Working group
OUTREACH of APPLICATION FOR SOCIETY
November, 2022

Einstein's Relativity in Action – the GPS Navigation System knows it

Have you ever wondered how your mobile phone knows where you are, or how it can guide you to where you want to go?

If so, this is a real-life example of an application of the principles of Einstein's theories of general and special relativity being applied in practice - our Global Positioning System (GPS). Indeed, research in theoretical physics and mathematics can lead to innovations that affect everyday life.

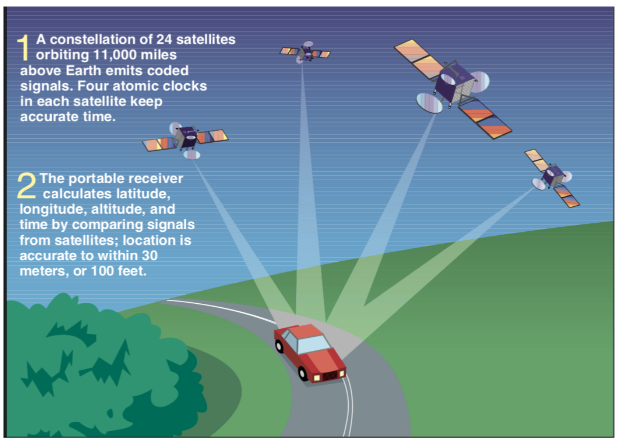
GPS - precision for our daily life
(Oleksiy Mark/Shutterstock)

What is GPS and how does it work?

Nowadays technology makes it very easy for us to know where we are and when we are in a certain position without having to know how it works we just have to look at our GPS - though you have probably experienced failures in remote places.

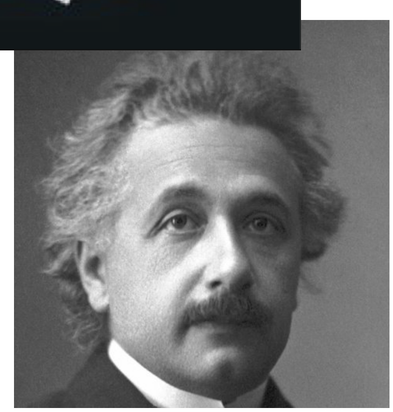
The Global Positioning System (GPS) is a network of satellites and receiving devices used to determine the location of something on Earth, for example your mobile phone. Today's GPS receivers are so accurate that they can pinpoint their location (latitude, longitude, and altitude) to within one centimeter.

It was invented aready in 1973 and was originally limited to use by the US military. The GPS device records the exact time at which it receives this information from each satellite and then evaluates how long it took for each signal to arrive. To a first approximation, by multiplying the elapsed time by the speed of light, it can work out how far away it is from each satellite, compare these distances and work out its own position.



Each of the satellites has several atomic clocks that contribute very precise time data to the GPS signals. GPS receivers decode these signals, effectively synchronising each receiver with the atomic clocks, which tell time by measuring the rapid oscillations of atoms. They are so precise that they will not lose even a second of time in billions of years.

Sketch (www.nasonline.org/publications/beyond-discovery/the-global-positioning-system.pdf)



What is less well known is, that in order to do this accurately, we need to take into account Einstein's theories of space and time. It's not that difficult to see why. GPS tells us our position in space and time and both space and time are goverened by the theories of special and general relativity.

Intermezzo

Special relativity SR
describes the movement of bodies and fields in space and time and states that all laws of physics have the same form in all non accelerated reference systems. It states that

- the speed of light in vacuum has the same value in all non accelerated reference systems
- lengths and time duration depend on the state of motion of the observer and therefore moving clocks go slower
- that there is no absolute space and no absolute time
- that mass and energy are equivalent $E = m c^2$

General relativity (GR)
GR states that the observed gravitational effect between masses results from their warping of the four-dimensional space-time. Einstein's description of gravity explains several experimentally observed effects, e.g.

- the deflection of light by the sun
- the existence of black holes - celestial objects of such high density that even light cannot escape their gravity
- gravitational lenses that deflect light from stars and galaxies
- the slowing down of time due to gravity (gravitational time dilation)
- the existence of gravitational waves

Watch here a video of Albert Einstein explaining the general theory of relativity.

Back to GPS
Einstein's general theory of relativity explains why the clocks in the satellites tick faster. Similarly, the theory of special relativity explains why they tick slower. This can be confusing!

So in more detail:
According to GR, **atomic clocks at different altitudes and therefore in different gravitational fields tick at different rates**. The frequency of the atoms' radiation is reduced when observed in stronger gravity, closer to the Earth. The closer the clock is to the source of gravity, the slower time passes; the farther away the clock is from gravity, the faster the time passes. For the Earth and the satellite, this makes a difference of 45 microseconds per day. For a satellite travelling at 3.874 kilometers per second, the clocks in the satellite aremoving at great speed, and that makes **these clocks appear to run slower than the clocks on Earth by about 7 microseconds per day, as explained by SR**.

Thus, the differences from a naive expectation, of just assuming that the signals are transmitted at the speed of light, are 45 microseconds per day from GR and -7 microseconds per day from SR, respectively,giving a total difference of 38 microseconds per day. This results in a mispointing of 11 km per day or 8 m per minute.
So without Einstein's corrections, GPS would become inaccurate within seconds!

In fact, before this was properly taken into account, the atomic clocks in the first GPS satellite, were were not properly slowed dow.

This video gives you a good overview.

Connection to IPPOG:

Opera (The Oscillation Project with Emulsion-tRacking Apparatus) was an instrument used to detect neutrinos. These are very light, neutral elementary particles that were produced at CERN. The neutrinos were measured with a detector near Rome. GPS was used to precisely determine the distance (730 km) between the production and detection of the neutrinos. In 2011, the Opera collaboration announced that they had observed neutrinos, that appeared to be travelling faster than light, violating special relativity.
Later the researchers found the reason: A link from a GPS receiver to the OPERA master clock was loose, causing a mismeasurement of the distance, and making the neutrinos to seem to travel faster than light.

Wrap up

In summary, the GPS would not properly work if we did not know about relativity and apply the necessary corrections. Indeed, not taking this into account properly lead to a failure of a launch of one of the satellites in 2014. Learn the full story in this video.
Hence, GPS is an indirect prove that Einstein's principles hold.

Useful LInks:

- How Einstein's general theory of relativity killed off common-sense physics (The conversation 11/2015)
- GPS, (National Geographics)
- What s GPS and how do global positioning systems work? (GEOTAB)
- What is the theory of general relativity?