GRAVITO-RADIATIVE FORCE (DETECTION OF GRAVITATIONAL WAVES)

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Abstract

Einstein's general relativistic wave equation predicts a gravitational wave, and that prediction is confirmed by an astronomical observation. His equation of motion, on the other hand, predicts that a gravito-radiative force, due to a gravito-tensor potential, exists. The gravito-radiative force propagates through space, tries to induce a mass quadrupole moment in Earth's crust, through the rotation of Earth with respect to the center od Earth. However, Earth's crust is rigid, and resists such deformation. Only pendulum-bobs co-moving with Earth's crust are accelerated horizontally. We placed two verticity meters (motionless pendulums) at Boulder, Colorado, and observed some gravitational waves as coincidental displacements of their bobs. Typical gravitational wave we observed is an impulse of about 10^{-8} m/s, and that corresponds to the energy decay rate of about 10^{51} J/s at the galactic center, and the energy of the galactic nucleus is about 10^{54} J.

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1 Einstein's general relativistic wave equation

In terms of the metric

$$(ds)^2 = g_{ij}dx^i dx^j, \tag{1.1}$$

where $x^0 = ct,\ x^1 = x,\ x^2 = y,\ x^3 = z$, Einstein [1] proposed an equation

$$R_{ij} - \frac{1}{2}g_{ij}R = \frac{8\pi G}{c^4}T_{ij}, \tag{1.2}$$

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where T_{ij}, in the right-hand side, is the ij component of the energy- momentum-stress tensor, such that $T_{00} = -\mu c^2$, taking the mass density as μ. The quantity on the left-hand side is called the Einstein tensor. If we introduce gravitational potentials by

$$g_{ij} = \delta_{ij} - \phi_{ij} + \frac{1}{2}\phi\delta_{ij}. \tag{1.3}$$

where

$$\delta_{00} = 1,\ \delta_{11} = \delta_{22} = \delta_{33} = -1,\ \delta_{ij} = 0 \ \text{ if } \ i \neq j, \tag{1.4}$$

$$\phi = \phi_{00} - \phi_{11} - \phi_{22} - \phi_{33}, \tag{1.5}$$

and

$$\frac{\partial \phi_{ij}}{\partial x^i} = 0 \ \text{ (Lorentz condition)}, \tag{1.6}$$

and assume that all terms higher than linear in ϕ are negligible in the Einstein tensor, then eq. (1.2) becomes:

$$\left(\nabla^2 - \left(\frac{\partial}{c\partial t}\right)^2\right)\phi_{ij} = \frac{16\pi G}{c^4} T_{ij}. \tag{1.7}$$

In an empty space, where $\mu = 0$, the right-hand side of this equation is zero and shows that the ϕ_{ij} propagate with speed c. This is the *gravitational wave*. For this reason we may call eq. (1.7) Einstein's wave equation. When the mass forms a point mass M moving with a velocity $\mathbf{v}$, located at $\mathbf{r}$ from the observation point p at time t, then eq. (1.7) gives:

$$\phi_{00} = \frac{4GM}{c^2 r}, \tag{1.8a}$$

$$\phi_{0\alpha} = -\frac{4GMv_\alpha}{c^3 r}, \quad \alpha = 1, 2, 3, \tag{1.8b}$$

$$\phi_{\alpha\beta} = \frac{4GMv_\alpha v_\beta}{c^4 r} = v_\alpha \phi_{0\beta}/c, \quad \alpha, \beta = 1, 2, 3. \tag{1.8c}$$

If there are more than one sources we can simply add them on the right hand sides of these equations. We neglect the retardation effect in the present paper.

Assuming a continuity between the mass source and the gravitational field produced, Landau and Lifshitz derived in [2] an expression of the rate of the energy loss, $-d\mathcal{E}/dt$, of the mass source due to the emission of the gravitational wave as

$$-\frac{d\mathcal{E}}{dt} = \frac{2G}{45c^5}(\sum M(3v_\alpha \dot{v}_\beta - \delta_{\alpha\beta} v\dot{v}))^2, \tag{1.10}$$

where the summation is over all source masses and their velocity and acceleration components. Taylor and Weisberg found in [3] that the decay of the orbital motion of binary pulsar PSR 1913+16 follows this theoretical prediction. Thus the existence of gravitational wave is established. The sun is orbiting around the galactic center at $v = 250$ km/s. Its acceleration toward the galactic center is estimated to be $\dot{v} = v^2/r = 3 \times 10^{-10}$ m/s^2, taking the distance to the galactic center $r = 3 \times 10^{20}$ m.

The solar energy (mc^2) of 2×10^{47} J is decaying down at the rate of 0.1 J/s according to eq. (1.10). At the end of this paper, we will report that a typical gravitational wave (impulse) we observed is responsible to $Mv\dot{v}$ of about 10^{53} m/s^2. Accepting to eq. (1.10) it corresponds to 10^{51} J/s of energy loss rate from the galactic nucleus, if the duration time of the impulse is 10 s. If the mass of the galactic nucleus is about 10^{39} kg this number is about equal to the corresponding energy, mc^2 = 10^{54} J. We are observing decays of black bodys at the galactic center.

Einstein also proposed in [1] an equation of motion for a test particle with coordinates x^i as:

$$\frac{d^2x^i}{ds^2} = -\Gamma^i_{jk}\frac{dx^i}{ds}\frac{dx^k}{ds} \equiv F^i_E/m, \tag{1.11}$$

where Γ^i_{jk} is a component of Christoffel symbols and m is the mass of the test particle to be considered. The last expression of this equation defined the Einstein force, F^i_E, to be discussed below.

If we take the gravitational potentials introduced by eq. (1.3) and neglect nonlinear terms, we obtain as in [4]:

$$F^0_E/m = -\frac{c^2}{2(1-\frac{1}{2}\phi_{00})}\frac{dt}{ds}\frac{d\phi_{00}}{ds}, \tag{1.12}$$

$$\begin{aligned}\mathbf{F}_E/m = &-\frac{c^2}{4}\nabla\phi_{00} - c\frac{\partial\boldsymbol{\phi}}{\partial t} + c\mathbf{V}\times(\nabla\times\boldsymbol{\phi})\\ &+\frac{\partial[\mathbf{v}(\mathbf{V}\cdot\boldsymbol{\phi})]}{c\partial t} + \left[(\mathbf{V}\cdot\nabla)\boldsymbol{\phi} - \frac{1}{2}\nabla(\boldsymbol{\phi}\cdot\mathbf{V})\right]\frac{(\mathbf{V}\cdot\mathbf{v})}{c},\end{aligned} \tag{1.13}$$

where $\mathbf{V}$ is the velocity of the test particle, and we do not differentiate $\mathbf{V}$ by t. The terms in the second line of eq. (1.13) are due to the tensor potentials. Using eq. (1.12) in $d^2t/ds^2 = F^0/mc^2$, we obtain:

$$\frac{dt}{ds} = \frac{1}{c(1-\frac{1}{2}\phi_{00})}, \quad \text{or} \quad s \simeq ct(1-\frac{1}{2}\phi_{00}). \tag{1.14}$$

Thus Einstein's equation of motion, eq. (1.11), reduces to

$$\frac{d^2\mathbf{r}}{dt^2} = \mathbf{F}_E/m, \tag{1.15}$$

to the first order.

Einstein's equation of motion gives the acceleration of a test particle produced by the (derivatives of) gravitational potentials existing at the position of the test particle at a given time. Thus it is appropriate for a receiving antenna of an incoming gravitational wave.

Newton's theory of gravity. Galileo equivalence principle

Newton did not consider the gravitational field. He simply assumed that between masses M and m placed at a distance r, an attractive force

$$\mathbf{F}_N = \frac{GMm\mathbf{r}}{r^3} \tag{2.1}$$

exists. Thus he did not have a wave equation, but note that this is the first term of $\mathbf{F}_E$ as given by eq. (1.13).

Newton's equation of motion is:

$$m\frac{d^2\mathbf{r}}{dt^2} = \mathbf{F}_N, \tag{2.2}$$

which reduces to:

$$\frac{d^2\mathbf{r}}{dt^2} = \frac{GM\mathbf{r}}{r^3}. \tag{2.3}$$

Equation (2.3) exhibits the Galileo equivalence principle. Equation (1.15) shows that the Einstein force, $\mathbf{F}_E$ satisfies the Galileo equivalence principle. Einstein [8] claimed that the Galileo equivalence principle is applicable to mass-zero particles also. Because such mass-zero particles propagate with speed c in the empty space, characterized by $ds = 0$, Newton's equation (2.2) is not suitable, and Einstein proposed eq. (1.15) to replace eq. (2.3).

According to Newton's third law:

$$M\dot{\mathbf{v}}_M = -m\dot{\mathbf{v}}_m, \tag{2.4}$$

we can regard a very massive (M) gravity source as a coordinate origin around which a test particle of a small mass ($m \ll M$) is moving according to eq. (2.2). Earth is orbiting around the sun in a nearly circular orbit. If we take a coordinate system rotating around the origin (the sun) with a constant angular velocity $\boldsymbol{\omega}$, eq. (2.2) is transformed as:

$$m\frac{d^2\mathbf{r}'}{dt^2} + 2m\boldsymbol{\omega} \times \frac{d\mathbf{r}'}{dt} + m\boldsymbol{\omega} \times (\boldsymbol{\omega} \times \mathbf{r}') = \mathbf{F}_N, \tag{2.5}$$

where $\mathbf{r}'$ is the coordinate of the test particle measured in the rotating frame, such as Earth orbiting around the sun. It is possible to choose $\boldsymbol{\omega}$ to satisfy

$$\omega^2\mathbf{r}' - \boldsymbol{\omega}(\boldsymbol{\omega} \cdot \mathbf{r}') = \frac{GM\mathbf{r}'}{r'^3}, \tag{2.6}$$

which can be simplified if we choose $\boldsymbol{\omega} \cdot \mathbf{r}' = 0$. When the test particle is co-moving with the center of Earth, eq. (2.6) reduces to $md^2\mathbf{r}'/dt^2 = 0$, in which the Newtonian gravitational force due to the sun completely disappears. This situation, however, does not imply that the gravitational force is a fictitious force, because the sun, the source of the gravitational force, still exists. In fact, if the test particle is co-orbiting with the center of Earth around the sun, but is located off the center of Earth as

$$\mathbf{r}' = \mathbf{r}_s + \mathbf{r}'_E, \tag{2.7}$$

where $\mathbf{r}_s$ and $\mathbf{r}'_E$ are the position of the center of Earth measured from the sun and the position of the test particle measured from the (orbiting) center of Earth, respectively, then eq. (2.6) reduces to

$$m\frac{d^2\mathbf{r}'_E}{dt^2} + 2m\boldsymbol{\omega} \times \frac{d\mathbf{r}'_E}{dt} = \frac{GM_s\mathbf{r}'}{r'^3} - \frac{GM_s\mathbf{r}_s}{r_s^3} + \frac{GM_E\mathbf{r}'_E}{r'^3_E}, \tag{2.8}$$

where we added the Newtonian gravitational force due to the center of Earth (M_E is the mass of Earth if the test particle is outside of Earth's crust). The difference between the gravitational force due to the sun at the test particle and that at the center of Earth is called the tidal force.

The same calculation can be applied to the Einstein force (see [5]), which is approximately given by eq. (1.13). Here we notice that $\mathbf{V}$ appears in $\mathbf{F}_E$, but

$$\mathbf{V} = \mathbf{V}_s + \mathbf{V}_E, \tag{2.9}$$

where $\mathbf{V}_s$ and $\mathbf{V}_E$ are the velocity of the center of Earth relative to the sun and that of the test particle relative to the center of Earth, respectively. For terms linear in $\mathbf{V}$ in eq. (1.13), we can simply add them to the left-hand side of eq. (2.9), taking $\mathbf{V}_s$ for $\mathbf{V}$ to eliminate them after the transformation into the orbiting frame. Thus only $c\mathbf{V}_E \times (\nabla \times \boldsymbol{\phi})$ remains in the tidal force [5].

Synge performed in [6] the above transformation for the original Einstein's equation of motion, (1.11), to eliminate the F^i_E completely at an observation point, and then found the remaning terms, called *geodesic deviation*, for a test particle placed slightly out of that observation point. To the first order in $\mathbf{V}$, his geodesic deviation is identical to our tidal forces as stated above. Weber took in [7] the geodesic deviation, but neglected the $\mathbf{V}_E$ term arbitrarily. Because the gravito-radiative force, to be discussed in section 4 below, is proportional to $\mathbf{V}$, he missed the gravito-radiative force in his discussion on gravitational waves.

Generalized Galileo-Lorentz transformation

As shown in eq. (1.13), $\mathbf{F}_E$ reduces to the Newtonian gravity force, $\mathbf{F}_N$, in the first approximation, and eqs. (1.11) and (1.15) satisfy the Galileo equivalence principle. Therefore, Einstein's claim that eq. (1.11) is a relativistic equation of a test particle under gravity is very reasonable. It is relativistic because he claimed that it is applicable to light also.

Newton's equation of motion, eq. (2.2), is invariant under the Galileo transformation

$$\mathbf{r} = \mathbf{r}_\circ + \mathbf{V}t \quad \text{with} \quad \frac{d\mathbf{V}}{dt} = 0 \quad \text{and} \quad \mathbf{V} \cdot \mathbf{F}_N = 0. \tag{3.1}$$

Similarly, Einstein's equation of motion (1.11) is invariant under

$$x^i = x^i_\circ + L^i s, \quad \text{with} \quad \frac{dL^i}{ds} = 0 \quad \text{and} \quad L_i F^i_E = 0. \tag{3.2}$$

In the non-relativistic limit, where eqs. (1.14) and (1.15) are obtained, we see that our transformation (3.2) reduces to the Galileo transformation (3.1). When $F^i = 0$, or gravitational forces are zero, we see that

$$(L^0)^2 + (L^\alpha)^2 = 1, \tag{3.3}$$

which gives the Lorentz transformation. Our transformation (3.2) thus may be called a generalized Galileo-Lorentz transformation.

As Einstein claimed that eq. (1.11) is applicable to light (see [8]), he also meant that a (bending) light path is invariant under the generalized Galileo-Lorentz transformation.

E&M theory and general relativity

By taking the scalar potential ϕ and the vector potential $\mathbf{A}$ two of Maxwell's equations are automatically satisfied and the remaining two Maxwell's equations can be written as:

$$\left(\nabla^2 - \left(\frac{\partial}{c\partial t}\right)^2\right) A^i = -\mu_\circ J^i, \tag{4.1}$$

where

$$A^0 = \phi/c, \quad A^1 = A_x, \quad A^2 = A_y, \quad \text{and} \quad A^3 = A_z, \tag{4.2}$$

and

$$J^0 = c\rho, \quad J^1 = J_x, \quad J^2 = J_y, \quad \text{and} \quad J^3 = J_z \tag{4.3}$$

are the charge density and components of charge current density, respectively. The Lorentz condition

$$\nabla \cdot \mathbf{A} + \frac{1}{c^2}\frac{\partial \phi}{\partial t} = 0 \tag{4.4}$$

is assumed and $4\pi k/\mu_\circ = c^2$.

We see that Maxwell's equations are the wave equations in E&M theory, corresponding to Einstein's wave equation, eq. (1.2), in the general relativity theory. The only mathematical difference is that E&M theory is a vector theory, whereas the general relativity theory is a tensor theory.

Eq. (4.1) is solved to obtain E&M scalar and vector potentials in the same way as eq. (1.8a) and (1.8b), except that kq appears instead of GM, and q is the source charge. Again, traditionally, the *causality principle* is assumed to take only the retarded potential and disregard the advanced potentials. Thus Maxwell's equations describe emission, not absorption, of radiation (light).

For a theory of receiving antenna, we take an equation of motion of an electron with charge $-e$:

$$m\frac{d^2\mathbf{r}}{dt^2} = e(\nabla\phi + \frac{\partial \mathbf{A}}{\partial t} - \mathbf{V} \times (\nabla \times \mathbf{A})), \tag{4.5}$$

which is obtained as Minkowski forces invariant under the Lorentz transformation. In reality, most of the electrons are bound to atoms, and we need quantum mechanics to describe their behavior. But in metals (conductors) there are some free electrons and the classical eq. (4.5) is applicable. The second term of eq. (4.5) is what antenna physicists call a far field (see [9]), which carries energy out of a source, charge q accelerated by $\dot{v}$, as

$$-\frac{d\mathcal{E}}{dt} = \frac{2k(q\dot{v})^2}{3c^3}. \tag{4.6}$$

We notice amazing similarities between eqs. (4.5) and (1.13). In eq. (1.13) we notice that the first term in $\mathbf{F}_E$, the Newtonian gravitational force, is a near-field force, proportional to $1/r^2$, just like the Coulomb force in E&M. The third terms in both eqs. (4.5) and (1.13) correspond to each other. Therefore, the third term in eq. (1.13) may be called the gravito-magnetic force.

The second term in $\mathbf{F}_E$, which is very similar to the second term in the right-hand side of eq. (4.5), contributes as a far-field force, proportional to 1/r. Neglecting the retardation effect in eq. (1.8b), it reduces to

$$-c\frac{\partial \boldsymbol{\phi}}{\partial t} = 4G\sum_a \frac{M_a\dot{\mathbf{v}}_a}{c^3 r_a}. \tag{4.7}$$

There has to be more than one interacting source mass to have an acceleration in each of them. If these source masses are located close to each other compared to the distance to the test particle, r_a in the denominator of eq. (4.12) would not depend on a much, and the summation in eq. (4.7) would be reduced to $\sum_a M_a\dot{\mathbf{v}}_a$, but this is zero, according to Newton's third law, eq. (2.4). The fourth term of $\mathbf{F}_E$ in eq. (1.13) is also a far-field force. As stated in relation to eq. (2.9), Earth, orbiting around the sun with $\mathbf{V}_s$ experiences a force exerted by

$$\mathbf{F}_{rad,Earth}/m_E = -4G\sum_a M_a \frac{\partial[\mathbf{v}_a(\mathbf{V}_s \cdot \mathbf{v}_a)]}{c^4 r\partial t}, \tag{4.8}$$

relative to the sun. In eq. (4.8) we assumed that the source masses are confined in a small volume compared to the distance from the test particle. In this case, the summation does not reduce to zero even under Newton's third law. In fact, the result corresponds to eq. (1.10) (see [10]). We call this part of the Einstein force, $\mathbf{F}_E$, a gravito-radiative force $\mathbf{F}_{rad}$. Equation (4.8) gives the part of $\mathbf{F}_{rad}$ exerted on the center of Earth relative to the sun. To obtain its tidal component when the test particle is in an Earth-bound laboratory, we take $\mathbf{V}_E$ as stated in Section 2, eq. (2.9). Because Earth rotates around its North-South axis, a laboratory located on its surface at latitude Θ moves with

$$V_E = 464\cos\Theta \quad \text{m/s} \tag{4.9}$$

toward the East relative to the center of Earth.

Take the z-axis along the North direction and x- and y- axes in the East-West plane, which contains an Earth-bound observation point. Let the spherical angles that $\mathbf{v}_a$ and $\dot{\mathbf{v}}_a$ make in this xyz-system be θ, φ, and θ', φ', respectively. If the longitude of the observation point is Φ, then we obtain the East component of the gravito-radiative force due to the source masses as:

$$F_{rad}(E)/m = -\frac{4GV_E}{c^4 r}\sum M_a v_a \dot{v}_a \sin\theta \sin\theta' \sin(\Phi-\varphi)\sin(\Phi-\varphi'). \tag{4.10a}$$

In general, its North component, $F_{rad}(N)$, also exists:

$$F_{rad}(N)/m = -\frac{4GV_E}{c^4 r}\sum M_a v_a \dot{v}_a [(\cos\Theta\cos\theta + \sin\Theta\sin\theta\cos(\Phi-\varphi))\sin\theta'\sin(\phi-\varphi')$$
$$+(\cos\Theta\cos\theta' + \sin\Theta\sin\theta'\cos(\Phi-\varphi'))\sin\theta\sin(\Phi-\varphi')]. \tag{4.10b}$$

In these formulas, subscripts a of the angles, θ, θ', φ, and φ', are omitted for simplicity.

Almost everything in our Earth-bound laboratory is rigidly fixed to Earth's crust by quantum mechanical intermolecular forces. Only a pendulum-bob is free to move horizontally, responding to incoming gravito-radiative forces. Our "free electron" is a pendulum-bob. Figure 1 illustrate $F_{rad}(E)/m$, given by eq. (4.10a), for a simplified case of $\theta = \theta' = \pi/2$. Earth's crust is rigid and resists the quadrupole deformation $F_{rad}(E)$ tries to induce. But the pendulum-bob (verticity meter) located at each longitude, Φ, can be shifted to detect the gravitational wave produced by a burst at the galactic center. Our verticity meter is a simple motionless pendulum [11]. Mizushima and Zimmerer constructed in [12] two verticity meters at Boulder, Colorado, and have monitored the East-West and North-South displacements of the pendulum-bob to about 1 μm since 1997. We have found a few coincidences between the two verticity meters, and reported them in [12]. Since then, we observed in [13] coincidences on April 24 and July 14 of 1997, September 21 of 1998, and Feb. 3, Feb. 5, May 27 and June 16 of 1999. Figure 2 report one of them as an example. More data will be reported in [13]. So far these data indicate that the gravitational waves, we detect, are typically impulses of about 10^{-8} m/s each. If the duration is 10 s, the corresponding F_{rad}/m is about 10^{-9} m/s^2. Taking the distance to the galactic center, $r = 3\times10^{20}$ m, it requires to be $Mv\dot{v} = 10^{53}$ J/s. If $M = 10^{39}$ kg, then $v\dot{v}/c = 10^5$ g, where $g = 9.8$ m/s^2. As stated before, the rate of energy taken out by the corresponding gravitational wave is 10^{51} J/s according to eq. (1.10), which is nearly equal to the energy, $mc^2 = 10^{54}$ J, of the galactic nucleus itself. In order to find the nature of the sources of these gravitational waves, however, it is necessary to find the latitude and longitude dependences of the signals as predicted by eqs. (4.10a) and (4.10b).

Some possible effects of the gravitational waves on the motions of astronomical bodies are predicted in [14].

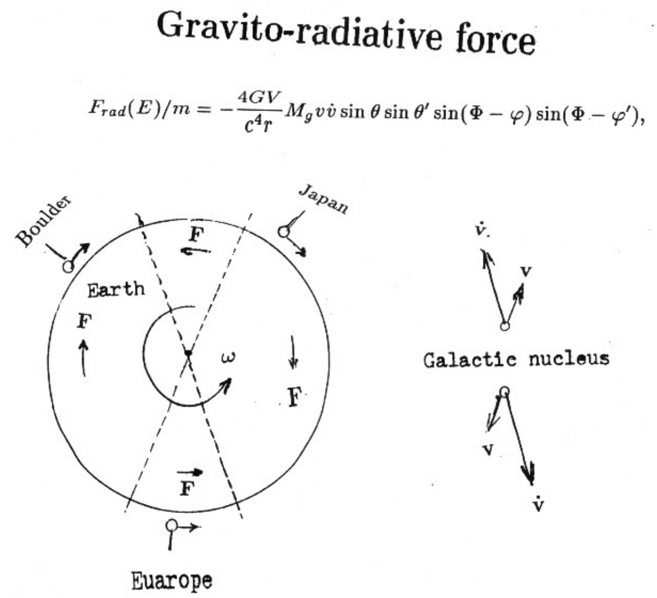

Figure 1. Illustration of eq. (4.10a), $F_{rad}(E)$, produced on Earth by a burst at the galactic nucleus as indicated on the right-hand side.

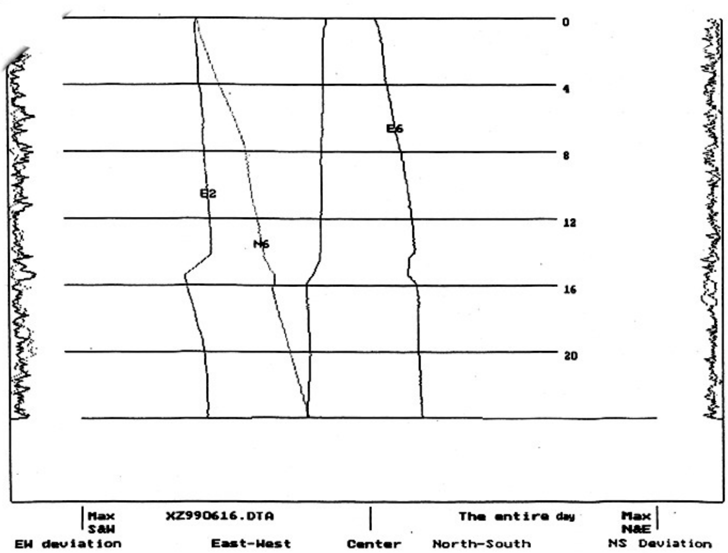

Figure 2. Coincidences of the verticity meters at 2 pm (MDT) and 3:30 pm (MDT) of June 16, 1999, between E2 and E6 lines, which are East-West displacements of the 2-m and 6-m pendulum-bobs, respectively. The left is West, and the full horizontal scale is 80 μm. No coincidence are seen in the North-South displacements, indicating that $\theta = \theta' \simeq \pi/2$ in these cases. The slope of the E2 line from 2 pm to 3:30 pm is about 10^{-8} m/s.

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