A New Non-locality Feature and Some of Its Physical Implications

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In quantum mechanics non-locality refers to an interaction or influence that goes beyond a local space-time region. Typical examples are the quantum correlations of entangled elementary particles and the interference patterns in a double-slit experiment. While according to Bell's theorem or the principle of superposition of quantum states it is the breakdown of local realism that is responsible for producing the statistical correlations or interference patterns that are predicted by quantum mechanics, it is not always without dispute what the exact roles of locality and realism are in these occasions. Here we present some physical scenarios where the non-local feature involved means the ability of light photons to detect a subtle difference in their macroscopic experimental settings, and it turns out that this new feature of non-locality is not only above the locality-or-realism debate but also represents a rather new understanding of the unbroken wholeness of Nature. What is most impressive, however, is the fact that this new non-locality feature has some interesting consequences for some century-old issues in physics and astrophysics, for example, the Moon origin debate, the real physical mechanism behind the principle of relativity, and the apparent conflict between the astronomical phenomenon of stellar aberration and the null result of the Michelson-Morley experiment, just to name a few.

1. Introduction

It is truly amazing that quantum non-locality, which initially emerged as what would be referred to as "spooky action at a distance"[1], has since not only found rigorous theoretical basis [2-3] but also past every important experimental test [4-10]. Since the predictions of quantum mechanics have been fulfilled in each case, there seems to be no disagreement over the accuracy of the physical and mathematical aspects of quantum non-locality, but what is frequently in controversy, however, is its conceptual framework and philosophical implications, as is evidenced by the existence, and persistence, of several past and on-going debates which are centered around, for example, whether quantum mechanics is complete or not [1-2], [11-13], the breakdown of which, locality or realism, is the exact cause for the violation of Bell's inequality [8], [14-21], and whether or not quantum entanglement can be used to transmit faster than light signals [11-12], [22-23]. While these debates help to clarify certain aspects of quantum non-locality in general, it may also be a good idea to seek new frontiers, or ask new questions, in the research of non-locality where the situation is free from any conceptual difficulty or controversy; and in particular, concerning a recent result of non-local realistic model of quantum correlation [20-21], it would be interesting to learn whether non-locality can be independently proved without sacrificing the realism that has been cherished by the physics community for centuries. Further, given the increasing space scales that are involved in the experimental demonstrations of non-locality [7, 10], it would also be desirable to know whether the truthfulness of non-locality is subject to any space upper-limit at all. Note that an affirmative answer to both of these questions will not only resolve some of the aforementioned debate issues in an elegant way, but also significantly deepen our understanding of, and confidence in, non-locality itself, and it is in this spirit that we are reporting in the current paper a new feature of non-locality which involves only physical laws that are essentially deterministic in nature and which has also proved to be true in an arbitrary macroscopic space scale. Our results are also believed to be a timely response to the call of "transforming the second quantum revolution from the present stage of basic research to a full- fledged technological revolution" which has been made by Aspect [21] and others.

2. Study of Terrestrial and Interplanetary Ranging Data

The terrestrial ranging data from the Global Positioning System (GPS), which were collected primarily for the purposes of positioning and navigation for users on or around the Earth, have been summarized into the following GPS range measurement equation [24-25]:

$$\left|\vec{R}_r(t_r)-\vec{R}_s(t_s)\right|=c\left|t_r-t_s\right| \tag{1}$$

where t_s and t_r are the GPS time readings of light signal's transmission and reception, respectively; $\vec{R}_s(t_s)$ and $\vec{R}_r(t_r)$ are the source and receiver positions with respect to the reference frame of the Earth centered inertial (ECI) at the appropriate moments; and $c = 299792.458$ km/s is the vacuum speed of light. Note that theoretically the ECI is an envisioned Earth with only orbital motion but no self-rotation, but practically, if all motions being concerned are in Earth's north-south direction so that the Earth's self-rotation does not significantly impact the measurement result, then the frame of Earth can also be treated approximately as the ECI frame. Note also that we have omitted the influences of the Earth's ionosphere and troposphere and other possible factors from equation (1) since they are irrelevant to our current discussion, as will be evident from each context being considered. While it may not be surprising that equation (1) has revealed the fact that for all GPS positioning and navigation purposes light propagates at the constant speed c relative to the ECI reference frame, this fact is not to be taken for granted either, as will be made clear by a comparison of this equation with the interplanetary ranging equation to be introduced below.

The interplanetary ranging data were obtained as a result of determining the ephemerides of the Moon and other planets within the solar system, and these data were summarized into the following interplanetary range measurement equation [26]:

$$u = \left| \vec{R}_B(t_r - d) - \vec{R}_A(t_r - d - u) \right| / c \tag{2a}$$

$$d = \left| \vec{R}_A(t_r) - \vec{R}_B(t_r - d) \right| / c \tag{2b}$$

Where t_r is the ephemeris time reading of the radio signal's reception at an Earth-born antenna; u and d are the light-times of the up-leg (from antenna to planet) and down-leg (from planet back to antenna), respectively; $R_A(\cdot)$ and $R_B(\cdot)$ are respectively the solar-system barycenter positions of the antenna and the signal bounce point on the planet or a spaceship that takes off from it; and c is the vacuum speed of light. Again, we have omitted influences which are irrelevant to our discussion, and these include the time delays due to the Sun's gravity potential, the electron content of solar corona, and the Earth's atmosphere. It is emphasized that for the purposes of interplanetary ranging and ephemeris determination, a key fact being used in equations (2) is the simple truth that radio signals travel at a constant speed c relative the inertial reference frame of the solar-system barycenter, or approximately the Sun centered inertial (SCI), not relative to the ECI or any other reference frame.

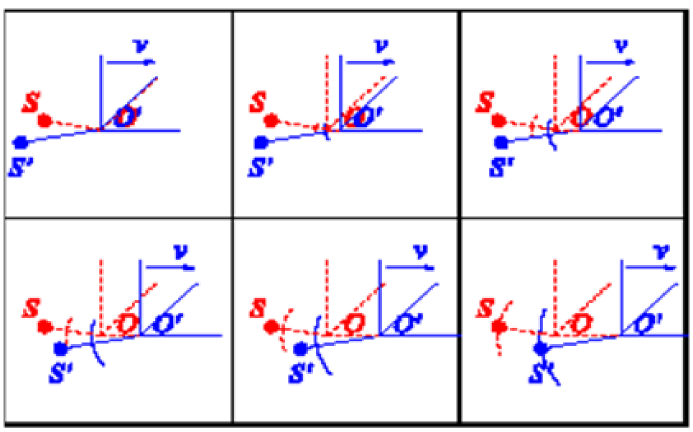

Fig. 1. Separate mechanisms of light propagation. In the simulation the dashed and solid lines show different physical connections between the sources and observers, O' is the actual light source while O plays the role of an instantaneous light source for observer S. These facts are the physical foundations for the simultaneous truthfulness of the ECI and SCI mechanisms of light propagation. Note that $v = c/2$ has been chosen to achieve better effect of illustration.

Eqs. (1) and (2) may seem to be rather innocent looking while examined separately, but they have profound implications when viewed together. To fully appreciate this, we first need to understand that if a radio signal is transmitted from an ECI-born antenna, then according to our current practice, and understanding, it is the GPS ranging equation that is used if this signal is to be received by an observer who is fixed on the ECI or who has originated his motion from the ECI and is moving on or orbiting it [24-25]; and it is the interplanetary ranging equation that is used if the signal is to be received by an observer who is fixed on another planet in the solar system or who is on his trip from the planet to the Earth ([26]). Next, let us envision a situation where both ranging equations (1) and (2) are simultaneously involved. For example, we can assume that two spaceships, spaceship S′ who is fixed on the ECI, and spaceship S who has originated its motion from Venus and is remaining stationary relative to the SCI, are roughly located at the same position within the SCI at a certain moment, so that a radio signal transmitted at this moment from an ECI-born antenna O′, whose instantaneous location relative to the SCI is denoted by O, can be received by both spaceships S′ and S (Fig. 1).

Now, the simultaneous truthfulness of both the GPS and interplanetary range measurement equations ensures that if at the moment of the signal's transmission spaceships S′, S are at the same distance from antenna O′, then it will take the signal the same amount of time to reach both of them, as will be shown by a simple application of these range measurement equations to the given physical conditions, which were specifically designed to fit into these equations.

But how can this be? The mystery seems to lie in the non-local feature of reality, and by this we mean light photons to be received by spaceships S′ and S have to propagate according to different mechanisms, referred to as the ECI mechanism and the SCI mechanism respectively, from the very beginning as if they foreknow their destinies the moment they leave the antenna; and this has to be so because, had the opposite been true, the photons to be received by both spaceships would have had the same position and would have traveled at the same speed at any moment after they leave the antenna until they cover a distance that is roughly equal to the length of $O'S'$. But then, since those photons to be received by spaceship S had been carried forward some distance by the ECI, they would still have some distance to go before they reach their destiny and therefore would not be able to finish their trip within the given amount of time just mentioned.

Thus non-locality means that light photons from a given source propagate to observers in different inertial reference frames with different mechanisms, and clearly this reflects a far more profound connection between different parts of the macroscopic world than what is generally expected.

Note that in dealing with Eqs. (1), (2) above we have implicitly adopted a unifying time basis, and this is perfectly justified since GPS time and ephemeris time differ only by roughly a constant rate, which implies that a simple time translation of the form $t + t_0$, where t_0 is a constant, transforms one of these equations into the same time basis as the other within a slight drifting error rate [27] of less than, for example, 60 nanoseconds/day ≈ $7/10^{13}$. Obviously there is no way for such an insignificant time error rate to affect our argument in this article where the motion related possible effect is of order $v/c = 29.78/299792.458$ = 1/10,000, with $v = 29.78$ km/s being the orbital speed of the Earth, and where the time scale involved is only seconds (for details, see item C in Section 5: Implications of non-locality).

It should be pointed out that while the acceptance of separate mechanisms in ECI and SCI for the propagation of light is necessary for the simultaneous truthfulness of both the GPS and interplanetary ranging equations, and it allows us to derive the non-locality conclusion that we need, it would be ideal for us to specifically describe what these mechanisms are and how exactly they work. To answer these questions, let us assume that spaceship S in the previous example actually takes off from Venus, it comes to follow the Earth in its orbital motion around the Sun, and then lands on the Earth. Noted that before the landing, it is the interplanetary ranging equation that applies to the determination of the range between the Earth-born antenna and spaceship S, and after the landing, it is the GPS ranging equation that applies. In other words, the source-observer relation apparently experiences a fundamental change during the above process, where before the landing the source-observer relation reflects that of the Earth and Venus, which we know are connected by the common SCI background, or platform, where they were formed billions of years ago; yet after the landing, the source and the observer become a physically connected whole and therefore their relation is reflected by the new ECI background. It is interesting to note that these two different mechanisms of light propagation can be further understood in view of two well-known physical principles, namely, light speed's independence of the motion of light source and the principle of relativity, respectively, which we are to detail below.

In fact, it can be easily seen from the simulation in Fig. 1 that the radio signal from antenna O′, which is moving relative to the SCI frame, propagates to spaceship S as if it were from an SCI-stationary light source O, thus the motion of antenna O′ relative to the SCI has no impact on what light speed will be measured by spaceship S. This is what we called light speed's independence of the motion of light source, which is unequivocally supported by the interplanetary range measurement equation where what is relevant is only the position, not velocity, of antenna O′ relative to the SCI at the moment of the signal's transmission. It should be emphasized that this light speed's independence of the motion of light source is not to be extended to include observer-motion since the inclusion of observer position at the moment of the signal's reception in the interplanetary ranging equation has automatically taken the influence of observer-motion into account. On the other hand, even though both spaceship S′ and antenna O′ are moving relative to the SCI frame with the same velocity v, the applicability of the ECI ranging equation to them, which is a direct consequence of our assumptions, allows us to derive a constant light speed c that is independent of this motion v, or in other words, their motion relative to the SCI is in fact undetectable. Note, however, that traditionally the undetectability of (quasi-)uniform motion has been deemed as one of the equivalent formulations of the principle of relativity; thus we conclude that light speed's independence of the motion of light source and the principle of relativity are the two physical mechanisms of light propagation that imply non-locality. We will further elaborate on the principle of relativity shortly.

3. Detection of Different Physical Connections

An acute mind may have noticed that in dealing with the antenna and spaceships in the previous example we have adopted a clock synchronization technique that is based on a unifying time scale of, for example, the SCI frame, yet we will show now that in order to discern the non-local nature of reality that is concerned here, this is not only a desirable choice, but also a necessary one. To see why this is the case, let us assume, without changing any other condition, that in the previous example spaceship S, instead of remaining stationary relative to the SCI, is following antenna O′ (and the ECI) with exactly the same velocity $v = 29.78$ km/s relative to the SCI frame, so that now antenna O′, spaceship S′, and spaceship S all remain stationary relative to each other.

Question: What light speed will be measured by spaceship S?

Note that in order to solve our current problem of one-way range measurement, we need to adapt equation (2a) by setting $d = 0$ and $u = t_r - t_s$ where t_s and t_r are the ephemeris time readings of the signal' transmission and reception, respectively, so that we have

$$t_r - t_s = \left|\vec{R}_B(t_r) - \vec{R}_A(t_s)\right| / c \tag{3}$$

If we choose the orbital plane of the Earth around the Sun as the XOY-plane of the SCI frame, and the initial location of antenna O′ relative to the SCI at $t = t_s$ as its coordinate origin with positive x-axis pointing to the direction of the orbital motion of the Earth, and further, let the constant distance between antenna O′ and spaceship S be denoted by d, then it is easily seen that under first order approximation we have $R_A(t_s) = 0$, and $R_B(t_r) = -d + v(t_r - t_s)$. Substituting these relations into equation (3) and solving for $t_r - t_s$ from the resulted equation, we obtain

$$t_r - t_s = d / (c + v) \tag{4}$$

Equation (4) shows that although the light source (antenna O′) and the observer (spaceship S) remain stationary relative to each other, the observer actually measures a light speed of not c but $c + v$; and further note that clock synchronization is not an issue here since according to all current theories the source and observer are situated within the same inertial frame.

On the other hand, since the ECI-based GPS range measurement equation applies to antenna O′ and spaceship S′ according to our assumption, we easily conclude that spaceship S′ will measure the usual light speed constant c. It is then clear that antenna O′ and spaceship S′ cannot be simply treated as independently moving within the SCI frame in which case a wrong light speed of $c + v$ would be calculated, as is evident from above. Again, clock synchronization is not a problem here since antenna O′ and spaceship S′ are also in the same inertial frame.

So what makes the above light speed difference? Apparently relative motion is not the answer, since all three, antenna O′, spaceship S′, and spaceship S, are in the same inertial frame; yet it can be concluded again that non-locality seems to provide the answer, and this time by non-locality we mean light photons' ability to detect how the light source and the observer are physically connected, that is, whether they are related through the SCI or ECI frame, or equivalently, whether the observer is fixed on Earth or has originated his motion from another planet and is following the Earth with the same velocity. This detection of different physical connections explains why in both the previous and the current examples the photons going to both spaceships S′, S are able to "foreknow" their destinies the moment they leave the antenna.

Thus we conclude that light photons are capable of detecting, and reacting to, a more subtle and more profound aspect of an experimental setting than just relative motion, and in fact our conclusion here is supported by other independent experimental evidences which we shall present below.

4. Orbital versus Self-rotational Motion

We may have reason to think that the null result of an experiment tends to tell us nothing important about it, but apparently there is an exception, and that was the famous M&M experiment [28] which has profoundly impacted the development of modern science; yet unfortunately there is evidence that even until today the significance of this experiment has not been fully explored and fully understood. To appreciate this point of ours, we need to make a brief comparison of the M&M experiment, whose null result is in connection with the Earth's orbital motion around the Sun, with the terrestrial Sagnac effect [29-30], whose non-zero value is induced by the self-rotational motion of the Earth, as follows:

The M&M experiment, whose experimental setting-up is essentially an interferometer with two perpendicular arms, was originally designed and carried out to detect the Earth's orbital motion relative to the presumed absolutely stationary light medium called "ether", yet surprisingly, the experiment and its likes kept giving a null result, hence it seems to be safe to conclude that the Earth's orbital motion around the Sun, which is quasi-inertial/uniform in nature, is not detectable. Note that if this null effect represents a physical law, then we would expect a similar experiment carried out on a satellite or spaceship orbiting the Earth to produce the same result. But what is frequently neglected are the facts that: (a) in the M&M experiment both the light source and the observer (detecting telescope) are fixed on the moving Earth, and (b) the null result of the experiment was true only within the experimental accuracy of that time, both of which plays a fundamental role in understanding the significance of the M&M experiment, as we shall demonstrate shortly.

On the other hand, it was shown by Sagnac [31] in 1913 that rotational motion is detectable through the interference fringe shift of light photons that are traveling along the opposite directions of a light loop that is set up on a rotating platform, but what interests us most is the implication of this experiment for Earth's self-rotation, and it is to our knowledge that today the detection of Earth's self-rotational motion with light photons is in fact a routine and that this effect has been built into the working mechanism of the GPS [24-25], [30]. Thus Sagnac effect has nothing to do with the experimental scale involved but has everything to do with its self-rotational nature.

It is then seen that the M&M experiment produced a null result not only because of the undetectability of the Earth's orbital motion but also because of the experimental limit of that time when the experiment was performed; yet we shall show below that the undetectability of quasi-inertial orbital motion and the detectability of self-rotational motion, when combined, have a profound implication.

In fact, let us assume that we have two identical spaceships, denoted by R′ and R, with both of them not only carrying identical interferometers as the one used in the M&M experiment but also having their interferometers set up in an identical manner within them. Next, let us assume that spaceship R′ is sent into a geostationary orbit around the Earth while spaceship R is fixed on a platform that extends from the ground all the way to the same height as spaceship R′, so that both spaceships not only have the same tangential speed relative to Earth but also position in a symmetric manner with respect to the Earth center O (Fig. 2).

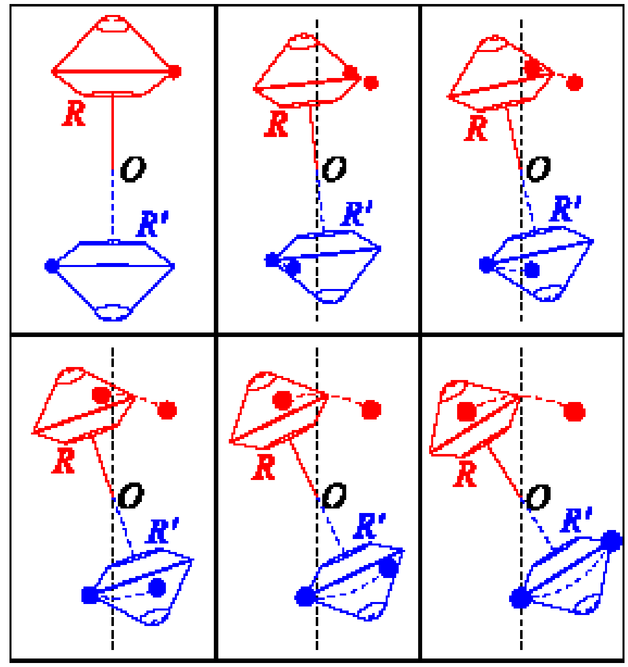

Fig. 2. Non-local detection of experimental settings. In the simulation the dashed line between each pair of solid dots represents the actual light path, so the light speed detected by spaceship R is $c-v=c-c/2=c/2$, while that by spaceship R′ is simply c. The orbital motion of spaceship R′ is indicated by its dashed line connection with Earth center O, and the self-rotation of spaceship R is indicated by its solid line, rigid connection with the Earth. The different reactions of light photons to quasi-inertial orbital motion and self-rotation agree, respectively, with the null result of the M&M experiment and the non-zero terrestrial Sagnac effect. Also, spaceship R is said to be in self-rotation because physically it is part of the self-rotational Earth. Lastly, the tangential speeds of both spaceships were taken to be $v=c/2$ for illustration purpose.

Question: Will the interferometers in spaceships R′ and R produce the same interference fringe shift?

The answer is no if our above understanding of the difference between orbital and self-rotational motions is correct, since in that case the interferometer within spaceship R′ would give a null result due to its undetectable orbital motion while the interferometer within spaceship R would give a non-zero result due to its detectable self-rotational motion. We point out, however, that the photons involved in both scenarios apparently have exactly the same immediate experimental settings to detect, and the only difference between these spaceships is the fact that one is moving independently from the Earth while the other is physically connected with it as a whole.

Thus we conclude again that light photons seem to have the ability to detect a subtle difference in their macroscopic experimental settings, and this is another demonstration of what is referred to as the non-local feature of reality in this article.

5. Implications of Non-Locality

The argument and examples presented so far in this article have clearly demonstrated that the propagation, and detection, of light signals is essentially a non-local phenomenon, therefore it will not surprise us if this feature of non-locality has some interesting consequences; and below are some of them:

A. It tells us something profound about the principle of relativity.

One of the equivalent formulations of the principle of relativity is that uniform motion is not detectable if both the light source and the observer are confined within that moving reference frame, and it is only by now that it becomes clear what this exactly means and why, and how, the principle of relativity works as it does. To fully appreciate this, we will first mention the fact that if we take a reference frame simply to mean all objects that remain stationary relative to each other, then there is no way for the principle of relativity to be true. In fact, the calculations in Section 3 "Detection of Different Physical Connections" have clearly shown that there are situations where both the light source and the observer are moving but remain stationary relative to each other, so that they would be in the same inertial reference frame in the traditional sense, but a measured light speed of $c+v$ or $c-v$ does indicate the detectability of the uniform motion being concerned. This clearly shows that in order for the principle of relativity to be true, the concept of inertial reference frame cannot just mean stationary state of relative motion; it has to mean something deeper, and this is the physical connection that we introduced earlier which allows us to differentiate the source-observer relation between antenna O′ and spaceship S, where uniform motion is detectable, and that between antenna O′ and spaceship S′, where uniform motion is undetectable.

In short, the principle of relativity works if and only if the light source and the observer have a more intimate physical connection than just remaining stationary relative to each other, and this reveals the true mechanism that is behind the principle of relativity.

B. It effectively resolves the apparent conflict between stellar aberration and the null result of the M&M experiment; or at least provides an alternative solution to the above century-old problem.

From what has been discussed so far, it is clear that the null result of the M&M experiment is due to the undetectability of Earth's quasi-inertial orbital motion through experimental techniques that are confined within the ECI frame, which in turn means that both the light source and observer (detecting telescope) have to be fixed on the ECI, and this allows light signal to propagate at the usual constant speed c along any direction within the ECI frame, producing a zero fringe shift when the two perpendicular light beams come back to meet. Note that the GPS range measurement equation and ranging data provide unequivocal support for this explanation.

On the other hand, stellar aberration is clearly explained by that part of the Earth's orbital motion which is perpendicular to the incoming, parallel light rays from distant stars, so that with a proper choice of variables (Fig. 3) we derive an aberration angle $\alpha = \arctan[v\sin\theta/(c - v\cos\theta)] \approx (v/c)\sin\theta$, where θ is the angle between the Earth's orbital velocity vector and the incoming light ray, v is the Earth's orbital speed, and c is the vacuum speed of light. It is then easily obtained that α is oscillating between -20.5 and 20.5 arc-seconds. In short, stellar aberration is explained by the fact that light rays from distant stars are propagating at the constant speed c relative to the SCI frame. Note that the interplanetary ranging data and measurement equation provide clear evidence for this explanation.

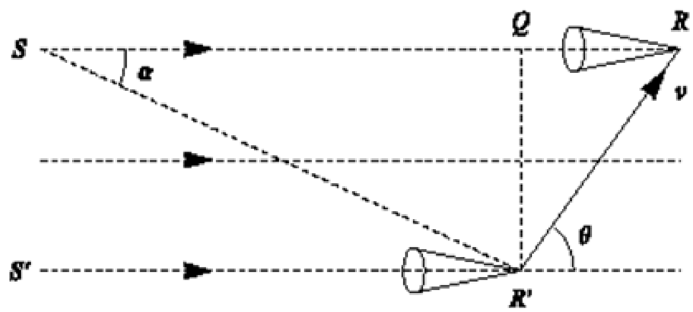

Fig. 3. An explanation of stellar aberration. The telescope at R′, in order to receive light from the star at position S, has instead to point to position S′ at angle α from S to counter its own velocity v. In the time interval $[0, T]$, we have $SR = cT$, $SQ = SR - QR = cT - vT\cos\theta$, $QR' = vT\sin\theta$, so that $\tan\alpha = QR'/SQ = v\sin\theta/(c - v\cos\theta)$, or equivalently $\alpha = \arctan[v\sin\theta/(c - v\cos\theta)]$

But how can light propagate at a constant speed relative to both the SCI and ECI frames? The answer lies in, as we have shown earlier, the non-local nature of reality, and by this we mean that different experimental settings, in particular, different source-observer relations, determine different mechanisms of light propagation, the details of which have already been presented.

Thus, through non-locality, the null result of the M&M experiment and stellar aberration can both hold true without conflicting with each other.

C. It has something important to say about the origin of the Moon.

If non-locality is a reflection of how objects in this world are profoundly connected, as we have argued so far, then it is no surprise at all that it has something to do with revealing the origin of the Moon, which apparently is also a story of how objects, in this case the Moon, the Earth, and possibly another planet, are related. Note that the origin of the Moon has been a topic of debate for quite a while, and popular hypotheses include those assuming that, early in Earth's history, the Moon: (I) fissioned from the Earth (Rotational or Pure Fission) [32], (II) formed independently from, but closely together with, the Earth (Binary Accretion) [33], (III) was captured from a Sun-centered orbit into an Earth-centered orbit (Intact or Disintegrative Capture) [34-35], and (IV) formed as the result of a giant collision of a Mars-like planetoid with the primitive Earth (Collisional Ejection or Giant Impact) [36]. It is interesting to note that, in view of the non-local perspective and evidences presented in this article, both the pure fission and collisional ejection hypotheses have assumed, or implied, a different physical connection from the intact or disintegrative capture and binary accretion hypotheses which allows them to be differentiated, the details of which are as follows:

First of all, according to all current theoretical and experimental evidences, for any object which has originated its motion from the Earth and is orbiting around it, its position relative to the Earth is determined through the GPS ranging equation, which in turn is based on the fact that light propagates at a constant speed c relative to the ECI reference frame; yet it has long been observed, and in fact firmly established, that the Moon's position is not calculated by the GPS ranging equation but instead by the interplanetary range measurement equation whose foundation is the fact that light propagates at the constant speed c relative to the SCI frame. One would be curious to know how much error will be caused if the wrong range measurement equation is chosen, and to answer this question, let us use the Horizon system of the Jet Propulsion Laboratory of California Institute of Technology to generate a table of one-way light-times from the Moon to the Earth for the period of, say, 11/23/2011–12/21/2011, and Fig. (4a) shows the Moon-Earth ranges converted from these data should the ECI frame be improperly chosen as the actual physical background. On the other hand, the Horizon system also allows us to generate the ephemerides for the Moon and the Earth for the same period, which gives us the actual Moon-Earth ranges as shown in Fig. 4(b). Note that the maximum time scale involved in these range data is (average Earth-Moon distance)/(light speed)=(405444.187 km)/(299792.458 km/s)≈1.35 s, which justifies our earlier conversion between the two time bases of the SCI and ECI ranging equations.

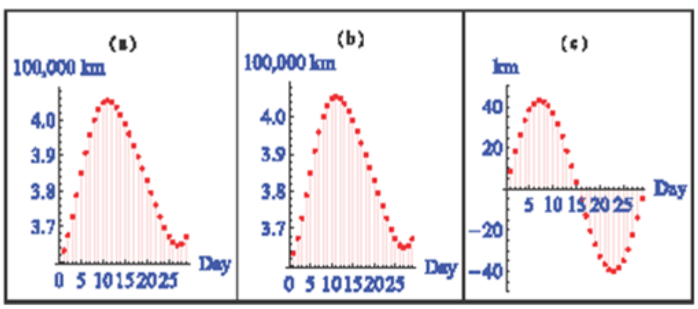

Fig. 4. Moon-Earth ranges and errors. Systematic errors for the Moon-Earth range come into existence as the result of a wrong choice of the range measurement equation, and these errors are calculated as the differences between the converted ranges based on one-way light-times from Moon to Earth by using the ECI frame as background and the actual Moon-Earth ranges based on their accurate ephemerides. In the figure: a, converted Moon-Earth ranges; b, actual Moon-Earth ranges; c, range errors.

Lastly, by comparing the converted and actual ranges, we obtain a maximum range error of about 43 km (Fig. 4(c)) which corresponds to a root-mean-square range error of about 30 km. But the actual root-mean-square ranging error was about 30 cm in the 1970's, and it has been improved to 3 cm since the 1990s![37]

It is then concluded that, in relation to the Earth, the Moon is a "foreign" object, by which we mean that either it formed elsewhere in the solar system and was captured by the Earth, or it might have formed nearby, but independently from, the Earth; but it cannot have fissioned from the Earth before going into its Earth-centered orbit since in that case the ECI-frame based GPS ranging equation would have been invoked to determine its position and velocity in order to reflect this intimate physical connection between the Moon and the Earth.

But could the Moon be the result of a giant collision of a Mars-sized planet with the Earth at an early stage of their formation when both were very hot, as has been assumed by the collisional ejection hypothesis (CEH)? If the understanding of non-locality in this article is correct, such a possibility can also be ruled out, and this is so because any such collision must have involved a profound interaction between the primordial Mars-like planet and the Earth, so as to form a connected whole before what would become the future Moon was separated from it [38-40]. It is then deduced that, just like what happens to any Earth-originated, Earth-orbiting object, the Moon's position would again be determined by the ECI-frame based GPS range measurement equation, which we know is not true.

Thus, if the non-locality argument in this article is sound, then of all the four hypotheses regarding the origin of the Moon, the only viable theories are capture and binary accretion. Indeed, the quantum optical evidence presented above regarding the Moon-Earth relation does fit into the capture hypothesis perfectly well, however, no conclusive answer can be given regarding the binary accretion hypothesis without further assumptions being made about it.

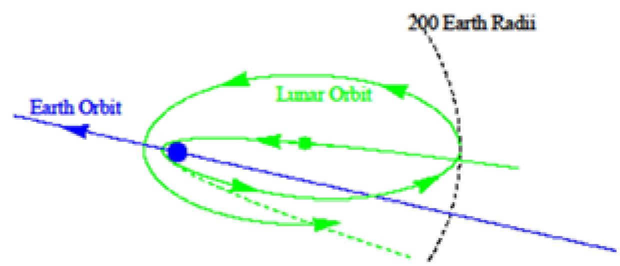

Fig. 5. The tidal capture of Moon. As has been shown by Malcuit et al. [41-42], during this process of tidal capture the Moon transferred from a Sun-centered orbit to an Earth-centered orbit; the sketch is reproduced, and edited, with the permission of the Astronomical Review journal.

While this has not proved the definite truthfulness of the capture hypothesis, it does suggest that this is a serious option, and the question now is reduced to whether or not it is kinematically and dynamically possible for such a capture to happen, and in fact, it is, as has been shown by Malcuit and others in their research papers [41-42] where the authors have not only demonstrated the feasibility of a "tidal capture of Moon" by Earth but also have proved the existence of a "stable capture zone", which is a region of parameter space where nearly all simulations result in stable capture orbits.

But we feel there is a need to say more about the CEH, currently the prevailing hypothesis regarding the origin of the Moon. In fact, research work in recent years is challenging several, if not all, fundamental premises of the CEH; for example:

- The ratios of the Moon's volatile alkali elements seem not to be in agreement with the predictions of the CEH [43].
- The presence of water and other volatile elements contradicts the CEH's volatile depletion claim [44].
- The Moon has too distinct a bulk composition to have largely been derived from the Earth's mantle [45].

- The Moon is also too deficient in siderophile elements to have mainly originated from an impactor that accounts for the high lunar iron oxide [46].
- The CEH not only suggests an early age (before 4,450 million years ago) for the happening of the assumed "collision" [46-47] but also invokes the formation of magma oceans for both the Earth and Moon [43], [48-49]; yet newest evidences have shown that either the Moon is too young (4,360±3 million years) or did not have a global magma ocean [50], while the Earth seems to have not had a magma ocean at all [43].

We are aware that some of the above geochemical difficulties may be resolved by modifying the CEH, yet how to simultaneously resolve them all is definitely an unanswered question, and currently it seems to be in no way clear if this is possible at all. Yet it is in this very respect that the capture theory for the origin of the Moon has an obvious advantage since it is largely free from the geochemical constraints that the CEH and other hypotheses are subject to. Needless to say that more work is necessary to ultimately work out the origin of Moon, but it is a pleasant surprise to know that quantum optical evidence may play an important, if not decisive, role in it.

It is just wonderful that a couple of "illusive" photons in the eyes of some modern physicists may have revealed a secret that began billions of years ago!

6. Conclusion

In deriving the non-local result regarding light photons' different reactions to orbital motion and self-rotation, we have assumed that the detection of quasi-inertial orbital motion by radio/optical method represents a physical law, in the sense that the observed phenomenon is repeatable under similar conditions irrespective of the different macroscopic experimental scales involved. It should be realized that what the above assumption claims is exactly the content of the principle of relativity, which is clarified earlier in this article and which has incorporated the idea of physical connection in its interpretation to ensure its truthfulness.

A similar assumption has also been made when we draw the conclusion regarding the origin of the Moon, where we have reasoned that if it is the ECI range measurement equation that applies to the determination of the position and velocity of an Earth-originated, Earth-orbiting spaceship or satellite, then the same equation has to apply to the determination of the range between the Moon and Earth had they been a physically connected whole before the Moon separated from the Earth and went into its Earth-centered orbit.

Finally, given the nature and accuracy of the ranging data presented in this article, if an experimentalist is to play any role at all in effecting the non-locality feature being concerned, it would be to decide which one of the ECI- and SCI-mechanisms of light propagation comes into play, rather than to alter any of these mechanisms themselves; and as a consequence, any such role of the experimentalist is to reinforce our non-local conclusion rather than weaken it, since now the experimentalist has become an integral part of the whole experimental setting. Counterintuitive this may appear to be, it would be a good idea to leave this possibility open, which we know is in perfect agreement with the Copenhagen interpretation of quantum mechanics.

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Supplementary Information

All the simulations and other graphical illustrations in this article are produced with the aid of the Mathematica software developed by the Wolfram Research, Inc., whose website is: http://www.wolfram.com/.

Also, we have used the web-interface of the Horizon system of the Jet Propulsion Laboratory of California Institute of Technology to generate all necessary ephemerides and one-way light-times, and the URL is: http://ssd.jpl.nasa.gov/horizons.cgi.

In particular, for one-way light-times from Moon to Earth, we have used the following ephemeris setting:

Ephemeris Type: OBSERVER; Target Body: Moon [Luna] [301]; Observer Location: Geocentric [500]; Time Span: Start=2011-11-23, Stop=2011-12-21, Step=1 d;Table Settings: defaults; Display/Output: default (formatted HTML).

And the settings for Moon and Earth ephemerides for the given period are, respectively:

Ephemeris Type: VECTORS; Target Body: Moon [Luna] [301]; Coordinate Origin: Solar System Barycenter (SSB) [500@0]; Time Span: Start=2011-11-23, Stop=2011-12-21, Step=1 d; Table Settings: defaults; Display/Output: default (formatted HTML);

And

Ephemeris Type: VECTORS; Target Body: Earth [Geocenter] [399]; Coordinate Origin: Solar System Barycenter (SSB) [500@0]; Time Span: Start=2011-11-23, Stop=2011-12-21, Step=1 d; Table Settings: defaults; Display/Output: default (formatted HTML).