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Research Article

Maxwell Equations and Light Propagation in Rotating Frames

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Abstract

In the current paper we present a generalization of the Maxwell equations in a frame in uniform circular motion with respect to an inertial frame of reference. We show an immediate application to the propagation of electromagnetic waves in frames in uniform rotation. The solution is of great interest for real time applications because earth-bound laboratories are inertial only in approximation. The motivation is that the real life applications include accelerating and rotating frames with arbitrary orientations more often than the idealized case of inertial frames; our daily experiments happen in the laboratories attached to the rotating Earth. We are interested in deriving the Maxwell equations in rotating frames of reference. Our paper deals with centrally rotating frame.

Keywords: General coordinate transformations; Light propagation in uniformly rotating frames; Maxwell equations; Uniform rotation motion

PACS: 03.30, +p, 52.20.Dq, 52.70.Nc

Introduction

Real life applications include accelerating and rotating frames more often than the idealized case of inertial frames. Our daily experiments happen in the laboratories attached to the rotating, continuously accelerating Earth. Usually, such experiments are explained from the perspective of an external, inertial frame because special relativity in rotating frames is viewed as more complicated. In the present paper, we will construct a straightforward explanation by applying the formalisms developed in previous work [1-7].

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The euler-lagrange equations for motion on a uniformly rotating disc

In an inertial frame K the coordinates are (T, R, Φ, Z). In a frame K 'rotating with respect the inertial frame, the coordinates are (t, r, ϕ, z). The angular speed of rotation between the two frames is Ω. The transformation between the frames is [8] (Figure 1):

$$\begin{aligned} T &= t \\ R &= r \\ \Phi &= \phi + \Omega t \\ Z &= z \end{aligned} \qquad (2.1)$$

We have the total differential operators:

$$\begin{aligned} \frac{\partial}{\partial T} &= \frac{\partial}{\partial t} \\ \frac{\partial}{\partial R} &= \frac{\partial}{\partial r} \\ \frac{\partial}{\partial Z} &= \frac{\partial}{\partial z} \\ \frac{\partial}{\partial \Phi} &= \frac{\partial}{\partial \phi} + \Omega \frac{\partial}{\partial t} \end{aligned} \qquad (2.2)$$

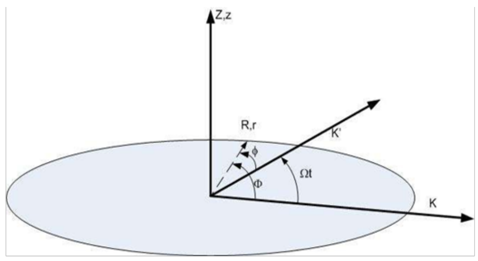

Figure 1: Centrally rotating frame of reference.

The divergence and the curl for a vector function $F = F_R \hat{R} + \hat{\Phi} + F_Z \hat{Z}$ expressed in cylindrical
Co-ordinates are:

$$div(\mathbf{F}) = \frac{1}{R}\left[\frac{\partial (RF_R)}{\partial R} + \frac{\partial F_\Phi}{\partial \Phi}\right] + \frac{\partial F_Z}{\partial Z} - \frac{F_R}{R} + \frac{\partial F_R}{\partial R} + \frac{1}{R}\frac{\partial F_\Phi}{\partial \Phi} + \frac{\partial F_Z}{\partial Z} \qquad (2.3)$$

$$curl(\mathbf{B}) = \left(\frac{1}{R}\frac{\partial F_Z}{\partial \Phi} - \frac{\partial F_\Phi}{\partial Z}\right)\hat{R} + \left(\frac{\partial_{F_R}}{\partial Z} - \frac{\partial_{F_Z}}{\partial R}\right)\hat{\Phi} + \frac{1}{R}\left(\frac{\partial (RF_\Phi)}{\partial R} - \frac{\partial F_R}{\partial \Phi}\right)\hat{Z}$$

The Maxwell equations in the inertial frame are:

$$\begin{aligned} div(\mathbf{E}) &= 0 \\ div(\mathbf{B}) &= 0 \\ curl(\mathbf{E}) &= -\frac{\partial B}{\partial T} \\ curl(\mathbf{B}) &= -\frac{1}{c^2}\frac{\partial E}{\partial T} \end{aligned} \qquad (2.4)$$

The above can be written, in cylindrical coordinates, according to (2.3) as:

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$$\frac{E_R}{\partial R}+\frac{\partial E_R}{\partial R}+\frac{1}{R}\frac{\partial E_\Phi}{\partial \Phi}+\frac{\partial E_Z}{\partial Z}=0$$

$$\frac{B_R}{R}+\frac{\partial B_R}{\partial R}+\frac{1}{R}\frac{\partial B_\Phi}{\partial \Phi}+\frac{\partial B_Z}{\partial Z}=0$$

$$\left(\frac{1}{R}\frac{\partial E_Z}{\partial \Phi}-\frac{\partial E_\Phi}{\partial Z}\right)\hat{R}+\left(\frac{\partial E_R}{\partial Z}-\frac{\partial E_Z}{\partial R}\right)\hat{\Phi}+\frac{1}{R}\left(\frac{\partial (RE_\Phi)}{\partial R}-\frac{\partial E_R}{\partial \Phi}\right)\hat{Z}=-\frac{\partial B}{\partial T}$$

$$\left(\frac{1}{R}\frac{\partial B_Z}{\partial \Phi}-\frac{\partial B_\Phi}{\partial Z}\right)\hat{R}+\left(\frac{\partial B_R}{\partial Z}-\frac{\partial B_Z}{\partial R}\right)\hat{\Phi}+\frac{1}{R}\left(\frac{\partial (RB_\Phi)}{\partial R}-\frac{\partial B_R}{\partial \Phi}\right)\hat{Z}=\frac{1}{c^2}\frac{\partial E}{\partial T} \quad (2.5)$$

The last two equations, written on a component by component basis, become:

$$\frac{1}{R}\frac{\partial E_Z}{\partial \Phi}-\frac{\partial E_\Phi}{\partial Z}=-\frac{\partial B_R}{\partial T}$$

$$\frac{\partial E_R}{\partial Z}-\frac{\partial E_Z}{\partial R}=-\frac{\partial B_\Phi}{\partial T}$$

$$\frac{E_\Phi}{R}+\frac{\partial E_\Phi}{\partial R}-\frac{1}{R}\frac{\partial E_R}{\partial \Phi}=-\frac{\partial B_Z}{\partial T}$$

$$\frac{1}{R}\frac{\partial B_Z}{\partial \Phi}-\frac{\partial B_\phi}{\partial Z}=-\frac{1}{c^2}\frac{\partial E_R}{\partial T}$$

$$\frac{\partial B_R}{\partial Z}-\frac{\partial B_Z}{\partial R}=-\frac{1}{c^2}\frac{\partial E_\Phi}{\partial T} \quad (2.6)$$

$$\frac{B_\Phi}{R}+\frac{\partial B_\Phi}{\partial R}-\frac{1}{R}\frac{\partial B_R}{\partial \Phi}=-\frac{1}{c^2}\frac{\partial E_Z}{\partial T}$$

Combining (2.5), (2.6) with (2.2) we get the Maxwell equations in the rotating frame:

$$\frac{E_R}{r}+\frac{\partial E_R}{\partial r}+\frac{1}{r}\left(\frac{\partial E_\Phi}{\partial \phi}+\Omega\frac{\partial E_\Phi}{\partial t}\right)+\frac{\partial E_Z}{\partial z}=0$$

$$\frac{B_R}{r}+\frac{\partial B_R}{\partial r}+\frac{1}{r}\left(\frac{\partial B_\Phi}{\partial \phi}+\Omega\frac{\partial B_\Phi}{\partial t}\right)+\frac{\partial B_Z}{\partial z}=0 \quad (2.7a)$$

$$\frac{1}{r}\left(\frac{\partial E_z}{\partial \phi}+\Omega\frac{\partial E_Z}{\partial t}\right)-\frac{\partial E_\Phi}{\partial z}=-\frac{\partial B_R}{\partial t}$$

$$\frac{\partial E_R}{\partial z}-\frac{\partial E_z}{\partial r}=-\frac{\partial B_\Phi}{\partial t}$$

$$\frac{E_\Phi}{r}+\frac{\partial E_\Phi}{\partial r}-\frac{1}{r}\left(\frac{\partial E_R}{\partial \phi}+\Omega\frac{\partial E_R}{\partial t}\right)=-\frac{\partial B_z}{\partial t}$$

$$\frac{1}{r}\left(\frac{\partial B_z}{\partial \phi}+\Omega\frac{\partial B_Z}{\partial t}\right)-\frac{\partial B_\Phi}{\partial z}=-\frac{1}{c^2}\frac{\partial E_R}{\partial t}$$

$$\frac{\partial B_R}{\partial z}-\frac{\partial B_z}{\partial r}=-\frac{1}{c^2}\frac{\partial E_\Phi}{\partial t}$$

$$\frac{\partial B_\Phi}{\partial r}-\frac{1}{r}\left(\frac{\partial B_R}{\partial \phi}+\Omega\frac{\partial B_R}{\partial t}\right)=-\frac{1}{c^2}\frac{\partial E_Z}{\partial t} \quad (2.7b)$$

In practice, the components of the vectors E, B do not depend of coordinates, they may depend only on time, so the above equations simplify to:

$$\frac{E_R}{r}+\frac{\Omega}{r}\frac{\partial E_\Phi}{\partial t}=0$$

$$\frac{B_R}{r}+\frac{\Omega}{r}\frac{\partial B_\Phi}{\partial t}=0 \quad (2.8a)$$

$$\frac{\Omega}{r}\frac{E_z}{\partial t}=-\frac{\partial B_R}{\partial t}$$

$$0=-\frac{\partial B_\Phi}{\partial t}$$

$$\frac{E_\Phi}{r}-\frac{\Omega}{r}\frac{\partial E_R}{\partial t}=-\frac{\partial B_z}{\partial t}$$

$$\frac{\Omega}{r}\frac{\partial B_z}{\partial t}=-\frac{1}{c^2}\frac{\partial E_R}{\partial t}$$

$$0=-\frac{1}{c^2}\frac{\partial E_\Phi}{\partial t}$$

$$\frac{B_\Phi}{r}-\frac{\Omega}{r}\frac{\partial B_R}{\partial t}=\frac{1}{c^2}\frac{\partial E_Z}{\partial t} \quad (2.8b)$$

Equations (2.7a), (2.7b), (2.8a), (2.8b) mix variables from the inertial frame K and the rotating frame K', we need to fix that. We know from the rules of vector transformation in cylindrical coordinates that:

$$E_R=E_r\cos\Omega t-E_\phi\sin\Omega t$$

$$E_\Phi=E_r\sin\Omega t+E_\phi\cos\Omega t$$

$$B_R=B_r\cos\Omega t-B_\phi\sin\Omega t$$

$$B_\Phi=B_r\sin\Omega t+B_\phi\cos\Omega t$$

$$E_Z=E_z$$

$$B_Z=B_z \quad (2.9)$$

Substituting (2.9) in (2.7a), (2.7b) we get the general Maxwell equations in the rotating frame:

$$\frac{E_r\cos\Omega t-E_\phi\sin\Omega t}{r}+\frac{\partial E_r}{\partial r}\cos\Omega t-\frac{\partial E_\phi}{\partial r}\sin\Omega t+\frac{1}{r}\left(\begin{array}{l}\frac{\partial E_r}{\partial \phi}\sin\Omega t+\frac{\partial E_\phi}{\partial \phi}\cos\Omega t+\\ +\Omega^2E_r\cos\Omega t-\Omega^2E_\phi\sin\Omega t+\Omega\frac{\partial E_r}{\partial t}\sin\Omega t+\Omega\frac{\partial E_\phi}{\partial t}\cos\Omega t\end{array}\right)+\frac{\partial E_Z}{\partial z}=0 \quad (2.10a)$$

$$\frac{B_r\cos\Omega t-B_\phi\sin\Omega t}{r}+\frac{\partial B_r}{\partial r}\cos\Omega t-\frac{\partial B_\phi}{\partial r}\sin\Omega t+\frac{1}{r}\left(\begin{array}{l}\frac{\partial B_r}{\partial \phi}\sin\Omega t+\frac{\partial B_\phi}{\partial \phi}\cos\Omega t+\\ +\Omega^2B_r\cos\Omega t-\Omega^2B_\phi\sin\Omega t+\Omega\frac{\partial B_r}{\partial t}\sin\Omega t+\Omega\frac{\partial B_\phi}{\partial t}\cos\Omega t\end{array}\right)+\frac{\partial B_Z}{\partial z}=0$$

$$\frac{1}{r}\left(\frac{\partial E_z}{\partial \phi}+\Omega\frac{\partial E_z}{\partial t}\right)-\left(\frac{\partial E_r}{\partial z}\sin\Omega t+\frac{\partial E_\phi}{\partial z}\cos\Omega t\right)=\Omega B_r\sin\Omega t-\frac{\partial \mathrm{B}_r}{\partial t}\cos\Omega+\frac{\partial \mathrm{B}_\phi}{\partial t}\sin\Omega+\Omega\mathrm{B}_\phi\cos\Omega t$$

$$\frac{\partial E_r}{\partial z}\cos\Omega t-\frac{\partial E_\phi}{\partial z}\sin\Omega t-\frac{\partial E_z}{\partial r}=-\frac{\partial B_r}{\partial t}\sin\Omega-\Omega B_r\cos\Omega t-\frac{\partial B_\phi}{\partial t}\cos\Omega+\Omega B_\phi\sin\Omega t$$

$$-\frac{\partial B_z}{\partial t}=\frac{1}{r}\left(E_r\sin\Omega t+E_\phi\cos\Omega t\right)+\frac{\partial E_r}{\partial r}\sin\Omega t+\frac{\partial E_\phi}{\partial r}\cos\Omega t-$$
$$-\frac{1}{r}\left(\frac{\partial E_r}{\partial \phi}\cos\Omega t-\frac{\partial E_\phi}{\partial \phi}\sin\Omega t\right)-\frac{\Omega}{r}\left(\frac{\partial E_r}{\partial t}\cos\Omega t-\frac{\partial E_\phi}{\partial t}\sin\Omega t-\Omega E_r\sin\Omega t-\Omega E_\phi\cos\Omega t\right)$$

$$\frac{1}{c^2}\left(\Omega E_r\sin\Omega t-\frac{\partial E_r}{\partial t}\cos\Omega t+\frac{\partial E_\phi}{\partial t}\sin\Omega t+\Omega E_\phi\cos\Omega t\right)=\frac{1}{r}\left(\frac{\partial B_z}{\partial \phi}+\Omega\frac{\partial B_z}{\partial t}\right)-\frac{\partial B_r}{\partial z}\sin\Omega t-\frac{\partial B_\phi}{\partial z}\cos\Omega t$$

$$\frac{\partial B_r}{\partial t}\cos\Omega t-\frac{\partial B_\phi}{\partial z}\sin\Omega t-\frac{\partial B_z}{\partial r}=-\frac{1}{c^2}\left(\frac{\partial E_r}{\partial t}\sin\Omega t+\Omega E_r\cos\Omega t+\frac{\partial E_\phi}{\partial t}\cos\Omega t-\Omega E_\phi\sin\Omega t\right)$$

(2.10b)

$$-\frac{1}{c^2}\frac{\partial E_z}{\partial t}=\frac{B_r\sin\Omega t+B_\phi\cos\Omega t}{r}+\frac{\partial B_r}{\partial r}\sin\Omega t+\frac{\partial B_\phi}{\partial r}\cos\Omega t-\frac{1}{r}\left(\begin{array}{l}\frac{\partial B_r}{\partial \phi}\cos\Omega t-\frac{\partial B_\phi}{\partial \phi}\sin\Omega t+\\ +\Omega\frac{\partial B_r}{\partial t}\cos\Omega t-\Omega^2B_r\sin\Omega t-\Omega\frac{\partial B_\phi}{\partial t}\sin\Omega t-\Omega^2B_\phi\cos\Omega t\end{array}\right)$$

Substituting (2.9) in (2.8a), (2.8b) we get the Maxwell equations in the rotating frame for the practical cases whereby the components of the vectors E, B do not depend of coordinates:

$$\frac{E_r\cos\Omega t-E_\phi\sin\Omega t}{r}+\frac{\Omega}{r}\frac{\partial E_r}{\partial t}\sin\Omega t+\frac{\Omega}{r}\frac{\partial E_\phi}{\partial t}\cos\Omega t+\frac{\Omega^2}{r}E_r\cos\Omega t-\frac{\Omega^2}{r}E_\phi\sin\Omega t=0$$

$$\frac{B_r\cos\Omega t-B_\phi\sin\Omega t}{r}+\frac{\Omega}{r}\frac{\partial B_r}{\partial t}\sin\Omega t+\frac{\Omega}{r}\frac{\partial B_\phi}{\partial t}\cos\Omega t+\frac{\Omega^2}{r}B_r\cos\Omega t-\frac{\Omega^2}{r}B_\phi\sin\Omega t=0 \quad (2.11a)$$

$$\frac{\Omega}{r}\frac{\partial E_z}{\partial t}=-\frac{\partial B_r}{\partial t}\cos\Omega t+\Omega B_r\sin\Omega t+\frac{\partial B_\phi}{\partial t}\sin\Omega t+\Omega B_\phi\cos\Omega t$$

$$\Omega B_r\cos\Omega t-\Omega B_\phi\sin\Omega t+\frac{\partial B_r}{\partial t}+\frac{\partial B_\phi}{\partial t}\cos\Omega t=0$$

$$-\frac{\partial B_z}{\partial t}=\frac{E_r\sin\Omega t+E_\phi\cos\Omega t}{r}-\frac{\Omega}{r}\left(\frac{\partial E_r}{\partial t}\cos\Omega t-\frac{\partial E_\phi}{\partial t}\sin\Omega t-\Omega E_r\sin\Omega t-\Omega E_\phi\cos\Omega t\right)$$

$$\frac{\Omega}{r}\frac{\partial B_z}{\partial t}=-\frac{1}{c^2}\left(\frac{\partial E_r}{\partial t}\cos\Omega t-\frac{\partial E_\phi}{\partial t}\sin\Omega t-\Omega E_r\sin\Omega t-\Omega E_\phi\cos\Omega t\right)$$

$$\frac{\partial E_r}{\partial t}\sin\Omega t+\Omega E_r\cos\Omega t+\frac{\partial E_\phi}{\partial t}\cos\Omega t-\Omega E_\phi\sin\Omega t=0 \quad (2.11b)$$

$$-\frac{1}{c^2}\frac{\partial E_z}{\partial t}=\frac{B_r\sin\Omega t+B_\phi\cos\Omega t}{r}-\frac{\Omega}{r}\left(\frac{\partial B_r}{\partial t}\sin\Omega+\Omega B_r\cos\Omega t+\frac{\partial B_\phi}{\partial t}\cos\Omega-\Omega B_\phi\sin\Omega t\right)$$

Application

Aberration and Doppler Effect of Electromagnetic Rays Propagation in a Uniformly Rotating Frame vs. the same Rays as Viewed in an Inertial Frame. Assume that in the inertial frame we have an electromagnetic wave propagating in the plane perpendicular to Z:

$$(E_R,E_\Phi,E_Z)=(A\sin(\omega T-K.R),0,0)\ (B_R,B_\Phi,B_Z)=(0,0,B\sin(\omega T-K.Z))$$

(Where $K=(K_x,K_y,K_z)$ is the wave-vector of the electromagnetic front in frame (R,Φ,Z). Let's Examine the Doppler Effect and electromagnetic beam aberration. This is a critical issue in the explanation of the Mossbauer rotor experiments. Let f_{em} be the frequency emitted by the radiation. Source and let F_{obs} be the observed frequency. Let Ψ be the phase of the radiation wave as measured in the inertial frame and let ψ be the phase in the rotating frame.

$$\psi=F_{obs}\left(T-\frac{(K_xX+K_yY)}{c}\right) \quad (3.1)$$

$$\psi=f_{em}\left(t-\frac{k_xx+k_yy}{c}\right)=f_{em}\left(\tau\gamma-\frac{k_xx+k_yy}{c}\right)=f_{em}\left(\gamma T-\frac{k_xx+k_yy}{c}\right)$$

$$=\gamma f_{em}\left(T-\frac{k_x/\gamma}{c}x-\frac{k_y/\gamma}{c}y\right) \quad (3.2)$$

$$x=r\cos\phi=X\cos\Omega t+Y\sin\Omega t$$

$$y=r\sin\phi=-X\sin\Omega t+Y\cos\Omega t \quad (3.3)$$

$$\psi=\gamma f_{em}\left(T-\frac{k_x\cos\Omega T-k_y\sin\Omega T}{\gamma c}X-\frac{k_y\cos\Omega T+k_y\sin\Omega T}{\gamma c}Y\right) \quad (3.4)$$

From the wave phase invariance $\Psi=\psi$ it would be naive to claim:

$$F_{obs}=\gamma f_{em} \quad (3.5)$$

$$K_x=\left(k_x\cos\Omega T-k_y\sin\Omega T\right)/\gamma$$

$$K_y=\left(k_y\cos\Omega T-k_x\sin\Omega T\right)/\gamma \quad (3.6)$$

Such a conclusion is incorrect because expression (3.4) depends on T both explicitly and implicitly. Not all is lost if we consider just the particular case when the axes of the two systems of coordinates align, as in the case of the Mossbauer rotor experiments. This happens when

$T=\frac{2n\pi}{\Omega},(n=0,1,2,3.....)$ With that, (3.4) becomes:

$$\psi=\gamma f_{em}\left(\frac{2\pi}{\Omega}n-\frac{k_x}{\gamma c}X-\frac{k_y}{\gamma c}Y\right) \quad (3.7)$$

On the other hand, (3.1) becomes:

$$\Psi=F_{obs}\left(\frac{2\pi}{\Omega}n-\frac{K_xX+K_yY}{c}\right) \quad (3.8) \quad (3.8)$$

From the frame-invariance of the phase, by comparing (3.7) and (3.8) we obtain:

$$F_{obs}=\gamma f_{em} \quad (3.9)$$

$$K_x=\frac{k_x}{\gamma} \quad (3.10)$$

$$K_y=\frac{k_y}{\gamma} \quad (3.11)$$

There is no aberration since the vectors $(K_x,K_y)(k_x,k_y)$ and are collinear. An excellent confirmation of the relativistic Doppler Effect was achieved by the Mossbauer rotor experiment [9]. Gamma rays are sent from a source in the middle of a rotating disk (Figure 2) to an absorber at the rim and a stationary counter is placed beyond the absorber. The characteristic resonance absorption frequency of the moving absorber at the rim should decrease due to time dilation, so the transmission of gamma rays through the absorber increases, which is subsequently measured by the stationary counter beyond the absorber. The maximal deviation from time dilation was 10^{-5}. Such experiments were performed by [10-13]. According to (3.9) the measured frequency is $F_{obs}=\gamma f_{em}$. Conversely, if the positions of the source and the absorber are swapped, the formalism developed above predicts the measured frequency to be:

$$F_{obs}=\frac{f_{em}}{\gamma} \quad (3.12)$$

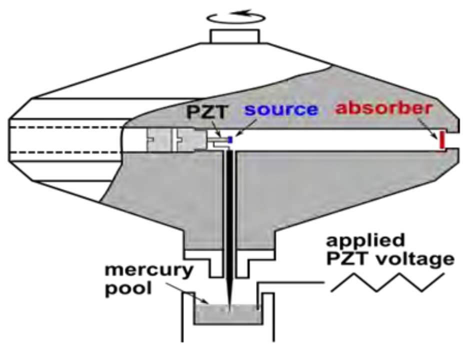

Figure 2: The Mossbauer rotor experiment.

The relationship between the frequencies in the rotating frame as a function of the natural frequency in the inertial frame is, for an emitter located at distance absorber R ' from the center and the distance at *R* is [14,15]:

$$\frac{v'}{v}=\sqrt{\frac{1-(R\Omega)^2}{1-(R'\Omega)^2}} \quad (3.13)$$

Obviously, if $R' = R$ the effect is null, as observed in the Champeney experiment [16,17].

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Conclusion

We have derived the Maxwell equations for the case of a rotating frame of reference. Real life applications include accelerating and rotating frames more often than the idealized case of inertial frames. Our daily experiments happen in the laboratories attached to the rotating, continuously accelerating Earth. Usually, such experiments are explained from the perspective of an external, inertial frame because special relativity in rotating frames is viewed as more complicated. We have attempted to "lift the veil" off the more mysterious rotating frames. A direct application is the formula of the relativistic Doppler Effect in the case of the emitter and absorber rotating with respect to a common center of rotation.

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