THE DEMONSTRATION CORNER

GPS Meets Einstein

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Column Editor's Note: The author of this article presented a fascinating talk about this topic at the 2010 OAPT Conference. Via the weblink provided in the article, readers can obtain access to a very useful student activity that demonstrates the importance of relativity in the operation of GPS.

The Global Positioning System (GPS) is one of the twentieth century's greatest engineering marvels. Today, it's the backbone of billions of dollars of economic activity. It's used by a vast array of occupations including farmers, construction workers, doctors and even professional athletes. And all this comes on top of the more familiar personal applications like satellite navigation in cars and for hiking.

As well as being immensely practical, the GPS also involves some pretty cool physics — even, strangely enough, Einstein's theory of relativity.

The GPS is based on network of 30 or so satellites that continually send out ultra-precise timing signals in the form of radio waves. By picking up a signal from one satellite, you can calculate your distance d from the satellite via the equation $d = v\,\Delta t$, where v is the radio wave's speed (the speed of light) and Δt is the time the wave takes to get from the satellite to you. Repeating this process for four satellites, you can pinpoint your location anywhere on Earth to within a few metres. To me, this level of accuracy is simply amazing.

But, where does relativity fit into the picture? The concept of *time dilation* in special relativity says the faster the speed of an object (relative to an observer), the slower the observer measures the object's time as passing. Interestingly, *general* relativity — Einstein's theory of gravity — also tells us there's another type of time dilation, one based on gravity. *Gravitational time dilation* says that the strength of a gravitational field affects the rate at which time passes. Clocks in weaker gravitational fields run faster than clocks in stronger fields.

Each GPS satellite houses a state-of-the-art atomic clock capable of measuring time to within a fraction of a nanosecond. The timing of the GPS signals is so precise, the system needs to take both types of time dilation into account for the GPS to work. The effects are tiny, just 7 microseconds a day from special relativity and 45 microseconds a day from general relativity. However, if these numbers are substituted into the equation $d = v\,\Delta t$, you get distances of 2 km and 12 km respectively over the course of a day[1]. That's more than enough to render GPS navigation completely useless if relativity is not properly factored in.

The GPS takes relativity into account by offsetting the timing of the atomic clocks slightly to compensate for the effects of time dilation. To me, this is a beautiful example of the usefulness of modern physics.

To help highlight the link between the GPS and relativity, Perimeter Institute has created a new classroom resource on the topic. "Everyday Einstein: GPS and Relativity" has a five-minute in-class video along with a 20-page teacher's guide. The guide includes extra information for teachers and five student worksheets and activities. Everything can be found on Perimeter's website at: http://www.perimeterinstitute.ca/en/Perimeter_Inspirations/GPS_%26_Relativity/GPS_%26_Relativity/

Teachers from across Canada can also order a physical copy for free from PI's website. I hope people find it a useful addition to their classrooms.

End Note

[1] To get the results 2 km and 12 km, you need to multiply the distances results by the number of seconds in a day, 86,400.

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Submissions describing demonstrations will be gladly received by the column editor.
