Tangherlini's Dissertation and Its Significance for Physics of the 21th Century

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Abstract: Here we comment on some of the most important results obtained by Frank Robert Tangherlini, in his Dissertation of 1958. We show that the main difference between the Tangherlini transformations and the Lorentz transformations arises from a special method synchronizing two clocks spatially separated in two different inertial reference frames as was suggested by Tangherlini, which is different from Einstein's method of synchronization suggested earlier. It is shown, despite the aforementioned circumstance and also despite the fact that the Tangherlini transformations differ from the Lorentz transformations (in particular, the Tangherlini transformations allow the velocity of light to be anisotropic in a moving inertial frame of reference), the Tangherlini transformations provide adequate explanations to all known well-verified experimental tests of the Special Theory of Relativity. Several possible applications of the Tangherlini transformations could give an explanation to the effects, already predicted by physicists but not yet registered. In particular, once the effects have been experimentally observed (a possible violation of the Lorentz-invariance may be involved), the effects might be more properly described with use of the formalism of the Tangherlini transformations.

During the last seven decades, physicists have discussed kinematic theories which are claimed as alternatives to the Special Theory of Relativity, or are based on transformations of the spatial coordinates and time from one inertial frame into another one which differ from the Lorentz transformations [1]. Meanwhile, despite the fact that several suggested transformations can explain numerous basic experiments of the Special Theory of Relativity, in particular — the Michelson-Morley experiment [2, 3], not one of the suggestions except the Tangherlini transformations [4] and the Sjödin transformations [5], which generalize the former, are able to give a proper explanation to all known experimental tests of the Special Theory of Relativity, in particular — the interference experiments, the measurements of the transverse Doppler effect, and the increased lifetimes of decaying high energy particles. In addition, these alternative transformations can deal with the effects in the rotating frame of the Sagnac experiment [6–10] in which the Einstein

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synchronization procedure cannot be used nor that involving slowly-moved clocks, as was pointed out for the latter case by Tangherlini in a thought experiment described in his general relativity lectures [11], and verified some years later in the well-known Hafele-Keating experiment [12, 13].

It should be noted that, in the framework of most of the aforementioned transformations, due to the specific methods of synchronization of spatially separated clocks, the velocity of light is isotropic only in a single (preferred) inertial reference frame. In the framework of these transformations, the velocity of light still remains isotropic and invariantly constant (equal to c), and independent of the velocity of the source, in agreement with the Special Theory of Relativity, while, in contrast, the value of the transverse Doppler effect predicted according to these transformations (excluding those of Tangherlini and Sjödin) differs from the value predicted by the Special Theory of Relativity, and hence are in disagreement with present experimental evidence. Recall that the constancy of the velocity of light in vacuum in any direction and its independence from the velocity of the radiating source, in an arbitrary inertial frame of reference, are well-verified experimental postulates of the Special Theory of Relativity, which follow directly from the Lorentz transformations [14].

Not one of the transformations alternative to the Lorentz transformations has been so actively discussed in the scientific press as the Tangherlini transformations obtained in 1958 [4]. The discussion has led to a large amount of literature on the subject. The interest to the Tangherlini transformations has been due to the fact that they can be useful in the search for a theoretical explanation of a possible "delicate violation" of the Lorentz-invariance (this is employed sometimes in order to explain several exotic phenomena such as the origin of high-energy cosmic beams, the origin of dark matter and dark energy, several cosmological models, and also quantum gravity models, see [15–24]). Anti-relativists suggest that the Tangherlini transformations can be used as a proof for an absolute (preferred) inertial frame of reference, which is connected with the "luminiferous ether", and as a proof for the violation of Lorentz invariance in physical phenomena. Hence, they declare that the Tangherlini transformations refute the validity of the Special Theory of Relativity. Other researchers emphasize that the Tangherlini transformations are not merely an alternative but an equal replacement for the Lorentz transformations, hence the Special Theory of Relativity is no more than one of many equivalent theories describing physical processes from the viewpoints of observers located in two different inertial frames. Probably, not many of the participants who have discussed the Tangherlini transformations (this discussion started in 1977, after Reza Mansouri and Roman U. Sexl published the paper [25]) have read Tangherlini's original Dissertation of 1958 [4], wherein he deduced the transformations and studied their applications to classical theory and quantum theory. Most scientists know only the later publications of 1961 and 1994 [11, 26], which give the transformations with different deductions and fewer applications. For more than fifty years the Dissertation was able to be accessed, as a manuscript copy, only at the Stanford University Library. Its appearance here in the present issue of *The Abraham Zelmanov Journal* [4] marks its first date of publication. Moreover, it is prefaced by the very interesting discussion written by Frank Robert Tangherlini himself [27], and is accompanied by his fine comment [28] to §8.1 of [11], where he gives an explanation about several properties of the Maxwell electrodynamics on the basis of the transformations.

In his Dissertation [4], Tangherlini uses a special system of units which is specific to several studies on the theory of relativity. In this system, time has the same dimension as length (so that Tangherlini means time t as a regular time multiplied by c, the velocity of light in vacuum), while velocities are dimensionless. In other words, a velocity he uses is a regular velocity divided by c. As a result, the velocity of light in vacuum in this system of units equals 1. This makes the understanding of the obtained result a little complicated. Meanwhile, in the preparation of the manuscript for publication, the Editor of the journal and the Author have decided to keep the original notations and the system of units unchanged for historical reasons. In contrast, in what follows, we will use the regular system of physical units when discussing the Tangherlini transformations and their sequels in physics, which will make their understanding a lot easier.

The main task we are targeting in this paper, which accompanies Tangherlini's Dissertation [4], are comments on the results obtained therein. The biography of Tangherlini and the circumstances of his Dissertation were given in detail in the publications [29, 30]. We therefore limit ourselves to only a brief survey of the events.

Frank Robert Tangherlini was born on March 14, 1924, in Boston (Massachusetts, USA), in the family of a worker. In 1943, during the World War II, he volunteered to be drafted into the U.S. Army, and later volunteered, after arriving in England in 1944 as an infantry replacement, to serve in the 101st Airborne Division as a paratrooper. After parachute training in England, he was dispatched to France, and then fought in Belgium and Germany. He also participated in bloody Battle of the Bulge in the Ardennes, where many of his paratrooper friends were killed in action. In 1946, he returned to the USA and was honorably discharged from the U.S. Army. In 1948, he obtained his BSc (cum laude) from Harvard University, followed by an MSc from the University of Chicago (1952), and a PhD from Stanford University (1959). During 1952–1955 he worked in the space industry in San Diego, and during 1958–1960 he served as a National Science Foundation postoctoral fellow, and from 1960–1994, he worked as a faculty member, or on the staff of different universities and research institutes in the USA and Europe. At the present time he is retired. He lives in San Diego, California, where he is still active in scientific research. The field of his scientific interest is very wide and covers the Special Theory of Relativity, dimensionality of space, relativistic cosmology, Mach's principle, etc. His most important scientific results are the transformations he deduced while working on his Dissertation of 1958. Later, these became widely known as the *Tangherlini transformations* (in 1958 Tangherlini used another, less successful term the *Absolute Lorentz Transformations*). His chief supervisor in this work was Sydney David Drell (b. 1926), the well-known expert in Quantum Electrodynamics who later became a friend of Andrew D. Sakharov. At the initial stage of Tangherlini's work, his actual supervisor was Donald R. Yennie, also well-known for his work on quantum electrodynamics, and who had been appointed his supervisor by Leonard Isaac Schiff (1915–1971) who was the chairman of the Stanford physics department, and was also responsible for Tangherlini receiving a fellowship to continue his graduate studies at Stanford. In June, 1958, Tangherlini reported his results at a colloquium of physics at Stanford University, and then submitted the Dissertation to the Physics Section of the Graduate Division. Positive reviews of the dissertation were submitted by Drell and Schiff. Afterwards, following the receipt of a National Science Foundation postdoctoral fellowship, Tangherlini went to the University Institute for Theoretical Physics in Copenhagen (this Institute was later called Bohr Institute). While abroad, Tangherlini was graduated with a PhD degree from Stanford University in absentia.

The direct and inverse Tangherlini transformations are introduced by means of a special method of synchronization of spatially separated clocks located in two inertial frames of reference, one of which is taken to be the preferred frame in which the one-way speed of light is c, and the other frame is moving relative to it with speed v, in which the speed of light varies with direction and v as discussed below. In this method, the clocks are synchronized by signals travelling with an infinitely high speed. Already in 1898, Henri Poincaré in his paper [31] and his address [32] delivered on September 24, 1904, at the Congress of Arts and Sciences in St. Louis (Missouri, USA), pointed out the significance of faster-than-light synchronization methods in effecting the outcome of the measurements of the velocity of light, and some years earlier, in 1898 [31] had given an interesting discussion of the meaning of simultaneity. This problem was also considered in 1934 by Leonid I. Mandelshtam (1879–1944), in his lectures on the physical grounds of the theory of relativity [33] read in 1933–1934 at Moscow University. Sergey M. Rytov (1908–1996) restored Mandelshtam's lectures after his death, on the basis of the records made by Gabriel S. Gorelik, Maxim A. Divilkovski, Michael A. Leontovich, Z. G. Libin, who heard the lectures, and also on the basis of Mandelshtam's draft notes. Then Rytov published the lectures in 1950 [33] (second edition [34] was printed in 1972). In his lecture, held on March 10, 1934, Mandelshtam was engaged in polemics with anti-relativists on the formulation of the causality principle in the Special Theory of Relativity, and on the problem of the simultaneity of events in different inertial frames of reference. In these polemics, Mandelshtam focused the attention of the listeners on the fact that Reichenbach's method of synchronization does not violate the causality principle*. He said:

> "Thus, the requirement that the causality principle must not be violated in the definition of simultaneity can be simply satisfied … if there would be a signal travelling at infinite speed, the requirement that the causality principle must be true would give a simple condition universally to all frames [of reference]. … Thus, it is required to understand that there should not be *such* a faster-than-light signal, which may generate *action*. … If I make use of a process, which cannot produce action, this does would violate the causality principle. … Many researchers tried to give such a definition to simultaneity, which they believed does not depend on the possibility of its empirical determination, but rather arises from the supposition that there is an apriori simultaneity".†

Proceeding further, Mandelshtam considered a possibility of synchronization of spatially separated clocks, in different inertial frames of ref-

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[*] Here Mandelshtam obviously considered the method of synchronization of spatially separated clocks suggested by Hans Reichenbach (1891–1953) in [35,36], which is quite different from the synchronization method suggested by Einstein [14].

[†] Here Mandelshtam attempted to focus the attention of the listeners on the fact that synchronization of clocks by infinite speed signals leads to simultaneity in all inertial frames of reference.

erence, by phase velocity signals (phase velocity may be as faster than light as possible). Such signals transfer neither action nor information. Therefore, if a phase velocity approaches infinity, the causality principle is not violated. Unfortunately, Mandelshtam, in his lectures [33, 34], arrived at the conclusion that this method of synchronization is unable to be realized in practice. This is because he considered the phase velocity of a signal produced by a mechanical device like scissors, namely — the motion of the cross-point of a scissors, which is realized with only a finite phase velocity. Therefore Mandelshtam had not realized the principal step in this research: he had not deduced transformation of the spatial coordinates and time from one inertial reference frame to another one, synchronized by infinite speed signals. It is probable that 1934 was too early a time for this principal step that was made only 24 years later, by Tangherlini.

In this connexion, we should emphasize an interesting and important paper, published by Albert Eagle, the British mathematician who, already in 1938, was extremely close to the Tangherlini transformations. In his paper [37], Eagle considered a method of synchronization of spatially separated clocks by a mechanical shaft, rotating by a clock engine located at its centre. The clocks under synchronization were fixed at the shaft's butt-ends. This method of synchronization was also considered in Eagle's second paper [38]. Albert Eagle, being an obvious anti-relativist[*], held the erroneous belief that a mechanical shaft rotates as a perfectly rigid body, so that torsional perturbations would travel instantaneously along it. Meanwhile, as we know, the perturbations do not propagate instantaneously along the shaft, but with the sound velocity specific to the substance of the shaft. This velocity is many orders slower than light[†]. Eagle targeted his publications [37, 38] as a proof for the reality of an absolute (preferred) reference frame con-

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[*] This fact concerning his personality can be easily concluded from his papers [37, 38] and, especially, from his other paper [39].

[†] We note that, aside for this simplest reason, synchronization of clocks by a rotating shaft is sensitive to the relativistic change of the figure of the shaft in a resting inertial frame of reference, as was considered by Ives (1882–1953), in [44], in the example of a rotating double Fizeau cogwheel (actually, a double obturator). When Stefan Marinov (1931–1997) performed his single-way measurements of the velocity of light using two mechanically connected systems consisting of rotating mirrors [45], he met a criticism from the side of Simon James Prokhovnik (1920–1994) who pointed out the inconsistency of this method of synchronization [46, 47]. Despite this criticism, Marinov continued measurements based on this synchronization method, but with another mechanical system which was similar to the previous one (it was a modified double obturator called by him the "coupled shutters" system). See [48] and literature referred therein, for Marinov's experiments.

nected with "luminiferous ether". Meanwhile, in spite of his incorrect considerations on the basis of the Newtonian views on absolute simultaneity which were already obsolete in 1938, Eagle [37] arrived at the transformations of the spatial coordinate x and time t associated with an observer's inertial frame of reference to the corresponding space-time coordinates in another inertial reference frame in the x-direction. Eagle's expressions for the transformation of x and t agree with the corresponding expressions of the Tangherlini transformations (1). Direct and inverse transformations for the transverse coordinates y and z were not discussed by Eagle, but he did note that the inverse transformation for the x and t coordinates was not of the same form as the direct transformation, as did Tangherlini.

Unfortunately, Eagle's key paper [37] was ignored by the scientific community from the time commencing in 1938 when it was first published. The sole reference to this paper, which we have found in the scientific literature, appeared in Eagle's second paper [38]*. Why? No simple answer can be given to this question. In any case, whatever be the answer, the real physical sense of the transformations was only achieved 20 years later in Tangherlini's thesis of 1958, in which their derivation and application is discussed clearly and in detail. Dmitri Rabounski, who also discussed Eagle's papers [37, 38], commented this situation as follows [41]:

> "After reading Eagle's paper of 1938, and his following paper, I arrived at the conclusion that Eagle obtained his transformations of the spatial coordinate and time, which particularly meet the Tangherlini transformations, as a result of a formal blindfold of combinations, not a systematical research. Besides, he was mistaken about the obtained result due to his erroneous disbelief in the theory of relativity. His appeal is that the presence of a physical medium fixed to (accompanying) the space as a whole is in contradiction with the theory of relativity. This is absolutely wrong and seems naive. He merely had no clear understanding of the theory of relativity — the geometrical theory of space-time and matter — and how the theory works. The second paper authored by Eagle is a logical continuation of his erroneous views on the theory of relativity, based on the principles of classical physics. According to him, "true synchronization" is synchronization of

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*Max Jammer in his book *Concepts of Simultaneity* [40], published in 2006, refers to authors who criticized Eagle's synchronization procedure. Tangherlini refers to Jammer's book in his *Preface of 2009 to "The Velocity of Light in Uniformly Moving Frames"* [27].

> clocks in the Newtonian sense, while all the remaining methods of synchronization leads to non-observable (imaginary) effects, which are unable to be registered in real measurements. In particular, Eagle referred to his first paper of 1938 as an example of how the use of "true synchronization" manifests that all effects of the theory of relativity are non-real, imaginary. Eagle's conclusion is in contradiction to the many decades of experimental verifications of the theory of relativity performed in different experiments with high precision of measurement. In fact, Eagle had no idea about the real physical sense of his formal mathematical deduction. He was in captivity of the views of classical physics, and failed the possibility of all other research methods in physics (the theory of relativity, for instance). This is the same as, given all explanations on the basis of the wave theory of light, denying all the results obtained in the framework of the corpuscular theory".

In continuation of this discussion, Tangherlini wrote recently in his private letter dated June 01, 2009 [42]:

> "With respect to Dr. Rabounski's penetrating criticism, I would add further that Eagle's obvious anti-relativity bias led him to reject the general theory of relativity, and this was most ironic, and indeed tragic, because a key principle in general relativity is Einstein's principle of general covariance which permits arbitrary transformations of the coordinates, and hence permits the transformation Eagle was using when supplemented by the transformation for the transverse y and z coordinates. In fact I would like to take this opportunity to emphasize to you and Dr. Rabounski that I probably would never have undertaken the writing of my thesis were it not for the *logical justification provided by general covariance* for making use of such a transformation when supplemented by the metric postulate as mentioned in the Introduction to my thesis".

Meanwhile, we should pay tribute to Eagle's paper [37], despite the fact that Eagle himself misunderstood the physical sense and meaning of his pioneering result. He was the first person who obtained, in a purely formal way, a part of the common transformations of the spatial coordinates and time which were developed in detail later by Tangherlini, and are known as the Tangherlini transformations.

What is interesting is that, in already 1922, a method of synchronization of spatially separated clocks by means analogous to a locomotive wheel pair was suggested by Carl Axel Fredrik Benedicks, the Swedish physicist who considered a rotating wheel (that can be any space body, the Earth for instance) as an original time-giver [43]:

> "Let us return to the top, which seems to offer a somewhat clearer example of an original time-giver. . . . the question arises, how its time-indication may be applied to another process which might occur at a great distance. The simplest example is that where the second process is also an identical, rotary one that is, another identical top, rotating on the same fixed plane. Simultaneity or synchronism is said to prevail if a radius vector of the one is always parallel to a corresponding radius of the other. We ask, in what way can this definition be applied? Evidently, it can be realized in the way used to synchronize two paired wheels of a locomotive; that is, a solid movable connecting rod is pivoted at the end points of two radii, where the length of the rod is equal to the distance separating the two axles. As the two radii have been assumed to be equal, they will during the motion also remain parallel. In principle this will fully define simultaneity, so long as the axes of rotation remain parallel. The first rotating body, A, is the standard which determines time; the second body, B, may act as a *clock* or timepiece, by exactly reproducing A's time. . . . We say that *two distant clocks are synchronous, provided that their hands are moving as though their axles were connected by one rigid axle, consisting of an absolutely solid body.* This is the simpler form of synchronizing frequently used, for example, in synchronizing two wagon-wheels belonging to the same axle. . . . This definition of synchronism is precise, and has no ambiguity. It is founded only upon the fundamental basis for all measurement of time the accepted unchangeability of the rotation process chosen as standard and upon pure geometry the fundamental basis of which is the existence of the absolutely solid body".

This method of synchronization meets that suggested by Eagle [37, 38]. However, in contrast to Eagle, Benedicks [43] had no idea about respective transformations for the spatial coordinates and time. Also, Benedicks assumed that there are absolutely rigid bodies, i.e. bodies in which signals propagate instantaneously from one end to the other, and hence his proposal encounters the same difficulty as Eagle's proposal, and as was remarked earlier, he seemed unaware that torsional waves, or waves in material bodies more generally, propagate with a finite velocity.

Tangherlini also suggested another method of synchronization of spatially separated clocks, the "external synchronization", which was given in detail later, in his general relativity article [11]. He writes [42]:

> "It was the difficulty I encountered with the failure to find empirical evidence to support faster-than-light signalling that led me to turn to external synchronization, which represents an experimental procedure one can carry out now with existing equipment, that can be used to verify the basic predictions of the transformation empirically, as you discuss. ... Actually *I did not make any hypotheses as to how the instantaneous signals would arise* in my thesis, so my synchronization would include the light spot method, but would be more general. The tachyons (as they are now called) were only mentioned in the concluding Chapter 12 of the thesis as a conceivable way of implementing the instantaneous synchronization, but the argument in the body of the thesis is *independent* of any way of achieving such a synchronization; in a sense, therefore, it is purely mathematical of the type: if we assume X, then the following is the case. ... Actually, I didn't mention external synchronization there, until my later publication *An Introduction to the General Theory of Relativity* (see in *Supplemento al Nuovo Cimento*, 1961, ser. X, vol. 20, 1–86)".

Many physicists believed (and, indeed, still believe) this to be impossible, because superluminal speeds are attributed only to hypothetical faster-than-light particles — tachyons* [49,50]. In fact, synchronization of this kind can be performed. The easiest case is the one where all clocks of both the moving inertial frame of reference and the resting frame of reference are located along the same line. To perform such

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*Tachyons — faster-than-light particles were first coined in the scientific publications on the theory of relativity in the pioneering paper of 1962 [51], authored by Olexa-Myron Bilaniuk, Vijay Deshpande, and George Sudarshan, who worked in Department of Physics and Astronomy, University of Rochester, New York. They pointed out the historical fact that, in pre-relativity times, Thomson, Heaviside, and Sommerfeld had considered particles moving faster than the velocity of light in vacuum. They considered the possibility of such particles in the framework of the Special Theory of Relativity. This term, "tachyon", was introduced into science by Gerald Feinberg (1933–1992) five years later, in 1967 [52], while Feinberg worked at Rockefeller University, New York, the same city as his predecessors. In this background story, many researchers and historians of science missed the fact that Frank Robert Tangherlini was actually the first person who considered the possibility of tachyons and faster-than-light signals, in a very general sense, in the framework of the Special Theory of Relativity, already in 1958. Unfortunately, most papers and books on the history of tachyons do not mention this fact. See [53], for instance. Meanwhile, the most important surveys of this theme such as [50, 54] referred to Tangherlini's goal with respect to this problem. In the last decade [55, 56], the possibility that tachyons had been produced was investigated at CERN.

"instantaneous" synchronization in this case, the "light spot method" should be used, where a light spot travels with a phase velocity which may exceed the velocity of light. This method was suggested by Vitaly L. Ginzburg (b. 1916) in [57], and, in more detail, in the common paper by Boris M. Bolotovskiĭ (b. 1928) and Vitaly L. Ginzburg [58]. In these papers, the motion of a light spot along a screen was considered, where the light spot was due to a light beam produced by a source (searchlight) rotating with an angular velocity Ω. If two points, say A and B, are equally distanced at a very large distance R from the searchlight, the linear velocity v of the light spot on the screen should satisfy the condition $v = R\Omega \gg c$. Of course, a light spot cannot transfer energy/information from A to B (with any velocity, both subluminal and superluminal): photons coming in A never come to B, hence the causality principle is still true, without violation in the experiment. Thus, huge speeds much faster than light are attributed to the light spots produced by the radiation of pulsars [57–60]. More details about synchronization of distant clocks by the light spot method are considered in our works [60–62].

Thus, Frank Robert Tangherlini has deduced transformations for the spatial coordinates and time from one inertial frame of reference to another one in the case where clocks located in both inertial reference frames are synchronized by infinite speed signals in the sense of that which was considered above.

Although not discussed in his Dissertation [4], in his later investigations, Tangherlini also considered another method of synchronization not involving faster-than-light signals, as described in detail in Appendix A of his 1994 paper *Light Travel Times Around a Closed Universe* [26]. This is the so-called "external synchronization", consisting of two steps. First, light signals synchronize clocks which are spatially separated from each other in the same resting ("preferred") inertial frame of reference. Then, these already synchronized clocks of the "preferred" inertial frame are used for synchronization of clocks of moving inertial frames of reference during those moments of time when each of the moving clocks physically meets one of the resting (synchronized) clocks in space. In this method of synchronization, inertial frames of reference are non-equal to each other: the inertial frame where clocks were first synchronized is "preferred" to all remaining (moving) inertial frames.

What is interesting is that Mandelshtam, already in 1934, considered a method of synchronization, which would also give rise to absolute simultaneity in the inertial reference frames K and K', as he described in his lectures [33, 34]:

> "...Suppose we have a frame [of reference], and one set up synchronization in it by a method, for instance — by the Einsteinian method ... Let us also have another frame [of reference]. I could arbitrarily set up synchronization in this other frame [of reference] so that clocks located in it would always show the same time as that displayed by the clocks of the first frame [of reference]".

This is however not the same as Tangherlini's method of external synchronization. Tangherlini, when found Mandelshtam's achievements in the 2000's (his lectures were published only in Russian, so inaccessible to most scientific community), says [42]:

> "This is *not* true for my transformation because (think of the clocks on the train going past the station) after the brief moment of synchronization, the clocks on the train run more slowly than the clocks on the station platform, this is why high energy muons decay significantly more slowly than muons at rest in the laboratory!"

Meanwhile, with use of both methods of synchronization, not all inertial frames of reference are equal: that inertial frame of reference, wherein the first synchronization was performed, becomes preferred to all remaining inertial reference frames. In particular, Mandelshtam wrote [33, 34]:

> "...in this case, we cannot require the relativity principle. ... When Einstein says that the relativity principle takes a place in nature, this means that, if all definitions of age are given equally in any frames [of reference], events [in any reference frames] will be processed equally".

Mandelshtam had not realized any step towards respective transformations in this case. This fact manifests, again, the outstanding thinking and courage Tangherlini showed in scientific research: he worked without looking back on the authoritative persons in science, mostly conservators, so he reached the advanced results which were out of the access for many other scientists.

Consider the direct and inverse Tangherlini transformations

$$\left.\begin{aligned} &x' = \gamma\,(x - vt)\,, && x = \gamma^{-1} x' + \gamma v t', \\ &y' = y, && y = y', \\ &z' = z, && z = z', \\ &t' = \gamma^{-1}\, t\,, && t = \gamma t'\,, \end{aligned}\right\} \qquad (1)$$

where x, y, z, t and x', y', z', t' are the spatial coordinates and time in the inertial reference frames K and K' respectively, c is the velocity of light in vacuum, v is the velocity of the reference frame K' with respect to the preferred reference frame K (we assume it to be moving along the x-axis), while $\gamma = 1/\sqrt{1-v^2/c^2}$ is the so-called Lorentz-factor.

Comparatively, the classical Lorentz transformations are

$$\left.\begin{aligned} x' &= \gamma\,(x - vt)\,, & x &= \gamma\,(x' + vt')\,, \\ y' &= y\,, & y &= y', \\ z' &= z\,, & z &= z', \\ t' &= \gamma\,(t - vx/c^2)\,, & t &= \gamma\,(t' + vx'/c^2)\,. \end{aligned}\right\} \qquad (2)$$

It is obvious that, according to the Tangherlini transformations (1), time t' of a moving inertial frame of reference is slower than time t by the factor γ. That is, the Tangherlini transformations lead to the transverse (relativistic) Doppler effect as in Einstein's Special Theory of Relativity [14]. The direct Tangherlini transformations, which are the first column in formula (1), differ from the direct Lorentz transformations, the first column in (2), by only the transformation of time due to the different methods used in the synchronization of clocks in inertial frames of reference.

Both direct and inverse Lorentz transformations take the same form upon reflecting the velocity, while the direct and inverse Tangherlini transformations are not (see the final part of Tangherlini's comment [28] for detail). Besides, in contrast to the Lorentz transformations, which form a Lie group whose parameter is the velocity, the Tangherlini transformations do not form such a group, since as is clear from (1), the inverse of the Tangherlini transformation does not have the same form as the direct transformation, nor do the product of two such transformations have the same form as the direct transformation. On the other hand, Tangherlini [63] has pointed out that the transformations are members of the group of linear space-time transformations that keep simultaneity invariant, of which the Galilean transformations form a proper Lie subgroup. Also, along with the Lorentz and Galilean transformations, the Tangherlini transformations are also members of the linear unimodular group, i.e., the group of linear space-time transformations with unit determinant, as mentioned in his thesis. The asymmetry of the direct and inverse Tangherlini transformations is connected with the fact that two inertial reference frames K and K' having Galilean (rectangular Cartesian) coordinate frames are equal in the framework of the Lorentz transformations, while in the framework of the Tangherlini transformations the inertial reference frames are non-equal: K still possesses the Galilean (rectangular) coordinate frame because the observer is resting in this frame, while the coordinate frame of K' is non-Galilean (oblique-angled).

Here we should note that the term "Lorentz transformations" was introduced by Henri Poincaré [64, 65]* in 1905, and he also discussed their group properties, as did Einstein in that same year.

Proceeding from the Tangherlini transformations (1), one can obtain a formula connecting the co-linear velocities V and V', measured in the inertial reference frames K and K' respectively, or, similarly, the law of composition of velocities according to the Tangherlini transformations

$$V' = \frac{V - v}{1 - \frac{v^2}{c^2}} \tag{3}$$

as originally obtained by himself in [4]. As visible, this formula is quite different from the law of composition of velocities $V' = \frac{V - v}{1 - vV/c^2}$, which holds according to the Lorentz transformations.

Having the law (3) as a base, Tangherlini [4] has also obtained a formula for the velocity of light in vacuum, measured in a moving inertial reference frame K', and referred to as c'

$$c' = \frac{c}{1 + \frac{v}{c}\cos\theta'}\,, \tag{4}$$

where the angle θ' is counted from the x'-axis in the moving inertial frame K'.

In a common case, where light travels in an optical medium whose refraction coefficient is n, measured in a resting inertial reference frame K, the velocity of light in a moving inertial reference frame K', according to Tangherlini [4] takes the form

$$c' = \frac{c}{n + \frac{v}{c}\cos\theta'}\,. \tag{5}$$

It is clear that formula (4) explains the results obtained in the Michelson-Morley experiment [2, 3] and the Kennedy-Thorndike experiment [67]. This is because, following from (4), the total time of light's travel forward and backward does not depend on the velocity v of the

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[*] Hendrik Antoon Lorentz (1853–1928) passed through a long way, full of many tests, to his understanding of the Special Theory of Relativity. He stopped his research when was at a minor step from the acquisition of the transformations [66].

inertial reference frame K' moving with respect to the preferred inertial reference frame K. Moreover, as was shown in [1], the Tangherlini transformations provide a clear explanation to all interference experiments targeted on checking the Special Theory of Relativity, in particular — the Sagnac experiments [6–10]. And also, as remarked above (see page 121), Tangherlini synchronization can be used to carry out calculations in a rotating frame of reference in which it is not possible to synchronize clocks by the standard methods of Special Relativity.

A simple explanation of the physical sense of the Tangherlini transformation is given by Giancarlo Cavalleri and Carlo Bernasconi [15]. The invariance of the velocity of light and the non-conservation of the simultaneity of events, spatially separated in different inertial frames of reference, are often considered as specific properties of the Special Theory of Relativity. Therefore, Tangherlini [4] formulates his own version of the theory of relativity, where the absolute simultaneity of spatially separated events is allowed, and the velocity of light becomes non-invariant. In the framework of the "standard" Special Theory of Relativity, the velocity of light determined by formula (4) should not be a physical (observed) velocity, but a coordinate velocity. Actually, the conservation/non-conservation of simultaneity and the invariance/non-invariance of the velocity of light depend on the employed method of synchronization of clocks, located in different inertial frames of reference. This fact leads to an infinite number of versions of transformations from one inertial reference frame to another one [5]. In this row, two kinds of transformations — the Lorentz transformations and the Tangherlini transformations — are the limiting cases of the Sjödin transformations [5].

Michael A. Miller, Yuri M. Sorokin, and Nikolai S. Stepanov [68], and then Anatoly Logunov [69] take under consideration an arbitrary linear transformation from Galilean coordinates x, y, z, t of an inertial reference frame to coordinates X, Y, Z, T of a so-called "generalized" inertial reference frame. Such transformations mean non-orthogonal (oblique-angled) coordinate nets X, Y, Z, T [68] described by the metric tensor whose components are constants. As was shown in [69], if we assume different parameters of the components of the metric tensor in the "generalized" inertial frame of reference, different formulae can be obtained for the components of the coordinate velocity of light (V_X, V_Y, V_Z) in the "generalized" frame, and the velocity is anisotropic in a general case, while in contrast, in the Special Theory of Relativity, as is well-known, the speed of light takes the same value for all inertial frames of reference and is isotropic.

Tangherlini [70] was able to show that when the standard canonical commutation relations of Quantum Mechanics in the Schrödinger representation are enlarged to included the energy and time, and one assumes that the energy and momentum transform as a four-vector, these commutation relations are not only invariant under the Lorentz transformations, but under all non-singular linear space-time transformations, which would include the general transformations discussed above.

The main advantage of the Lorentz transformations, in contrast to the other kinds of transformations of the spatial coordinates and time, consists in the Einsteinian method of synchronization of spatially separated clocks that keeps the velocity of light isotropic and constant in transferring from one inertial frame of reference to another one. In "generalized" inertial frames of reference, which are a result of the Tangherlini transformations in particular, no so-called pseudo-forces (the centrifugal force of inertia, or Coriolis' force, for instance) appear as in non-inertial frames of reference where such forces play the rôle equal to the force of gravity. In this connexion, incorrect claims, from the past to the present, can be found in the scientific publications. Thus, Hans C. Ohanian [71] claimed, incorrectly, that the Reichenbach method of synchronization of clocks [35, 36], upon being realized in an inertial frame of reference, should inevitably lead to the formal appearance of the pseudo-forces in the inertial reference frame.

At first, the Tangherlini transformations did not attract much of the attention of scientists. This situation changed after 1977, when an anisotropy in the Cosmic Microwave Background Radiation had been definitely verified in observations on board a U2 sub-stratosphere airplane performed by George Smoot's team [72]*. In fact, this means that the inertial frame of reference connected with the Earth moves in the cosmos with a velocity of about 360 km/sec with respect to a preferred inertial frame of reference, in which the Microwave Background Radiation is "most" isotropic and the common momentum of all masses of the Universe is probably zero. As a result of the experimental success, different suggestions arose to the origin of the observed anisotropy in the Cosmic Microwave Background Radiation as due to the anisotropy of the velocity of light, so the Tangherlini transformations became of interest. The first persons who turned our attention to the Tangherlini transfor-

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*The dipole-like anisotropy was first observed in the ground-based observations performed by Edward K. Conklin in 1969 [73], then studied in the balloon observations by Paul S. Henry in 1971 [74] and by Brian E. Corey and David T. Wilkinson in 1976 [75]. The main reason for Smoot's success of 1977 [72], and his fame which followed later, was very certain observations of the anisotropy.

mations as a possibility of explaining the results of the Michelson-Morley experiment [2, 3], following Tangherlini himself*, were Reza Mansouri and Roman U. Sexl [25]: they said in the bibliography to their first paper that the transformation had been considered by Tangherlini. Afterwards, many papers were published, wherein the Tangherlini transformations were employed: see, for instance, [5, 15, 71, 76–91].

There are also numerous papers wherein the Tangherlini transformations were "re-discovered" anew. These are Stefan Marinov's publications of the 1970's [92–94], the paper of 1992 [95] authored by Ernest W. Silvertooth and Cynthia K. Whitney, the papers [96–98] published by Nikolai V. Kupryaev commencing in 1999, and the paper of 2001 [99] by Juri A. Obukhov and Igor I. Zakharchenko. Looking along the scientific literature, we found a note on the absence of priority concerning the earliest of the "re-discovering" papers: Giancarlo Cavalleri and Giancarlo Spinelli [100] commenting on the transformations appearing in Marinov's publications of the 1970's, and claimed by him as his own original achievement, gave the priority to Tangherlini who had actually obtained these already in 1958, although they were not published in a journal until 1961 [11], and it was to this article to which Sexl and Mansouri referred. All the rest of the papers "re-discovering" the Tangherlini transformations were published only much later, commencing in the 1990's, so the absence of priority in those papers was not found somewhere being discussed in the scientific literature.

Interestingly, Frank Robert Tangherlini met Stefan Marinov in person at the *General Relativity 9th Meeting* in Jena, Germany, in 1980. Tangherlini wrote, in his private letter dated October 14, 2006, about how this happened [101]:

> "I met Marinov under a most curious circumstance: he had put up over the doorway of a hall, where many passed through, a poster of about 1/3 meter wide and about 2 meters long in which he criticized me, in artistic calligraphy, for not having followed up on my transformations. I found this very strange behaviour. After all, why didn't he write directly to me, or arrange a meeting at a conference? So I suspected then he was somewhat crazy, although possibly artistically talented. With any crazy person, one shouldn't spend too much time on him except as an example of how people in science, just as in every day life, can go astray".

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*In his Nuovo Cimento article of 1961 [11], Tangherlini wrote: "Finally we should note that the usual results of special relativity can obtained from the line element (1.17) and co-ordinate transformation (1.16), as we have already shown for the problem of sending light signals out and back".

In recent years, a second wave of increasing interest in the Tangherlini transformations has risen due to the possibility of a small anisotropy of the velocity of light claimed by the Grenoble group of experimentalists [102, 103] (see also [104–106]). At the present time, there are neither definitely verified experimental facts nor fundamental principles of physics which could require the failure of the Lorentz-invariance in inertial reference frames (see [33, 107], for instance). Meanwhile, physicists are still continuing experimental and theoretical attempts to find violations of Lorentz invariance, and also theoretical grounds to these in the course of interpretation of bizarre physical phenomena such as those in cosmology, quantum gravity, quantum field theory, particle physics, space beam physics and super-high energy physics (see, in particular, [18, 19, 107]). One regularly connects this possible violation, without which CPT-invariance of quantum field theory and the law of charge conservation of classical electrodynamics cannot be violated, with a possible violation of the space-time symmetry due to, say, processes at the Planck (small) scale or due to additional (hypothetical) measurements producing a new vector or tensor field which acts onto physical bodies depending on their velocity and orientation in space (which is different for particles and anti-particles). As a result, theoretical physicists expect various new effects such as a length contraction and time dilation in addition to the Lorentz ones, a variation of the electromagnetic field polarization, a non-zero rest-mass of photons, changes of the masses of decaying particles and of their decay channels, and also many other effects which depend on the motion of the inertial frame of reference wherein the processes occur. The simplest case of theories that violate Lorentz invariance is the so-called Doubly Special Theory of Relativity (see [20, 108–111], for instance), wherein elementary particles cannot be accelerated up to a velocity exceeding the velocity of light, nor can they acquire an energy exceeding a fixed numerical value specific to each particle (the so-called Planck energy). The aforementioned vector or tensor field has no direct connexion to the gravitational field. Whether such possible violations of Lorentz invariance would lead to changes of the gravitational field of a moving body, or to changes of the properties of a black hole that are not predicted by the General Theory of Relativity are issues for further research.

Putting aside gravitation, it is useful to study various consequences of the violation of Lorentz invariance. In particular, as already discussed above, the possibility of introducing alternative methods of synchronizations in a given inertial frame. In this regard, it is important to keep in mind that whether clocks are synchronized according to the Einstein procedure, or externally, one has not changed inertial frames, but effectively one has merely introduced another set of clocks in the same inertial frame. In addition to the Tangherlini synchronization which has already been described, still another form of synchronization has been suggested by Torgny Sjödin in his paper of 1979 [5] in which clocks are synchronized etc. The discussion in Chapter 6 of Tangherlini's thesis, entitled *Measurements with Signals Travelling with Finite Velocities*, to some extent anticipates Sjödin's considerations, in that Tangherlini considers the possibility of other signals propagating with constant speeds greater than or less than the speed of light relative to the rest frame.[*]

Even if digressing from gravitation and other effects of the General Theory of Relativity, different scenarios of the violation of the Lorentz-invariance are useful to be studied on the basis of not only the Lorentz frames of reference (their preference is due to the Einsteinian method of synchronizations of clocks, where the out and back travel times for light are equal), but also on the basis of other inertial frames in which there has been an alternative synchronization of clocks. In particular, the time dilation is to be considered/described by the use of a frame of reference whose clocks are synchronized by infinite speed signals (in practice — a respective light spot). Such reference frames were studied by Tangherlini, when he compared descriptions of physical processes obtained in such a reference frame to the well-known Lorentz description. A larger class of *alternatively synchronized inertial frames*, where clocks are synchronized by signals travelling with a finite speed which can exceed the velocity of light, was suggested later by Torgny Sjödin in his paper of 1979 [5].

The Tangherlini transformations and also the Sjödin transformations which generalize them gave rise to a substantial discussion a quarter century ago, and then found respective places in the Special Theory of Relativity. Despite the fact that the Tangherlini and Sjödin transformations can yield the same results as the Special Theory of Relativity, these transformations are more complicated than the Lorentz transformation since they don't leave the speed of light invariant. However, physicists will probably turn to these transformations each time when there is

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[*] In this concern, Tangherlini writes [42]: "…changing synchronization *does not change the inertial frame*. Think of it this way. You have a train moving with constant velocity relative to the railroad station. You may synchronize clocks according to Einstein on the train, or according to my method, which is related by a local time transformation to the Einstein synchronization, or to that of Reichenbach, or to that of Sjödin, but that doesn't change the uniform motion of the train. It is only when one considers transformations from, say, the station to the train, or vice versa that one has changed inertial frames".

even the smallest chance that they are encountering Lorentz-invariance violating effects in their experiments.

The anisotropy of the coordinate velocity of light c' (3), measured in a moving inertial frame of reference K', is the price one has to pay to keep simultaneity unchanged between all inertial frames of reference. Note: *within a given inertial frame*, there is agreement everywhere in *that* frame as to when two events are simultaneous, after the clocks have all been synchronized, say, by the Einstein method, and in this sense *simultaneity is absolute within a given frame.* It is whether simultaneity within one frame agrees with simultaneity within another frame that the problem of relative simultaneity arises.

Because the Tangherlini transformations are linear, Maxwell's equations are invariant with respect to the transformations. Meanwhile, as shown by Tangherlini [4], in a moving inertial reference frame K' an effective "optical medium" appears which makes the velocity of light different in the forward and backward directions, with respect to the motion of K'. Hence, the Tangherlini transformations in common with the Lorentz transformations can provide adequate description of physical processes in a moving inertial frame of reference, but the Lorentz transformations are more useful in this deal because they keep the velocity of light constant and isotropic in all inertial frames of reference.

Finally, it should be mentioned that Tangherlini in his thesis used the fact that since Maxwell's equations can be written in generally covariant form, they obviously hold under his transformations as well as for the Lorentz transformations. However, because his transformations are linear and unimodular, as are the Lorentz and Galilean transformations, and also include the Lorentz contraction and time dilation, which the Galilean transformations do not, he found that despite the difference with the Lorentz Transformation as to synchronization, a set of tensorial expressions for the electromagnetic fields could be extracted that were exactly the same as for the Lorentz transformation, so that the equations of motion of a charged particle, when written in term of proper velocity and proper acceleration (i.e., derivatives taken with respect to proper time) could be written so as to take the *same form* as for the Lorentz transformation, and, importantly do not involve the velocity of the moving frame relative to the rest frame. He points out in the thesis that there exist a second set of equations of motion which do not reduce to the equations of motion, as seen by the observer in the moving frame who uses the Lorentz transformation, that explicitly involve the velocity of the moving frame relative to the rest frame, but that in the absence of any way to synchronize the clocks in the moving frame with the rest frame, these equations of motion are unobservables. He also points out that the d'Alembertian operator is not invariant under his transformation and that this is a consequence of the fact that the one-way velocity of light in the moving frame has not remained invariant in the moving frame as is the case for the Lorentz transformation, but that in the absence of the possibility of synchronization with the rest frame, this anisotropy is unobservable, in agreement with observation.

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