - 1.39 \cdot 10^{-10}$. Thus, the associated frequency deviation due to the factor $1/\gamma$ is unlikely to be detectable, because of an additional frequency deviation due to the classical Doppler effect, which is several orders of magnitude stronger and additionally depends on the constantly changing position of the satellite relative to the receiver. Therefore, the effect is irrelevant to engineering. However, time dilation itself cannot be neglected in engineering, because it can cause clocks in different reference frames to gradually lose their synchronization.

Many experiments have convincingly shown that, under certain conditions, atomic and chemical processes can be slowed [3]–[9]. Special relativity argues that this time dilation is caused by the mere existence of relative velocities. However, thought experiments demonstrate that the assumption that a relative velocity can be the cause of a time dilation leads to a logical contradiction.

Figure 4 illustrates such an experiment. The experimental setup consists of a rotatable disk with a radius of, for example, $r = 5$ m at the edge of which, exactly opposite each other, two atomic clocks A and B are attached, which rotate when the disk is set in rotation. If the disk rotates with angular velocity $\omega = 2$ Hz (approximately 19 rpm), then both atomic clocks have a tangential speed of $v = \omega\,r = 10$ m/s. However, their relative speed v_r to each other is constant $v_r = 2\,v = 20$ m/s, and atomic clock A perceives from its own perspective how atomic clock B is orbiting it.

This does not change if the disk's center of rotation is shifted on a direct line between atomic clock A and atomic clock B. For example, if the center of rotation is exactly beneath atomic clock A, then, with unchanged ω, the relative velocity v_r is still equal to $2\,v$. Only the radial acceleration of the two atomic clocks changes because of a shift in the center of rotation and can become asymmetric. As can be seen, by shifting the center of rotation, the experiment can be transformed smoothly and with fixed relative speed into an experiment similar to that of Kündig [6].

According to special relativity theory and the Kündig experiment, atomic clock A should perceive a transverse Doppler effect at a radio signal emitted by atomic clock B. Therefore, a permanent red shift by a factor of $1/\gamma(v_r)$ should be observed. According to the usual method of argumentation, atomic clock B would run more slowly than atomic clock A by a factor of $1/\gamma(v_r)$. If both atomic clocks A and B were synchronized before the experiment, and the disk were allowed to rotate for 1 day, then atomic clock B should lag atomic clock A by approximately 0.19 ns after the disk has stopped. This conclusion contradicts logic, because the experiment is symmetrical, and the result should not depend on which clock is labeled atomic clock A.

If the experiment were to actually be performed, both clocks A and B would be found to show less time than a third stationary clock C that was also synchronized before the experiment. However, if the center of rotation under clock A were shifted, then only clock B would slow down. This effect would obviously be caused by the radial acceleration. The relative velocity v_r, in contrast, could not be the cause, because v_r does not depend at all on the choice of the center

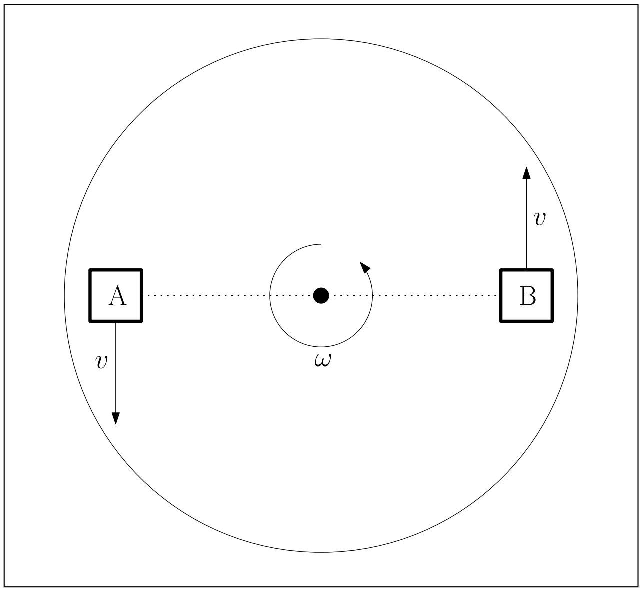

Figure 4. Thought experiment: Two atomic clocks A and B are mounted on a disk that rotates for 1 day with angular velocity ω. Both atomic clocks have a tangential speed of v. Their relative speed to each other is constantly $2\,v$. Of note, the relative speed remains constant when the center of rotation is shifted on the dashed line.

of rotation on the connection line between atomic clock A and atomic clock B.

These considerations show that time dilation principally cannot be explained by relative velocities, but, similarly to the experimentally excellently researched gravitational time dilation, must be attributed to the presence of forces. The solution of Maxwell's equations (2) without time dilation is therefore quite plausible.

VI. Interpretation

As became evident in section IV, Maxwell's equations lead to a classical Doppler effect. The Lorentz transformation, in contrast, requires a relativistic Doppler effect, i.e., it implies the existence of a time dilation due to relative velocities. However, as shown in section V, time dilation cannot be justified by means of relative velocities.

If Maxwell's equations are solved for the Hertzian dipole in the rest frame of the transmitter, and then the calculated electric and magnetic fields are substituted into the Lorentz force, a field that does not contain any Doppler effect is obtained. However, this field should also be valid for moving receivers, because the Lorentz force explicitly considers the velocity of the receiver. The missing Doppler effect for moving receivers is clearly in contradiction to reality, because the Doppler effect is a well known and easily detectable phenomenon for electromagnetic fields. Thus, standard electrodynamics without the Lorentz transformation does not represent a valid electrodynamics. Only the Lorentz transformation ensures, as can be seen from equation (15), that a Doppler effect occurs, and the propagation velocity of the electromagnetic force is equal to c in every frame of reference.

Both aspects are very important, and the question arises as to whether the Lorentz transformation is without alternative and whether a certain degree of inconsistency must necessarily be accepted. The answer to this question is no, because such pragmatism promises initial quick successes but later leads to stagnation. Furthermore, there are good alternative hypotheses to the special theory of relativity that have its strengths but not its weaknesses.

The key concept of these alternative hypotheses is to assume that the electromagnetic force is mediated by field quanta or force carriers. In quantum electrodynamics, these field quanta are usually referred to as virtual photons. The basic concept of special relativity is that these field quanta move at the speed of light in any inertial frame, owing to the mathematical structure of spacetime. Alternatively, virtual photons could be hypothesized to move at arbitrary speeds, and each receiver decides individually which virtual photons to interact with and which to ignore [10].

Several variants of this filter hypothesis based on virtual photons exist. The simplest is that the receiver, i.e., an electric charge, can absorb a virtual photon only if its velocity in its own rest frame is c. This remarkably simple basic principle explains almost all relativistic effects and experiments except for special-relativistic time dilation [10]. However, as has been shown, this concept is highly questionable. Moreover, the hypothesis explains the origin of the magnetic force in permanent magnets and in current-carrying wires, because it can be used to derive Weber electrodynamics.

As can be easily seen, this filter mechanism for virtual photons ensures, on the subatomic level, that the force between pairs of emitters and receivers moving uniformly with respect to each other always propagates at the speed of light c. This aspect is obvious, given that a receiver that is at rest relative to the transmitter interacts with other virtual photons than a receiver that is moving relative to the transmitter. *Each* receiver therefore has the impression, independently of its relative velocity to the transmitter, that the electromagnetic wave propagates at the speed of light, which is precisely the characteristic of solution (2) of Maxwell's equations. However, the alternative hypothesis implies that the field of the electromagnetic force cannot simply be distorted with a linear coordinate transformation, because each reference frame perceives the electromagnetic field in an individual manner. In addition, no simple linear mapping function exists with which the field of one reference frame could be transformed into the field of another reference frame.

Instead, the electromagnetic field must be computed by solving Maxwell's equations in the rest frame of each individual receiver. In this way, for the Hertzian dipole, solution (2) is obtained and, because velocity $\boldsymbol{v}$ is a freely chosen parameter, holds for all sufficiently uniformly moving reference frames. Furthermore, by supposing the filter hypothesis, the velocity $\boldsymbol{v}$ is clearly not only the velocity of the transmitter in the rest frame of the receiver but also the relative velocity. Consequently, equation (2) can also be used when not only the transmitter but also the receiver is moving with respect to an observer with trajectory $\boldsymbol{r}_d(t)$. In this case, equation (4) becomes

$$\boldsymbol{R} = \boldsymbol{r}_d(t) - \boldsymbol{r}_s(t), \tag{17}$$

and for velocity $\boldsymbol{v}$ in equations (2) and (3), the following applies:

$$\boldsymbol{v} = -\dot{\boldsymbol{R}}. \tag{18}$$

The field $\boldsymbol{F}$ then represents the total electromagnetic force, i.e., the effect of the magnetic and electric force taken together, acting at time t on the receiver at location $\boldsymbol{r}_d(t)$. Of note, $\boldsymbol{v}$ is a relative velocity. Thus, the force (2) depends solely on relative quantities.

As can be clearly seen, in equation (17), a *Galilean transformation* is applied. This application is justified because the third uninvolved observer is a receiver as well. Therefore, the observer perceives a different field to that perceived by the actual receiver. According to the filter hypothesis, assuming that the observer's own field is also real for the receiver would be incorrect, since the field perceived by the observer is completely irrelevant for the transmission of force between the transmitter and receiver. The special theory of relativity fundamentally differs from the filter hypothesis in this aspect, because it implicitly assumes that the electromagnetic field is essentially identical for the sender, receiver and observer, and appears only linearly projected. The filter hypothesis, in contrast, is nonlinear, does not require spacetime and justifies the postulates of special relativity with the statement that the electromagnetic field is subjective for each receiver.

Of note, the splitting into magnetic and electric fields, as is common in canonical electrodynamics, is not necessary in Weber electrodynamics. The magnetic forces can be shown to result only from the fact that an isolated system of point charges with various velocities cannot be electrically neutral toward the outside in all inertial frames. Therefore, velocity-dependent forces remain. The magnetic force is one of them. More details regarding this subject can be found in the literature on Weber electrodynamics. The current state of research has been summarized in [11], which provides a sound overview.

VII. Summary

This article first showed, by means of several examples, that the solution of Maxwell's equations for a uniformly moving Hertzian dipole in the rest frame of a receiver is plausible and perfectly suitable as a three-dimensional electromagnetic model for satellites and other moving sources of electromagnetic waves. Furthermore, the article clarified that the Doppler effect, which is intrinsically contained in Maxwell's equations, is not the same as the relativistic Doppler effect, because the latter additionally contains a time dilation caused by relative velocities. Therefore, a contradictory aspect exists in canonical electrodynamics, because it should not matter whether Maxwell's equations are solved in the rest frame of the receiver without Lorentz transformation and Lorentz force, or the standard method is used to solve Maxwell's equations in the rest frame of the transmitter, and then the fields are transformed into the rest frame of the receiver by means of Lorentz transformation.

The author of this article is convinced that the solution of Maxwell's equations in the rest frame of the receiver is physically correct without additional time dilation. To support this possibility, a thought experiment was presented, which shows that a relative velocity cannot be the cause of time dilation and that other explanations are needed.

The article concludes with a discussion of a quantum mechanical hypothesis that has the advantages of special relativity but avoids its contradictions, and, unlike special relativity, perfectly fits the solution of Maxwell's equations. In particular, the quantum mechanical explanation, the so-called filter hypothesis, ensures that electromagnetic waves propagate at the same speed c in all inertial frames without a transmission medium and that each inertial frame is equivalent.

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