Galilei Covariant Electrodynamics of Moving Media with Applications to the Experiments of Fizeau and Hoek

H.E. Wilhelm
Department of Materials Science and Engineering,
University of Utah, Salt Lake City, Utah 84112

Galilei-covariant electrodynamics is generalized for moving dielectric media with motion induced polarization for dielectric permittivities $\epsilon(\omega) > \epsilon_o = 10^{-9}/36\pi$ *As/Vm. The interferometric experiments on light propagation in (i) flowing water by Fizeau and (ii) resting water by Hoek, relative to a terrestrial laboratory frame S (which moves with a velocity* $\mathbf{v}^\circ = -\mathbf{w} \sim 3\times10^5$ m/s *relative to the absolute cosmic frame* S^o *with isotropic light propagation) are explained quantitatively without resort to relativistic space-time concepts. The experiment of Hoek is shown to reveal a polarization effect in the induced electric ether field* $\mathbf{w}\times\mathbf{B}$*, due to the terrestrial vacuum substratum velocity* $\mathbf{w}$*. Thus, the Hoek experiment refutes the special theory of relativity.*

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Introduction

The electrodynamics of moving media is one of the unsolved problems of physics (Sommerfeld 1965). The nonrelativistic Lorentz theory is not Galilei-covariant, and thus leads to contradictions when the same electrodynamic phenomenon is analyzed in different inertial frames Minkowski's relativistic electrodynamics is flawed by an unsymmetric stress-energy tensor, predicting torques on ponderable matter not observed in experiments. These difficulties (Sommerfeld 1965) are shown to be due to physical defects, namely disregard of (*i*) the existence of an absolute cosmic reference frame S° $(\mathbf{w} = 0)$ with isotropic light propagation (Penzias & Wilson 1965, Henry 1971) and (*ii*) the physical vacuum substratum (velocity $\mathbf{w}$) effects on electromagnetic (EM) fields in all other inertial frames $S(\mathbf{w} \neq \mathbf{0})$ with unisotropic light propagation (Wilhelm 1985a).

The electrodynamics for arbitrary inertial frames $S(\mathbf{r}, t, \mathbf{w})$ with vacuum substratum (ether) velocity $\mathbf{w}$ has been given by Wilhelm (1985a) and applied to quantum mechanics in EM fields (Wilhelm 1985b), the vacuum electrodynamics of charged particles (Wilhelm 1990a,b), the Cerenkov radiation in vacuum (Wilhelm 1991) and in dielectrics (Wilhelm 1992a), and unipolar EM induction as a vacuum substratum effect (Wilhelm 1992b). However, there are some applications involving moving dielectric media with dielectric constants $\epsilon(\omega) > \epsilon_o = 10^{-9}/36\pi$ As/Vm (optical wave guides with moving dielectrics, EM wave and radiation transport in cosmic media), in which motion induced electric polarization and speeding up or slowing down of EM waves can be observed by means of interferometric methods. For this reason, we generalize here the electrodynamics for inertial frames $S(\mathbf{r}, t, \mathbf{w})$ with vacuum substratum flow $\mathbf{w}$ to dielectric media with velocity field $\mathbf{v}(\mathbf{r}, t)$ and electric polarization in the induced electric field $(\mathbf{v} - \mathbf{w})\times\mathbf{B} = \mathbf{v}^\circ\times\mathbf{B}^\circ = \mathbf{inv}$ (Wilhelm 1985a).

The presented Galilei-covariant electrodynamics of moving media with induced electric polarization is applied to a quantitative explanation of the classical (reconfirmed) experiments of Fizeau (1851) and Hoek (1868). Whereas in the Fizeau experiment induced polarization in the electric field $\mathbf{v}\times\mathbf{B}$ (but not in the field $\mathbf{w}\times\mathbf{B}$) is observed, electric polarization in the ether field $\mathbf{w}\times\mathbf{B}$ is observed in the Hoek experiment. Since the Hoek experiment reveals an ether effect, it is of fundamental importance for the further development of physics.

Electrodynamics of Moving Dielectric Media

We add to the generalized, Galilei-covariant Maxwell equations for inertial frames $S(\mathbf{r},t,\mathbf{w})$ with ether velocity $\mathbf{w}$ (Wilhelm 1985a), the effect of induced polarization (in Galilei-invariant form) to obtain the corresponding Galilei-covariant electrodynamic equations for isotropic dielectric media $(\epsilon > \epsilon_o)$ with electrical conductivity σ and velocity field $\mathbf{v}(\mathbf{r},t)$. The resulting EM field equations for (nonmagnetic, $\mu = \mu_o$) dielectric media with velocity field $\mathbf{v}(\mathbf{r},t)$ and vacuum substratum velocity $\mathbf{w}$ are for an arbitrary inertial frame $S(\mathbf{r},t,\mathbf{w})$ (standard MKS notation):

$$\nabla\times(\mathbf{E}+\mathbf{w}\times\mathbf{B}) = -\left(\frac{\partial}{\partial t}+\mathbf{w}\bullet\nabla\right)\mathbf{B} \tag{1}$$

$$\nabla\bullet\mathbf{B} = 0 \tag{2}$$

$$\nabla\times\mathbf{H} = \left(\frac{\partial}{\partial t}+\mathbf{w}\bullet\nabla\right)\left[\epsilon_o(\mathbf{E}+\mathbf{w}\times\mathbf{B})+\mathbf{P}\right]+\mathbf{j}-\rho\mathbf{w} \tag{3}$$

$$\nabla\bullet\left[\epsilon_o(\mathbf{E}+\mathbf{w}\times\mathbf{B})+\mathbf{P}\right] = \rho \tag{4}$$

where

$$\mathbf{P} = (\epsilon-\epsilon_o)\left[(\mathbf{E}+\mathbf{w}\times\mathbf{B})+(\mathbf{v}-\mathbf{w})\times\mathbf{B}\right] \tag{5}$$

$$\mathbf{j}-\rho\mathbf{v} = \sigma\left[(\mathbf{E}+\mathbf{w}\times\mathbf{B})+(\mathbf{v}-\mathbf{w})\times\mathbf{B}\right]+\nabla\times\left[\mathbf{P}\times(\mathbf{v}-\mathbf{w})\right] \tag{6}$$

and

$$\mathbf{D} = \epsilon\mathbf{E}, \quad \mathbf{B} = \mu_o\mathbf{H} \tag{7}$$

for isotropic dielectric media with electric permittivity $\epsilon > \epsilon_o$ and non-magnetic permeability $\mu = \mu_o = 4\pi 10^{-7}$ Vs/Am [in magnetic media $\mu \neq \mu_o$, induced magnetic polarization is a small effect of order $(\mathbf{v}-\mathbf{w})^2/c_o^2$].

The induced polarization effects in (1)—(7) are completely negligible for common dielectrics with $\epsilon \simeq \epsilon_o$. The electric polarization $\mathbf{P}$ in the Lorentz field $\mathbf{E}+\mathbf{v}\times\mathbf{B}$, (5), has been written in a form to reveal the Galilei invariance of $\mathbf{E}+\mathbf{v}\times\mathbf{B}$. Note that the electric current density $\mathbf{j}$ in (6) is composed of the space charge current $\rho\mathbf{v}$, the conduction current $\sigma(\mathbf{E}+\mathbf{v}\times\mathbf{B})$, and the polarization current $\nabla\times[\mathbf{P}\times(\mathbf{v}-\mathbf{w})]$.

The EM field equations (1)–(6) are Galilei-covariant owing to the field and operator invariants $\mathbf{E}+\mathbf{w}\times\mathbf{B} = \mathbf{E}'+\mathbf{w}'\times\mathbf{B}'$, $\mathbf{B}=\mathbf{B}'$, $\rho=\rho'$, $\mathbf{P}=\mathbf{P}'$, $\mathbf{j}-\rho\mathbf{w} = \mathbf{j}'-\rho'\mathbf{w}'$, $\mathbf{j}-\rho\mathbf{v} = \mathbf{j}'-\rho'\mathbf{v}'$, $\mathbf{v}-\mathbf{w} = \mathbf{v}'-\mathbf{w}'$, and $\partial/\partial t+\mathbf{w}\bullet\nabla = \partial/\partial t'+\mathbf{w}'\bullet\nabla'$, $\nabla=\nabla'$ (medium invariants $\epsilon=\epsilon'$, $\mu_o=\mu_o'$, $\sigma=\sigma'$) in Galilei transformations between the inertial frames $S(\mathbf{r},t,\mathbf{w})$ and $S'(\mathbf{r}',t',\mathbf{w}')$ with $\mathbf{w}-\mathbf{w}' = \mathbf{v}(\mathbf{r},t)-\mathbf{v}'(\mathbf{r}',t') = \mathbf{u}$, where $\mathbf{u}$ is the velocity of S' relative to S (Wilhelm 1985a).

For the analysis of EM wave propagation in ideal dielectric media with properties $\epsilon(\omega)$, $\mu=\mu_o$, absence of free charge carriers ($\rho=0$, $\sigma=0$), and velocity field $\mathbf{v}(\mathbf{r},t)$, (1)–(6) reduce to:

$$\nabla\times\mathbf{E}^\circ = -\frac{\mathrm{d}\mathbf{B}}{\mathrm{d}t} \tag{8}$$

$$\nabla\times\mathbf{H} = \frac{\mathrm{d}(\epsilon_o\mathbf{E}^\circ+\mathbf{P})}{\mathrm{d}t}+\nabla\times(\mathbf{P}\times\mathbf{v}^\circ) \tag{9}$$

$$\nabla\bullet\mathbf{B}=0, \quad \nabla\bullet(\epsilon_o\mathbf{E}^\circ+\mathbf{P})=0 \tag{10}$$

where

$$\mathbf{P} = (\epsilon-\epsilon_o)(\mathbf{E}^\circ+\mathbf{v}^\circ\times\mathbf{B}) \tag{11}$$

and

$$\frac{\mathrm{d}}{\mathrm{d}t} = \frac{\partial}{\partial t}+\mathbf{w}\bullet\nabla \tag{12}$$

$$\mathbf{E}+\mathbf{w}\times\mathbf{B} = \mathbf{E}^\circ, \quad \mathbf{v}-\mathbf{w} = \mathbf{v}^\circ \tag{13}$$

are abbreviations. Since $\rho=0$ and $\sigma=0$, the curls of the magnetic field $\mathbf{H}$ have their sources in the displacement current $\mathrm{d}(\epsilon_o\mathbf{E}^\circ+\mathbf{P})/\mathrm{d}t$ and polarization current $\nabla\times(\mathbf{P}\times\mathbf{v}^\circ)$, both being Galilei field invariants (Wilhelm 1985a).

In the following, we apply (8)–(13) to homogeneous (ϵ) dielectric media in uniform translation in an inertial frame $S(\mathbf{r},t,\mathbf{w})$, so that $\mathbf{v}^\circ = \mathbf{v}-\mathbf{w}$ is a constant vector independent of $\mathbf{r},t$. Under consideration of (7), (8), and (11), equation (9) becomes with $c_o = (\mu_o\epsilon_o)^{-1/2}$ (light velocity in vacuum substratum) and $\epsilon^* = \epsilon/\epsilon_o$:

$$\begin{aligned}\nabla\times\mathbf{B} = c_o^{-2}\Big\{&\frac{\mathrm{d}\mathbf{E}^\circ}{\mathrm{d}t}+(\epsilon^*-1)\frac{\mathrm{d}\mathbf{E}^\circ}{\mathrm{d}t}-(\epsilon^*-1)\mathbf{v}^\circ\times(\nabla\times\mathbf{E}^\circ)\\ &+(\epsilon^*-1)\nabla\times\left[\mathbf{E}^\circ\times\mathbf{v}^\circ+\mathbf{v}^{\circ 2}\,\mathbf{B}-(\mathbf{B}\bullet\mathbf{v}^\circ)\mathbf{v}^\circ\right]\Big\}\end{aligned} \tag{14}$$

where

$$\mathbf{v}^\circ\times(\nabla\times\mathbf{E}^\circ) = \nabla(\mathbf{v}^\circ\bullet\mathbf{E}^\circ)-\mathbf{v}^\circ\bullet\nabla\mathbf{E}^\circ \tag{15}$$

$$\nabla\times(\mathbf{E}^\circ\times\mathbf{v}^\circ) = \mathbf{v}^\circ\bullet\nabla\mathbf{E}^\circ-\mathbf{v}^\circ\,\nabla\bullet\mathbf{E}^\circ \tag{16}$$

and

$$\nabla\bullet\mathbf{E}^\circ = \epsilon^{*-1}(\epsilon^*-1)\mathbf{v}^\circ\bullet\nabla\times\mathbf{B} \tag{17}$$

by (10) and (11). By means of (15)–(17), some algebra reduces (14) to the simpler equation (if $\nabla\times\mathbf{B}$ terms with scalar and dyadic coefficients of order $(\mathbf{v}^\circ/c_o)^2 \ll 1$ are neglected on the LHS of (18))

$$\nabla\times\mathbf{B} = \epsilon^* c_o^{-2}\left\{\frac{\mathrm{d}\mathbf{E}^\circ}{\mathrm{d}t}+\left(1-\epsilon^{*-1}\right)\left[2\mathbf{v}^\circ\bullet\nabla\mathbf{E}^\circ-\nabla(\mathbf{v}^\circ\bullet\mathbf{E}^\circ)\right]\right\}, \quad (\mathbf{v}-\mathbf{w})^2 \ll c_o^2 \tag{18}$$

Taking the curl of (18) gives, under consideration of (8), the fundamental wave equation for uniform dielectric media with constant velocity field $\mathbf{v}$:

$$c^2\nabla^2\mathbf{B}=\left(\frac{\partial}{\partial t}+\mathbf{w}\bullet\nabla\right)^2\mathbf{B}$$
$$+2\left(1-\epsilon^{*-1}\right)(\mathbf{v}-\mathbf{w})\bullet\nabla\left(\frac{\partial}{\partial t}+\mathbf{w}\bullet\nabla\right)\mathbf{B}, \qquad (19)$$
$$(\mathbf{v}-\mathbf{w})^2 \ll c_o^2$$

where $c(\omega)=\left[\mu_o\epsilon(\omega)\right]^{-½}$ is the phase velocity of light in the (nonmagnetic) dielectric when at rest in the ether frame $S°$.

For plane EM waves $\mathbf{B}=\mathbf{B}_o\exp(i\omega t-i\mathbf{k}\bullet r)$ with frequency ω and propagation vector $\mathbf{k}$ in the direction of the unit vector $\mathbf{k}°=\mathbf{k}/k$ where $k=2\pi/\lambda$, (19) yields as dispersion equation for EM waves in the moving ($\mathbf{v}$) dielectric in the presence of vacuum substratum flow $\mathbf{w}$

$$(\omega-\mathbf{k}\bullet\mathbf{w})^2-2\left(1-\epsilon^{*-1}\right)[(\mathbf{v}-\mathbf{w})\bullet\mathbf{k}](\omega-\mathbf{k}\bullet\mathbf{w})-k^2c^2=0,$$
$$(\mathbf{v}-\mathbf{w})^2\ll c^2 \qquad (20)$$

Since $\left|(\mathbf{v}-\mathbf{w})\bullet\mathbf{k}\right|^2\ll k^2c^2$ for $(\mathbf{v}-\mathbf{w})^2\ll c(\omega)^2$, (20) has the simple solution $(k=|\mathbf{k}|)$

$$\omega-\mathbf{k}\bullet\mathbf{w}\simeq kc+\left(1-\epsilon^{*-1}\right)(\mathbf{v}-\mathbf{w})\bullet\mathbf{k},$$
$$(\mathbf{v}-\mathbf{w})^2\ll c^2 \qquad (21)$$

Equation (21) is Galilei-invariant, and reduces for vanishing ether velocity, $\mathbf{w}=0$, to the corresponding formula of the Lorentz and Minkowski theories (Sommerfeld 1965). The phase velocity $V=\omega/k$ of the EM waves in the moving $(\mathbf{v})$ dielectric is in the presence of ether flow $\mathbf{w}$

$$V=c+\mathbf{w}\bullet\mathbf{k}°+\left(1-\mathbf{n}^{-2}\right)(\mathbf{v}-\mathbf{w})\bullet\mathbf{k}°,$$
$$(\mathbf{v}-\mathbf{w})^2\ll c^2 \qquad (22)$$

where $n(\omega)=\epsilon^*(\omega)^{½}$ is the refractive index of the dielectric. As will be seen later, the term $\mathbf{w}\bullet\mathbf{k}°/n^2$ in (22) is instrumental for the explanation of the Hoek experiment.

Due to the velocity $\mathbf{v}$ of the dielectric medium (relative to the laboratory frame S), every atom "i" initially at the location $\mathbf{r}_i$ is at the position $\mathbf{r}=\mathbf{r}_i+\mathbf{v}t$ at time $t>0$. Hence, the apparent EM frequency ω' an atom (polarized by the EM wave $\mathbf{E},\mathbf{B}$) experiences at time $t>0$ is (Doppler effect)

$$\omega'=\omega-\mathbf{k}\bullet\mathbf{v}\simeq\omega\left[1-\left(\frac{v}{c}\right)\cos\theta\right],$$
$$|\mathbf{v}|\ll c,\quad |\mathbf{w}|\ll c \qquad (23)$$

where $\theta=\angle(\mathbf{v},\mathbf{k})$ and $\omega/k\simeq c(\omega)$ in first approximation. Note that the restrictions in (23) are more severe than the previous condition $(\mathbf{v}-\mathbf{w})^2\ll c^2$, but fully adequate for applications. Since $c=c_o/n(\omega')$ and $n=n(\omega')$, expansion of the refractive index gives

$$\mathbf{n}(\omega')=\mathbf{n}(\omega)+\left[\frac{\mathrm{d}\mathbf{n}(\omega)}{\mathrm{d}\omega}\right]\mathrm{d}\omega'$$
$$=\mathbf{n}(\omega)\left[1-\left(\frac{v}{c(\omega)}\right)\cos\theta\frac{\mathrm{d}\ln\mathbf{n}(\omega)}{\mathrm{d}\ln\omega}\right] \qquad (24)$$

In the same approximation, the Doppler shifted phase velocity in the moving $(\mathbf{v})$ dielectric with ether velocity $\mathbf{w}$ becomes

$$V=c+\left(1-\mathbf{n}^{-2}+\frac{\mathrm{d}\ln\mathbf{n}}{\mathrm{d}\ln\omega}\right)v\cos\theta+\frac{w\cos\phi}{n^2}, \qquad (25)$$
$$|\mathbf{v}|\ll c,\quad |\mathbf{w}|\ll c$$

where $\phi=\angle(\mathbf{w},\mathbf{k})$, and $n=n(\omega)$, $c=c_o/n(\omega)$. This fundamental equation shows that the EM wave $(\omega,\mathbf{k})$ in the moving dielectric is speeded up or slowed down, depending on the angles θ and ϕ, by the velocity $\mathbf{v}$ of the dielectric and the ether velocity $\mathbf{w}$, with the characteristic coefficients

$$F=1-n^{-2}+\frac{\mathrm{d}\ln n}{\mathrm{d}\ln\omega},\quad W=\frac{1}{n^2} \qquad (26)$$

The superficial interpretation of F as a "drag on the ether" in the dielectric due to its motion $\mathbf{v}$ is misleading, since it would imply that the ether has an infinite number of different densities $\rho_o(\omega)$ in the dielectric depending on the frequency ω of the EM wave.

The speeding up or slowing down of EM waves with phase speeds $c<3\times10^8\,\mathrm{m/s}$ has a maximum value (i) $Fv\sim10^3\,\mathrm{m/s}$ due to the velocity $\mathbf{v}$ of the dielectric (for macroscopic bodies $v_{\max}\sim10^3\,\mathrm{m/s}$) and ($ii$) $Ww\approx10^5\,\mathrm{m/s}$ due to the terrestrial ether velocity $\mathbf{w}$ ($w=3\times10^5\,\mathrm{m/s}$). For these reasons, $Fv \lll c$, and $Ww\ll c$, *i.e.*, the speeding up or slowing down of EM waves is a very small effect. Accordingly, the complicated equations of the electrodynamics of moving media need not to be used in most applications (Sommerfeld 1965, Wilhelm 1985a).

However, the speeding up or slowing down of EM waves due to the motion $\mathbf{v}$ of the dielectric or the terrestrial ether flow $\mathbf{w}$ are of considerable interest as phenomena of basic physics. These small effects can be measured by means of interference methods as shown first in the classical experiments of Fizeau (1851) and Hoek (1868).

Experiment of Fizeau

In the Fizeau (1851) experiment (Figure 1), a light beam emitted from the source Q is split into two coherent components "1" and "2" by a semi-transparent mirror M_o. The beam "1" is guided clockwise along the path $M_o\to M_3\to M_2\to M_1\to M_o\to T$, whereas the beam "2" is guided counter-clockwise along the path $M_o\to M_1\to M_2\to M_3\to M_o\to T$, by the mirrors $M_{1,2,3}$. The interference of the beams "1" and "2" is observed in the telescope at T. The beam "1" travels in the direction of the water flow velocity $\pm\mathbf{v}$, whereas the beam "2" travels in the opposite direction to the water flow velocity $\pm\mathbf{v}$, both in the upper (+) and lower (–) water tubes. Fizeau (1851) observed a shift in the interference pattern at T after the waterflow $\mathbf{v}$ was switched on in the connected water tubes ($\pm$).

According to (25), the phase velocities $V_{1,2}^{\pm}$ of the beams "1" and "2" in the upper (+) and lower (–) water tubes are ($v=|\mathbf{v}|$)

$$V_{1,2}^{+} = c \pm \left(1 - n^{-2} + \frac{d\ln n}{d\ln\omega}\right)v \pm \frac{\mathbf{w}\bullet\mathbf{k}^{\circ}}{n^{2}}, \qquad (27)$$
$$|\mathbf{v}| \ll c, \quad |\mathbf{w}| \ll c$$

and

$$V_{1,2}^{-} = c \pm \left(1 - n^{-2} + \frac{d\ln n}{d\ln\omega}\right)v \mp \frac{\mathbf{w}\bullet\mathbf{k}^{\circ}}{n^{2}}, \qquad (28)$$
$$|\mathbf{v}| \ll c, \quad |\mathbf{w}| \ll c$$

where the unit propagation vector $+\mathbf{k}^{\circ}$ is in the direction $M_3 \to M_2$ or $M_o \to M_1$, whereas $-\mathbf{k}^{\circ}$ indicates wave propagation in the opposite direction through the water tubes ($\pm$). Accordingly, the beams "1" and "2" interfere at T with the phase time difference

$$\Delta t = t_2 - t_1 = L\frac{\left(V_1^{+} - V_2^{-}\right)}{V_1^{+}V_2^{-}} + L\frac{\left(V_1^{-} - V_2^{+}\right)}{V_1^{-}V_2^{+}}$$
$$\simeq 4L\left(1 - n^{-2} + \frac{d\ln n}{d\ln\omega}\right)\frac{v}{c^{2}}, \qquad (29)$$
$$|\mathbf{v}| \ll c, \quad |\mathbf{w}| \ll c$$

since

$$V_1^{+}V_2^{-} \simeq c^{2} \simeq V_1^{-}V_2^{+}, \quad \left(\frac{\mathbf{v}}{c}\right)^{2} \ll 1, \quad \left(\frac{\mathbf{w}}{c}\right)^{2} \ll 1 \qquad (30)$$

where L is the effective length of the water tubes ($\pm$). Since $v, w \ll c$ in (27)–(28), the restrictions $v^2, w^2 \ll c^2$ in (30) are more than satisfied. Note that in the nominators of (29) the ether terms $\pm\mathbf{w}\bullet\mathbf{k}^{\circ}/n^{2}$ subtract out rigorously.

According to (29), the fringe shift $\Delta Z = c_o\Delta t/\lambda$ observed in the Fizeau interferometer is due to the speeding up of the wave beam "1" and the slowing down of the wave beam "2", by the velocity $\mathbf{v}$ of the water (dielectric with $\epsilon(\omega) \gg \varepsilon_o$). Since $w/c_o \sim 10^{-3}$, the ether terms of order $(w/c_o)^2 \sim 10^{-6}$ in the denominators of (29) may not be measurable in the Fizeau experiment.

Experiment of Hoek

In the Hoek (1868) experiment (Figure 2), a light beam emitted from a source Q is split up into two coherent components "1" and "2" by the semi-transparent mirror M_o. Beam "1" is guided clockwise along the path $M_o \to M_3 \to M_2 \to M_1 \to M_o \to T$, whereas the beam "2" is guided counter-clockwise along the path $M_o \to M_1 \to M_2 \to M_3 \to M_o \to T$, by the mirrors $M_{1,2,3}$. The beams "1" and "2" travel through a long tube filled with water at rest ($\mathbf{v} = \mathbf{0}$ relative to the laboratory frame S) in the opposite directions $M_3 \to M_2$ and $M_2 \to M_3$, respectively, and their interference fringe pattern is observed in the telescope T.

Hoek (1868) oriented the water tube parallel to the direction of the (estimated) Earth velocity $\mathbf{v}^{\circ} = -\mathbf{w}$ relative to the ether frame S°, and hoped to detect a fringe shift in the interference pattern after rotating the water tube (rigidly connected to his interferometer) by an angle $\Delta\phi = \pi$ into the opposite direction. Figure 2 shows the velocity $\mathbf{v}^{\circ}$ of the water tube relative to S° in the direction $M_3 \to M_2$, and the ether velocity $\mathbf{w} = -\mathbf{v}^{\circ}$ (since $\mathbf{v}^{\circ} = \mathbf{v} - \mathbf{w} = -\mathbf{w}$ for $\mathbf{v} = \mathbf{0}$) in the opposite direction $M_2 \to M_3$. Although light should propagate faster downstream the ether flow $\mathbf{w}$ than upstream the ether flow $\mathbf{w}$, the accuracy of the interferometer did not permit Hoek to detect a fringe shift, $\Delta Z = c_o\Delta t/\lambda \simeq 0$, after rotating the water tube from the direction $+\mathbf{v}^{\circ}$ into the direction $-\mathbf{v}^{\circ}$. Similarly, he did not observe fringe shifts after rotating the water tube by an angle $\Delta\phi = \pi$ from other initial directions in space.

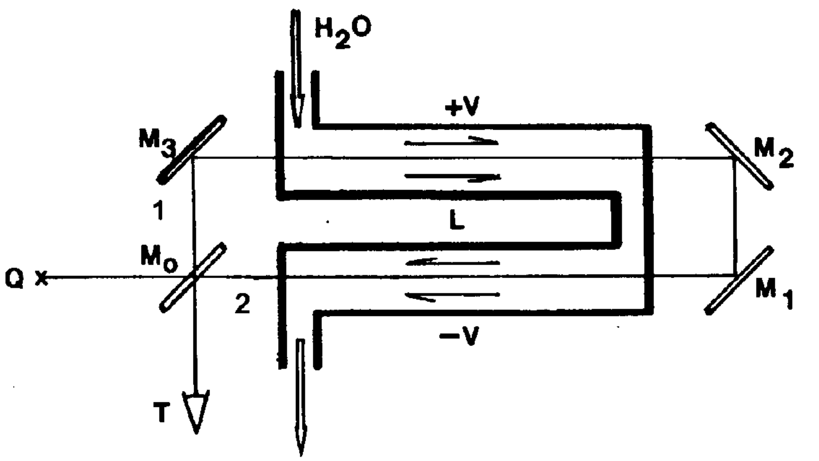

Figure 1—Interferometer of Fizeau: Water flowing with velocities $\pm\mathbf{v}$ in laboratory S.

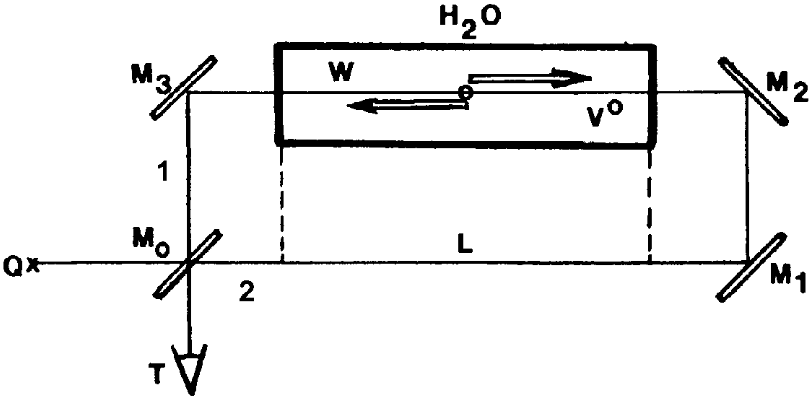

Figure 2—Interferometer of Hoek: Water at rest in laboratory S, and flowing with velocity $\mathbf{v}^{\circ}$ *relative to substratum* S° ($\mathbf{w}$ = *substratum velocity in water, S).*

The surprising experimental result of Hoek is readily explained by (25), which gives for the phase velocity of light in a dielectric (water) at rest in S $(\mathbf{v} = \mathbf{0})$

$$V = c + w\frac{\cos\phi}{n^2}, \quad |\mathbf{w}| \ll c \tag{31}$$

where $c = c_o/n$ and $n(\omega)$ is the refractive index of the water. For the light paths in air, $n = 1$ and $c = c_\circ$ (see Figure 2). Under consideration of the direction of the ether velocity $\mathbf{w}$ in Figure 2, the travel time for the clockwise beam "1" is

$$t_1 = \frac{L}{\left({c_o}/{n} - {w}/{n^2}\right)} + \frac{L}{c_o + w} + \Delta t_o, \quad |\mathbf{w}| \ll c \tag{32}$$

and for the counter-clockwise beam "2"

$$t_2 = \frac{L}{c_o - w} + \frac{L}{\left({c_o}/{n} + {w}/{n^2}\right)} + \Delta t_o, \quad |\mathbf{w}| \ll c \tag{33}$$

where L is the length of the water tube in the region $M_3 - M_2$ or the projected length in the air space $M_o - M_1$ (Δt_o are identical travel periods of the beams "1" and "2" in the remaining air paths). Accordingly, the difference of the phase times of the interfering light beams "1" and "2" is:

$$\Delta t = t_1 - t_2 = -\left(\frac{2L}{c_o}\right)\left(\frac{w}{c_o}\right)^3\left(1 - n^{-2}\right), \quad |\mathbf{w}| \ll c \tag{34}$$

It is readily shown that Δt has the same magnitude if the water tube is rotated by an angle $\Delta\phi = \pi$, *i.e.*, when the ether velocity points in the direction $M_3 \to M_2$ (Figure 2). It is seen that the phase time difference of the beams "1" and "2" is small, of the order $(w/c_o)^3 \sim 10^{-9}$ in comparison to $2L/c_o$. Thus, (34) explains the experiment of Hoek (1868), who used an interferometer which was by far not accurate enough to detect fringe shifts due to phase time differences of third order $(w/c_o)^3$.

Ether effects of order $(w/c_o)^2$ have been measured by Ives and Stilwell (1938, 1941) in their famous interferometric experiment on the rate of a moving atomic clock. However, it remains to be shown whether modern laser interferometers will permit the measurement of the fringe shift effects $\Delta Z = c_o\Delta t/\lambda \sim (w/c_o)^3$ of third order in (w/c_o) of the Hoek experiment.

Formula (31) of the Galilei-covariant electrodynamics (1)–(7) of moving dielectrics can also be deduced phenomenologically from the result $\Delta t \simeq 0$ of the Hoek experiment. Designating the "effective" ether velocity in the resting water ($\mathbf{v} = \mathbf{0}$ in S) with $\mathbf{w}'$, we obtain as before (see Figure 2)

$$t_1 = \frac{L}{\left({c_o}/{n} - w'\right)} + \frac{L}{c_o + w} + \Delta t_o \tag{35}$$

$$t_2 = \frac{L}{c_o - w} + \frac{L}{\left({c_o}/{n} + w'\right)} + \Delta t_o \tag{36}$$

Hence

$$\Delta t = t_1 - t_2 = 2L\left[\frac{w'}{\left({c_o^2}/{n^2} - w'^2\right)} - \frac{w}{\left(c_o^2 - w^2\right)}\right] \tag{37}$$

and

$$w' = \frac{w}{n^2}\frac{\left[1 - \frac{w'^2}{{c_o^2}/{n^2}}\right]}{\left(1 - {w^2}/{c_o^2}\right)} \simeq \frac{w}{n^2}, \quad \left(\frac{w}{c_o}\right)^2 \ll 1 \tag{38}$$

from $\Delta t \simeq 0$ (Hoek 1868). Equation (38) is (31) for $\phi = 0$. In an analogous way, $w' = \left(w/n^2\right)\cos\phi$ can be derived from Δt=0 for other angles $\phi \neq 0$.

The Hoek experiment is of fundamental importance for physics, since it shows that not the velocity $\mathbf{v} = (0)$ of the dielectric (water) relative to the laboratory S, but the velocity $\mathbf{v}^{\circ} = -\mathbf{w}$ of the dielectric (water) relative to the cosmic frame S° is essential for the speeding up or slowing down of EM waves in "moving" dielectrics. As seen from (22), these interactions of EM waves with dielectrics exist only if the dielectric has an absolute velocity $\mathbf{v}^\circ = \mathbf{v} - \mathbf{w} = \mathbf{inv} \neq \mathbf{0}$ relative to the cosmic frame S°. This experimentally confirmed fact (Fizeau 1851, Hoek 1868) is not surprising, since EM fields are excitations of the vacuum substratum by Galilei-covariant electrodynamics. Thus, the Hoek experiment not only refutes the principle of the relativity of velocity (Sommerfeld 1965) but also the relativistic denials of an EM wave carrier and a preferred cosmic reference frame S° (S° confirmed also by other experiments, *e.g.*, Penzias & Wilson (1965) or Henry (1971)).

Conclusions

The Galilei-covariant electrodynamics (1)–(7) of moving media is free from the deficiencies of the non-covariant Lorentz theory and the relativistic Minkowski theory (unsymmetric EM stress-energy tensor). The speeding up and slowing down of EM waves in dielectric media, which move with a velocity $\mathbf{v}^\circ = \mathbf{v} - \mathbf{w} \neq \mathbf{0}$ relative to the cosmic or substratum frame S°, are small effects since $v_{\max}/c_o \sim 10^{-5}$ and $w/c_o \sim 10^{-3}$, which, therefore, need not to be considered in most electrodynamic applications (Sommerfeld 1965, Wilhelm 1985a). However, these absolute EM space-time effects are of fundamental significance for basic physics, since they can be measured by means of interferometric experiments, *e.g.*, those of Fizeau (1851) and Hoek (1868). The presented Galilei-covariant electrodynamics of moving media explains not only the experiments of Fizeau, but also the experiment of Hoek, which can not be understood within the frame of the previous theories.

The Hoek (1868) experiment refutes the following (false) concepts of the special theory of relativity and Lorentz-covariant electrodynamics: (*i*) the non-existence of an EM wave carrier in vacuum, (*ii*) the relativity of physical velocities (relative to the observer), and (*iii*) the denial of the existence of a preferred cosmic reference frame S°. Other experiments which refute the special theory of relativity are those of Sagnac (1913), Penzias & Wilson (1965), Henry (1971), Aharonov-Bohm (Wilhelm 1992a), the Cerenkov effect in dielectrics (Wilhelm 1992a), and EM induction in unipolar generators with corotating disc and magnet (Wilhelm 1992b). Experimentalists are encouraged to redo the experiments of (*i*) Fizeau and (*ii*) Hoek since it might be possible to detect with modern interferometer techniques also the ether effects of order (*i*) $(w/c)^2$ and (*ii*) $(w/c)^3$, which would provide even more undeniable evidence for Galilean or absolute space-time physics.

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