Orbiting particles’ analytic time dilations correlated with the Sagnac formula

Brian Coleman

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BC Systems (Erlangen, Germany)—VelChronos, Moyard, Co. Galway, Ireland
email: brian.coleman.velchron@gmail.com

Abstract
Eastward and westward orbiting plane time dilation formulae which could be envisaged for Hafele&Keating’s 1971 equatorial clocks experiment (idealised), were incorrectly derived in the 2004 textbook Relativity in Rotating Frames, even though exact analytic expressions actually result directly from velocity composition. Moreover the same equations together yield the classic formula for Sagnac’s analogous 1913 experiment where interference fringe patterns from monochromatic light waves emitted in opposite directions around a rotating wheel, shifted in accordance with wheel direction and rate of rotation—an observation which has been misinterpreted by some to challenge special relativity theory.

1 Hafele-Keating’s experiment idealised

The first—indirect—substantiation of own-time ‘stretchings’ was achieved in 1938 by Ives & Stilwell and later in 1963 [2] by statistical comparisons of time stretched ‘half lives’ of high speed (≈ 0.9c) muon particles generated by cosmic rays from outer space which were measured at high altitude and at sea level. Direct observations of time dilation were not made until 1971 [3], as described in [6]: “In the real world, ...an experiment [was performed in 1971]... by Hafele and Keating ... by means of commercial flights (carrying caesium beam atomic clocks) around the world in eastwards and westward directions....Strangely enough, an exact theoretical prediction [of clock differences] in full theory seems to be lacking (or maybe lost somewhere in the literature)....” (Relativity in Rotating Frames textbook).

We consider an idealised form\(^1\) of the 1971 experiment. A clock mounted in a balloon X firmly anchored above the rotating Earth’s equator, traverses an equatorial ring fixed in a reference frame \(I\). As the Sun is so distant, frame \(I\) may be assumed to be effectively nonrotating and inertial.

\(^1\)Avoiding the question of how a ground clock might be differently affected by gravity.
Referencing Figure 1, balloon X’s tangential speed in frame $I$ is $v_x = r\omega$, where $r$ is X’s distance from the Earth’s centre and $\omega$ its rate of axial rotation in radians per second (both as measured in inertial frame $I$). A precision clock $\tau_x$ attached to X is zero-synchronised with the identical clocks $\tau_+$ and $\tau_-$ of two planes which simultaneously fly past point X in the eastwards anticlockwise (+) and westwards clockwise (−) directions respectively.

The two planes orbit around the Earth at constant tangential positive speed $s_+$ and negative speed $s_-$ relative to the co-moving inertial frame of the $I$-ring’s momentarily ‘local’ elevated equatorial point. They return to X at slightly different times. It need not be assumed that $s_-$ and $-s_+$ are equal. On the eastward plane’s return to point X, its clock ‘circum-time’ $\tilde{\tau}_x$ is compared with X’s then current clock time $\tilde{\tau}_x$ (the tilde ‘overline’ symbolizes round trip values). Likewise the westward plane’s circum-time $\tilde{\tau}_x$ is compared with the corresponding X clock reading $\tilde{\tau}_x$. Of interest are the two circum-time differences $\tilde{\tau}_+ - \tilde{\tau}_x$ and $\tilde{\tau}_- - \tilde{\tau}_x$, in terms of measurable parameters $r$, $v_x = r\omega$, $s_+$ and $s_-$.  

As demonstrated by the clock worldlines in Figure 2, the eastwards (+) plane moving ahead of X at $I$-frame relative orbital speed $v_+$ (not measured) at about two-thirds (say) of the circumference point X’s speed $v_x$, meets X again after X has progressed through somewhat over half an $I$-frame circumference. It will by then have traversed (in frame $I$) one whole circumference more than X. The westwards (−) plane moving ‘backwards’ from X in the opposite direction at $I$-frame tangential speed $v_-$ meets up with X (as we shall see) slightly before the eastwards plane does, and its $I$-frame trajectory added to that of X’s makes up one whole $I$-frame circumference.

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2We refer to the three clocks themselves as $\tau_x$, $\tau_+$ and $\tau_-$. Actual clock round trip ‘circum-values’ are designated with tilde overheads.
1.1 I-frame circum-times

Unmeasured plane I-frame circum-distances $\tilde{d}_\pm$ and circum-times $\tilde{t}_\pm$ relate as:

$$\tilde{d}_+ = v_+ \tilde{t}_+ = v_+ t_+ + 2\pi r \quad \text{and} \quad \tilde{d}_- = v_- \tilde{t}_- = v_- t_- - 2\pi r \quad \text{i.e.}$$

$$I\text{-frame circum-times: } \tilde{t}_\pm = \pm 2\pi r / (v_\pm - v_x). \quad (1)$$

Relativistic velocity composition gives us the unmeasured orbital speeds of the planes in frame $I$:

$$v_\pm = \left( v_x + s_\pm \right) / \left( 1 + v_x s_\pm / c^2 \right). \quad (2)$$

According to the ‘triple gammas’ relationship:

$$\frac{\gamma_\pm}{\gamma_x \gamma_{s_\pm}} = 1 + \frac{v_x s_\pm}{c^2}. \quad (3)$$

As $\gamma_x^2 = 1/(1 - v_x^2/c^2)$, substituting (2) and then (3) in (1) gives:

$$\pm 2\pi r = \left( \frac{v_x + s_\pm}{1 + v_x s_\pm / c^2} - v_x \right) \tilde{t}_\pm = s_\pm \left( \frac{1 - v_x^2 / c^2}{1 + v_x s_\pm / c^2} \right) \tilde{t}_\pm = \frac{s_\pm \tilde{t}_\pm / \gamma_x^2}{1 + v_x s_\pm / c^2} = \frac{s_\pm \tilde{t}_\pm / \gamma_x^2 / \gamma_{s_\pm}^2}{\gamma_x^2 / \gamma_{s_\pm}^2}, \quad \text{i.e.}$$

$$I\text{-frame circum-times: } \tilde{t}_\pm = \pm 2\pi r \frac{\gamma_x \gamma_\pm}{s_\pm \gamma_{s_\pm}}. \quad (4)$$

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3 Using ‘plus/minus’ subscripts to avoid writing each time almost identical equations twice.

4 $\frac{1}{\gamma^2} = 1 - \frac{w^2}{c^2} = \frac{1 + \frac{2w^2}{c^2} + \left( \frac{w}{c} \right)^2 - \left( \frac{w}{c} \right)^2 - \frac{2w^2}{c^4} - \left( \frac{w}{c} \right)^2}{\left( 1 + \frac{w^2}{c^2} \right)^2} = \frac{(1 - \left( \frac{w}{c} \right)^2)(1 - \left( \frac{w}{c} \right)^2)}{\left( 1 + \frac{w^2}{c^2} \right)^2} = \frac{1/(\gamma^2 \gamma^2)}{\left( 1 + \frac{w^2}{c^2} \right)^2}.$
2 Orbiting clock differences

Our idealised equal altitude clocks are all identically effected by gravity. However although they orbit in inertial frame $I$ at differing constant rotation rates and so at zero tangential acceleration, we need to ‘tacitly’ assume that clock time progressions are not influenced by the resulting differing radial (centrifugal) accelerations.\(^5\) Hence by virtue of equatorial symmetry, the time dilation formula $\Delta t = \gamma \Delta \tau$ generally relates the unmeasured \(I\)-times (no \(I\)-frame $t$-clocks are actually deployed) as: $\tilde{t}_\pm = \tilde{\tau}_\pm \gamma_\pm = \tilde{\tau}_{x\pm} \gamma_x$. Accordingly:

$$\tilde{\tau}_\pm - \tilde{\tau}_{x\pm} = \tilde{\tau}_\pm \left( 1 - \frac{\tilde{\tau}_{x\pm}}{\tilde{\tau}_\pm} \right) = \tilde{t}_\pm \left( 1 - \frac{\gamma_\pm}{\gamma_x} \right).$$

Substituting (4) into (5):

$$\tilde{t}_\pm - \tilde{t}_{x\pm} = \pm \frac{2\pi r \gamma_x}{s_x \gamma_{x\pm}} \left[ 1 - \frac{\gamma_x}{\gamma_{x\pm}} \right].$$

Substituting from (3), the desired analytic formulae are:

**Eastward/Westward clock relative dilations**

$$\tilde{\tau}_\pm - \tilde{\tau}_{x\pm} = \pm \frac{2\pi r \gamma_x}{s_x} \left[ \frac{1}{\gamma_{x\pm}} - \left( 1 + \frac{v_x s_x}{c^2} \right) \right].$$

(6)

These equations in terms of measurable parameters $r$, $v_x$, $r$, $s_+$ and $s_-$, constitute the correct hitherto ‘missing’ theoretical relationship.

3 The ‘equivalent’ Sagnac equation

If plane speeds were the same i.e. $s_+ = -s_- = s$, then from (6)

$$[\tilde{\tau}_- - \tilde{\tau}_{x-}] - [\tilde{\tau}_+ - \tilde{\tau}_{x+}] = \frac{2\pi r \gamma_x}{s} \left[ \frac{1}{\gamma_s} - \left( 1 - \frac{v_x s_x}{c^2} \right) \right] - \frac{2\pi r \gamma_x}{s} \left[ \frac{1}{\gamma_s} - \left( 1 + \frac{v_x s_x}{c^2} \right) \right].$$

**Arbitrary symmetric speeds clock dilations differential—The Sagnac formula**

$$\Delta \tilde{\tau}_{+/} = \frac{4\pi r^2 \omega \gamma_x}{c^2} = \frac{4\pi \omega \gamma_x}{c^2} \frac{A}{\sqrt{c^2 - r^2 \omega^2}} = \frac{4\pi \omega}{\sqrt{c^2 - r^2 \omega^2}}.\tag{7}$$

$A = \pi r^2$ is the cross sectional area of the idealised ‘ring’ equator (and $v_x = r \omega$). Equation (7) is independent of plane speed $s$. Hence if the ‘planes’ are replaced by ‘photons’ it must be and is identical to the Sagnac formula.\(^7\)

\(^5\)This assumption appears to be vindicated and is widely accepted by physicists.

\(^6\)Obtained from the Lorentz transformation for a home frame observer of a moving clock.

\(^7\)Also the RRF book’s equation (10.25) where $\Omega = \omega$ and $R = r$. 

4
The Sagnac experiment constitutes an analogous analytically equivalent ‘cosmic limit speed’ case of the idealised Hafele-Keating experiment.

This observation—which of course requires ‘missing’ equations (6), does not appear to have been made in the literature (at least prior to the paper’s initial unsuccessful submission in 2008 [9]).

4 A single rotating clock’s time dilation

Dilation equations (6) will also apply in general to circular trajectories of constant rotation speed particles. So if \( s_x = -v_x \) i.e. \( v_x = 0 \), \( \gamma s_x = \gamma x \) and the westward plane remains stationary in frame \( I \) at the starting point, then (6) gives us the rotating \( X \) clock’s dilation:

\[
\tilde{\tau}_x - \tilde{\tau}_s = \frac{2\pi r \gamma x}{v_x} \left[ \frac{1}{\gamma x} - (1 - \frac{v_x^2}{c^2}) \right] = \frac{2\pi r}{v_x} \left[ 1 - \frac{1}{\gamma x} \right].
\]

Dividing this by \( X \)’s \( I \)-frame circum-time \( \tilde{t}_x = \frac{2\pi r}{v_x} \) we then obtain for scaled relative velocity \( v_x/c = \sin \alpha \):

\[\frac{\tilde{\tau}_x - \tilde{\tau}_s}{2\pi r/v_x} = 1 - \frac{1}{\gamma x} = 1 - \cos \alpha. \tag{8}\]

5 Measurements and conclusions

Hafele and Keating’s atomic clocks, which were transported in commercial aircraft taking off and landing several times and not actually travelling along the equator, provided only approximate results. These however were broadly consistent with expected time gain and time loss and, as mentioned, were the first ever direct observations of time ‘dilations’. Sagnac experiment results on the other hand, comply with the Sagnac formula [4].

The landmark experiment performed in 1913 by George Sagnac\(^9\) led to the French physicist claiming that the speed of light is not constant. Sagnac’s reasoning was seized upon by some academics to challenge basic special relativity theory. Ironically nevertheless, actual absence of such direction-dependent interference fringe shifts would invalidate special relativity—contrary to Sagnac’s original reasoning. Paradoxically, observed Sagnac experiment’s ‘apparent’ rotation-dependent speed of light manifest in the interference fringe shifts, indeed confirms limit speed constancy. This inevitable fact is further corroborated by the correlation between the Sagnac equation and the analytically established orbiting clocks dilation formulae.

\(^8\)Equation (8) can of course be directly obtained from equations (1) and (5).

\(^9\)Franz Harrass had done similar work earlier in Jena.
6 A journal’s unsavoury U-turn

The origin of this paper, a retitled slightly enhanced version of a reviewed but unpublished 2008 paper [9], has a curious background and a surprising sequel.

In the 1990’s, papers supporting Sagnac’s denial of relativity theory were published by Al Kelly. In 2008, a second fellow Dubliner (physicist/researcher Roy Johnston) requested the present author to investigate this ‘delicate’ matter. As this was clearly an interesting subject, the task was taken up enthusiastically. Widely covered in the literature, the Sagnac experiment (and the Sagnac formula) turned out to be fairly easy to understand. However the analogous Hafele & Keating equatorial clocks experiment—in idealised form—did not appear to be analytically treated anywhere.

Unaware then of the above quoted RRF 2004 book [6], the present author set about deriving time dilation formulae (6) above and also came up with a ‘representative’ eastwards/westwards clocks difference of 268 ns (nanoseconds). Shortly afterwards a web reference to the RRF book was spotted and a copy obtained. Chapter 5 of that book also presented a 268 ns clock difference for the same idealised scenario, but its equations (5.19/20), which differed from equations (6), turned out to be incorrect.11

A paper submitted to the Foundations of Physics in August 2008 was not accepted due to a second reviewer’s negative yet thoroughly confused remarks—in spite of a highly positive first reviewer’s assessment:

“This very short paper deals with the Hafele - Keating experiment, and gives a simple and thorough analysis, according to the principles of special relativity. The underlying ideas are very simple, and it is useful that they are recalled, since often this experiment is the origin of misunderstandings on the principles of special relativity, as the author says. Accordingly, I believe that the paper is correct and can be published as is.”

A request to the RRF book co-editors for their opinion on this elicited a reply which very generously fully and unreservedly endorsed the positive FoP reviewer’s assessment. An appeal to FoP challenging its negative reviewer’s inept and unsubstantiated comments failed. Referring to “the large amount of formulas and the somewhat confusing figure,” FoP then ventured a U-turn

10Supported by Italian physicist Franco Selleri, author of the RRF book’s chapter 4, whose opinions are not shared by its other contributors. In an Irish Times letter in 1996, Trinity College (Dublin University) physics faculty put on record that Alphonsus Kelly’s lecture held at that university had been instigated by a student group—not by college officials.

11As graciously later acknowledged by an RRF book co-editor. Rates of rotation had been added linearly (equation (5.15)) without taking relativistic velocity composition into account, a simple mistake unthinkable had the velocity addition path been adopted. On the other hand, formulae (6) above and the incorrect RRF equations (5.19/20), though different, produced arithmetical results identical to within 20 places of decimals.

12The paper had less than half the number of equations in the RRF chapter and was a quarter the size. The crucial explanatory diagram was a carefully generated computer graphic—Figure 2.
‘disclaimer’: “We often have to reject correct and interesting papers such as yours”. Thus instead of publishing a paper clearly acknowledged as having corrected the RRF book’s important indeed highlighted yet erroneous dilation formulae, the FoP journal choose to ignore it. Ironically both the RRF book and the FoP journal had the same publisher—Kluwer (Dordrecht/Boston/London).

A later attempt in 2011 to post the (retitled) paper on arXiv [12] was blocked with the ‘anonymous’ statement: “Our moderators maintain that your article is not of interest to the [physics] community.”

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References


\[ \text{arXiv.org eMail 23rd Sept. 2011, reference submit/0320889.} \]
sum/difference of the local Earth position’s speed and the plane’s speed relative thereto.


[9] Coleman B Sagnac dilation expressions exactly and simply established unpublished submission to Foundation of Physics FOOP-S-08-00393/FoP653 (“We often have to reject correct and interesting papers such as yours.”)


[11] Coleman B 2009 Time ‘dilation’ and length ‘contraction’ - abuse of the present tense in special relativity and missed formulae such as for the Hafele-Keating/‘Sagnac effect’ experiment Seminar April 24th Institut Non Linéaire de Nice Sophia Antipolis