How to Define Aberration of Light

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Stellar aberration is a much more diverse phenomenon than it is seen on the face of it, which makes it hard for understanding without a proper classification and unambiguous definitions. Its first branching out takes place depending on what is the cause of aberration – is it a jump in the velocity of the telescope or the star (including the possibility of many little jumps one after the other) or it is just motion with a uniform velocity that is responsible for the aberration. These two kinds of aberration may be called *dynamic* and *stationary*, respectively. The first of them may be defined as a jump in the visible position of the star that results from the jump in the velocity. Dynamic aberration could undergo further splitting only once – depending on whose velocity experiences the jump – telescope or star's. The change in telescope's velocity might be connected, say, with diurnal rotation (dynamic or Bradley's aberration). As for the second option – with the jump in velocity made by the star – this class of dynamic aberration is empty. There is no way for the star to make a first-order inclination of the wave front of the ray of light emitted towards the Earth, which makes any further branching meaningless.

Not so for stationary aberration. It may be defined as a difference between the apparent position of the star as seen through the telescope and the true position of the star established by an army of calibrated rods and clocks which have been sent by telescope's operator to surround the star and make an unambiguous direct measurement of its whereabouts according to traditional Einstein's rod-and-clock theory. The first branching out of this aberration takes place depending on what is implied by the true position of the star, from which its apparent position is counted – whether it is the position taken by the star at the moment of the emission of light towards the telescope (instrumental stationary aberration), or from the position, taken by the star at the moment of arrival of light at the telescope (planetary stationary aberration). A linear superposition of these two aberrations may be called a total or relativistic aberration including the Terrell effect. Of these three kinds of aberrations only total aberration is an invariant and does not depend on the choice of the inertial frame of reference. As for the other two, the instrumental aberration takes place only in the frame of the star while the planetary aberration exists only in the frame of the telescope. Thus, everything has found its proper place, which excludes any further loophole for blaming relativity as being unable to manage with aberration of light.

1. Introduction

In spite of its apparent simplicity, aberration seems to be one of the most intricate effects in special relativity. The outbursts of activity on this topic in literature belong to different times and perhaps to different generations of scientists [1-13] – starting as early as in the twenties [1-4] and going on up to the end of the last century [13]. The essential reason for all these disturbances was always the same. It was a bewildering seeming contradiction between relativity and the doubtless astronomical evidence stored up during a number of centuries. There cannot be any doubt that motion of the Earth causes annual and diurnal aberrations. Therefore, it is the matter of fact that motion of the measuring instruments relative to the star causes the aberration. But there is also other evidence referring to binary stars. The relative motion of these stars with respect to each other (and hence, with respect to the Earth) is never followed by any aberration, though motion of these stars sometimes is much faster than that of the Earth round the Sun. Therefore, it is also the matter of fact that motion of the star relative to the measuring instruments does not cause aberration. The contradiction is so plain that some astronomers were pretty sure that relativity had been fatally disproved by this evidence and was widely used only due to the ignorance of most of physicists in astronomical affairs [1- 6]. Even those who tried to disprove special relativity [14] did not try to propose a new *experimentum crusis* based on aberration because it seemed hard to invent more convincing evidence than that which already existed. It could not seem but surprising that nobody had ever succeeded in using that evidence for measuring the velocity of an ether drift. The failure in using the asymmetry of aberration for measuring an ether drift has been, of course, not the matter of chance. If correctly run, the astronomical evidence does conform to special relativity, as has been shown in literature for several times [7-13].

Though it is the change in the uniform velocity that is responsible for annual or diurnal aberration, it is not the same whom that change belongs. The result depends on whether it is the telescope or the star that changes its velocity. If it is the telescope, then aberration takes place. But if it is the star, then no signs of aberration should be expected in full accordance with the experimental evidence. This cannot contradict special relativity because the presence of a change in the velocity (or "a transfer from one inertial frame to another", as it is sometimes put) takes the problem out of the range of Einstein's first postulate. This asymmetry is of the same nature as that of the well-known clock paradox [15], where one of the two twin-brothers leaves for a space trip, then returns home and turns out younger than his sibling who has stayed at home and never has changed his velocity. Though this argumentation seems quite adequate, streamlets of bewilderment still were flowing in the recent literature [13]. At the first sight, they could seem groundless, but after a sober speculation, it became clear that there did remain a good reason for doubts, which sometimes visited the minds of the contemporaries in connection with discovery and study of the Terrell effect throughout the second half of the last century [16-21]. It is clear that that effect is a certain kind of aberration. It is proved by the relevant mathematical derivations, that do not differ from those which are used to describe aberration of light [20,21]. But from the other hand, there is no need in a change of the velocity for the Terrell effect to exist. We may be sure that the apparent shape of binaries is, in fact, distorted by their motion and that this distortion is not connected with a change in their velocity.

To do away with all this misunderstanding, an appropriate definition of aberration is needed. But this is impossible to do without a relevant classification of aberration, which turns out much more branched phenomenon than it is seen on the face of it, no matter that it is formally described by the same mathematics. Therefore, the answer to the question "What is aberration of light?" should sound like this: "It depends on what kind of aberration is meant", and only after an appropriate clarification, an unambiguous definition can be formulated. In other words, the definition of aberration must be as many-fold as aberration itself.

2. Dynamic aberration

Dynamic aberration is the change in an apparent angular position of the star which happens when the telescope changes the uniform velocity of its motion. It is nothing else but well-known Bradley's aberration. The role of the true position of the star is played here just by the current image of the star before its jump.

The physical reason for dynamic aberration can be explained by means of the following example. Let us imagine a radio telescope, which consists of two spatially separated high frequency probes, aligned along the front of the incident plane electromagnetic wave coming from the star [22]. The high frequency signals, picked up by the probes, are sent to the inputs of a phase detector located exactly midway between the probes. If the phase detector shows zero phase difference between the two signals, this means that the probes are aligned exactly along the wave front, i.e. perpendicularly to the direction to the star. After such device starts from rest to motion with a uniform velocity v directed along the wave front, the phase detector begins to move against the signal coming from the front probe and off the signal coming from the back probe. This makes the phase difference between the inputs deviate from zero. To return it to zero, the telescope must be inclined by a certain angle and so does the apparent direction to the star in accordance with the laws of aberration. An optical telescope behaves in a similar way [23], though the functions of the probes and feeders connecting the probes with the focus of the lens (with the "phase detector") are distributed over space and intermingled, which impedes a distinct explanation. The rays of light collecting in the focus to form an image undergo the phase shifts caused by motion of the telescope, which results in the apparent inclination of the direction to the star.

It should be stressed that it is the telescope and not the star that must change its velocity to cause the Bradley aberration. If the telescope were at rest and the star started from rest to motion, then the apparent position of the star seen in the telescope would never jump by any angle. There, would be, though, a delay needed for light to reach the observer. That delay would not be the same for different points of the star, which would cause a distortion of the shape of the star, as well as other attributes of the Terrell effect. But this process would be finished only after the transient is over, so that it would refer not to dynamic but rather to static aberration, which would be considered in the next section. As for the dynamic aberration, no signs of it will be seen when the jump in the velocity is made by the star without any disturbance in motion of the telescope.

Though dynamic aberration behaves asymmetrically, it does not contradict special relativity, because the measuring instruments, fixed to the telescope and to the star, can unambiguously reveal which of them changes its uniform velocity. A similar situation takes place in the clock paradox. As it is a dynamic effect, it may be out of the range of special relativity, so that a violation of symmetry is not forbidden. And so is the behavior of binary stars, whose rotation does not influence their apparent angular positions in the telescope which is at rest. This means that dynamic aberration may be only instrumental. It makes no sense to look for a definition of planetary or total aberration if this aberration is dynamic. That is why dynamic aberration in Figure 1 does not branch out any farther.

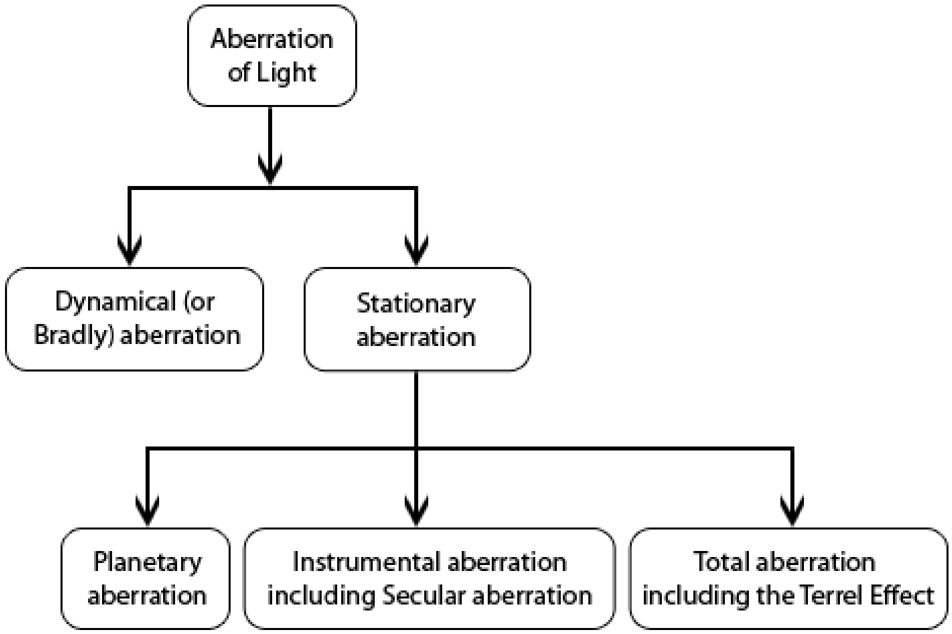

Figure 1: Kinds of stellar aberration presented in a classification tree.

3. Stationary aberration

Let us pass to the more complicated situation when neither the telescope nor the star ever changes its uniform velocity. This means that the apparent position of the star in the telescope does not change at all, and so does the true star's position, which is not seen in the moving telescope and must be established elsewhere. Being concerned with only physical feasibility of our definitions and turning the blind eye to the ways of their practical realization, we may use for example the traditional method which is based on Einstein’s theory of rods and clocks. To realize that method, the whole interstellar space might be filled with landmarks stationed, say, with respect to the star. Each landmark should be equipped with a standard clock. All distances between the landmarks could have been calibrated with standard rods, and all the clocks should have been checked with each other by means of electromagnetic signals. Then in the frame of the star, the true position of the star could be obtained without any telescope. Any observer, fixed to the frame of the star and located at a certain point *O* shown in Fig. 2 would be able to know the direction of line *OS* connecting him with the point *S* where the star is located. For the sake of simplicity let *OS* be perpendicular to the trajectory of the telescope.

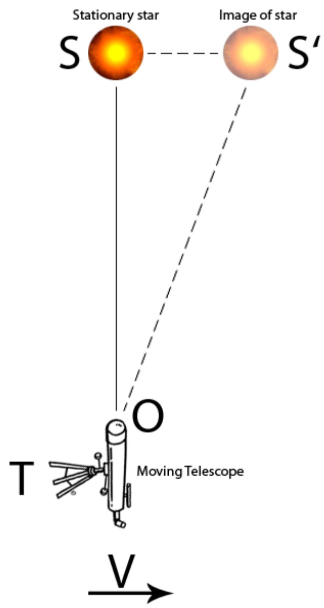

Figure 2: When a *stationary* star *S* is observed through a telescope *T* which *moves* at a uniform velocity *v* the apparent position of the star *S'* is seen ahead of the star as a result of instrumental aberration within the telescope's optical system.

Our next step will be to specify more exactly what we imply by the "true position of the star" – is it the point taken by the star at the moment of light emission or it is the position of the star at the moment of observation. These two options correspond with two different kinds of stationary aberration – *instrumental* and *planetary* aberration respectively, whose formal definitions may read in the following way:

An **instrumental stationary aberration** of the star is a difference between the true position of the star at the moment of light emission and the apparent position of the same star in the moving telescope. In this definition, the true position of the star is based on Einstein's theory of rods and clocks. As for the instrumental reason for the aberration, it is relativity of simultaneity that inclines the wave front of light within the moving telescope. This aberration takes place only in the frame of the star and cannot exist in the frame of the telescope.

A **planetary stationary aberration** of a moving star is a difference between the true position of this star at the moment of light arrival at the telescope and the apparent position of the same star in the telescope which is at rest. In this definition, it is again that the true position of the star is based on Einstein's theory of rods and clocks. As for the instrumental reason for the aberration, it is now motion of the star and time-of-flight effects that take place while light is propagating between the star and telescope. This aberration takes place only in the frame of the telescope and cannot exist in the frame of the star.

It is important that both the stationary aberrations – instrumental and planetary – are able to coexist at the same time – each in its own frame of reference. This is in contrast with dynamic aberration (caused by a change in the velocity of telescope's motion) where only instrumental aberration (in the frame of the star) is possible and there is no way for the moving star whatsoever to undergo a planetary aberration (in the frame of the telescope). This coexistence suggests introducing one more kind of stationary aberration which will be a linear superposition of the instrumental and planetary aberrations. Such aberration will have two essential advantages:

1. Having embraced both the relevant frames of reference – that of the star and that of the telescope – this aberration will be a relativistic invariant which will work in all inertial frames of reference without any tricks characteristic for dynamic aberration.

2. In the frame of the telescope, the true position of the star is taken at the moment of light arrival at the telescope, which will make the Terrell effect one of the main phenomena explained by this aberration.

In accord with these advantages, this aberration might be called *total* or *relativistic*. Its understanding might be concretized by Table 1 on the next page.

Table 1: Total stationary aberration as a superposition of instrumental and planetary aberrations.

Frame of reference	**Kind of aberration** Instrumental	Planetary	Total
Frame of the star	0	1	1
Frame of the telescope	1	0	1

"1" and "0" identify existence and non-existence of the relevant kind of aberration in the frame involved; the words "Instrumental" and "Planetary" associate the true position of the star either with the moments of light emission from the star or its arrival at the telescope; as for the total aberration (alias relativistic aberration or the Terrell effect), it is nothing else but a linear superposition of instrumental and planetary aberrations.

When looking at this instructive table, we see that the instrumental and planetary aberrations, widely used in astronomy (but not in the early works on relativity!), are just components of a more general concept of total aberration which fits relativity like glove because it is invariant and depends only on relative motion of the star and telescope.

There are two kinds of stellar phenomena involved in total stationary aberration. The first of them is connected with the apparent angular position of the star (a regular stationary aberration) while the second one is associated with the shape of the star (the Terrell effect). The regular total aberration might be associated with some lonely stationary star whose apparent position in a telescope (either moving or stationed) is always shifted by a constant angle with respect to the true position. To measure this aberration, the observer has to know indeed a lot of information about the true position of the star on the base of calibrated rod-and-clock network. The observer has to know so much that his or her success in measuring the stationary aberration looks somewhat illusory. If the observer knows the true position of the star, then what for is he or she measuring the aberration?

In contrast to the regular stationary aberration, the Terrell effect looks much more sensible. Watching through a telescope, which is either at rest or in motion, the observer may have a lot of fun seeing the contracted elliptical star to apparently restore its circular contour and to partly show its back side which normally is expected to be invisible. And no rod-and-clock network is needed to obtain the true shape of the star. The Lorentz contraction has been confirmed so many times that the observer can believe in its reality even without special verification.

At the first sight, it might seem very strange that the Terrell effect is so relativistic – especially in the frame of the telescope where planetary aberration, i.e. kinematics of the star or its parts, looks as the only reason for the effect. Moreover, the Terrell effect suggests its being “anti-relativistic” because it tries to mask the Lorentz length contraction by turning the apparent contour of the contracted star into an ideal circle. That's why sometimes we read in literature that the Terrell effect has nothing to do with relativity. Very often it is opposed to relativity as either "time-of-transition effect", or "just a consequence of the finite speed of light", or else the effect, based on rather "seeing" than "observing" [16] and so on. To test such estimations, it is enough to have a look at these "time-of-flight" effects from the frame fixed to the star. When the star is at rest and the telescope in motion, the same distortions of the shape are seen through the telescope. But what is the reason for these distortions now, when the star is at rest and all the "time-of-flight" effects have expired? Isn't that reason purely instrumental? Isn't it hidden inside the telescope? Isn't it directly connected with the relativity of simultaneity [12] as was explained above? And is there any distinct border between "relativistic" and "classical" effects, if their being either relativistic or classical depends on the choice of inertial frame of reference? A lot of other examples can be presented against the existence of such border. An electron moves past a magnet with a Lorentz force exerted on it. Isn't this force of purely classical origin? A magnet moves past an electron which is at rest. Its winding is electrified, which creates an electric force exerted on the resting electron. Isn't this effect purely relativistic? And what about the law of electromagnetic induction – shall we regard it as classical and not relativistic? The only reason for its being classical is the time of its discovery. Be it discovered after relativity (using relativity as a starting point), it would be everywhere called relativistic and, most likely, opposed to classical physics.

The Terrell effect has also one more pleasant feature that helps to override the concern about the true shape of the star. Terrell’s aberration is always repairable. The instrumental reason responsible for it is always the same. When the observer insists on seeing the star from a single point instead of spreading his activities to the neighboring regions of space, he or she ignores the main achievement of special relativity – the relativity of simultaneity – with aberration as an inevitable corollary of this negligence.

Once relevant, synchronized spatially separated clocks come on the scene, the aberration disappears giving the place to the true shape of the star. Usually this can be done just mentally, which makes unnecessary any further search for the true shape of the star. The simplest example of such an “artificial” aberration was described in the first works devoted to Terrell’s discovery [16,17]. It was just a moving rod observed through a stationary telescope. It is a common knowledge that at least two synchronized spatially separated clocks are needed to get a true image of such a rod. But what will happen if one gives up the second clock and tries to use only one of them? The result of course will be wrong or, in other words, there will be Terrell’s aberration defined as a difference between the apparent shape of the rod as seen through the telescope and the true shape and size of the same rod measured on the two-clock basis.

4. Conclusion

Stellar aberration, to have all its paradoxes solved, must be branched out into a number of varieties according to their properties and origin. If it is the change in the telescope's velocity that is responsible for aberration, then aberration is dynamic. It is caused, for example, by Earth's rotation round either its axis or the Sun (the Bradley aberration). But if neither the telescope, nor the star ever changes its velocity, then the aberration is stationary, with a constant difference between the apparent and the "true" positions of the star observed through the telescope. One of the most spectacular examples of stationary aberration is the Terrell effect.

In the case of dynamic aberration it is not the same which of the two objects changes its velocity – the telescope or the star. If it is the star, then no aberration is observed, since there are no physical reasons for a shift of the apparent position of the star. But if it is the telescope that changes its velocity, the rays of light which propagate to the focus inside the telescope undergo phase shifts responsible for aberrational displacement of the apparent position of the star.

Dynamic aberration does not lend itself to further branching out. As for stationary aberration, its farther resolving into varieties depends on how and when the "true" stationary position of the star is measured. If the apparent and "true" positions of the star are observed from a single point (they are rather "seen" than measured), then stationary aberration is reduced only to the Terrell effect and has no other varieties. But if the "true" position of the star is measured with standard instruments which are distributed over space outside the telescope, then further branching out takes place into three varieties depending on the moment of time when the "true" position of the star is registered. Two such moments of time are possible. One of them corresponds to the departure of light from the star to the telescope. The other one is coincident with the arrival of light at the telescope. If the "true" position of the star is registered at the first of these moments, than aberration can be explained only in terms of the processes which take place within the telescope, so that the relevant aberration might be called instrumental. It might be identified with secular aberration, if the latter were so slow that it would not make any sense to rely on the apparent position taken by the star many centuries ago.

In the opposite case, when the "true" position of the star is measured at the moment of the observation, the relevant aberration may be called planetary and is identical to the Terrell effect. Planetary aberration is non-symmetrical and exists only in the frame of the telescope. Instrumental aberration is also non-symmetrical, but exists only in the frame of the star. A linear superposition of these two aberrations is a relativistic invariant and might be called "total" or “relativistic” as being independent of the fact what is in motion and what is at rest – the telescope or the star. From the pedagogical standpoint, it seems helpful to know that all these varieties of aberration have their own good reasons to occur and can be explained in terms of both relativity and classical physics.

5. References

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