What the Global Positioning System Tells Us about Relativity

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1. What is the GPS?

The Global Positioning System (GPS) consists of a network of 24 satellites in roughly 12-hour orbits, each carrying atomic clocks on board. The orbital radius of the satellites is about four Earth-radii (26,600 km). The orbits are nearly circular, with a typical eccentricity of less than 1%. Orbital inclination to the Earth's equator is typically 55 degrees. The satellites have orbital speeds of about 3.9 km/s in a frame centered on the Earth and not rotating with respect to the distant stars. Nominally, the satellites occupy one of six equally spaced orbital planes. Four of them occupy each plane, spread at roughly 90-degree intervals around the Earth in that plane. The precise orbital periods of the satellites are close to 11 hours and 58 minutes so that the ground tracks of the satellites repeat day after day, because the Earth makes one rotation with respect to the stars about every 23 hours and 56 minutes. (Four extra minutes are required for a point on the Earth to return to a position directly under the Sun because the Sun advances about one degree per day with respect to the stars.)

The on-board atomic clocks are good to about 1 nanosecond (ns) in epoch, and about 1 ns/day in rate. Since the speed of light is about one foot per nanosecond, the system is capable of amazing accuracy in locating anything on Earth or in the near-Earth environment. For example, if the satellite clocks are fully synchronized with ground atomic clocks, and we know the time when a signal is sent from a satellite, then the time delay for that signal to reach a ground receiver immediately reveals the distance (to a potential accuracy of about one foot) between satellite and ground receiver. By using four satellites to triangulate and determine clock corrections, the position of a receiver at an unknown location can be determined with comparable precision.

2. What relativistic effects on GPS atomic clocks might be seen?

General Relativity (GR) predicts that clocks in a stronger gravitational field will tick at a slower rate. Special Relativity (SR) predicts that moving clocks will appear to tick slower than non-moving ones. Remarkably, these two effects cancel each other for clocks located at sea level anywhere on Earth. So if a hypothetical clock at Earth's north or south pole is used as a reference, a clock at Earth's equator would tick slower because of its relative speed due to Earth's spin, but faster because of its greater distance from Earth's center of mass due to the flattening of the Earth. Because Earth's spin rate determines its shape, these two effects are not independent, and it is therefore not entirely coincidental that the effects exactly cancel. The cancellation is not general, however. Clocks at any altitude above sea level do tick faster than clocks at sea level; and clocks on rocket sleds do tick slower than stationary clocks.

For GPS satellites, GR predicts that the atomic clocks at GPS orbital altitudes will tick faster by about 45,900 ns/day because they are in a weaker gravitational field than atomic clocks on Earth's surface. Special Relativity (SR) predicts that atomic clocks moving at GPS orbital speeds will tick slower by about 7,200 ns/day than stationary ground clocks. Rather than have clocks with such large rate differences, the satellite clocks are reset in rate before launch to compensate for these predicted effects. In practice, simply changing the international definition of the number of atomic transitions that constitute a one-second interval accomplishes this goal. Therefore, we observe the clocks running at their offset rates before launch. Then we observe the clocks running after launch and compare their rates with the predictions of relativity, both GR and SR combined. If the predictions are right, we should see the clocks run again at nearly the same rates as ground clocks, despite using an offset definition for the length of one second.

We note that this post-launch rate comparison is independent of frame or observer considerations. Since the ground tracks repeat day after day, the distance from satellite to ground remains essentially unchanged. Yet, any rate difference between satellite and ground clocks continues to build a larger and larger time reading difference as the days go by. Therefore, no confusion can arise due to the satellite clock being located some distance away from the ground clock when we compare their time readings. One only needs to wait long enough and the time difference due to a rate discrepancy will eventually exceed any imaginable error source or ambiguity in such comparisons.

Experiment	Description	Year
Bradley	Discovery of aberration of light	1728
Fresnel	Light suffers drag from the local medium	1817
Airy	Aberration independent of the local medium	1871
Michelson-Morley	Speed of light independent of Earth's orbital motion	1881
De Sitter	Speed of light independent of speed of source	1913
Sagnac	Speed of light depends on rotational speed	1913
Kennedy-Thorndike	Measured time also affected by motion	1932
Ives-Stilwell	Ions radiate at frequencies affected by their motion	1941
Frisch-Smith	Radioactive decay of mesons is slowed by motion	1963
Hafele-Keating	Atomic clock changes depend on Earth's rotation	1972
GPS	Clocks in all frames continuously synchronized	1997

Table 1. Independent experiments bearing on Special Relativity

Several of the experiments bearing on various aspects of SR (see Table 1) gave results consistent with both SR and LR. But Sagnac in 1913, Michelson following the Michelson-Gale confirmation of the Sagnac effect for the rotating Earth in 1925 (not an independent experiment, so not listed in Table 1), and Ives in 1941, all claimed at the time they published that their results were experimental contradictions of Einstein SR because they implied a preferred frame. In hindsight, it can be argued that most of the experiments contain some aspect that makes their interpretation simpler in a preferred frame, consistent with LR. In modern discussions of LR, the preferred frame is not universal, but rather coincides with the local gravity field. Yet, none of these experiments is impossible for SR to explain.

For example, Fresnel showed that light is partially dragged by the local medium, which suggests a certain amount of frame-dependence. Airy found that aberration did not change for a water-filled telescope, and therefore did not arise in the telescope tube. That suggests it must arise elsewhere locally. Michelson-Morley expected the Earth's velocity to affect the speed of light because it affected aberration. But it didn't. If these experimenters had realized that the aether was not a single entity but changed with the local gravity field, they would not have been surprised. It might have helped their understanding to realize that Earth's own Moon does not experience aberration as the distant stars do, but only the much smaller amount appropriate to its small speed through the Earth's gravity field.

Another clue came for De Sitter in 1913, elaborated by Phipps [3], both of whom reminded us that double star components with high relative velocities nonetheless both have the same stellar aberration. This meant that the relative velocity between a light source and an observer was not relevant to stellar aberration. Rather, the relative velocity between local and distant gravity fields determined aberration. In the same year, Sagnac showed non-null results for a Michelson-Morley experiment done on a rotating platform. In the simplest interpretation, this demonstrated that speeds relative to the local gravity field do add to or subtract from the speed of light in the experiment, since the fringes do shift. The Michelson-Gale experiment in 1925 confirmed that the Sagnac result holds true when the rotating platform is the entire Earth's surface.

When Ives and Stilwell showed in 1941 that the frequencies of radiating ions depended on their motion, Ives thought he had disposed once and for all of the notion that only relative velocity mattered. After all, the ions emitted at a particular frequency no matter what frame they were observed from. He was unmoved by arguments to show that SR could explain this too because it seemed clear that nature still needed a preferred frame, the motion relative to which would determine the ion frequencies. Otherwise, how would the ions know how often to radiate? Answers to Ives dilemma exist, but not with a comparable simplicity.

Richard Keating was surprised in 1972 that two atomic clocks traveling in opposite directions around the world, when compared with a third that stayed at home, showed slowing that depended on their absolute speed through space -- the vector sum of the Earth's rotation and airplane speeds -- rather on the relative velocities of the clocks. But he quickly accepted that astronomers always use the Earth's frame for local phenomena, and the solar system barycentric frame for other planetary system phenomena, to get results that agreed with the predictions of relativity. Being unaware of LR, he did not question the interpretation at any deeper level.

Experiment	Type	Notes on Reciprocity
Bradley	Aberration	Moon exempt
Fresnel	Fresnel drag	Existence of aether

Airy	Existence of aether	Water in ‘scope ignored
Michelson-Morley	No universal aether	Aether “entrained”?
De Sitter	c independent of source	Double star aberration
Sagnac	c depends on rotation	Local gravity field non-rotating
Kennedy-Thorndike	Clocks slow	Motion w.r.t. local gravity field
Ives-Stilwell	Ions slow	"
Frisch-Smith	Mesons live longer	"
Hafele-Keating	Clocks depend on rotation	Preferred frame indicated
GPS	Universal synchronization	Preferred frame = local gravity

Table 2. Independent experiments bearing on Special Relativity

Table 2 summarizes what the various experiments have to say about a preferred frame. These experiments confirm the original aether-formulated relativity principle to high precision. However, the issue of the need for a preferred frame in nature is, charitably, not yet settled. Certainly, experts do not yet agree on its resolution. But of those who have compared both LR and SR to the experiments, most seem convinced that LR more easily explains the behavior of nature.

8. How does the resolution of the "twins paradox" compare in LR and SR?

In LR, the answer is simple: The Earth frame at the outset, and the dominant local gravity field in general, constitutes a preferred frame. So the high-speed traveler always comes back younger, and there is no true reciprocity of perspective for his or other frames.

In SR, the answer is not so simple; yet an explanation exists. The reciprocity of frames required by SR when Einstein assumed that all inertial frames were equivalent introduces a second effect on "time" in nature that is not reflected in clock rates alone. We might call this effect "time slippage" so we can discuss it. Time slippage represents the difference in time for any remote event as judged by observers (even momentarily coincident ones) in different inertial frames.

For example, we would argue that, if it is 9/1998 here and now, it is also 9/1998 "now" at Alpha Centauri. But an observer here and now with a sufficiently high relative motion (say, 99% of c; gamma = 7) might judge that it is 9/1994 at Alpha Centauri "now" (meaning that he just left there one month of Earth time ago, and it was 8/1994 then). Or he might judge that it is 9/2002 at Alpha Centauri "now" (meaning that he will arrive there in one month of Earth-elapsed time, and will find the time to be 10/2002). These differences of opinion about what time it is at remote locations are illustrations of time slippage effects that appear only in Einstein SR to preserve the frame independence of its predictions.

So as a traveler passes Earth in 8/1994 at a speed of 0.99c , time slippage effects begin to build up. Seven months later by his natural clock, the traveler arrives at Alpha Centauri. His own GPS clock shows four years of elapsed time, and indeed Alpha Centauri residents who think they are calendar-synchronized with Earth agree that the twin arrives in 9/1998. But the traveler is convinced by Einstein SR that only one month of Earth time has elapsed since he passed Earth and noted the time as 8/1994. The traveler, upon arriving at Alpha Centauri, claims that the time is "now" 9/1994 on Earth. Alpha Centauri residents claim it is "now" 9/1998 on Earth. The difference is the time slippage predicted by SR.

If the traveler orbits Alpha Centauri at a speed of 0.99 c, then whenever he is headed in the direction of Earth his opinion changes to Earth time "now" is 9/2002. And whenever he is again headed away from Earth, Earth time is once again 9/1994. Earth time "now" changes continually, according to SR, because of these time slippage effects needed to retain frame reciprocity. Earth residents -- even the ones who died in 1998 -- are oblivious to their repeated passages into the future and past of the traveling twin, with concomitant deaths and resurrections.

So when the traveler finally does return, he will indeed find that time on Earth is 10/2002, just as his GPS clock shows. He accounts for this as two months of elapsed time on Earth's slow-running clocks during his own 14-month (by his natural clock) journey, plus 8 years of "time slippage" when the traveler changed frames. There is no logical or mathematical inconsistency in this resolution, which is why SR remains a viable theory today.

We are, of course, free to question whether or not this mathematical theory retains a valid basis under the principles of causality. For those of us who answer "yes", LR is unnecessary, and inelegant because it depends on a preferred frame. For those of us who answer "no", LR is then the better descriptor of nature, requiring the sacrifice of symmetry (“covariance”) to retain causality.

9. What physical consequences arise from the differences between LR and SR?

In SR, speed causes changes in time and space themselves, not just in clocks and rulers. Rest-

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