Does GPS Navigation Rely upon Einstein's Relativity?

Barry Springer
11450 N. Meridian Rd, Falcon, Colorado 80831
e-mail: bspringer@skybeam.com

A large scale overview of GPS system operation is provided and the process of achieving a navigation solution is explained. The process is based on classical physics. The one instance where a prediction of General Relativity (GR) appears to be realized is shown to be consistent with predictions of GR, but does not serve as a proof of GR. A closed loop feedback control system approach is shown to provide the error detection and correction that produces the high accuracy of the GPS system, without reliance on Einstein's relativity.

1. Introduction

We begin with a typical example of misunderstanding of GPS system operations and the popular, but erroneous, assertion that GPS relies upon Einstein's theories of relativity:

"The engineers who designed the GPS system included these relativistic effects when they designed and deployed the system." [1]

"Relativity is not just some abstract mathematical theory: understanding it is absolutely essential for our global navigation system to work properly! " [1]

In fact, it is difficult to find where Einstein's theories of relativity would actually affect the daily navigational performance of GPS. This is because the GPS system is not static system, pre-adjusted for purported relativistic effects, but a globally dynamic closed loop control system that continuously measures and corrects timing and positional errors to achieve the high accuracy navigation and time transfer performance for which it is famous.

To understand this last statement, a simplified big picture description of the GPS system operation is needed.

1. Obtaining a GPS Navigation Solution

Let's start with the GPS navigation solution. It takes three parameters to express a general navigation solution – such as longitude, latitude, and elevation. If time is not precisely known at the receiver, which is usually the case, it will be estimated by an iterative process starting with GPS broadcast time.

Solving for a unique location in three-dimensional space requires four range vectors from four accurately known locations. So, if we want to ensure that every spot on earth has simultaneous view of at least four satellites, and we model the earth as a six-sided cube with four satellites to each face, then we would need a minimum constellation of 4 satellites x 6 sides = 24 satellites. This is the minimum design size for the GPS constellation.

The downlink signal from each GPS satellite includes information concerning the satellite's orbit and location, called the ephemeris, and time of the signal broadcast. The distance from receiver to each satellite is the time difference between each satellite's broadcast time and estimated receiver time multiplied by the expected average signal propagation speed.

Estimation of receiver time starts with the latest time received from among the four GPS signals plus the shortest offset time if that satellite were directly overhead. The initial estimated receiver time would then be incremented until the most accurate navigation solution is found.

Eight location positions are possible by triangulating four satellite range vectors, three at a time. As the estimated receiver time closes in on the correct time, four of the solved positions will begin to converge upon one another and the other four positions will diverge to deep space. The estimated receiver time for which the average difference among the four solved positions is the smallest will be the best estimate of receiver time. The average of the four solved positions will be the reported position. The average error between the reported position and the four solved positions will be the reported position error.

Classical physics so far, without Einstein's relativity.

2. GPS Error Detection and Correction

The GPS Master Control Station (MCS) continuously receives inputs from a collection of globally dispersed Monitor Stations (MS). The location of each MS has been pre-determined by high accuracy survey. By processing the GPS signals received at each MS, the GPS solved location of each MS can be compared with the known survey locations.

The difference between the GPS solved location and the surveyed location is an error vector that can be associated with the group of GPS satellites used in the particular MS navigation solution. Each satellite will generally be within view of more than one MS, therefore clock and ephemeris errors from each satellite will contribute to more than one MS location error vector, allowing for the errors to be isolated.

By use of a fairly complex computer program, based on the Kalman filter, clock and ephemeris adjustment rates can be allocated and forward propagated for each GPS satellite such that, if all of the calculated adjustments were made, the summation of error vectors for GPS location solutions until time of next planned adjustment would be minimized. This constitutes a constellation wide closed loop control solution that determines and allocates errors, then implements forward corrections throughout the constellation to minimize average navigation and time transfer errors world-wide. [2]

3. Pre-launch Clock Frequency Adjustment

There is one effect in the operational cycle of a GPS satellite that deserves a bit more explanation -- that of pre-launch clock frequency. GPS atomic clocks are adjusted to a slightly lower frequency on the ground, so that when they assume their final orbital altitude, their operating frequency will be close to the desired nominal. This accommodates a known effect attributed to the gravitational field.

Proponents of Einstein's theories might seize this moment to declare victory for General Relativity (GR). I would caution – not so fast. The gravitational clock rate shift is predicted by GR, but observing the predicted shift does not of itself prove GR.

4. Competing Gravitational Theories

A competing theory of gravity, described by Nicholas Fatio and George LeSage, posits that the source of gravity is a mass flow of "ultra mundane corpuscles." These corpuscles are now referred to as "gravitons" and Fatio-LeSage theory is generally referred to as a "pushing theory of gravity." [4]

The Fatio-LeSage force of gravity is modeled as a shadowing effect, where two bodies shadow each other from a universal isotropic flux of gravitons. This creates a differential force on each body that pushes them together. The shadowing effect produces the appearance of attraction between the two gravitating bodies, and the computed effect has a $1/r^2$ distance relationship, just as with Newton's formula for gravity. [4]

If we were to postulate that frequency of atomic vibrations is also related to a general flux rate of some universally pervasive particles such as gravitons, then a clock ascending from earth into space would encounter an increased particle flux rate and therefore run faster. Would that then prove pushing gravity? No, it would not, just as observing the same effect did not prove GR.

The point is that clock rate vs. gravity is an observed effect, which is neither uniquely explained by GR nor by pushing gravity. Furthermore, if navigation were the only GPS system mission, accurate on-orbit time keeping would not even be required. The only requirement would be that all on-orbit GPS clocks must be closely synchronized in time.

Therefore, considering just the GPS navigation mission, the clock frequency pre-set prior to launch would not even be required.

Accurate synchronization of on-orbit GPS clocks with standard ground time is only required for the precision time transfer mission that GPS also supports, but not for the navigation mission.

5. Primary GPS Error Sources

The greatest sources of GPS errors are related to integrated electrical charge effects along the satellite to receiver signal paths and to the relative satellite geometry of the navigation solution.

GPS to receiver signal paths traversing regions of highly charged ionosphere, such as routinely occur in low elevation reception paths crossing the day/night terminator, will experience varying signal propagation speeds, which can induce significant satellite to receiver range errors. These errors can be corrected if both the L1 and L2 signals are received and processed. This signal propagation speed correction would usually be performed in military GPS receivers, but most likely not in civilian receivers. [5]

Co-planar geometric solutions involving satellites spread low on the horizon, such as at high latitude, will produce strong lat./lon. solutions and weak elevation solutions. Conversely, co-linear geometric solutions involving satellites generally clustered overhead, such as in city canyons, will produce strong elevation solutions and weak lat./lon. solutions. Generally, even geometric dispersal of satellites produces the most accurate navigation solutions. The geometric strength or weakness of the navigation solution will be seen in the reported position error estimate.

Down the list of other possible contributing errors, one will encounter receiving problems when there are high relative velocities between a GPS satellite and a GPS receiver. Such situations might occur when using GPS signals for attitude determination or position location onboard another satellite. [2]

But, even in such cases, the relativity problem is simply Doppler frequency shift pushing the received frequencies out of the receiver pass band, not a Lorentz type relativistic correction.

Thus far, we have not yet found where Einstein's relativity is "*absolutely essential for our global navigation system to work properly*" as has been asserted. [1]

6. Is Einstein's Relativity Required for GPS Navigation?

There are mathematical purists who will insist that relativistic effects can be found in the GPS system that could be eliminated through corrections based on Einstein's relativity. But even they admit that "*introducing the gamma factor makes a change of only 2 or 3 millimeters to the classical result*." [2] Such small error corrections, if even valid, would represent only a 0.1% adjustment in a typical navigation solution accurate to 2 or 3 meters.

We have found no need to be concerned about adjustments for Einstein's relativity effects with regard to GPS navigation operations – they are simply not required.

7. Conclusion

The GPS global navigation system delivers phenomenal performance by virtue of architectural design as a closed loop control system that dynamically identifies, allocates and corrects errors, and does so routinely without reliance on Einstein's relativity.

8. References

[1] Richard Pogge, Real-World Relativity: The GPS Navigation System, http://www.astronomy.ohio-state.edu/~pogge/Ast162/Unit5/gps.html, 2009.

[2] Tom Van Flandern, Open Questions in Relativistic Physics, Aperion, 81-90, 1998.

[3] Henry Fliegel and Raymond DiEsposti, GPS and Relativity: an Engineering Overview, The Aerospace Corp, 1992.

[4] Matthew Edwards, Pushing Gravity, Aperion, 65-78, 2002.

[5} John Klobuchar, Ionospheric Effects on GPS, GPS World, April 1991.