Astronomy Cast 212 for Monday, December 20, 2010: GPS Navigation

Fraser: Welcome to Astronomy Cast, our weekly facts-based journey through the Cosmos, where we help you understand not only what we know, but how we know what we know. My name is Fraser Cain, I'm the publisher of *Universe Today*, and with me is Dr. Pamela Gay, a professor at Southern Illinois University – Edwardsville. Hi, Pamela! How are you doing?

Pamela: I'm doing well, Fraser. How are you doing?

Fraser: I'm good. We're both very well rested. You went on a cruise in Europe. I went on a cruise in the Caribbean, and yeah, it's good.

Pamela: And you're tanner than I am!

Fraser: No! It was like an icebox, well the Caribbean was warm, but southern Florida was cold…cold…colder than home. So I moved back to the west coast for warmth. And I know the timing is all messed up – we're actually recording this in January, but the date is December, so…last week we talked about the old way that navigators used to find their way around the planet by looking at objects in the sky and doing some tricky math. The new navigation system, of course, is the Global Positioning System, and it helps you find your spot on the planet with amazing accuracy. Let's see where this system came from and how it works. Let me just get this off the record, just so people can know my political leanings here – I love GPS! I think GPS is the coolest thing ever! I've got an ipad and it's got a GPS on it, and you're driving down the road and you can see where you are on Earth – it's really awesome! So that's it. If people can keep this in mind as we do this show – I totally love GPS. But the current GPS systems that we have today are very different from the beginning idea. So where did the concept of a satellite-based navigation system come from?

Pamela: Well, it's basically military -- U.S. military -- not as warm and fuzzy as ipad. It's a U.S. military 'we need to know where we are because we're doing things in the dark late at night and we don't want to turn on the lights.' It's a system for deploying things, bombing things, destroying things without being able to see them.

Fraser: Yeah, that does take a little of the shine off it.

Pamela: Yeah, kind of… a lot.

Fraser: Right, so the military decided that they needed some way to work at night -- you know work in fog, work in the clouds, so…

Pamela: …work in deserts with no markings, and satellites are a good way to do it.

Fraser: So what did they come up with originally?

Pamela: Well, this is basically an extension of the idea of "OK, so I left the city, I went 300 miles straight west, I then went 400 miles straight North, where am I? You can figure it out.

Fraser: That's dead reckoning.

Pamela: That's dead reckoning. Then combine with that the idea of triangulation. You look at something you figure out "OK, I know I'm this far away from this object, therefore I can figure out the distance by knowing that." These are two different ways of figuring out where things are located in space.

Fraser: Right, and you can be standing in a spot, you can see a mountain over that way, and a tall building over in that other direction, and some tower and then you can work out your angles to those objects and determine where you are if you have a map showing where they are.

Pamela: Right. Now, with satellites, it's not as easy, but in some ways, it's easier because you can stick a whole lot of satellites in orbit. And that's what we did. There's 27 GPS satellites orbiting the planet, 3 of them are sitting in reserve, 24 of them are constantly sending out happy little messages of I am here I am here! Where they actually articulate where they are in time and space sending out messages that include their ephemeris information and atomic clock information

Fraser: And the atomic clock is the important part.

Pamela: Well, actually both of them are equally useful information, so if I said I am 300 miles from a city, and I never say where that city is on the planet, being 300 miles from it – not so useful, and the time is actually that I'm-300-miles-away information. So the satellites have to be hanging out saying "I AM HERE!" saying where they are, and by saying where they are, and when that statement comes from, someone receiving that information can say "OK, I know what time it is where I am. I know what time it was when that information was sent." And that difference in time gives you the distance because of the speed of light -- that's convenient. And when the satellite tells you where it is, it tells you how far you are from a known point. Now, this gets complicated to think about in 3 dimensions. So let's think real fast about 2-dimensional space on the surface of a planet. If I say I'm 300 miles away from Calgary (which I am picking because it's kind of in the middle of a whole lot of flat), so if I say I'm 300 miles from Calgary, that tells me that I'm somewhere on a circle that's 300 miles in radius. Now, I don't know where I am on that circle. Now, if I say I'm also 5 miles away from farmer Brown's farm, I can now know, I'm 5 miles away (radius) from that farm.

Fraser: That kind of cross in two points.

Pamela: Right, so that narrows down my location on the planet to two places. That's kind of cool! So add to that I'm one mile from the gas station – well, that's another circle. So if your measurements are accurate you can now, taking this distance from Calgary, this distance from the farm, and this distance from the gas station, figure out exactly where you are on the surface of the planet.

Fraser: But you need those three points. One doesn't help you, two narrows it down to two spots, but three gives you one single location.

Pamela: Right. Now the problem with dealing with satellites is it's not a circle that you're dealing with anymore because you can be on any side of the satellite you want to be. You can even be on the other side of the satellite closer to the moon rather than the side that's closer to the Earth.

Fraser: Right, they're like spheres around these satellites.

Pamela: Right, so satellites orbit I think about 12,000 miles up, then that gives me an awful large sphere I could be located anywhere on, and the surface of the planet isn't exactly flat. You could be on top of a mountain, you could be in a building, you could be in a coal mine -- although the satellite signals aren't likely to reach under the ground...

Fraser: or you could be near to the equator where the planet bulges, or near the poles where the planet's less bulged.

Pamela: …bottom of a gorge, there are lots of places you could be that are either higher or lower, you could even be in an aircraft, and aircraft use GPS.
So now I'm dealing with this sphere, and when I'm dealing with this sphere, I no longer can use just three spheres because I still have multiple locations I could be, so now it requires four satellites -- four spheres -- that hopefully overlap in one point. Now, when we talk about error in GPS positioning, because any of you who've ever used an iphone know when you get that little blue dot that lets you know where you are, it has a light blue circle around it on the surface of your map and that circle represents the error, and sometimes you end up with like "I'm somewhere in the state of Ohio," because it can't get enough satellite signals, and that's where you get a large circle of error, and sometimes you just get a little tiny Starbucks-sized circle of error, and that circle of error comes from error in the timing. So if you think about it, I know the signal came within plus or minus nanoseconds, and if I was dealing with my distance from Calgary, farmer, and gas station, that would be the thickness of the circle lines. So instead of having a precise, absolute point-point-point on the surface of the planet, I actually have with the thickness of those three line converges, which might be a Starbucks-sized intersection point. Now, when I'm dealing the spheres, what I'm

dealing with is the thickness of the skin of those spheres, which comes together to create a 3-dimensional error in “up-down, left-right, forward and back,” and so the errors are simply timing errors.

Fraser: Now, when you say a timing error, is that a problem with the original clock? Is that a problem with my clock?

Pamela: It’s a little bit of all of the above.

Fraser: Is the speed of light changing as it goes through changes in the atmosphere?

Pamela: No, that isn’t an issue. The speed of light is the speed of light is the speed of light. This is the thing by which all clocks tick.

Fraser: But it doesn’t change as it goes through the atmosphere.

Pamela: Well, the speed of light does change as it goes through the atmosphere. We don’t worry about that one. That one is just built into the calculations. We know where the atmosphere begins; we know where the atmosphere ends – we’re good! But there are minor errors built into the system, and built into the fact that…well, your cell phone has to know exactly “when” it is, and your cell phone doesn’t have an atomic clock built into it…

Fraser: Which is really good, I think…if we were carrying around atomic clocks -- that would be bad.

Pamela: [laughing] It would be a whole lot heavier and not fit into my front pant pocket nearly so well.

Fraser: Yeah…”accurate time cancer.”

Pamela: Right. Well, atomic clocks aren’t all nuclear decays, most of them are oscillations, so we don’t have to worry about cancer from oscillations.

Fraser: OK, good…just lugging around a 100-pound clock…

Pamela: [laughing] Yeah, I’m not that fond of cesium. Anyway, as we’re now wandering off the topic...So, your cell phone, mostly kind of sort of has accurate time. It’s constantly updating its time off of towers, which are hopefully updating their time off the network of atomic clocks, but this can lead to small errors in your handheld system. Now, it also used to be -- and this has been fixed -- it used to be that the U. S. military didn’t want other people to know precisely where they were, and since the way these satellites work is they’re just hanging out in space going: “I’m here! I’m here! I’m here!” over and over and over -- anyone can listen to their signals. So when they first put it out, they had an encrypted signal and then they had the public signal, and the public signal had built-in random timing errors, and these built-in random timing errors kind of meant that you only knew where you were within a 100 meters, which is pretty good unless you're trying to bomb a house, which was what the military was concerned about.

Fraser: But I can see that from their point of view it's kind of frustrating. You build this enormous expensive satellite navigation system to give you an edge over the enemy and then they can also use it as well.

Pamela: Right. So they built in this fudge factor, this randomization, and the thing was that very determined geologists found ways around this. So if I know where I am within 100 meters, and my friend knows where they are within 100 meters, and my other friend knows where they are within 100 meters, there's probably only one solution if we know precisely where I am relative to my two friends, and they know precisely where they are relative to the other two – me and the third friend, second friend – three people involved. Anyways, if all three of us know exactly where we are relative to one another, we can figure out exactly where we are relative to the planet using the fact that there's probably only one solution that allows all three of our measurements that have error bars and the exact locations that we think we're at.

Fraser: Right, so geologists would use multiple GPSs to overcome the error and find out where they were, and I'm sure that the enemy countries would do the same thing, so I'm sure that's a big reason that they eventually got rid of that error, which is great. That takes away all the joy when you don't know where you are within a 100 meters….turn right at this street, which isn't there. That's official now, that's gone now there's no error anymore.

Pamela: Well, there's still minor error, it's the whole "turn left in 5 meters" and you realize, "No, no that left already occurred. Sorry, Mr. GPS System, you lied."

Fraser: Right, but the U.S. military is not injecting an artificial error into it on purpose. That's gone.

Pamela: Right. So we still have these small low-scale, not-good-enough-to-land-a-plane-using-simply-your-Garmin-GPS-device, but the thing is they're landing airplanes using mostly GPS and other control systems that give accurate positions.

Fraser: Yeah, I mean this is one of those situations where we get all these unintentional wonderful benefits with the horrible military technology, but now you get…we're going to have cars that drive themselves. As I said, you can go for a hike and you can see exactly where you are on the Earth. Getting lost is harder; it's still possible…

Pamela: It's still possible, again, that five meter error really can matter at times, but the thing is with the differential idea that geologists and presumably other militaries came up with, we can now, by saying "OK I have a fixed reference point. This pillar at this airport – I know exactly where this pillar is and this pillar. I can use it as another known space in my coordinate system." And that allows us to take the 24 satellites orbiting the planet, find 4 of them, find the known source, and now I know where I am to within centimeters, sometimes millimeters, and this allows us to land planes!

Fraser: So is this like the assisted GPS system?

Pamela: I don't know. I haven't heard that fact.

Fraser: OK. The three G's and the iphone and the ipad and a lot of these they have a GPS plus, or something like that, so it uses the GPS and it also uses the cell tower network as an additional reference to give you that super-duper accuracy.

Pamela: The thing about cell phones is they're not using just the satellite system. I was just recently in Venice, and if you've ever been to Venice it is an island of alleyways, and in order to use the GPS system to figure out where you are, you have to have a clear line of sight to at least 4 satellites, and if you're in one of these little tiny alleyways, that is not going to happen. And the way phones and Garmin devices and other devices often compensate – especially, iphones – is they look to see, "OK, what cell networks can I pick up? What wireless networks can I pick up?" And it takes all of this extra information, and uses that extra information: "Can I hit 3 cell towers instead? Can I hit 3 open known location wireless networks instead?" and figure out from that more information on where you are.

Fraser: Yeah, and I've noticed that when you're in a cell service area, the GPS is a lot more accurate. Now, we're using the word GPS – the Global Positioning System – but that's like a brand; that's like saying "Coke is delicious," and not talking about it just being cola, so in fact, this satellite navigation system, this is just one that's currently being developed, but there are others in the works and there have been others in the past, right?

Pamela: Right, so the issue is the U. S. has its GPS system and this is the one that all the commercial software is using: all of your Garmens, all of your moovoos (I think that's a network that may be an MP3 player. Forgive me if I screw that one up), your iphones, your androids, your hiking devices, all of these things are plugging into the U. S. system. It works everywhere on the planet, which says something about how the U. S. military was thinking. But the Soviet Union, now Russia -- clearly not so big a fan of having to rely on U. S. technology, so the Russian global navigation was in use by the Russian military only until 2007, running a parallel system that they could use for their own we'd-really-like-to-bomb-that-house-over-there day-to-day problems. There are also plans for the Chinese to build a compass navigation system. The European Union is looking to build the Gallileo positioning system, which I love because Gallileo knew nothing about relativity. So if you actually use the math Gallileo would have known, it will fail miserably, but I'm going to assume that the European Union simply took their most famous astronomer in history, used his name, and will apply relativity liberally.

Fraser: Right. Now, we, in the past, have talked about how relativity plays a part in GPS navigation. So, how does it work?

Pamela: Well, we have two different problems we have to deal with (and this is where I encourage all of you to go back and listen to our relativity episodes): the first problem that we have to deal with is these silly little satellites that do such a wonderful job ARE IN MOTION. A lot of people think that they're geosynchronous satellites that constantly stay in the exact same place over the planet, but they're not. That would actually cause problems because the only place you can stick geostationary orbits is over the equator, which means you wouldn't really have GPS at the poles of the planet, and who knows? Maybe you'd like to bomb an iceberg…

Fraser: So, imagine these are a cloud of buzzing bees around the planet. They're not staying in one spot; they are constantly in motion.

Pamela: So each of them has a 12-hour orbit; they go around the planet twice a day, and they're orbiting just like you said – in a cloud -- so everyone has at least four in sight at any moment and in particularly lucky moments, you have twelve of them you can use to get your position very accurately.

Fraser: …to within a nanometer.

Pamela: I wouldn't go that far, but you can get it accurately, so when one things is in motion compared with another, you have to start dealing with time dilation issues, so according to special relativity, the fact that these satellites are moving relative to the person standing lost on a street corner causes a slowing down of the satellite's clock, relative to that stationary person, of about 7 microseconds per day if you stayed lost for an entire day. So, you have, on one hand, moving satellite, non-moving human. That leads to the two clocks getting more and more out of sync as the satellite continues to orbit over time – that's one thing.

Fraser: Right, and this just adds up. The satellite is launched, it has a clock on-board, the satellite is orbiting the planet around and around, and this time dilation just builds up over time, right?

Pamela: Right and so this is an ongoing problem that we have to correct for, and that's OK – it's math. It means that we can do the calculation, but if you don't take relativity into account, the difference between the two clocks will build up over time, and how far off your position is gets worse and worse and worse over time.

Fraser: …which is pretty amazing. So, is the satellite doing the math? Are the people on Earth doing the math? Probably both.

Pamela: It's a combination of both, but that isn't actually the only problem we have to deal with because if that was the only problem we have to deal with, you figure out, "OK, this sucker is orbiting at a constant rate, I just reset the clocks and move on with life, but if you did only that, you would still be wrong.

Fraser: Wow! Tell me how I'm wrong. How would I be wrong?

Pamela: So, the other problem is we're within a "gravity well." So here on the surface of the Earth, we experience more gravity than the spacecraft up in orbit, and this difference in gravity is not identical, but it's kind of sort of analogous to moving faster. So just like the satellite clock slows down because of its motion, our clock slows down because of our higher gravity, and this is actually a greater fact because we're that much closer to the center of the earth, our clocks are slowing down 45 microseconds per day compared to that satellite.

Fraser: 45 microseconds…and how much is the difference from its speed?

Pamela: So, we have satellites slowing down each day 7 microseconds compared to no differences in gravity compared to non-motion, then we have --because of the difference gravity -- we're slowing down 45 microseconds per day, so take the difference we're looking at depending on where you are on the surface of the Earth between 35 and 45 microseconds per day of relativity-induced differences in clocks.

Fraser: Right. So within days/weeks/months if you didn't account for that, your timing signals would be worthless.

Pamela: Right, and so just one week of not taking this into account is the difference between starting out one day in Columbus, OH and a week later being somewhere over Detroit.

Fraser: Right, and that's a week, so give it a year and you could be anywhere on Earth, and at that point the satellite's no help at all.

Pamela: Right, so we have to take relativity into account, and so they actually when they built the GPS satellites, they based their clock on a slower tick rate, so that we can take into account these differences over time.

Fraser: Well, that is incredible! I didn't know that it was that significant. So thanks, "Einstein!"

Pamela: Relativity isn't a complete science. We still don't get the insides of black holes. We still haven't unified it with anything, but you know what we know about it sure works and allows us to know exactly where we are. And one of the more terrifying things is someone who flies constantly. I've learned when they build all of these autopilot systems, they build it so that the autopilot can land the airplane! So, all of those A-Team episodes where Hannibal is landing the plane…

Fraser: Yeah, "Is anybody a pilot?"

Pamela: Right! No, no, no – autopilot does that now.

Fraser: Feel free to let the plane land itself. I can't wait for my car to drive itself. That will be amazing!

Pamela: Yeah, I don't trust myself on ice and snow, and I'm not sure how I feel about computers on ice and snow, but dry roads – I'm looking forward to that.

Fraser: Yeah, I would happily give up my control to a computer. No problem. Alright, well that's great, Pamela. Thanks a lot, and we'll talk to you next week.

Pamela: Sounds good, Fraser. I'll talk to you later.